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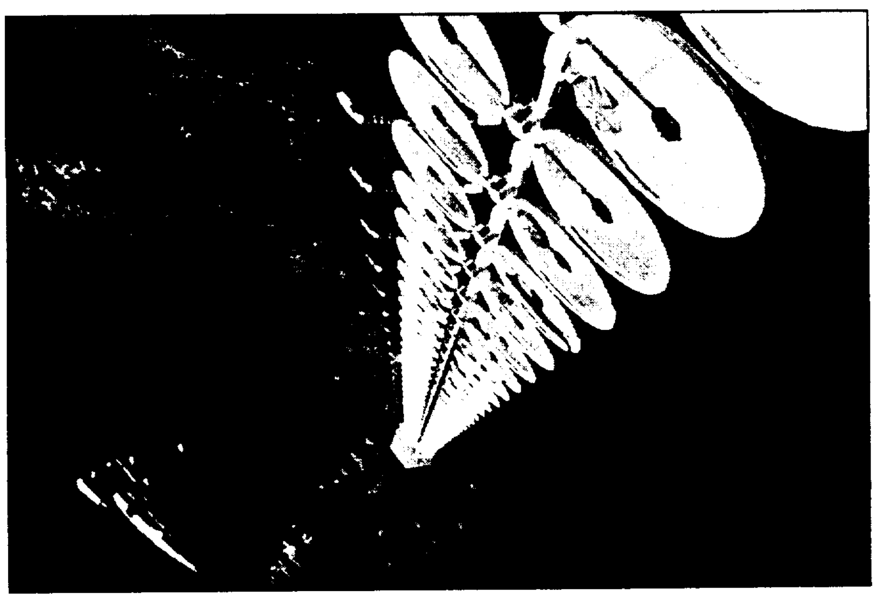
Launch Vehicle Assessment for Space Solar Power

Covering the Period August 15, 1998 to December 15, 1998



Submitted By:

Dr. John R. Olds, Project PI
Georgia Institute of Technology
Space Systems Design Lab
School of Aerospace Engineering
Atlanta, GA 30332-0150

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Launch Vehicle Assessment for Space Solar Power:

A Supplemental White Paper Reviewing Procedures and Issues

Dr. John R. Olds
Space Systems Design Laboratory
Georgia Institute of Technology
Atlanta, GA 30332-0150

Sponsored by: NASA Grant NAG8 –1547, NASA – Marshall Space Flight Center

Background:

A recently completed study at Georgia Tech examined various launch vehicle options for deploying a future constellation of Space Solar Power satellites of the Suntower configuration. One of the motivations of the study was to determine whether the aggressive $400/kg launch price goal established for SSP package delivery would result in an attractive economic scenario for a future RLV developer. That is, would the potential revenue and traffic to be derived from a large scale SSP project be enough of an economic "carrot" to attract an RLV company into developing a new, low cost launch vehicle to address this market. Preliminary results presented in the attached charts show that there is enough economic reward for RLV developers, specifically in the case of the latest large GEO-based Suntower constellations (over 15,500 MT per year delivery for 30 years). For that SSP model, internal rates of return for the 30 year economic scenario exceed 22%. However, up-front government assistance to the RLV developer in terms of ground facilities, operations technologies, guaranteed low-interest rate loans, and partial offsets of some vehicle development expenses is necessary to achieve these positive results.

This white paper is meant to serve as a companion to the data supplied in the accompanying charts. It's purpose is to provide more detail on the vehicles and design processes used, to highlight key decisions and issues, and to emphasize key results from each phase of the Georgia Tech study.

Candidate Vehicle Descriptions:

As a point of departure, Georgia Tech started with the three top finishing launch vehicle designs and one additional "wildcard" from NASA's recent Highly Reusable Space Transportation (HRST) study. The HRST study had a goal of achieving direct recurring costs under $400/kg

($200/lb) for payloads in the range of 10 MT to 20 MT and flight rates less than 200 flights/year. To achieve this goal, vehicle concepts had to be highly operable and reliable, require very little maintenance between flights, have sufficient system and subsystem robustness (typically substantial design margins), and contain long life airframe and engine components. HRST-class vehicles typically require no more than $3M - $4M in labor, propellant, and replacement hardware per flight. Airframe service life is on the order of 1000 flights and engine service life is on the order of 500 flights. By comparison, the current Space Shuttle system requires more than $350M in recurring costs per flight, and its service life is around 100 flights for the Orbiter airframe and only a few flights between major overhauls for the main engines.

The four HRST-class vehicles investigated in this SSP study were:

1. *Argus* with Maglifter launch assist

2. *Hyperion*

3. ACRE-92

4. SSTO-R with rocket sled launch assist

Argus

Argus is a rocket-based combined-cycle (RBCC) single-stage-to-orbit (SSTO) launch vehicle utilizing a Maglev sled and track system to accelerate it to Mach 0.8 for horizontal liftoff. *Argus* uses two LOX/LH2 supercharged ejector ramjet (SERJ) engines for primary motive power and transitions from airbreathing to rocket mode at Mach 6. Like the rest of the vehicles considered, *Argus* is unpiloted and operates autonomously from liftoff to landing. *Argus* employs a lightweight composite airframe in a high fineness ratio, axisymmetric wing-body configuration. Advanced subsystem and material technologies are used throughout. For example, the wings and other highly loaded structures are made of advanced metal matrix composites such as Titanium-aluminide. Propellant tanks are graphite/epoxy. Subsystems include high power density fuel cells, EMA's, lightweight avionics and power distribution, and built-in test monitoring sensors. Thermal protection is all passive with a combination of TUFI ceramic tiles, TABI blankets, and ultra-high temperature ceramic (UHTC) nosecap and leading edges.

Hyperion

Hyperion is a horizontal takeoff, horizontal landing RBCC SSTO launch vehicle. It is powered by five LOX/LH2 ejector scramjet engines, but is also equipped with a separate pair of ducted fans for limited subsonic landing operations. *Hyperion* operates in airbreathing scramjet

mode up to Mach 10 and requires significant airframe-engine integration. The *Hyperion* forebody is conical on the bottom and elliptical on the top. The aftbody provides an expansion surface for the engine exhaust. Airframe and subsystem technologies are similar to those in *Argus*. Both *Argus* and *Hyperion* were entered into the original HRST vehicle evaluation process by John Olds of Georgia Tech.

ACRE-92

ACRE-92 is a vertical takeoff, horizontal landing LOX/LH2 all-rocket launch vehicle. It is powered by five new long life, high thrust-to-weight rocket engines (T/W = 92 at sea level). Landing is unpowered. It employs a wing-body configuration similar to that found on the all-rocket SSTO from NASA's Access to Space study. Subsystem and materials technologies are consistent with *Argus*. ACRE-92 was originally entered into the HRST study by Dan Levack of Boeing Rocketdyne.

SSTO-R with Rocket Sled Launch Assist (SSTO-R/LA)

The SSTO-R/LA is a horizontal takeoff, horizontal SSTO rocket vehicle. Like *Argus*, it employs a launch assist system to achieve an initial velocity and eliminate the need for heavy takeoff gear. In this case the launch assist system is a rocket-powered sled and track system and the launch speed is only Mach 0.25. Main propulsion for the SSTO-R/LA vehicle is provided by three lightweight LOX/LH2 rocket engines. The vehicle configuration is a medium fineness ratio wing-body. Subsystem and materials technologies are consistent with *Argus*. The SSTO-R/LA was entered into the HRST study by Gordon Woodcock formerly of Boeing Huntsville.

For the present study, all four HRST concepts were (originally) modified to deliver 20 MT and were "leveled" to the same technology assumptions. In addition, Georgia Tech worked with NASA Kennedy Space Center to identify changes in the vehicles that will help to increase the operability of the concepts and reduce their associated operations costs. Key were the increase in vehicle design "margin" (factors of safety on structural components and landing gear), de-rating engines to 90% of design thrust, increasing the use of commercial-off-the-shelf (COTS) subsystem components to reduce inventory costs, eliminating active airframe cooling where possible, reducing numbers of distinct fluids on board, and integrating tankage where possible. These "operability" versions of the SSP/HRST concepts are documented in the attached presentation materials. Drawings, weight statements, and lists of changes since HRST are also given.

SSP Evaluation Procedure:

This project was performed in three phases. Phase 1 examined the economic performance of all four vehicle concepts when configured to deliver 20 MT payloads in support of a MEO-based Suntower mission model. Phase 2 performed several trade studies on payload size, Suntower mass and deployment schedule, and government economic incentives for the leading concept from phase 1 – the SSTO-R/LA. Phase 3 examined the *Argus* and SSTO-R/LA concepts in support of a new, larger GEO-based Suntower architecture. Detailed results are shown in the attached presentation materials. Specific processes and issues are reviewed below.

SSP Payload Size, Packaging, and Destination

In all cases, the candidate RLV was assumed to deliver containerized payload components to a circular LEO parking orbit (300 km). These packages are to be subsequently delivered to the Suntower assembly orbit by an (uninvestigated) space-based orbital transfer system for robotic assembly. Over the mission model (about 250 flights/year for the first two phases and over 450 flights/year for phase 3) the RLV's were assumed to average 95% of their maximum payload capacity on a given flight. This presents a somewhat demanding packaging challenge to the Suntower designers, but we have assumed this type of manifesting percentage would be possible, if not necessary, for such as long term transportation problem. During phase 1 and phase 2, the containerized payloads were assumed to average 19 MT (95% of 20 MT) with a volume of 226 m^3. In phase 3 (and the 40 MT payload trade study in phase 2), the average payload was increased to 38 MT (95% of 40 MT) with a volume of 452 m^3. Payload volumes are the same across all four vehicle concepts, but the particular cargo bay shape (cylinder, square, etc.) changes depending on the best match for the launch vehicle configuration.

Two payload destination cases were originally run for each vehicle – one case was launched from Kennedy Space Center to a 300 km circular, 28.5° inclination orbit and a second case simulated a launch from a fictitious launch site near the equator to a 0° inclination orbit. MECO conditions were a 94 km x 281 km elliptical orbit in both cases. The remaining ΔV was performed by on-board cryogenic OMS propulsion (sized for 183 m/s on-orbit ΔV). Performance parameters between these two sites were slight (measured in terms of propellant mass fraction required). During this study, the mode of transportation to be used for in-space transportation was yet to be determined. Therefore it was unclear whether the orbital transfer system could remove 28.5° of plane change by itself or if the launch system would be required to place the payload packages directly into an equatorial orbit. The results presented on the attached charts assume that the launch site is <u>equatorial</u>, therefore the vehicle sizes and weight-based investment costs are slightly optimistic for a KSC launch. However, the burden on the in-space transportation component to perform a plane change is eliminated.

Vehicle Synthesis Process

POST was used to perform the trajectory optimization for each vehicle. Mass Ratios, LOX/LH2 mixture ratios, and wing loadings were determined from these analyses. Georgia Tech already had trajectory files for *Argus* and *Hyperion* (our entries into the HRST study), but new POST trajectory models were created for ACRE-92 and SSTO-R/LA. Aerodynamic data was generated for each concept using APAS. Mass properties were determined using Georgia Tech's in-house mass estimating relationship spreadsheets. Similar technology assumptions and weight reductions were made for each vehicle. "Operability" considerations were also included for each vehicle as described later. Propulsion parameters (I_{sp}, thrusts) were determined using Georgia Tech's in-house SCORES code for the two rocket vehicles (ACRE-92 and SSTO-R/LA) and with our SCCREAM code for the two RBCC-powered vehicles (*Argus* and *Hyperion*).

To converge a given design, the aerodynamic dataset was first generated and subsequently scaled photographically as necessary. Several iterations were typically required between propulsion, mass properties, and trajectory optimization to converge internal performance variables for each concept. These iterations were performed by a team of graduate student engineers at Georgia Tech. The result of this iterative synthesis process was a "closed" vehicle design in each case, a multi-level weight statement for each vehicle, and a converged outer mold line geometry (length, wingspan, etc.).

Economic Assessment Following Vehicle Synthesis

After the designs were converged, Georgia Tech's in-house cost estimation and economic simulation tool CABAM was used to estimate vehicle DDT&E and theoretical first unit (TFU) costs for each vehicle. These analyses depend on NAFCOM-style weight-based cost estimating relationships with complexity factor adjustments for each engine or other component made by analysts at Georgia Tech. For a given fleet size, overall fleet procurement costs were estimated using an 80% learning curve for units produced beyond the first. Facilities costs, operations costs, and financing costs were other key inputs into the economic analysis. SSP revenue was assumed to be $400/kg in all cases (except for a trade study on that variable in phase 2)

Facilities Costs

A simplified construction of facilities model was used in throughout the economic analyses in this study. The simplified facilities model assumes that Maglev ($800M each) and rocket-sled launch facilities ($150M each) can support up to 200 flights each per year. A simple runway like that used by *Hyperion* can support multiple flights per day if necessary. On the other hand, a vertical takeoff launch pad, like that used by ACRE-92, can support only 50 flights per year per facility ($500M each). For all concepts, payload processing facilities must be augmented for each

additional 50 flights per year ($50M base and an additional $50M per 50 annual flights). Similarly, vehicle maintenance and depot facilities were assumed to be incremented for each 5 flight vehicles added to the fleet ($10M for each 5 vehicles in the fleet). In all cases, the funding for these ground facilities was assumed to be provided by the government (or some international governmental partnership) not the RLV company. The RLV company was assumed to pay a $50,000 user fee per flight to offset the cost of operating and maintaining the facilities. This proves to be an important assumption for increasing the IRR returned to RLV, Inc. Due to dollar discounting, the importance of up-front costs in determining the economic performance of a concept is greatly magnified.

Operations Costs

Operations cost per flight for each of the different concepts and their expected turnaround time (flights per airframe per year) were key inputs to the CABAM model. The requisite cost per flight numbers as a function of flight rate were extrapolated from data generated by Mike Nix from NASA – Marshall using the OCM/COMET tool originally developed by General Dynamics. An OCM/COMET model for HRST vehicles was obtained from the Operability Wing of NASA's on-line Virtual Research Center. This model was used to predict several operations cost per flight for all four concepts at a range of annual flight rates. This data was then used to create regression models of ops costs vs. flight rate for each concept. OCM/COMET includes labor charges, propellant costs, and maintenance hardware costs (LRU's). Georgia Tech added $50,000 per flight to this base number to account for liability and hull insurance payments in additional to the $50,000 site use fee described above.

It should be noted that this ops model was originally created by Mr. Nix for the HRST study, not specifically for the SSP study. The latter has higher flight rates and a 20 MT payload. However, our assumption has been that this model and data from it are still applicable to the current SSP study. Operations costs are a significant input to the overall life cycle cost model, and the validity of this assumption should perhaps be updated and revised in future analyses.

In general, the OCM/COMET model shows a significant decrease in per flight operations costs at high flight rates, asymptotically approaching a value of under $4M/launch at flight rates near several hundred per year. *Hyperion* is consistently the lowest operations cost vehicle, *Argus* second, ACRE-92 third, and SSTO-R/LA the most expensive (however, differences are less than $0.75M per flight at higher rates). During phase 3, the payload was increased to 40 MT for *Argus* and SSTO-R/LA. For these 40 MT cases, the construction of facilities costs were increased by 15%, the base ops costs per flight from OCM/COMET were increased by 10% per flight, and incremental propellant costs were included directly for each concept (10¢/lb for additional LOX and 25¢/lb for additional LH2).

Operability Changes to the Vehicles

Our Georgia Tech team worked with engineers from Kennedy Space Center to predict vehicle turnaround times for each of the four initial concepts. The KSC team used their new Architectural Assessment Tool (AAT) to predict the number of flights per vehicle airframe per year. An early preliminary assessment determined that no HRST vehicle would have a flight rate of more than about 26 flights per airframe per year (*Argus*) or about a two week turnaround time. The KSC team led by Edgar Zapata, Carey McCleskey, and Rus Rhodes, recommended a number of changes to each of the initial HRST vehicles to increase their operability. As documented in the attached presentations, primary changes consisted of adding extra margin in key structural components, de-rating the engines to 90% thrust to reduce stress and increase engine life, and increasing the use of COTS components in the subsystems. In addition, heavy use of operations technologies such as vehicle health monitoring and automated checkout are required. As a result of these changes, the SSP-version vehicle sizes and weights generally increased by 5% - 10%, but annual utilization rates increased to over 34 flights per airframe per year in all cases. *Argus* even increased to 46 flights per airframe per year. Note that the KSC model did not predict data for the SSTO-R/LA vehicle. Turnaround times for that vehicle were estimated by Georgia Tech personnel based on expected relationships with the other three vehicles.

Fleet Size – Turnaround time vs. Service Life

An interesting finding regarding fleet size resulted from our turnaround improvement efforts. Our initial assumption from HRST was that individual airframes have service lives of only 1000 flights before retirement (engines have 500 flight service lives). The required fleet size is determined from either service life or annual flight rate. For example, the phase 1 model required 8,440 flights over 30 years and thus 9 vehicles were required in the fleet. By turnaround time, the peak annual flight rate of 307 flights would require only 7 airframes for *Argus* (i.e. roundup(307/46)). Thus the service life turned out to be the dominating factor in determining fleet size. This relationship held true for all vehicle and all phases of the current SSP project. This result suggests that the assumption on a 1000 flight service life should be revisited in future studies. Is a longer airframe life possible and/or justified? Unfortunately, current analysis tool and mechanisms employed in conceptual design are inadequate to predict service life from the limited vehicle detail available in the early phases of design. In fact, any differentiation of service life between the four concepts could not even be reliably estimated for this study.

Calculation of Overall Economic Metrics

CABAM was used throughout the study to predict economic performance parameters for each vehicle/mission scenario. Key assumptions made at the beginning of the study and held constant throughout the three phases include: government offset of 20% of the airframe and 100%

of the development costs (but none of the production), government funding for 100% of ground facility construction, a constant source of revenue from SSP at the rate of $400/kg of payload delivered, low interest rate, government-backed loan rates of 10% and later 7.5%, and a 3:1 debt-to-equity ratio model for raising necessary capital for RLV, Inc. From these assumptions (and other assumptions regarding corporate tax rates, discount rates, and depreciation schedules), CABAM can be used to estimate key economic parameters such as IRR (based on constant-year earnings before interest and taxes) and net present value. An overriding economic goal of this study was to achieve an RLV, Inc. IRR of greater than 20%.

There are several issues that result from these assumptions that should be highlighted. As previously mentioned, dollar discounting means that up-front government contributions are very important to increase the resultant IRR. This is especially true of construction of facilities. However, the assumption made in the current study that the government would offset 100% of facilities has the effect of artificially favoring more expensive ground facilities (since RLV, Inc. doesn't pay!). For example, *Argus* uses a very expensive (over $3B) set of Magnetic-levitation track facilities to reduce the size and cost of the flight vehicle. The Maglev track essentially serves as a "free" first stage for *Argus* paid by the government while there is no such advantage for *Hyperion*. Some of the economic results in this study would have to be revisited if an equal (or even a zero) government contribution was made to each concept for facilities and other non-recurring costs. Put another way, *Argus* and SSTO-R/LA may look better than the other competitors largely because of unequal government contributions.

