REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)* 10-06-2006	**2. REPORT TYPE** Technical Paper	**3. DATES COVERED** *(From - To)*

4. TITLE AND SUBTITLE **THRUST AUGMENTED NOZZLE (TAN) the New Paradigm for Booster Rockets (Preprint)**	**5a. CONTRACT NUMBER** F04611-02-C-0001 **5b. GRANT NUMBER** **5c. PROGRAM ELEMENT NUMBER**
6. AUTHOR(S) Melvin J. Bulman (Aerojet)	**5d. PROJECT NUMBER** 484702JT **5e. TASK NUMBER** **5f. WORK UNIT NUMBER**
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Aerojet P.O. Box 13222 Sacramento CA 95813-6000	**8. PERFORMING ORGANIZATION REPORT NUMBER** AFRL-PR-ED-TP-2006-195
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Research Laboratory (AFMC) AFRL/PRS 5 Pollux Drive Edwards AFB CA 93524-70448	**10. SPONSOR/MONITOR'S ACRONYM(S)** **11. SPONSOR/MONITOR'S NUMBER(S)** AFRL-PR-ED-TP-2006-195

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited (AFRL-ERS-PAS-2006-138)

13. SUPPLEMENTARY NOTES

Presented at the 42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Sacramento, CA, 9-12 July 2006.

14. ABSTRACT

Rocket-powered launch vehicles require high thrust when taking off and high vacuum specific impulse (Isp) later in the mission. These two requirements are in conflict since a large area ratio nozzle operating at sea-level pressure is less efficient in producing thrust and the jet may separate from the nozzle causing destructive forces. Aerojet's Thrust Augmented Nozzle (TAN) concept overcomes these conventional engine limitations by injecting additional propellants and combusting in the nozzle. The TAN concept represents no less than a change in the rocket propulsion paradigm. Higher thrust to weight of the engine can reduce the engine weight, which can be traded directly for increased payload. Launch vehicle mission effective Isp can be significantly improved by using TAN to safely fill a high area ratio nozzle at sea level while significantly increasing thrust. The thrust augmenting propellants can be different from the core engine, enabling the benefits of dual fuels on mission performance. Possibly the most important benefit of TAN is increased engine system reliabilities by operating the engine core at a reduced chamber pressure and making up the required thrust by operating TAN. This paper describes the TAN concept, and how it overcomes these classic booster engine problems as supported by test results and a representative simulated mission.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Stephen Hanna
a. REPORT **Unclassified**	**b. ABSTRACT** **Unclassified**	**c. THIS PAGE** **Unclassified**	A	10	**19b. TELEPHONE NUMBER** *(include area code)* N/A

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18

Thrust Augmented Nozzle (TAN): the New Paradigm for Booster Rockets (Preprint)

Melvin J. Bulman[*]
GenCorp Aerojet, Rancho Cordova, California, 95670

Rocket-powered launch vehicles require high thrust when taking off and high vacuum specific impulse (Isp) later in the mission. These two requirements are in conflict since a large area ratio nozzle operating at sea-level pressure is less efficient in producing thrust and the jet may separate from the nozzle causing destructive forces. Aerojet's Thrust Augmented Nozzle (TAN) concept overcomes these conventional engine limitations by injecting additional propellants and combusting in the nozzle. The TAN concept represents no less than a change in the rocket propulsion paradigm. Higher thrust to weight of the engine can reduce the engine weight, which can be traded directly for increased payload. Launch vehicle mission effective Isp can be significantly improved by using TAN to safely fill a high area ratio nozzle at sea level while significantly increasing thrust. The thrust augmenting propellants can be different from the core engine, enabling the benefits of dual fuels on mission performance. Possibly the most important benefit of TAN is increased engine system reliabilities by operating the engine core at a reduced chamber pressure and making up the required thrust by operating TAN. This paper describes the TAN concept, and how it overcomes these classic booster engine problems as supported by test results and a representative simulated mission.

