Pyrotechnically Actuated Gas Generator Utilizing Aqueous Methanol

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A gas-generating device was developed to supplement the ram-air inflation of a supersonic ballute. The device is designed to initially pressurize the ballute following deployment, exposing and orienting its ram-air inlets to free-stream air for complete inflation. The supplemental pressurization decreases the total inflation time, and increases the likelihood of a successful inflation. The device contains a reservoir filled with an aqueous mixture of methanol that, when released in to the interior of the ballute, rapidly vaporizes due to the low ambient pressure. Upon activation of the device, a pair of redundant firing mechanisms initiate pyrotechnic charges that pressurize and rupture the reservoir, resulting in ejection of the methanol in to the ballute. In addition to its role in inflation, the device serves as the structural connection to the ballute. Analytical models were developed for the inflation capability of the device, which were verified using vacuum chamber testing of developmental hardware. Static, deployment, and environmental testing demonstrated the functionality of the firing mechanism and reservoir under several temperature and pressure conditions. Finally, the device was successfully operated during the first Supersonic Flight Dynamics Test (SFDT) of NASA's Low Density Supersonic Decelerator (LDSD) project. The design architecture is scalable to accommodate different quantities of gas generation, can be adjusted to operate in a variety of temperature and atmospheric pressure regimes, and provides a robust device that may be installed with minimal risk to personnel or hardware.

Nomenclature

C_p	specific heat capacity
m	mass
p	pressure
Q	heat
R	gas constant
T	temperature
V	Volume
X	mass fraction
ΔH_f	latent heat of fusion
ΔH_v	latent heat of vaporization
η	efficiency
ρ	density

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EM	Engineering Model
FM	Flight Model
IA	Inflation Aid
LDSD	Low Density Supersonic Decelerator
PDD	Parachute Deployment Device
NIST	National Institute of Standards and Technology
SIAD	Supersonic Inflatable Aerodynamic Decelerator
SFDT	Supersonic Flight Dynamics Test

I. Introduction

Due to the presence of a solid rocket motor in the center of the flight test vehicle, the Low Density Supersonic Decelerator (LDSD) supersonic parachute was stowed approximately 1.1 m from the vehicle axis of symmetry (centerline of the vehicle to centerline of the parachute can). This off-centerline position precluded the ability to mortar deploy the 100 kg parachute pack due to the excessive structural requirements of such a mortar and the large tip-off moments imparted to the vehicle in flight. This resulted in the need to extract the parachute from its container via a pilot system, referred to as the Parachute Deployment Device (PDD).

The PDD system consists of a mortar, a supersonic ram-air inflated ballute, and a bridle assembly. A ram-air inflated supersonic ballute was selected over a supersonic pilot parachute for to its higher drag coefficient, greater stability, and more deterministic opening behavior at the relatively high deployment Mach condition. The LDSD supersonic flight test vehicle is shown in figure 1 with the PDD-related components indicated.

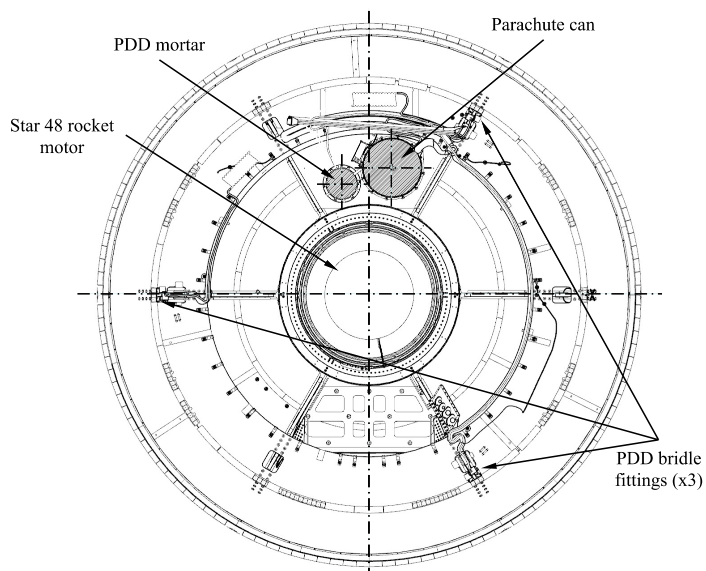


Figure 1: LDSD supersonic test vehicle with PDD components indicated.

At a nominal altitude of 50 km and a Mach number of approximately 2.75, the ballute is ejected from the test vehicle by the mortar and the ballute inflates upon reaching the end of its bridle assembly. The ballute remains attached to the vehicle for five seconds to stabilize and obtain drag performance data, then the bridles are cut away from the vehicle and the ballute extracts the parachute pack for deployment. Figure 2 shows the deployed state of the ballute behind the test vehicle.

The ballute, shown in figure 3, was designed to inflate by the ingestion of incoming air at supersonic speeds through its air inlets. However, there is the possibility the ballute may not properly inflate, or inflate too slowly, under the influence of air ingestion alone. An additional gas-generating device, the Inflation Aid

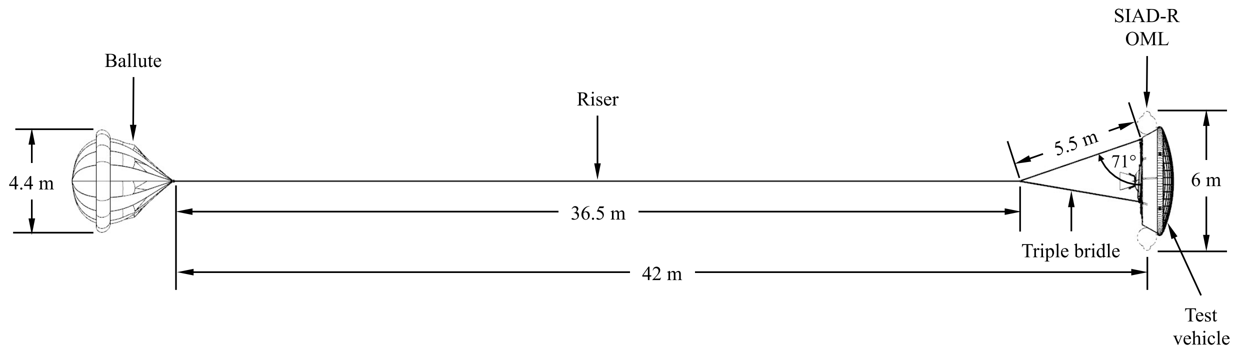


Figure 2: Ballute in its deployed state behind the test vehicle.

(IA), is used to pressurize the ballute and open the air inlets. The successful performance of the IA serves to accelerate and increase the likelihood of proper ballute inflation.

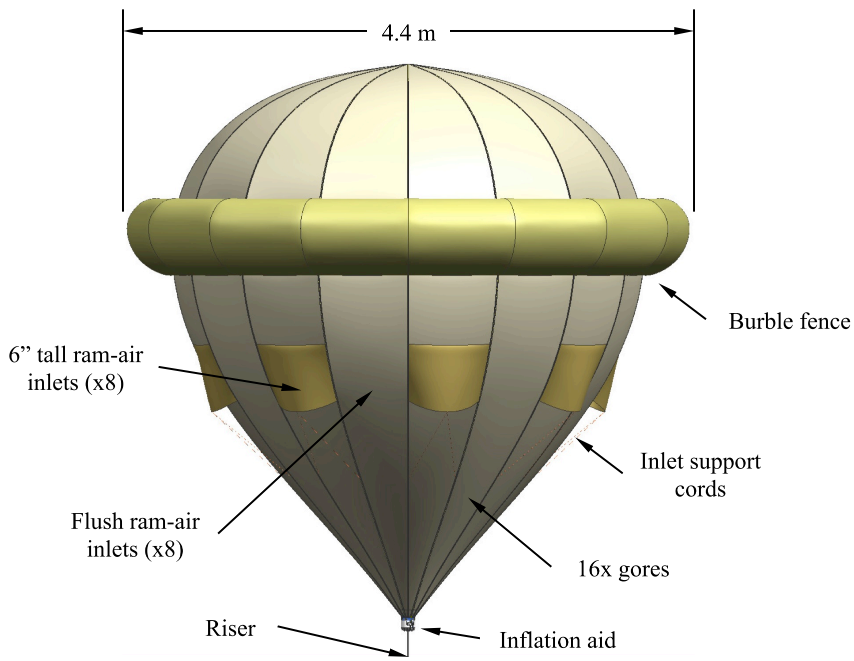


Figure 3: Ballute diagram.

Gallon and Witkowski describe the parachute deployment process in greater detail.[1] Tanner et al. provide a summary and analysis of the PDD system performance,[2] and Woodruff et al. describe the ballute in greater detail[3] . This paper presents a general summary of the IA device, the pre-flight analysis and testing of the device's components, and its performance during the first LDSD supersonic test flight in the summer of 2014.

II. Inflation Aid Development

II.A. Device Requirements

The addition of the IA to the PDD system architecture occurred late in the design cycle. The IA was a response to concerns that the ballute may not properly inflate, or inflate too slowly, under the influence of air ingestion alone. The driving requirement of the IA was to generate 50% of the expected ballute internal pressure with a 95% confidence (accounting for dispersions in the predicted flight trajectories) within 0.4 seconds of the initiation of the IA. Note that the ballute's internal pressure is a function of the freestream dynamic pressure and Mach number due to its use of ram-air inlets, thus the IA could not target a single pressure value.

However, as the purpose of the IA was to increase the likelihood of successful inflation, it must not degrade the performance of the existing PDD system. The IA (whether operated or not) must not preclude the ballute from inflating due to ram-air ingestion.

