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Development of Staged Combustion Aft-Injected Hybrid (SCAIH) Propulsion at Cesaroni Technology Inc

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The stage combustion aft-injected hybrid (SCAIH) motor offers several significant advantages over classical hybrid propulsion, while maintaining beneficial characteristics of both solid and liquid propulsion namely; low residual fuel (1-2%), relatively high performance, and simplicity for thrust vector control. The SCIAH system operates by utilizing an independent gas generator solid propellant, which burn extremely fuel-rich. This warm gas is mixed with a liquid oxidizer in a post combustion chamber analogous to liquid propulsion allowing higher mixing efficiencies to be achieved. Over a three year program an experimental sub-scale SCAIH motor was designed & fabricated at Cesaroni Technology Inc. This paper describes the details of the development through five full hot-fire tests (durations up to 18 seconds) using liquid oxygen. The unique gas generator solid propellant employed with the motor was developed over a series of 66 batches and 127 ballistic tests achieving burn times over 60 seconds. The successful testing of this sub-scale motor clearly showed the feasibility of the SCAIH concept. It demonstrated reliable ignition, stable operation, and a significant increase in performance over typical solid propellants. An additional benefit yet to be realized is the simplicity to which thrust vector control can be achieved since the pivot location occurs at the gas generator chamber where the temperatures are relatively cool (1700^{o}F). This will be demonstrated within the next phase through integration of TVC hardware directly on the sub-scale SCAIH motor presently described.

Nomenclature

AP	=	ammonium perchlorate
CEA	=	chemical equilibrium with applications
CTI	=	Cesaroni Technology Incorporated
GG	=	gas generator
GOX	=	gaseous oxygen
HTPB	=	hydroxyl-terminated polybutadiene
I_{sp}	=	specific impulse
LEO	=	low earth orbit
LOX	=	liquid oxygen
L/D	=	length/diameter ratio
N2	=	nitrogen gas
O/F	=	oxidizer to fuel ratio
SCAIH	=	staged combustion aft-injected hybrid
TVC	=	thrust vector control
SRM	=	solid rocket motor

I. Introduction

There are many issues and difficulties associated with conventional hybrid propulsion, specifically scalability, low-regression rates (< 0.03 in/s), high residual fuel (>10%), and shifting O/F ratio. These issues have plagued hybrid propulsion for decades and have grossly limited their application into large motors and launch vehicles. Due

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to these slow burn rates conventional hybrids have very large L/D and often require complex multi port fuel grains ("wagon wheels") in order to provide sufficient mass flow rates. These grains typically require additional support structure for the fuel grain, adding not only weight but often result in fuel "slivers" being produces which can cause incomplete burning and possible nozzle blockage. This ultimately results in the high residual fuel and a low fuel mass fraction. The classical hybrid fuel regression rate typically reduces in a non-linear fashion when the ports open up, causing shifts of O/F ratio during the burn, which results in a performance loss. Since mixing of the fuel and oxidizer occurs along the fuel grain surface this mechanism is limited through boundary layer interaction. This leads to non-constant mass fluxes and hence varying fuel regression rates along the fuel grain resulting in non-uniform burnout and/or slivers which can potentially lead to nozzle blockage. The Staged Combustion Aft-Inject Hybrid (SCAIH) system overcomes many of these difficulties through its inherent operation and offers a new approach.

II. SCAIH Concept

The SCAIH motor differs compared to classical hybrids in that it uses a fuel-rich solid propellant gas generator (GG) grain instead of a inherit fuel grain. Combustion of this solid GG propellant produces a warm fuel-rich gases (≈ 1700°F), which is then injected/mixed with additional liquid oxidizer in a separate post combustion chamber. The injector process is similar in nature to liquid propulsion systems. Combustion then occurs between the warm fuel gas and the supplementary oxidizer (≈6000°F) and expelled out a nozzle in a conventional manner.

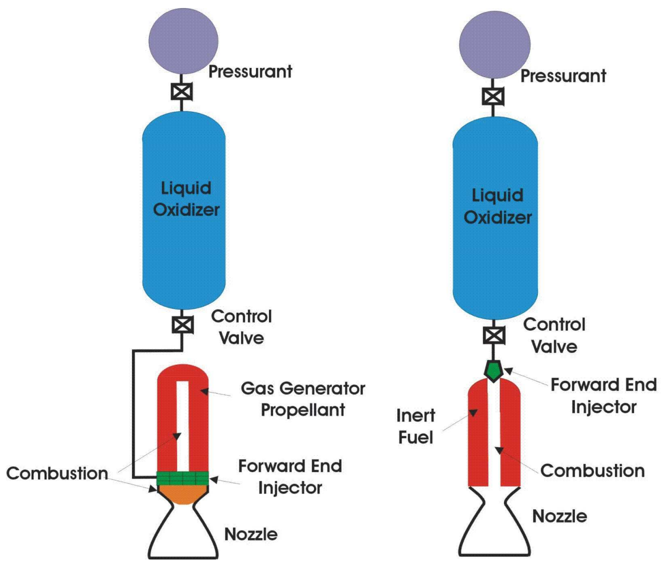

Figure 1. Comparison of classical hybrid system (LEFT) and SCAIH systems (RIGHT)

The unique fuel-rich solid GG propellant is structured to have a minimum amount of oxidizer particles within the grain, which serves two purposes. The first is to achieve the highest fuel rich gas possible in order to maximize the output performance (Isp) when mixed with the additional liquid oxidizer (i.e LOX). The second is to maintain the equivalent safety benefits associated with hybrid propulsion (i.e. storage, transportation, etc). This is achieved because the GG propellant grain will only sustain combustion at an elevated pressure (> 350 psi) and therefore behaves as an non-explosive grain under ambient conditions.

Since the GG grain is a solid propellant with reduced oxidizer it behaves and performs similar to conventional solid propellants (i.e exhibits pressure dominated burn rate operation). Burn rates are significantly higher (0.08-0.24 in/s) than classical hybrids. Additionally because the oxidizer particles are embedded within the solid propellant the decomposition of the fuel is not driven by the boundary layer mixing process so no shifting O/F ratio occurs. This also allows the GG propellant to have scalable and predictable characteristics, which has an immense benefit during motor development as sub-scale testing becomes directly applicable. With the high burn rates and no O/F ratio shift, it allows the fuel grain to have less complex shapes (such as "wagon wheels") and ultimate leads to a drastic reduction in residual fuel (≈ 2%). The combustion of the GG propellant acts independently so the injection process is de-coupled and therefore more efficient liquid propulsion style injectors can be utilized, such as a coaxial shear or swirl injector.

One of the other major advantages of the SCAIH motor system is the simplicity that thrust-vector control (TVC) can be achieved. As the GG propellant has a relatively low flame temperature of 1669^{o}F the material requirements are drastically reduced. This allows pivoting of the post combustion chamber/nozzle assembly upstream of the injector manifold in a similar manner to a liquid bi-propellant system.