Nomenclature

AR = nozzle area ratio
Isp = specific impulse
GLOW = gross liftoff weight
P = pressure
TAN = Thrust Augmented Nozzle

I. Introduction

Launch vehicle engines must operate at sea level and in near-vacuum conditions. They require high thrust at takeoff when the vehicle is heaviest. Most of the ascent to orbit is flown in near-vacuum conditions. To minimize propellant usage, the vehicle requires as high a mission average specific impulse (Isp) as practical. A high vacuum Isp requires a large area ratio nozzle and hydrogen fuel. These requirements are in conflict since the large area ratio nozzle operating at sea-level pressure is less efficient in producing thrust. This is due to the gases over-expanding to a pressure below the ambient. This results in a portion of the nozzle generating negative thrust as shown in Fig. 1. The exhaust jet will separate from the nozzle at extreme area ratios, causing destructive forces. This problem has been recognized since the 1960s. Mechanical solutions to this problem such as a variable area nozzle and an altitude compensating plug nozzle all would add complexity and weight to the engine while still yielding less thrust at sea level than at vacuum. The current approach is to operate the engine at extremely high chamber pressures to avoid nozzle separation with the largest possible expansion ratio. The ideal engine will have 2 to 3 times more thrust at liftoff than at the end of the mission as shown in Fig. 2 to avoid excessive acceleration loads when the vehicle mass

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[*] Technical Principal, Advanced Development Engineering, Dept. 5276, P.O. Box 13222, Bldg 20019, AIAA Associate Fellow.

is about 10 percent of the liftoff value. This requires deep throttling of the engine that can have performance and reliability consequences.

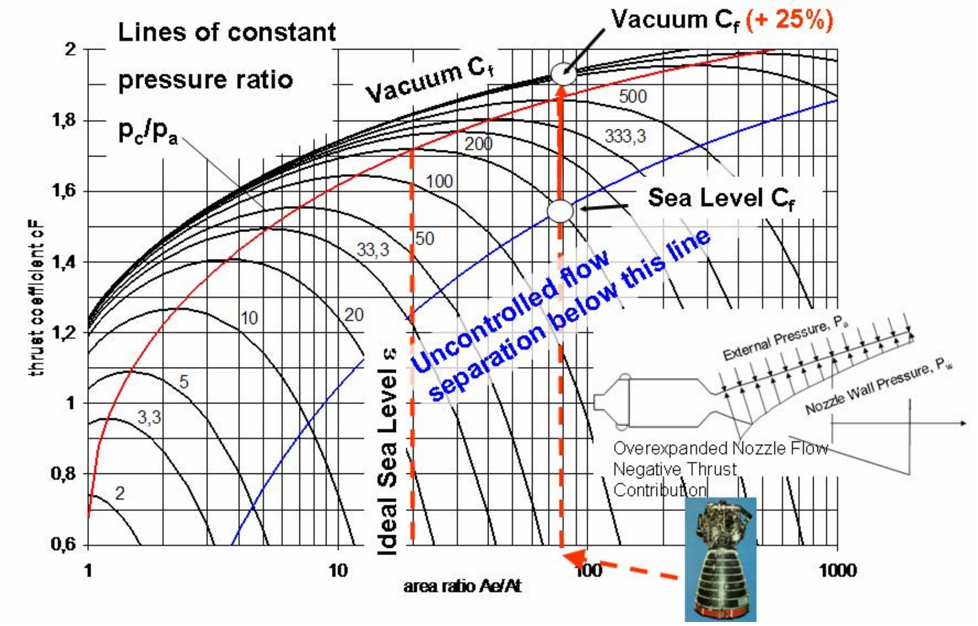

Figure 1. Sea-level operation limits rocket nozzle area ratio.

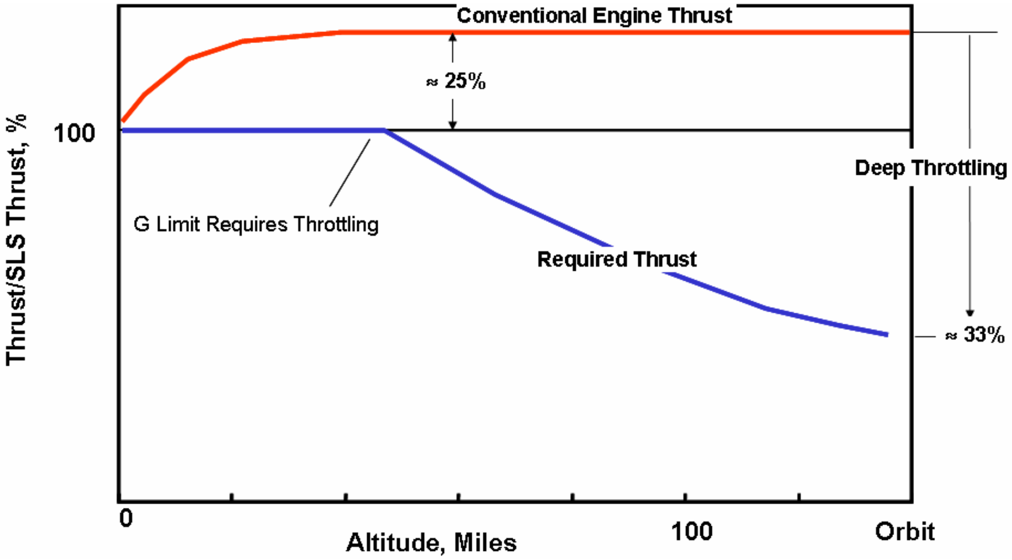

Figure 2. An ideal booster rocket would produce more thrust at sea level.