Traditionally, gas-generating devices (such as those found in automobile airbags) utilize the rapid combustion of pyrotechnic materials to produce hot gases. The combustion is typically initiated using an electric source. Alternatively, the Goodyear Corporation developed a device during the Mars Voyager program that used the evaporation of liquid methanol instead of combustion.[4,5] Upon release from its container, the methanol rapidly evaporated in the low pressure of the ambient test environment. The gas generated was used to inflate a soft-good drag body similar to the LDSD SIAD device.

Both the pyrotechnic and previous methanol gas-generating devices presented a few problems for the PDD system:

1. The ballute must only be inflated once it has been extracted from its containment bag. If it is inflated while still in the bag, it may be damaged.

2. The bag is stripped off once the ballute reaches the end of its bridle, the tether that connects it to the SFDT vehicle, at a distance of more than 40 meters. Any initiation of the device must take place remotely. An electrically actuated device would require a remote power source and an independent distance or time-based trigger.

3. The device must be able to withstand the high acceleration loads (up to 800 g's) generated during the PDD mortar fire event, and during the snatch event when the ballute reaches the end of its bridle, without initiating. The previous methanol-based device utilized a bag for containing the methanol, which posed significant risk of rupture.

4. The inflation of the ballute takes place in a highly dynamic environment, and it is unknown exactly what shape the un-inflated ballute will assume at the time of inflation. The hot gases generated by a pyrotechnic device have the potential to damage the ballute material if they are directed against it.

5. Structural damage could occur if the ballute was over-pressurized, either locally due to material that has yet to unfold from its packed configuration, or globally due to air inlets that fail to open. Once initiated, pyrotechnic devices typically cannot be throttled or shut off, which could result in over pressurization.

II.B. Previous Research and Technologies

Research in to various methods for gas generation yielded several possible options, which included a pyrotechnic propellant, pressurized helium, and a methanol/water mixture. The pyrotechnic option was dismissed because of the potential for damage to the ballute caused by high-temperature combustion gases. The helium approach was dismissed because of the large volume envelope that would be required by the storage tank. Ultimately, the methanol solution approach was selected for the design.

Once the methanol solution was selected, a method for remotely initiating the device was investigated. While initiation could involve an electronic timer or time-delay pyrotechnic device, the preferred solution was to take advantage of the large forces generated during the ballute line-stretch and bag-strip events. The mechanical means of initiation was most easily implemented using a lanyard that was attached to the ballute burble fence, which would be tensioned as the burble fence was stripped from the ballute bag.[2]

A lanyard initiation scheme lent itself to a device similar to those used on modern firearms. In firearm ammunition, a pyrotechnic initiator (primer) and small amount pyrotechnic propellant are used to generate gases, which can be used to do work. Instead of propelling a projectile, the gases could be used to pressurize and rupture a vessel containing the methanol solution.

II.C. Theory of Device Operation

The IA takes advantage of the phase change parameters for methanol. It is a liquid at standard temperature and pressure. However, methanol vaporizes in the decreased pressure experienced at ballute deployment. Goodyear Aerospace originally investigated the use of a phase change liquid for ballute inflation in the 1960's.[4,5] However, the methanol will not completely vaporize unless there is enough energy available to make the phase transition (provide the heat of vaporization). The energy provided by the low-pressure deployment environment is not enough on its own to guarantee complete vaporization. Therefore, a combination of methanol and water is used to aid the deployment of the ballute. Water is added to the methanol because it freezes under the deployment conditions, liberating more energy for the methanol to vaporize and inflate the ballute. Energy is also provided by the structure of the inflation aid and the ballute itself.

II.C.1. Properties of Methanol (CH_4O)

At ground-ambient conditions, pure methanol has a density of 791.8 kg/m^3, a gas constant of 259.5 J/kg-K, and a specific heat of 2.386 kJ/kg-K (Ref 6). The saturation temperature and the heat of vaporization change with pressure and temperature, respectively, and are estimated in figures 4 and 5.

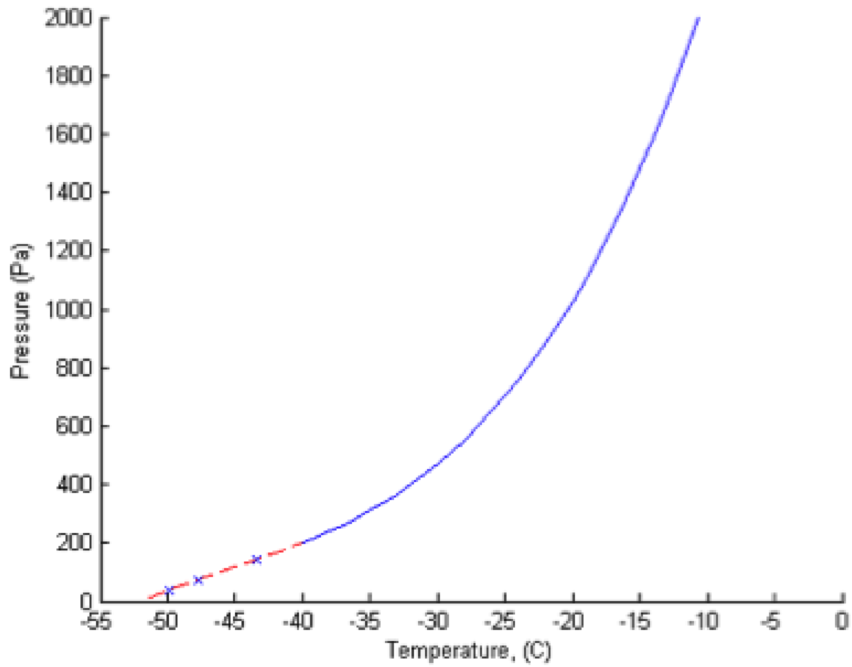


Figure 4: Methanol saturation temperature as a function of pressure. The blue solid line represents data from NIST webbook.[6] The red, dashed line is extrapolated data from that curve into the region of interest for this problem. The blue x's mark the three possible deployment conditions.

Data for the saturation temperature of methanol was gathered from National Institute of Standards and Technology (NIST) Webbook[6] and is plotted in blue in figure 4. The NIST data was extrapolated to include the relevant pressure range for this application and is represented by a dashed red line in figure 4. It is important to note that increased error is associated with the extrapolated region, since it lies beyond the region for which data could be found.

Potentially the most important variable in the ballute inflation design is the heat of vaporization for methanol. Data from the Methanol Institute[7] was used to approximate this parameter, see figure 5. The heat of vaporization changes substantially with temperature. Therefore, the deployment conditions drive the amount of energy required to pressurize the ballute.

II.C.2. The Role of Water (H_2O) and Sub-scale Testing

Water is used to provide energy for this application by freezing under the deployment conditions. At sea level conditions, pure liquid water has a density of 1000 kg/m^3 and water vapor has a gas constant of 461.5 J/kg-K and a specific heat of 4.187 kJ/kg-K (liquid phase).

It should be noted that water could actually take up a lot more energy than it contributes if it were to vaporize instead of freeze. Just like methanol, the water requires substantial energy to vaporize (almost an order of magnitude more than it produces by freezing). The heat of vaporization of water is much larger than for methanol. Therefore it is important to rule out this problem. Sub-scale testing of water and

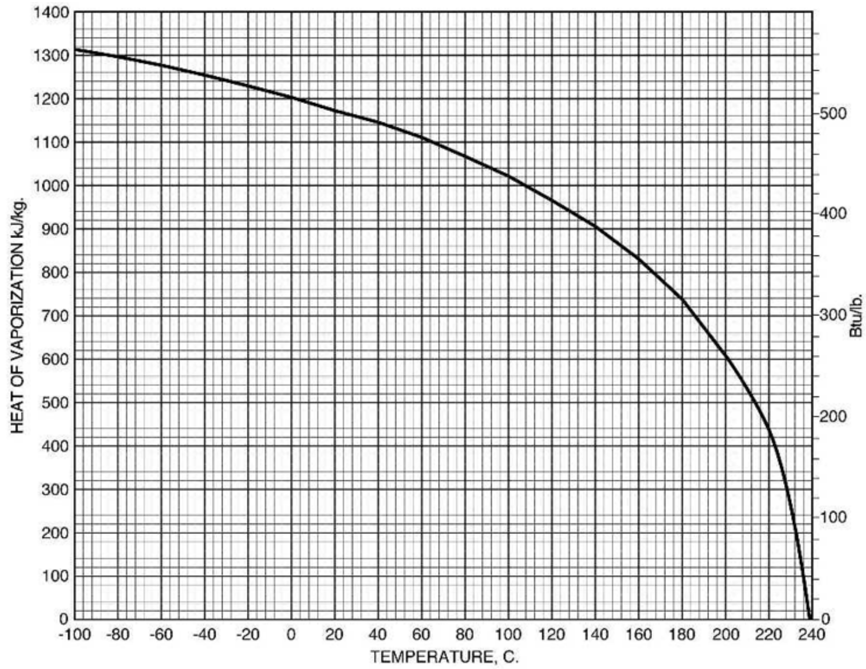


Figure 5: Latent Heat of vaporization as a function of temperature for Methanol. Data from the Methanol Institute[7]

methanol mixtures was performed in a bell jar pressure chamber at JPL. The testing confirmed that at room temperature and deployment pressure, the methanol vaporizes while the water forms ice. Ice crystals were clearly shown through the clear glass bell jar. These tests also showed that the water will transition from ice to water vapor relatively quickly due to an abundance of heat sources in the test chamber (e.g. thick metal baseplate, glass jar). This often resulted in a double pressure peak. The first peak was determined to be mainly methanol (though in many cases slightly high for the prediction due to excess available energy) and the final pressure approached that expected if both the methanol and water were to vaporize.

