Augmenting the Space Shuttle with a Space Station and Tug

Jess M. Sponable*
USAF, Los Angeles, California
and
Aaron R. DeWispelare†
USAF, Wright-Patterson AFB, Ohio

Nonlinear optimization techniques are used to quantify the impact of adding a space fueling station and reusable tug to the Space Transportation System (STS). The Shuttle deploys all space traffic to the station at which a tug is used to launch a representative satellite fleet across the entire gamut of inclinations and altitudes. Annual Shuttle launches are calculated by summing the total mass required to deploy and operate the system and dividing by the Shuttle cargo mass capacity. The station altitude and inclination are variables specified when Shuttle launches are minimized. Launch rates for one- two-, and three-station scenarios are compared to the author's estimate of the corresponding rates for current STS operations. The use of both chemically and ion-propelled tugs are evaluated. Applying vector optimization to the latter minimizes both the average tug flight time and annual Shuttle launches. The resulting efficient operating frontier specifies a set of optimal inclinations, altitudes, and tug sizes. The Shuttle launch rates for the chemical and ion systems are potentially less than for current STS projections. Equally important for existing ion thruster technology, the round trip flight time of the tug to geosynchronous orbit can be less than 60 days.

Nomenclature

a	= semimajor axis
A	= acceleration
B	= ballistic coefficient
F	= launch frequency
g	= gravitational acceleration
i	= inclination
I_{SOC}	= SOC inclination
ISP	= specific impulse
M	= mass
MM	= Shuttle mass at MECO
MSP	= specific mass
N	= number of
P_{THR}	= thrust input power
R_{SOC}	= SOC radius
T_{THR}	= thrust
μ	= gravitational parameter

Subscripts

AVG	= average
DEPLOY	= OTV deployment flight
f	= final
FT	= fuel tank
o	= initial
ORB	= Orbiter
PL	= payload
RETURN	= OTV return flight
SAT	= satellite
STR	= ion OTV structure & avionics
THR	= ion thruster

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*Chief, Global Positioning System Shuttle Integration, USAF Space Division.
†Associate Professor, Dept. of Aeronautics and Astronautics, Air Force Institute of Technology. Member AIAA.

Introduction

THE Space Transportation System (STS) is designed to enhance the effectiveness and streamline the life cycle cost of launch and satellite systems. One example is the Shuttle's ability to extend average system lifetimes by returning or repairing malfunctioning satellites prior to orbital deployment. This capability is especially significant in light of a 1974 study estimating that over half of the first month spacecraft failures occur on the first operational day in orbit.[1] Although still in its infancy today, orbital retrieval, repair, service, and test operations may eventually reduce factory and launch base test requirements, and give rise to a sequel to the Factory-to-Pad test concept employed with military and some civil satellites; namely, Factory-to-Orbit testing.[2]

Although the Shuttle has great potential, it also has some inherent limitations. The Shuttle's expense and inability to reach higher altitudes limits its direct use for repair, service, and retrieval to valuable low Earth orbit satellites. The limited extravehicular access and flight duration further constrain the Shuttle's utility as an orbital work platform. The Shuttle's chief virtue is exactly what it was designed for—repetitively hauling large, massive cargos into orbit. Unfortunately, as currently employed, the Shuttle cannot take full advantage of its cargo hauling capabilities. Indeed, reasonable estimates of the average Shuttle loading may range from as low as 40% to as high as 75% of its payload mass capacity to orbit. A logical extension to the STS, overcoming many of the Shuttle's drawbacks, is the construction of an orbiting space fueling station (Space Operations Center, SOC) and tug (Orbital Transfer Vehicle, OTV).

An augmented STS composed of the SOC, OTV, and Shuttle binds our national space assets into an integrated system. The SOC and OTV system may consist only of an unmanned service module and OTV launched on one Shuttle flight. The service module would be used to store fuel for transfer to the OTV and maintain the OTV between flights. Operated in this manner the system is somewhat similar to an advanced version of the Orbital Maneuvering Vehicle (OMV) being evaluated by NASA. Conversely, the SOC could be a manned space station with a variety of operational missions as depicted in Fig. 1. In any case, the SOC serves as a central logistics depot from which personnel can deploy and eventually maintain the satellite fleet. Although not exhaustive, the satellite deployment mission lends itself to quantitative analysis. Specifically, the economic feasibility of an augmented STS is evaluated in this study.

Operating the augmented STS presents a logistics problem analogous to the classic linear programming transportation problem first formulated by G.B. Dantzig nearly four decades ago. The problem assumes that on the average, the Shuttle cargo's are topped off to 100% mass capacity with propellant for use in orbit. The Shuttle deploys the SOC, OTV, satellites, personnel, fuel, and other consumables directly to the SOC. An OTV is then fueled at the SOC for deployment of the satellites to their final orbits. The fuel used by the OTV can easily be modeled as a monopropellant, LOX/H_2 or mercury for an ion engine. The fuel could be carried in tanks similar to those in the orbital maneuvering system (OMS) once proposed for use in the Shuttle cargo bay. The OMS kit could carry over 10,000 kg of additional OMS fuel to orbit with the installation of the 3400 kg, 3-m-long kit. The disadvantage of such tanks and plumbing is that they limit both cargo length and mass capacity for satellite systems sharing the bay.