The high Isp of hydrogen fuel is offset by its low density (4.5 lbm/cu ft). At a mixture ratio of 6:1 with liquid oxygen (LOX), the mean propellant density is only 22 lbm/cu ft. A vehicle that uses a dense fuel such as RP-1 during the early portion of the mission can benefit from mean propellant densities over twice that of a strictly hydrogen fueled vehicle.

Thrust augmentation in the form of an afterburner is in common use in turbojet engines to increase thrust. Jet engine afterburners increase thrust through the addition of fuel downstream of the turbine and to increase the thrust of the engine. However, the augmentation in a turbojet engine is limited by the available unburned oxygen from the main combustor.

Afterburning can also be used in rocket engines through the combustion of propellants injected and burned downstream of the rocket nozzle throat. Aerojet has patented an afterburning rocket called the Thrust Augmented Nozzle[1] (TAN). Figure 3 shows the TAN concept. Fuel and oxidizer are injected downstream of the nozzle throat where they burn to increase engine thrust when it is needed most during the first minute(s) after takeoff. TAN thrust augmentation is virtually unlimited since both fuel and oxidizer are injected. The thrust increase is nearly proportional to the nozzle area ratio. High area ratio nozzles not only allow but also demand high augmentation to fill the nozzle without separation.

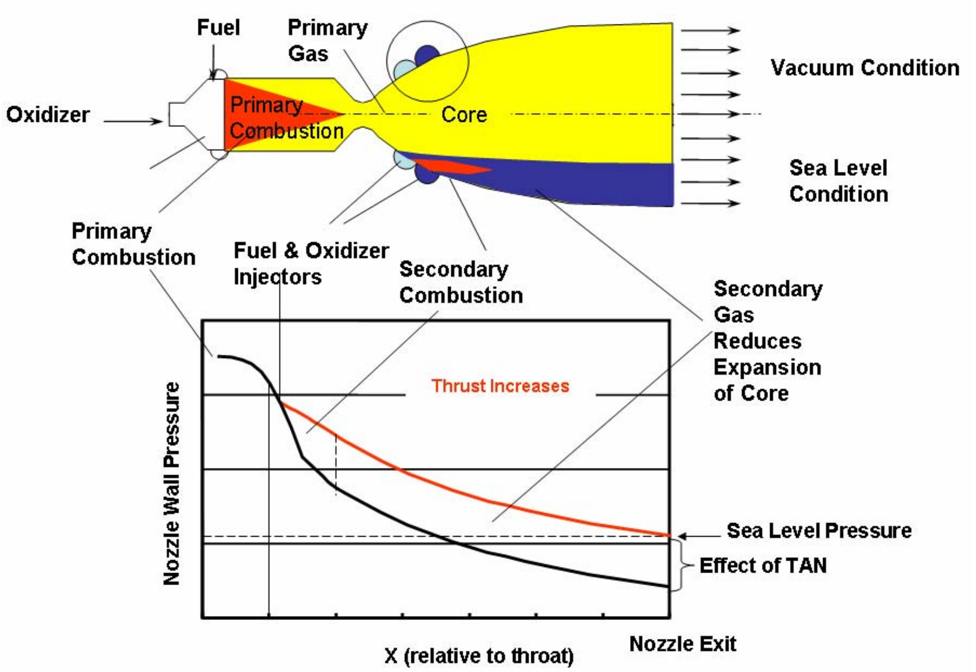

Figure 3. The TAN concept offers large thrust increases at sea level.

