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ABSTRACT

As aerospace industries are forced to compete in an environment of declining federal budgets and increased competition, 'design for performance' is quickly giving way to 'design for cost.' Many modern launch vehicle programs are initiated with the goal of lowering the cost of delivering payloads to orbit while limiting investment costs and yielding a reasonable rate of return. Designers of new vehicles will need tools to quickly evaluate not only the costs, but also the revenue potential of various design options. To provide information that can be used to drive design decisions or an optimization process, these economic analysis tools must be fully integrated into the design environment.

This paper reports the status of research to create a design-oriented economic analysis tool for conceptual launch vehicle design (called CAM). An overview of each CAM component is presented — program definition, non-recurring costs, recurring costs, market evaluation, and revenue. As a demonstration, CAM is used to optimize the end-customer launch prices to four individual launch markets for a multi-market capable two-stage-to-orbit launch system. The vehicle utilizes rocket-based combined-cycle engines on the booster stage and has two interchangeable rocket upper stages (one for GTO missions and one for LEO missions). Business-oriented results such as rate of return, and sensitivities to government investment, airframe life, and operations costs are presented.

NOMENCLATURE

APAS	Aerodynamic Preliminary Analysis Syst.
CA	contributing analysis
CAM	Cost Analysis Module (the current tool)
CER	cost estimating relationship
CSTS	Commercial Space Transportation Study
DDT&E	design, development, test & evaluation
GTO	geosynchronous transfer orbit
IRR	internal rate of return
KSC	NASA - Kennedy Space Center
LCC	life cycle cost
LEO	low earth orbit
LH2	liquid hydrogen
LOX	liquid oxygen
MER	mass estimating relationship
NASCOM	NASA Cost Model
POST	Program to Optimize Simulated Traject.
PTP	point-to-point global market segment
q	dynamic pressure ($1/2\ \rho V^2$, psf)
RBCC	rocket-based combined-cycle
RFP	request for proposal
RLV	reusable launch vehicle
SERJ	supercharged ejector ramjet (RBCC eng.)
SSA	Space Station Alpha
SSTO	single-stage-to-orbit
TFU	theoretical first unit
TPS	thermal protection system
TSTO	two-stage-to-orbit
$96	1996 U. S. dollars
$TY	then-year U. S. dollars (inflation adjusted)

INTRODUCTION

The transition to a 'design for cost' environment will require launch vehicle companies to develop reliable and accurate (computer) tools for estimating cost and then to *integrate* the tools into the design

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process so that designers can use cost-derived information to guide their design decisions. In response to the first requirement, several publicly available cost estimation models for launch vehicles have been created (references 1-4). However, true integration of cost into the conceptual design process has proved difficult.

Traditionally, cost is one of the last analyses to be performed — outside of the 'core' disciplines such as aerodynamics, propulsion, performance, and vehicle sizing and synthesis. The completed, 'optimized' vehicle design (typically lowest empty weight or highest payload) is passed to the cost analyst for generation of final acquisition and life-cycle cost estimates. No formal mechanism exists for feeding back cost-derived information into the design, much less to use it to drive optimization decisions. Recently however, this situation has begun to improve.

In the last five years, several researchers have reported success in including cost in the launch vehicle design optimization process. Gregory and colleagues at NASA - Ames have included a life-cycle cost (LCC) module in a monolithic code for the design of hypersonic, airbreathing launch vehicles.[5] Moore, Braun, and Powell at NASA - Langley and Unal at Old Dominion University have been successful at integrating design and development (DDT&E) cost analysis into a set of tightly-coupled disciplinary codes for an SSTO rocket design.[6,7] In both of these cases, cost has been included as an integral part of the design process and new cost information is immediately generated as the vehicle changes size.

Business pressures, increased competition, and new national priorities, however, are now requiring designers to look beyond LCC and consider broader, market-derived influences on new launch vehicles. To reduce early government investment and provide incentives for lower costs, NASA has recently asked aerospace companies to share the development cost and risk associated with new launch systems (e.g. the X-33 and the original X-34 cooperative agreements). Aerospace companies are expected to recoup their investments by collecting revenues on the operational system. In such a business environment, decision makers will be concerned with key economic indicators such as market capture, market size, cash flow, internal rate of return (IRR), net present value, and maximum debt. To be useful to these decision makers (and the vehicle designers trying to optimize a new launch system), an economic analysis tool must be able to estimate *market economics* as well as life cycle costs.