A hypothetical fleet of satellites deployed by the OTV in this study is contained in Table 1. The model emphasizes polar orbiting satellites, and excludes much of the commercial and foreign equatorial traffic. Both high and low satellite launch frequencies (F_{SAT}) are portrayed in the table.

The basic premise is that the augmented STS requires fewer Shuttle launches to construct and support than current STS launch requirements. To compare the two launch rates, Table 2 first estimates average current launch requirements with satellites being deployed directly from the Shuttle to their operational orbits. Estimating the current launch requirements for the traffic model in Table 1 is very difficult due to a lack of detailed information about the traffic model and the lack of STS manifesting expertise. Present-day problems associated with cargo size, cargo mass, bay placement, clearances, center of gravity, and conflicting availability dates make any assessment of the number and timing of Shuttle launches difficult to defend. Although these real-world problems are significant, maturing STS operations and a carefully augmented STS design should go far towards minimizing adverse manifesting impacts in the future. In any case, as used in this paper, current launch requirements with the associated flight rates and load factors do not exactly correspond to their equivalent values on a NASA manifest. Instead, they are simplistic estimates of what launch rates for a future manifest might look like with the incorporation of the assumptions detailed below.

The author's estimates in Table 2 were derived by calculating the mass of solid fuel required to deploy the satellites to their final orbits from the Shuttle parking orbit. Total annual mass transported to orbit is then summed up and divided by the appropriate fraction of Shuttle cargo mass capacity yielding annual Shuttle launch requirements. The method's three drawbacks are: first, the mass of any airborne support equipment (ASE) is ignored, resulting in a low estimate of annual launches. For example, over 30% of the mass of McDonnell Douglas Corporation's PAM-DII Upper Stage System is ASE. Including the ASE mass of such payloads would increase the Table 2 launch rates by a similar percentage. Second, the parking orbit inclinations are assumed to be the same as the satellite mission inclinations for all but the first two missions, thus allowing for no plane change capability. Realistically, upper stages launched from the Orbiter would need significantly more fuel mass for any plane change capability, again resulting in a low estimate of annual launches.

Table 1 Postulated satellite traffic model

Hypothetical missions, no.	Semi-major axis, km	Eccentricity	Inclination, deg	Mass, G	Launch frequency, no./R High	Launch frequency, no./R Low
1	41,000	0.0	0.0	2000	3.0	2.25
2	20,000	0.0	0.0	500	0.5	0.375
3	6700	0.0	28.5	25,000	0.5	0.375
4	65,000	0.0	55.0	1500	4.0	3.0
5	25,000	0.7	65.0	1500	0.5	0.375
6	12,000	0.0	90.0	4500	3.0	2.25
7	6700	0.0	98.0	8000	5.0	3.75

Table 2 Author's prediction of current STS ,launch requirements

	Traffic model			
	Low STS launches/yr Mass load factor		High STS launches/yr Mass load factor	
	0.40	0.75	0.40	0.75
Mission				
1	2.57	1.37	3.84	2.05
2	0.16	0.08	0.23	0.12
3	0.98	0.52	1.50	0.80
Subtotal	3.71	1.97	5.57	2.97
4	3.27	1.74	5.06	2.70
5	0.27	0.14	0.43	0.23
Subtotal	7.25	3.85	11.06	5.90
6	2.25[a]	2.25[a]	3.00[a]	3.00[a]
7	3.75[a]	3.75[a]	5.00[a]	5.00[a]
Total	13.25	9.85	19.06	13.90

[a] A maximum of one Shuttle launch per satellite is assumed due to the low cargo mass capacity at higher inclinations.

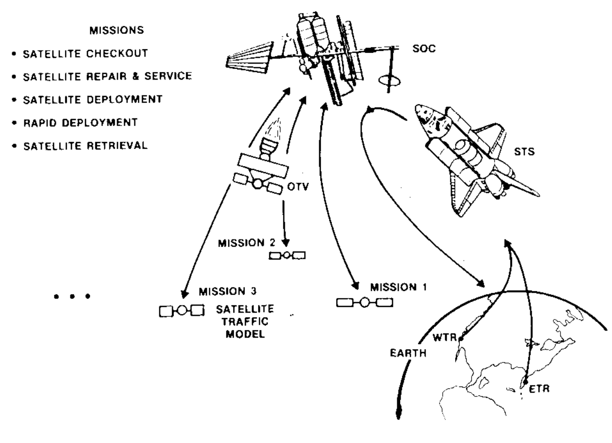

Fig. 1 Augmented STS.

Finally, the Shuttle cargo masses were calculated using a relatively high Orbiter mass at atmospheric reentry (M_{ORB}) of 85,000 kg and 88,041 kg for the Low and High Traffic Models, respectively. This results in slightly lower Shuttle cargo mass capacities than those used by NASA to calculate Shuttle flight charges (29,500 kg or 65,000 lbs to a 28.5-deg, 160-n.m. orbit). Because of the lower Shuttle mass capacity, average launch rates in Table 2 are high in comparison to a NASA manifested Shuttle with the 29,500-kg capability. The Shuttle cargo mass capacities used to calculate the launch rates in the table are between 3 and 8% lower than NASAs 29,500 kg for the Low Traffic model. For the High Traffic model, mass capacity is between 14 and 20% lower. Consequently, the launch rates of Table 2 are higher than a NASA manifested Shuttle by similar percentages.

