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Study of a High-Energy Upper Stage for Future Shuttle Missions

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ABSTRACT

Space Shuttle Orbiters are likely to remain in service to 2020 or beyond for servicing the International Space Station and for launching very high value spacecraft. There is a need for a new STS-deployable upper stage that can boost certain Orbiter payloads to higher energy orbits, up to and including Earth-escape trajectories. The inventory of solid rocket motor Inertial Upper Stages has been depleted, and it is unlikely that a LOX/LH2-fueled upper stage can fly on Shuttle due to safety concerns. This paper summarizes the results of a study that investigated a low cost, low risk approach to quickly developing a new large upper stage optimized to fly on the existing Shuttle fleet. Two design reference missions (DRMs) were specified: the James Webb Space Telescope (JWST) and the Space Interferometry Mission (SIM). Two categories of upper stage propellants were examined in detail: a storable liquid propellant and a storable gel propellant. Stage subsystems other than propulsion were based largely on heritage hardware to minimize cost, risk and development schedule span. The paper presents the ground rules and guidelines for conducting the study, the preliminary conceptual designs achieved, the stage mass breakdowns and flight mass margins, assessments of technology readiness/risk, potential synergy with other programs, and preliminary estimates of development and production costs and schedule spans. Although the Orbiter Columbia was baselined for the study, discussion is provided to show how the results apply to the remaining STS Orbiter fleet.

INTRODUCTION

The High-Energy Upper Stage (HEUS) study was a six-month effort performed by Northrop Grumman Space Technology (NGST) for NASA Marshall Space Flight Center in the last half of 2002 under NASA Contract NAS8-01110. This work identified the planning, funding, technology development and risk areas for a new, Orbiter-compatible upper stage that would utilize either storable hypergolic liquid propellants or storable hypergolic gel propellants to perform the JWST and SIM reference mission orbit injections. Design approaches considered the ease of accommodating different propellant loads to enable stage use on other future missions as well.

Overall study emphasis was to structure a development program and select hardware designs for low risk, with technology that is or can be approaching a Technology Readiness Level[1] (TRL) of 7 (system prototype demonstration in a space environment). The development cycle (goal of 48 months to first flight) and selected technologies were examined for possible synergies with other NASA, DoD and commercial programs, including expendable launch vehicle applications.

Guidelines and requirements for performing the HEUS study were a combination of MSFC criteria and NGST-derived criteria. Key parameters are summarized in Table 1. For this study, the Shuttle payload bay lift capability was obtained from the Proposed NSTS 07700 Control Weight document[2], including baselining use of Remote Manipulator System (RMS) for deployment. Additional details on the study requirements, design and component trades and iterations, and final results are contained in the HEUS Study Final Report[3].

Table 1. HEUS Study Key Requirements & Guidelines

- JWST mass = 5400 kg (C3 = - 0.69 km2/sec2, _V = 3169 m/s)
  SIM mass = 5000 kg (C3 = +0.40 km2/sec2, _V = 3219 m/s)
  HEUS max. loaded mass = 15,542 kg (JWST/OV-102)
- JWST stowed dimensions = 4.57 x 9.78 m
  SIM towed dimensions = 4.57 x 11.18 m
  HEUS max. length = 5.31 m (SIM/OV-102)
- Shuttle characteristics based on the use of OV-102 (Columbia) with a "hand-off" orbit of 160 NM @ 28.45° inclination
- Shuttle safety per NSTS 1700.7B, KHB 1700.7A, and MIL-STD-1522A
- Assume _V reserve of 1 percent
- Provide RCS for PYR control and _V anytime during flight; 80,100 N-sec total impulse with redundant 90–180 N thrusters
- HEUS-to-spacecraft adapter mass = 45 kg (100 lbm)
- Wire harness from HEUS to the payload and HEUS battery to payload (spacecraft) have a combined mass = 34 kg (75 lbm)
- Mass contingencies shall be:
  _ 30 percent for new components,
  _ 5 percent for "off-the-shelf" heritage, and
  _ In-between these two extremes, Contractor assessment based on experience and best practices
- Important considerations:
  _ Contamination (inc. engine firing plume)
  _ Injection accuracy (comparable to EELV)
  _ Electrical power from batteries (baseline no solar arrays)
  _ Shuttle flight/abort loads and c.g. requirements
  _ Autonomous avionics
  _ Low thrust (<5000 N) boost is not appropriate for study

Northrop Grumman incorporated the results from previous upper stage studies, particularly the Adaptable Space Propulsion System (ASPS) study and the Shuttle Upper Stage (SUS) study, to rapidly converge on the selected, "baseline" configurations discussed below.

The study successfully identified component technologies, system designs, program planning, and program costs for development-to-first flight of both a

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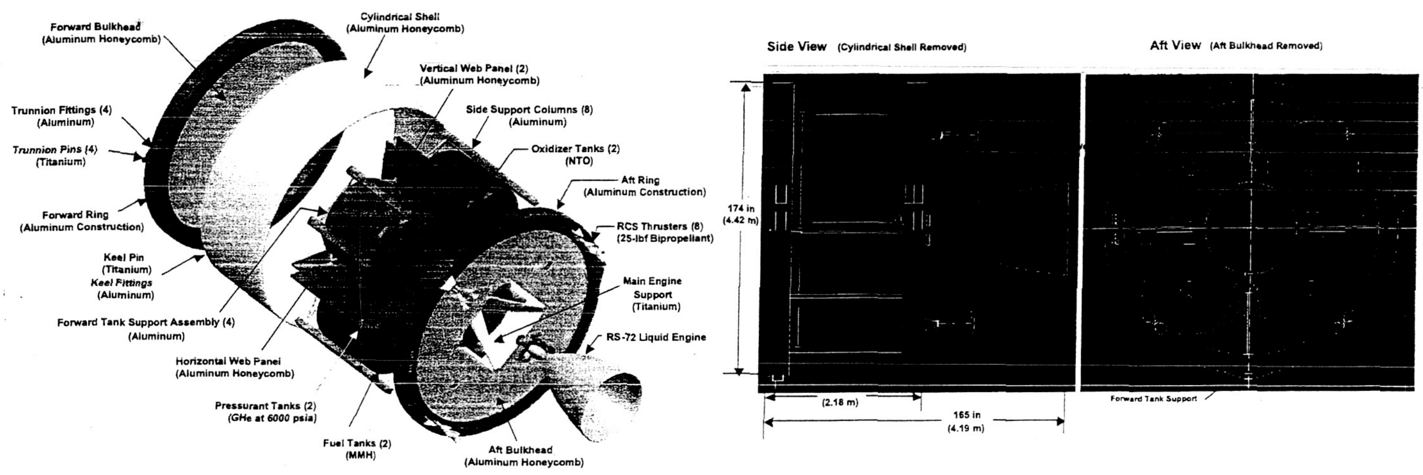