The research reported in this paper builds on and extends the work of previous researchers by addressing not only life cycle costs associated with a launch vehicle, but also the *potential revenue* that the vehicle might produce. A new economic analysis tool called CAM (for cost analysis module) is currently in the early stages of development. CAM contains components for program definition, non-recurring costs, recurring costs, market elasticity and capture, and revenue. These components provide a capability to calculate cash flow, IRR, maximum debt, and other key business variables. For demonstration purposes, the tool is used to calculate key economic indicators for a two-stage-to-orbit conceptual launch vehicle. In addition, CAM is used to optimize the end-customer launch prices to several markets to maximize attainable IRR. A description of CAM and the experimental results follow.

ECONOMIC ANALYSIS TOOL (CAM)

Overview

CAM is currently a multi-spreadsheet economic analysis tool capable of generating annual figures for major LCC contributors and expected annual revenues. These values are then combined to form summary business indicators such as IRR. CAM currently runs under Microsoft Excel on a Macintosh personal computer. A UNIX-based version is planned and will be available in the near future.

CAM enables flexible 'what if' analyses and quick executions of first order economic analyses to aid decision making and design optimization. CAM requires vehicle component weights, vehicle payload capability, and a set of economic and market assumptions as inputs. Typical assumptions include market elasticity and market capture vs. end-customer launch prices. For each vehicle design, the cost analyst is also required to make subjective adjustments to the

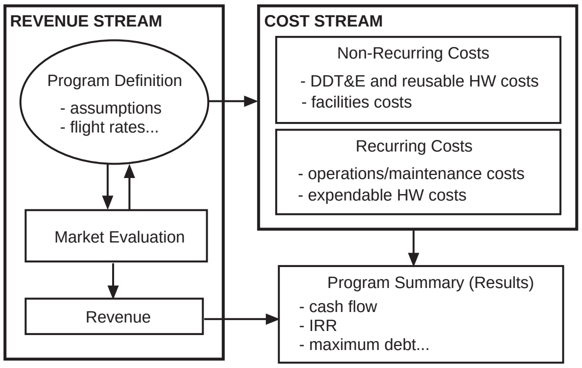

Figure 1 - CAM Structure

life cycle cost model as necessary — technology complexity factors, reusable hardware life spans, operations cost adjustments, additional facilities requirements, etc.

A schematic of the structure of CAM is shown in figure 1. CAM has two internal information flows. The first is a 'cost' stream of information that includes non-recurring costs (DDT&E, reusable hardware production, and facilities construction) and recurring costs (operations, maintenance, and expendable hardware production). The second information stream is a 'revenue' stream. Annual revenue is derived from launch prices, market size, and flight rates. The two information streams are combined to create annual cash flow which, in turn is used to determine IRR, net present value, cumulative cash flow, and other business-oriented indicators.

Each of the internal components of CAM is currently implemented as a separate spreadsheet. Internal variables are linked between individual spreadsheets and iteration takes place automatically. Given a set of inputs, CAM can operate autonomously. Currently, many of the inputs must be entered manually at the start of an analysis. Future, more design-oriented versions of CAM will use scripting techniques to automatically read an input file, execute the economic analysis, and write an output file. The ultimate goal is to integrate a UNIX-based version of CAM into a multidisciplinary design optimization environment for conceptual launch vehicle design. An overview of each CAM component follows.

Program Definition Component

The CAM 'control panel' is its program definition component. Major economic assumptions such as inflation rate, corporate tax rate, discount rate, and launch prices are input in this component. Reusable hardware acquisition spreads, reusable hardware life spans, the year of initial operational capability, and the operational period are also input here. By changing launch prices for each market (e.g. \$2000/lb of payload to LEO), the designer can perform 'what if' studies and sensitivity analyses. When CAM is used to optimize a given output, this component serves as the optimizer interface. Note that for the present demonstration, an inflation rate of 4%, a corporate tax rate of 30%, and a discount rate of 25% were assumed. Launch prices were selected to maximize IRR.

Non-Recurring Cost Component

The non-recurring cost component of CAM uses vehicle subsystem weights to calculate design, development, test, and evaluation costs (DDT&E) and theoretical first unit cost (TFU) for reusable hardware components. With appropriate learning and production rate effects, TFU is extended to estimate total production costs for reusable hardware. Facilities construction costs can also be included.