The Table 2 calculations were made for Shuttle load factors of both 75 and 40% of cargo mass capacity to orbit. Mission planners at NASA consider 75% of cargo mass or length capacity to be a full load in their costing models, while 40% is probably a low estimate of the average Shuttle loading to date. The 75% figure is used by NASA to calculate flight charges based on the 29,500-kg cargo capacity discussed above. Missions at inclinations above 28.5 deg have smaller cargo mass capacities. In summary, the launch estimates of Table 2 are somewhat lower than they would be in a NASA manifested Shuttle due to the exclusion of ASE and the lack of an upper stage plane change capability. The launch estimates are somewhat higher than they would be in a NASA manifested Shuttle due to the relatively low Orbiter cargo mass capacity. Consequently, the overall estimate of average launch rates in Table 2 should not be construed as being identical to the rates in an equivalent NASA manifest. However, it does provide a reasonable estimate of what launch rates in a future manifest might look like.

The amount of propellant needed by the augmented STS varies dramatically with the altitude and inclination of the SOC. A nonlinear optimization program called the Sequential Unconstrained Minimization Technique (SUMT) is used to specify values for the variable SOC altitude and inclination.[3] One minimized performance index is the annual mass of fuel consumed by OTV flights, SOC orbit maintenance, and the Shuttle's OMS. Alternatively, the annual number of Shuttle launches is minimized by calculating the total mass required to deploy and operate the system and dividing by the Shuttle cargo mass capability. Both performance indices yield essentially equivalent results, although only the latter is reported in this paper. Each is efficiently minimized by the SUMT program, requiring less than 0.5 s of central processor time per batch run. Another technique utilizes a vector optimization process to minimize two performance indices: the number of Shuttle launches and the average flight time for an ion propelled OTV.[4] The tradeoff between the two provides an indication of whether current ion engines can deploy satellites fast enough to satisfy operational requirements. The major difficulty with the ion propelled OTV, not specifically addressed in this paper, is the lack of developed high-energy power supplies needed to power ion thrusters. Consequently, instead of using an actual design weight, a specific mass in kilograms/kilowatt is used to model the mass of the power supply required.

The launch minimization model directly assesses the launch costs associated with the augmented STS. Of special significance is the ability to identify the costs associated with placing one SOC at a 28.5-deg inclination vs two SOC's at 28.5 and 57.0-deg inclinations. The sensitivity of annual Shuttle launches is measured by varying parameters such as the OTV mass and the various engine specific impulses. The resulting impact on annual launches gives cost saving insight into the most efficient operating modes for an augmented STS. Minor changes to the model accurately assess the impact of increasing the specific impulse of the SOC and OTV engines into the range of the ion motor. Also evaluated is the impact of an OTV rendezvous with the Shuttle at a 160-km (86-n.m.) altitude, and subsequently returning to the SOC with the Shuttle payload. The rendezvous altitude used is probably too low for an operational system in that the Shuttle orbit would decay into the atmosphere within a few days. Periods of peak solar activity further complicate the orbital decay problem. In any future operational system, either the rendezvous altitude must be raised or docking with the OTV and cargo transfer must be accomplished immediately after orbital insertion. In either event, further studies using more realistic atmospheric models would be needed to better define the optimal rendezvous altitude.

Solution Methodology

Minimization of annual Shuttle launches requires knowing how much mass is transported to orbit. The masses of the SOC (M_{SOC}), OTV (M_{OTV}), satellites (M_{SAT}), fuel (MF), and the annual resupply cargo (M_{CARGO}) are assumed or calculated using the Satellite Traffic Model. Key assumptions include:

1) The SOC orbit is circular, with an altitude between 120 and 800 km.

2) The atmosphere is modeled as a rotating sphere whose density decreases exponentially with altitude. A constant scale height directly specifies the fuel consumption rate required to maintain the SOC orbit.

3) The OTV deploys each satellite individually, while the retrieval mission is not evaluated.

4) Challenger, with its median mass, is the generic Orbiter used in this study. No reaction control system (RCS) fuel is used during flight; Challenger ascends to orbit fully loaded and returns to Earth empty.

5) Velocity changing maneuvers are modeled as impulsive Hohmann transfers for the chemically propelled OTV. The low-thrust ion propelled OTV ideally requires an infinite number of revolutions in its transfer orbit.