The assumption that the debt-to-equity ratio of privately raised capital would be kept in a 3:1 ratio essentially keeps the same proportion of debt for each concept and mission considered. However, concepts that require larger non-recurring investments require the RLV developer to raise more absolute equity funding at the beginning of the scenario. The issue to an RLV developer might be, is it better to have a scenario with 22% IRR but requires $5B of startup equity, or one that has an 18% IRR with $4B of startup equity? In this study, preference was given to the higher IRR and the issue of raising adequate equity was left unresolved.

Phase 1 Study Results and Issues:

In phase 1, all four concepts were evaluated against the (then baseline) MEO Suntower constellation outlined in the attached presentation materials. This scenario called for the delivery of one 4850 MT Suntower to orbit annually for 30 years (in 19 MT pieces). With the 10% refurbishment schedule on 10 year cycles also assumed, resultant flight rates ranged from 251 per year to 307 per year. The interest rate for private debt financing was assumed to be 10% for this phase. The two preferred concepts emerging from this phase were the SSTO-R/LA concept and *Argus*. *Argus* had the advantage of low operations costs, but the SSTO-R/LA vehicle had the

lowest DDT&E and fleet procurement costs, and also had a lower initial debt requirement and lower financial costs. IRR's for both concepts were calculated to be only a mediocre 7.9%. SSTO-R/LA had a slightly better net present value, although all NPV's were negative when using a 25% discount rate. Recall that SSTO-R/LA also has lower facilities requirements, and this also requires a lower government investment. While it's economic performance was not even close to the required 20% IRR goal (in fact costs per kg were already near the expected $400/kg SSP price without including profit!), the SSTO-R/LA was considered the best option in phase 1 by a slight margin over *Argus*.

Hyperion and ACRE-92 performed relatively poorly in this initial assessment. *Hyperion* had the lowest operational costs, but it's highest overall non-recurring expenses and resultant financing costs caused it's IRR to suffer. ACRE-92 had a combination of high DDT&E and procurement costs (second only to *Hyperion*) and the second highest ops costs. In addition, ACRE-92 resulted in the highest facilities requirement to the government. IRR's for these two concepts were found to be less than 5.5%.

Phase 2 Study Results and Issues:

Phase 2 work consisted of several trade studies and sensitivity analyses for the SSTO-R/LA vehicle. Debt interest rate, Suntower deployment rate, Suntower mass, vehicle payload capacity and additional commercial Space Transportation Study (CSTS) market overlays were the primary variables considered. The results are documented in the attached presentation materials.

7.5% Interest Rate

At the suggestion of NASA study participants, a 7.5% "optimistic" government loan guarantee program was considered and this was found to decrease financing costs for the baseline case by nearly $4B over the 30 year mission model. In support of this scenario, it has been pointed out that there has been some discussion among members of the U. S. House of Representatives regarding the feasibility of such a low rate guarantee. While this does not affect IRR since IRR was calculated before interest and taxes, it does significantly lower the life cycle cost of the venture.

CSTS Markets

Similarly, adding the CSTS commercial and government LEO cargo delivery markets was found to add as many as 350 flights per year to the SSP mission model and significantly increase revenues and IRR. Two options were considered for the CSTS market overlays. In the first case, the CSTS market were afforded the same low $400/kg price that SSP had negotiated as an "anchor tenant". This created the most new markets and flights, but did not necessarily maximize profits on

those markets for RLV, Inc. In the second case, the commercial and government CSTS market prices were optimized to provide the most financial return to RLV, Inc. This meant charging more per kg of payload and reducing flights and markets, but also reducing costs of operations and new vehicles purchases. The IRR of the optimized CSTS overlay increased IRR by more than 7 percentage points. Optimized prices resulting from this analysis were approximately $1700/kg for commercial CSTS payloads and $3000/kg for (less price elastic) government payloads. SSP payload price was always held to $400/kg.

Suntower Mass vs. Deployment Rate

At the second SSP Technical Interchange Meeting, it was suggested by Jay Penn of the Aerospace Corporation that higher flight rates would be necessary to reduce operations costs for future RLV's to the levels required by SSP. Increasing deployment rates to 1.5/year or 3/year (and thus decreasing the constellation deployment period) has that effect, but the lower per flight operations costs were not found to offset the costs of larger facilities and fleet sizes required to support that traffic. However, increased traffic due to larger individual Suntower mass was found to be very beneficial to the RLV economic scenario. Essential, a larger Suntower mass increases the total mass delivered to orbit over the 30 year deployment period and thus the total revenue is increased.

This is an interesting situation for the overall SSP venture. Increasing Suntower mass helps the RLV developer's economic scenario (where the ETO transportation fees are revenue), but almost certainly hurts the economic scenario for SSP, Inc. (where the ETO transportation fees are expenses). The impact of increasing mass on the SSP, Inc. economic scenario was not considered by researchers at Georgia Tech.

Vehicle Payload Mass

NASA SSP program participants also suggested that larger payload vehicle payload capacities might be beneficial, and this was found to be true for the SSTO-R/LA system investigated in phase 2. 10MT, 20 MT, and 40 MT SSTO-R/LA configurations were considered. Larger payload vehicles have larger DDT&E, larger procurement costs, larger facilities costs, and larger operations costs (due to fewer flights per year and a larger vehicle). However, the revenue of a 40 MT payload vehicle is twice that of a 20 MT vehicle per flight. Costs per flight were only found to increase by about 50% per flight while revenues increased by 100% over the baseline 20 MT vehicle case.

Phase 3 Study Results and Issues:

In October of 1998, a beneficial change in the Suntower configuration and deployment schedule was made by overall SSP study participants lead by Harvey Feingold of SAIC. The MEO Suntower constellation was abandoned in favor of a larger, GEO-based constellation of 30 Suntowers. These larger Suntowers had over triple the mass per Suntower of the MEO Suntowers (15561 MT vs. 4850 MT). This proved to be exactly the type of change that was necessary to make the RLV economic scenario attractive. Phase 3 efforts at Georgia Tech adopted the CSTS overlay, the 40 MT payload, and the 7.5% interest rate from phase 2 and reexamined *Argus* and SSTO-R/LA for the new GEO Suntower mission scenario. For this scenario, annual flight rates ranged from 410 to 497 for just the SSP missions. Note that it was hypothesized that *Argus* might be more attractive at these higher flight rates based on its lower ops costs, hence the reason for reexamining that particular concept.

IRR's for phase 3 were over 22% for both *Argus* and SSTO-R/LA for the basic GEO SSP model. With the optimized CSTS overlay, IRR's increased to nearly 25%. *Argus* had a slight advantage in phase 3 cost/kg due to lower ops costs, but IRR's of the two vehicles are very close due to the lower up-front costs of SSTO-R/LA. Over the 30 mission model, best case revenues for the optimized CSTS overlay are close to $240B for RLV, Inc. while total life cycle costs incurred are near $80B (in 1998 dollars).

In our experience, achieving the goal of 20% IRR requires cost per kg payload to be less than 1/2 of the expected price per kg. That is, overall life cycle <u>cost</u> per kg of payload delivered should be less than $200/kg for this model. For *Argus*, the best case costs were $147/kg. For SSTO-R/LA, the best case costs were $160/kg. Achieving this low cost goal was the result of a combination of several factors.

1. Having sufficient total flights in the model to amortize vehicle DDT&E and fleet costs

2. Achieving very low operations cost with new ways of doing ops and high annual flights

3. Augmenting "anchor" SSP revenues with CSTS market traffic to increase profits

4. Reducing financing costs for initial capital (low interest loans, smaller cheaper vehicles)

5. Government assistance to reduce up-front costs (facilities/launch assist, and DDT&E offsets)

Overall Study Conclusions:

The results from phase 3 of this study support the conclusion that, yes, the latest GEO-based SSP scenario does produce an attractive economic scenario for a potential RLV developer even if the revenues are limited to only $400/kg. With proper support from the government, the sustained, high traffic mission model from the SSP creates a steady revenue source that enables RLV, Inc. to recoup startup costs and still provide an adequate return on investment.

Acknowledgements:

The work of this study was conducted by graduate and undergraduate students in the Space Systems Design Lab at Georgia Tech. Jeff Scott served as study lead and performed aerodynamic analysis and vehicle layout tasks. Laura Ledsinger performed trajectory optimization. David McCormick performed mass properties analysis. Rocket engine analysis was performed by David Way. RBCC propulsion analysis was performed by John Bradford. Becca Cutri-Kohart assisted NASA KSC in the operability and turnaround analyses. Jeff Whitfield and Ashraf Charania performed cost analyses and economic assessments.

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Dr. John R. Olds
Director, Space Systems Design Lab
Georgia Institute of Technology
Atlanta, GA 30332-0150
December 18, 1998

Launch Vehicle Assessment for Space Solar Power

Summary of Phase 1 Preliminary Studies

June - August 1998

Dr. John R. Olds, Jeff Scott, Jeff Whitfield, Laura Ledsinger, John Bradford, Ashraf Charania, Dave McCormick, Dave Way

Space Systems Design Laboratory
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA

GT Project Chronology

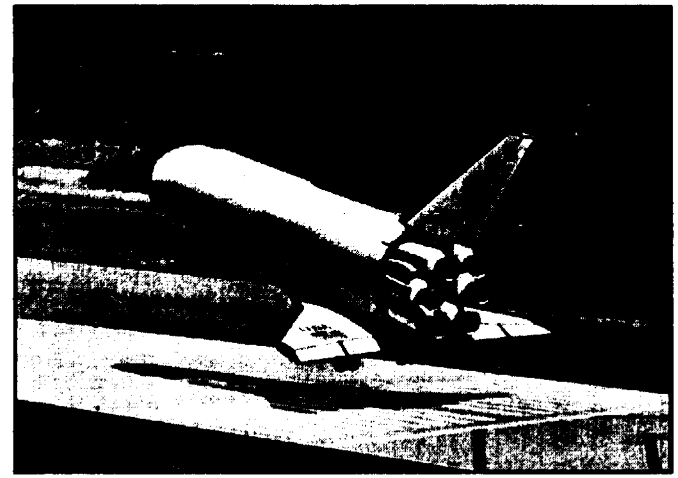
June - August 1998 (phase 1)	Performed preliminary sizing and economic evaluations on all four ETO candidates sized for 20 MT payload. Used 4850 MT MEO-based Suntower concept (one per year). Preliminary best concept appeared to be HTHL SSTO-R/LA.
August - October 1998 (phase 2)	Performed several sensitivity studies on SSTO-R/LA vs. deployment rate, payload size, ST mass, CSTS mission overlays, and govm't incentives. 40 MT payload size and larger Suntower mass appeared beneficial, but ETO IRR was still poor.
October - December 1998 (phase 3)	Updated Suntower to 15,561 MT GEO based triplet (higher flight rates). Reconsidered 40 MT *Argus* and 40 MT SSTO-R/LA. Economic results for both systems are now favorable, IRR's > 22%

Phase 1 Project Goals

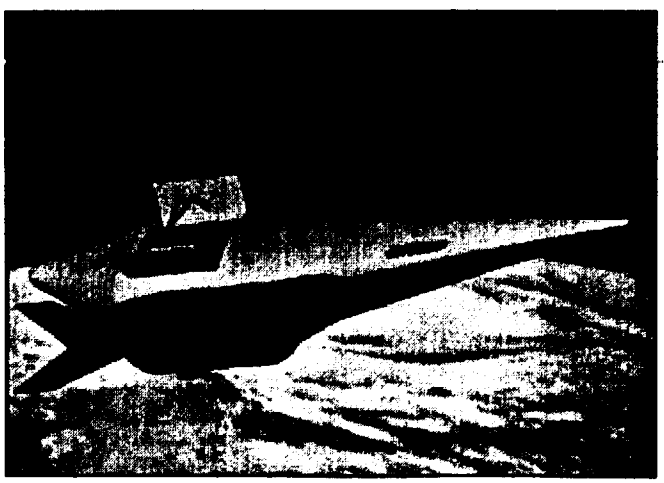
- Perform preliminary assessments of 4 HRST concepts
  - include performance, weight, size, and life cycle cost
- Use consistent assumptions and analysis tools
  - 'level' any technology differences between concepts
    - all concepts will use advanced technologies (like Argus)
- Identify economic "attractiveness" of SSP for ETO
  - do any of the HRST vehicles make sense at $400/kg price?
  - what concept or concepts are preferred?

SSP Launch Vehicle Candidates

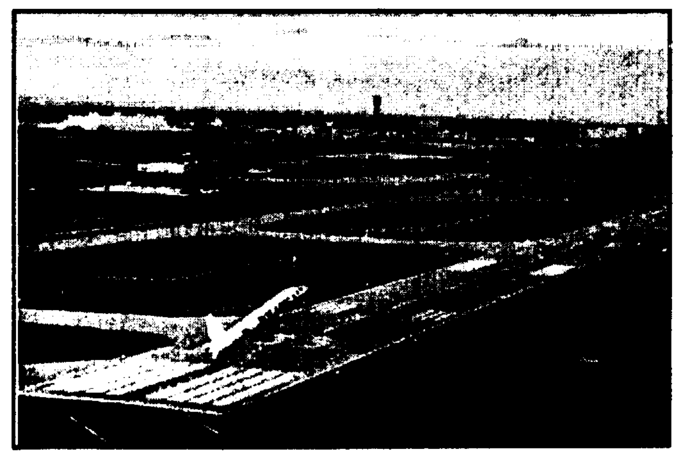
Argus w/Maglifter Launch Assist



ACRE-92 VTHL all-rocket SSTO (Notional)



Hyperion RBCC SSTO



SSTO-Rocket w/Sled Launch Assist (Notional)

Preliminary Assessment of all Four SSP ETO Candidates for MEO Suntower Mission

GT SSP Project -- Phase 1

SSP Vehicle Sizing Results (ϕ1)

	Argus	*Hyperion*	*ACRE-92*	*SSTO/Sled*
Equatorial Launch Site†				
Mass Ratio (W_i/W_f)	5.592	4.950	7.571	6.960
LOX/LH2 mixture (wgt)	3.765	2.971	6.9	6.9
Sizing ("Ops" versions)				
Gross Mass	589 MT	785 MT	982 MT	635 MT
Dry Mass	75 MT	124 MT	98 MT	61 MT
Maximum Payload	**20 MT**	**20 MT**	**20 MT**	**20 MT**
Operations				
Flights/airframe/year	46 flights ††	35 flights ††	34 flights ††	37 flights
Airframe/engine life	1000/500 flts.	1000/500 flts.	1000/500 flts.	1000/500 flts.

† - Equatorial trajectory results assume containerized payload drop off at 0° inclination by 300 km circ. MECO is at 94 x 281 km x 0°.

†† - data supplied by KSC using NASA's AAT flight rate tool, SSTO-R/Sled flight rate estimated by Georgia Tech

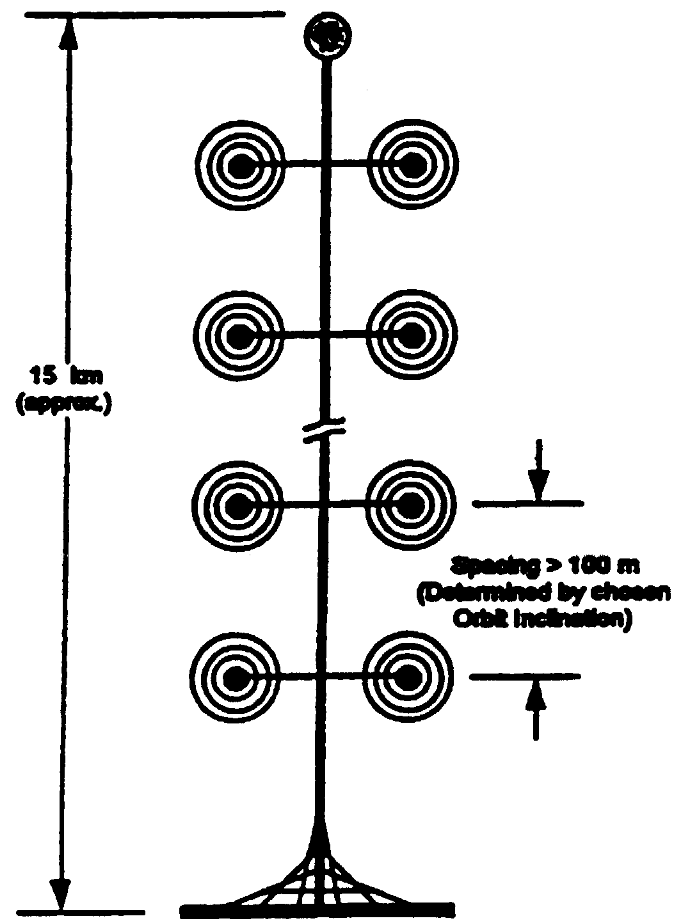
Phase 1 MEO Suntower ETO Mission Model

MEO Suntower (ϕ1)

Suntower Data

Mass/each	4,850 MT†
Orbits (km):	
Delivery	300 @ 0°
Operational	12,000 @ 0°
Dimensions/each	~15 km (height)
Power on Ground	400 MW

† - VRC/SSP wing document SAIC-1, 06/01/98



MEO Suntower Deployment (ϕ1)

Georgia Tech Baseline
30 Suntower Architecture

Launch Rate	1 per year (4850 MT)
Constellation Size	30
Deployment Period	30 years
Refurbish Percentage	10% of initial mass
Refurbish Period	10 year centers per tower

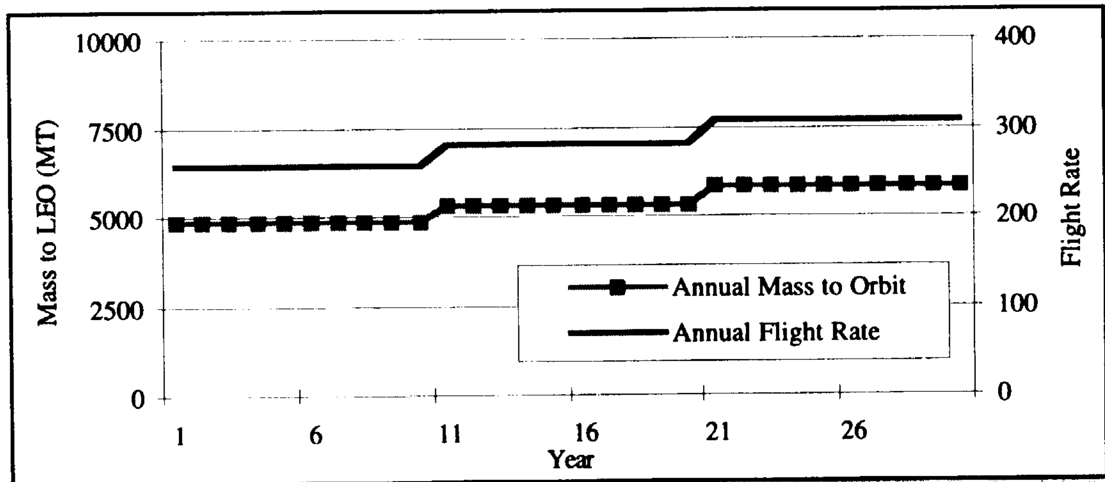
19 MT delivered per flight †

Initial flight rate = 256/year

Peak flight rate = 307/year

160,050 MT to LEO (30 yr.)