Most publicly available cost estimation tools use weight-based cost estimating relationships (CER's) to approximate subsystem development or acquisition costs. The individual subsystem costs are summed and additional 'wrap' factors are applied to account for system integration, test hardware, cost contingency, etc. While the accuracy of weight-based CER's can be debated, a weight-based strategy was adopted for use in CAM. The CER's used by CAM for both DDT&E and TFU are of the form,

$$\text{cost} = C_f * A * (\text{weight})^B$$

where A and B are coefficients derived from regression analysis of similar historical hardware. C_f is a complexity factor that is used by the cost analyst to adjust the estimate for new technologies, different materials, increased production labor requirements, etc. The NASCOM database[2] was used as a source of A and B coefficients for most subsystems in the current example. Complexity factors were based on C_f's used for a similar TSTO airbreathing/rocket system previously investigated as part of NASA's Access to Space study.[8] Program wrap factors were taken from NASCOM. Note that in a design environment, subsystem weights and therefore costs will change as the design evolves. For the current demonstration, however, the vehicle weights were fixed.

The non-recurring cost component of CAM includes an input for facilities costs in various years of a program. For the demonstration, very approximate facilities costs were derived from similar data created by Lockheed - Martin for an SSTO RLV study.[9] Future versions of CAM will incorporate a more detailed mechanism for estimating facilities requirements and construction costs.

For the present RBCC TSTO example, the government was arbitrarily assumed to contribute 100% of all engine-related DDT&E, 75% of all facilities cost (some of which might be existing facilities), and 20% of airframe DDT&E. CAM uses fixed-year 1996 U.S. dollars ($96) and inflation adjusted then-year U.S. dollars ($TY) for internal calculations.

Recurring Cost Component

Recurring costs are primarily generated by expendable hardware production and system operations and maintenance costs. Expendable hardware TFU is calculated with weight-based CER's and is adjusted for learning and production rate effects. Accurate estimation of operations and maintenance costs for advanced launch vehicles is a detailed process that requires a complex assessment of maintenance requirements, manpower, spares, propellant costs, etc. In it's present form, CAM uses a simple 'place holder' model for operations costs that accounts for decreased cost per flight as the flight rate increases and also as total number of flights increases (similar to a production rate effect and a learning effect). The reference 'first flight' operations cost for the current demonstration was scaled from operations costs generated by Lockheed - Martin for it's previously mentioned SSTO RLV study.[9] Future versions of CAM will include a more detailed operations cost component based on the models created by General Dynamics for the Transportation Systems Analysis study.[4]

Market Evaluation Component

The calculation of potential revenue strongly depends on the size of future launch markets and the percentage of those markets that a new launch vehicle is expected to capture. Four different market segments are utilized in CAM — LEO cargo, LEO passengers, GTO cargo, and very high speed global point-to-point delivery missions. Here, LEO cargo and passengers were both assumed to be delivered to Space Station Alpha orbit (220 nmi. circular, 51.6° inclination). Each market segment is price elastic with respect to an appropriate end-customer launch price (i.e. the market size depends on the price). A market capture percentage for each segment vs. launch price is included to account for the effects of competition.