Figure 1. HEUS Baseline Liquid Stage

storable liquid-fueled stage and a storable gel-fueled stage. A pump-fed liquid stage was estimated to require $154M non-recurring over a 4.5–5 year span, with recurring unit stage cost at $36M based on initial buy of four units. The pump-fed gel stage was estimated to require $185M non-recurring over a 6-year span, with recurring unit stage cost at $39M based on initial buy of four units. These estimated costs are in FY2003 dollars.

BASELINE LIQUID STAGE SUMMARY

Major propulsion and structural items comprising the selected liquid stage resulting from the HEUS study are shown in Figure 1. The stage uses a straightforward structural design employing low-cost aluminum and aluminum honeycomb construction. Propellant tank axial loads are handled by the "pentagon" support trusses at the forward end while the lateral loads are handled by the forward and aft bulkhead acting as shear panels. Four side trunnion fittings and single keel interface with the Shuttle bay mounting provisions. The stage contains four boss-mounted propellant tanks arranged side-by-side. 56-inch diameter MMH tanks and 66-inch diameter NTO tanks, both about 74 inches long, supply propellants to a main axial engine and two redundant banks of four RCS bipropellant engines, each canted so as to provide PYR control when fired in selected pairs. Much smaller pressurant tanks are mounted off the web panels. A single pump-fed RS-72 main engine is mounted to the titanium aft engine support, which in turn attaches to four aft corners of the internal webs.

The 90-inch long engine is submerged into the aft volume between the tanks giving an overall stage length of about 165 inches. This is well under the maximum allowable length of 209 inches for the stage plus adapter (driven by the SIM DRM) using the RMS and 227 inches using the SPDS. If needed for packaging and/or thermal reasons, the engine submergence can be reduced with negligible effect on weight.

Stage avionics units (not shown in the drawing) would be mounted in two reinforced, hinged panels cut-outs of the cylindrical shell. The outer surface of these hinged panels would have a second-surface silvered Teflon coating to provide radiation cooling for the internally mounted avionics.

The associated key features of this stage are summarized in Table 2. The performance values are based on the JWST DRM using the RMS for deployment. The stage was sized to match the OV-102 lift capability.

Table 2. Liquid HEUS Key Features

- **Overall Stage**
  - 1,570 kg stage dry weight (including 16.6% contingency)
  - 12,466 kg prop and pressurant weight (including residuals)
  - 14,037 kg total loaded stage weight
  - 281 kg dry wt margin (17.9%) for JWST DRM using RMS
  - 4.19 m overall stage length (165 inch)
- **Main Propulsion Subsystem and Tankage**
  - Single 55,380 N (12,450 lbf) gas generator cycle RS-72 engine using NTO/MMH propellants
    - 338.5 sec vacuum Isp; 895 psia Pc and 300 Ae/At nozzle extension
    - Regeneratively-cooled chamber; *radiation-cooled nozzle* extension
    - Engine in development; based on XLR-132 turbopump and Aestus I technology
  - Engine gimbaled in pitch/yaw axes up to 5 deg using EMAs
  - Four graphite-overwrapped, boss-mounted propellant tanks with PMDs
    - Two 66 x 74-in oxidizer tanks and two 56 x 74-in fuel tanks
  - GHe tank pressurization at 120 psia using redundant electronic solenoid valves
    - Two 6000 psia graphite-overwrapped pressurant tanks
- **Reaction Control Subsystem**
  - Eight 110 N (25 lbf) aft-mounted NTO/MMH thrusters integrated with main propulsion feed system
  - Provides roll control during burn(s); PYR control during coast; and _V for CCAM (stage collision avoidance)

HEUS performance margins for the SIM DRM are greater. Additional performance margin can be obtained

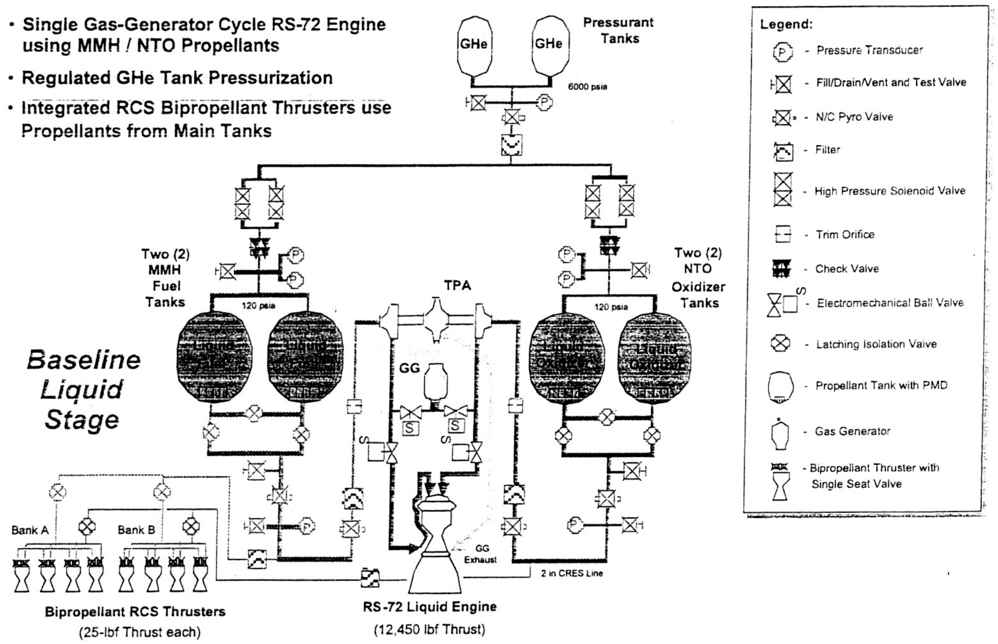


Figure 2. HEUS Baseline Liquid Stage Propulsion Schematic

by using the lighter-weight SPDS (Stabilized Payload Deployment System). The contingency indicated in Table 2 is the overall stage dry weight contingency arrived at by summing the contingencies applied to individual subsystem components per Table 1.

