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Concept and Design Details of a Universal Gas–Gas Launch Escape System

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Human space exploration vehicles must be designed with a reliable and safe launch escape system to be activated in the event of a failure on the pad or at altitude. A safe, reliable, highly flexible, and adaptable launch escape system that can be used with most proposed commercial space capsules was conceived after conducting propulsion and configuration trade studies. The outcome of these studies is a novel gas–gas propulsion system with a tractor-configuration-based launch escape system. Preliminary design of this joint universal launch escape and assist system is detailed. It is designed to accelerate a crew capsule away from a launch vehicle in case of an emergency on the pad or during the early portions of the trajectory at up to approximately 300,000 ft of altitude. It is designed to tractor the spacecraft to a sufficient altitude and with enough downrange translation so that the parachute landing system of the capsule can safely function. During mid- and high-altitude aborts, a reentry gravity-reduction mode of this novel escape system can start and stop its high-pressure gaseous oxygen and gaseous methane engines and can direct thrust in such a way as to shape the reentry trajectory to reduce the abort reentry deceleration. Finally, it has an ascent-assist mode that can be used to offset the normal payload penalty in the event that the emergency abort function is not used.

Nomenclature

g = acceleration of gravity, ft/s^2.
I_{sp} = specific impulse, s
Δv = velocity change, fps

I. Introduction

SEVERAL companies are either developing or building crewed space capsules. All of these vehicles will need a launch escape system (LES). As multiple new spacecraft developers seek to enter the commercial market, the need for a near-term, safe and reliable solution to the problem of launch escape in the event of a distress situation becomes apparent. The goal for the joint universal launch escape and assist system (JULEAS) presented here is to provide a commercial LES design that can be universally used on a variety of alternative capsules.

Four types of launch escape systems have been used ever since the first human space flight in 1961. Ejection seats were used in the Vostok spacecraft that carried Yuri Gagarin into orbit. They were also used in the Gemini capsule and during the first four space shuttle missions [1]. Ejection seats have limited capability in terms of both allowable ejection altitude and maximum aerodynamic pressure.

After the Space Shuttle *Challenger* loss in 1986, the In-flight Crew Escape System (ICES) was installed on the shuttles [2]. ICES calls for putting the space shuttle in a stable glide on autopilot, blowing the hatch, extending a pole through the hatch, and then having the crew slide out on the pole to clear the orbiter's left wing and parachute to the ground. The crew wears advanced crew-escape suits during ascent and descent to facilitate high-altitude bailouts.

The tractor systems are the most extensively used LES, and they have also been installed in the Mercury, Apollo, and Soyuz capsules and were proposed for the Orion capsule [3]. Installation of a tractor LES typically make the capsules statically and dynamically stable, so the allowable crew-escape envelope in terms of altitude, airspeeds, and launch vehicle pitch and yaw angles is the largest of all of the LES systems.

An example of a pusher system is the Max Launch Abort System (MLAS) [4]. Although pushers have never been used operationally, a pad-abort flight test on the MLAS was performed in July 2009. Most capsules are inherently unstable flying nose-first, and fins are required to stabilize them (Fig. 1). If the fins do not fold, then they can have a severe negative impact on the overall stability and control of the launch vehicle, since the unfolded fins would be on the nose of the launch vehicle.

Solid rockets have historically been the choice to power a LES [5]. However, using solid rockets makes the design of a universal LES difficult. Each commercial capsule will require different thrust profiles and impulse requirements, because their mass parameters (including weight, center of gravity, mass moment of inertia, and aerodynamic drag) are different. Hence, using solid rocket propulsion, each capsule would need its own individualized LES design. Designing a LES around a solid rocket also requires several technical compromises. The thrust of a solid rocket varies greatly with preignition propellant temperature, while the total impulse remains relatively constant. For example, the Apollo LES had an average thrust of 121,000 lb force (lbf) and burn duration of 4.2 s when the preignition propellant temperature was 20°F. At 120°F, the maximum vacuum thrust was much greater at 200,000 lbf and burn duration was much shorter at 2.6 s. The average thrust was greater than 147,000 lbf between 0.12 and 2.0 s at a pressure altitude of 36,000 ft and 70°F [6]. The lower thrust at 20°F had to be sufficient to safely separate the Apollo capsule from the Saturn launch vehicle, not only on the pad but also in flight when the acceleration produced by the LES had to exceed Saturn's acceleration. At 120°F preignition propellant temperature, the Apollo LES thrust was 67% larger than

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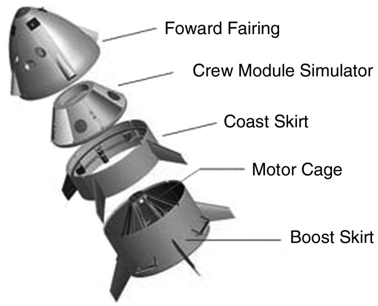

Fig. 1 MLAS was a demonstration of a pusher system (NASA image).

required. This meant the capsule structure and all of the components inside the capsule had to be sized to be 67% stronger and likely heavier than required for a safe launch escape.

A solid-rocket-powered LES also requires a separate rocket motor for each function. For example, the Apollo LES had three separate motors to provide for the launch abort function, the tower jettison function, and the pitch-control function. As a result, only 3100 lb of the Apollo LES's 8910 lb total weight was abort propellant, which amounts to a propellant mass fraction of only 35%.

II. Universal Gas–Gas Launch Escape System Concept Description

Instead of developing several different LESs, a multipurpose JULEAS could be designed, built, and extensively tested. Significant cost benefits could be possible with such a system, since the limited resources and time available could be devoted to perfecting a single system, rather than duplicating the effort over multiple systems. JULEAS is similar to the modern aircraft ejection seat, in which one vendor provides ejection seats to different aircraft manufacturers with only minimal modifications to accommodate various aircraft designs (for example, Martin-Baker[¶]).

The only structural changes projected for the multipurpose LES will be modifications to the boost protective cover and the attachments between JULEAS and the capsule. No changes to the JULEAS propellant tanks or rocket engines are anticipated. Thrust and total impulse can be changed easily by adjusting the amounts of propellant in the JULEAS tanks. JULEAS uses an innovative high-pressure gas–gas propulsion system consisting of gaseous oxygen and gaseous methane as propellants.