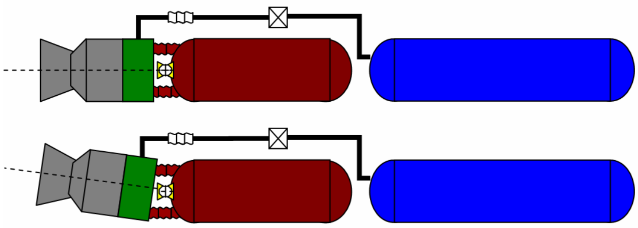

Figure 2. Depiction of thrust vector control for a SCAIH motor

III. Previous SCAIH work

Due to the dominance of solid and liquid propulsion within industry today, hybrid propulsion often appears as a relatively new concept, but classical hybrid propulsion systems have been investigated rather extensively over the last two decades. Conversely the SCAIH system has not drawn much attention. To complicate matter further it has often been referred to under several different names; "gas generator hybrid", "aft-injected hybrid", "staged combustion hybrid", "secondary injection hybrid." The SCIAH system is not a revolutionary concept and has been investigated briefly in the past with a select few cases.

In 1990 NASA funded several hybrid studies under their Hybrid Propulsion Technology Program aimed as a potential replacement for solid rocket booster of the space shuttle. Atlantic Research Corporation was awarded a contract and their study investigated both a classical hybrid system and a gas generator hybrid system (SCAIH). A detailed 314 pg report[1] was completed which focus on the preliminary design of all aspects associated components for both hybrid systems. Actual component hardware was not developed or tested within this study. Additional a life cycle analysis was conducted for both hybrid systems. This cultivated in the selection of the gas generator hybrid cycle (SCAIH).

In 1991 Culver[2] investigate the direct comparison between forward injected (classical) hybrids and aft-injected hybrid (SCAIH). A conceptual design approach coupled with life cycle cost was developed for each and a pump-fed oxidizer system was utilized. The results showed that the forward injected hybrid (classical) had a 25% higher payload delivery costs compared to aft-injected hybrids (SCAIH). Also in the same year Culver and Mueggenburg[3] investigate the application of a vane/platelet injector for use with the gas generator hybrid (SCAIH). This mainly focused on platelet injector itself along with the fabrication process used by Aerojet. The application was reviewed but no formal hardware or testing with a gas generator hybrid was conducted.

In 2001 a program funded by NASA was undertaken to look at the gas generator hybrid (SCAIH) for an upper stage. This work focused on developing two sub-scale test motors (11-inch & 24-inch diameters) with full hardware[4],[5]. The oxidizer selected for these sub-scale motors was 90% hydrogen peroxide with use of a catalyst pack. The initial focus was on the development of the solid gas generator fuel grain, which consisted of AP, HTPB, and PPG with oxidizer levels of 40-70%. This fuel was given a DoT class 1.4c rating and used in "endburner" configurations for the sub-scale motors . Following this, seven hot-fire tests of the 11-inch and four tests of the 24-inch motor was conducted. The results showed good ignition, stable motor pressure, and high combustion efficiency at operational pressures of 200 psi.

IV. Trajectory Simulation

Traditionally there is always a compromise/trade with regards to solid vs. liquid propulsion systems in terms of performance and complexity when applied to launch vehicles. Classical hybrid motors offer a potential compromise between the two, but suffer from additional issues already discussed. The advantages put forth by the SCAIH technology make it ideally suited for the "small" launch vehicles class (payload of 100-1000kg to LEO). When looking into larger class of launch vehicles (payload > 1 ton) the pressure-fed SCAIH system does not trade favorably as the improved performance of a liquid bi-propellant system outweighing the reduction in plumbing and complexity. Given that the SCAIH technology is relatively new concept without any flight heritage, a trajectory simulation was conducted to validate the rational for using it. This simulation focused on a small launch vehicle aimed towards the micro-satellite community (10-150kg payload class). This industry has seen a significant increase in capabilities & productivity but still suffer from a lack of a dedicated launcher. The allure for such a launch vehicle is becoming increasingly more prevalent, and the desire for an indigenous Canadian system has gained substantial interest. For these reasons the approach taken was to define a smaller three stage launcher which uses a common SCAIH motor architecture to help reduce both development time & cost. The nominal mission profile was a 220lbm (100kg) payload to 438 mile (700km) circular orbit as requested by program sponsor (Department of Defence Canada). The launch site for the simulation was based out of Churchill, Manitoba, Canada (latitude = 59^{o}). A trade study was conducted to determine the optimum number of motors to use within each stage. From this it was established the best configuration was to use three identical SCAIH motors within Stage 1, whereas Stage 2 has a single motor (utilizing a larger expansion ratio nozzle). Stage 3 uses a sub-scale version of this common SCAIH motor. This allowed the technology to be designed, developed and tested on the smaller third stage helping reduce the development cost & time.

The trajectory simulation was conducted using a commercial software package ASTOS v5.1.1[6] . This software was produced by the Institute of Flight Mechanics and Control at the University of Stuttgart, in conjunction with the European Space Agency (ESA). ASTOS allows the optimization of 3-DOF launch trajectories for a wide range of scenarios. It has the capabilities of 6-DOF re-entry, orbit transfers, and emergency aborts, however for this application only the conventional launcher trajectories were implemented.

For this preliminary design trajectory the launch vehicle used inputs based on the SCAIH system that would be reasonable obtained in a full motor development campaign. Conservative propellant mass fractions were used for each stage as detailed design/sizing of components is beyond the scope of this simulation.

Table 1. Key parameters for a single common SCAIH motor

Total SCAIH Mass, lbm	7688
GG Propellant Mass, lbm	2714
LOX Mass, lbm	3801
Structural Mass, lbm	1173
O/F Ratio	1.4
Operating Pressure, psi	700
Burn Time, s	113.5
Performance Efficiency	92%
S1 Expansion Ratio	13.8
S2 Expansion Ratio	60

A. Results

From the trajectory simulation the baseline vehicle was first optimized to reduce the overall gross lift-off weight of the launch vehicle while achieving the desired 438mile (700km) orbit with 220lbm (100kg) payload. This resulted in a total launch vehicle mass of 31,837 lbm (14,440kg), with the key parameter for the individual common SCAIH motor shown in Table 1. From this baseline vehicle further trajectory simulations were conducted to determine the maximum payloads available based for different mission profiles as shown in Figure 3. Based on the results of these simulation it clearly showed that the SCAIH concept is feasible for a small launch vehicle as described above.

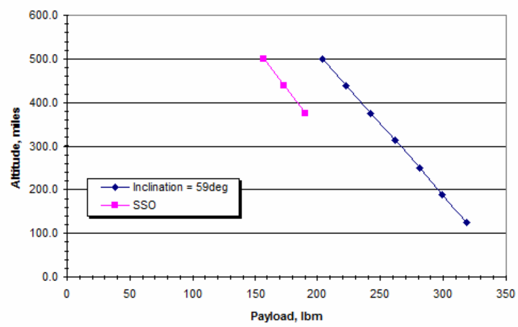

Figure 3. Launch vehicle capablities

V. Gas Generator Propellant Development

The SCAIH is a relatively new concept so in order to evaluate the operation in actual an actual rocket motor a prototype test motor was developed at Cesaroni Technology Inc (CTI). As mentioned previously one of the advantages of the SCAIH provides over classically hybrids is that the system is scalable allowing the sub-scale test motor results & operation to be directly applicable to a full scale motor. Experimental testing was conducted in two parts; independent solid GG propellant testing and secondly a fully integrated sub-scale SCAIH motor.