It is possible that some of the water could vaporize leading to higher ballute pressures. The maximum pressure due to vaporization of water is pressure dependent. The saturation temperature of water in a fully inflated ballute (from methanol vaporization) is about $-2\,^{\circ}\mathrm{C}$, however, it is closer to $-15\,^{\circ}\mathrm{C}$ before the ballute is inflated. As such, the corresponding maximum pressure is dependent on when the water transitions to vapor. It is important to make sure the ballute can withstand the additional pressure, however, no credit can be taken for the additional pressure because the main function of the water is to freeze (liberating energy for methanol vaporization).

II.C.3. Water/Methanol Mixture

Methanol requires a substantial amount of energy to vaporize. As discussed in the previous section, water is added to the system to liberate heat (as it freezes) and enable more complete vaporization of the methanol. A mixture of 75% methanol and 25% water (by mass) was selected based on Refs. 5 and 4 and some testing conducted at JPL.

There are some drawbacks to the particular combination being used. While adding water to the methanol helps, the flash point of the 75/25 mixture is still approximately $15\,^{\circ}\mathrm{C}$.[8] Therefore, the mixture must be treated as extremely flammable. The mixture also must be kept from freezing, because it could damage the container. Freezing temperature of various mixtures of water and methanol is given in figure 6. Thankfully, for a 75% concentration of methanol, the mixture will freeze at approximately $-107\,^{\circ}\mathrm{C}$. This temperature is considerably lower than the lowest expected temperature of the inflation aid, thus the liquid mixture will not freeze prior to initiation.

The density of mixtures of methanol and water are given in figure 7. For a mixture that is 75% methanol and 25% water by mass, the density can be calculated via Eq. 1 as a function of the fluid temperature in

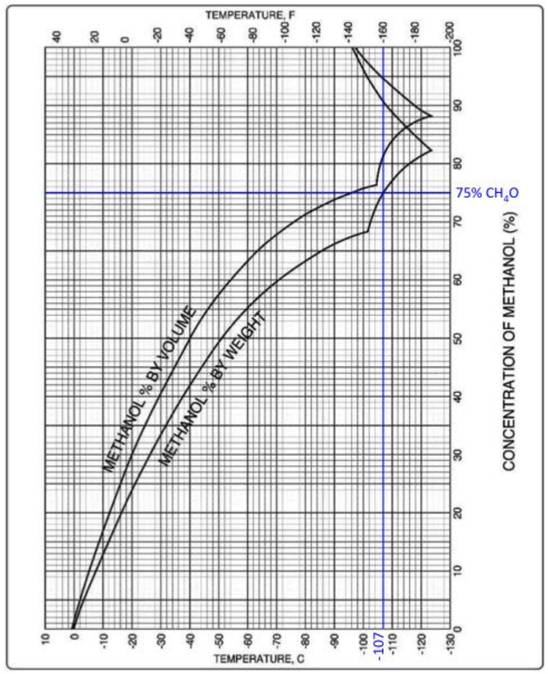


Figure 6: Freezing temperatures of mixtures of methanol and water.[9]

degrees Celsius.

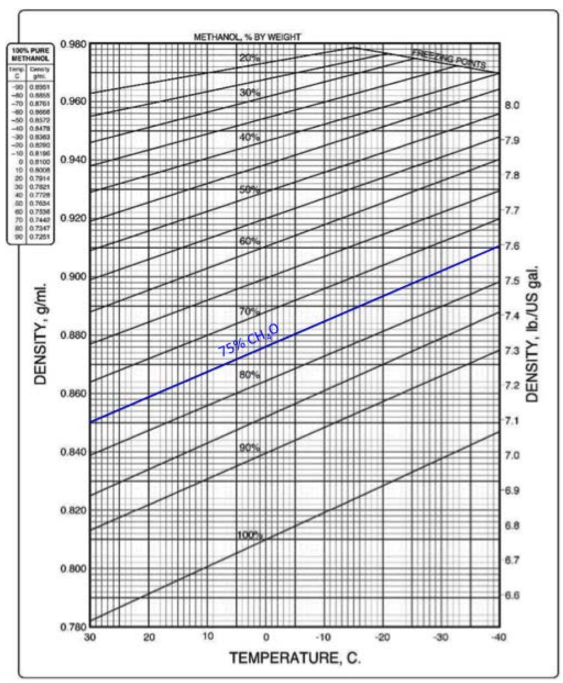


Figure 7: Density of methanol and water mixture ratios.[10]

$$\rho = -8.6107 \times 10^{-4} T + 0.87597 \tag{1}$$

II.C.4. Methanol and Water Volume Required for Inflation Aid

The mass of methanol required to fill a given volume (m_{CH_4O}) assuming complete vaporization can be estimated by assuming that methanol behaves as an ideal gas as in Eq. 2. This assumption is valid because methanol typically has a compressibility factor very near one.[11] The amount of methanol needed to generate the required ballute pressure is calculated under the worst-case conditions.

$$m_{CH_4O} = \frac{p_b V_b}{R_{CH_4O} T_{sat,CH_4O}} \tag{2}$$

The methanol mixture needs to provide an initial ballute pressure (p_b) of half of the ballute internal pressure under the deployment conditions, with a 95% confidence. As a starting point for the design, the maximum required ballute pressure was assumed to be 500 Pa. Additional margin was added by targeting an inflation pressure 5% above the ballute pressure. The estimated deployment conditions are listed in table 4 of the Appendix. The "worst-case" condition corresponds to a deployment at 55 km, which yields the lowest ambient pressure. The corresponding saturation temperature of methanol is approximately −57.7 °C (215.5 K). The volume (Vb) of the ballute is approximately 28.1 m^3. Using these inputs, the mass of methanol required for the inflation aid is approximately 0.265 kg

To achieve a 75/25 mass ratio between methanol and water, respectively ($X_{CH_4O} = 0.75$), the required mass of water is equal to 0.088 kg per Eq. 3. Thus the total mass of methanol and water mixture is 0.353 kg.

$$m_{H_2O} = m_{CH_4O} \left(\frac{1}{X_{CH_4O}} - 1 \right) \tag{3}$$

Per figure 7, the density of a mixture of water and methanol changes based on temperature. The allowable temperature of the IA ranges from 90 °C, when the unit is heated within the PDD pack, to 3 °C, the lowest operating temperature expected during flight of the SFDT vehicle. Under these conditions, the density of the methanol mixture ranges from 0.807 g/cc to 0.873 g/cc. The range of fluid volumes subsequently varies from 404.2 cc at 3 °C to 442.1 cc at 90 °C. The volume of the Inflation Aid reservoir, and pressure of any air remaining in a partially filled reservoir also changes with temperature. To allow for uncertainties in the fill amount, and prevent a breach of the rupture disk due to methanol expansion, the volume of the reservoir was selected to be 440 cc, with 29 cc of ullage at room temperature.

II.C.5. Methanol Vaporization Energy

The methanol requires a substantial amount of heat to vaporize, which can be calculated from Eq. 4. The heat of vaporization (ΔH_v) for methanol is temperature dependent, as shown in figure 5. The maximum amount of energy required to vaporize the methanol will occur when the system is the coldest.

$$Q_{v,CH_4O} = m_{CH_4O} \Delta H_{v,CH_4O} \tag{4}$$

The available energy to vaporize the methanol, Eq. 5, comes from various sources in this system, including the sensible heat from depressurization (Q_{s,CH_4O}), the heat of fusion from the water in the mixture (Q_{f,H_2O}), as well as heat from the ballute material (Q_b), and the IA reservoir itself (Q_{IA}).

$$Q_{avail} = Q_{s,CH_4O} + Q_{f,H_2O} + Q_b + Q_{IA} \tag{5}$$

The sensible heat from depressurization of the methanol is given in Eq. 6. The IA and ballute are insulated from the ambient temperature by the presence of the vehicle thermal blanketing, and thus T_{deploy} will be higher than the ambient temperature.

$$Q_{s,CH_4O} = m_{CH_4O} C_{p,CH_4O} (T_{deploy} - T_{sat,CH_4O}) \tag{6}$$

Assuming all of the water freezes and liberates its energy for methanol vaporization, its heat of fusion will also be available. The heat of fusion of water ($\Delta H_{f,H_2O}$) is 334 KJ/kg, and its contribution is calculated using Eq. 7

$$Q_{f,H_2O} = m_{H_2O} \Delta H_{f,H_2O} \tag{7}$$

The heat from the ballute fabric scales with the amount of fabric in contact with the methanol/water mixture, and is estimated assuming a specific heat ($C_{p,b}$) of 1.44 kJ/kg-K. The best-case scenario assumes that there is 100% contact between the liquid and the ballute (η_b= 1). A more conservative scenario of 10% contact (η_b= 0.1) was used for design calculations. The ballute mass is approximately 10 kg, and the available energy from the ballute is given from Eq. 8.

$$Q_b = \eta_b m_b C_{p,b}(T_{deploy} - T_{sat,CH_4O}) \tag{8}$$

The IA reservoir itself can impart some energy (Q_{IA}) into the liquid for vaporization, which is calculated using Eq. 9. The IA mass is approximately 2.2 kg and constructed mainly from aluminum, with a specific heat ($C_{p,Al}$) of 0.9 kJ/kg-K. However, the liquid is only in contact with a portion of the inflation aid, assumed to be approximately 10% (η_{IA}=0.1).

$$Q_{IA} = \eta_{IA} m_{IA} C_{p,IA}(T_{deploy} - T_{sat,CH_4O}) \tag{9}$$

The amount of methanol that can be vaporized using the available energy, and the corresponding increase in ballute pressure that will result can be calculated using Eqs. 10 and 11, respectively.

$$m_{avail,CH_4O} = \frac{Q_{avail}}{\Delta H_{v,CH_4O}} \tag{10}$$

$$p_{avail,CH_4O} = \frac{m_{avail,CH_4O} R_{CH_4O} T_{sat,CH_4O}}{V_b} \tag{11}$$

If the PDD system is at the local ambient temperature when the SFDT is launched, the minimum estimated temperature will be 3 °C at the time of PDD deploy. The energy contributions for an unheated PDD were calculated using the properties listed in table 6 in the Appendix, and the results are presented in table 2. The results indicate that there remains a significant energy deficit, and the maximum attainable pressure is 295 Pa.