One other design feature of the JULEAS is its ascent-assist (AA) mode, which will be used on every flight to offset some of the payload penalty that results from having to carry the mass of the LES. JULEAS uses the launch abort propellant for the AA mode, which can result in a lower total launch vehicle mass. The Constellation program considered this for their solid-fueled Orion capsule launch abort system (LAS) and determined that, in theory, firing the LAS could increase mass to orbit by 1000 lb. However, the added structural tension loading on the capsule and everything below it required adding structural mass that resulted in an overall decrease in mass to orbit. If the Orion LAS thrust could have been reduced, which in turn increases burn time, then there would be no excessive loads in the structure, and increased mass to orbit with an AA mode could be possible.

The projected reliability of JULEAS's gas–gas propulsion system will constantly improve as it is flown, since the demonstrated reliability of any system is a function of the number of consecutive successful tests or operations. The capability to operate the escape propulsion system on every flight in the AA mode provides flight data to evaluate the system and demonstrate reliability. Compared with a solid-fueled LES that is not operated on every flight and whose reliability is fixed by the number of development tests, JULEAS has the potential to be shown to be more reliable with each flight flown.

JULEAS also has a reentry gravity-reduction (RGR) mode that can start and stop JULEAS engines, and direct thrust in such a way as to shape the reentry trajectory to reduce the reentry abort deceleration during mid- and high-altitude distress scenarios.

Simplicity drives reliability and safety. Recently, HMX was issued a patent [7] for an integral orbital maneuvering system and abort system that has several advantages for future highly reusable human spaceflight vehicles. While working on this concept, the authors recognized the advantages that could be derived from a nonsolid, nonhybrid, nonliquid orbital maneuvering system. A gas–gas propulsion system requires no separate pressurization system, propellant settling, or active thermal management while on orbit. Although the tanks are undoubtedly heavier than similar vessels for liquids, the advent of very-high-performance materials [8] has made the weight penalty tolerable, when traded against the cost and complexity of other approaches. In fact, the abort propellant mass fraction of JULEAS is the same as the Apollo LES [9].

To have a relevant performance comparison, a JULEAS approach was sized for an Apollo-class capsule (13,000 lb) escaping from the 6,400,000 lb Saturn V rocket [10]. Clearly, for today's commercial applications, the actual JULEAS would be sized differently from what is shown in this section, since commercial operators are expected to use the Falcon 9, Atlas V, Taurus II, or Delta IV launch vehicles (Fig. 2). Some of these rockets are more than 10 times smaller than the Saturn V. Certain characteristics of the gas–gas propulsion system greatly aid in sizing one baseline JULEAS system to accommodate all potential capsules, and these characteristics are described later.

Figure 3 depicts subsystems of JULEAS. At its current sizing, JULEAS is 26 ft long and weighs less than 8000 lb. The rocket section of the subsystem is cylindrical and houses four gas–gas rocket engines. It is topped by a nose cone containing sensors and four cold-gas attitude control thrusters. The JULEAS tower is connected to a boost protective cover that completely covers the capsule. This cover protects the capsule from the rocket exhaust and protects the capsule from the heating generated by launch vehicle boost through the atmosphere. The cover remains attached to the tower and is carried away when the launch escape assembly is jettisoned. This means that the capsule ascent thermal protection is not carried all the way to orbit.

Figure 4 depicts the JULEAS compared with the Apollo and Orion LES. The height was sized to be approximately the same as the Apollo LES. One characteristic of the JULEAS is its larger diameter, as compared with the Apollo LES. JULEAS's is 44.25 in. in diameter, compared with Apollo's 26 in. JULEAS has a larger diameter due to its lower-density propellants. The reason for this is JULEAS gas–gas propellant bulk density is about four times less than Apollo's solid fuel, considering the volumetric loading fraction of solid fuels.

Fig. 2 JULEAS installed on top of SpaceX's Dragon capsule.

[¶]Data available online at http://www.martin-baker.co.uk/home.aspx [retrieved 2 September 2010].

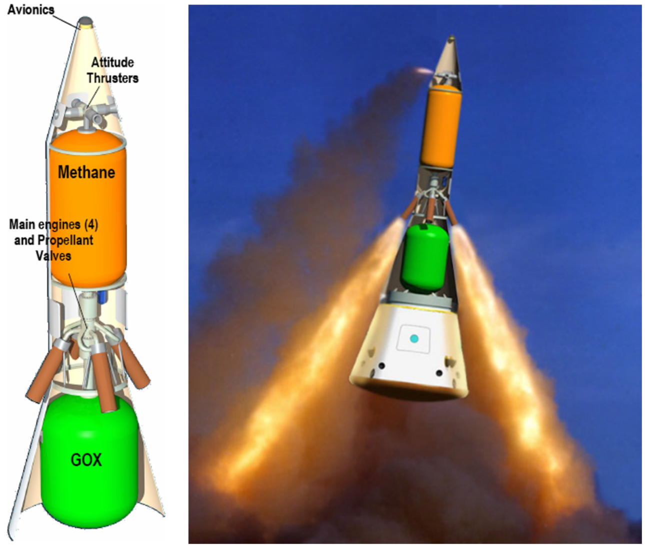

Fig. 3 JULEAS launch escape system uses high-pressure gaseous oxygen and methane propellants.

The JULEAS rocket nozzles are smaller than the Apollo LES. The reason for this is that the thrust chamber pressure is more than three times greater than Apollo's. The size of thrust chambers and nozzles is a direct function of chamber pressure, and increasing chamber pressure increases thrust from a given engine size, with some improvement in specific impulse I_{sp} as well.

III. Detailed Description of JULEAS Subsystems

JULEAS consists of a boost protective cover, intertank structure, gas–gas propellant tanks, four rocket engines, four cold-gas attitude control thrusters, a nose cone, and instrumentation.

A. Boost Protective Cover

The boost protective cover is similar in construction and design to the Apollo LES and would be custom-made for each customer's capsule. The Apollo LES was made of layers of impregnated fiberglass, honeycomb-cored laminated fiberglass, and cork. It covered the spacecraft to prevent charring of external surfaces during boost out of the Earth's atmosphere. It also protected the capsule from the rocket exhaust of the launch escape motor. The baseline JULEAS design provided here is about 8 ft tall and 8 ft in diameter and weighs about 930 lb. The boost protective cover is jettisoned with JULEAS.

B. Intertank Structure

The intertank structure is a monocoque tube made of either aluminum or composite with rings as required for assembly and servicing, similar to a structure used in research, sounding, and target rockets. The bottom ring of the structure can provide a vertical offset built into the JULEAS thrust vector direction to induce a slight pitch during abort. The Apollo LES used a 2.75 deg vertical offset.