Two sequential Hohmann transfers deploy each satellite to the appropriate traffic model apogee, then to its final altitude and inclination. The OTV returns to the SOC via the same transfer orbits. For low-thrust transfers, Alfano[5] and Wiesel recently derived the minimum flight time characteristic velocities (ΔVs) required for radius and plane changes accomplished independently:

$$\Delta V = \begin{cases} \left(a_0^{-1/2} - a_f^{-1/2}\right) \cdot \mu^{1/2} \\ \dfrac{\pi}{2} \cdot (i_0 - i_f) \cdot (\mu/a)^{1/2} \end{cases} \tag{1}$$

Once the ΔV's are known, the rocket equation is used to calculate the annual fuel mass (MF) consumed by the Shuttle OMS (MF_{OMS}) and OTV (MF_{OTV}) engines:

$$MF = M_f \cdot (e^{\Delta V/ISP \cdot g} - 1) = M_0 \cdot ((1 - e^{-\Delta V/ISP \cdot g}) \tag{2}$$

Similarly, the annual SOC engine fuel consumption required to overcome atmospheric drag (MF_{SOC}) is calculable from the definition of specific impulse (ISP):

$$M\dot{F} = (M \cdot A) / (ISP \cdot g) \tag{3}$$

For a chemically propelled OTV, fuel consumption is calculated by assuming a constant dry mass of 2,270 kg. The mass of the ion propelled OTV is dependent on a third variable specified by the minimization procedure, the number of ion thrusters (N_{THR}) installed:

$$M_{OTV} = M_{STR} + N_{THR} \cdot (M_{THR} + M_{FT} + MSP \cdot P_{THR}) \tag{4}$$

To calculate the number of OTVs needed the flight time (TIM) must be calculated by integrating Eq. (3):

$$TIM = (MF \cdot ISP \cdot g) / (N_{THR} \cdot T_{THR}) \tag{5}$$

where T_{THR} is the individual ion engine thrust. The number of OTV's needed (N_{OTV}) is then given by the product of the average round trip flight time (TIM_{AVG}) and the number of OTV missions required by the traffic model.

To determine the annual number of modeled Shuttle launches from the total mass transported to orbit, the payload mass must be known. Since no RCS propellant is consumed during flight, the payload mass is

$$M_{PL}(I_{SOC}, R_{SOC}, N_{THR}) = MM - M_{ET} - MF_{OMS} - M_{ORB} \tag{6}$$

This is a conservative assumption since the unused RCS fuel increases the Shuttle mass in orbit, thus requiring additional OMS fuel to propel the Shuttle and slightly decreasing the available payload mass while slightly increasing the number of modeled Shuttle launches.

The standard main engine cutoff (MECO) masses for various inclinations are estimated with NASA flight planning data, and modeled in a third-order regression analysis.[6] The maximum 3σ error is less than 250 kg for both the Eastern Test Range (ETR) and Western Test Range (WTR).

Because of the precision inherent in the standard MECO mass determination, the calculated number of annual Shuttle launches (F_{ORB}) is also very precise. The modeled Shuttle cargo for the augmented STS was purposefully set somewhat low at 21,300 kg or 47,000 lbs to a 160 n.mi. orbit inclined at 28.5 deg. The resulting annual launch rates for the augmented STS are somewhat higher than they would otherwise be, thus compensating for not incorporating the mass of fuel storage tanks and plumbing as well as any possible overestimation of the launch rates of Table 2. The accuracy of both the payload mass and the resultant annual Shuttle launches could easily be adjusted by varying the STS flight profile and assumptions used to make the calculations. In its most general form, with the augmented STS deploying a fixed number of satellite missions (N_{SAT}) for a 16-year lifetime, the problem reduces to[7]

MIN:

$$F_{ORB} = [MF_{SOC} + MF_{OMS} + MF_{OTV} + M_{CARGO} + \sum_{j=1}^{N_{SAT}} (M_{SATj} \cdot F_{SATj}) + (M_{SOC} + N_{OTV} \cdot M_{OTV}/16] / M_{PL} \tag{7}$$

and/or

$$TIM_{AVG} = \sum_{j=1}^{N_{SAT}} [TIM_{DEPLOYj} + TIM_{RETURNj}) / N_{SAT}] \tag{8}$$

Subject to constraints:

$28.5 \text{ deg} < I_{SOC} < 57 \text{ deg}$	ETR constraint
$56 \text{ deg} < I_{SOC} < 104 \text{ deg}$	WTR constraint
$6{,}500 \text{ km} < R_{SOC} < 7{,}200 \text{ km}$	Altitude constraint
$MF_{OMS} < 10{,}830 \text{ kg}$	OMS fuel capacity
$M_{PL} > 0 \text{ kg}$	Payload mass
$N_{THR} > 0$	Number of ion thrusters
$N_{OTV} > 0$	Number of ion OTV's

To analyze the problem, six related minimization models were evaluated. Model 1 minimizes the total annual fuel consumption of the SOC, OTV, and Shuttle OMS. Model II is identical only the annual number of Shuttle launches required to deploy and operate the augmented STS with a chemical OTV is minimized. Model III is the same, only the OTV makes a rendezvous with the Shuttle at a 160 km altitude, and returns to the SOC with the Shuttle payload. Model IV deletes the OTV/Shuttle rendezvous and utilizes an ion propelled OTV. Model V uses both the ion OTV to deploy satellites and the chemical OTV to rendezvous with the Shuttle. Model VI is the same as V only it calculates the number of ion propelled OTVs required to support the traffic model, and simultaneously minimizes average flight times. These six models are summarized in Table 3 along with four scenarios. Each scenario contains either one, two (two cases), or three SOC's servicing various combinations of the satellite missions. Comparing the four scenarios in each of the five models allows the planner to evaluate which is the most efficient operating mode.