A schematic for the baseline HEUS liquid stage configuration is provided in Figure 2. The system uses a single, gas-generator cycle RS-72 main engine. The engine is gimbaled using EMAs to provide pitch and yaw control during burns. The system contains four graphite-overwrapped propellant tanks (2 MMH fuel and 2 NTO oxidizer). The tanks have a 0.045 inch aluminum liner and a Propellant Management Device (PMD). Propellant is fed to the engine in parallel from the tanks (i.e., all tanks are emptied simultaneously). Tank pressurization is provided by GHe from two 6000 psi graphite-overwrapped tanks. Based on technology flown on the NGST GeoLITE satellite, high-pressure solenoid valves (with inputs from redundant pressure transducers) are used to regulate propellant tank pressures, thereby eliminating more costly and less reliable proportioning regulators. The RCS bipropellant thrusters are arranged in two banks for redundancy and directly integrated into the main propulsion system for maximum weight savings. The RCS thrusters provide roll control during main engine burns and pitch, yaw and roll control during coast periods. All eight thrusters are normally used but the mission could be completed in a back-up mode using only four. The system contains isolation valves necessary to meet Shuttle safety requirements.

Additional subsystems comprising the total upper stage are also common to the selected gel stage and are discussed below in the section "Common Subsystems and Features".

BASELINE GEL STAGE SUMMARY

Major propulsion and structural items comprising the baseline HEUS gel stage are shown in Figure 3. The basic stage configuration is nearly identical to that of the liquid stage, with tankage dome shape and length being one major difference. This configuration also includes a 27-inch diameter spherical N_2H_4 tank on the aft bulkhead to supply the main engine GG and monopropellant RCS thrusters.

The stage contains four boss-mounted propellant tanks arranged side-by-side. The 56-inch diameter MICOM gel fuel tanks and 66-inch diameter NTO gel oxidizer tanks are both about 79.5 inches long. The gel tanks, with spherical domes to accommodate an internal rolling metal diaphragm for positive expulsion, are actually longer than the liquid baseline tanks but they package slightly better within the stage structure and provide more volume for engine submergence. The single 55,600 N (12,500 lbf) pump-fed, gel main engine is mounted to the titanium aft engine support, which in turn attaches to four aft corners of the internal webs.

The 115-inch long main engine is submerged into the aft volume between the tanks giving an overall stage length of about 175 inches. As with the liquid stage (10 inches shorter), this is still well under the maximum allowable length of 209 inches for the stage plus adapter using the RMS, or 227 inches using the SPDS. Again, the engine submergence could be reduced with negligible effect on weight.

The associated key features of this stage are summarized in Table 3. The performance values are based on the JWST DRM, but unlike the case with the liquid stage, the mass values are based on using the SPDS

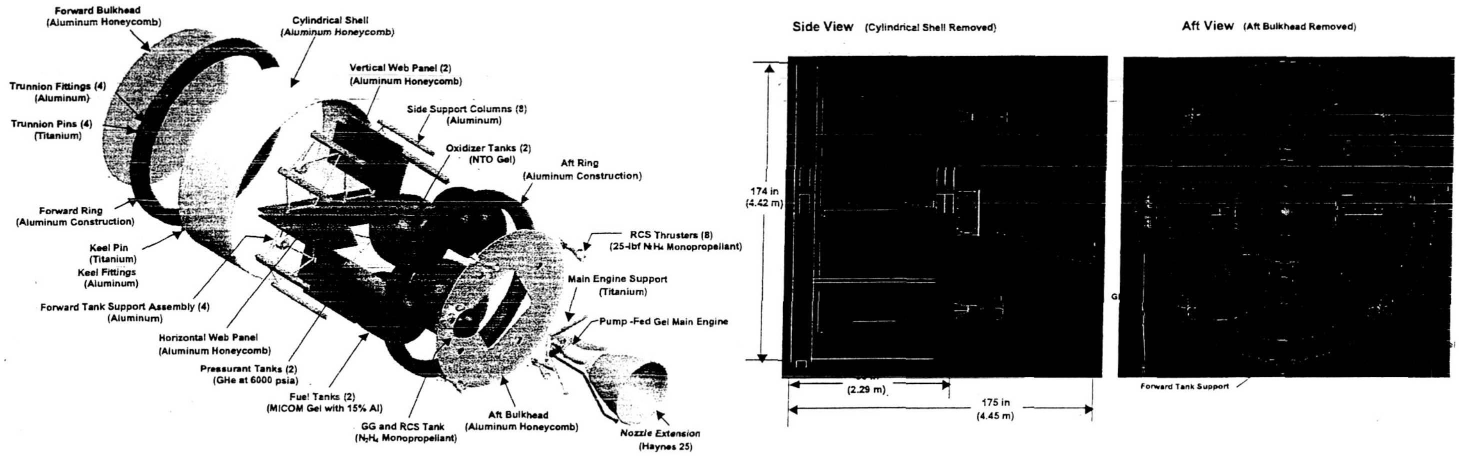


Figure 3. HEUS Baseline Gel Stage

for deployment to maintain positive dry weight margin. If the RMS is used for payload/stage deployment, the dry weight margin is reduced to -15% (due to the 485 kg difference between RMS and SPDS). As with the liquid stage, the gel stage was sized to match the OV-102 lift capability and performance margins for the SIM DRM are greater.