C. Propellant Tanks

The propellant tanks are of state-of-the-art all-composite construction using carbon-fiber bosses (not metal bosses). The tanks will use the SAPPHIRE 77 resin and carbon-fiber system that offers a high ratio of pressure volume to weight (PV/W) and have been demonstrated to be compatible with cryogenic fluids such as oxygen, hydrogen, and room-temperature petroleum or alcohol-based fuels. JULEAS uses room-temperature gaseous oxygen (GOX) and methane as propellants, and the tank is compatible with these gases.

GOX is loaded into the tank at 22.7 lbm/ft^3, while methane is loaded at 12.1 lbm/ft^3. These propellant densities yield a tank pressure of 4500 lbf/in.^2 psia when the tank contents are at 120°F. This peak temperature of 120°F is the same as in the Apollo LES specification and represents the highest propellant temperature expected during a hot Florida summer day. The tanks are designed to a maximum expected operating pressure (MEOP) of 5000 psia and have a safety factor of 2. They are also designed to leak before they burst (i.e., leak pressure is 10,000 psia). The tanks are commercial items (manufactured by Microcosm, Inc.; see Fig. 5) and meet all commercial safety standards and MIL-STD-1522A [11]. Although the microcosm tanks are flight-proven for cryogenic applications, our propellants are only near room temperature, which is a much less severe environment for the tanks. These propellant tanks have a very high ratio of pressure volume to weight (PV/W) and comprise less than 20% of the JULEAS mass.

The 670 lb GOX tank external diameter is 53 in. and volume is 86 ft^3, sufficient to carry 1950 lb of GOX at 4500 psia and 120°F. The 44-in.-diam methane tank volume is 56 ft^3, weighs 430 lb, and carries about 680 lb of methane at the same conditions. The wall thickness of both tanks is approximately 0.75 in.

Heaters are installed either inside or outside the tanks to keep the gas propellants at 120°F, even when the outside air temperature is 20°F. Internal heaters would be standard explosive-resistant electric heaters. These internal heaters are commonly used in hazardous environments such as oil and chemical processing. Alternately, an outside surface heater, similar to those used to heat residential propane tanks in cold climates, can be used. Note that composites are an excellent insulator to heat flow across the fibers; they are 200 times better insulators than aluminum and only 15 times worse than foam. To maintain the tank contents at 120°F during a chilly 20°F day requires less than 300 W/tank, assuming that 1-in.-thick foam insulation is incorporated in the construction of the tanks. The heating requirements diminish during warmer days and vanish altogether on a hot day. Solids can also be heated; for example, the first stage of the Minotaur launch vehicle was heated.

D. Impulse

The JULEAS preliminary design detailed in this paper has over $515,000\ \text{lbf} \cdot \text{s}$ of total impulse in the vehicle axis for launch escape,

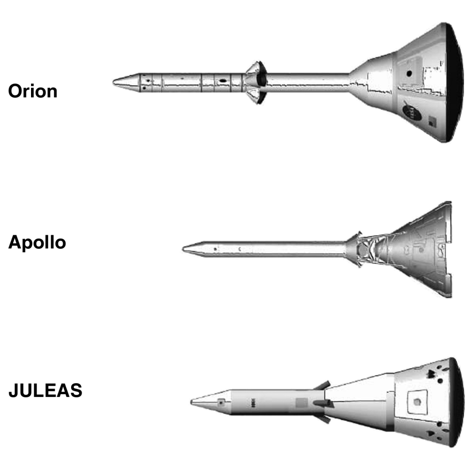

Fig. 4 Comparison between tractor LESs.

Fig. 5 Existing composite tanks (microcosm).

the same as the Apollo LES, equal to 24 $g \cdot s$. JULEAS's total impulse is bounded by a pad abort. Enough total impulse must be loaded to achieve a minimum altitude for safe parachute deployment and to achieve a minimum downrange so that the capsule is not blown back toward the pad when subjected to high (2σ) winds. Other aborts, such as mid- or high-altitude aborts, can be successfully completed with much less total impulse.

In addition, JULEAS delivers 45% of that impulse within the first 2 s after abort initiation; again, the same as Apollo. Here, the requirement is to deliver enough initial impulse so that the capsule separates from a launch vehicle while simultaneously being subjected to maximum aerodynamic pressure that typically occurs when velocity is near Mach 1. Aerodynamic drag will tend to push the capsule back into the launch vehicle; hence, transonic drag tends to size the minimum escape acceleration and LES initial thrust impulse and thrust levels. JULEAS thrust levels are also similar to the Apollo at 148,000 lbf [6].

An additional $37,700$ lbf $\cdot$ s of impulse is loaded for the tower jettison function, since tower jettison is completed using the same engines as for launch escape. Again, the impulse in the vehicle axis is the same as Apollo to ensure the tower clears the capsule. Tower jettison impulse and thrust levels are bounded by the requirement to safely separate the LES at about 300,000 ft from a still accelerating launch vehicle when the LES is no longer needed.

In addition, another 1750 lbf $\cdot$ s of impulse is loaded for attitude control. The thrust and impulse are the same as those used by Apollo. The key requirement here is to reorient the capsule quickly for parachute deployment during a low-altitude abort. A low-altitude abort is defined as anywhere between a pad abort to an abort below 25,000 ft.

Finally, 6% was added for propellant residuals; hence, the total loaded impulse (measured along the engines' centerlines and with a projected I_{sp} of 280 s) is about $700,000$ lbf $\cdot$ s.

E. Propellants

The four gas–gas engines use GOX and methane at an oxidizer-to-fuel (O/F) ratio of approximately three. These propellants are maintained at 120°F. There is no requirement to continuously top off the propellant tanks with more propellant.

In addition, gas–gas propellants are storable and can remain stable at room temperatures for a very long time (several years). Unlike current storable propellants such as hydrazine or nitrogen tetroxide, GOX and methane are not considered toxic, and so the special handling and safety precautions associated with either hydrazine or nitrogen tetroxide are avoided. A GOX leak would harmlessly mix with the atmosphere, while any leaking methane would simply disperse upward instead of pooling, in a manner similar to natural gas (natural gas is 88 to 99% methane). In addition, hydrazine and nitrogen tetroxide would require pressurization systems to deliver the propellants to the engines.