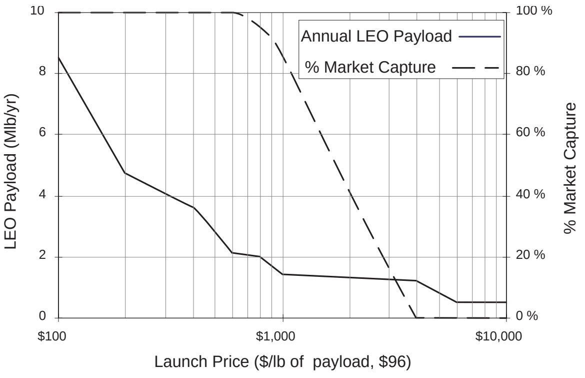

Figure 2 - LEO Cargo Market

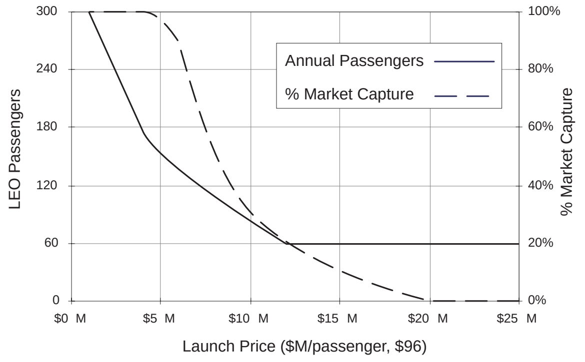

Figure 3 - LEO Passenger Market

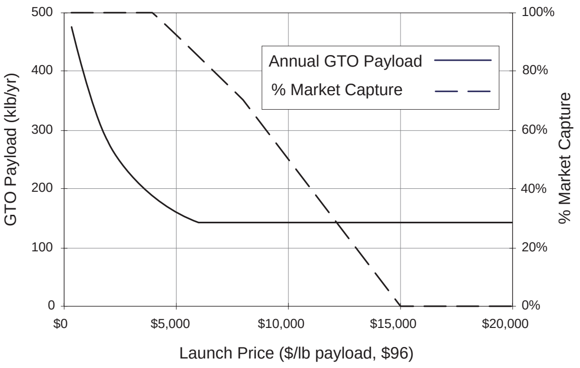

Figure 4 - GTO Cargo Market

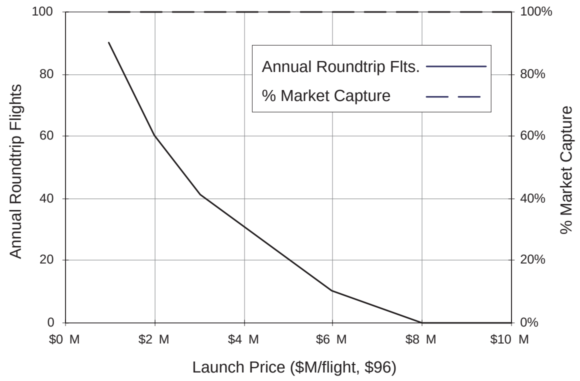

Figure 5 - Very High Speed Global Point-to-Point Market

Captured market is the product of market size and market capture percentage. New vehicles priced above or near currently operating vehicles cannot expect a large captured market. Each market segment is user definable, but is considered constant over time.

The market definitions used in the present demonstration are shown in figures 2 - 5. The LEO cargo, LEO passenger, and GTO cargo markets (figures 2 - 4) were derived from NASA's Commercial Space Transportation Study (CSTS).[10] The CSTS study researched many future markets in order to determine their potential size and elasticity with respect to launch price. The potential markets ranged from traditional markets such as communications and remote sensing to more speculative markets such as space-based advertising and space tourism. Figures 2 - 4 do not include some of the most speculative CSTS markets (most notably nuclear waste disposal). Market capture percentages for each segment were estimated based on current launch prices and predicted trends.

The very high speed global point-to-point delivery market segment (figure 5) was assumed to exhibit similar elasticity with respect to end-customer price. This small, notional segment was created to represent future requirements for extremely high value, extremely urgent small package delivery such as short-lived biological specimens, volatile pharmaceuticals and chemicals, or transient alloys or materials. Typical customers were assumed to be domestic companies with overseas partners and subsidiaries (thus operating from fixed, predetermined city pairs or 'PTP ports'). 50% of the global hypersonic delivery market was assumed to originate from a point near KSC to a point in the Pacific rim. The remaining 50% was assumed to go to a point in western Europe.

Revenue Component

For a given vehicle payload capability and an annual captured market, CAM determines annual flight rates to each market segment. Theoretical vehicle payload capabilities are penalized by a payload packaging inefficiency factor to account for losses derived from multiple manifesting. For the current study, a payload inefficiency factor of 15% was assumed. That is, a vehicle theoretically capable of delivering 10,000 lb. to LEO was only allowed to deliver 8,500 lb. per flight and thus required more annual flights to deliver all of the cargo from the captured market. Annual revenue is calculated as the product of flight rate and launch price for all market segments. For the present demonstration, vehicle mission reliability was assumed to be 100%.

Program Summary Component

After the annual cost and revenue streams are calculated, the two are combined in the program summary component to generate annual cash flow. In this component of CAM, inflation is imposed and corporate income tax is paid. Investment tax credit is allowed for those years when the program had a non-recurring investment and also suffered a negative net cash flow. This 'adjusted' annual cash flow is used to calculate key business economic indicators such as IRR and net present value. Cumulative cash flow is used to estimate maximum debt and break-even year. The final cumulative cash flow at the end of the program is also calculated. The results returned to the program definition component as a completed economic analysis.

TSTO RBCC LAUNCH VEHICLE

Students in the spacecraft and launch vehicle graduate design sequence at Georgia Tech recently investigated a number of two-stage-to-orbit launch vehicles in response to a fictitious request for proposal (RFP). According to the RFP, designs were required to be TSTO, utilize rocket-based combined-cycle (RBCC) engines on the booster stage, and reach full operational capability in the year 2010 (after an initial three year ramp up). The system was to operate until the year 2025. Low development and operations cost were preferred. In addition, candidate concepts were to be designed to economically compete in four future market segments. The market segments were the same as those defined in figures 2 - 5 (i.e. cargo to LEO, passengers to LEO, cargo to GTO, and very high speed global PTP delivery). The ability to return cargo from LEO was also desired. One of the most attractive candidate concepts was chosen to serve as a reference design to evaluate and demonstrate the capabilities of CAM.