Table 2: Energy Summary for Deployment at 55 km Altitude with Deployed Hardware at 3 °C

Energy	Amount (kJ)
Req'd for methanol vaporization	-317.1
Depressurization	+38.9
Fusion of liquid water	+29.4
Ballute contact	+87.4
Inflation aid contact	+12.0
Deficit for full vaporization	-149.3
Vaporized Mass, m_{avail,CH_4O}	0.148 kg
Pressure Generated, p_{avail,CH_4O}	295.1 Pa

The amount of available energy may be increased if the temperature at deployment is increased. Prior to launch, the PDD pack is heated to 80 °C such that, at the time of deployment the minimum temperature of the IA is 40 °C.[2] The energy contributions for a heated PDD were calculated using the properties listed in table 7 in the Appendix. At the elevated temperature the IA nearly becomes self-sufficient, as shown in table 3.

Figure 8 shows the results from an 8,000-case Monte Carlo simulation of the expected inflation pressures produced using the flight vehicle trajectory dispersion. The simulation assumes an IA with an initial temperature of 40 °C and 0.353 kg of methanol solution. The contour lines represent the ballute dynamic pressure for the given deployment altitude and velocity. As shown in the scale to the right, the color of each point indicates the inflation pressure as a fraction of the ballute pressure for that case. Cases with fractions greater than 0.5 satisfy the requirement that the inflation pressure is at least 50% of the ballute dynamic pressure.

A histogram may be generated from the results of a simulation like the one shown in figure 8. Figure 9 presents the results for two such simulations. The figure on the left corresponds to a deployment temperature

Table 3: Energy Summary for Deployment at 55 km Altitude with Deployed Hardware at 40 °C

Energy	Amount (kJ)
Req'd for methanol vaporization	-303.0
Depressurization	+68.4
Fusion of liquid water	+29.4
Ballute contact	+140.7
Inflation aid contact	+19.3
Deficit for full vaporization	-45.2
Vaporized Mass, m_{avail,CH_4O}	0.246 kg
Pressure Generated, p_{avail,CH_4O}	489.1 Pa

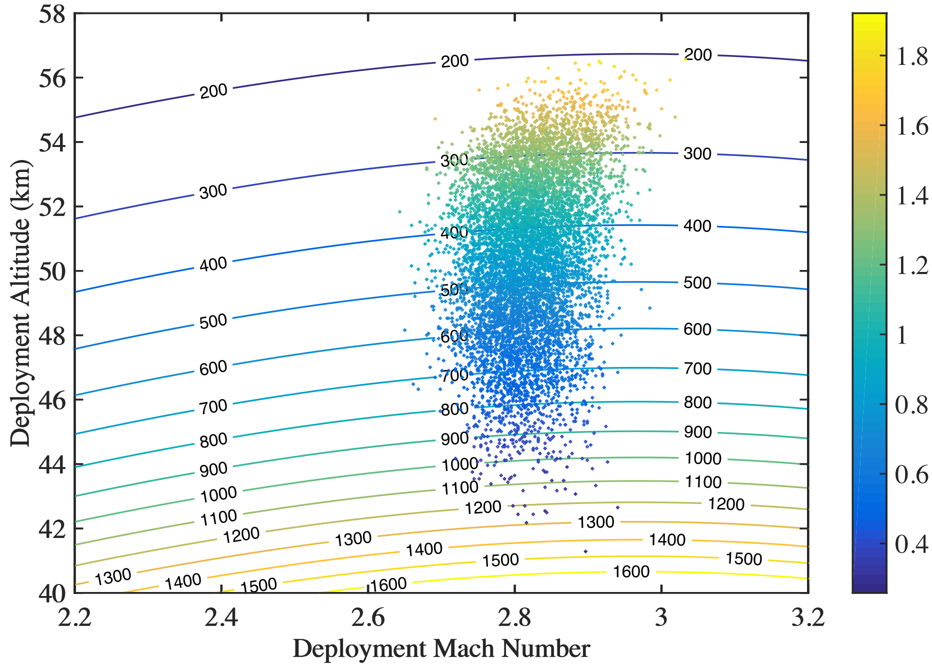
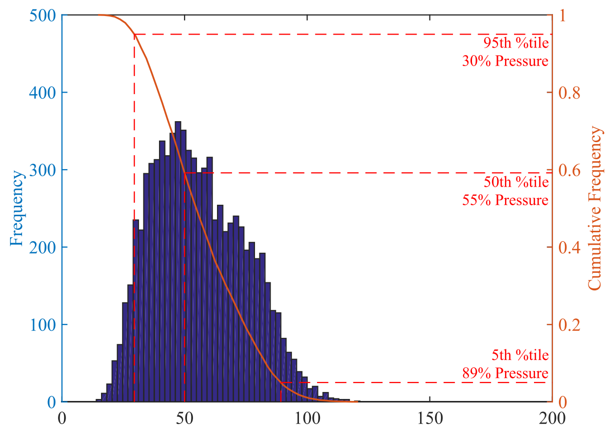
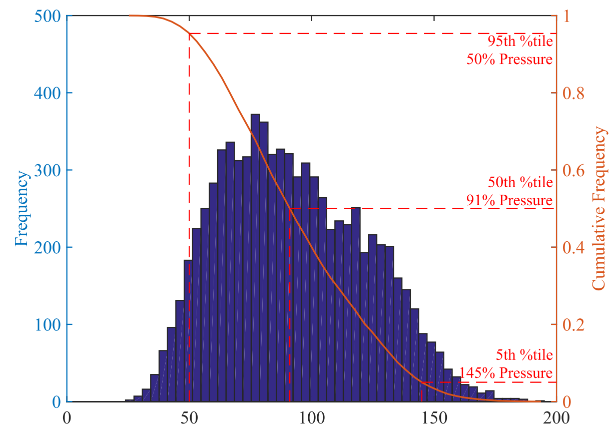


Figure 8: Monte Carlo simulation of the expected inflation pressures produced using the flight vehicle trajectory dispersion for an IA at 40 °C with 0.353 kg of methanol solution. The contour lines represent the ballute dynamic pressure for the given deployment altitude and velocity. The color of each point indicates the inflation pressure as a fraction of the ballute pressure for that case.

of 3 °C, while the figure on the right corresponds to a deployment temperature of 40 °C. As indicated in the figure, the 95th percentile minimum inflation pressure is 30 percent of the ballute pressure if the IA is unheated. If the deployment temperature is increased to 40 °C, the 95th percentile minimum pressure increases to 50 percent of the ballute pressure, and satisfies the IA performance requirement.



(a) Deployment at 3 °C



(b) Deployment at 40 °C

Figure 9: Histogram of the results of two 8000-case Monte Carlo simulations of the expected inflation pressure as a percentage of the ballute internal pressure. The simulations assume 0.353 kg of methanol solution and the indicated deployment temperature for the IA and ballute.

II.D. Overview of Device Components

The IA device, shown in figures 10 and 11, consists of a housing, which contains a pair of redundant firing mechanisms and combustion chambers, a reservoir that is filled with an aqueous methanol solution, and a rupture disk. The forward (venting) end of Inflation Aid is inserted in to the mouth of the ballute, and threads in to an attachment shroud that forms the mechanical connection to the ballute. The riser from the SFDT vehicle connects to a pin on the aft end of the IA. An aerodynamic shroud shields the exposed part of the device from the oncoming supersonic air flow. Two redundant trigger lanyards run along side the ballute, and are inserted in to the firing mechanism.