Perhaps one of the most challenging aspects to the SCAIH concept is with the GG propellant formulation. An initiative was undertaken at Cesaroni Technology Inc over the course of two years to develop this proprietary GG propellant formula. It is based on a traditional ammonium perchlorate/hydroxyl-terminated polybutadiene (AP/HTPB) style solid propellant along with conventional quantities of catalysts, curative, burn rate modifiers, etc. It was tailored to maximize the amount of fuel produced during decomposition, by minimizing the oxidizer content (AP). This was done in accordance to maximize the Isp of the SCAIH system. However a threshold level of AP is still required in order to sustain independent combustion at elevated pressure levels. This key feature allows the safety benefits associated with classical hybrids to be maintained.

Due to the lower oxidizer content (AP), the solid load fraction of the propellant slurry was reduced. As such, the main focus of the GG propellant campaign was to investigate alternative substances for this role that would;

- provide an additional fuel source (i.e. increase system Isp)
- sustain nominal/stable combustion at elevated pressures but extinguish below 300 psi
- provide relatively quick burn rates (between 0.08-0.16 in/s)
- reliable ignition
- satisfactory physical properties associated with propellant mixing, casting, etc

An initial screening of potential candidates was conducted using the standard NASA Lewis computer program CEA[7] (Chemical Equilibrium with Applications). This investigation was focused on narrowing the field of possible candidates based on the performance increase (i.e maximize fuel production of the decomposed GG propellant). Following this, a series of 66 trial propellant batches were manufactured ranging in sizes from 3-330 lbm (1.5-150 kg). This allowed both the physical properties to be evaluated and provided samples for ballistic testing.

These propellant batches were tested/evaluated using five different experimental motors which evolved in complexity and size and was made possible due to the GG propellant scalability characteristics. The primary focus with these experimental motors was to determine the burn rate parameters (pressure exponent & coefficient). As the motors evolved in complexity other key aspects were investigated/reminded such as ignition, residual fuel, scalability, and extinguish characteristics.

Table 2. Summary of ballistic motor used and area's investigated

	Motor Designation				
	S M	**4-M**	**8-AWS**	**12-EB**	**12-M**
Grain Type	EB	BATES	EB	EB	EB
Motor Diameter	5in (127mm)	4in (101mm)	8in (203mm)	12in (305mm)	12in (305mm)
# of Batches	26	13	11	8	2
# of Tests	39	47	49	27	10
Grain Size [kg]	1.5	1.7	1.6-12.5	4.5-28	35
Grain Profile	Stepped Endburner	Center Perforated (BATES)	Endburner	Endburner	Center Perforated (BATES)

A. Results

The final GG solid propellant consisted of a blend of AP (30%-55%), HTPB (15%-35%), fuel additives (10%-40%) and small quantities of curative, catalyst, burn rate modifiers. This final batch formulation was designated GG-CSLV60. From CEA this final batch formulation theoretical properties are shown in Table 3 for both the GG independently and when mixed with LOX for a SCAIH application.

Experimental testing of GG-CSLV60 was conducted in both the 12-EB & 12-M motors. From this, ballistic data shows a traditional burn rate dependence on pressure (Figure 4). The burn rate exponent was found to be 0.71. This is higher compared to traditional high solid loaded AP/HTPB propellant (≈ 0.4).

When investigating the residual fuel, the 12-M motor hardware provides a fair representation of the real world expected residual since the propellant grain profile utilized a center perforated "BATES" grain. During testing it was found that the average residual fuel for the 12-M motor was 2.2% on average with a standard deviation of 0.8%. This is a drastic reduction in residual fuel when compared to classical hybrid systems (typically 8-10%). For completeness the average residual found with the "End-Burn" grain configuration was found to be 2.4% with standard deviation of 1.3%

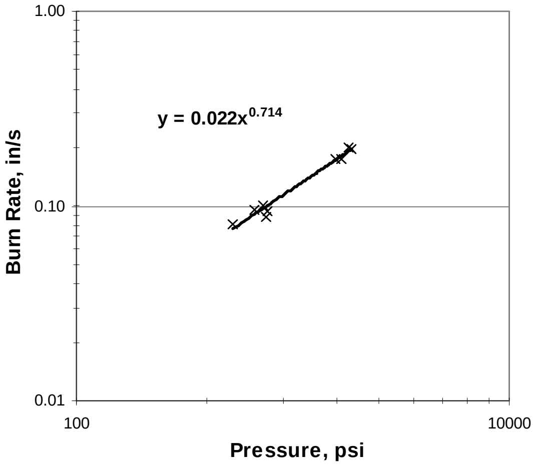

Figure 4. Burn rate data from ballistic testing of 12-M experimental test

One of the main characteristics associated with hybrid propulsion that becomes very appealing is the enhanced safety aspects. In general classical hybrids are perceived to be safer during transportation, storage, and handling since the fuel grain is inert and can be separated from the oxidizer. As described above this GG propellant had a minimum AP content, but a threshold level was still required. To maintain the safety advantage the GG propellant was required to show that it would only sustain combustion at elevated pressures and readily extinguish under ambient conditions. This was demonstrated in two methods. The first was to take a sample of the GG propellant (5in diameter) and expose it to an ignition flame for 10 seconds to allow sufficient time for combustion to occur. Upon removal of the ignition flame it was clearly demonstrated that the propellant extinguished. The second method was to relieve the pressure within an operational motor while undergoing combustion and demonstrate that the GG propellant will extinguish. As can be seen in Figure 5 upon the opening of the relief port the GG propellant immediately terminated combustion. A typical pressure trace from a test using a grain from the same propellant batch is also shown for comparison (slightly lower operating pressure).

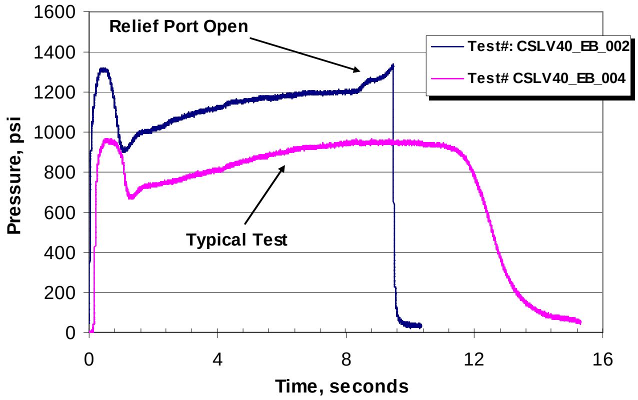

Figure 5. Pressure data using 8-AWS motor when pressure is relieved to ambient

Figure 6. Fuel grain after pressire relief (LEFT) equivalent grain before test (RIGHT)

Due to the success of enabling the extinguishing characteristics under ambient conditions caused the ignition process of the GG propellant to be rather challenging. Throughout the course of this campaign the ignition process evolved in complexity. In the early stages (SM motor) it simply consisted of an igniter squib together with a booster pellet and additional uncured solid propellant paste smeared onto the surface. This evolved with the 4-M motor by replacing the propellant paste with small solid propellant grains allowing greater control since the grain dimensions could be altered. Finally a stand-alone pyrogen igniter with an independent orifice was used where the hot gases generated from the solid propellant were used to igniting the surface of the GG propellant. By utilizing an independent pyrogen igniter (starter cartridge) not only allowed precise control of the grain dimensions but also choked the flow so that the starter cartridge mass flow was unaffected by any variation with the ignition sequence of the GG propellant. Therefore the pressure developed in the GG propellant chamber could be independently controlled/tailored to suit as the GG propellant ramps up in pressure. In the early stages of development there was a slight overshoot as this tailoring process was underway (as evident in Figure 5). With further refinement the ignition process for the final GG propellant formulation was well established and allowed a relatively smooth transition as seen in Figure 7.