Solid rocket motors can be extremely dangerous to the ground crews and facilities, because they are already fully fueled. Both Brazil and India have suffered fatalities due to accidental ignition of solid fuels. A solid rocket ignited inside a launch vehicle assembly building would be catastrophic. Hybrid rockets suffer from issues relating to performance, regression rate, and time to full thrust that makes packaging them as a LES difficult. Nitrous oxide, a common oxidizer used in hybrids, requires heating or cooling on the pad depending on outside air temperature for propellant conditioning. Nitrous oxide is also a monopropellant and can explode under certain conditions. Table 1 is a comparison summary of various propellant options for launch escape systems. Gas–gas has significant advantages over other types of propellants for a LES.

F. Rocket Engines

A gas–gas rocket engine uses the mechanical energy contained in the compressed gas to thermodynamically expand the gas into the engine's thrust chamber. The advantage of this method of propellant delivery is that it is extremely simple, reliable, and predictably safe, since it is governed by physical law. Tank contents will cool as tank pressure decreases during an abort burn (GOX to 62°F and methane to 38°F at the point of propellant exhaustion).

Unlike solid rocket motors, these engines can be throttled, stopped, and restarted. Compared with solid rockets, specific

Table 1 Description and comparison of various propellant types for launch escape systems

Description	Pros	Cons
	Gas–gas propellants	
1) $I_{sp} \sim 280$ s 2) Candidate propellant type: a) Gaseous oxygen/methane	1) Throttleable: with on/off 2) Nontoxic propellants 3) No separate pressurization system 4) No continuous topoff required 5) Nozzles and combustion chambers are compact and easy to package due to high chamber pressure 6) Common propellant source for ACS	1) Large volume for propellant tanks due to lower density of its propellants
	Solid propellants	
1) $I_{sp} \sim 260$–270 s 2) Candidate propellant type: a) Conventional solid	1) Compact, easy to package 2) Crew-escape systems experience 3) No pressurization system	1) Limited or no throttling capability 2) No on/off features 3) Very difficult to use as ACS 4) Separate motors for each function
	Liquid propellants	
1) $I_{sp} \sim 270$ s 2) Candidate propellant types: a) Liquid oxygen (LOX)/ethanol b) LOX/RP-1 c) N_2O_4/hydrazine d) H_2O_2/RP-1	1) Throttleable: with on/off 2) Nontoxic propellants available 3) Common propellant source for ACS	1) Separate pressurization system 2) Large volume for propellant and pressurant tanks 3) Complex plumbing 4) Nontoxic propellants can be cryogenic and require continuous topoff 5) Noncryogenic propellants are usually highly toxic or can catastrophically decompose
	Hybrid propellants	
1) $I_{sp} \sim 260$ s 2) Candidate propellant types: a) LOX/HTPB (hydroxy-terminated polybutadiene) b) Nitrous oxide/HTPB c) H_2O_2/HTPB d) Nitrous oxide/paraffin	1) Throttleable: with on/off 2) Nontoxic propellants available 3) Possible common propellant source for ACS	1) May require separate pressurization system for some propellants 2) May be difficult to package, since a long length-to-diameter ratio may be required for motor 3) May be difficult to achieve high thrust & impulse for short periods of time 4) Possible high propellant residuals can reduce propellant mass fraction

impulse I_{sp} is relatively high, with a theoretical I_{sp} of over 310 s at sea level and increasing with altitude (the expected delivered sea level I_{sp}, accounting for both combustion and nozzles losses, is about 280 s).

Each of the launch escape engines has a nozzle diameter of about 6.5 in. and nozzle expansion ratio of four. Thrust is about 46,000 lbf each at sea level, increasing with altitude, and decreasing as propellants are expended. If better performance is desired, then the nozzle expansion ratio can be easily enlarged to increase both I_{sp} and thrust. For example, a nozzle expansion ratio of 9 would only increase nozzle diameter to 10 in., but would increase I_{sp} by 12 s.

The four installed engines are angled at 30 deg from the vehicle axis, so they provide a total of 148,000 lbf of thrust at sea level in the vehicle axis, accounting for both the cosine angle loss and the force of the exhaust on the boost protective cover. The engines deliver more than $230,000$ lbf $\cdot$ s of impulse in the vehicle axis within the first 2 s of a pad abort, followed by a lower-thrust sustainer burn caused by the naturally occurring tank pressure dropoff. The engines provide enough impulse to lift a 13,000 lb capsule and carry it more than a mile away from the launch vehicle.

Engines are fabricated from silica phenolic using an involute wrap fabrication technique. Since the engines can be started and stopped, some of the impulse can be used to help shape the trajectory after a high-altitude abort in such a way as to reduce reentry deceleration.

These engines also double as the launch ascent-assist power plants in the event that the abort function is not used. For launch assist, the total thrust is throttled to less than 50,000 lbf to prevent overstressing the spacecraft structure. The burn duration is about three times longer and the engines provide additional ΔV to the entire launch vehicle.

On all missions, these engines are also used as the tower jettison engines. Total thrust in this application is about 37,000 lbf, which is the same as Apollo. The engines operate for about 1 s and jettison JULEAS after it is no longer required or after a launch abort and before parachutes are deployed for recovery.

One important feature of the gas–gas approach is that thrust levels can be tailored very easily. Changing out Venturi orifices in the feed lines changes the mass flow into the chamber, thus increasing or lowering chamber pressure and thrust. Easy adjustment of thrust to match requirements for both launch vehicle blast overpressure and fireball hazards and to match structural loading limits or unique trajectory requirements of customer spacecraft could provide safety and schedule advantage.

Although a potential exists for a change in O/F ratio during abort engine operation, since the cold-gas attitude control thrusters draw methane from the same tank as the abort/tower jettison engines, any such O/F change would be small. The 1750 lbf $\cdot$ s impulse for attitude control would use only 22 lb of methane (assuming I_{sp} of 80 s for the attitude control thrusters), about 2.5% of the loaded methane. This would shift the abort engine's O/F ratio by only 0.1. The performance of the bipropellant abort thrusters are not sensitive to such O/F changes (see Fig. 6).

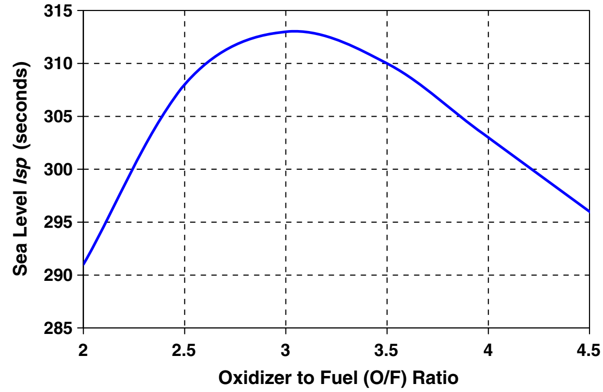

Fig. 6 Theoretical (no losses assumed) I_{sp} at sea level with nozzle expansion ratio of 4 for GOX–methane engines.