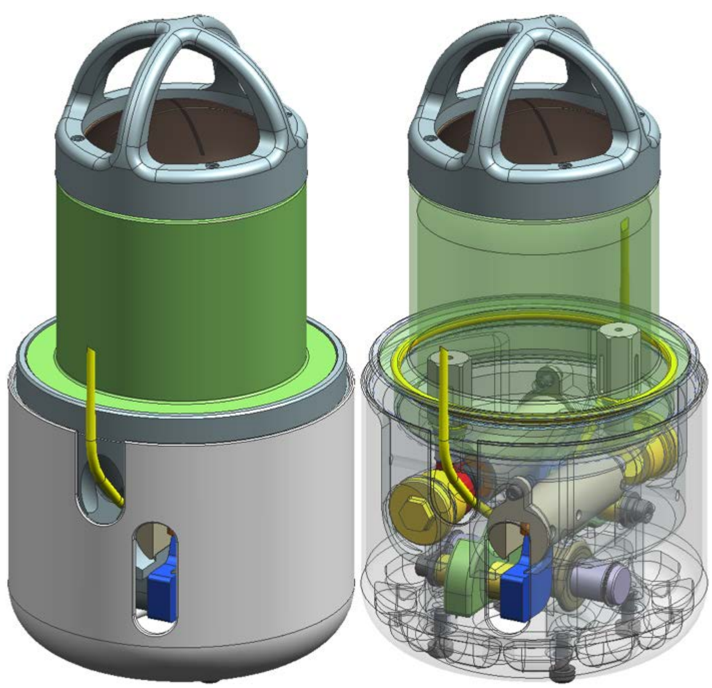
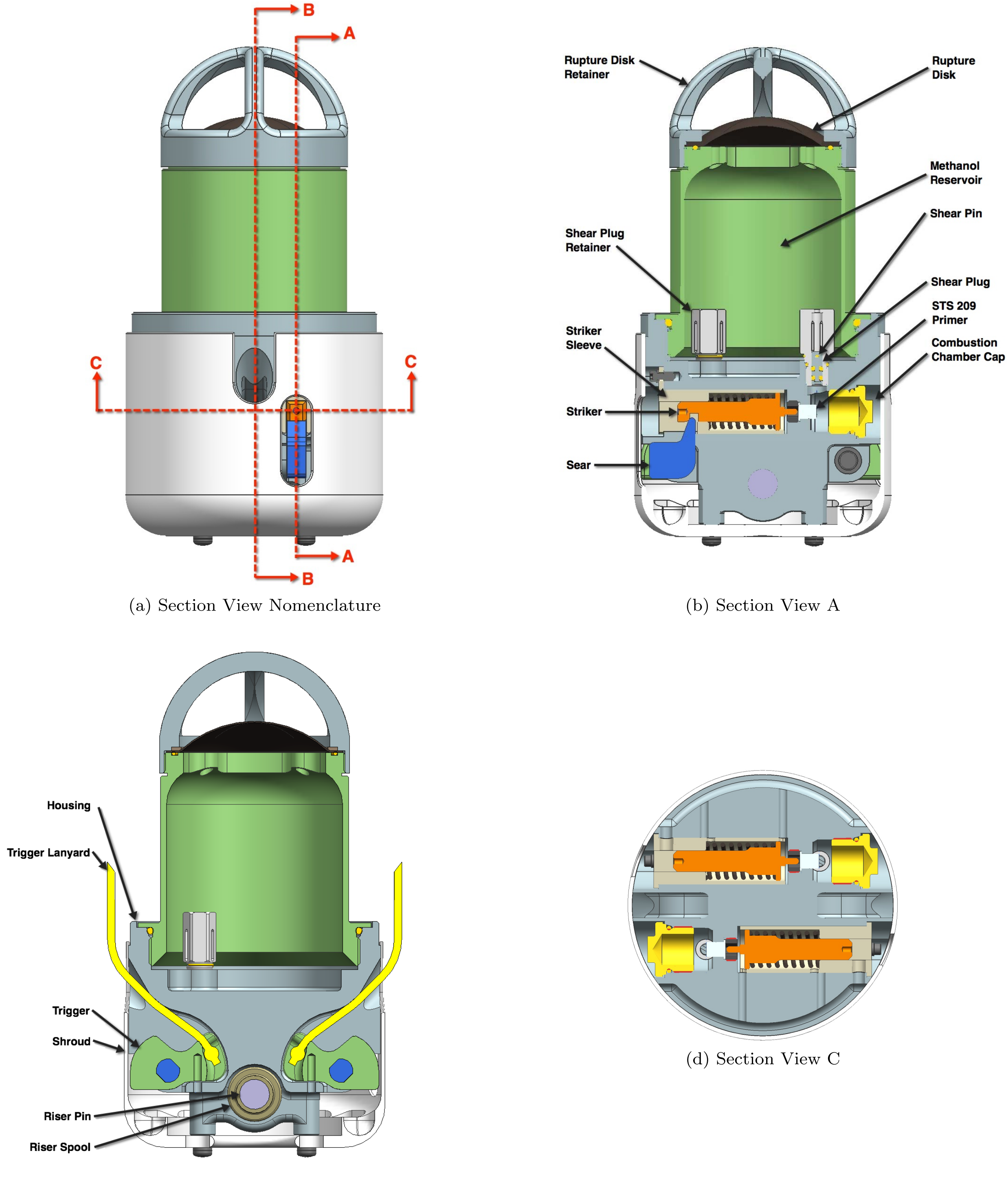


Figure 10: The Inflation Aid Assembly.

The housing is fabricated from 7075-T7351 aluminum. A chemical conversion coating protects the internal surfaces of the housing from corrosion due to contact with the methanol solution and black powder. The housing serves several roles, and as a result is the most complex component of the IA. The housing aligns the



(a) Section View Nomenclature

(b) Section View A

(c) Section View B

(d) Section View C

Figure 11: Cross-section views of Inflation Aid Assembly.

firing mechanism components and the shot shell primers, contains the black powder combustion chambers, forms liquid-tight seals with the methanol reservoir, and forms the primary load path between the riser and the ballute.

The triggers, sears, and strikers are fabricated from hardened Maraging 300 steel. This material was selected in order to provide high strength and hardness, while reducing the size of the firing mechanism components. The striker sleeves are fabricated from Nitronic 60® stainless steel in order to reduce the potential of galling with the striker.

The pyrotechnic ordnance consist of two STS 209 shot shell primers, and 1.2 g of smokeless black powder in the combustion chambers, 600 mg per chamber. The primers are pressed in to the housing, and retained via a set screw. The combustion chambers are sealed with hardened 17-4PH stainless steel caps, and 300-series stainless steel shear plugs. The plugs reside within hardened 17-4PH retainers that are threaded in to the housing. Brass pins retain the plugs, until they are sheared off when the combustion chamber pressures exceed 3000 psi, allowing the combustion gasses to pressurize the reservoir.

The reservoir used on the SFDT-1 flight was fabricated from 6061-T651 aluminum with a chemical conversion coating. The design for subsequent flights has been modified, and the material has been changed to electroless nickel-plated 7075-T351. The change was made in order to strengthen the reservoir and improve the galling resistance of the threaded interfaces with the housing and rupture disk retainer. The rupture disk retainer clamps the rupture disk against the reservoir, and disperses the exiting flow of methanol once the disk has burst.

The rupture disk is made from a nickel alloy, and is designed to rupture when the pressure within the reservoir reaches approximately 500 psi. Adequate dispersion of the methanol was observed when using a rupture disk with a significantly lower burst pressure, however the higher-pressure disk was selected to increase robustness of the design in its operating environment. When the IA is heated, thermal expansion of the methanol generates internal pressures in excess of 200 psi. The acceleration of the IA during the riser snatch event can generate pressures in excess of 120 psi as the methanol is pressed against the disk.

The interfaces between the combustion chamber caps, shear plug retainers, reservoir, and housing were designed to the SAE J1926 fluid port specification,[12] while the rupture disk utilizes an O-ring face seal with the reservoir. All fluid and gas-retaining interfaces utilize silicone O-rings that are resistant to methanol.

II.E. Firing Mechanism Operation

The firing mechanism of the IA, shown in figure 12, contains a configuration and components similar to the design found in many modern firearms. The activation of the IA takes place as follows, and is also shown in figure 13:

1. The ballute pack (with the IA inside) is ejected from the test vehicle with a mortar, and travels away from the SFDT vehicle, while paying out bridle line.
2. The pack snatches when it reaches the end of the riser, and the ballute is stripped out of its bag.
3. The ballute unfolds, tensioning the Trigger Lanyards and pulling them out of the IA.
4. Initially, compression springs hold the strikers in the forward extended position. The sears are engaged in the slot of the Strikers, and rotated clockwise by the compression springs until they hit a hard stop. The triggers, mounted on the shafts of the sears are also rotated clockwise, and retain the knotted trigger lanyards within their cavities. As load is applied to the lanyards, they rotate the triggers, which rotate the sears, which retract the strikers, compressing the springs.
5. As the lanyards and triggers travel through their range of motion, the sears will eventually rotate to a point where they lose contact with the strikers.
6. The strikers are no longer restrained by the sears, and are propelled forward by the springs until they contact the primers, initiating combustion.
7. The sears and triggers, no longer in contact with the strikers, continue to rotate. Once the triggers have rotated sufficiently, the lanyards are pulled free. The sears and strikers continue to rotate until they contact hard stops.
8. The primers ignite charges of black powder in the combustion chambers, which burn until the pressure in the chambers is sufficiently high to shear the shear pins, releasing the shear plugs, and venting the gas in to the methanol reservoir.
9. The pressure increases in the reservoir until the rupture disk bursts, venting the methanol solution in to the interior of the ballute.