As the development campaign progressed and evolved it can also be seen that the burn times were extended substantially with several successfully demonstrated over one minute. As shown in Figure 7 a slight increase in pressure was commonly present near burn out and was more predominant with the "Endburner" configuration motors. This was attributed to the minor settling of the low solids loading AP particles throughout the cure cycle of the propellant possible combined with some coning. Further refinement of the GG propellant, along with improvement to mechanical properties to reduce these minor effects will be conducted in future programs.

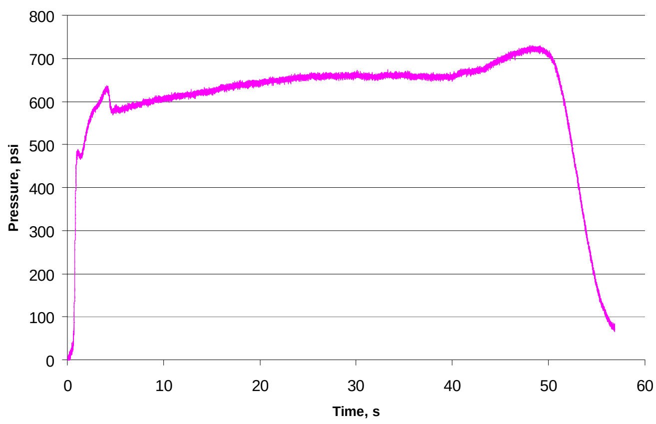

Figure 7. Pressure data from ballistics test of 12-EB motor with final batch formulation

Table 3. Theoretical parameter for solid gas generator propellant (from CEA)

	GG (+LOX)	GG
Pressure [psi]	1000	1000
Vacuum Isp, sec (specific impulse)	316.9	192.8
Sea-Level Isp, sec (specific impulse)	290.4	176.5
c* [ft/s] (characteristic velocity)	5692	3450
Flame Temperature [^{o}F]	6033	1662
Optimum O/F Ratio	1.4	N.A

VI. Sub-Scale Motor and Facility Description

Following the GG propellant campaign, a sub-scale SCAIH experimental motor was designed and fabricated. Since this sub-scale motor is experimental by nature, the components were not of flight-weight status to reduce cost & time, while allowing an increase in margins of safety. As outline in Section III there have been very few SCAIH motors that have ever been developed or demonstrated, and the only hardware tested to date utilized hydrogen peroxide as an oxidizer and operated at a significantly lower pressure (200psi). Due to this, the primary objective of this sub-scale motor was to prove the basic operation of the SCAIH concept using real world hardware. To achieve this, the goals were to demonstrate;

- reliable ignition & shut-down,
- stable combustion,
- operating pressures around 700psi,
- performance output (Isp),

The hardware of the SCAIH motor was based around the existing twelve inch diameter "Endburner" configuration (12-EB) used when conducting the ballistics testing for the GG propellant. This provided the feature to have an adjustable jackscrew in the forward closure to allow different GG propellant grain lengths to be used. The nozzle section of the 12-EB motor is replaced by a manifold where the oxidizer and fuel-rich gas from the GG propellant are fed into. Additional components are then attached to the manifold in a downstream fashion. As described previously due to the unique characteristics of the GG propellant, this option is made possible since the combustion process is de-coupled from the rest of the system. Essentially the fuel-rich gases produced are simply fed into the manifold.

For this SCAIH motor a single full scale injector was incorporated. The injector style selected was a high efficient shear coaxial injector, which is ideally suited given the native presence of a gaseous fuel and liquid oxidizer. A heavy-walled stainless steel combustion chamber incorporating an ablative liner was implemented. The nozzle used was an ablative compression molded phenolic with a graphite throat insert. This nozzle was taken from existing production Pro-150 solid rocket motor produced by Cesaroni Technology Inc to help reduce cost and development time. An under expanded conical profile was used for simplicity and ease of manufacturing.

An earlier systems trade study for the SCAIH concept was conducted and the oxidizer selected was liquid oxygen (LOX). Therefore testing of the sub-scale motor was conducted using LOX and a pressurized feed system analogous to full scale motor and trajectory simulation (Section IV).

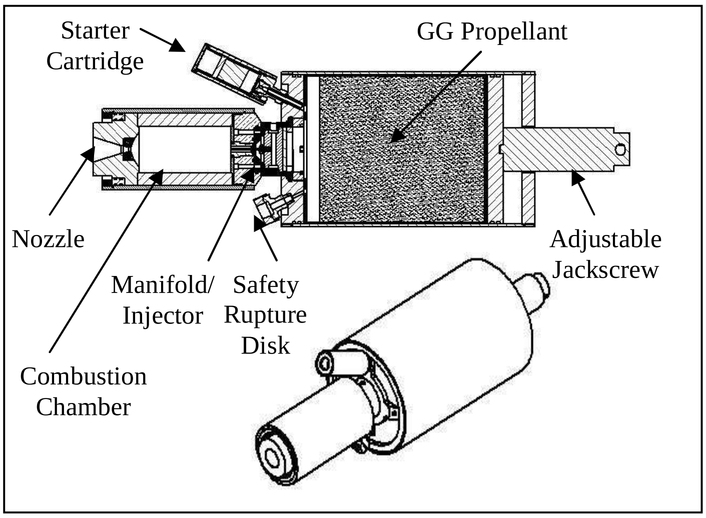

Figure 8. CAD model cross section view of SCAIH motor with describtions of major components