Reference Concept Overview

The reference concept (figures 6 - 8) consists of a reusable, horizontal take-off first stage (booster) and two interchangeable upper stages. The first upper stage is expendable and is used for delivering unmanned payloads to geosynchronous transfer orbit (GTO). The second upper stage is reusable and can be used for rotating crew or cargo to low earth orbit (LEO) and back. The reference configuration is similar to an early version of the German Sänger TSTO concept.[11]

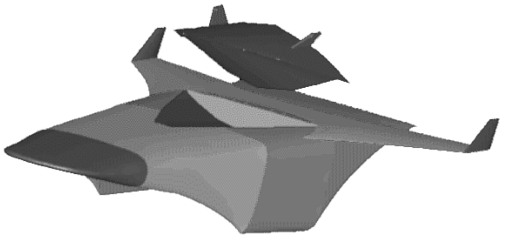

Figure 6 - TSTO RBCC Concept

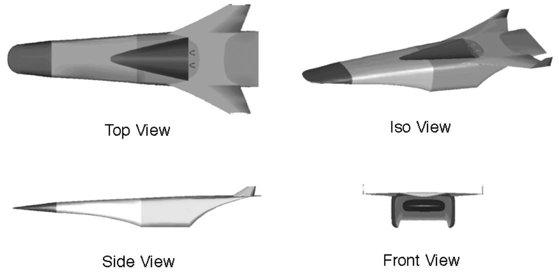

Figure 7 - Booster Configuration

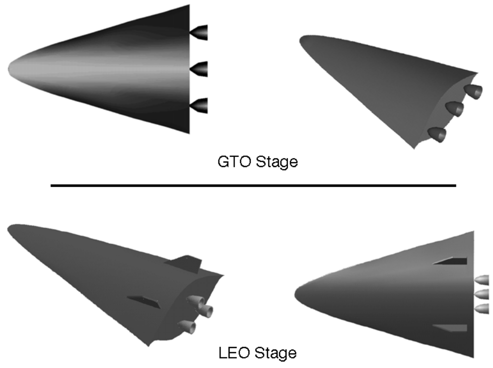

Figure 8 - Upper Stage Configurations

The lifting body booster is powered by a set of five supercharged ejector ramjet (SERJ) RBCC engines. The SERJ engines (figure 9) combine elements of rocket and airbreathing propulsion in a single engine and can operate in ejector, fan-ramjet, ramjet, and ‘pure’ rocket modes.[12-14] The booster uses cryogenic LOX/LH2 propellants and is fully reusable. A cavity on the back of the booster accommodates either upper stage in a partially recessed configuration. The booster is piloted by two crew members.

For orbital missions, the booster/upper stage combination takes off horizontally from a runway at KSC, accelerates to Mach 2 with the engines in ejector mode, changes to fan-ramjet mode between Mach 2 and 3, and then switches to ramjet mode at Mach 3. From Mach 3 to Mach 6, the vehicle flies a constant dynamic pressure boundary (q) of 1500 psf. At Mach 6, the RBCC engine switches to rocket mode, the vehicles leaves the q boundary and accelerates to a lower q Mach 8 staging condition. After staging, the vehicle returns to the launch site in fan-ramjet mode (Mach 2 cruise) and lands horizontally.

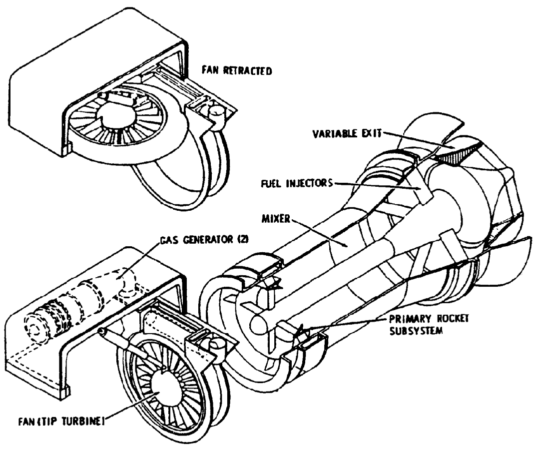

Figure 9 - SERJ RBCC Engine (ref. 14)

The PTP mission does not require a second stage and consists primarily of a hypersonic Mach 5 cruise phase nested between subsonic segments near takeoff and landing. A fairing covers the upper stage cavity to reduce drag. PTP payloads are small and are accommodated in the crew cabin.