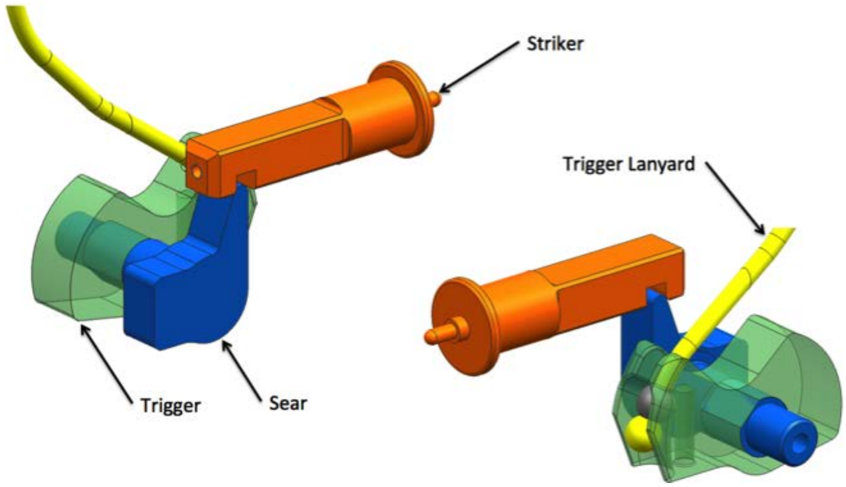
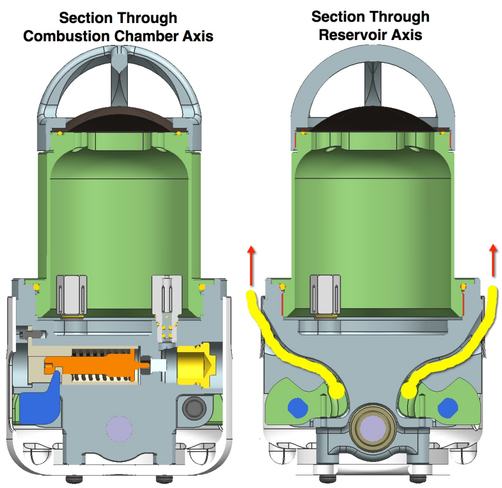
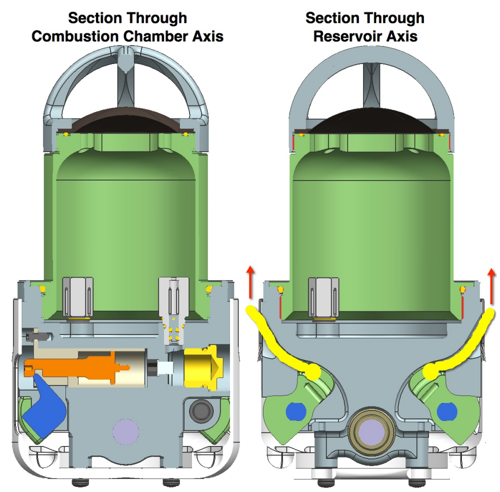


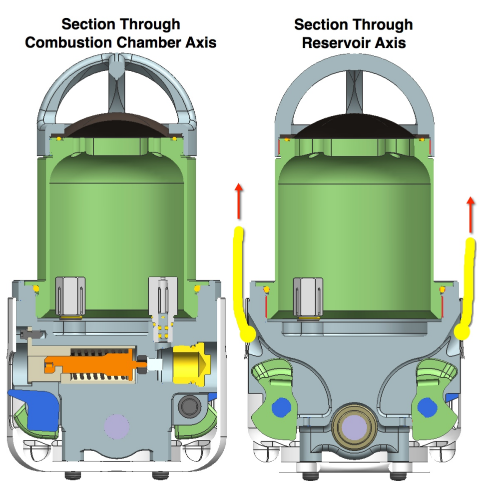
Figure 12: Detail view of the IA Firing Mechanism components.



(a) Initial Lanyard Motion



(b) Maximum Striker Retraction



(c) Striker/Primer Contact, Lanyard Release

Figure 13: The Inflation Aid firing process, from lanyard pull to striker contact with primer. In step "a" trigger lanyard pull is initiated. In step "b" the striker is retracted as the lanyard rotates the trigger and sear. Finally, in step "c" the striker is thrust forward by the compression spring, initiating the primer.

II.F. Gas-Generating Propellant

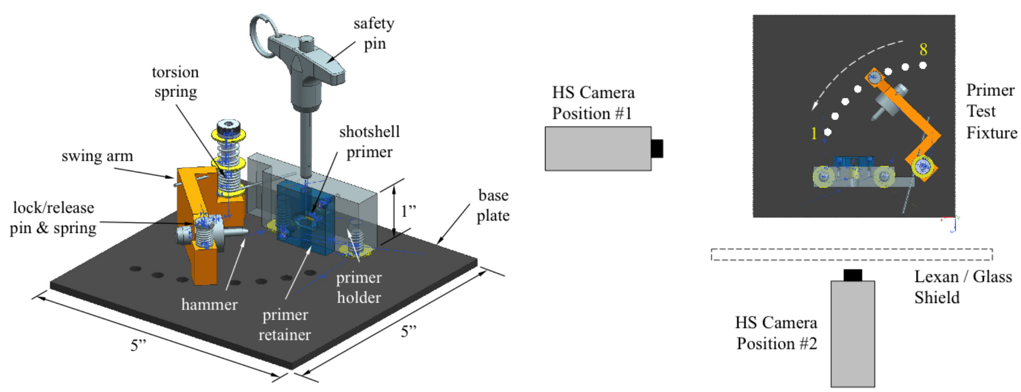
The purpose of the propellant is to increase pressure in the methanol reservoir above the burst pressure of the rupture disk, resulting in a discharge of the methanol from the IA. The initial propellant combustion occurs in a small combustion chamber in order to increase the temperature and pressure, and thus the efficiency of the combustion process. Once the combustion chamber pressure exceeds a prescribed value, governed by the force required to shear pin, the gases are vented in to the reservoir.

Smokeless black powder was selected as the propellant material due to its wide availability and relatively low risk of accidental discharge due to the shock or temperature environment expected during handling and flight. A series of discharge tests using a developmental model of the IA determined that a propellant charge of 400 mg, in a combustion chamber with a volume of 4 cm^3, with a shear pin that ruptures at 3000 psi, generates sufficient pressure to burst the rupture disk. In order to provide an adequate margin of safety in the event of low propellant performance, a 600 mg nominal propellant charge was selected. In the flight design of the IA, the propellant charge and shear pin remain the same as those used in developmental testing, however the combustion chamber volume was decreased to 3.76 cm^3.

III. Pre-flight Performance Testing

III.A. Bench-Top Primer Testing

A standard off-the-shelf STS 209 shot shell primer was used to ignite the high-temperature powder within the IA. The primary reason for using a percussive initiator instead of an electrical initiator (such as a NSEI) is because the ballute is trailing behind the vehicle by approximately 140 ft at the time that the IA needs to be initiated. Although the primers are widely used in firearms, the amount of impulsive force required to initiate the primer was not known (and is not provided by the manufacturer). As such, the percussive force required to initiate the primer was determined through testing. Primer testing was performed inside the Pyrotechnics Laboratory at JPL using the Primer Test Fixture, shown in figure 14a.



(a) Primer Test Fixture

(b) Primer Test Setup

Figure 14: Primer Test Details.

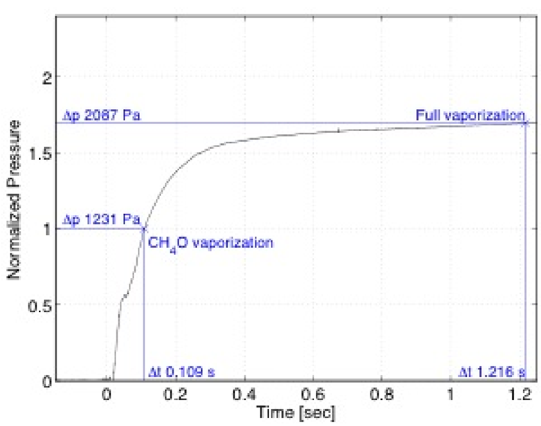
The primer was placed in the holding block and is held inside by the retainer plate. A pin was inserted through the retainer plate as a safety measure to prevent accidental primer ignition. A swing arm with a hammer on the end was energized using a torsional spring and could be cocked at various locations on the base plate using the lock/release clevis pin. This clevis pin was restrained underneath the base plate using a cotter pin. Upon release of the cotter pin, the release spring ejected the clevis pin and the swing arm rotated to impact the primer. The amount of spring force was calculated based on the position of the swing arm and the rated torsional load of the spring. The velocity of the firing pin at impact was measured using photogrammetry collected from high-speed video, as shown in figure 14b. Through this testing, the primers were shown to fire when the firing pins had a kinetic energy of about 0.6 J, and a momentum of 73 kg-mm/s. In order to provide an additional margin of safety, a compression spring was selected to provide the striker with approximately 1.0 J of energy and a momentum of 230 kg-mm/s.

III.B. Vacuum Chamber Inflation Testing

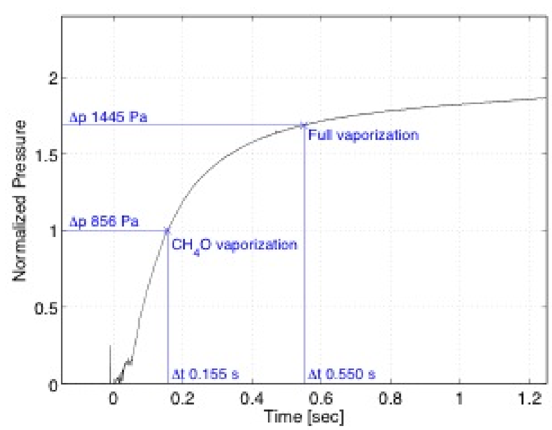
Vacuum chamber testing on a prototype design of the IA was conducted in the 10 ft vertical thermal vacuum chamber at JPL. The purpose of these tests was to observe how the methanol/water mixture is ejected from the IA into a near vacuum and how the mixture subsequently vaporizes. Various instruments were present to record the vaporization process and to measure the pressure delta caused by the vaporization. Vacuum chamber testing occurred in two parts. First, the IA device ejected methanol and water into the chamber so that the dispersion and vaporization could be visually observed; the results are shown in figure 15. Secondly, a ballute test article and a pressure tap were attached to the IA, as shown in figure 16. The liquid mixture was exhausted into the ballute, causing inflation, and internal pressure measurements were taken, with the results shown in figure 17.

Four successful tests were run, and the recorded pressure change (normalized to expected pressure from 100% methanol vaporization) is shown for each test below. Note that different absolute pressures were obtained during each test because different amounts of methanol were used in each test.