G. Valves and Manifold

Two 4-in.-i.d. ball valves, linked together and actuated by a single hydraulic piston, are used to start and stop the engines. The hydraulic fluid is pressurized by tank gas. All four engines are manifolded off the single set of valves for reliability and compactness. Valve material includes Nitronic 60 for balls and Monel for lines and fittings, and all possible lines are welded to eliminate leaks. Venturis, similar to those used in the Apollo lunar module descent engine, are incorporated to lock up flow rates and to prevent chamber-pressure variations coupling to the feed system.

H. Ignition

The current baseline is to employ pyrotechnic igniters using NASA standard initiators. However, two alternative ignition concepts bear further examination. One is the use of TEA/TEB (triethylaluminum/triethylborane) hypergolic slugs (used in the F-1, RS-27, and most Russian engines) and torch igniters (used by the SSME, J-2, and RL10).

I. Attitude Control Thrusters

Four cold-gas attitude control system (ACS) thrusters use high-pressure methane gas from the JULEAS fuel tank to generate a minimum of 4000 lbf thrust each. Delivered I_{sp} is expected to be about 80 s at sea level, increasing with altitude. Although the I_{sp} is low compared with other types of rockets, JULEAS cold-gas ACS thrusters are designed to be simple, safe, and reliable and can be turned on and off repeatedly, producing very small, finely controlled, thrust pulses (impulse bits). In addition, the valves operate at room temperature, not at the high temperatures of the Orion's LAS solid-fueled attitude control system. Finally, since the JULEAS has a relatively large diameter, there is adequate volume in the nose cone to package the ACS thruster nozzles, valves, and associated plumbing.

Since the combination of JULEAS plus the capsule is statically stable flying nose-first [i.e., the center of gravity (c.g.) is forward of the center of pressure (c.p.) by over 3 ft], the ACS thrusters are used only for gross steering and are not required to actively stabilize the capsule and JULEAS combination (see Fig. 7). The stack will naturally weathervane into the relative airstream. However, without JULEAS, the capsule is very unstable nose-first.

After an abort, the ACS thrusters orient the capsule so that the heat shield is forward and the parachutes are aft. They are also used during an abort to tilt the capsule away from the launch vehicle. In the case of pad or very-low-altitude abort, they provide an initial pitch maneuver toward the Atlantic Ocean. The location of ACS inside the nose cone (see Fig. 3) gives the thrusters a long moment arm. As a consequence,

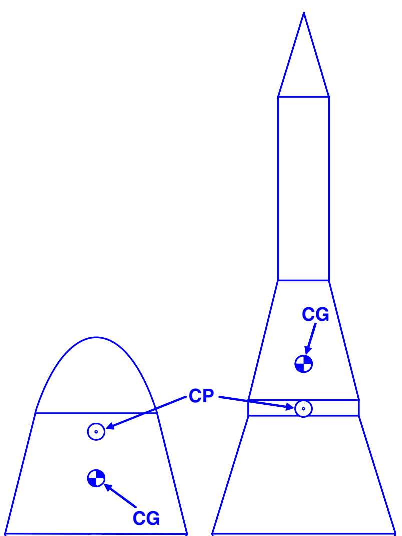

Fig. 7 JULEAS installation moves c.g. forward of c.p. and makes the stack very stable.

the ACS thrusters can rotate the capsule 180 deg and bring it to a stop in 8.6 s using only 1600 lbf · s of impulse (4000 lbf thrust for 0.2 s, followed 8.2 s later by similar burn in the opposite direction to stop rotation).

J. Nose Cone

In addition to the ACS thrusters, the nose cone contains an instrument package. The instrument package provides static ports through which pressure changes are measured; if desired, this information is provided to the flight control system of the spacecraft and launch vehicle. The launch vehicle guidance system can use this information to determine aerodynamic incidence angle and dynamic pressure data.

K. JULEAS Mass Properties

Table 2 presents a mass budget for JULEAS. It was prepared in accordance with the procedures described in [12]. Tank weights were estimated by comparing to existing Microcosm tanks. The nose cone, intertank structure, and boost protective cover weights were estimated by assuming the same area weight as Atlas V interstage structure ($4.75\ \mathrm{lb/ft^2}$). A carbon composite panel with the same area weight would be 0.55 in. thick. Plumbing and valves were sized in aluminum using a structural safety factor of 4 on a MEOP of 5000 psia and diameters were chosen to ensure flow velocities did not exceed $300\ \mathrm{ft/s}$ (to minimize pressure drops). Thrusters, electric, avionics, and separation hardware were estimated by comparison with other existing hardware. Mass growth allowances were taken from Table 1 (mass growth allowance and depletion schedule) in [12].

JULEAS has the same total impulse and thrust as the Apollo LES. Note that the mass margin between the JULEAS predicted weight of 7229 lb and Apollo LES 8910 lb is 19%, which is greater than the 15% recommended by Table 2 in [1]. Also note that propellant mass fraction is 35%, which is the same as for Apollo LES (see Sec. II).

IV. Capabilities and Concept of Operations

The JULEAS capabilities and concept of operations fall into several categories, including pad and low-altitude aborts, high-altitude abort, and launch assist. The altitude of the spacecraft principally determines the categories. There still exists the capability to abort using the capsule's service module propulsion after JULEAS propellant has been used for ascent assist and after JULEAS has been jettisoned.

A. Pad or Low-Altitude Aborts

Low-altitude aborts are below 25,000 ft of altitude. An abort would typically be commanded either automatically or by the capsule crew when a time-critical event occurs. These events are typically determined by the launch vehicle provider and include loss of thrust on one or more engines on the launch vehicle; excessive vehicle angular rates in any of the pitch, yaw, or roll planes; and fire/deflagration of the launch vehicle.

On Apollo, a lockout system prevented the automatic system from operating before liftoff. However, the Apollo astronauts could start an abort during the countdown, all the way until normal spacecraft separation from the launch vehicle.

When an abort is initiated either manually or automatically, a command is normally sent to cut off the booster engines. However, range safety requirements may impose a time restriction [13]. For example, the Saturn V engines were left on for the first 30 s after liftoff to ensure that the vehicle cleared the pad.