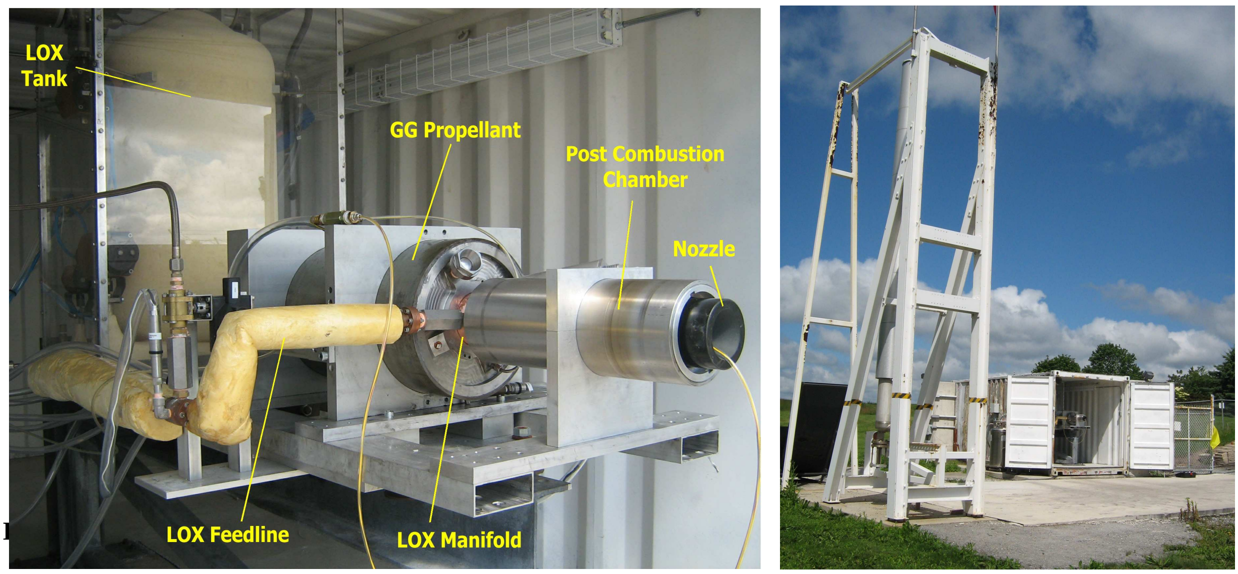

Figure 9. SCAIH motor assembled on thrust stand

The infrastructure for this cryogenic oxidizer feed system had to be designed, fabricated and developed in parallel under this program. A 16 inch diameter LOX tank with a 27.5 gal (104L) capacity was fabricated in-house and insulated with a polyurethane spray foam specific for cryogenic applications (BX-265). All plumbing lines were also insulated with this spray foam for thermal loss reduction. The oxidizer feed system is designed for a maximum operating pressure of 1000psi, which is limited through the pressure relief valve setting. The LOX is supplied in standard 118 gal (450L) Dewar containers. The LOX tank is filled from the supply Dewar at low pressure through a flexible vacuum insulated line. The tank incorporates a guided wave radar level sensor (Magnetrol Eclipse Model-705) which is used to monitor both the amount of LOX during the filling procedure and also to determine mass flow of LOX during operation. Pressurization of the tank is accomplished through a supply of three high pressure gaseous nitrogen bottles, with regulators set to associated test conditions. Another high pressure nitrogen tank is used to purge the lines during motor operation. A separate low pressure nitrogen purge (5 psi) is also fed into the plexiglass container housing the LOX tank to evacuate it of ambient saturated air to avoid ice build up. A schematic of the plumbing architecture is shown in Figure 11. All valves are pneumatically actuated and operated remotely by a programmable logic control unit. This PLC unit also activated the ignition sequence and all pre-determined sequencing of the valves eliminating human interaction (Figure 10). The SCAIH motor was tested in the largest of three thrust stands available at Cesaroni Technology (30,000lbf capacity) as it allowed for semi-permanent installation during the testing campaign. The facilities incorporated a 16 channel DAQ card operating at a sample rate of 1000 Hz. During SCAIH motor testing, one channel was used for measure axial thrust, a second channel was used to measure the LOX tank level, and five channels were used to monitor pressures (LOX tank, LOX inlet line, starter grain cartridge, GG propellant chamber, and the post combustion chamber). All pressure transducers were piezoresistive style. Both the LOX tank and line pressure used a specific cryogenic pressure transducer (with a higher level of accuracy +/- 2 psi) whereas the other three used a lower cost transducer (accuracy of +/- 6.25psi).

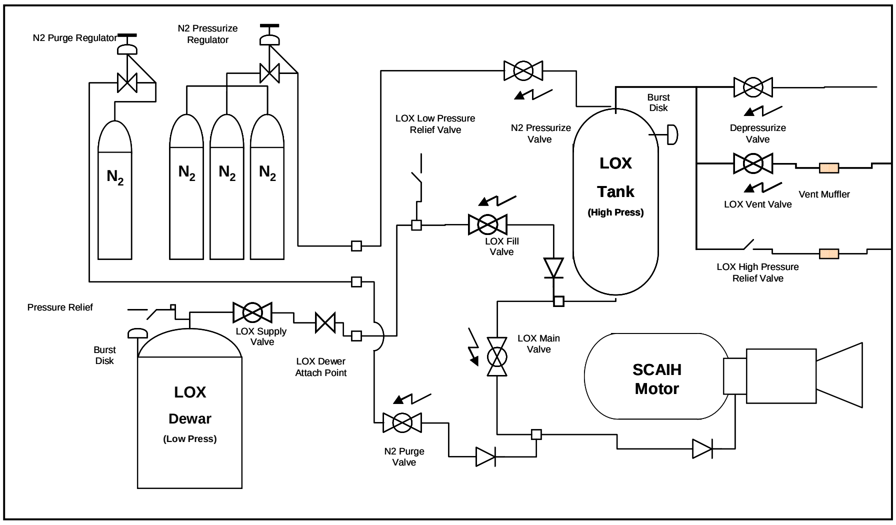

Figure 11. Schematic of oxidizer feed system (LOX)

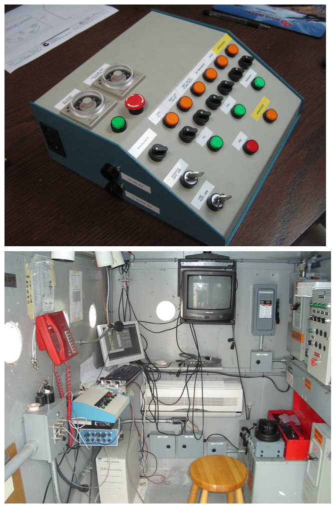

Figure 10. Programmable logic control unit (top) remote concrete bunker control room (bottom)

A. Experimental Testing Sequence of Events

Once all the appropriate hardware components are assembled for the SCAIH motor and connected to the oxidizer feed system a sequence of events occurs before (Pre-Test) and during a test session. For all tests conducted an oversized GG propellant grain is intentionally employed to allow independent combustion of the GG propellant to occur both before and after the introduction of the LOX flow. The GG propellant is allowed to burn for approximately 4-8 seconds prior to introducing the LOX flow (discussed in further detail in Section VII)

Pre-Test	
a) LOX Tank Chill	(12-15 min)
b) LOX Tank Fill	(3-5 min)
c) Chill lines & manifold	(90 s)
d) Line purge with N_2	(3 s)
e) Pressurize LOX Tank	(2-3 minutes)

SCAIH Motor Test Fire:	
i) Starter grain cartridge ignition	(@ 0 s)
ii Starter cartridge burnout	(@ 4 s)
ii) GG propellant combustion	(Duration = 4s-8s)
iv) Main LOX valve open	(Test duration = 9s-18 s)
v) Main LOX valve close / N_2 Purge	(until GG burn out)

VII. Results

A total of five SCAIH motor tests were conducted and allocated for this program (along with a preliminary inert test using liquid nitrogen (LN2) instead of LOX). This preliminary test using LN2 allowed investigation into all the sequencing of events and establishing flow rates and injector parameters. As outline in Section VI the goal with this experimental motor was to prove the SCAIH concept and demonstrate reliable ignition, stable combustion, and output performance. The primary focus of the first test using LOX was to simply demonstrate the feasibility of the SCAIH concept when mixing it with the fuel-rich gas. Following this inaugural test, modification to the testing facilities/parameters was conducted incrementally to improve on the SCAIH general operation.