1. Test 1 contained no ballute and the IA was left at room temperature (20 °C). It released the methanol mixture into the vacuum chamber volume.
2. Test 2 also did not use a ballute, but the IA was cooled with an LN2 cold plate to −12 °C (15 °C below the anticipated worst-case cold scenario). It is important to note that the walls of the chamber were still at room temperature, so any methanol in contact could draw significant thermal energy.
3. Test 3 had a 4.2 m (near full-scale) ballute secured to the IA and all contents were at room temperature (20 °C). The 10 ft. chamber diameter was about 3.5 ft smaller than the fully inflated ballute diameter.
4. Test 4 also had a ballute over the I/A. The IA was cooled with an LN2 cold plate to −12 °C.



(a) Test 1

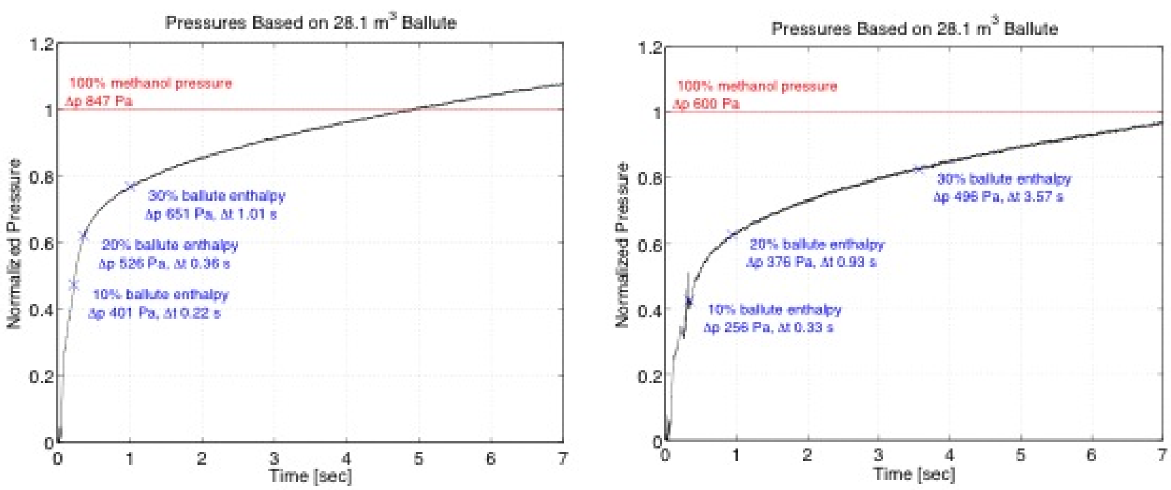


(b) Test 2

Figure 15: Normalized pressure increase as a function of time for Vacuum Tests 1 and 2. Pressure increases are normalized by the amount corresponding to 100% methanol vaporization..

It is evident from the pressure curves that the ballute creates an energy-limited system. Full vaporization of the methanol does not occur until 5 to 8 seconds after firing, as compared to the tests without a ballute, which took about 0.15 seconds. Tests 3 and 4 show that about 50% of the methanol can be vaporized if 10% of the ballute's energy is extracted.

Figure 16: Test Article for Vacuum Tests 3 and 4.



(a) Test 3 (b) Test 4

Figure 17: Normalized pressure increase as a function of time for Vacuum Tests 3 and 4. Pressure increases are normalized by the amount corresponding to 100% methanol vaporization..

III.C. Bench-Top Firing Mechanism Testing

Seven series of tests were performed on the firing mechanism in order to verify its functionality and inform the design of the trigger lanyard. Each series involved discharging both of the firing mechanisms, one-at-a-time, for a total of fourteen tests. All of the tests were performed on the engineering model (EM) IA at the Pyrotechnic Laboratory at JPL. The mechanism was activated via a lanyard that mimicked the flight design in every test, but other variables such as the method of applying tension and the ambient temperature were modified.

The purpose of the tests in Series 1 was to demonstrate whether the firing mechanism would operate using a lanyard that was pre-tensioned to the load expected from the ballute. The lanyard was aligned at an angle of approximately 20 degrees relative to the IA axis. An in-line load cell was used to set and monitor the tension, while a leg of the lanyard at the IA end was restrained to the test fixture using a 3-ring release.

The test setup is shown in figure 18. The test was initiated when the 3-ring release was activated. Successful operation of the mechanism was observed for both 80 and 100 lb of lanyard tension. Following the Series 1 tests, a plastic thread liner was inserted in to the combustion chamber to protect the threads from the primer discharge. The Series 2 tests were identical to Series 1, except that the lanyard was aligned with the IA axis. The combustion chamber was also filled with a powder that would serve as a visual cue for determining when the primer had fired during Mortar Testing of the ballute pack.[2]

(a) Series 1 firing mechanism bench-top test setup. The load cell is visible in the upper right hand corner.

(b) Close up view of housing and trigger lanyard during Series 1 bench-top test. The 3-ring release is visible to the left of the housing.

Figure 18: Series 1 Bench-Top Test Setup

For the Series 4 and Series 6 tests, the trigger lanyard was slowly pulled by hand while the lanyard tension was measured using a load cell. The IA was also placed in a thermal chamber, which allowed for measuring the effect of temperature on activation load. The minimum force required to activate the mechanism, 32.3 lb, was measured at a temperature of 80 °C, which represented the upper qualification temperature limit at the time of test. The maximum force required, 45.5 lb, was measured at a temperature of −24 °C, which represented the lower operating temperature limit at the time of test. The Series 5 tests demonstrated that the mechanism behavior when activated using a dynamic load (a weight dropped at a height) was identical to the previous quasi-static tests.

The bench-top test campaign was conducted in parallel with the ballute trigger lanyard design effort. Once the lanyard design was completed, the Series 7 tests were conducted to validate the final lanyard actuation scheme.[2] In both tests the IA end of the lanyard was retained in the 3-ring release while the ballute end of the lanyard was stretched to achieve the desired load. The first test represented the flight design load of 125 lb, and required approximately 6 inches of stroke. The second test represented the 125% of the flight design load, approximately 150 lb, and required 8.5 inches of stroke. The response of the firing mechanism was nominal in both tests.

III.D. Vacuum Leak Testing

A leak test was performed on the IA to verify the functionality of the methanol reservoir seals. The test was conducted over a period of 72 hours in a vacuum chamber at JPL using the EM IA, as shown in figure 19. The test was conditions were ambient temperature and a pressure of less than 300 mTorr (actual minimum pressure prior to back-fill was 9.7E-5 Torr). The test article was weighed prior to and after the test, and no mass loss was observed.

The assembly and leak testing of the IA were both performed at approximately 20 °C. While leak testing would have ideally been performed at the extremes of the non-operating temperature environment, the nature of the design makes it resistant to leakage. The housing, reservoir, and rupture disk retainer are all made from aluminum. The shear plug retainers are 17-4PH and the plugs are 300 series stainless steel. The rupture disk is nickel and the O-rings are silicone. At temperatures above 20 °C, the expansion of the O-rings will compensate for any reduction in clamping force between the rupture disk and its retainer, and increased clearance between the shear plugs and their retainers.

At temperatures below 20 °C, the increase in rupture disk retainer clamping force will compensate for the shrinkage of the face seal O-ring. The only area of concern for methanol leakage in a cold environment is at

Figure 19: IA Vacuum Leak Test.

the interface between the shear plugs and their retainers, although analysis indicates that no clearance will be present at the lower operating temperature limit. The PDD pack was heated to an elevated temperature for the SFDT test, so leakage was not a concern; however, if an IA is used in a low-temperature application, further thermal-vacuum leak testing should be conducted.

III.E. Propellant Energy Margin Test

As part of qualification of the IA hardware, two types of propellant margin tests were performed on the IA: energy margin, strength margin. For both tests, the IA reservoir was filled completely with water, and discharged via hand pull of a Y-shaped trigger lanyard. The discharge event was observed using high-speed photography, although the pressures in the combustion chambers and reservoir were not measured. The testing occurred in the blast chamber of the JPL Pyrotechnics Laboratory using the EM IA. An example of the test setup is shown in figure 20.