Although the potential of the TAN process is very high, it was not obvious that it would work and required demonstration before anyone would be willing to invest in its application. In 2002, Aerojet conducted a successful proof of concept (POC) demonstration with single stage gaseous hydrogen/oxygen injection. The more difficult task was burning liquid RP-1 and LOX in the nozzle. The short residence time and relatively low pressures in the nozzle are not favorable for burning fuels like liquid RP-1. Aerojet has applied the injection and combustion technologies from our Dual Mode Ramjet/Scramjet (DMRJ) programs to this problem. With Aerojet and AFRL funding, we designed and tested a Dual Fuel TAN engine in 2005. Figure 4 shows test firings with TAN on and off. The high combustion efficiency of the RP-1 is evident in the plume color. A typical LOX RP-1 engine has a yellow sooty flame, indicating incomplete combustion with raw RP-1 exiting the nozzle. In our Dual Fuel TAN testing, a purple plume was very similar to those seen in an afterburning turbojet engine. Figure 5 plots the thrust increase measured during a typical dual fuel TAN test.

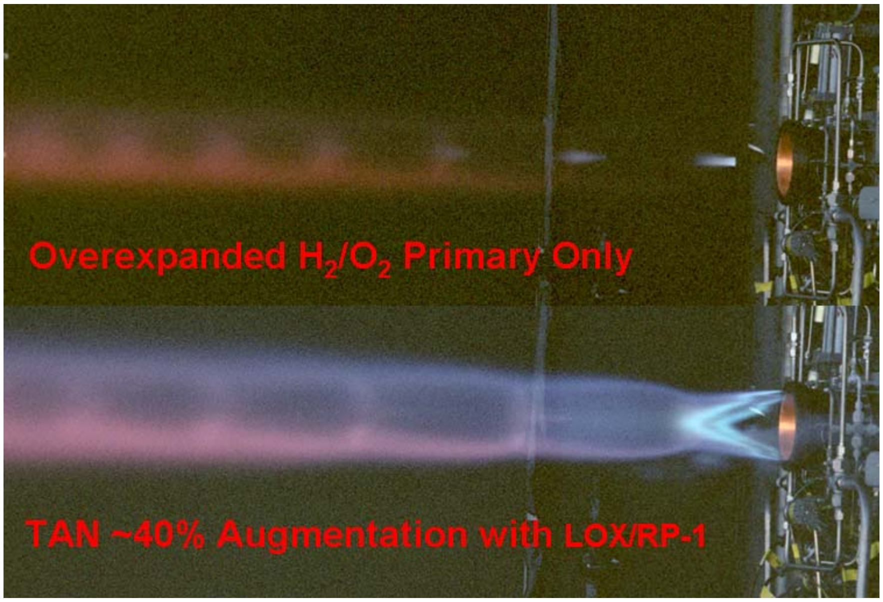

Figure 4. Dual Fuel TAN test firing at Aerojet.

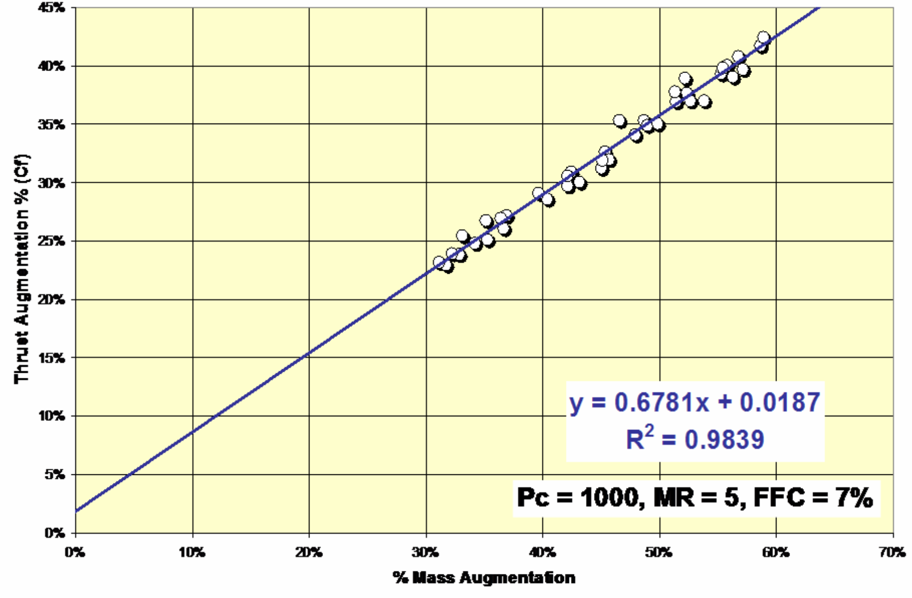

Figure 5. TAN thrust increases over 40 percent demonstrated.