8,440 ETO flights (30 yr.)



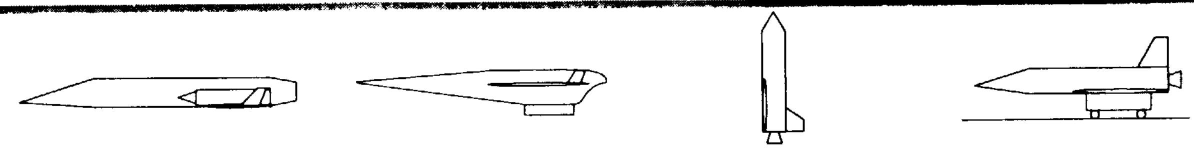
No relays are included in the baseline architecture

† *Note: 5% of maximum 20 MT payload assumed lost to ASE, EM tether, packaging losses, etc.*

Basic Economic Assumptions (ϕ1)

- Government Incentive Package to ETO Developer
  - 100% of engine DDT&E
  - 20% of airframe DDT&E
  - 100% of ETO ground facilities (RLV, Inc. pays user fee every flight)
- 3-to-1 Debt-to-Equity Financing (75% borrowed)
  - 10% interest rate guaranteed by USG
- ETO Development Schedule
  - DDT&E: 2004 - 2008
  - production: 2009 - 2010
  - first revenue flight: 2010

Suntower ETO Cost Results (ϕ1)

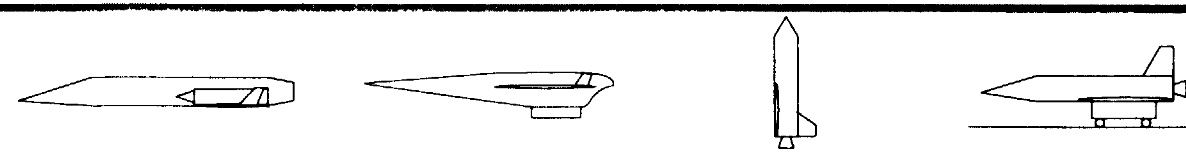


	Argus	Hyperion	ACRE-92	SSTO/Sled
Vehicle/Fleet Data				
TFU (incl. engines)	$1.300 B	$1.925 B	$1.913 B	$1.172 B
Ops cost/flight (@250/yr.)†	$3.25 M	$3.15 M	$3.35 M	$3.85 M
Fleet size required	9	9	9	9
New launch facilities††	2 Maglev tracks	-	6 launch pads	2 sled tracks
LCC Contributors (98$)				
DDT&E (including engines)	$5.50 B	$6.85 B	$6.47 B	$4.64 B
Fleet acquisition (80% l/c)	$7.63 B	$11.29 B	$11.22 B	$6.87 B
Facilities (total CoF)	$2.02 B	$0.42 B	$3.42 B	$0.72 B
Flight/Ground Operations	$27.43 B	$26.59 B	$28.27 B	$32.49 B

† - extrapolated from HRST Ops Team Final Report, VRC Operability wing; also includes $50k/flight for liability insurance and $50K/flight for range fee per GT

†† - Maglev and Sled tracks support up to 200 flights/yr each; vertical launch pads support up to 50 flights/yr each

Economic Performance (ϕ1)



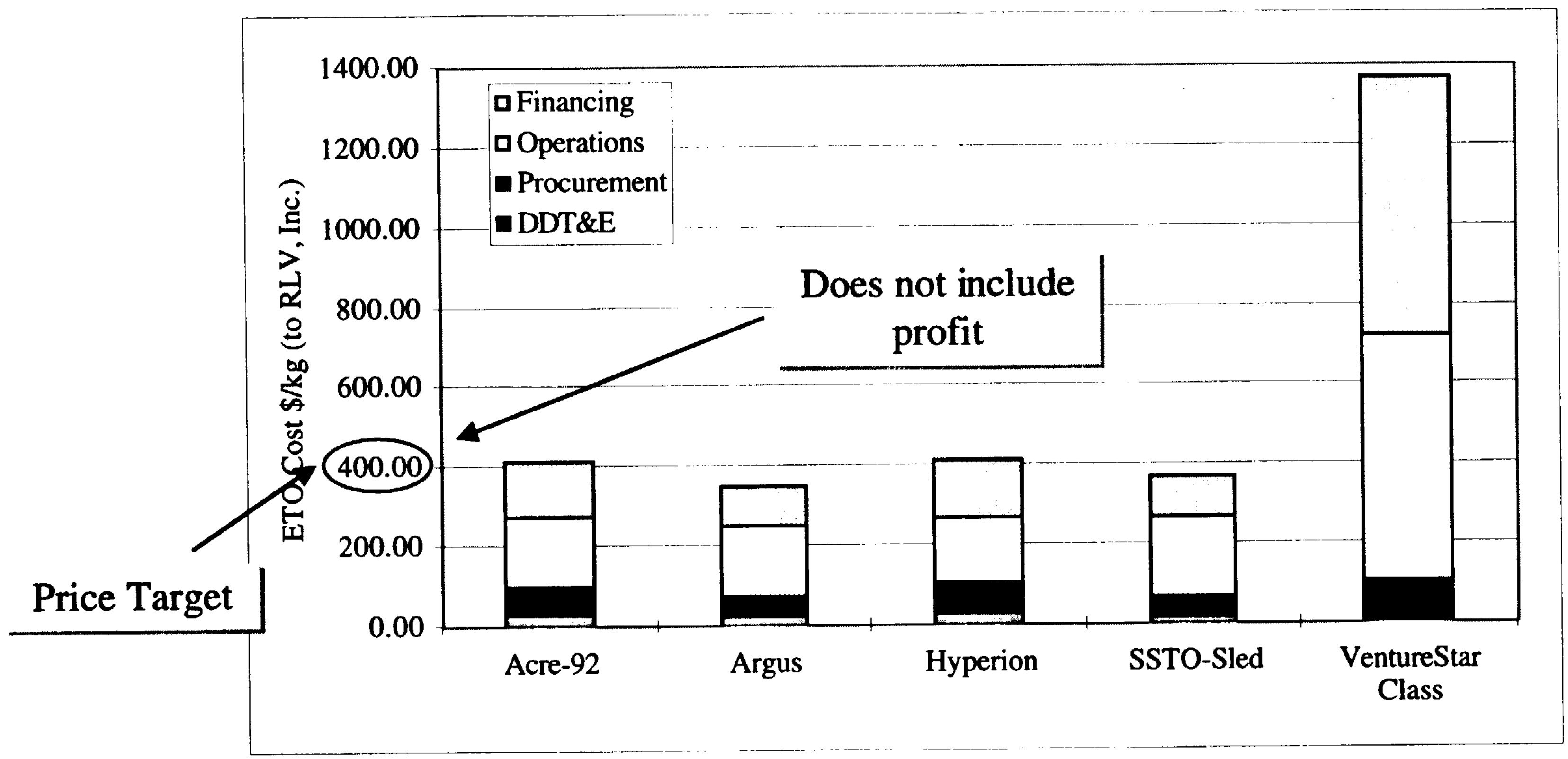
	Argus	Hyperion	ACRE-92	SSTO/Sled
Cash Flow Summary				
Total SSP revenues†	$64.14 B	$64.14 B	$64.14 B	$64.14 B
Total direct costs††	$42.58 B	$45.15 B	$49.38 B	$44.72 B
Financing costs (10% rate)	$16.18 B	$22.83 B	$22.28 B	$14.16 B
Initial Investments Req'd				
Initial Gov't incentives	$3.63 B	$2.23 B	$5.03 B	$1.96 B
Initial private equity	$ 2.99 B	$4.53 B	$4.48 B	$2.62 B
Economic Indicators				
Internal Rate of Return (IRR)	7.9 %	5.6 %	5.5 %	7.9 %
Net Present Value (25% disc.)	(794) M	(1160) M	(1136) M	(696) M
Breakeven year	2035	NA	NA	2035

!

Rather poor

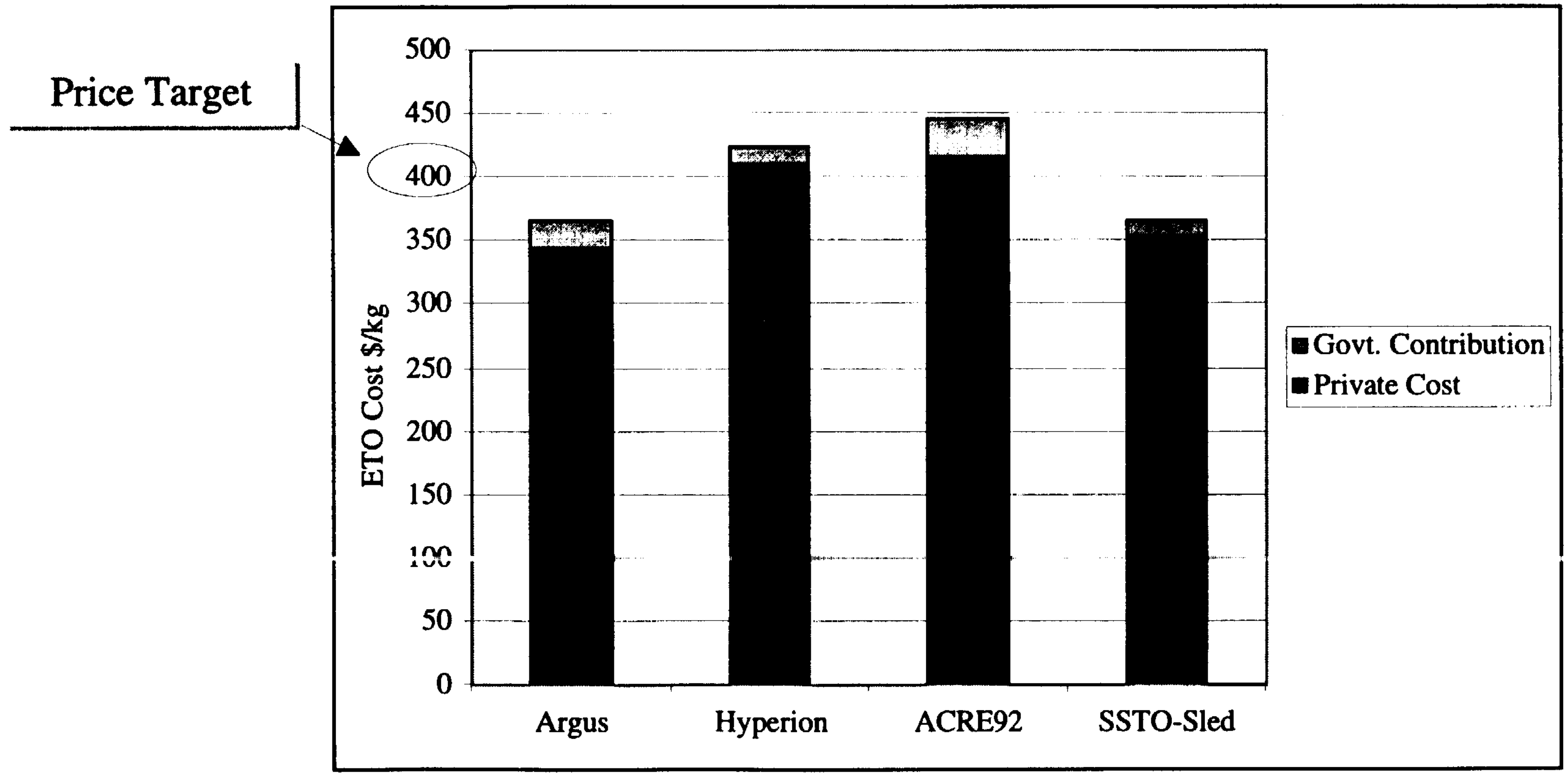
† - at basic $400/kg SSP price, exclusive SSP traffic model; †† - includes DDT&E, acquisition, facilities, ops prior to gov't incentives

ETO Cost Contributors (ϕ1)



Smaller Argus and SSTO-sled result in lowest cost/kg but still do not leave much room for profit

Government Incentive (ϕ1)



<u>Up-front</u> government contributions only slightly reduce private cost/kg but have significant benefit on IRR

Phase 1 Observations

- $400/kg SSP price may not be sufficient for RLV, Inc.
  - best case IRR is less than 8%, not economically attractive
  - current SSP traffic model generates too little revenue and too few flights to properly amortize DDT&E, financing
- SSTO-R/LA and *Argus* have the "best" economics
  - smaller, simpler vehicles reduce DDT&E and fleet costs
    - note: ground launch assist infrastructure assumed to be developed by gov't (rocket sled or Maglev), thus those costs are not incurred by RLV, Inc!
  - slight edge to SSTO-R/LA due to lower up-front costs
    - better IRR and NPV for SSTO-R/LA (however *Argus* has lower ops and thus may be better at higher flight rates)

Phase 1 Observations (cont'd)

- ACRE-92 and *Hyperion* have too much up-front cost
  - higher # of engines, higher dry weights, highest DDT&E and TFU (*Hyperion*)
  - also ACRE-92 suffers from the highest per flight ops costs
- Airframe and engine service life are key (1000/500 flts)
  - fleets are currently life limited, not turnaround time limited
  - current models do not accurately link design changes with life

Trade studies to look for improvements are recommended. Larger payload capacities and larger traffic models may help IRR.

Phase 1 Vehicle Sizing and Weight Statement Details

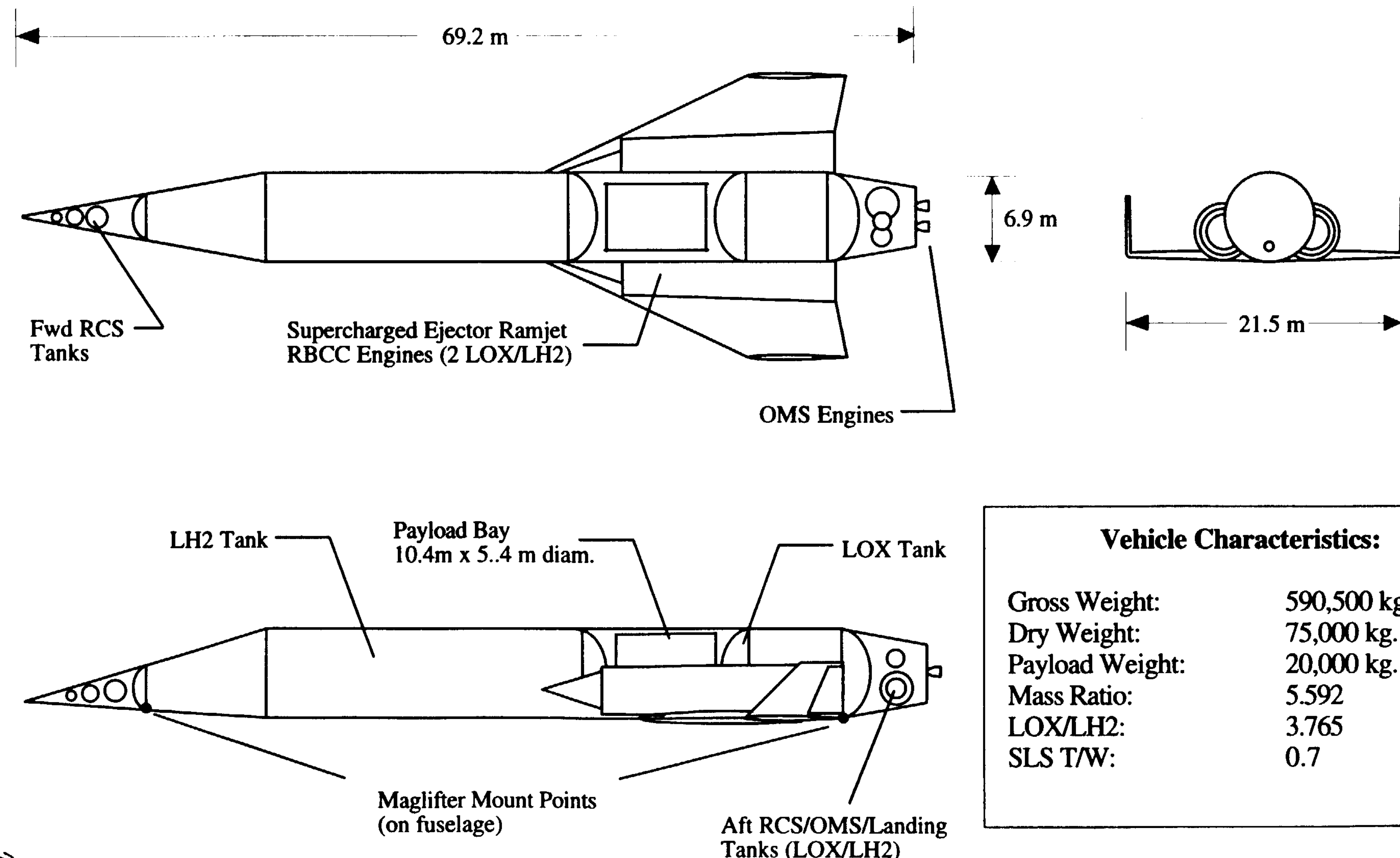
Vehicle Changes from HRST

- Standardized P/L bay volume to 226 m^3 and capacity to 20 MT
  - volume is constant, but P/L bay shape changes with concept
  - 20 MT capacity was arbitrarily chosen for phase 1 designs
- Updated POST trajectory data for all four concepts
  - slight updates to mass ratio and mixture ratio calculations
  - assessed both equatorial and KSC launch sites to 94 x 281 km MECO
    baselined 600 fps OMS ΔV for all vehicles (on-orbit and deorbit)
- Increased TPS unit weights to reflect updated heating models
- Made several changes to *Hyperion* to improve Ops (per KSC)
  - integral main LH2 tank, LH2 flyback fuel for ducted fans, eliminated active cooling, reduced to 2 ducted fans, etc.