To minimize separation problems and maintain commonality, both the upper stages are externally configured as waveriders (optimized for Mach 8 staging). The LEO upper stage is fully reusable and is designed to deliver 10,000 lb. of cargo to Space Station Alpha (SSA) orbit (220 nmi. circular, 51.6° inclination) and return to an unpowered horizontal landing at KSC. This stage operates autonomously (no crew or crew cabin), but can be configured to carry eight passengers to SSA by replacing the payload with a special life support module in the payload bay. The LEO upper stage uses three advanced LOX/LH2 staged-combustion, throttleable rocket engines.

The expendable GTO stage is constrained to the same gross weight as the LEO stage for commonality and it's trajectory is optimized to insert a maximum amount of payload into geosynchronous transfer orbit. The GTO stage uses three (somewhat lower technology and less expensive) gas generator LH2/LOX engines that cannot be throttled. It should be noted that the waverider configuration produced a very expensive GTO stage. As will be shown, the highest system IRR results when the GTO stage and therefore the GTO market segment are eliminated from the reference concept.

All three stages assumed graphite/epoxy materials for the airframe and LH2 tanks. Aluminum-lithium was baselined for LOX tanks. Propellant tanks were integral wherever possible. The booster and the reusable LEO upper stage used advanced passive TPS (ceramic tiles, blankets, and advanced carbon-carbon). The expendable GTO upper stage used a simple ablative TPS. Advanced lightweight subsystems were assumed for all stages.

Reference Concept Analysis Procedure

The reference concept analysis procedure involved seven different contributing analyses (CA's) — aerodynamics, performance, booster propulsion, booster sizing, LEO stage sizing, GTO stage sizing, and thermal protection systems. Aerodynamic analysis for the reference concept was performed using APAS[15] and MaxWarp 2.0[16] and trajectory optimization was performed with POST[17] on a Silicon Graphics Indigo2 UNIX workstation. Subsystem and component level weights for each stage were determined from parametric mass estimating relationships (MER's). The MER's were based on regression analysis of historical data and advanced technology predictions. TPS material types for various parts of each stage were determined using historical data and approximations of local heating rates from trajectory analysis.

The weights and sizing CA's and the TPS CA were implemented as individual spreadsheets on a personal computer. Approximately 70 variables were linked between the spreadsheets for automatic internal iteration. Manual iteration was used to converge propellant mass fractions, gross weights, and aerodynamic reference areas between POST and the linked spreadsheet set. Convergence was typically obtained after three or four manual iterations. As previously mentioned, the reference vehicle design was considered fixed for the current research, so CAM economic analysis was performed as a standalone post-process.

Reference Concept Data

Detailed weight statements were generated for each of the three stages for the converged reference design. Summary weights and sizes are shown in table 1. A 20% dry weight margin is included on the booster

Table 1 - TSTO RBCC Reference Data

Booster	
dry weight	88,380 lb
upper stage weight	136,740 lb
ascent propellants	273,750 lb
other fluids	10,030 lb
gross weight	498,900 lb
length	136.5 ft
wingspan	67.8 ft
LEO upper stage	
dry weight	27,080 lb
payload to SSA	10,000 lb
ascent propellants	96,180 lb
other fluids	3,480 lb
gross weight	136,740 lb
length	60 ft
GTO upper stage	
dry weight	20,310 lb
payload to GTO	5,090 lb
ascent propellants	110,760 lb
other fluids	580 lb
gross weight	136,740 lb
length	60 ft

and the LEO upper stage. A 10% dry weight margin is included on the GTO upper stage.

ECONOMIC ANALYSIS RESULTS

The goal of the current demonstration was to maximize IRR for the TSTO RBCC by simultaneously optimizing the end-customer prices to each of the four market segments. Economic variables such as maximum debt, break-even year, and cumulative cash flow at the end of the program were also desired. To begin the process, detailed weight statements for each stage, appropriate CER complexity factors, and previously mentioned programmatic assumptions were input into CAM.

Not unexpectedly, initial optimization efforts using a gradient-based optimizer (Microsoft Excel's Solver) met with difficulty. Due to the high number of integer variables (e.g. flight rates, production quantities), the economic design space is not smooth and contains many local maxima for IRR. The gradient-based optimizer repeatedly found local maxima, but not a global optimum. As a 'brute force' method, a grid search of 8,000 points was initially used to locate the neighborhood of the global maximum. The gradient-based optimizer was then used for a fine tuned local search. In the future, the grid search portion of this multi-step search technique will be replaced with a more efficient search method (e.g. genetic algorithms) to reduce search time.