Next, ordnance or nonpyrotechnic mechanisms are used to separate the capsule from its service module, or booster tie-downs. These mechanisms could include devices to cut structural ties, guillotines to cut service and supply umbilicals between the capsule and the launch vehicle, or quick disconnects for electrical power and data connections.

The JULEAS valves are commanded to concurrently open and ignite the four launch escape motors. Ignition is ensured by using flight-proven standard pyrotechnic igniters. However, there are other options of TEA/TEB and torch igniters for this type of application. All ignition options will be redundant and can provide multiple starts (two are required for nominal operation). Solid rockets require three steps for main engine ignition (initiator, booster charge, and main stage), while the gas system requires only two (igniter function and main stage); hence, gas–gas engine ignition might be more reliable than solid rocket motor ignition.

The JULEAS is sized for an initial acceleration of about 7 g. The attitude control motors fire as required to steer the capsule to the side of the launch vehicle and toward the Atlantic Ocean. A typical pad-abort trajectory is presented as Fig. 8.

Despite the fact that the JULEAS gas–gas propulsion thrust profile decreases continuously after ignition, the JULEAS pad-abort separation distances are greater than the Apollo LES on a 20°F day. On a 20°F day, the Apollo LES launch escape rocket motor only produces 121,000 lbf of thrust instead of its nominal 147,000 lbf thrust (or 200,000 lbf on a 120°F day). The JULEAS gas–gas propellants are held at a constant 120°F with heaters, regardless of outside air temperature; hence, the thrust profile of the JULEAS engines does not vary with outside air temperature.

At time ~6.5 s after a pad abort was started, the four gas–gas engines are shut down. Their combined thrust at this point will have dropped to about 40,000 lbf. At time 12 s the attitude control thrusters turn the capsule so that its blunt end is toward the relative wind. About 3 s later, the tower separation devices are fired and the engines are restarted and fire for about 1 s. These actions carry the JULEAS assembly away from the capsule's landing trajectory. Less than 1 s later after tower jettison, the spacecraft's Earth landing subsystem is activated and begins its sequence of operations to bring the vehicle down safely.

Table 2 JULEAS mass properties

Item	Basic mass, lb	Mass growth allowance, %	Predicted mass, lb
Nose cone	110	16	128
ACS thruster group	125	20	150
Methane tank	371	16	430
Methane propellant	641	6	679
Intertank structure	290	16	336
Abort thruster group	920	20	1104
GOX tank	578	16	670
GOX propellant	1,840	6	1950
Boost protective cover	800	16	928
Thermal protection	600	20	720
Electric distribution	80	25	100
Avionics	15	25	19
Separation system	12	13	14
Total	6382	——	7229

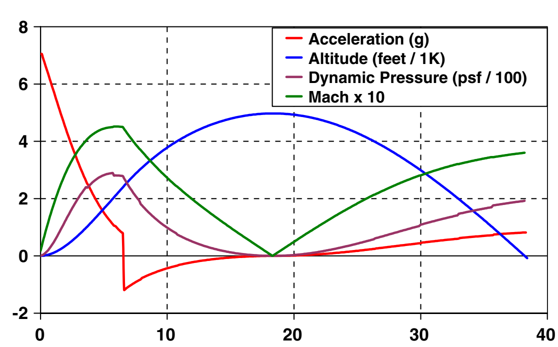

Fig. 8 JULEAS pad-abort trajectory has a peak altitude of almost 5000 ft, a peak Mach number of 0.45, a peak aerodynamic pressure of $290\ \mathrm{lb/ft^2}$, and peak acceleration of 7 g.

B. High-Altitude Aborts and RGR Mode

JULEAS is designed for high-altitude aborts, including the mesosphere or up to 300,000 ft of altitude. During a high-altitude abort, a capsule can be subjected to very high reentry decelerations. For example, in 1975, the Soyuz 18-1 mission aborted when the third stage failed to separate from the second stage but still ignited. The capsule experienced a reentry deceleration of larger than 20 g. The reason for the high deceleration is that reentry deceleration is a square function of the capsule's reentry velocity and a sine function of its reentry flight-path angle. Normal reentry from an orbit is initiated with a very shallow reentry angle; hence, they have reasonable reentry decelerations. An abort places the capsule in a ballistic trajectory, and reentry angle can be very steep, with a resulting high reentry deceleration.

The sequence can also differ for higher-altitude aborts in that not all of the abort impulse is required for safe separation from the booster. For example, the Apollo LES was jettisoned at about 300,000 ft altitude and at a booster velocity of 9800 fps. After LES jettison, aborts could still be completed with the Apollo service module engine only, which was only capable of generating about 0.3 g separation acceleration from the Saturn V.

Since the gas–gas propulsion system on JULEAS can be started and stopped, the opportunity exists to reduce the high decelerations produced by a high-altitude abort. In the RGR mode, the JULEAS rocket engines are first briefly fired to separate the capsule from the booster. Next, the attitude control thrusters point the stack so that it is pointed to the zenith (JULEAS nose pointed radially outward from the Earth). For aborts with a very shallow reentry angle (less than 15 deg), the JULEAS engines mostly shallow (reduce) the flight-path angle. For aborts with a very steep reentry angle (greater than 60 deg) the JULEAS engines mostly reduce the reentry velocity. For reentry angles between 15 to 60 deg, JULEAS reduces the reentry velocity and shallows the trajectory. These firings occur just before the reentry into the sensible atmosphere and the onset of reentry deceleration. The JULEAS can provide up to 650 fps of change in velocity ΔV for this purpose and is capable of providing a 2 to 3 g reduction in peak reentry acceleration (see Fig. 9). When the JULEAS engines thrust has decayed to below 40,000 lbf, then the tower separation devices are fired and carry the JULEAS assembly away from the capsule's reentry trajectory. The capsule's own attitude control thrusters then turn the capsule blunt end forward (if it is not already in that position) for reentry.

This abort option is a second method that closes any possible black-zone risks for EELVs. A black zone is a time period during the launch profile when there is no safe escape or abort possibility in the event of a distress condition. It can also be closed at the cost of 1–3% payload mass by slightly depressing the otherwise lofted trajectory for vehicles such as the Atlas 401 or by adding an engine (i.e., the Atlas 402). However, a depressed trajectory will still impose severely high gravity forces on the crews in the range of 15–16 g. While considered acceptable for this survival mode, it nonetheless can and does cause injury. For example, one Soyuz crewman in the 18-1 mission abort was removed from flight status due to injuries sustained in the abort.