More Ops-focused Changes (All)

- Added additional weight margin to key structures (+10%)
  - increases airframe life (hopefully enables 1000 flights/airframe)
  - reduces ops inspection costs and improves TAT (helps justify low ops $)
  - more robust wings, tails, tanks, P/L structure, and primary structure
- Added weight to subsystems to reflect use of COTS (+5%)
  - use of commercial-off-the-shelf subsystems reduces DDT&E and TFU
  - reduces LRU/inventory costs for ops
  - affects avionics, power, actuation, electrical distribution, ECLSS
- De-rated engines to 90% of maximum thrust for normal ops
  - cooler running, longer life engines (hopefully enables 500 flights/engine)
  - reduces ops inspection time/costs and improves turnaround time
  - estimated by adding +10% weight to engine and feed system weights

Argus SSP Vehicle (φ1)



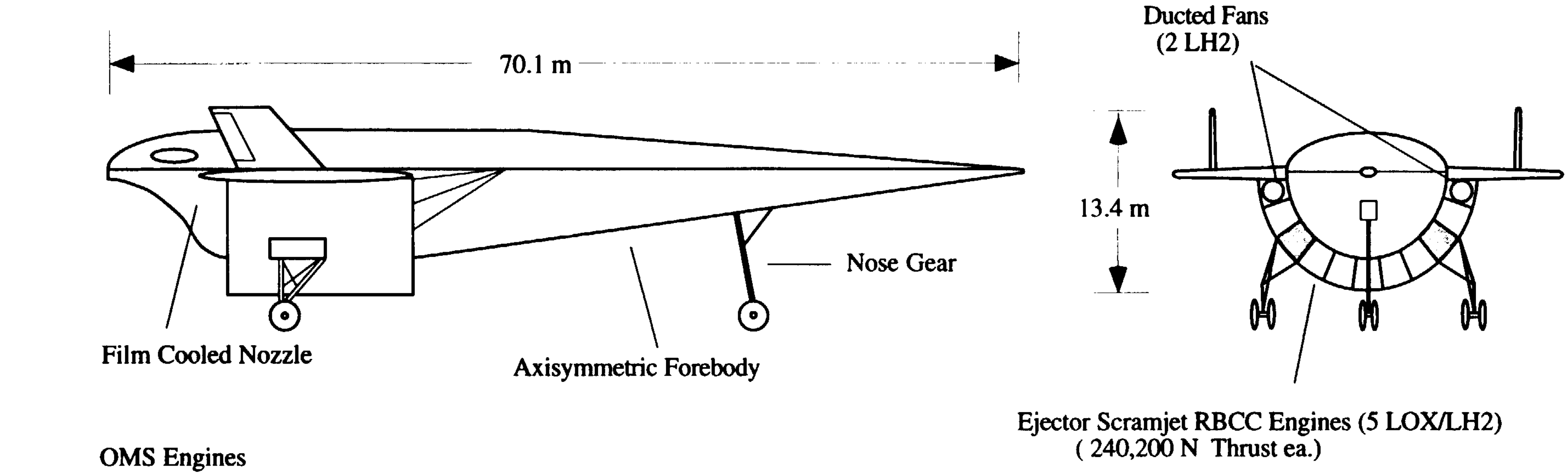
Vehicle Characteristics:

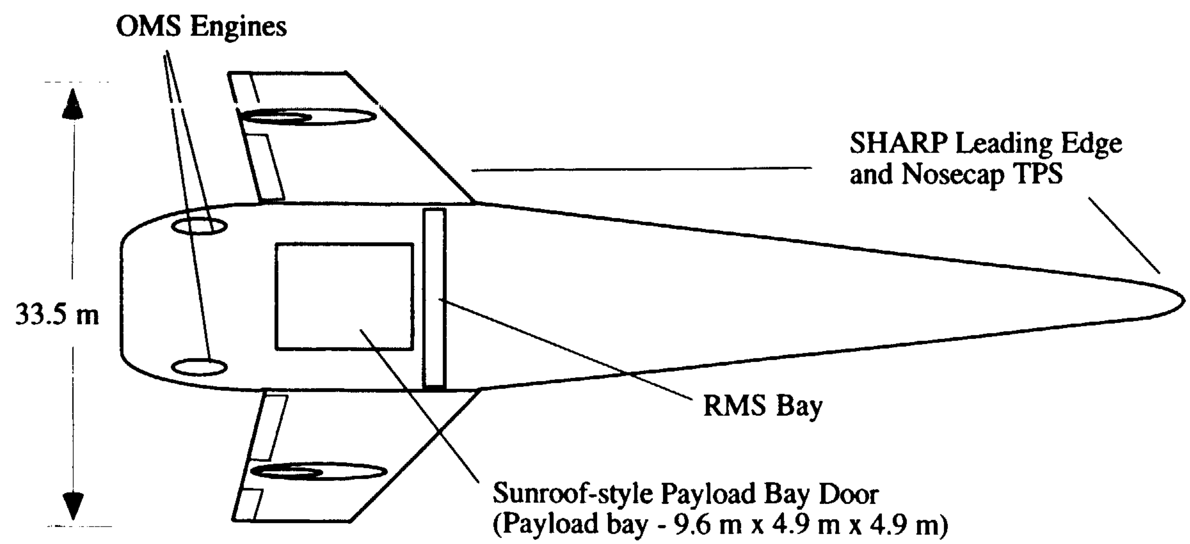
Gross Weight:	590,500 kg.
Dry Weight:	75,000 kg.
Payload Weight:	20,000 kg.
Mass Ratio:	5.592
LOX/LH2:	3.765
SLS T/W:	0.7

Argus Weight Statement (ϕ1)

Name	Weight (kg)
Wing and Tail Group	11,500
Body Group (incls. Tanks)	16,020
Thermal Protection	5,440
Main Propulsion	21,960
OMS/RCS Propulsion	1,560
Subsystems and Other Dry Weights	8,870
Dry Weight Margin (15%)	9,800
Dry Weight	75,150
Payload	20,000
Other Inert Weights (residuals, etc.)	10,450
Insertion Weight	105,600
Ascent Propellants	484,910
Gross Lift-off Weight	590,510

Hyperion SSP Vehicle (ϕ1)





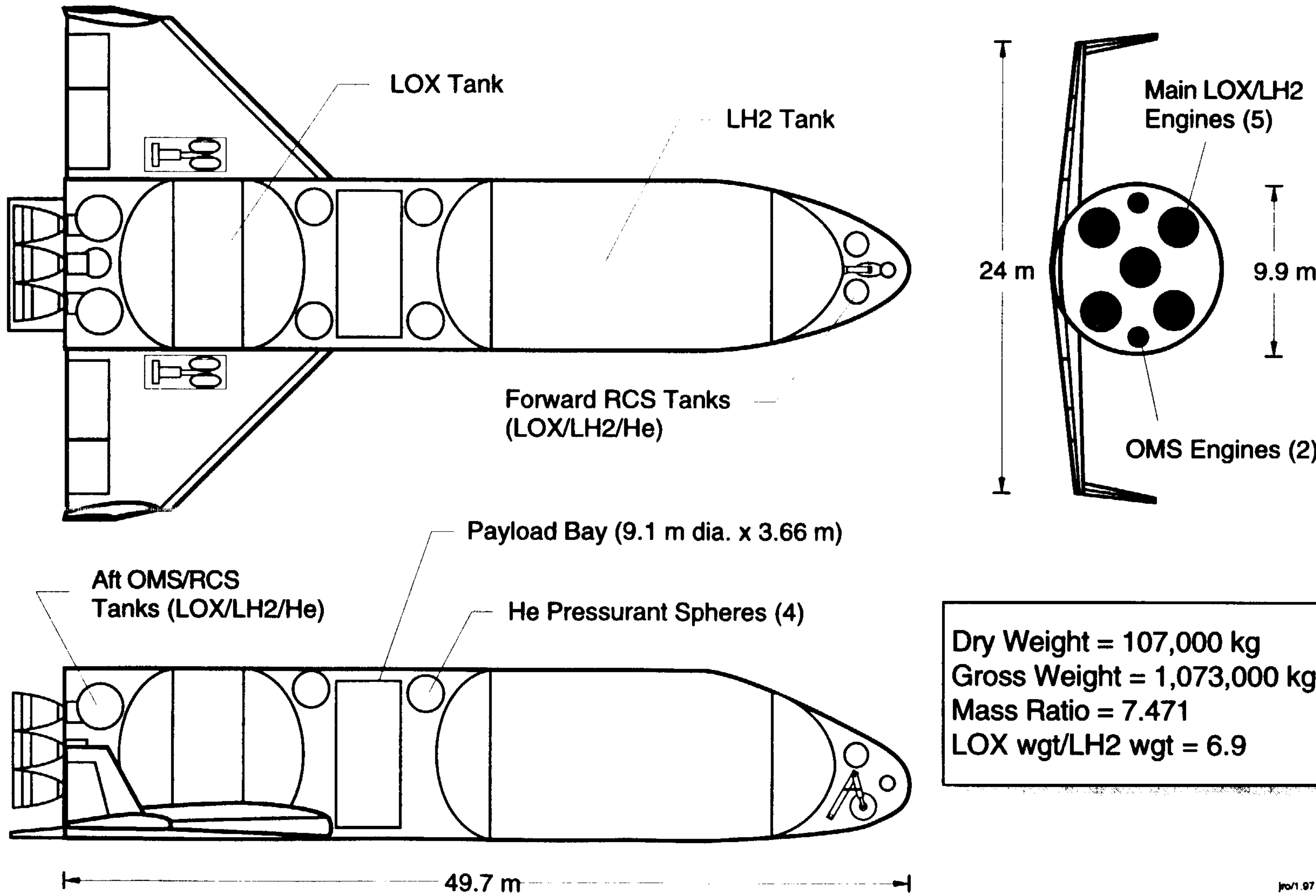
Vehicle Characteristics:

Gross Weight:	786,400 kg.
Propellant Weight:	627,300 kg.
Payload Weight(LEO):	20,000 kg.
Inert Weight:	124,100 kg.
Mass Ratio:	4.95

Hyperion Weight Statement (ϕ1)

Name	Weight (kg)
Wing and Tail Group	21,670
Body Group (incls. Tanks)	30,340
Thermal Protection	3,180
Main Propulsion	22,880
OMS/RCS Propulsion	3,120
Subsystems and Other Dry Weights	26,660
Dry Weight Margin (15%)	16,180
Dry Weight	124,030
Payload	20,000
Other Inert Weights (residuals, etc.)	14,800
Insertion Weight	158,830
Ascent Propellants	627,420
Gross Lift-off Weight	786,250

ACRE-92 SSP Vehicle (ϕ1)



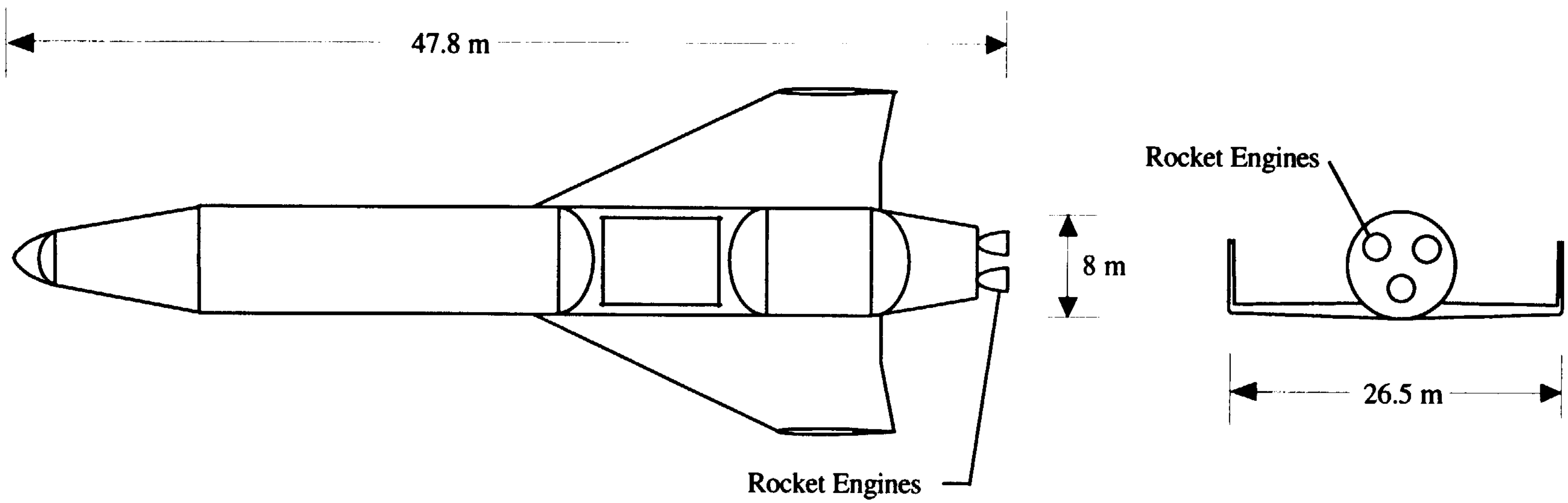
Dry Weight = 107,000 kg
Gross Weight = 1,073,000 kg.
Mass Ratio = 7.471
LOX wgt/LH2 wgt = 6.9

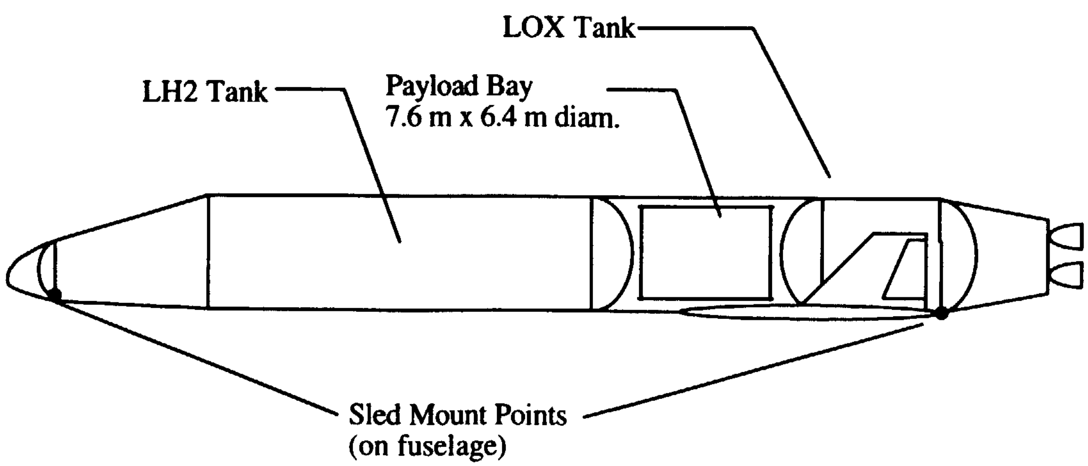
jro/1.97

ACRE-92 Weight Statement (ϕ1)

Name	Weight (kg)
Wing and Tail Group	6,030
Body Group (incls. Tanks)	40,770
Thermal Protection	8,190
Main Propulsion	20,630
OMS/RCS Propulsion	4,230
Subsystems and Other Dry Weights	13,120
Dry Weight Margin (15%)	13,950
Dry Weight	106,920
Payload	20,000
Other Inert Weights (residuals, etc.)	16,700
Insertion Weight	143,620
Ascent Propellants	929,380
Gross Lift-off Weight	1,073,000

SSTO-R/LA SSP Vehicle (φ1)





Vehicle Characteristics:

Gross Weight:	636,000 kg
Dry Weight:	61,370 kg
Payload Weight:	20,000 kg
Mass Ratio:	6.960
LOX/LH2:	6.90
SLS T/W:	0.8
Liftoff Speed:	112 m/sec.

SSTO-R/LA Weight Statement (ϕ1)

Name	Weight (kg)
Wing and Tail Group	13,210
Body Group (incls. Tanks)	15,020
Thermal Protection	4,400
Main Propulsion	11,740
OMS/RCS Propulsion	1,160
Subsystems and Other Dry Weights	7,830
Dry Weight Margin (15%)	8,000
Dry Weight	61,360
Payload	20,000
Other Inert Weights (residuals, etc.)	10,050
Insertion Weight	91,410
Ascent Propellants	544,830
Gross Lift-off Weight	636,240

Launch Vehicle Assessment for Space Solar Power

Summary of Phase 2 Trade Studies

August - October 1998

Dr. John R. Olds, Jeff Scott, Jeff Whitfield, Laura Ledsinger, John Bradford, Ashraf Charania, Dave McCormick, Dave Way

Space Systems Design Laboratory
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA

GT Project Chronology

June - August 1998 (phase 1)	Performed preliminary sizing and economic evaluations on all four ETO candidates sized for 20 MT payload. Used 4850 MT MEO-based Suntower concept (one per year). Preliminary best concept appeared to be HTHL SSTO-R/LA.
August - October 1998 (phase 2)	Performed several sensitivity studies on SSTO-R/LA vs. deployment rate, payload size, ST mass, CSTS mission overlays, and govm't incentives. 40 MT payload size and larger Suntower mass appeared beneficial, but ETO IRR was still poor.
October - December 1998 (phase 3)	Updated Suntower to 15,561 MT GEO based triplet (higher flight rates). Reconsidered 40 MT *Argus* and 40 MT SSTO-R/LA. Economic results for both systems are now favorable, IRR's > 22%

Phase 2 Project Goals

- Build on results of Phase 1 GT study
  - SSTO-R w/launch assist appeared most attractive
  - *Argus* concept was a close second
- Use trade studies to explore ETO design space
  - look for ways to improve mediocre IRR from phase 1
  - determine sensitivities to changes in SSP mission model
  - recommend changes in vehicle and/or SSP model

Our phase 2 efforts were focused on improving the mediocre IRR's in phase 1 and recommending key changes

Summary of SSP Trade Studies with SSTO-R w/Launch Assist

GT SSP Project -- Phase 2

August - October 1998

Trade Studies Performed (φ2)

1. SSP launch price (\$200/kg - \$1000/kg)
2. Vehicle payload capacity (10/20/40 MT)
3. Degree of government financial support
4. Suntower deployment rate (1/1.5/3 year)
5. Suntower mass (2425/4850/7275 kg)
6. CSTS payload market overlay (non-SSP)

Trade Study Baselines (φ2)

Baselines used as points of departure in trade studies during this phase...