During the grid search process, it was evident that the highest IRR's were obtained when the GTO market segment was eliminated from consideration. That is, the best results were obtained with GTO $/lb of payload prices greater than $15,000/lb. At these prices, the captured GTO market (fig. 4) and the corresponding GTO stage flight rate are reduced to zero. Thus the need to develop the rather expensive expendable GTO stage and its engines is eliminated. Although somewhat surprising, this conclusion is consistent with Sänger's similar decision to eliminate it's GTO stage for economic reasons. This conclusion is certainly influenced by staging Mach number, GTO configuration, and other factors. Further research is recommended. For the remainder of the results reported here however, it was assumed that the GTO stage and the GTO market were to be eliminated for maximum IRR.

The maximum IRR and the corresponding optimum launch prices (in $96) for each of the market segments are shown in table 2. Annual flight rates to each of the four market segments are also listed. Note that the booster is required to fly nearly 140 times per

Table 2 - Optimum IRR Prices

maximum IRR	**15.1%**
break-even year	2014
maximum debt	$8.61 B ($TY)
LEO $/lb of payload	$1590
LEO $/passenger	$4.72 M
GTO $/lb of payload	>$15,000
PTP $/round trip	$4.45 M
annual LEO cargo flts.	93
annual LEO pass. flts.	19
annual GTO flights	0
annual PTP flights	26

year for the optimized case. Five booster airframes and ten LEO stage airframes are required to be produced. Corresponding cash flows in then-year dollars ($TY) are shown in figure 10.

Figure 11 shows the change in IRR, annual booster flights, and the size of the LEO market captured with respect to LEO $/lb of payload price in the region of the optimum. The maximum IRR can be identified at $1590, but note that the IRR response is relatively flat in that region. All other prices remain at their previously optimized values.

For the present assumptions, the maximum IRR is a rather disappointing 15.1%. For such a risky venture, interested companies will probably require IRR's in excess of 25% - 30%. Re-optimizing the vehicle for IRR might improve the results somewhat, but it is unlikely that large increases are possible without significant decreases in operations costs or increases in government development contribution.

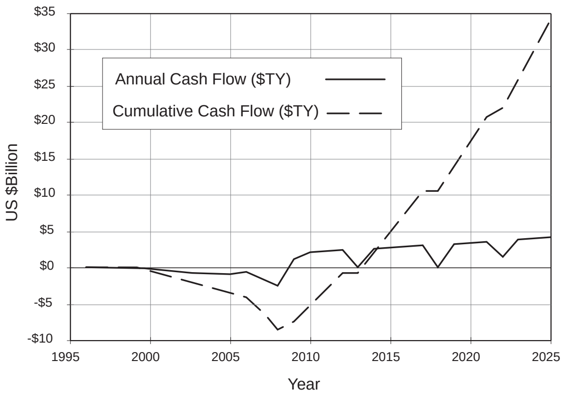

Figure 10 - Cash Flows for Optimized IRR Case

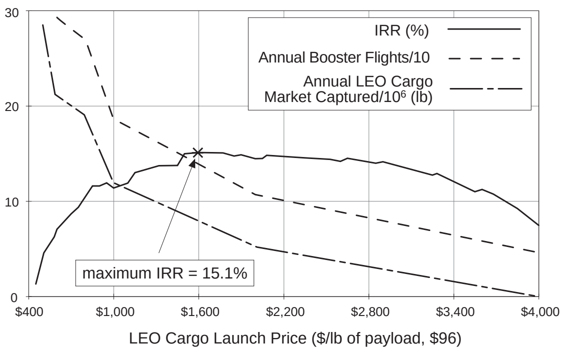

Figure 11 - Region of Maximum IRR

Sensitivities

With the four market prices set at their optimized values, sensitivity studies were conducted to determine the effect of three key assumptions on IRR, maximum debt, and final cumulative cash flow (shown as a ratio to the cumulative cash flow for the optimized IRR). Figure 12 shows the effect of changing the percentage of government contribution to vehicle airframe DDT&E. The baseline assumption is 20%. Note the significant improvement in IRR at the higher levels.

Figure 13 shows the effect of changing the life for reusable hardware. The baseline assumption is 500 flights for the booster airframe and 200 flights for the LEO upper stage (engines are assumed to last half of the airframe life time). For annual flight rates below 200 - 300, airframe lifetime is the primary driver for determining fleet size and production requirements.