Table 3. Gel HEUS Key Features

- **Overall Stage**
  - 1,830 kg stage dry weight (including 18.4% contingency)
  - 12,754 kg prop and pressurant weight (including residuals)
  - 14,584 kg total loaded stage weight
  - 219 kg dry wt margin (12.0%) for JWST DRM using SPDS
  - 4.45 m overall stage length (175 inch)
- **Main Propulsion Subsystem and Tankage**
  - Single 55,600 N (12,500 lbf) pump-fed gel engine using NTO gel/MICOM gel with 15% aluminum
    - 342.7 sec vacuum Isp; 750 psia Pc and 350 Ae/At nozzle extension
    - Fuel film- and ablatively-cooled chamber, radiation-cooled nozzle extension
    - Tungsten nozzle throat with graphite backing
    - Split-geared turbopump driven by hydrazine gas generator
  - Engine gimbaled in pitch/yaw axes up to 5 deg using EMAs
  - Four graphite-overwrapped, boss-mounted propellant tanks with rolling metal diaphragms for positive gel expulsion
    - Two 66 x 80-in oxidizer tanks and two 56 x 80-in fuel tanks
  - GHe tank pressurization at 200 psia using redundant electronic solenoid valves
    - Two 6000 psia graphite-overwrapped pressurant tanks
- **Reaction Control Subsystem**
  - Eight 110 N (25 lbf) N2H4 monopropellant thrusters fed off tank supplying to main engine gas generator; 225 sec Isp
  - Provides roll control during burn(s); PYR control during coast; and _V for CCAM (stage collision avoidance)

A schematic for the baseline HEUS gel stage configuration is provided in Figure 4. The system uses a single, gimbaled gel main engine with a turbopump assembly driven by a N_2H_4 gas generator. The chamber is fuel film- and ablation-cooled while the nozzle extension is radiation-cooled. The engine is gimbaled using EMAs to provide pitch and yaw control during burns.

The system contains four graphite-overwrapped propellant tanks (2 MICOM Gel fuel with 15% aluminum and 2 NTO Gel oxidizer). The tanks have a 0.045 inch aluminum liner and a rolling metal diaphragm for positive expulsion of the gel propellant. Propellant is fed to the engine in parallel from the tanks (i.e., all tanks are emptied simultaneously). As with the liquid stage, tank pressurization is provided by GHe from two 6000 psi graphite-overwrapped tanks and high-pressure solenoid valves (with inputs from redundant pressure transducers) are used to regulate propellant tank pressures. The RCS monopropellant thrusters are arranged in two banks for redundancy and use propellant from the pressure-regulated N_2H_4 gas generator supply tank. As on the liquid stage, the RCS thrusters provide roll control during main engine burns and pitch, yaw and roll control during coast periods. All eight thrusters are normally used but the mission could be completed in a back-up mode using only four. The gel system, like the liquid system, contains the isolation valves necessary to meet Shuttle safety requirements.

COMMON SUBSYSTEMS AND FEATURES

Both the liquid and gel configurations for HEUS require structure, thermal, electrical and avionics (GN&C, C&DH, COMM, etc.) subsystems—in addition to the propulsion subsystems previously discussed—to perform their intended missions as self-contained stages capable of autonomous orbit injection and payload release. These subsystems are fundamentally independent of the selected propellants and propulsion hardware and therefore are common to both stage configurations. The basis for selection of these subsystems was maximizing use of technically mature or heritage components/systems to achieve low risk, low cost designs. The features of the HEUS common subsystems are summarized in Table 4.