With a dual fuel augmented engine, the force accounting becomes a little more difficult since two different fuels are used that are burning at different pressures. We prefer to treat the TAN augmentation as if it were a separate booster engine that happens to share the same nozzle. When we burn the TAN propellants in the nozzle, we account for the increase in thrust as if were only due to the booster engine. In reality, TAN operation increases the thrust in two ways. First, the additional gases generated by the combustion of the TAN propellants increase the exit thrust of the engine. The second effect is the displacement of the core flow by this secondary flow. The additional gases flowing in the nozzle reduce the exit flow area available to the core reducing the overexpansion losses increasing the core thrust. When both of these thrust contributions are summed, amounting to 40 percent in a typical test, and assigned to the booster function, we realize an effective booster Isp of almost 260 seconds. This is a very respectable value for a sea-level Isp with a RP-1 booster engine. This “booster rocket” lives entirely within the sustainer rocket and has very little weight associated with it. The test facility limited the flowrate of the TAN propellants so the highest thrust augmentation demonstrated was 77 percent with a 500 psia primary chamber pressure.

II. Mission Analysis

A. Baseline Vehicle

We conducted a simple mission analysis to better understand the benefits of the TAN. We selected the single stage to orbit mission as most in need of TAN benefits.

For our baseline, we selected a 2.5 Mlb gross liftoff weight (GLOW) vehicle powered by seven up-sized SSME class hydrogen/oxygen engines operating at 3000 psia. Figure 6 shows the vehicle, which requires a little more than 100,000 cu ft of propellants to deliver 25,000 lb to orbit. Figure 7 shows the trajectory analysis for this vehicle. The orbit we used was 200 nm at 28 deg, the most readily accessible orbit from Cape Canaveral station. The engine has to throttle to 34 percent (3X or 1020 psia) to keep from exceeding the acceleration limits.

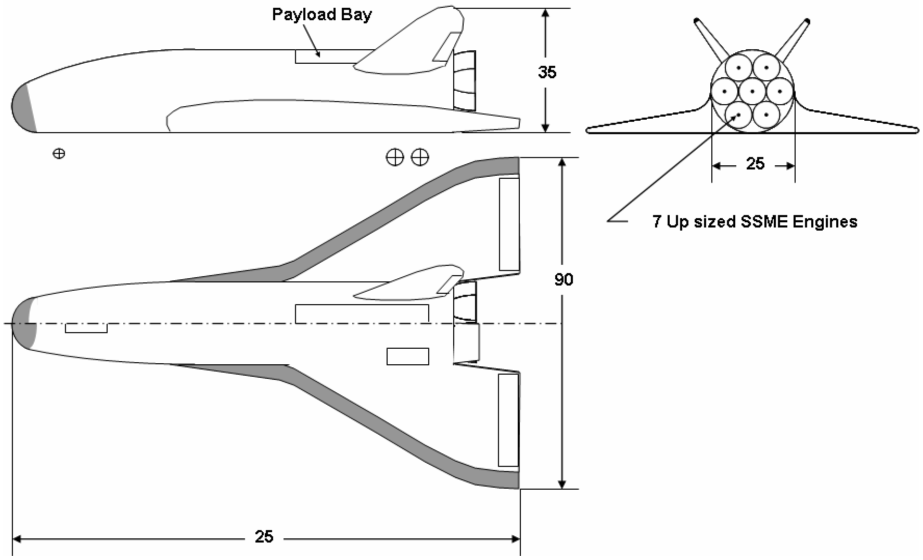

Figure 6. Baseline SSTO vehicle powered by seven up-sized SSME class engines.

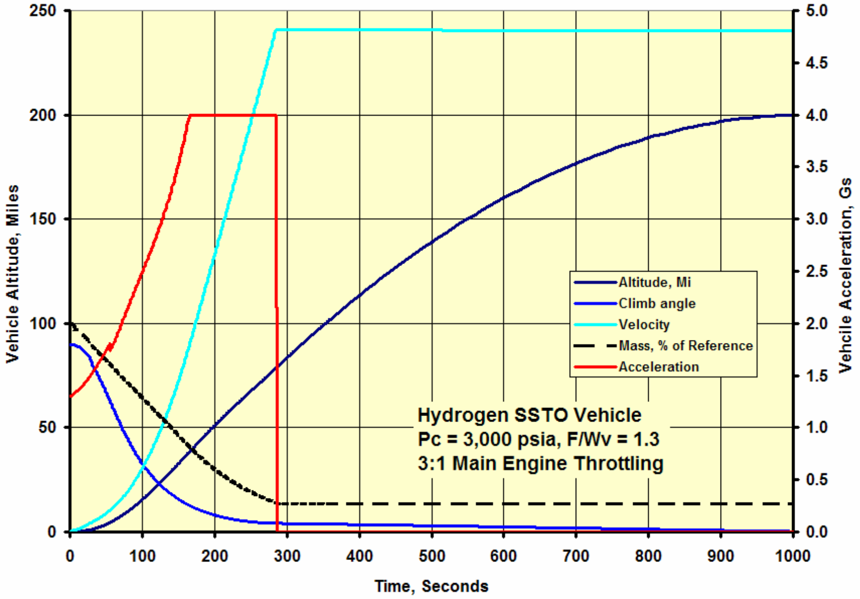

Figure 7. Baseline SSTO vehicle trajectory.