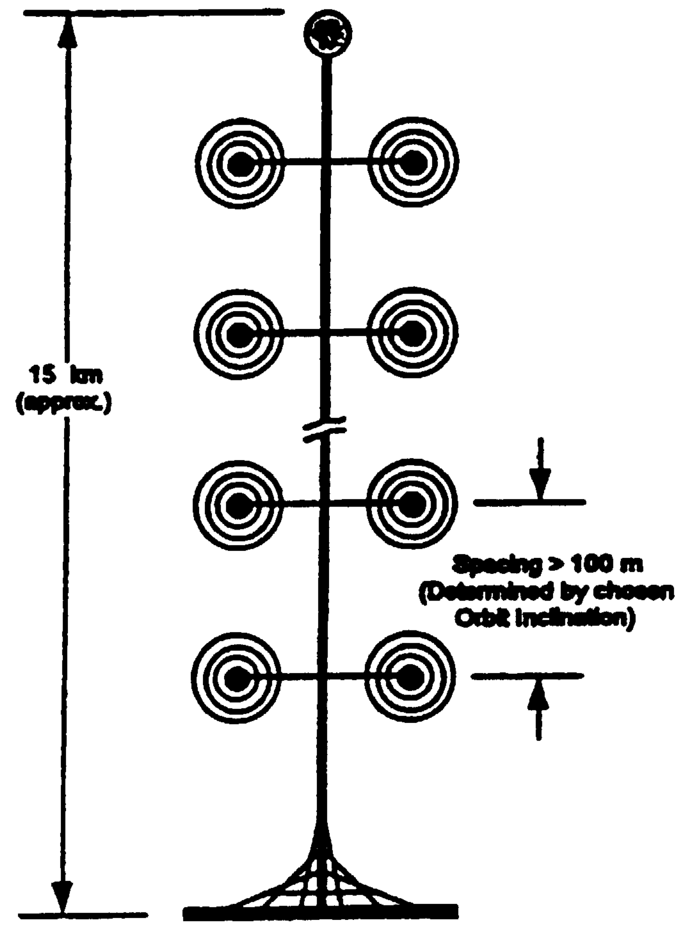
- 20 MT SSTO-R w/launch assist configuration
- Nominal government support (same as in phase 1)
  - 10% interest rate, plus facilities and some DDT&E
- 4850 MT MEO Suntowers (same as in phase 1)
  - one deployed per year for 30 years plus refurbishment
  - peak flight rate is 307/year (8440 flights in SSP model)
- $400/kg for SSP revenue (no CSTS markets in baseline)

MEO Suntower (ϕ2)

Suntower Data

Mass/each	4,850 MT†
Orbits (km):	
Delivery	300 @ 0°
Operational	12,000 @ 0°
Dimensions/each	~15 km (height)
Power on Ground	400 MW

† - *VRC/SSP wing document SAIC-1, 06/01/98*



Suntower Deployment (ϕ2)

Georgia Tech Baseline
30 Suntower Architecture

Launch Rate	1 per year (4850 MT)
Constellation Size	30
Deployment Period	30 years
Refurbish Percentage	10% of initial mass
Refurbish Period	10 year centers per tower

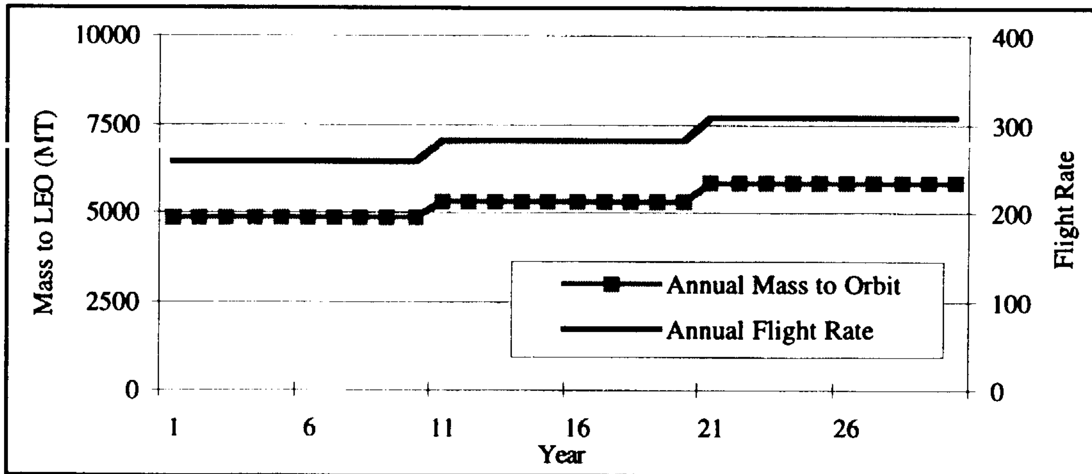
19 MT delivered per flight †

Initial flight rate = 256/year

Peak flight rate = 307/year

160,050 MT to LEO (30 yr.)

8,440 ETO flights (30 yr.)



No relays are included in the baseline architecture

† *Note: 5% of maximum 20 MT payload assumed lost to ASE, EM tether, packaging losses, etc.*

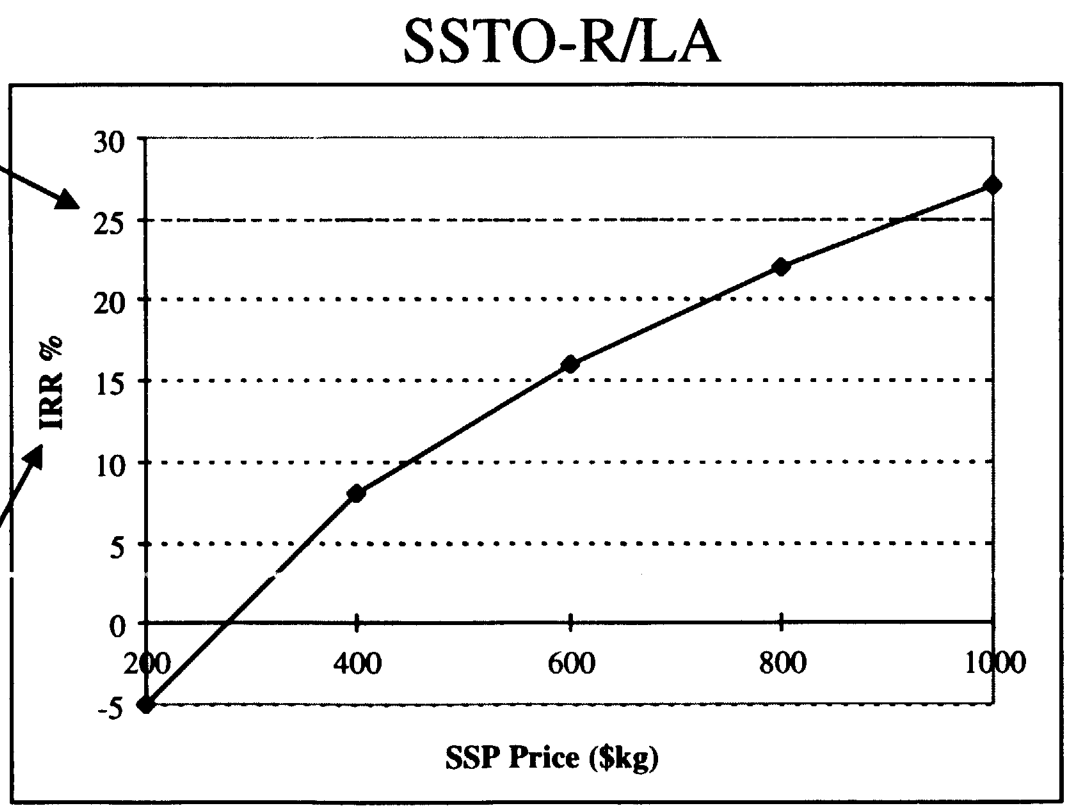
Economic Assumptions (ϕ2)

- Government Incentive Package to ETO Developer
  - 100% of engine DDT&E
  - 20% of airframe DDT&E
  - 100% of ETO ground facilities (RLV, Inc. pays user fee every flight)
- 3-to-1 Debt-to-Equity Financing (75% borrowed)
  - 10% interest rate guaranteed by USG
- ETO Development Schedule
  - DDT&E: 2004 - 2008
  - production: 2009 - 2010
  - first revenue flight: 2010

IRR vs. SSP Launch Price (ϕ2)

IRR goal should be >25% to make SSP attractive for ETO

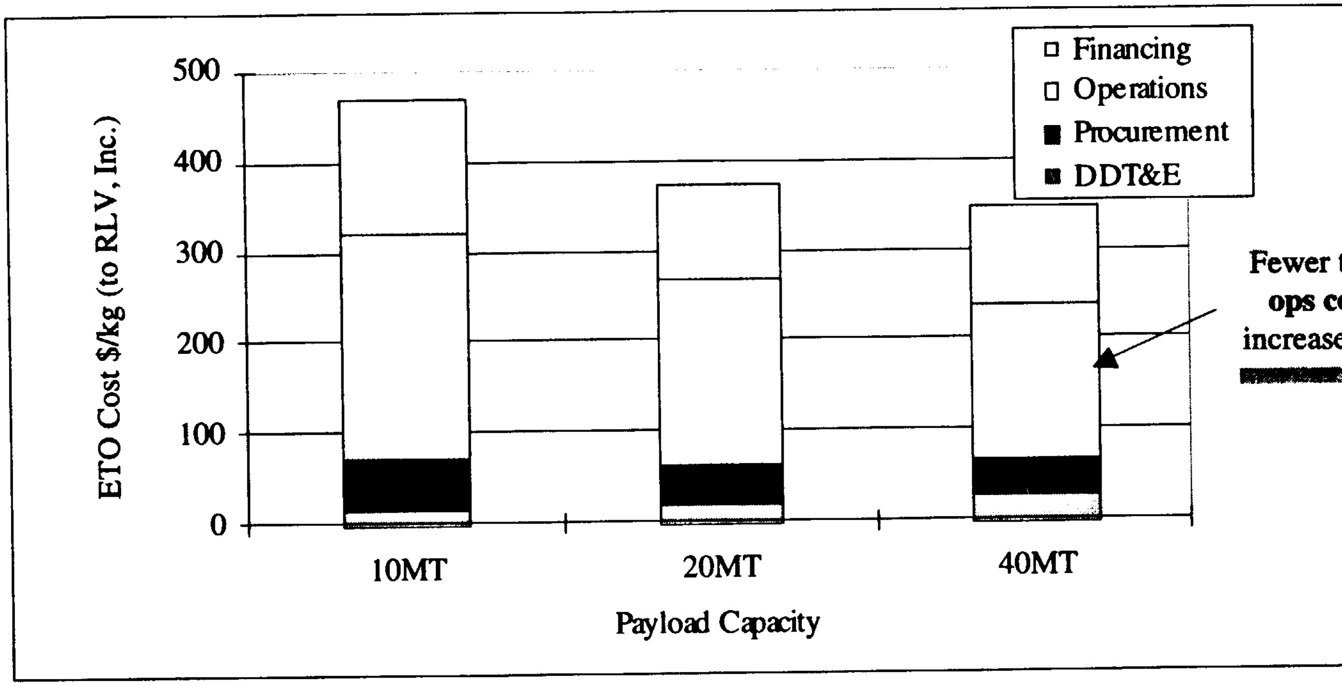
IRR is calculated from undiscounted free cash flow (prior to taxes and interest payments)



Increase in SSP launch price to $800 - $1000/kg is necessary to increase ETO segment IRR to more attractive levels

ETO Vehicle Payload Size (ϕ2)

SSTO-R/LA (30 Suntowers @4850 MT, 1 per year)



Fewer total flights lowers ops cost! (despite 67% increase in per flight costs)

Larger vehicle payload configuration reduces non-recurring and operations costs, and thus reduces SSP ETO cost per kg

ETO Vehicle Payload Size (ϕ2)

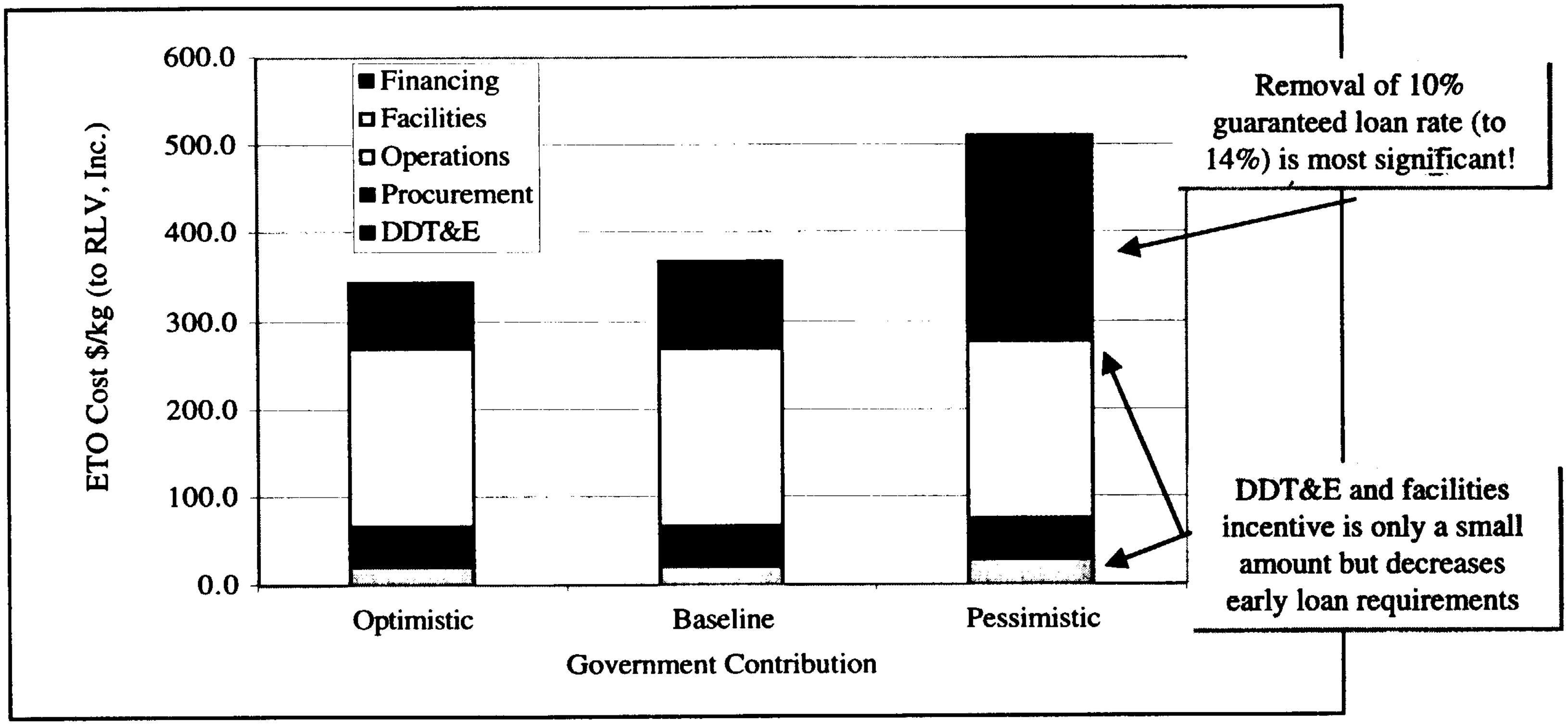
Undiscounted Cash Flow	*10 MT*	*20 MT*	*40 MT*
DDT&E (includes gov't engines)	$3.91 B	$4.64 B	$6.24 B
Facilities	$1.54 B	$0.72 B	$0.35 B
Fleet Procurement	$8.87 B	$7.27 B	$6.28 B
Operations	$39.76 B	$32.92 B	$27.68 B
Financing	$23.74 B	$16.13 B	$17.67 B
- less gov't contribution	-$2.52 B	-$1.96 B	-$1.93 B
Net LCC (to RLV, Inc.)	$75.03 B	$59.72 B	$56.29 B
SSP Revenue	$64.14 B	$64.14 B	$64.14 B
Internal Rate of Return (IRR)	4.74 %	7.49 %	8.49 %
Fleet Size	17	9	5
TFU	$0.89 B	$1.17 B	$1.58 B
Best per Flt Ops Cost†	$2.25 M/flt	$3.71 M/flt	$6.21 M/flt
Peak Flight Rate	613/yr	307/yr	154/yr
Total Flights in Model	16,860	8,440	4,230
Total SSP Mass Delivered	160,050 MT	160,050 MT	160,050 MT

Preliminary ops estimate only! More later

† - with $50k site fee and $50k insurance, preliminary ops cost does not capture effects of larger or smaller vehicles (only flight rate)

Government Incentive (ϕ2)

SSTO-R/LA (30 Suntowers @4850 MT, 1 per year)



Early government incentives and a 7.5% guaranteed loan rate are very important to ETO economic success

Government Incentive (ϕ2)

Undiscounted Cash Flow	*Optimistic*	*Baseline*	*Pessimistic*
DDT&E (includes gov't engines)	$4.64 B	$4.64 B	$4.64 B
Facilities	$0.72 B	$0.72 B	$0.72 B
Fleet Procurement	$7.27 B	$7.27 B	$7.27 B
Operations	$32.92 B	$32.92 B	$32.92 B
Financing	$12.07 B	$16.13 B	$36.97 B
- less gov't contribution	-$1.96 B	-$1.96 B	$0 B
Net LCC (to RLV, Inc.)	$55.66 B	$59.72 B	$79.97 B
SSP Revenue	$64.14 B	$64.14 B	$64.14B
Internal Rate of Return (IRR)	7.65 %	7.49 %	6.07 %

7.5% rate!

14% rate!