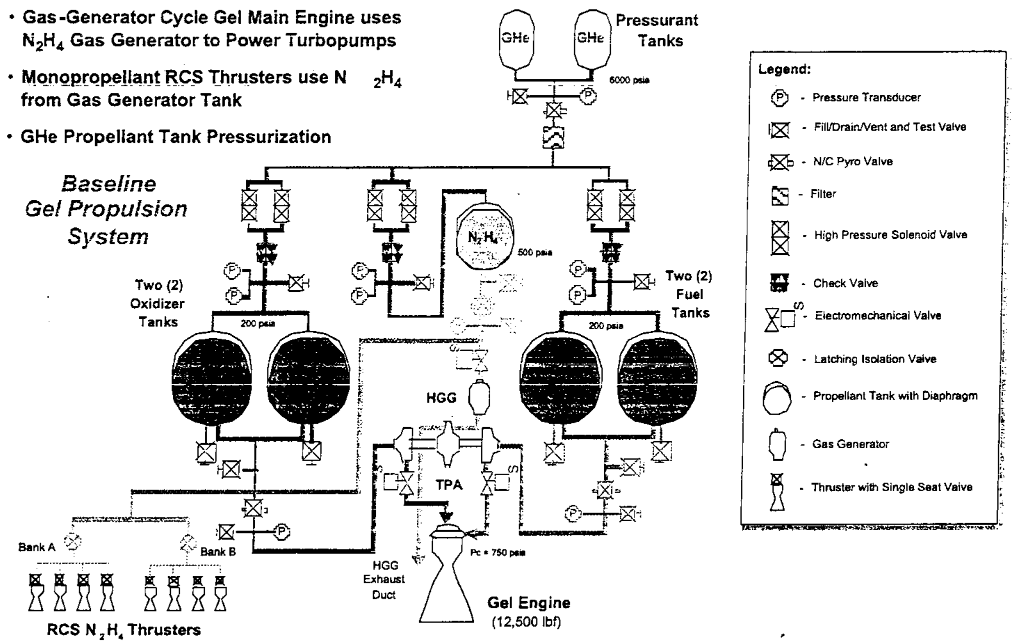


Figure 4. HEUS Baseline Gel Stage Propulsion Schematic

Table 4. Key Features of HEUS Common Subsystems

- **Structure**
  - Aluminum fore and aft rings with std. trunnion and keel fittings
  - Aluminum honeycomb cylindrical shell with internal horizontal and vertical shear web panels
  - Fore and aft Al honeycomb bulkheads with Ti engine support
- **Thermal Control**
  - MLI on external surface with beta cloth heat shield on aft end (behind main engine)
  - Heaters & thermostats for avionics and propulsion hardware
- **Electrical Power**
  - Single AgZn primary battery with 5320 W-hr (IUS heritage) provides power for stage avionics, propulsion valves, and TVC actuators
  - Ordnance Driver Module has 8 redundant firing commands for separation systems and valves; includes inhibits
  - Separate stage power harness
- **Guidance, Navigation & Control (GN&C)**
  - Two Fibersense IMU 600's with accelerometers
  - Attitude initialized using in-flight shuttle alignment maneuvers approach developed for IUS
- **Data Management/Command & Data Handling (C&DH)**
  - Single internally redundant data management unit
    - Redundancy management by internal, independent Configuration Control Module
  - Modern electronics modules with heritage to NPOESS, JWST, P461 and AHEF
    - Off-the-shelf rad hard power PC single board computer hosts all flight software
    - Standard plug-and-play I/O modules support interfaces to other subsystem hardware
- **Communications**
  - TDRSS-compatible transceiver with two omni antennas
- **Deployment Airborne Support Equipment**
  - Existing RMS baselined for liquid stage (SPDS provides additional performance); SPDS baselined for gel stage

The structure subsystem utilizes heritage designs from the Chandra, GRO, GeoLITE, EOS and FleetSatCom spacecraft, with an assessed TRL range of 7–9. The thermal control subsystem uses readily available hardware from numerous flight programs and is at TRL of 9, except for custom engine/GG insulation blankets. The electrical power subsystem baselined use of existing components from SSTI, GeoLITE and EOS flight spacecraft, achieving a TRL of 9. The GN&C and communications subsystems also rated TRL of 9 due to use of existing flight hardware from GeoLITE, TDRS, EOS, Centaur and classified programs. The C&DH subsystem (with on-board computer and command and sensor interface modules) makes use of GeoLITE and EOS flight hardware and software that requires customization for the HEUS mission, thereby earning a TRL 7 rating. Finally, the proposed deployment ASE uses existing STS flight hardware and is at TRL of 9.

SUMMARY WEIGHT COMPARISONS

Table 5 gives direct comparison of the various subsystem and total weights for both the baseline liquid and baseline gel configurations of HEUS. Both baseline stages are sized for the JWST DRM using the maximum OV-102 lift capability, and SPDS deployment was assumed for both stages to make this comparison.

The gel stage engine has higher Isp but this advantage is offset by (1) added GG N2H4 propellant needed for the gel engine TPA, (2) added RCS propellant (due to lower Isp of N2H4), (3) expected increased trapped residual gel propellant, and (4) increased GHe due to the higher gel tank feed pressure. The rolling metal diaphragm tank and ablative engine weights for the

Table 5. Weight Comparison of Liquid and Gel HEUS Configurations (all weights in kg)

	Liquid Stage	Gel Stage	Remarks
Propulsion	499.8	668.0	Gel propulsion increase of 168.2 kg (34%)
Prop/Press Tanks	285.7	378.4	Higher pressure, metal diaphragm tanks (+93 kg)
Engine	167.4	219.6	Heavier ablative chamber gel engine; Same TVC
GG/RCS N2H4 Tank	0.0	20.5	Added for gel stage (+20.5 kg)
Feed Sys	46.6	49.5	Nearly the same; Some different components
RCS	21.5	20.8	Nearly the same; Different thruster type
Structures	697.9	719.9	Added weight for GG and pressurant tank support
TCS	19.7	19.7	Same; No significant thermal differences
EPS	68.8	68.8	Same
Avionics	47.3	47.3	Same
Contingency	225.0	284.7	16.6% for Liquid Stage and 18.5% for Gel Stage
Total Stage Dry	1,580.0	1,829.3	Gel stage dry weight increase of 249.3 kg (16%)
Propellants	12,752.2	12,718.6	Lower gel prop from higher Isp; Offset by GG prop
Pressurant	20.4	35.6	Higher for gel due to increased tank pressure
Fueled Stage Wt	14,352.7	14,583.4	
Dry Wt Margin	450.1	219.3	Both Stages sized for JWST DRM and
Mass Fraction	88.6%	86.3%	OV-102 Lift Capability using SPDS ASE

gel stage are also higher than comparable components on the liquid stage.

Overall, the liquid stage is seen to provide greater dry weight margin, even adjusting for the slightly lower mass contingency associated with the slightly higher hardware maturity level. Nevertheless, both stages are within the maximum allowable mass, with net margins of 3% and 1.5%, respectively, including carrying contingencies of 17-19% as noted.

For reference, both stage configurations for both DRMs for both deployment approaches were examined for acceptable center-of-mass location within the Orbiter cargo bay; all conditions were found to be acceptable.

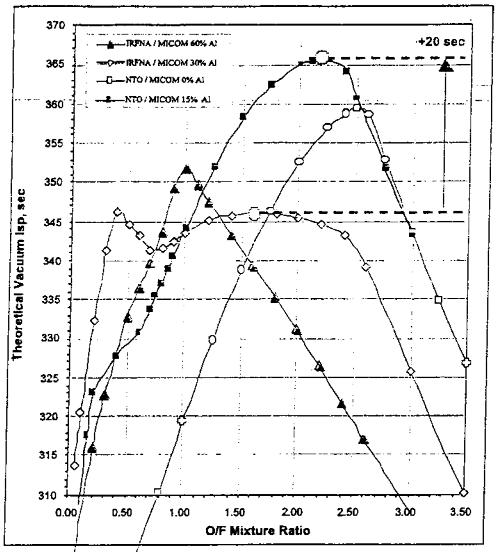
VARIATIONS TO BASELINE CONFIGURATIONS

Various alternative configurations were examined during the study to trade cost, development schedule span, technical and program risk, and performance against each other. Some key alternates were use of different storable propellant combinations (inc. H2O2 as an liquid oxidizer, N2H4 and JP-8 as liquid fuels, and 2-DAMEZ, N2H4 and alumizine-43 as gel fuel bases), different tankage number and geometry, pure pressure feed to eliminate main engine turbopump, solid vs. liquid vs. gel propellants feeding gas generators for turbopump drive, warm vs. cold gas pressurization, warm gas vs. monoprop vs. biprop thrusters for RCS, optional TVC actuation approaches, and adapting different flight-proven engines for the main engine. None of the variations evaluated had a significant overall benefit compared to the baseline configurations discussed above. In addition, GN&C trades evaluated Earth sensor/fine Sun sensor, star tracker, and IMU options. Details of these investigations are contained in the HEUS Study Final Report[3].