If JULEAS had been available for the Soyuz 18-1 abort, the result would have been about a 3 g reduction in peak reentry loads.

C. AA Mode

During a successful launch and when the booster is high enough and fast enough such that the abort function of the JULEAS is not needed, then the AA mode can be used. For Apollo, LES tower jettison occurred when the Saturn V climbed above 300,000 ft. At the same point in the trajectory for JULEAS, the four gas–gas motors are throttled to less than 50,000 lbf combined thrust and are fired for about 15 s. The throttle is slowly opened to maintain 50,000 lbf for as long as possible as the tank pressure decreases. The AA mode provides a change in velocity ΔV increase to the entire launch vehicle and can increase inserted mass to orbit. The gas–gas motors are limited to 50,000 lbf thrust to prevent overstressing the capsule's service module and other underlying structure.

As the JULEAS thrust decays to below 40,000 lbf, the tower separation devices are fired and the attitude control thrusters point the JULEAS assembly trajectory away from the capsule's ascent trajectory.

A trajectory simulation of the AA mode was completed with assuming an Atlas V 402 launch vehicle flying a trajectory to an International Space Station orbit (see Fig. 10). Installation of a 7300 lb JULEAS resulted in a 1300 lb loss in payload system weight, but the AA mode adds back 700 lb.

V. Development and Test Program

A major cost of any LES development is testing. During the Apollo LES development program, the pitch-control motor was test-fired 14 times, the tower jettison motor was test-fired 21 times, and the launch escape motor was test-fired 20 times. In addition, there were two pad-abort flight tests and five flight tests of the Little Joe II launch vehicle. Since a solid rocket motor thrust varies greatly with temperature, all of the three motor types had to be tested at three different preignition propellant temperatures of 20, 70, and 120°F [10].

Since JULEAS gas–gas propellants are temperature controlled to 120°F, integrated ground-test hot fires can be one-third of the Apollo LES. Since the abort motors also serve as the tower jettison motors, those tests are eliminated as well. Thus, a JULEAS test program could consist of approximately seven ground tests on a single abort engine, seven ground tests on the cold-gas thruster, and one integrated ground test with all four abort motors.

Thrust and total impulse may be changed for various capsules by adjusting the amounts of propellant in the JULEAS gas–gas tanks. Reducing the amounts of propellant will not require additional testing, because every engine operation results in a sweep of the thrust, impulse, and tank pressures. In other words, testing at the highest thrust and tank pressures automatically includes operations at lower thrust, total impulse, and tank pressures. However, testing will be needed to evaluate the JULEAS engine start and stop capability at

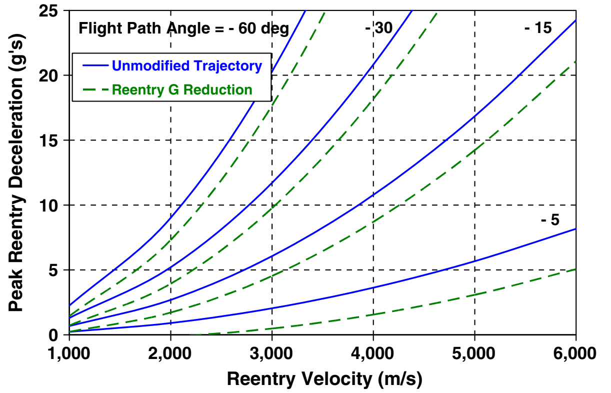

Fig. 9 JULEAS RGR mode can provide up to 3 g of deceleration reduction regardless of reentry flight-path angle or reentry velocity.

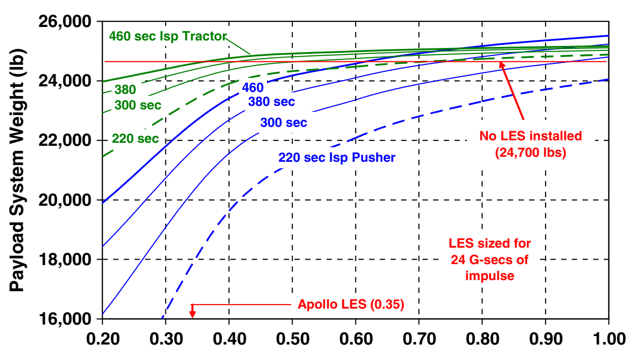

Fig. 10 AA mode for Atlas V 402 to a 220 n mile 51.6 deg orbit.

Table 3 JULEAS technical and programmatic risks

Risk description	Notes regarding assessment of risk and strategy for mitigation
Ablative chamber, coaxial post injector	Many examples have flown during the past 50 years. Two different injector designs should be used until the design review to provide risk mitigation.
Main propellant valve and manifold	These components are considered to be low risk, however, two vendors should be used to provide risk mitigation. They will be adapted from COTS valves.
Ignition subsystem	Three options are available and all should be carried to the first design review.
Linerless composite tanks	Flight-proven in 2001 and improved since then. Metal-lined backups available.
Monocoque structure	Many examples have flown during the past 50 years. Very low risk means no mitigation strategy is required.
Cold-gas thrusters	Many examples have been flown. We developed a similar thruster in 1994. Two vendors should be carried to design review to provide mitigation.
Launch-site selection	Two sites should be carried to design review to provide mitigation.
Office of Commercial Space Transportation launch waiver	Considered low risk, given waiver issuance policy for comparable testing efforts.

various tank pressures, but these tests may only require a single load of propellant. In contrast, solid rocket motor manufacturers cannot easily change peak thrust or total impulse after mixing the propellant and casting the motor. And although the JULEAS weight could be optimized if we size the rocket engines and tanks for each separate customer capsule design, the net gain is small, since both the engines and tanks constitute a comparatively small percentage of the JULEAS total loaded mass.

After a solid motor test, the entire motor is thrown away and the next test requires a completely new motor. Seventy-six motors were consumed in the Apollo LES tests. For the JULEAS gas–gas engine tests, the propellant tanks, valves, and manifolds can be reused. Only igniters need to be replaced between tests and thrust chambers replaced after full duration tests.

In terms of flight test, there have been significant advances made in simulation, both in vehicle dynamics and in computational fluid dynamics, since the Apollo LES test program [14–16]. Simulation can be used to predict the characteristics of JULIES both the pad and in-flight abort under safe distances constraints, [13]. To improve the confidence in the simulation tools, the data from the two Apollo pad-abort tests and five Apollo Little Joe flight tests could be used to benchmark and calibrate the simulation tools. Although we cannot predict at this time whether simulation alone will be able to satisfy NASA, commercial customers, and our own safety concerns, we believe that simulation can allow the completion of the JULEAS development with significantly fewer flight tests than with Apollo.