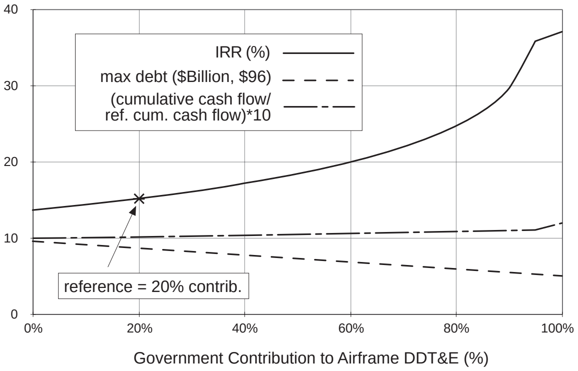

Figure 12- Sensitivity to Government Airframe DDT&E Contribution

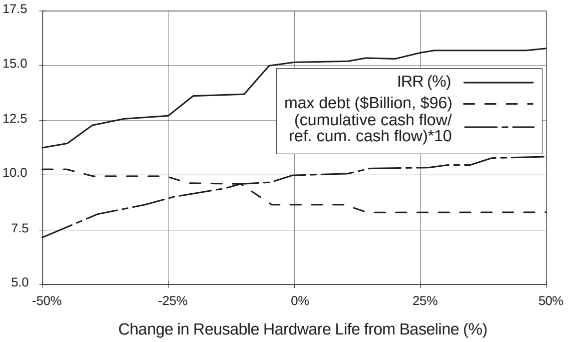

Figure 13 - Sensitivity to Reusable Hardware Life (both Booster and LEO upper stage)

Figure 14 shows the effect of changes in the operations cost assumptions. Although IRR is clearly affected by operations costs, the results indicate that much larger reductions in operations cost (an order of magnitude or two) will be required to raise IRR to acceptable levels.

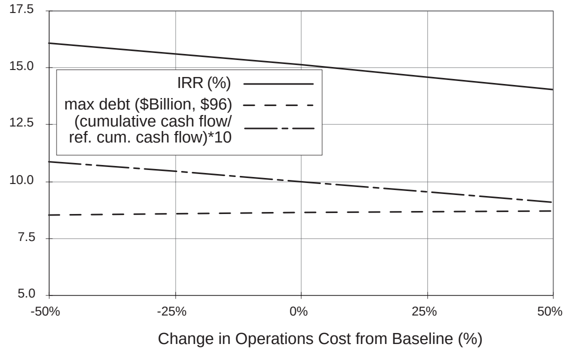

Figure 14 - Sensitivity to Operations Costs

CONCLUSIONS

This paper has outlined the status of a new economic analysis tool that is currently under development for conceptual launch vehicle design applications. By integrating life cycle cost and market economics (revenue, market elasticity), CAM provides business-oriented information that heretofore has been unavailable to decision makers. A demonstration of CAM on the design of a TSTO RBCC launch system was successfully performed. Among the specific results in the paper are:

1) The economic design space was observed to be very non-smooth and to contain a number of local maxima for IRR. This was primarily due to the number of integer variables in the economic models (flight rates, production runs, etc.). Gradient-based optimizers initially had difficulty locating the true maximum IRR. As a result, a multi-step search method was required. A grid search was initially used to locate the region of the optimum. A gradient method was then used to fine tune the maximum. Efficient optimization methods more suitable for this design space will be considered for future work. Genetic algorithms are one recommendation.

2) Although the TSTO launch system included an expendable GTO stage (to capture payloads in the GTO market), the maximum IRR for the system was found for cases where the GTO market segment and the GTO stage development costs were eliminated. Additional research is recommended to determine the influences of staging Mach number and vehicle configuration on this conclusion.

3) At 15.1%, the optimum IRR for the TSTO RBCC reference vehicle is probably too low to generate serious business interest. Significant increases in government contribution to airframe DDT&E or orders of magnitude reductions in operations costs are required to raise IRR above 25% - 30%.

FUTURE WORK

As previously discussed, CAM is currently under development and much additional work is required to bring it to operational status. In addition to the recommendations mentioned above, the following items will be addressed:

1) Improve the recurring cost component of CAM. Future versions will provide a flexible and more complete mechanism for modeling vehicle operations costs.

2) Improve the facilities cost modeling technique. Future facilities models will be sophisticated enough to reflect changes in the vehicle footprint.

3) Port CAM to a UNIX-based workstation to improve execution speed and allow the tool to be closely integrated with other conceptual design tools in a tightly-coupled multidisciplinary design optimization environment.

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