With a payload fraction of 1 percent, it does not take much loss in engine performance or weight increase to wipe out the payload. To see how sensitive the payload mass is to propulsion, we reduced the Pc to 1500 and lowered the engine F/We 10 percent, and lost most of the payload (payload from 25 klbm to 1.7 klbm). It is clear why no one would want to invest in such a risky endeavor.

B. TAN-Powered SSTO Vehicle

For the Dual Fuel TAN-powered vehicle, we kept the same outer mold line and just rearranged the tanks to accommodate more LOX and RP-1. For the TAN performance, we employed our TAN performance model that has been calibrated against both test data and computational fluid dynamics (CFD). For this analysis, we added some additional constrains to the model. The main constraint was the nozzle packaging. In the vehicle in Fig. 6, the base is 25 ft in diameter. With seven tightly packaged engines, we have a total exit area of 55,000 sq inches. We fixed this exit area and adjusted the sea-level thrust by varying the primary area ratio and amount of TAN propellants. We use thrust loading (Fsls/Ae) or TAN flow/primary flow as our primary variables.

Figure 8 shows how TAN flow, area ratio, and thrust loading vary for a primary Pc of 3000 and a secondary effective Pc of 600 psia. This chart can be read in two ways. When thrust loading is fixed, higher TAN flow results in a larger area ratio. When TAN flow is fixed, a higher thrust loading (demand) results in a smaller area ratio. Thrust loading is important since, with a fixed nozzle exit area, the thrust loading directly affect the lift off thrust and acceleration of the vehicle. The nozzle area ratio affects the vacuum Isp. This final interrelationship is shown in Figure 9. Our performance model tracks these constrains and relationships.

The Dual Fuel TAN vehicle changes the picture dramatically. When we run the mission performance model, we specify the initial vehicle thrust to weight (F/Wv) and amount of TAN flow to augment the thrust. The mission is flown and the amount of propellants of each type is tracked all the way to the orbital insertion burn. The GLOW of the vehicle is then iterated until the propellant volume meets the baseline value (101.3K cu ft). Increasing F/Wv or TAN flow increases the amount of RP-1 on the vehicle and vehicle GLOW. Longer booster burn times also increase GLOW but only a limited variation in the booster engine cutoff (BECO) was explored in this analysis. Figure 10 shows a high thrust mission. With about 50 percent of the propellants LOX/RP-1, we can add a million pounds of extra propellant to the vehicle without changing its outer mold line. The vehicle structural weight factors were increased proportional to the higher weight and acceleration loads. The TAN engine produces more thrust but is lighter that the baseline engine. Higher vehicle acceleration reduces the gravity losses more than the drag increased. Since much of the take off thrust is due to the augmentation, the basic (core) engine throat area is reduced, yielding a higher area ratio and higher vacuum Isp where most of the Delta V is generated as shown in Figs. 8 and 9.