To evaluate the impact of evolving technology, four levels of engineering parameters were postulated. Table 4 lists the parameter values common to all four levels and those that vary between levels. The Level 1 parameters included an OTV specific impulse corresponding to a LOX/H_2 engine with an overall OTV mass of 2,270 kg. These parameters served as a baseline on which the sensitivity analysis could be done. Level 2 incorporated the low traffic model and a lower Orbiter mass. The ion engine parameters are those of the 30 cm Hg ion thruster being developed by NASA's Lewis Research Center.[8] The Level 3 ion engine uses the same thruster, throttled to higher thrust. The last level is an extrapolation of existing technology. Crudely summarized, the first two levels are off-the-shelf technology (although the ion engines are not currently space-qualified); the third will probably be available in the near term; and the last is an extrapolation of what could be available by the turn of the century.

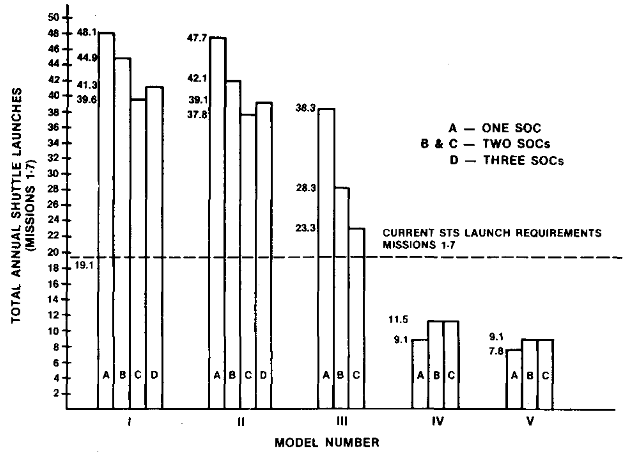

Fig. 2 Augmented STS annual Shuttle launches.

Table 3 Minimization models and multiple SOC scenarios

	Models		Scenarios
I	Minimize Orbiter, SOC, and OTV fuel consumption	A	1 SOC serving Missions 1-7
II	Minimize Model I Shuttle launches	B	2 SOC's serving Missions 1-3 and 4-7
III	Minimize Model II launches with OTV/Shuttle rendezvous	C	2 SOC's serving Missions 1-5 and 6-7
IV	Minimize Model II launches	D	3 SOC's serving Missions 1-3 4-5, and 6-7
V	Minimize Model II launches with ion OTV		
VI	Minimize Model V launches and average OTV flight time		

Table 4 Augmented STS engineering parameters

Common engineering parameters			
Ballistic coefficient	$B = 0.02$ kg/m^2	ET mass	$M_{ET} = 38{,}399$ kg
Scale height	$H = 30$ km	Ion fuel tank mass	$M_{FT} = 12$ kg
OMS specific impulse	$ISP_{OMS} = 331$ s	OTV mass	$M_{OTV} = 2270$ kg
OTV specific impulse	$ISP_{OTV} = 455$ s	Ion OTV structure mass	$M_{STR} = 300$ kg
SOC specific impulse	$ISP_{SOC} = 455$ s	Number ion thrusters	$N_{THR} = 20$

Advancing technological parameters	Technology levels 1	2 (Today)	3 (Near term)	4 (2000)
SOC mass kg	$M_{SOC} = 100{,}000$	same	same	200,000
Cargo mass, kg	$M_{CARGO} = 20{,}000$	same	same	26,250
Orbitr mass, kg	$M_{ORB} = 88{,}041$	85,000	same	80,000
Ion thruster mass, kg	$M_{THR} =$ 51,36	same	same	40.00
Ion thruster power, kw	$P_{THR} =$ 3.06	same	6.86	10.00
Ion thruster thrust, mN	$T_{THR} =$ 129,00	same	298.00	500.00
Specific mass, kg/kw	$MSP =$ 10,00	same	5.00	1.00
Ion thruster specific impulse, s	$ISP_{THR} = 2900.00$	same	3448.00	5000.00
Traffic model, no	is high	low	same	same

Results

The various models, scenarios, and technology levels were evaluated with the SUMT program. Each execution of SUMT specified the optimal inclination, altitude and, when applicable, the number of ion engines on each OTV. Payload mass, the number of ion OTV's required to support the traffic model, and fuel consumption of the Orbiter, OTV, and SOC are also specified by the optimization program.

Figure 2 summarizes the results of the first five models using Level 1 technology with one, two, or three SOC's in orbit. The annual launches depicted represent the total required to construct and supply all SOC's in orbit and deploy the satellites in the traffic model. The dotted line portrays the author's projection of what STS launch requirements would be without a reusable OTV. The estimates are from Table 2 with the Shuttle loaded to 40% mass capacity.