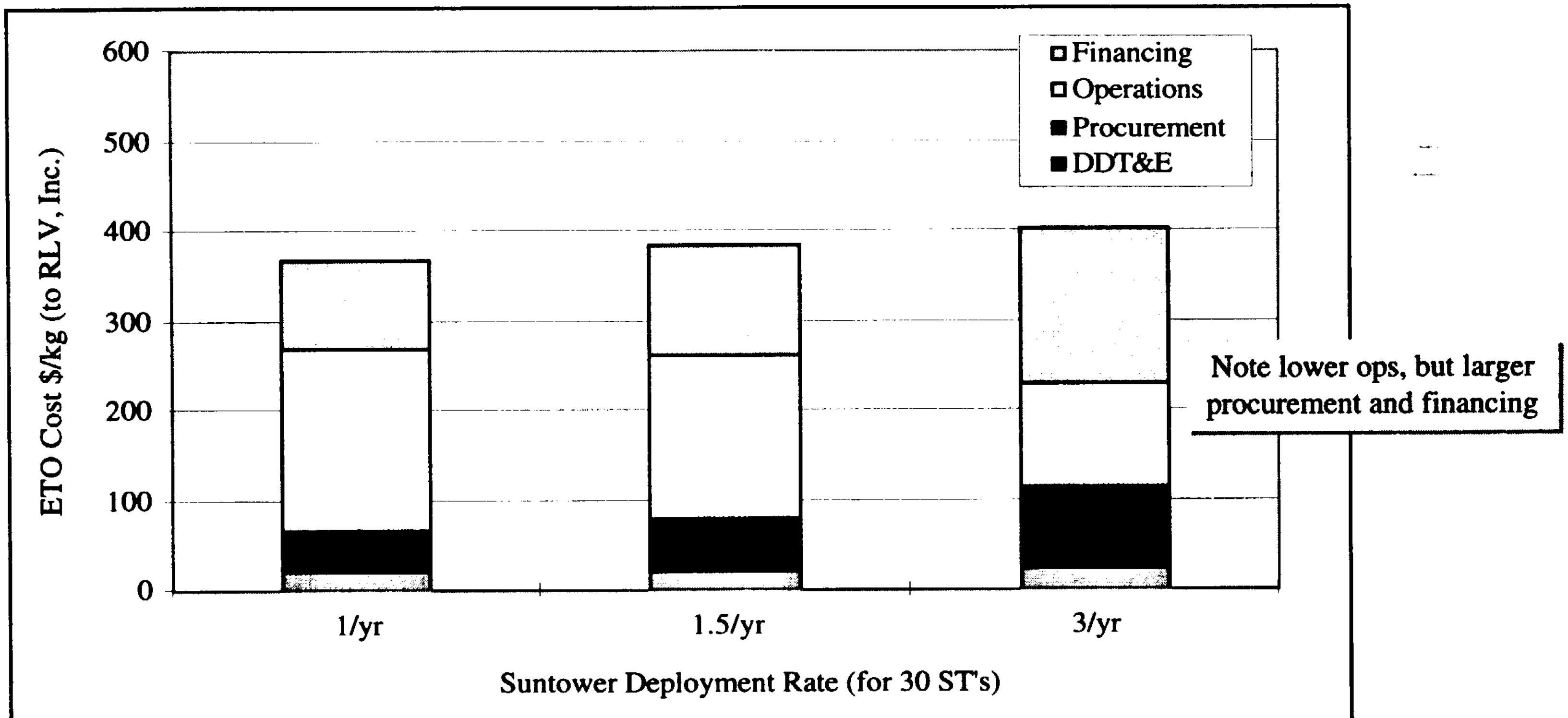
No government contrib. to facilities or partial DDT&E

Fleet Size	9	9	9
TFU	$1.17 B	$1.17 B	$1.17 B
Best per Flt Ops Cost†	$3.71 M/flt	$3.71 M/flt	$3.71 M/flt
Peak Flight Rate	307/yr	307/yr	307/yr
Total Flights in Model	8,440	8,440	8,440
Total SSP Mass Delivered	160,050 MT	160,050 MT	160,050 MT

† - with $50k site fee and $50k insurance

Suntower Deployment Rate (ϕ2)

SSTO-R/LA (30 Suntowers @4850 MT)



Faster Suntower deployment rate decreases overall ops cost, and nearly balances higher procurement and financing costs

** Note that low rate refurbishment in out years was not profitable for ETO for 1.5/yr and 3/yr cases, so was not captured*

Suntower Deployment Rate (ϕ2)

Undiscounted Cash Flow	*1/yr*	*1.5/yr*	*3/yr*
DDT&E (includes gov't engines)	$4.64 B	$4.64 B	$4.64 B
Facilities	$0.72 B	$0.98 B	$1.50 B
Fleet Procurement	$7.27 B	$8.96 B	$13.34 B
Operations	$32.92 B	$25.12 B	$16.78 B
Financing	$16.13 B	$18.58 B	$25.17 B
- less gov't contribution	-$1.69 B	-$2.22 B	-$2.74 B
Net LCC (to RLV, Inc.)	$59.72 B	$56.06 B	$58.69 B
SSP Revenue	$64.14 B	$61.11 B	$58.20 B
Internal Rate of Return (IRR)	7.49 %	11.22 %	17.41 %

Doesn't include higher interest payments

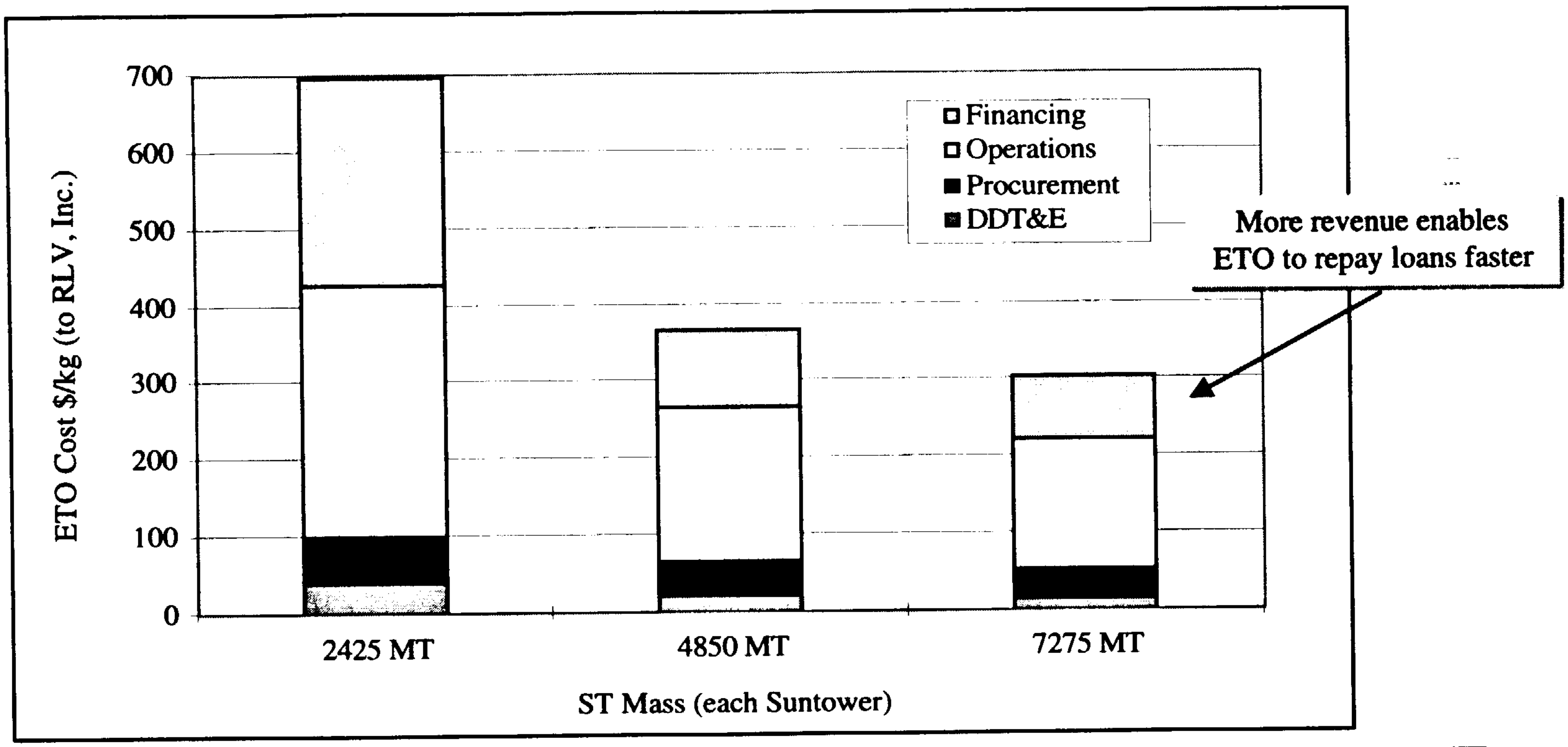
Fleet Size	9	12	21
TFU	$1.17 B	$1.17 B	$1.17 B
Best per Flt Ops Cost†	$3.71 M/flt	$3.04 M/flt	$2.19 M/flt
Peak Flight Rate	307/yr	422/yr	766/yr
Total Flights in Model	8,440	8,050	7,660
Total SSP Mass Delivered	160,050 MT	152,775 MT	145,500 MT

Note reduced traffic (10 year model)

† - with $50k site fee and $50k insurance

Individual Suntower Mass (ϕ2)

SSTO-R/LA (30 Suntowers, 1 per year)



Larger individual Suntower mass increases flight rates and thus revenue for ETO business, lowers <u>per kg</u> costs!

Individual Suntower Mass (ϕ2)

Undiscounted Cash Flow	*2425 MT*	*4850 MT*	*7275 MT*
DDT&E (includes gov't engines)	$4.64 B	$4.64 B	$4.64 B
Facilities	$0.41 B	$0.72 B	$1.03 B
Fleet Procurement	$4.71 B	$7.27 B	$9.49 B
Operations	$24.55 B	$32.92 B	$38.42 B
Financing	$21.78 B	$16.13 B	$19.36 B
- less gov't contribution	-$1.65 B	-$1.96 B	-$2.27 B
Net LCC (to RLV, Inc.)	$54.44 B	$59.72 B	$70.67 B
SSP Revenue	$32.01 B	$64.14 B	$96.01 B
Internal Rate of Return (IRR)	N/A %	7.49 %	11.95 %

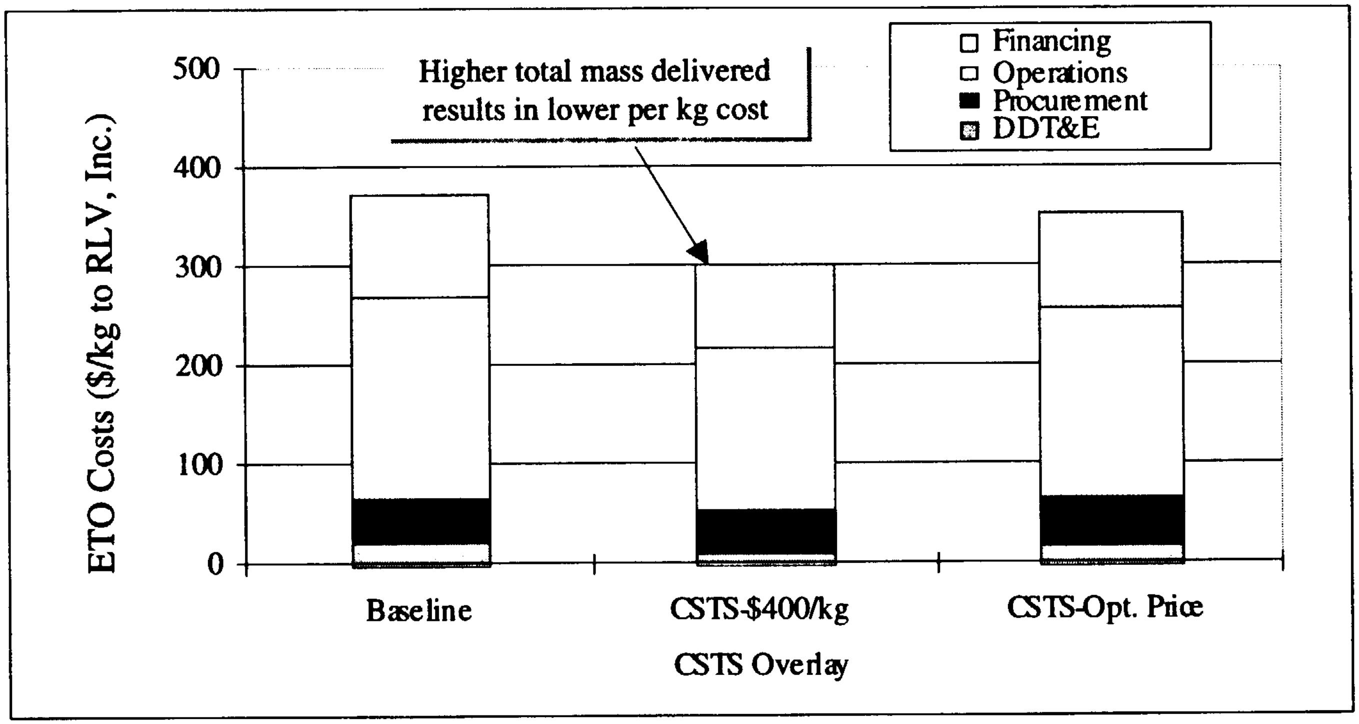
More revenue For RLV!

Fleet Size	5	9	13
TFU	$1.17 B	$1.17 B	$1.17 B
Best per Flt Ops Cost†	$5.50 M/flt	$3.71 M/flt	$2.89 M/flt
Peak Flight Rate	154/yr	307/yr	460/yr
Total Flights in Model	4,230	8,440	12,650
Total SSP Mass Delivered	80,025 MT	160,050 MT	240,075 MT

† - with $50k site fee and $50k insurance

Commercial Space Overlay (ϕ2)

SSTO-R/LA (30 Suntowers, 1 per year)



Low commercial transportation costs create high demand which results in lower cost per kg delivered.

Commercial Space Overlay (ϕ2)

Undiscounted Cash Flow	*Baseline*	*CSTS-$400/kg*	*CSTS-Opt Price*
DDT&E (includes gov't engines)	$4.64 B	$4.64 B	$4.64 B
Facilities	$0.72 B	$1.39 B	$0.78 B
Fleet Procurement	$7.27 B	$12.46 B	$8.41 B
Operations	$32.92 B	$44.70 B	$34.93 B
Financing	$16.13 B	$24.09 B	$17.80 B
- less gov't contribution	-$1.96 B	-$2.63 B	-$2.02 B
Net LCC (to RLV, Inc.)	$59.72 B	$84.65 B	$64.54 B
SSP Revenue	$64.14 B	$104.83 B	$104.39 B
Internal Rate of Return (IRR)	7.49 %	10.16 %	14.79 %

More revenue For RLV!

	Baseline	*CSTS-$400/kg*	*CSTS-Opt Price*
Fleet Size	9	19	11
TFU	$1.17 B	$1.17 B	$1.17 B
Best per Flt Ops Cost†	$3.71 M/flt	$2.29 M/flt	$3.25 M/flt
Peak Flight Rate	307/yr	670/yr	370/yr
Total Flights in Model	8,440	8,440	10,251
Total SSP Mass Delivered	160,050 MT	278,704 MT	180,896 MT

† - with $50k site fee and $50k insurance

Trade Study Observations (ϕ2)

- More SSP traffic helps RLV economic scenario
  - more mass to orbit and higher flight rates yield lower $/kg
  - more total SSP mass is preferred to faster deployment rate
  - accessing new CSTS markets can also help profits
  - RLV goal should be >2:1 price-to-cost ratio for >20% IRR
- Larger payload capacity RLV shows benefit (40 MT)
  - revenues/flight increase linearly, while costs do not
- Financing costs are *significant* economic driver
  - 7.5% gov't guaranteed interest rate can be enabling benefit

Launch Vehicle Assessment for Space Solar Power

Final Presentation - Summary of Phase 3 Results

December 15, 1998

Dr. John R. Olds, Jeff Scott, Jeff Whitfield, Laura Ledsinger,
John Bradford, Ashraf Charania, Dave McCormick, Dave Way

Space Systems Design Laboratory
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA

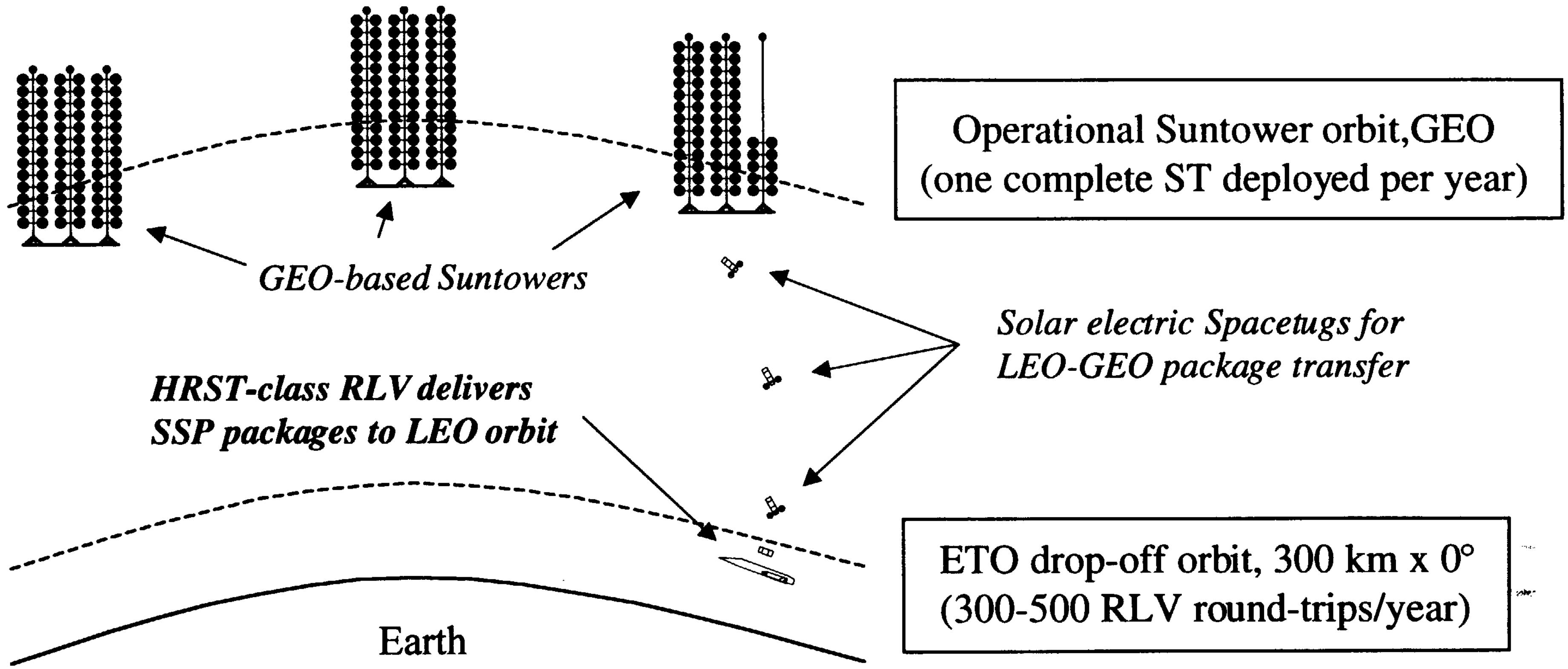
Space Solar Power Project

Overall Space Solar Power study goal is to determine if a space-based solar collection system can produce power for customers on Earth at competitive rates (< 5¢/kW-hr)

Must include costs of...