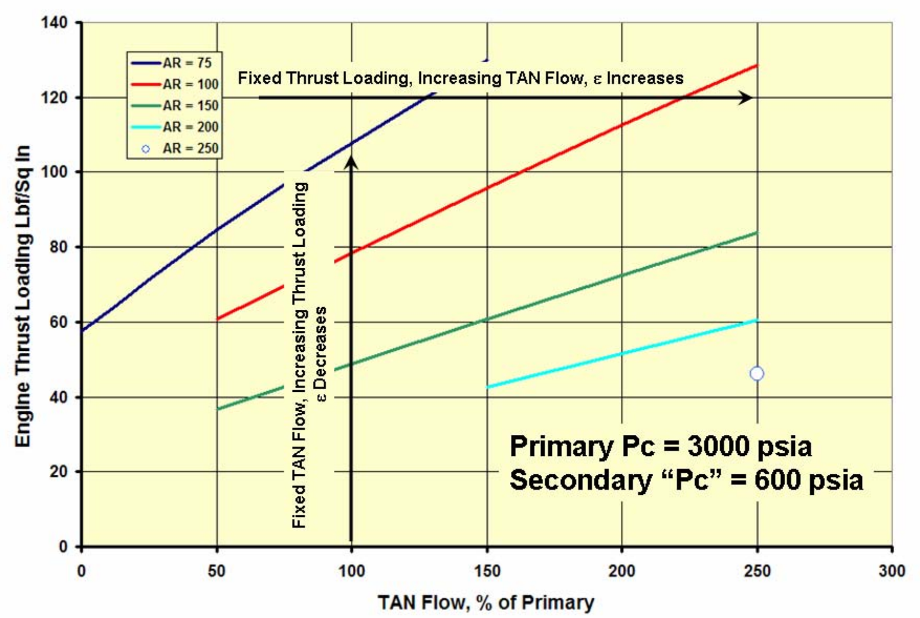

Figure 8. Our TAN performance model relates TAN flow, area ratio, and thrust loading.

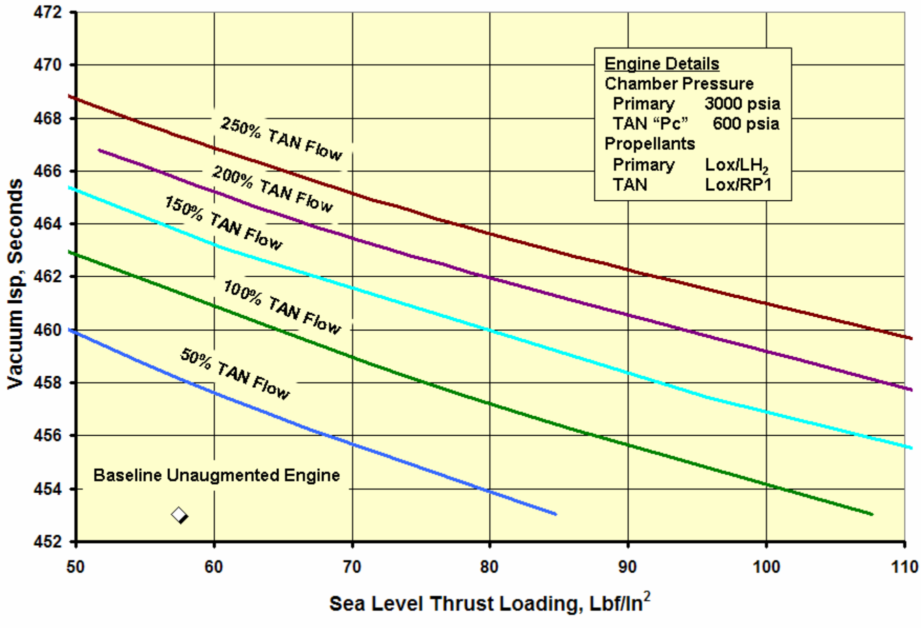

Figure 9. Our TAN performance model relates TAN flow, thrust loading, and vacuum Isp.

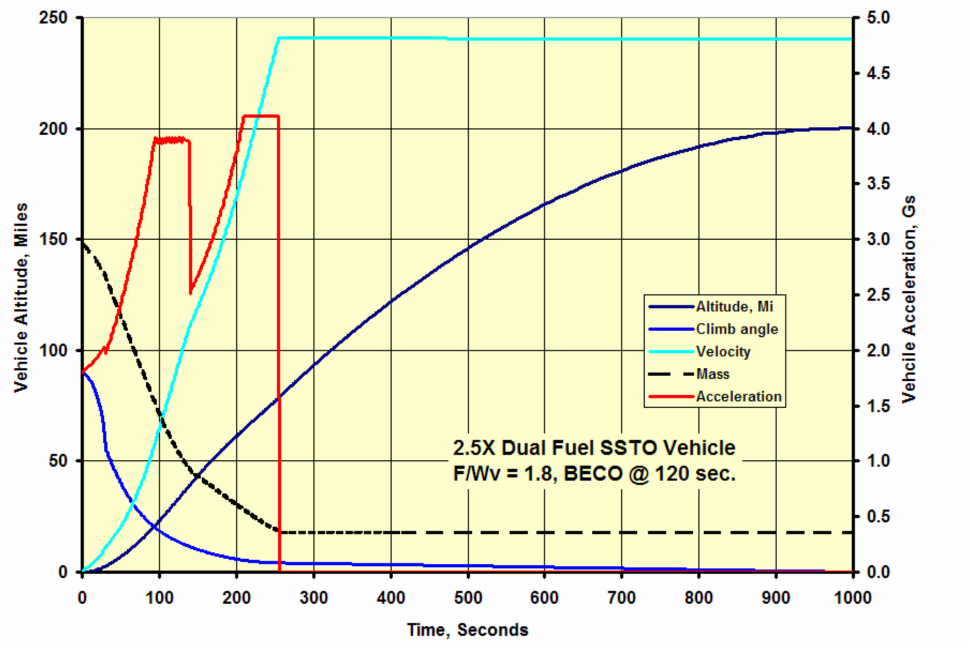

Figure 10. High thrust Dual Fuel TAN mission.