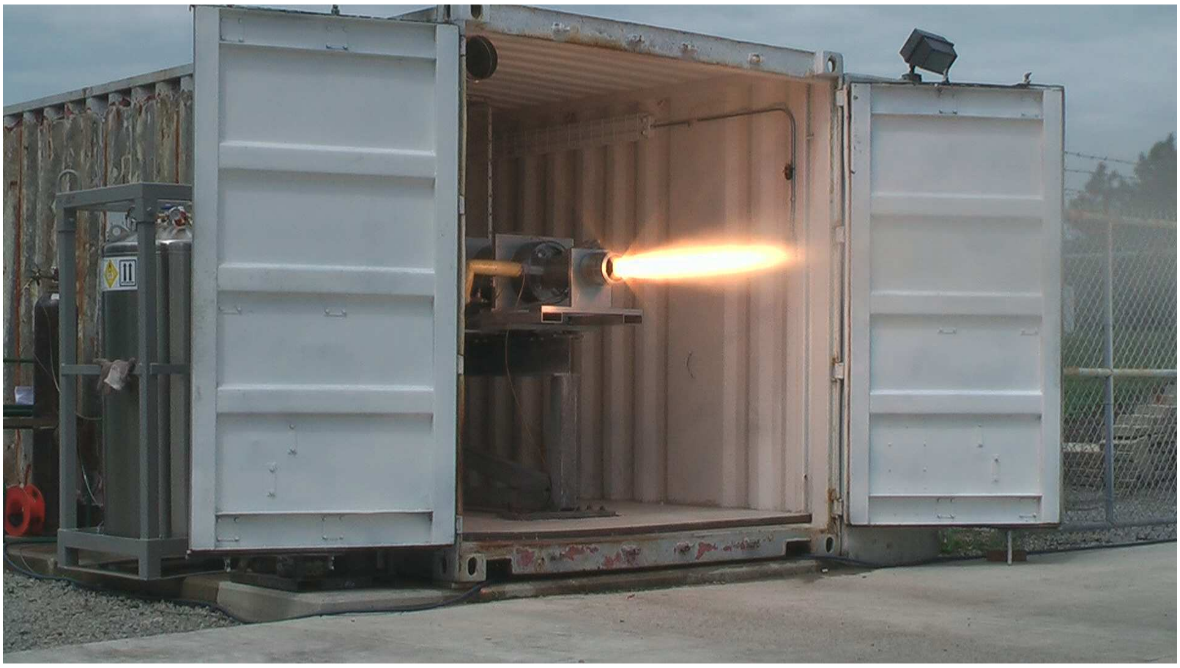

Figure 12. Testing of sub-scale SCAIH motor (Test #3)

A. Test #1

Given the novel aspects of the motor, the main goal with Test #1 was to demonstrate reliable start-up/shut-down of the motor and investigate the sequencing of events. For this reason, the duration of LOX flow for this initial test was limited to 9 seconds. Given the unknown nature of the GG propellant gases when mixed with LOX, a secondary igniter was placed within the post combustion chamber to ensure combustion, (also used during Test #2). This small secondary igniter consisted of a typical solid propellant grain in an "Endburner" configuration which housed its own insulator sleeve ensure linear burn profile. The grain was bonded to the faceplate insulator and ignited in unison with the starter grain cartridge. It was designed to burn for 12 seconds ensuring ignition between the fuel-rich gas and the incoming LOX flow. The additional mass flow from this secondary igniter was negligible (0.4% of total mass flow).

Ignition of the solid GG propellant by the starter grain cartridge was nominal, as previously predicted through the GG propellant development campaign. The starter grain cartridge burnout occurred 4.6 seconds after ignition allowing sufficient time for the GG propellant surface to ignite are reach steady-state pressure. The main LOX valve was opened 8.6 seconds after ignition of the GG propellant. Immediate combustion between the fuel-rich gas stream and the liquid oxygen was observed. There was a 3.3 second delay before full operational pressure was reached within the post combustion chamber. The main LOX valve was closed at 17.7 seconds and as can be seen in Figure 13 combustion between the fuel-rich gas and LOX was terminated. The GG propellant continued to burn until approximately 25.7 seconds as intended with a tail off extending until 30 seconds as nominal. A pressure drop of approximately 100 psi occurred during the test, which was caused by nozzle erosion. Upon post inspection, the nozzle throat diameter had eroded significantly (see Table 5). With a relatively small initial throat diameter this erosion translated to a dramatic impact on the post combustion chamber pressure. As can be seen the overall results were very encouraging from the inaugural test of the SCAIH concept. The motor demonstrated proper ignition and shutdown as expected. The motor exhibited no apparent un-stable combustion and steady-state pressure was reached within a reasonable time period. The post combustion chamber pressure showed oscillations of +/- 3.3% which is within the 5% suggested for stable combustion[8],[9,],[10]. It should be noted that acoustic high frequency combustion instability may still be present as the pressure data could only be captured at 1000Hz due to the limitations of the testing facilities. Investigation into a full combustion instability analysis would be required in future development as the motor parameters are refined and improved. For the purposes of this phase within the program (and this paper) the combustion stability will be broadly assessed based on the chamber pressure oscillations data collected.

A few minor changes were implemented to the facilities to improve the testing conditions. First it was observed in Test #1 that the tank pressure was increasing (+78 psi) as a result of the high pressure nitrogen valve remaining open throughout the operation. This conversely resulted in the LOX mass flow increasing slightly during the test. For all subsequent SCAIH motor tests this sequence was modified so the valve remained closed allowing the LOX tank to operate in a blow down scenario. Given the oversized tank ullage available this change resulted in a more uniform tank pressure with an obvious slight decrease due to consumption of LOX. A second modification was made to increase the duration of the line chill sequence in the pre-test operations from 30 to 90 seconds. It was observed that the chill sequence duration was not long enough to ensure that thermal equilibrium of the manifold, injector, and lines was reached. This change was done in an effort to try and minimize the delay for pressure build up within the post combustion chamber once LOX flow was initiated. This increased chill duration would assist in providing a more uniform LOX flow transition upon opening of the valve as it will help minimize the brief two phase flow (GOX/LOX) within the inlet line.

B. Test #2

Following the success of Test #1, the primary goal of the next SCAIH motor test was to determine the Isp performance output and to extend out the LOX flow duration (15 seconds) to investigate heat loads. Additionally, it was desired to slightly increase the post combustion chamber pressure closer to the define SCAIH operational level (700 psi) therefore the nozzle throat diameter was reduced (see Table 5).

As can be seen in Figure 14, there was a significant ignition delay of the GG propellant. The cause of this was likely due to the extended line chill sequence. This modification allowed cool gases to travel onto the GG propellant chamber for a longer period which cooled the propellant surface before ignition. As with any typical solid propellant and well documented, temperature affects both the burn rate and the ignition, and this characteristic would become more pronounced for a fuel-rich propellant such as this. Given the relatively short exposure of the cool gas the thermal gradient within the grain would be small therefore only the surface of the propellant would be adversely affected, resulting in the ignition delay experienced. The GG propellant did reach full operational pressure at approximately 5 seconds after ignition which was before the LOX was introduced (@ 9 seconds) so the overall effect on Test#2 is negligible. As with Test #1 a secondary ignition source was still placed within the post combustion chamber to ensure ignition.

With the modification to the nitrogen pressurization previously discussed the tank pressure drop resulted in a significantly less change then the Test #1 (-12psi vs +78 psi). This allowed the LOX mass flow to become more uniform as seen with the data from the LOX tank level sensor. As can be seen the motor still operated successfully and demonstrates good combustion stability. Again a significant pressure drop in the post combustion chamber was still apparent due to nozzle erosion (see Table 5). Due to this pressure drop the mass flow of both the LOX and the fuel-rich gas varied slightly throughout the test altering the O/F ratio which ultimately affects the performance. For this reason a maximum value for the specific impulse (Isp) will be reached throughout the test as the chamber pressure and O/F ratio conditions are balanced to optimum point for the specific test. To determine this, the instantaneous specific impulse was evaluated throughout the burn. Thrust was obviously directly measured, whereas the GG mass flow could be determined from the burn rate exponent & coefficient (previously established in Section V) combined with the pressure data measured within the GG chamber. This evaluated GG mass flow was validated and correlated against the measured mass of the GG propellant grain before and after the testing. The LOX mass flow was determined from the level sensor data and tank pressure. The additional small inert contribution due to the consumed ablative insulation was also accounted for based on a time average ablation rate. For this test the maximum specific impulse was found to be 242 seconds at approximately 550 psi.