1. Requisite Technology Maturation
2. Suntower Development and Production
3. Ground Infrastructure (rectennas, etc.)
4. In-space Transportation/Delivery Services
5. **ETO Transportation/Delivery Services** ← **Georgia Tech Task**

GEO Suntower Deployment (ϕ3)

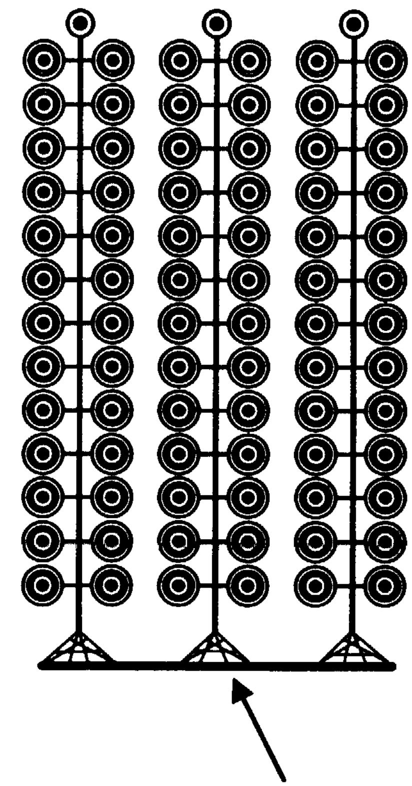


Low cost ETO delivery is a key part of the SSP strategy

Triple GEO Suntower Cluster (ϕ3)

GEO Suntower Cluster Data

ETO Mass/cluster:	15,561 MT @ 300 km (3 Suntowers @ 5187 MT ea.)
Orbits (km):	
Delivery	300 @ 0°
Operational	GEO @ 0°
Power on Ground:	1200 MW/cluster
RLV Packaging:	40 MT max. payload capacity 452 m^3 payload volume
Launch Rate:	1 cluster/year (3 Suntowers) 30 year deployment period 90 total Suntowers deployed



3 Suntowers deployed to one GEO location can serve a single receiver site on the ground

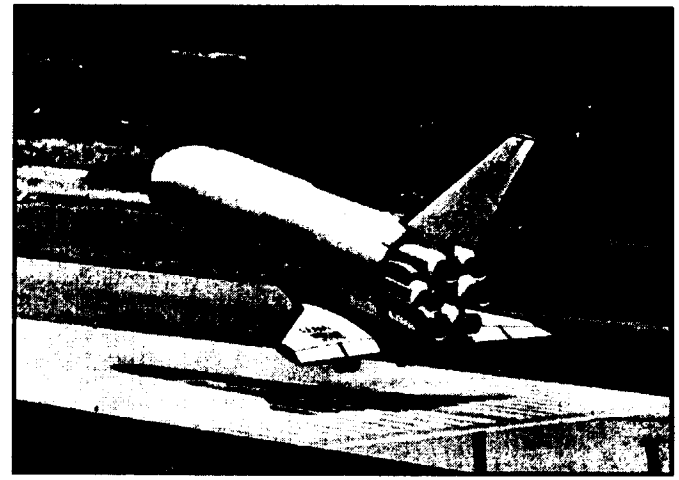
ETO Problem Statement for SSP

- SSP business strategy baselines purchasing launches
  - purchase launch services, not develop launch vehicles
  - Goal: SSP pays no more than $400/kg of payload when launched
  - ETO services operated as separate business from SSP
- NASA HRST study produced several low-cost launch vehicles
  - recurring costs per flight drop for operable designs with proper investments in key technologies
  - but potential revenue must offset *all* costs + financing

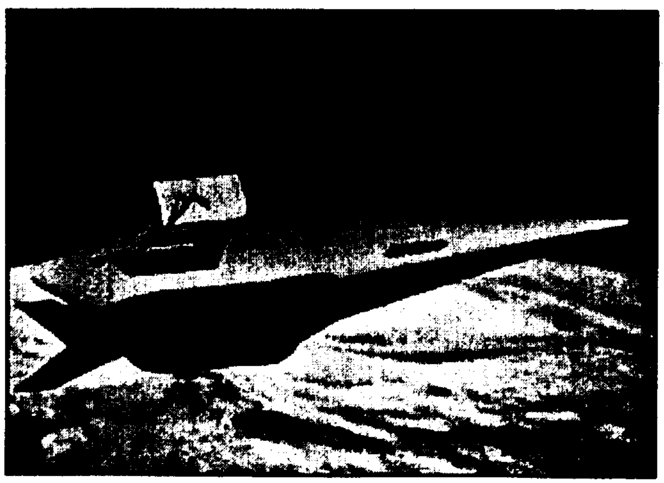
Issue: Is SSP mission and $400/kg price a large enough carrot to interest ETO community in developing a new RLV?

SSP Launch Vehicle Candidates

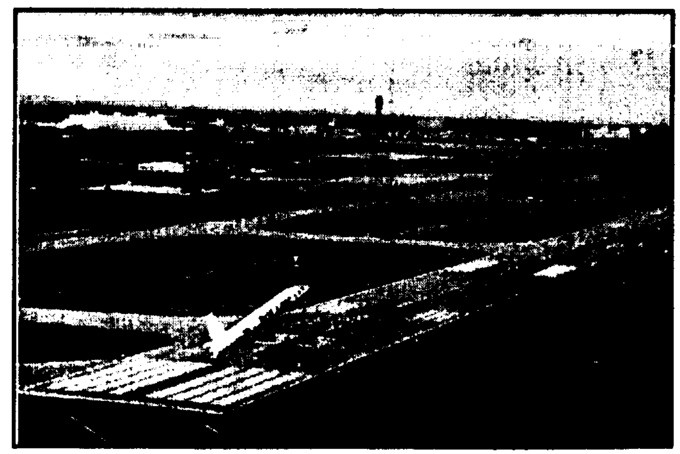
Argus w/Maglifter Launch Assist



ACRE-92 VTHL all-rocket SSTO (Notional)



Hyperion RBCC SSTO



SSTO-Rocket w/Sled Launch Assist (Notional)

Georgia Tech Project Goals

- Perform launch assessments of 4 HRST concepts
  - include performance, weight, size, and <u>life cycle cost</u>
- Use consistent assumptions and analysis tools
  - 'level' any technology differences between concepts
    - all concepts will use advanced technologies (like *Argus*)
- Identify economic "attractiveness" of SSP for ETO
  - do any of the HRST vehicles make sense at $400/kg?
  - which vehicle concept or concepts are preferred?
  - what government investment is required up-front?

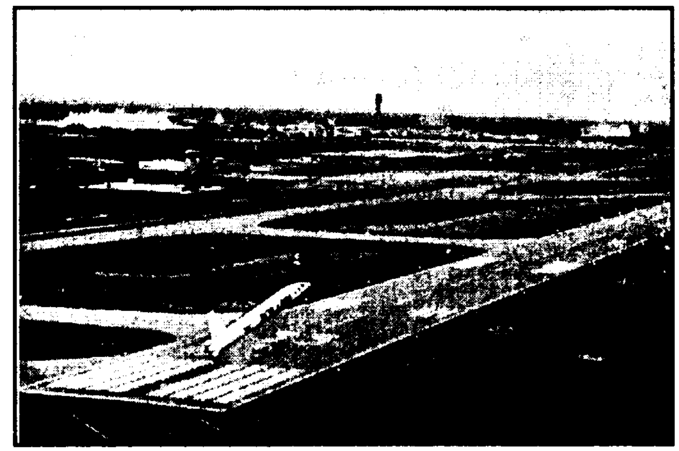
GT Project Chronology

June - August 1998 (phase 1)	Performed preliminary sizing and economic evaluations on all four ETO candidates sized for 20 MT payload. Used 4850 MT MEO-based Suntower concept (one per year). Preliminary best concept appeared to be HTHL SSTO-R/LA.
August - October 1998 (phase 2)	Performed several sensitivity studies on SSTO-R/LA vs. deployment rate, payload size, ST mass, CSTS mission overlays, and govm't incentives. 40 MT payload size and larger Suntower mass appeared beneficial, but ETO IRR was still poor.
October - December 1998 (phase 3)	Updated Suntower to 15,561 MT GEO based triplet (higher flight rates). Reconsidered 40 MT *Argus* and 40 MT SSTO-R/LA. Economic results for both systems are now favorable, IRR's > 22%

Best ETO Performers for SSP

And the results are...

Argus w/Maglifter Assist



HTHL SSTO-R w/Sled Launch Assist

Low operations costs (Argus) or low procurement costs (SSTO-R/LA) result in lower life cycle costs and IRR's > 22% even with SSP revenues of only $400/kg of payload!

Previous Lessons Learned

Earlier trade studies have helped to identify the best options for ETO to lower costs and improve economic attractiveness

- Reduce <u>early</u> costs to improve ETO IRR
  - select smaller, simpler and cheaper RLV (SSTO-R/LA or Argus)
  - assume government infrastructure & development support
  - government-backed, low interest loan is also very important (7.5%)
- Select RLV cargo capacity of 40 MT (of 10/20/40 MT considered)
  - revenue increases linearly with cargo, ops costs do not
  - vehicles must be designed for low operations costs in all cases
- Include "other" markets to increase flight rates & IRR
  - other commercial LEO markets can help increase revenue

Requirements for ETO Price Goal

Technologies	*System Influences*	*ETO Cost Drivers*
• ISE Design Environment - better, faster, cheaper • Simpler Designs - more COTS, less complexity	Lower Development Cost COTS Subsystems Faster Prototyping/Test	DDT&E Process $
• Smaller Vehicles - higher I* - higher T/We - higher prop. bulk density - lightweight structures - launch assist • Robust Vehicles & Engines - increased design margins - lower temps, pressures - robust subsystem design - multiple abort options	Lower TFU $ Longer Service Life Higher Reliability	Flight Hardware (Airframe) $
	Lower TFU $ Longer Service Life Higher Reliability	Flight Hardware (Propulsion) $
• Process Improvements - robotics, VHM, BIT • Vehicle Improvements - simpler TPS, access,MPS feed • Near-site Propellant Production	Faster Turnaround Time Fewer Ops Personnel Lower Prop Costs	Ground & Flight Operations $
• Gov't Backed Loans (<8%) • SSP-style Flight Rates • Gov't-Industry Development Partnership	Lower Interest Rates Adequate Traffic Base Early Gov't Support	Programmatics & Gov't Support $

All ETO Cost Drivers → **< $400/kg to LEO Price Goal**

Argus and SSTO-R/LA SSP Vehicle Configurations

GT Project -- Phase 3

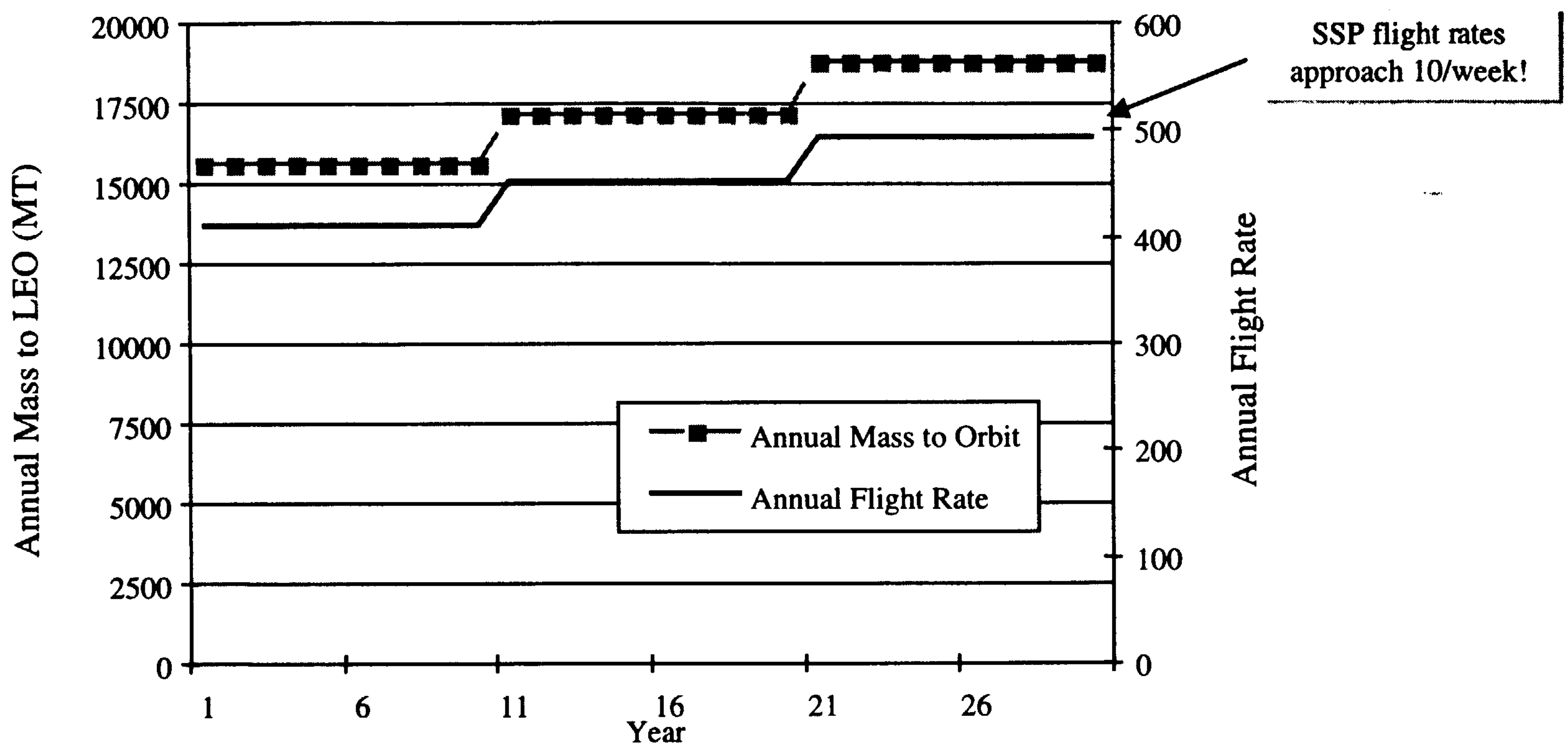
40 MT *Argus* and 40 MT SSTO-R/LA

Optimistic government support (7.5% interest rate, plus facilities and some DDT&E)

15,561 MT GEO Suntowers (one deployed per year for 30 years)

$400/kg for SSP revenue, plus CSTS LEO market overlay

SSP Mission Model (ϕ3)



Current SSP delivery model includes one Suntower GEO cluster per year for 30 years (plus annual refurbishment requirements)

Note: 5% of maximum 40 MT payload assumed lost to ASE, EM tether, packaging losses, etc.

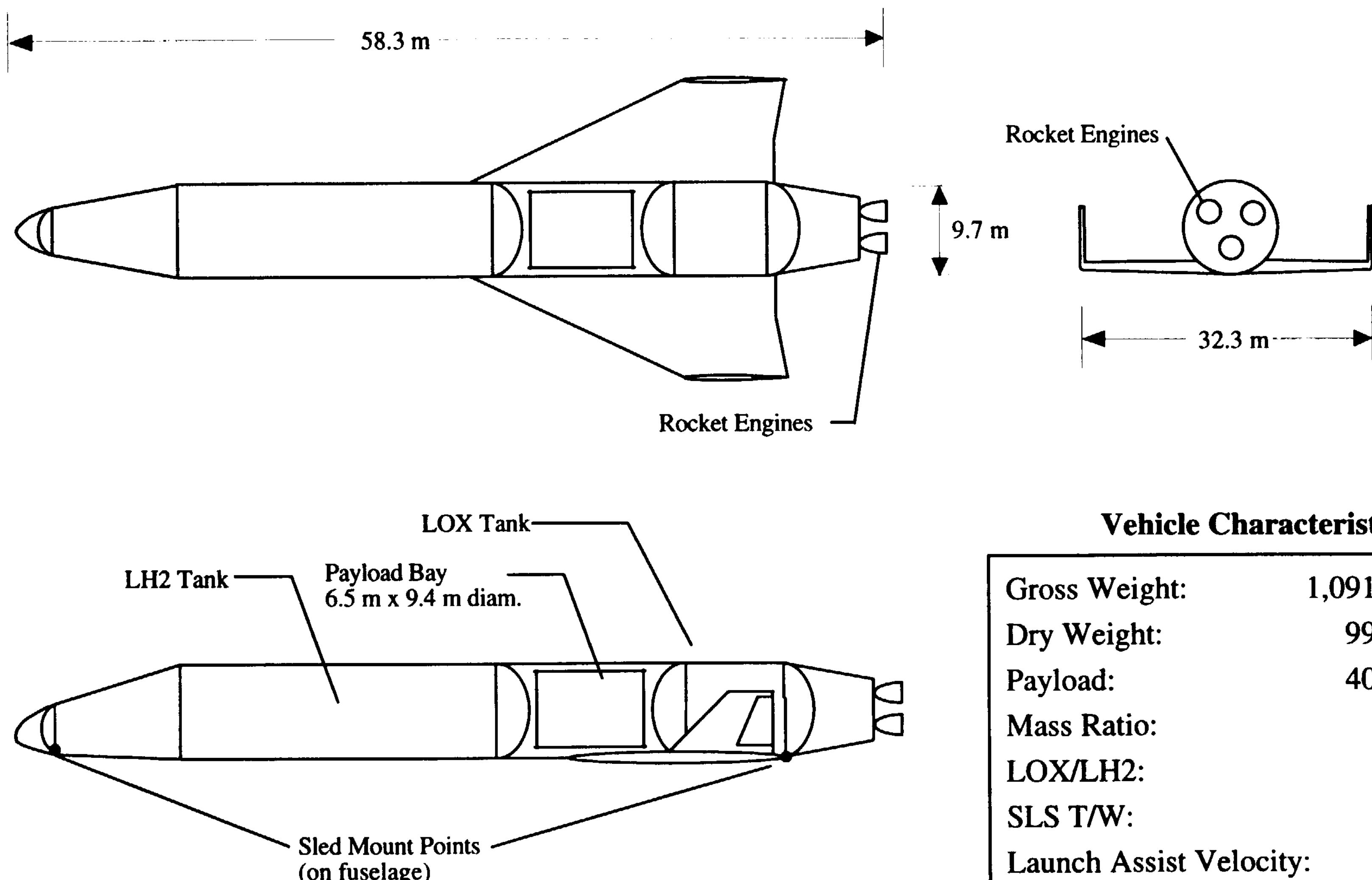
SSP Sizing Results (ϕ3)

	Argus	SSTO-R/LA
Equatorial Launch Site†		
Mass Ratio (W_i/W_f)	5.592	6.960
LOX/LH2 mixture (wgt)	3.765	6.9
Sizing ("Ops" versions)		
Gross Mass	957 MT	1092 MT
Dry Mass	114 MT	100 MT
Maximum Payload	**40 MT**	**40 MT**
Operations		
Flights/airframe/year	46 flights ††	37 flights
Airframe/engine life	1000/500 flights	1000/500 flights

† - Equatorial trajectory results assume containerized payload drop off at 0° inclination by 300 km circ. MECO is at 94 x 281 km x 0°.