USE OF GEL NITROGEN TETROXIDE

A significant development in the course of the study was recognition that using a new gel propellant combination would provide much better performance at relatively low additional risk. The gel stage concept started with the existing bipropellant combination of gel IRFNA oxidizer and gel MMH+aluminum ("MICOM" gel) fuel because this combination has been well characterized and demonstrated in tactical missile applications. However, at a targeted 30% wt aluminum loading, the MICOM gel combustion temperature was too high to permit proposing an ablative chamber with refractory throat for the anticipated long duration main engine firings (up to 700 seconds).

Increased performance is available by replacing the IRFNA gel oxidizer with a NTO gel oxidizer, as indicated in Figure 5. About 20 seconds additional specific impulse is obtained using the more energetic NTO oxidizer with a MICOM (MMH-based) gel fuel containing only 15% aluminum. Reducing the aluminum loading from 30% to 15% reduces theoretical combustion temperatures at optimum mixture ratios from about 3670K to 3450K, respectively, enough to then permit use of an ablative chamber liner and refractory throat insert. This achieves significant technical simplification and reduces cost and risk compared to regeneratively-cooling the main chamber with gel propellants. For reference, a propellant combination using gel NTO with gel MMH fuel containing 0% aluminum still outperforms the



- IRFNA gel oxidizer replaced with higher performing NTO gel oxidizer
  - ≠ More energetic oxidizer
  - ≠ Higher freezing point and vapor pressure acceptable for upper stage application
  - ≠ Combustion efficiency expected to be higher
- MICOM gel aluminum loading reduced from 30% to 15%
  - ≠ Limits combustion temperature
  - ≠ Minimizes two-phase flow losses
  - ≠ Maintains MMH-based MICOM gel formulation heritage
- Slightly lower density has negligible effect upper stage performance & weight

Figure 5. Benefit of Using Gel Nitrogen Tetroxide (NTO) Instead of Gel IRFNA

IRFNA/MICOM gel with 60% aluminum loading, which is the standard gel combination for tactical systems.

The IRFNA gel oxidizer offers slightly higher density while operating over a much wider temperature range (demonstrated in firings as low as –40 C). These benefits are of secondary importance for upper stage applications where Isp is paramount and propellant temperatures are easily managed. Based on previous studies performed outside of NGST and on in-house tests of the viability of gelling nitrogen tetroxide, NTO gel was chosen to replace IFRNA gel as the oxidizer for the baseline gel stage.

PROGRAM PLANNING

A key task of the HEUS study was to establish realistic development and production schedules for each baseline stage configuration. Study emphasis was on low risk programs using technology that is at or can readily attain a Technology Readiness Level of 7.

Due to lack of a qualified main engine for either configuration and considering the process of flying this new stage in an STS Orbiter, a two-unit qualification is necessary at the engine level and the integrated system level requires a prototype (PT) stage for ground testing and protoflight (PF) stage for first flight article with dummy payload.

The resulting development schedules are summarized in Table 6 (stage-level reviews) and Table 7 (sequence of major tests).

For the liquid stage configuration, the period of development-through-first flight is success-oriented, consistent with the program guidelines to minimize schedule span and consistent with the high level of maturity of the proposed main engine and other stage subsystems. Approximately the first year is allocated to development of critical components, the primary one being the RS-72 engine for the stage. The Boeing/Rocketdyne RS-72 has been demonstrated with

Table 6. Schedule for Major HEUS Stage-Level Reviews

Stage-Level Reviews	Liquid Stage, months after start	Gel Stage, months after start
Initial Sys Req'mts Review (SRR)	1	1
Interim SRR	6	12
Flight Safety Review (FSR), Ph 0	7	13
Conceptual Design Review	8	14
Final SRR	10	24
PDR	12	26
FSR, Phase 1	14	28
CDR	29	43
FSR, Phase 2	30	44
Manufacturing Readiness Review	30	44
Test Data Review #1	44	58
Test Data Review #2	50	64
FSR, Phase 3	51	65
Flight Readiness Review	56	70

Table 7. Schedule for Major HEUS Tests

Stage-Level Reviews	Liquid Stage, months after start	Gel Stage, months after start
Start main engine demo tests (supplier)	11	23
Start main engine DVT/Qual#1 tests (supplier)	17	31
Start STA vib/acoustic tests (NGST)	25	39
Start propulsion S/S hot fire tests (WSTF)	26	40
Complete main engine qual testing, Qual#2 (supplier/WSTF)	28	42
Start PT stage acoustic & T/V tests (NGST)	39	53
Start PT stage hot fire tests (AEDC)	43	57
Start FLT1 stage acoustic & T/V tests (NGST)	47	61
Start inert PT stage handling & Orbiter integration tests (KSC)	48	62
Complete flight software IVV testing (NASA IVVF)	54	68

multiple full thrust tests, but has not undergone qualification hot fire testing. Other important stage-level tasks (e.g., systems requirements development and reviews and the stage Conceptual Design Review) are accomplished in the first year; this permits ordering long-lead propulsion components to enable the start of engine demo testing just prior to stage-level PDR. Subsequent testing of a brassboard propulsion system with main engine is proposed for the White Sands Test Facility starting in month 26. Main engine qualification is scheduled to be completed by month 28, one month prior to stage CDR. An initial structure build for a structural test article (STA) will be upgraded to become the PT structure. Subsequently, a new structure build (following STA test analyses) will become the PF stage. For risk reduction, the PT is a "pathfinder" for the PF stage through the series of ground test verification/validation tests: vibration, acoustic, shock, thermal-vacuum, integrated system hot fire, and handling/Orbiter integration.