Several significant savings are apparent in the figure. First, the two SOC scenarios appear to be more efficient than either single or triple SOC systems. Second, by incorporating the OTV retrieval of lower-altitude Shuttle payloads, Model III reduces Shuttle traffic by increasing the payload transported to the SOC. The rendezvous strategy reduces Shuttle launch requirements by around 20 to 40%, depending on the system configuration and traffic model. The last noteworthy point is the extreme savings possible with the Model IV and V ion propelled OTV's. At 26 Shuttle flights per year, one estimate places the fiscal year 1983 launch costs at around $116 million each.[9] Since the ion OTV system reduces the number of annual Shuttle launches by as much as 11.3, the corresponding financial savings are $1.31 billion or $21 billion over the sytem's 16-year lifetime. However, flight times for the polar inclination missions are undesirably long.

For the chemical OTV, it became apparent early in the study that high-inclination satellite missions were also the least fuel efficient to deploy. To illustrate, Fig. 3 again depicts annual Shuttle launches for the first five models. However, only one SOC is used to service Satellite Missions 1 to 3 (below 28.5 deg inclinations) and 1 to 5 (below 65 deg inclinations). The two dotted lines again represent the estimated current STS launch requirements from Table 2. Level 1 technology is used in the five models. The second bar in the Model II and III graphs incorporates the more realistic Orbiter mass from Level 2 technology, while the third bar also incorporates fuel scavenging. The scavenged fuel is 5,000 kg of reserve propellant drained from the external tank (ET) after MECO and carried to the SOC for future use. Incorporation of a scavenging scheme may require even more tank and plumbing weight in the cargo bay than a simple augmented STS.

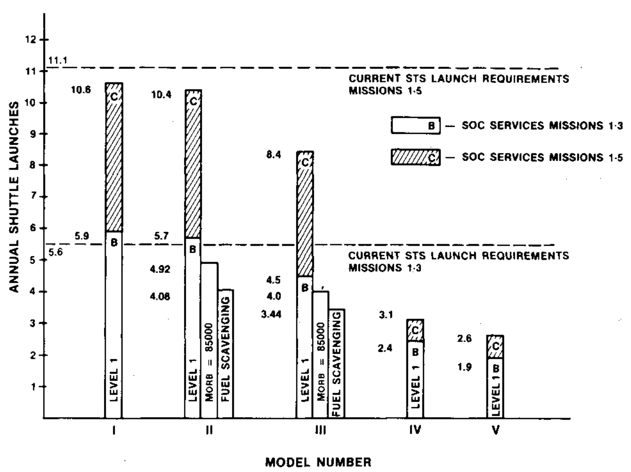

Fig. 3 Augmented STS annual Shuttle launches for low-inclination satellite missions.

Several significant savings are also apparent when the augmented STS deploys only low-inclination satellites. The rendezvous strategy again reduces Shuttle launch requirements by approximately 20%, while fuel scavenging saves approximately 15%. The latter savings may more than triple if all of the reserve fuel in the ET is scavenged. Using the $116 million Shuttle launch cost, a LOX/H_2 OTV, and deploying only satellite below a 28.5 deg inclination can save $260 million annually or cost an additional $310 million, depending on the Shuttle load factor and operating mode assumed. Similarly, if the SOC deploys only satellites below a 65 deg inclination, the best and worst cases result in annual savings of $430 million or additional costs of $520 million. When deploying the same satellite missions, the ion OTV gives annual savings between $320 and $990 million. The advantage of deploying only satellites below a 65 deg inclination is an average flight time of potentially less than 60 days. Additional economy of scale savings are also possible by incorporating higher, more realistic levels of commercial and foreign satellite traffic in the Table 1 model.

To determine the sensitivity of the calculated annual launches in Model II and Level 1 technology, the optimization program is rerun after incrementing the engineering parameters of Table 4 by fixed percentages. The results for several of the most and least sensitive parameters are portrayed in Fig. 4. Of special significance is the extreme sensitivity of the model to the ET mass, specific impulses, and the Orbiter dry mass. Annual model II savings for an increase in

OTV specific impulse is around \$12 million/sec. Annual savings for a decrease in ET mass, which corresponds to introducing an equivalent amount of scavenged fuel mass at MECO is \$130 thousand/lb. A decrease in Orbiter dry mass results in an annual savings of approximately \$100 thousand/lb. Also the dry mass of the LOX/H_2 OTV has a steep linear impact on annual launch requirements. The slope of 1.13 annual Shuttle launches per 100 kg implies that the annual operating cost of the system increases by \$1.3 million per kilogram increase in the OTV dry mass. Of the least sensitive parameters, the two most surprising are the dry mass of the SOC and annual resupply cargo. The insensitivity of both parameters suggests it is unnecessary to expend excessive resources designing a low-mass SOC or unduly limiting the mass of resupply cargo sent to the SOC.

In addition to the constant engineering parameters, the variable SOC inclination and orbit radius were incremented in Fig. 5. First, the inclination was incremented from 30 to 90° after setting the altitude to the value minimizing Shuttle launches. Conversely, the radius was incremented from 6,600 to 7,000 km (altitudes are 119 to 335 n. mi.) while maintaining the inclination minimizing Shuttle launches. The exponential sensitivity of annual launches to both variables illustrates the extreme importance of operating the augmented STS at the optimum inclination and altitude. Because the traffic model deployed by the OTV will change over the SOC lifetime, the results also suggest that a SOC capable of changing orbits is desirable.