C. Test #3

Based on the success of the previous tests the next two goals were to eliminate the secondary igniter and attempt to reduce the amount of nozzle erosion. Given the confidence in the previous tests, the LOX flow duration was extended even slightly further to 18 seconds.

Given the warm temperatures (1200K) of the fuel-rich gas produced from the GG propellant, spontaneous combustion with the incoming LOX stream was expected Earlier in the program development, an independent experiment was conducted that demonstrated using gaseous oxygen. For Test #3 the secondary igniter was removed while all the injector parameters remained the same. It was observed that immediate ignition occurred upon the opening of the main LOX valve. When looking at Figure 15, there was an immediate response (rise in pressure) and no significant delay in ramp up with the removal of this secondary igniter. This has immense benefits for the SCAIH motor system since it significantly simplifies the entire start-up sequence and greatly improves its reliability.

In effort to reduce nozzle erosion a different grade of graphite was implemented for the throat insert. This grade of graphite was used in previous programs developed at Cesaroni Technology Inc and had demonstrated superior erosion characteristics for solid propellant motors and reduces cost. However the results from Test #3 showed the nozzle erosion was actually worse (see Table 5). As can be seen in Figure 15 there is a dramatic pressure drop in the chamber pressure (approx 200psi), which was clearly due to the large change in throat area from erosion. Additionally this pressure drop causes a change in the O/F ratio as the oxidizer delivery system experience less back pressure. This in turn amplified the nozzle erosion with the excess oxygen available to form carbon oxides. Coupling this factor with the extend burn time of 4 seconds resulted in the drastic nozzle erosion experienced. It was also noticed upon post inspection that a significant amount of heat transfer was directed back towards the injector faceplate. Given the large variations in combustion chamber pressure and the LOX mass flow this is not unexpected since the mixing process would be significantly altered throughout the operation. In a similar fashion to Test #2 the maximum specific impulse was found to be 242 seconds at approximately the same 550 psi chamber pressure.

As mentioned above during Test #2 there was a delay in the GG propellant ignition caused by the cool gas during the chill sequence. To mitigate this problem a slight modification to the hardware was implemented, which consisted of placing a thin wax membrane over the entrance to the manifold from the GG propellant. This wax membrane simply eliminates the cool gases produced during the chill sequence from entering the GG chamber and is instead re-direct out the nozzle. As can be seen in Figure 15-17 this GG propellant delay was eliminated with this modification. This thin wax membrane is consumed rapidly within milliseconds of ignition and the mass contribution is negligible (0.01%).

D. Test #4

During the weeks between Test #3 and Test #4 the facilities at Cesaroni Technology Inc experienced an unexpected power surge. This unfortunately resulted in the loss of three pressure transducers (starter grain, Post CC, and GG Pressure). These pressure transducers were discontinued from the manufacturer and as a result had to be replaced with an alternative style. Unfortunately the replacement had reduced accuracy of +/- 12.5psi compared to the previous +/- 6.25 psi. This is the explanation for the increase in pressure fluctuations seen in the data Figure 16 & Figure 17 and is not a result of actual motor pressure fluctuations, combustion stability, or modifications.

Based on the results of Test #3 a few parameters were modified. Firstly the LOX tank pressure was increased in effort to bring the post combustion chamber pressure up to the desired 700 psi operational level. Next the time delay between ignition and opening of the main LOX valve was shortened (to 3.9 seconds) compared to previous tests. This was done in part for two reasons. The first was to demonstrate a shorter start-up sequence is capable as typically seen in a full scale application, and was deemed possible given the previous three tests conducted. The second reason was due to the fact that the GG propellant grain was slightly shorter (strictly due to post machining/manufacturing of the propellant grain). Since the grain was shorter, the total burn time available for the GG propellant itself was shorten. Therefore by introducing the LOX early allowed for the full 18 seconds of LOX flow to be realized as in Test #3. A finally modification was made to the injector dimensions in order to slightly lower the initial O/F ratio. The LOX injector post dimension remained the same however the fuel-rich gas orifice area was decreased by 11.7%. This was done in order to minimize the compounding effect once nozzle erosion throughout the test occurs.

The same graphite throat insert material in Test #3 was again used in Test #4 given the fact that previous heritage data all indicate it's will be a superior graphite for use in this application. As can be seen in Figure 16 the initial chamber pressure was successful in achieving the desired 700 psi level. Stable combustion is still shown (despite the poor quality pressure transducers). The shorten start-up sequence behaved nominal with the pressure ramp up rate in the post combustion chamber being equivalent to the previous tests. As with all previous tests excessive nozzle erosion was present (Table 5), which resulted in significant chamber pressure drop. The slight change in injector parameter was successful in lowering the start-up O/F ratio (by 0.2) compared to Test #3 and appears to have slightly mitigating effects on the erosion in the early portion of the burn. For this test the maximum specific impulse achieved was higher at 256 seconds due to the higher chamber pressures (700 psi). Also similar to Test #3 a large heat flux onto the injector faceplate insulation was noted during disassembly, which again was likely caused by the off-design operation of the injector mixing (i.e O/F ratio change)

E. Test #5

A fifth test was conducted with the principle purpose to complete the program deliverable of demonstrating the SCAIH operation. The LOX flow duration was shortened slightly to 14 seconds to collect data on the erosion rate and heat loads earlier within the burn. All the conditions were set equivalent to Test #4 with the exception that the main LOX valve was opened later into the test as was done in Test #1-3 (since ample GG propellant burn time was available). The results of Test #5 were very similar to Test # 4 as expected. The maximum specific impulse for this test was found to be 257 seconds again at approximately 700 psi. Table 4 gives a comparison to production motors currently used by launch vehicles and as can be seen the SCAIH does provide a significant improvement over typical solid propellants.

Table 4. Specific impulse comparison of SCAIH with typical solid and liquid (RP-1) propulsion

Motor/Engine	Type	Launch Vehicle	Delivered Isp @ Pressure		
			Sea-Level [s]	Vacuum [s]	Avg Pressure [psi]
SCAIH Test Motor	SCAIH	N/A	257	284	700
SRB [11,12]	Solid	Space Shuttle	237	269	620
UpAerospace (Ø=10in)*	Solid	Spaceloft XL	237	259	856
Castor 120 [12,13]	Solid	Taurus, Athena	N/A	280	1246
RD-107-11D511 [11]	Liquid	Soyuz	256	313	860
RD-180 [11]	Liquid	Atlas V	311	338	3800
Merlin 1C (SpaceX) [14]	Liquid	Falcon 1 & 9	275	304	982

* Motor developed at CTI for Spaceloft XL sounding rocket program and tested under same equipment/conditions as SCAIH motor