The result is 2.8 times the payload of the conventional high Pc SSTO. Table 1 compares the four optimized cases we ran. Dropping the TAN engine primary Pc to 1500 psia only costs us 16 percent of that large payload where we saw it essentially disappear with the conventional engine. Other benefits accrue with the Dual Fuel TAN. The low Pc TAN engine has a minimum throttle of 72 percent (1080 psia). All of these factors allow a much more reliable and lower cost engine.

Table 1. Mission summary.

	H2 Vehicle		Dual Fuel TAN Vehicle		
	Hi Pc	**Lo Pc**	**Hi Pc**	**Lo Pc**	**Units**
Mission ΔV	29940	30342	28714	29757	Ft/sec
F/Wv	1.3	1.3	1.8	1.5	
GLOW	2500	2500	3696	3642	KLbm
Sea Level Thrust	3250	3250	6652	5464	KLbf
Payload Wt	25	1.7	70.9	59.9	KLbm
Total Tank Volume	101.3	101.3	101.3	101.3	Kcuft
Lox	30.2	30.5	39.3	39.3	Kcuft
Hydrogen	69.9	70.7	51.6	53.2	Kcuft
RP-1	0.0	0.0	9.2	8.8	Kcuft
HC Fraction(mass)	0.0%	0%	50.7%	49.0%	
On Orbit Mass	299.5	274.2	395.2	357.1	KLbm
Mission Mass Ratio	8.3	9.12	9.4	10.2	
Total Tank Wt	49.1	49.6	54.7	55.2	KLbm
Wings, LG, TPS & Str	153.2	141.6	213.9	190.6	KLbm
Sea Level F/We =	45	40	119	106	
Primary Pc	3000	1500	3000	1500	psia
Area Ratio	78.0	40.0	121.0	68.7	
Wt Engines	72.2	81.3	55.7	51.5	KLbm
Mission Isp	438.6	426.7	399.2	398.3	Seconds

C. Other Applications for TAN

The cargo launch vehicle (CaLV) for the Exploration Program is currently envisioned to use five RS-68 engines at the base of a 33-ft-dia tank. If we apply TAN, the number of engines could be reduced to three with an area ratio up to 80 compared to the current 21.5. The takeoff thrust of the three TAN augmented RS-68s could be equal or higher than the five unaugmented engines and the vacuum Isp could be increased as much as 6 percent, increasing payload while reducing propulsion cost by as much as $40M. If pressure-fed Dual Fuel TAN RS-68s are employed, small LOX RP-1 drop tanks could provide even higher payload with minimal cost increase.

III. Conclusions

A new paradigm for booster rockets has been established! The Dual Fuel TAN feasibility has been demonstrated with LOX/RP-1 propellants at 2K thrust level with 28 tests with over 206 seconds of operation. Thrust augmentation up to 77 percent has been demonstrated with excellent performance. Augmentation levels are only limited by the available nozzle exit area and secondary propellant flowrate. TAN-powered vehicles have shown significantly higher performance potential with reduced payload delivery costs for expendable vehicles and 2 to 3 times the payload for reusable vehicles. This greater payload of a SSTO vehicle means we have more payload to trade away before we have a non-viable system even if development uncovers lower performance or increasing weights. This enables SSTO vehicles. Maybe the greatest benefit is the ability to reduce the engine operating conditions for longer life, enhanced reliability, and lower cost engines.

IV. Recommendations

Conduct mid-scale (40 klbf) hot-fire hardware demonstration with multi-stage liquid injection to determine the scaling factors on the injection and combustion process. Initiate large scale prototype engine development. Work with engine and vehicle integrators to incorporate TAN into current and future engine systems to provide the immediate benefits of thrust augmentation.

Acknowledgments

The author would like to thank Aerojet management for the IR&D funding and the USAF AFRL-Edwards personnel for their support in the development of the TAN test hardware and permission to publish this material.

References

[1] U. S. Patent 6,568,171.