For the case of the ion propelled OTV, several ion engine parameters in Model IV are also incremented by fixed percentages. Figure 6 illustrates the sensitivity of annual launches and OTV flight times to these parameters. Varying the ion engine parameters had a more significant impact on the OTV flight times than on the number of Shuttle launches. Of special significance is the relative insensitivity of the specific mass. The implication is that the mass of the power supply used to drive the ion thrusters does not have a major impact on either flight times or launch rates. The model IV linear sensitivity is approximately \$3.2 million/yr and three round trip flight days per pound of specific mass. Consequently, expensive and extremely lightweight solar arrays or nuclear reactors may not be required to power an ion propelled OTV.

Implementation of a vector optimization process to minimize both annual Shuttle launches and ion drive OTV flight time reveals the tradeoff between these two performance indices.[4] Essentially, both performance indices are simultaneously minimized. Figure 7 depicts the resulting efficient frontier on which the augmented STS should be operated. Each point on the curve is associated with an optimal SOC altitude, SOC inclination and an optimal number of ion thrusters on the OTV. The efficient operating frontier is calculated using a Model VI augmented STS, with one SOC deploying all of the traffic model missions. The three technology levels shown yield a consistent reduction in annual Shuttle launches and OTV flight times. The dotted efficient

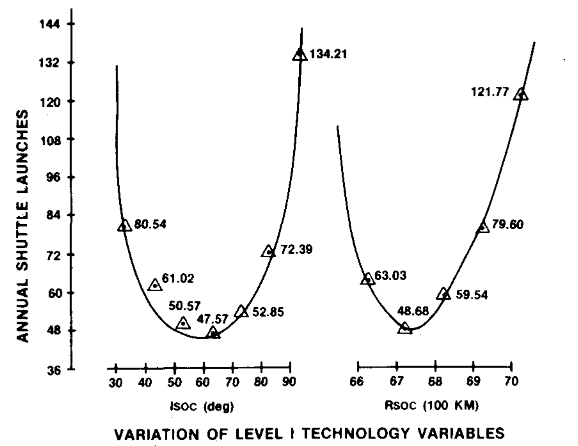

Fig. 5 Sensitivity of Model II problem variables.

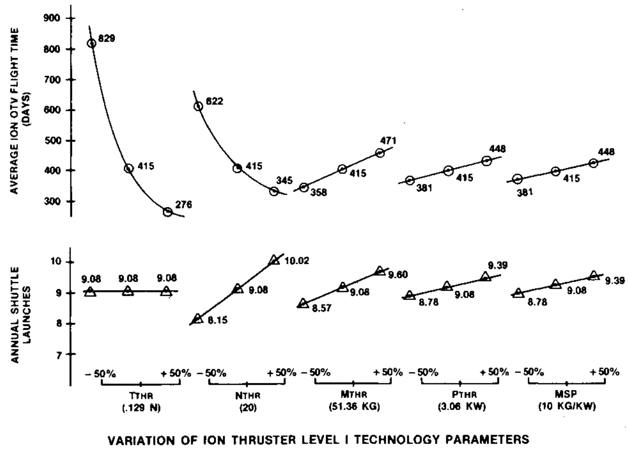

Fig. 6 Sensitivity of Model IV ion thruster parameters.

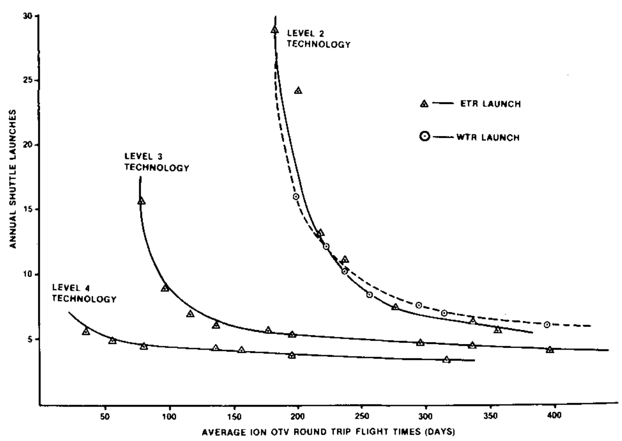

Fig. 7 Launches vs ion OTV flight times: one Model VI SOC.

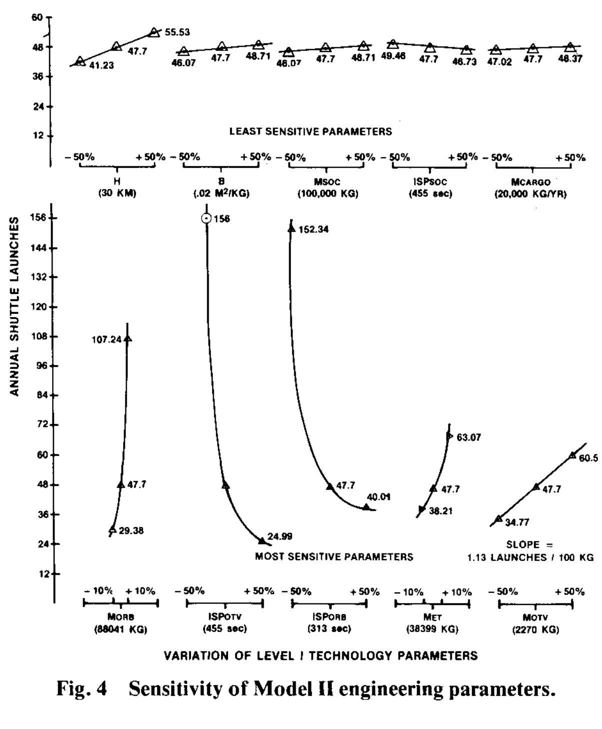

Fig. 4 Sensitivity of Model II engineering parameters.