For the gel stage configuration, the period of development-through-first flight is less success-oriented—primarily due to use the gel propellants and the requirement for a new pump-fed gel engine—and attempts to achieve a balance between cost and risk, with schedule span being a less critical driver. Approximately the first two years are allocated to development of critical components, the primary one being the main engine for the stage. As with the liquid stage, other important stage-level tasks are accomplished in parallel during this time to permit early ordering of long-lead propulsion components. This, in turn, enables engine qualification completion (month 42) and completion of demonstration testing of a brassboard propulsion system with main engine at the White Sands Test Facility (month 42) prior to stage-level CDR at month 43. Overall, the gel stage development cycle flow (including use of PT and PF articles) follows that of the liquid stage, except that key milestones occur 6-14 months later reflecting the lower maturity level at program start.

Understandably, the development programs for both stage configurations have heavy emphasis on the propulsion subsystems. Except for propulsion and structure, all other major HEUS subsystems will employ a large amount of space-qualified heritage hardware to lower development and flight risk and to reduce overall program cost. Excluding propulsion and flight software development and testing, no other subsystems or areas were assessed to be critical-path items for stage development. A total span of 29 months was allocated to flight software validation and verification based on NGST experience with similar flight system development.

RISK ASSESSMENTS

An in-depth risk assessment was not consistent with the study effort due to the preliminary nature of the program (many technical requirements undefined) and the conceptual nature of the stage design and major subsystems.

In general, however, the liquid stage development was assessed to have low overall risk at the integrated level and across all subsystems, primarily because it is based on existing, flight-proven technologies.

The baseline, pump-fed gel stage was assessed generally to have low-to-moderate overall risk, due to the following factors:

1. Lack of large experience base for gel NTO (nitrogen tetroxide, N_2O_4) propellant,
2. Extensive scale-up and lack of comparable use experience for large gel propellant tanks,
3. Lack of comparable test data on component operation of main engine thrust chamber and TPA due to long firing time (~700 sec) and space vacuum restart, and
4. Ground support equipment (particularly loading/unloading equipment) for gel propellants due to lack of experience with gel NTO and comparable size metal diaphragm propellant tanks.

The only gel stage subsystem/component rated above "moderate" risk is the main engine turbopump assembly, which received a "moderate-high" risk assessment due to lack of pump design data for gel propellants and the requirement to perform engine restart(s) following long coast periods during the mission. NGST rated development risk for the gel engine main chamber and nozzle as "moderate" based on extensive experience firing gels in ablative engines and manufacturing similar size ablative engines, while accounting for lack of firing data with gel NTO propellant.

The scope of this study did not include assessing the relative risk of flying the liquid stage versus the gel stage. By their nature, and as demonstrated in numerous tests, gel propellants will be inherently safer than liquid propellants in a stage application. Compared to liquids, gel propellants (1) won't flow if spilled or if an unpressurized line breaks, (2) have low vapor release due to "crusting over" behavior, (3) will burn apart if mixed and will then self-extinguish, and (4) are easier to clean up and inert following loading/off-loading operations or in event of spills. However, in-depth system analyses of detailed flight designs, supported by ground test data and verifications, is required to properly evaluate the relative flight risks between a liquid HEUS and a gel HEUS.

Risk levels were statused as of the present state of technology and significant risk reduction is possible with minimal R&D cost and schedule span. Recommended near-term risk reduction activities for the gel stage include:

- Obtain long-term (>1 year) physical characteristics (physical chemistry, materials compatibility, etc) of gel N_2O_4 or gel MON-3 with laboratory samples under a range of ambient temperature conditions,

- Perform a demonstration test of expelling gel NTO and gel MMH from a currently-available, large diameter rolling diaphragm tank of the proposed design,
- Perform a subscale demonstration hot fire test of gel NTO and gel MMH in an ablative-lined thrust chamber using a HEUS-representative duty cycle, and
- Perform full-scale demonstration tests of a 12,500 lbf thrust-equivalent turbopump pumping gel NTO and gel MMH over an abbreviated HEUS duty cycle.

SYNERGY ASSESSMENTS

NGST evaluated possible synergies between a new HEUS development and NASA and DoD activities related to mission needs for such a stage or some of the subsystems/components that would result from such development. The main focus was on possible synergy with existing liquid bipropellant (MMH/NTO baseline) high-energy upper stages, although the gel HEUS was also examined for possible synergy with other programs.

The HEUS stage (liquid or gel configurations) is designed to support the JWST and SIM Design Reference Missions and it could therefore support future payloads targeted for or requiring a STS or 2nd Gen RLV launch. A flight-qualified, Shuttle- or RLV-launched HEUS can provide primary or backup launch capability for certain critical payloads that might otherwise use an EELV with Centaur upper stage. Some potential future missions are:

- ♣ Future "National Asset" science payloads (follow-on's to Chandra, JWST, etc.)
- ♣ New Horizon Missions (new, heavy payloads)
- ♣ Potential future OMV-like vehicle
- ♣ Nuclear Space Initiative missions deployments (hi-rel launch)
- ♣ Future HEDS missions.

It is believed that the HEUS stage is far too large for consideration for the Orbital Space Plane (as presently envisioned), even assuming it will be designed with a payload bay and have missions to deploy propulsive payloads. A scaled down HEUS is possible if OSP evolves along these lines. Similar arguments apply to a Military Space Plane.

Synergism between the Air Force and NASA could be fruitful. The HEUS might serve as an "assured access" upper stage contingency for military EELV applications. Investigating synergies with launch vehicle or "upper stage" (e.g., ATV, HTV) providers outside the United States was beyond the scope of this study.

At the subsystem and component levels, there is likely to be some synergy with other NASA and DoD launch vehicle development. Due to NGST's HEUS development philosophy of using the maximum amount of heritage hardware in all areas (especially avionics, power, EPDS, GN&C, C&DH, thermal control, flight software), most of the synergy will be in the propulsion subsystem area. Major propulsion components that need to be developed for HEUS may also find ready application—perhaps in derivative designs—in other advanced propulsion systems for space access or in-space propulsion.