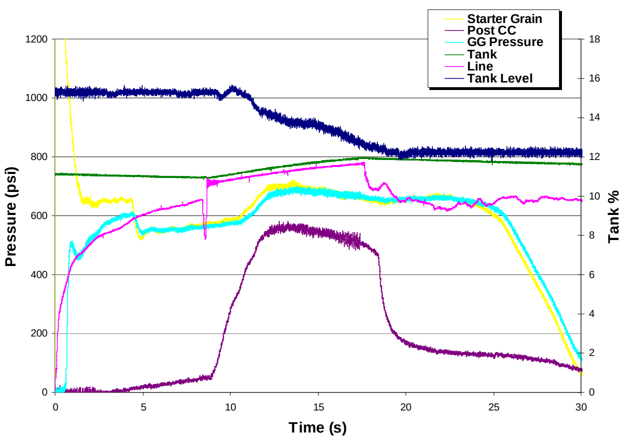

Figure 13. Sub-scale motor data from Test#1

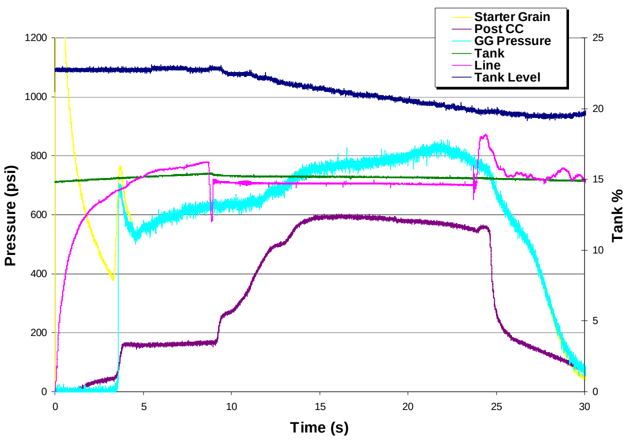

Figure 14. Sub-scale motor data from Test#2

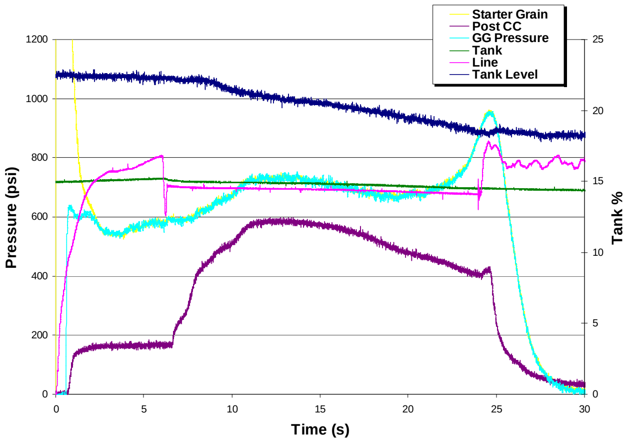

Figure 15. Sub-scale motor data from Test#3

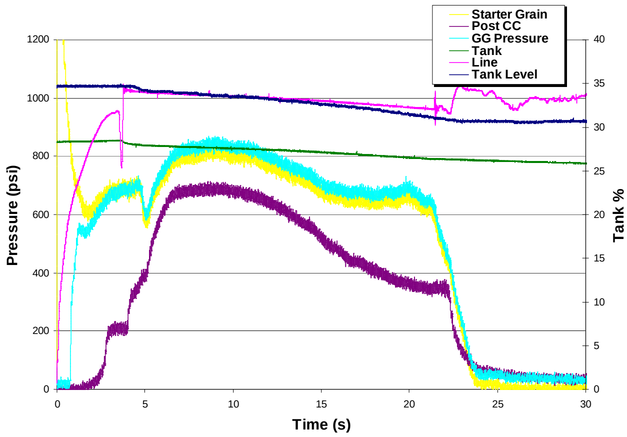

Figure 16. Sub-scale motor data from Test#4

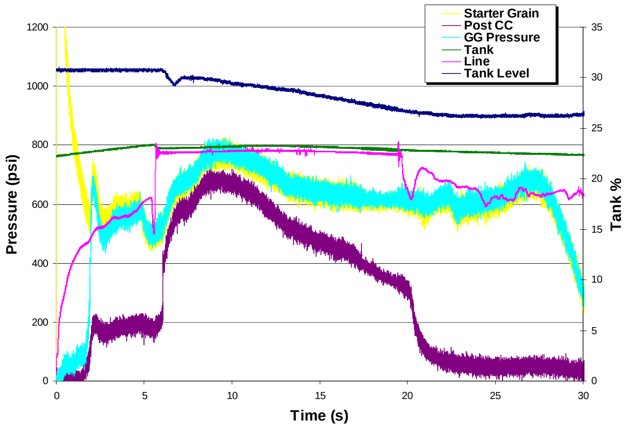

Figure 17. Sub-scale motor data from Test#5

F. Nozzle Erosion

As previously described, all five tests conducted experienced a significant amount of nozzle erosion. As mentioned in Section VI the nozzle employed for the SCAIH motor was leveraged off existing hardware used at CTI due to cost constraints and development time. This nozzle draws its heritage from a 6-inch diameter solid propellant production nozzle. Theses production nozzle experiences much shorter overall burn times (approximately 5 seconds) and has larger initial throat diameters. Therefore the negative influence of nozzle erosion for these production solid propellant motors is significantly less compared with the long burn time SCAIH motor.

Existing ablative materials (such as carbon/carbon composites) are already available for nozzle applications which experience more sever conditions than the current SCAIH motor. The primary restriction why these materials were not initially implemented for the sub-scale motor was strictly due to budgetary concerns. Conversely developing a cooled nozzle could also be conducted in the same effort. This was beyond the scope of this initial phase of development for this program. Given the similar nature of this SCAIH motor to a traditional liquid bi-propellant scheme, developing a nozzle to meet the SCAIH requirements should not be technically unfeasible and will be undertaken within the future development.

Table 5. Nozzle erosion data from experimental testing

	Test #1	Test #2	Test #3	Test #4	Test #5
Throat Diameter [in]	0.570	0.521	0.521	0.463	0.463
Eroded Throat Diameter [in]	0.754	0.711	1.078	1.091	0.943
Avg Erosion Rate [in/s]	0.010	0.006	0.016	0.018	0.017

VIII. Future Work

Currently the demonstration of thrust vector control for the SCAIH is being conducted over a two year program. This is to be integrated directly into the existing sub-scale SCAIH motor described within this paper. The simplicity and reduced cost to which this can be achieved will have a dramatic effect on the benefits of the SCAIH system which will be demonstrated through the sub-scale motor. Further development work is also required and presently underway to improve the nozzle material in order to reduce the nozzle erosion. Upon completion of eliminating the nozzle erosion issues a detailed analysis and optimization of the injector parameter can be conducted along with further investigation into combustion instability.

IX. Conclusion

A sub-scale staged combustion aft-injected hybrid motor was developed and successfully demonstrated through out five tests. The unique gas generator propellant was developed and incorporated into this sub-scale motor. An effective start-up sequence was clearly shown and refined, which included the validation of spontaneous ignition between the fuel-rich warm gas and liquid oxygen flow. Stable combustion was observed in all test cases, although a detailed analysis with high frequency pressure transducers and data acquisition equipment is still required.. The sub-scale motor did deliver a sea-level Isp of 257 seconds (Isp_{vac} = 282s) at an operating pressure of 700 psi, which was a significant improvement over typical solid propellant motor. An existing nozzle was used to reduce cost and development time, however significant nozzle erosion occurred which introduce additional complications with the injection parameters. Improving the nozzle is required before refinement of the injector can be done to increase efficiencies.

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