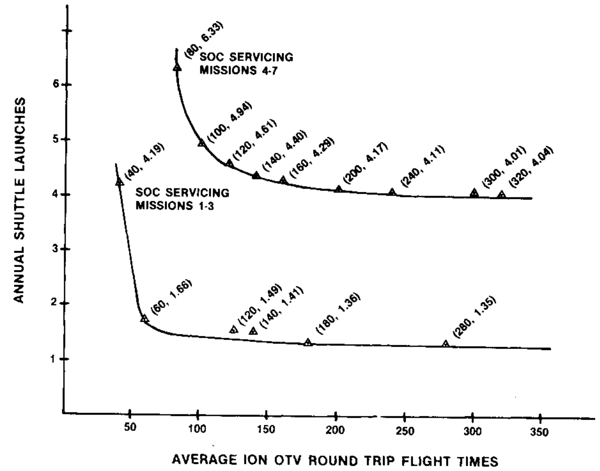

Fig. 8 Launches vs ion OTV flight times: two Model VI SOC's, level 3 technology.

frontier represents a SOC supplied by a WTR-launched Shuttle and is similar to the corresponding curve for an ETR-launched Shuttle. The similarity suggests that with an optimized agumented STS system there is not a great disadvantage to launching the resupply Shuttle from a higher latitude launch site such as Vandenberg AFB.

To further reduce OTV flight times, a dual SOC scenario was analyzed for Level 3 technology. The first SOC deploys missions 1 to 3, while the second deploys missions 4 to 7. Figure 8 depicts the resultant efficient operating frontier with the two ETR-supplied SOCs at 28.5 and 57.0 deg inclinations, respectively. The average round-trip flight time from the low-inclination SOC is only 60 days with 1.66 annual Shuttle launches. Both SOC's can be supplied by only 6.6 annual launches with average round trip flight times of less than 100 days.

Conclusion

The STS augmented by a SOC and OTV appears to offer many attractive advantages over current Shuttle operations. As presented in this paper, the augmented STS could deploy satellites in a manner similar to the OMV currently being evaluated by the NASA. The system's principle advantage is that it utilizes the Shuttle as a cargo vessel consistently loaded to capacity. Further, it eliminates the need for expendable upper stages, including satellite apogee kick motors, and provides a fuel depot or manned orbital platform for the expansion of activities in space. Although not quantitatively evaluated herein, the augmented STS could be utilized as a logistics depot. The SOC would provide facilities for orbital test, repair, and service operations to enhance the reliability and increase the lifetime of satellites in orbit. The evolutionary development of a Factory-to-Orbit test concept may reduce expensive factory and launch base testing. Combined with new satellite designs entailing modular maintenance, system self testing, and simplified hands-on test procedures, personnel in orbit may one day routinely salvage billions of dollars in satellite hardware.

The life cycle costs of such a system include design, orbital support, and launch costs, of which only the latter is estimated by this study. The math models used to calculate rates and associated costs are medium fidelity simulations. Future simulations, whether using optimization or other techniques, need to stress models of higher precision and refine the assumptions used to calculate operational costs. Theoretically, a rigorously derived and executed model would be able to assess the operational costs of an augmented STS accurately. The uncertainty in a high fidelity model would be primarily due to inaccuracies in the assumed satellite traffic model.

Launch costs calculated herein were evaluated for both the LOX/H_2 and ion propelled OTV. The LOX/H_2 OTV deploying satellites below a 65 deg inclination reduces annual Shuttle launch costs by as much as $430 million. Additional economy of scale savings may be achieved by including low-inclination commercial and foreign satellite traffic. Conversely, the annual launch costs may increase by as much as $520 million with the use of more conservative operating assumptions. By deploying the same low-inclination satellite missions, the ion propelled OTV offers annual savings ranging between $320 and $990 million. Perhaps more important, average OTV flight times for existing ion engine technology are potentially below 60 days.

The sensitivity analysis graphically illustrates the criticality of several design parameters. For example, efficiently operating the augmented STS requires an OTV with a high specific impulse and low mass. Conversely, it is unnecessary to design a station with a low mass or to limit the amount of resupply cargo unduly. Both the station and cargo masses must be large to increase the Shuttle launch requirements signficantly.

The models developed in this study have several applications. For the strategic planner, they offer a means of quantifying the utility and cost of various augmented STS configurations. Similarly, computer-aided design offers the engineer considerable insight into efficient buildup strategies and operating modes. With similar refined models, the entrepreneur of the future can assess the financial savings and risks associated with constructing and operating an augmented STS. The veracity of specific cost figures used in this study may be questioned; however, the insight into relative costs and the mathematical tools developed can be useful in the growing national debate over the utility and role of a space station.

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