†† - data supplied by KSC using NASA's AAT flight rate tool, SSTO-R/Sled flight rate estimated by Georgia Tech

SSTO-R/LA SSP Vehicle (ϕ3)



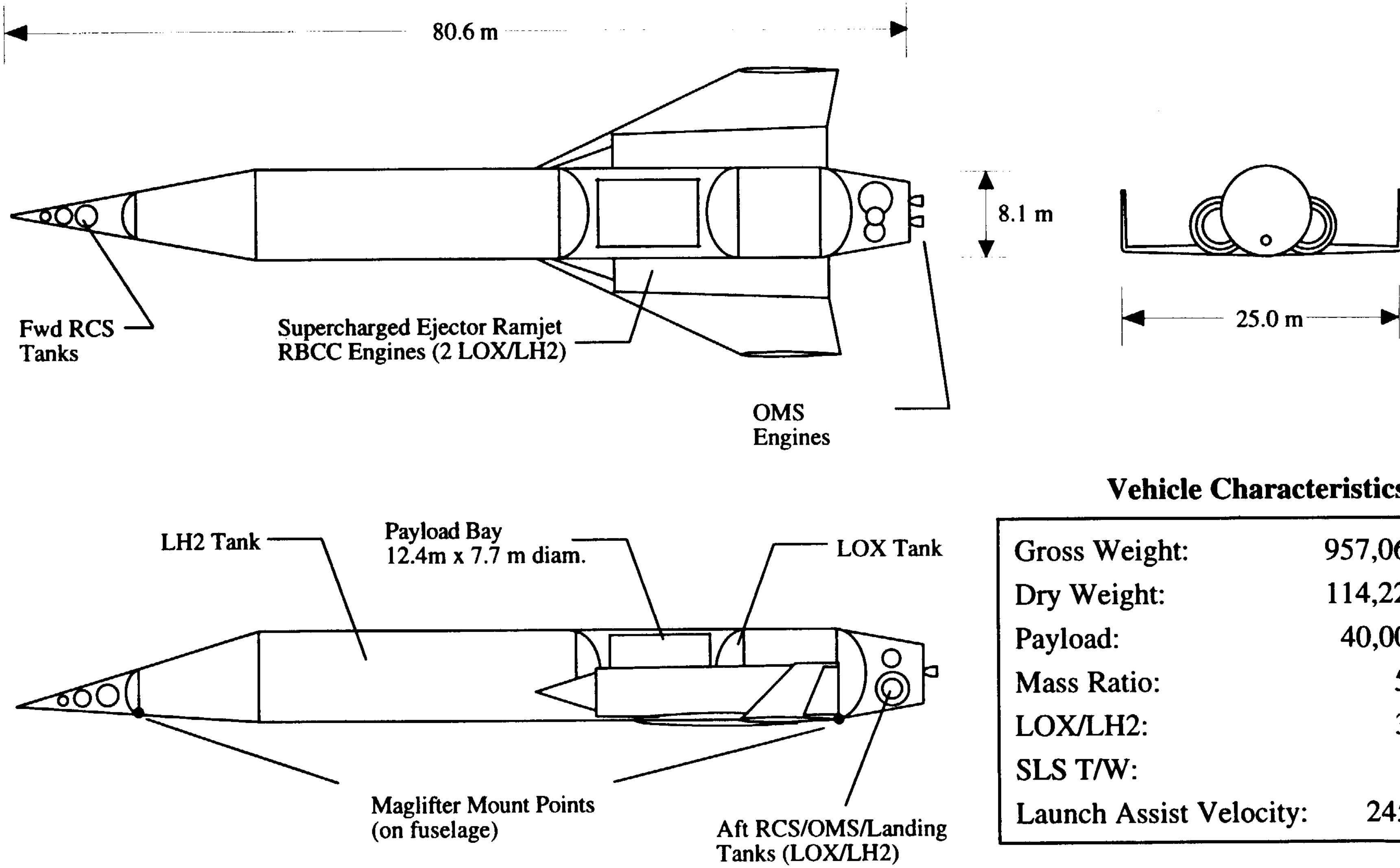
Vehicle Characteristics

Gross Weight:	1,091,830 kg
Dry Weight:	99,630 kg
Payload:	40,000 kg
Mass Ratio:	6.960
LOX/LH2:	6.90
SLS T/W:	0.8
Launch Assist Velocity:	110 m/s

SSTO-R/LA Weight Statement (ϕ3)

Name	Weight (kg)
Wing and Tail Group	22,860
Body Group (incls. Tanks)	23,750
Thermal Protection	6,460
Main Propulsion (3 LOX/LH2 rockets)	20,150
OMS/RCS Propulsion	2,150
Subsystems and Other Dry Weights	11,260
Dry Weight Margin (15%)	13,000
Dry Weight	99,630
Payload	40,000
Other Inert Weights (residuals, etc.)	17,240
Insertion Weight	156,870
Ascent Propellants	934,960
Gross Lift-off Weight	1,091,830

Argus SSP Vehicle (ϕ3)



Vehicle Characteristics

Gross Weight:	957,060 kg
Dry Weight:	114,220 kg
Payload:	40,000 kg
Mass Ratio:	5.592
LOX/LH2:	3.765
SLS T/W:	0.7
Launch Assist Velocity:	245 m/s

Argus Weight Statement (ϕ3)

Name	Weight (kg)
Wing and Tail Group	17,110
Body Group (incls. Tanks)	22,910
Thermal Protection	7,310
Main Propulsion (2 LOX/LH2 RBCC SERJ)	35,590
OMS/RCS Propulsion	2,710
Subsystems and Other Dry Weights	13,690
Dry Weight Margin (15%)	14,900
Dry Weight	114,220
Payload	40,000
Other Inert Weights (residuals, etc.)	16,930
Insertion Weight	171,150
Ascent Propellants	785,910
Gross Lift-off Weight	957,060

Argus and SSTO-R/LA Economic Results for SSP

GT Project -- Phase 3

40 MT *Argus* and 40 MT SSTO-R/LA

Optimistic government support (7.5% interest rate, plus facilities and some DDT&E)

15,561 MT GEO Suntowers (one deployed per year for 30 years)

$400/kg for SSP revenue, plus CSTS LEO market overlay

Basic Economic Assumptions (ϕ3)

- Government Incentive Package to ETO Developer
  - 100% of engine DDT&E
  - 20% of airframe DDT&E
  - 100% of ETO ground facilities (RLV, Inc. pays user fee every flight)
- 3-to-1 Debt-to-Equity Financing (75% borrowed)
  - <u>7.5% interest rate</u> guaranteed by USG
- ETO Development Schedule
  - DDT&E: 2004 - 2008
  - production: 2009 - 2010
  - first revenue flight: 2010

Major Cost Contributors (ϕ3)

	Argus	SSTO/Sled
Vehicle/Fleet Data		
TFU (incl. engines)	$1.615 B	$1.58 B
Ops cost/flight (@491/yr.)†	$2.43 M	$3.10 M
Fleet size required	14	14
New launch facilities††	3 Maglev tracks	3 sled tracks
LCC Contributors (98$)		
DDT&E (including engines)	$6.88 B	$6.24 B
Fleet acquisition (80% l/c)	$14.02 B	$13.39 B
Facilities (total CoF)	$3.43 B	$1.19 B
Flight/Ground Operations	$34.60 B	$44.02 B

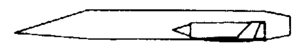
Lowest ops costs ($34.60 B)

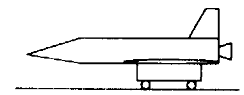
Lowest procurement costs ($13.39 B)

† - extrapolated from HRST Ops Team Final Report, VRC Operability wing; also includes $50k/flight for liability insurance and $50K/flight for range fee per GT

†† - Maglev and Sled tracks support up to 200 flights/yr each

Economic Performance (SSP-only)





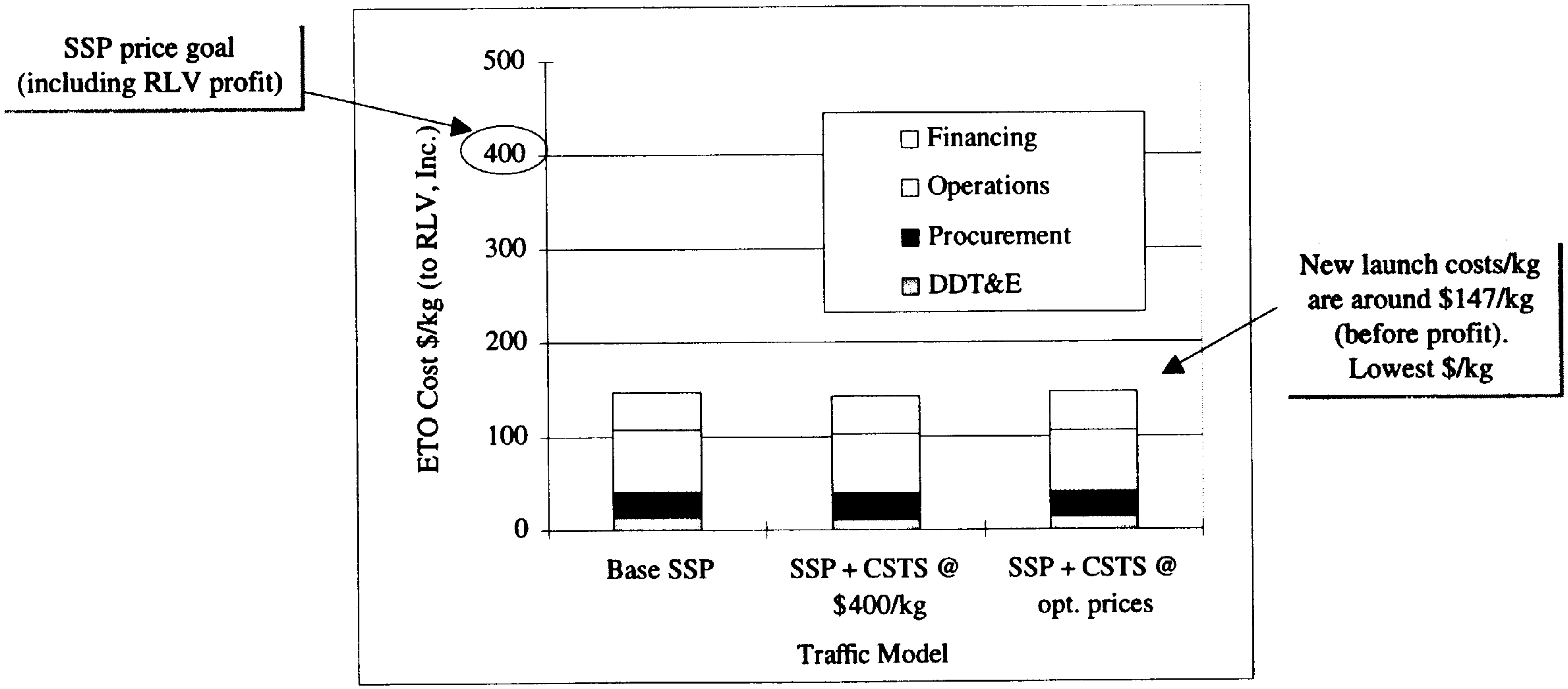
	Argus	SSTO/Sled
Cash Flow Summary		
Total SSP revenues†	$205.4 B	$205.4 B
Total direct costs††	$58.93 B	$64.84 B
Financing costs (7.5% rate)	$21.47 B	$20.31 B
Initial Investments Req'd		
Initial Gov't incentives	$5.26 B	$2.77 B
Initial private equity	$ 4.95 B	$4.51 B
Economic Indicators		
Internal Rate of Return (IRR)	22.03 %	22.02 %
Net Present Value (25% disc.)	$36.12 B	$34.06 B
Breakeven year	2010	2010

Gov't backed rate!! (→ Financing costs (7.5% rate))

† - at basic $400/kg SSP price, exclusive SSP traffic model; †† - includes DDT&E, acquisition, facilities, ops prior to gov't incentives

Argus Costs Per Flight (ϕ3)

30 Suntower GEO clusters, 1 triple per year



Argus has the lowest operations costs per flight and results in costs per flight well below RLV price goal of $400/kg

Argus Economic Performance (ϕ3)

Undiscounted Cash Flow	*Base (SSP Only)*	*SSP + CSTS all @$400/kg*	*SSP + CSTS optimized*
DDT&E (includes gov't engines)	$6.88 B	$6.88 B	$6.88 B
Facilities	$3.43 B	$4.59 B	$3.49 B
Fleet Procurement (80% l.c.)	$14.02 B	$17.46 B	$14.74 B
Operations	$34.60 B	$39.54 B	$35.56 B
Financing (interest)	$21.47 B	$25.32 B	$22.26 B
- less gov't contribution	-$5.26 B	-$6.42 B	-$5.32 B
Net LCC (to RLV, Inc.)	$75.14 B	$87.37 B	$77.61 B
Total Revenue	$205.4 B	$245.6 B	$243.4 B
Internal Rate of Return (IRR)	22.03 %	22.60 %	24.64 %
Fleet Size	14	19	15
TFU	$1.62 B	$1.62 B	$1.62 B
Best per Flt Ops Cost†	$2.43 M/flt	$2.02 M/flt	$2.34 M/flt
Peak Flight Rate	491/yr	673/yr	524/yr
Total Flights in Model	13,514	18,729	14,448
Total SSP Mass Delivered	513,513 MT	614,266 MT	531,565 MT

Commercial CSTS = $1760/kg,

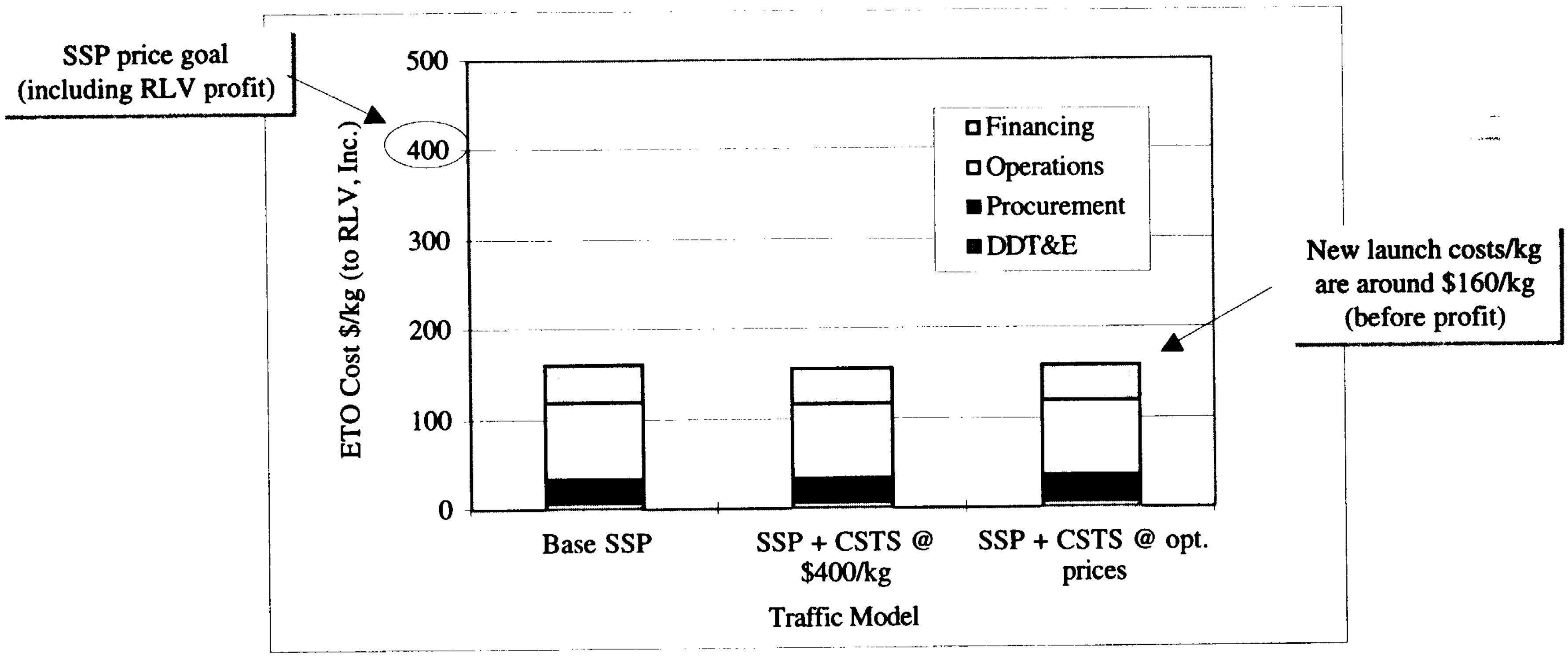
Gov't CSTS = $3007/kg

Large total revenue yields attractive IRR

† - with $50k site fee and $50k insurance, curve fit from Nix's OCM/Comet model with GT mods

SSTO-R/LA Costs Per Flight (ϕ3)

30 Suntower GEO clusters, 1 triple per year



SSTO-R/LA offers low procurement and financing costs which results in lower up-front expenditures and low price/kg

SSTO-R/LA Economic Perf. (ϕ3)

Undiscounted Cash Flow	*Base (SSP Only)*	*SSP + CSTS all @$400/kg*	*SSP + CSTS optimized*
DDT&E (includes gov't engines)	$6.24 B	$6.24 B	$6.24 B
Facilities	$1.19 B	$1.60 B	$1.24 B
Fleet Procurement (80% l.c.)	$13.39 B	$16.67 B	$14.07 B
Operations	$44.02 B	$50.41 B	$45.27 B
Financing (interest)	$20.31 B	$23.99 B	$21.07 B
- less gov't contribution	-$2.77 B	-$3.18 B	-$2.82 B
Net LCC (to RLV, Inc.)	$82.39 B	$95.73 B	$85.07 B
Total Revenue	$205.4 B	$245.5 B	$243.4 B
Internal Rate of Return (IRR)	22.02 %	22.61 %	24.79 %
Fleet Size	14	19	15
TFU	$1.58 B	$1.58 B	$1.43 B
Best per Flt Ops Cost†	$3.10 M/flt	$2.58 M/flt	$2.98 M/flt
Peak Flight Rate	491/yr	673/yr	524/yr
Total Flights in Model	13,514	18,729	14,448
Total SSP Mass Delivered	513,513 MT	614,266 MT	531,567 MT

Commercial CSTS = $1760/kg,

Gov't CSTS = $3000/kg

Large total revenue yields attractive IRR

† - *with $50k site fee and $50k insurance, curve fit from Nix's OCM/Comet model with GT mods*

SSP ETO Project Summary

- With sufficient traffic, $400/kg SSP price <u>is</u> attractive to RLV
  - large GEO Suntowers provide high annual revenue to RLV, Inc.
  - best-case IRR's exceed 22% (using 40MT *Argus* or SSTO-R/LA)
  - however, impact of increased Suntower mass on SSP, Inc. remains TBD
  - CSTS markets add to RLV IRR (and benefit those markets with low $)
- Government support & backing are critical to ETO developer
  - <u>up-front</u> DDT&E offset and facilities are important to increasing IRR
  - government backed interest rate (7.5%) critical to reducing life cycle costs

Conclusion: The current SSP traffic model <u>does</u> present an attractive economic carrot for potential RLV developers