A. Technical and Programmatic Risk

Risk management includes the processes concerned with identifying, analyzing, and responding to a potential risk. Table 3 lists our evaluation of the technical and programmatic risks for JULEAS.

B. Development and Test Schedule

The JULEAS development and test schedule could be half that of the Apollo LES. The Apollo LES design, development, and testing were completed over a five-year period (1961 to 1966) and were remarkably free of failures [6,10]. Unlike Apollo, the JULEAS gas–gas engines do not need to be tested at three different preignition propellant temperatures, and JULEAS launch abort and tower jettison engines are the same engine.

VI. JULEAS Technical Advantages

JULEAS has improved safety, due to not having any monopropellant in its propulsion, high safety factors in its tank design, and its statically stable tractor configuration. Reliability is improved, due to its low complexity and low cost to test. The RGR mode and the AA mode improve its operations relative to other LES approaches. Its design inherently supports a low-cost test program and a low unit cost. Table 4 summarizes the basic advantages of JULEAS.

VII. Conclusions

The preliminary design of novel gas–gas propulsion based tractor launch escape system has been conducted after completing propulsion and configuration trades to provide a universal commercial launch escape system that can be used on a variety of alternative capsules. The only structural changes expected will be modifications to the boost protective cover and the attachments

Table 4 Summary of features of JULEAS

Attribute	Features
Safety	1) Neither detonable monopropellants nor toxic propellants are used.
	2) High safety factors are used (2:1 on tanks and structures, 4:1 on lines and valves).
	3) Static stability is achieved by placing c.g. forward of c.p.
	4) ACS maximizes acceptable abort boundary conditions.
Reliability	1) Low cost to test (less than \$5000 of propellants per test) can allow demonstration of reliability statistics.
	2) Abort motors fired during every mission in AA mode provides flight data to demonstrate reliability.
	3) Proven cold-gas ACS thrusters used.
Operations	1) RGR mode can reduce reentry deceleration for mid to high-altitude aborts.
	2) AA mode improves inserted mass to orbit when JULEAS is not used for an abort.
Adaptability	1) Smaller capsules accommodated by filling tanks with less propellant and throttling engines.
	2) Adaptability of JULEAS concept allows rapid LES resizing.
Testing	1) No outside temperature effects results in reduced amount of testing (one-third of that required for solids)
	2) As capsule mass properties change, it is possible to adjust total impulse and throttling to maintain tested acceleration schedule. JULEAS may reduce the need to retest as mass properties change.
	3) The length of the boost protective cover can be adjusted for various customers to maintain the c.p. and c.g. relationship such that added flight-testing for stability and control issues may not be required.
	4) Test articles can be recovered by parachute to allow a large number of flight tests to be economically achieved.
Unit Cost	1) Low-cost propellants are used (less than \$5000 per flight).
	2) Most components are common with other aerospace and industrial products, which reduces unit costs.
	3) Since propellants can be loaded before mating with spacecraft, this can eliminate on-pad service requirements.

between the escape system and the capsule. No changes to its tanks or rocket engines are expected. During mid- and high-altitude aborts, the reentry *g* reduction mode of this escape system can start and stop its high-pressure gaseous oxygen and gaseous methane engines, and direct thrust in such a way as to shape the reentry trajectory to reduce the abort reentry deceleration. The LES has an ascent-assist mode that can be used to offset the normal payload penalty in the event that the emergency abort function is not used. A universal launch escape system that works with all of the commercial capsules can improve safety of human space exploration missions.

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References

[1] Arnold, H. J. P., *Man in Space, an Illustrated History of Spaceflight*, CLB Publishing, Surrey, England, 1993.

[2] Nagle, S., and Sinclair, G., "Space Shuttle Orbiter Update," AIAA Paper 1989-2406, July 1989.

[3] Boynton, J., and Kleinknecht, K., "System Design Experience from Three Manned Space Programs," *Journal of Spacecraft and Rockets*, Vol. 7, No. 7, 1970, pp. 770–784.

[4] Taylor, A., Kelley, C., Magner, C., Peterson, D., Hahn, J., and Yuchnovicz, D., "A Review of MLAS Parachute Systems," 20th AIAA Aerodynamic Oscillators Conference, San Jose CA, AIAA Paper 2009-2991, 2009.

[5] Sietzen, F., Jr., "Looking Back," *Aerospace America*, July 2006, pp. 34–39.

[6] Townsend, N. A., "Apollo Experience Report: Launch Escape Propulsion Subsystem," NASA TN D-7083, 1973.

[7] McKinney, B., and Hudson, G. C., "Integrated Abort Rocket and Orbital Propulsion System," U.S. Patent 7,484,692, HMX, Inc., issued 3 Feb. 2009.

[8] Sarigul-Klijn, N., "Aeronautical and Space Engineering Materials," *The Engineering Handbook*, edited by R. C. Dorf, 2nd ed., CRC Press, Boca Raton, FL, 2004, Chap. 196.

[9] Hudson, G. C., Sarigul-Klijn, M., McKinney, B., and Sarigul-Klijn, N., "Joint Universal Launch Escape & Assist System," U.S. Patent Application 61336983, filed 30 Jan. 2010.

[10] Hyle, C. T., Foggatt, C. E., and Webber, B., "Apollo Experience Report—Abort Planning," NASA TN D-6847, 1972.

[11] ""Standard General Requirements for Safe Design and Operation of Pressurized Missile and Space Systems," U.S. Air Force, MIL-STD-1522A, May 1984.

[12] "Mass Properties Control for Space Systems," AIAA, Std. X-120-200-X, Reston, VA, July 2006.

[13] "Hazard Analysis of Commercial Space Transportation, Volume II: Hazards," U.S. Department of Transportation, May 1988.

[14] Tantabini, P. V., "Integrated Flight Performance Analysis of a Launch Abort System Concept," AIAA Paper 2007-6622, Aug. 2007.

[15] Chan, W., Klopfer, G., Onufer, J., and Pandya, S., "Proximity Aerodynamic Analyses for Launch Abort Systems," AIAA Paper 2008-7326, Aug. 2008.

[16] Pandya, S., Onufer, J., Chan, W., and Klopfer, G., "Capsule Abort Recontact Simulation," AIAA Paper 2006-3324, June 2006.

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