UPDATE POST-COLUMBIA LOSS

The HEUS study concluded 22 January 2003 with a Final Presentation to NASA MSFC. On 1 February 2003, STS Orbiter Columbia and crew were lost due to in-flight breakup upon reentry. This study baselined Columbia because she had the lowest lift capability of the Orbiter fleet and because she did not have an ISS-docking airlock in the cargo bay (thereby accommodating longer length payloads). It is probable that all future Orbiter missions will require flying both the docking airlock and the RMS for enhanced safety. Therefore, certain HEUS study results need to adjusted for carrying the heavier, 567 kg RMS (485 kg increase over SPDS). However, the higher 23,337 kg control weight lift capability of the remaining fleet (2,260 kg increase over Columbia) more than offsets flying the RMS.

The ISS-docking airlock reduces the available cargo (HEUS + spacecraft) length by 84 inches to 565 inches using the RMS and by 66 inches to 601 inches using the SPDS. The smaller required SPDS deployment clearance enables a slightly longer envelope.

For the longer SIM spacecraft, the maximum allowable HEUS length during the study was 209 and 227 inches using RMS and SPDS, respectively. This provided 44 and 62 inches length margin for the liquid stage, and 34 and 52 inches margin for the gel stage. With the in-bay airlock, the maximum allowable stage length is reduced to 125 and 161 inches using RMS and SPDS, respectively. This requires the use of the SPDS and a slight reduction in gel stage length by increasing engine submergence and shortening the nozzle. The 10 to 14 inch reduction in nozzle length lowers expansion ratio and drops Isp by 3 sec. The increased propellant load capability associated with resizing the gel stage for the higher-performance orbiter fleet makes up for this Isp drop. The resized gel stage dry weight margin for the SIM DRM increases from 19% to over 50%.

For the 55-inch shorter JWST spacecraft, no HEUS length reductions from the study baseline are needed to fit inside the cargo bay with docking airlock. However, maintaining a single HEUS configuration to perform both DRMs would require a slightly shorter stage resized for the higher launch performance of the remaining Orbiter fleet. For the JWST DRM, the dry weight margin of a resized gel stage increases from 12% to near 40%. Other than the aforementioned cargo bay envelope and weight considerations, all HEUS study results remain applicable to the remaining Orbiter fleet.

CONCLUSIONS

The HEUS study was a six-month effort that successfully identified the planning, funding, technology development and risk areas for a new, Orbiter-compatible upper stage that will utilize either storable hypergolic liquid propellants or storable hypergolic gel propellants to perform the JWST and SIM reference missions. The study identified components, subsystems and integrated systems for both configurations and performed trade analyses to arrive at recommended, baseline designs. The gel stage was assessed as having about 20% greater non-recurring (i.e., development-through-first flight) cost and about 10% greater recurring cost compared to the liquid stage. The liquid stage development span is 5 years versus a 6-year development span for the gel stage. However, gel propellants offer significant safety advantages compared to liquid propellants. Assessments of overall development risk were "low" for the liquid stage and "low-moderate" for the gel stage.

The derived stage configurations, with DRM payloads, were shown to be compatible with STS Orbiter payload envelope and lift capabilities.

References

1. "Technology Readiness Levels, A White Paper", dated 6 Apr 1995, John C. Mankins, NASA Advanced Concepts Office, Office of Space Access and Technology
2. "Space Shuttle Lift Capability based on the Proposed NSTS07700 Control Weight", dated 12 July 2002, Space Shuttle Program Office, Space Shuttle Customer and Flight Integration Office, NASA Johnson Space Center, Houston TX
3. "High Energy Upper Stage Study, Final Presentation to NASA", dated 22 January 2003, performed as Subtask under NAS8-01110, Northrop Grumman Space Technology, Redondo Beach, CA

Acronym List

_V	velocity change
Ae/At	nozzle expansion ratio (exit-to-throat area ratio)
AEDC	Arnold Engineering Development Center
ASE	Airborne Support Equipment
C&DH	Command and Data Handling
CCAM	Collision & Contamination Avoidance Maneuver
CDR	Critical Design Review
DoD	US Department of Defense
DRM	Design Reference Mission
DVT	Design Verification Testing
EELV	Evolved Expendable Launch Vehicle
EMA	Electro-Mechanical Actuator
EOS	Earth Observation System
EPDS	Electrical Power & Distribution Subsystem
FSR	Flight Safety Review
FY	Fiscal Year
GG	Gas Generator
GN&C	Guidance, Navigation and Control
GRO	Gamma Ray Observatory
HEDS	Human Exploration and Development of Space
HEUS	High-Energy Upper Stage
IRFNA	Inhibited Red Fuming Nitric Acid
Isp	Specific Impulse
IVV(F)	Independent Verification and Validation (Facility)
JWST	James Web Space Telescope
Kg	kilogram (mass)
lbf	pound (force)
m	meter (length)
M	Million dollars (US)
MICOM	US Army Missile Command (now AAMCOM)
MLI	Multi-Layer Insulation
MMH	Monomethyl Hydrazine
MSFC	Marshall Space Flight Center
N	Newton (force)
N/C	Normally-Closed
NGST	Northrop Grumman Space Technology
NM	nautical mile
NTO	Nitrogen Tetroxide (N2O4, MON-3)
OMV	Orbital Maneuvering Vehicle
OSP	Orbital Space Plane
OV-102	Orbiter Vehicle 102 (Columbia)
Pc	Chamber Pressure
PDR	Preliminary Design Review
psi(a)	pounds-force per square inch (absolute)
PMD	Propellant Management Device
PYR	Pitch-Yaw-Roll
qual	qualification
RCS	Reaction Control System
RLV	Reusable Launch Vehicle
RMS	Remote Manipulator System
sec	second (time)
SIM	Space Interferometry Mission
SPDS	Stabilized Payload Deployment System
SRR	System Requirements Review
STA	Structural Test Article
STS	Space Transportation System
TPA	Turbopump Assembly
TRL	Technology Readiness Level
T/V	Thermal Vacuum
TVC	Thrust Vector Control
WSTF	White Sands Test Facility