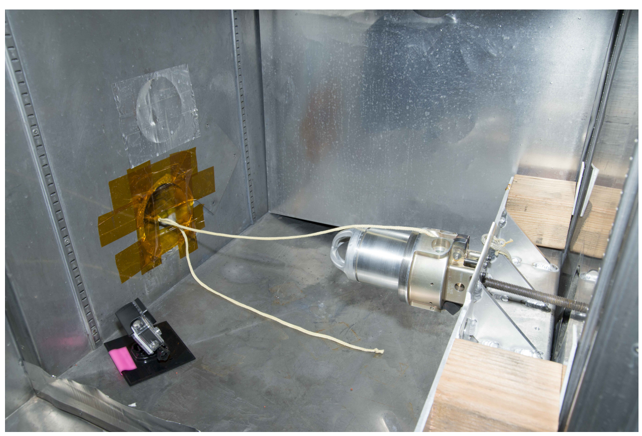
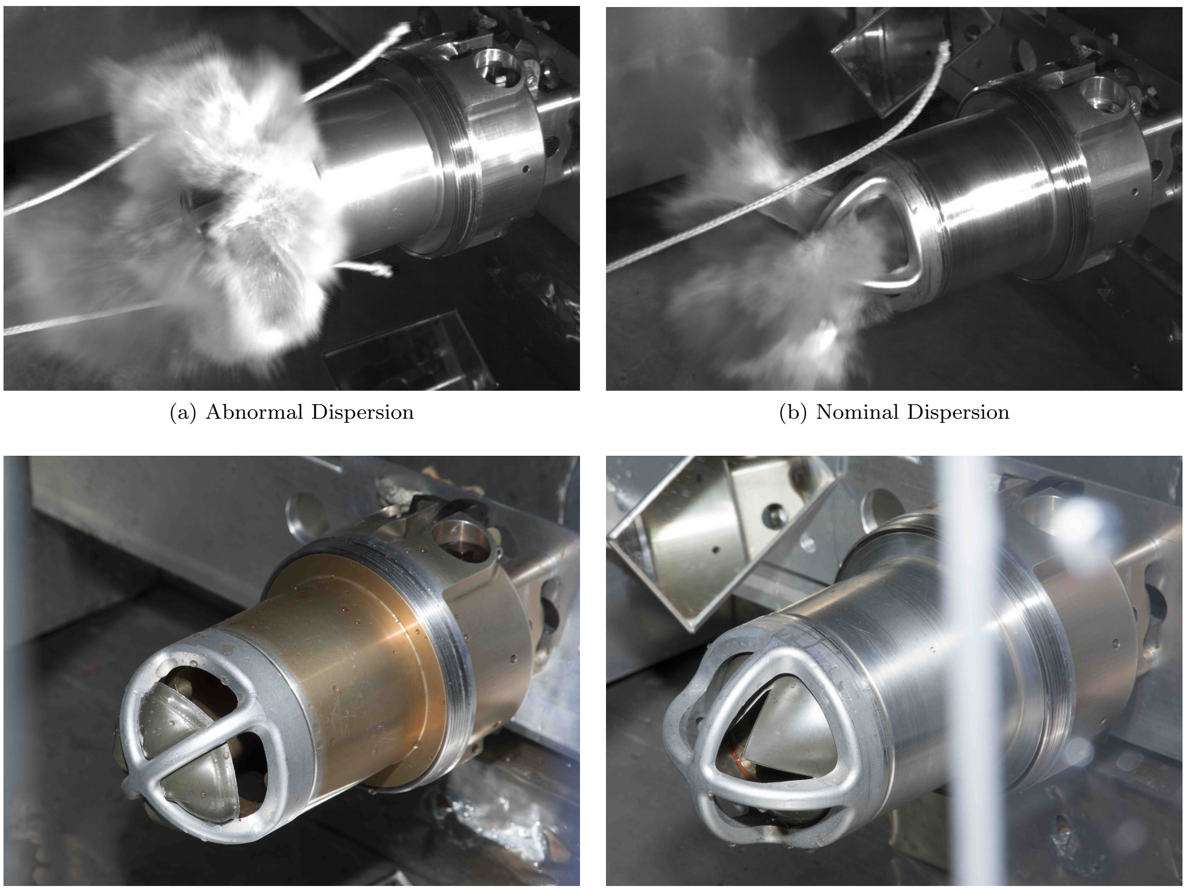


Figure 20: Propellant Margin Test Setup.

The strength margin tests involved firing both chambers of the IA simultaneously, with each chamber loaded to 120% of the nominal black powder charge. The test was designed to expose any risks to personnel or hardware safety due to structural failure. Although there was no structural failure of the IA, yielding of the reservoir was observed. The reservoir was designed such that no yielding would occur before rupture disk burst, with a factor of safety of at least 1.6. The rupture disk was designed to burst at a maximum pressure of 500 psi. Following the test, analysis using the as-built material properties indicated that, for the reservoir to yield but not rupture, the internal pressure was between 2000 and 2200 psi.

The existence of pressures above the burst pressure for the rupture disk is likely due to the extremely rapid rate of pressurization, and a water-hammer effect. The local pressure near the venting ports of the shear plug retainers increases too rapidly for the pressure wave to travel to the end of the reservoir and rupture the disk. In addition, any methanol that has been accelerated away from the vents is decelerated rapidly as it contacts the disk, resulting in a large pressure increase. The incompressibility of the water does not allow for any pressure relief, and the reservoir is yielded. In the event that the pressure caused a rupture of the reservoir, there would be little risk of damage to the ballute due to debris and the methanol would still be ejected in to the ballute. However, in order to reduce the risk of rupture, the reservoir design for the SFDT-2 and subsequent tests was modified to have positive margins of safety for the elevated pressures.

The energy margin test involved firing a single chamber of the IA, with a black powder charge that is 67% of the nominal amount. The test was designed to indicate whether the rupture disk would burst if only one propellant charge was initiated, and had lower than predicted gas-production. The first instance of test resulted in an unexpected failure mode of the rupture disk. Rather than splitting along its stamped seams, the rupture disk was pushed out from its clamped interface and pinned against the arched portion of the retainer, as shown in figure 21. This failure mode exhibited significantly reduced forward dispersion as the methanol exited the reservoir.



(a) Abnormal Dispersion

(b) Nominal Dispersion

(c) Abnormal Disk Failure, Post Test

(d) Nominal Disk Failure, Post Test

Figure 21: Energy Margin Testing of the IA. An abnormal rupture disk failure and the resulting dispersion are shown on the left. A nominal rupture disk failure and the resulting dispersion are shown on the right after the rupture disk retainer preload was increased.

The corrective action for the unexpected failure involved increasing the preload between the rupture disk and its retainer. When the test was repeated, the IA and rupture disk performance were nominal. An additional energy margin test was performed in a vacuum chamber at JPL. The test was conducted at ambient temperature and a pressure of 300 mTorr. The I/A reservoir was filled with 353 g of aqueous methanol (29 CC of ullage) instead of water, and a single firing mechanism was activated via a solenoid. The IA and rupture disk performances were nominal.

III.F. Structural Load Testing

A static structural load test was performed on the attachment shrouds, housings, split rings, and riser pins (all items in the load path between the ballute and riser) on a load frame at JPL using the EM IA, as shown in figure 22. The objective of the test was to verify functionality of the firing mechanism after application of the flight limit loads generated during riser snatch. The applied load was not sufficiently large serve as a structural load qualification test.

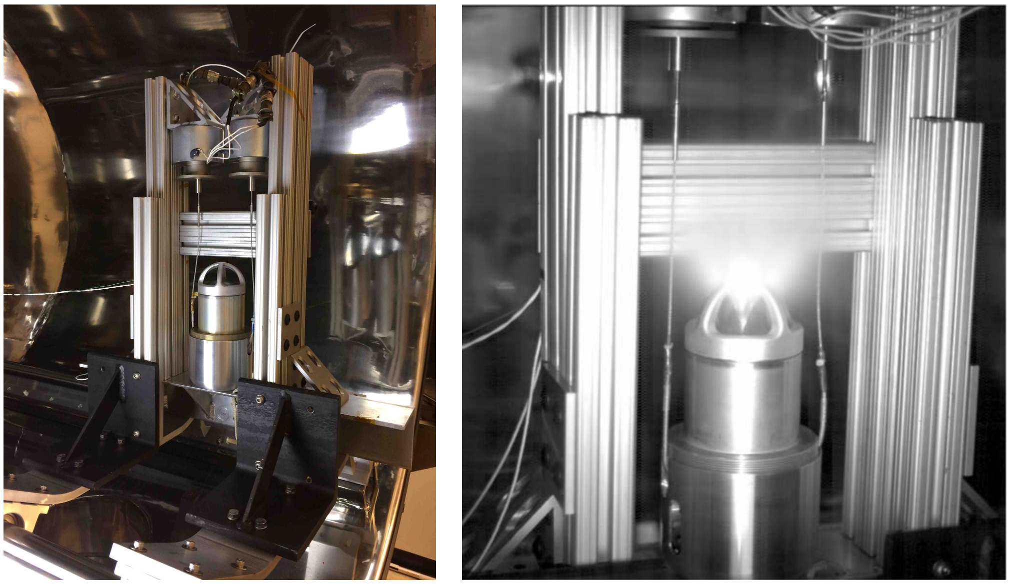
Figure 22: Structural Load Test.

Prior to the test, the firing mechanisms and a pair of inert primers were installed in to a housing. Another housing and a pair of shrouds were opposed and linked via a single piece of 1/4" twelve-strand nylon rope that was threaded through the ballute interfaces. A steel ring placed between the housings aligned the rope at the proper angle to the IA axes. A 6,000 lb load was applied to the riser pins via straps fabricated from 1" Kevlar webbing, with constructions identical to the flight riser design. Following the application of the load, the inert primers were replaced with live units, and successfully fired in a bench-top test.

III.G. Full Functional Testing

Prior to delivery for integration in to the SFDT-1 PDD, a full functional test was performed on the flight model (FM) IA. The objective of the test was two-fold: to demonstrate the functionality of the as-yet unexercised FM firing mechanism, and to observe the dispersion behavior of the methanol solution from the reservoir in vacuum conditions. The test was conducted in the eight-foot vacuum chamber at JPL, at room temperature, and a chamber pressure of 300 mTorr. The test setup, shown in figure 23a consisted of a fixture to which the IA was mounted, and a pair of steel lanyards that were connected to large solenoids. The solenoids could be actuated via a power supply that was located outside of the chamber. The absolute pressure inside the chamber was monitored via a pressure transducer and a data acquisition system located outside of the chamber. High-speed photography was used to record the behavior of the methanol following actuation of the IA, see figure 23b. The IA was loaded with a 1.2 mg propellant charge, and 353 g of methanol solution (29 CC of ullage).

A plot of the absolute pressure in the chamber with respect to time after initiation is shown in figure 24. While the volume of the ballute is approximately 28.1 m^3, the volume of the vacuum chamber was approximately 3.0 m^3. Consequently, a pressure increase of 500 Pa in the ballute would correspond to 4,680 Pa (0.68 psi) in the chamber. The internal pressure increased by 0.68 psi after approximately 0.56 seconds, which is slower than the 0.40 seconds requirement for the IA.



(a) Full Functional Test Setup. (b) Methanol Discharge.

Figure 23: Full Functional Test of the FM IA.

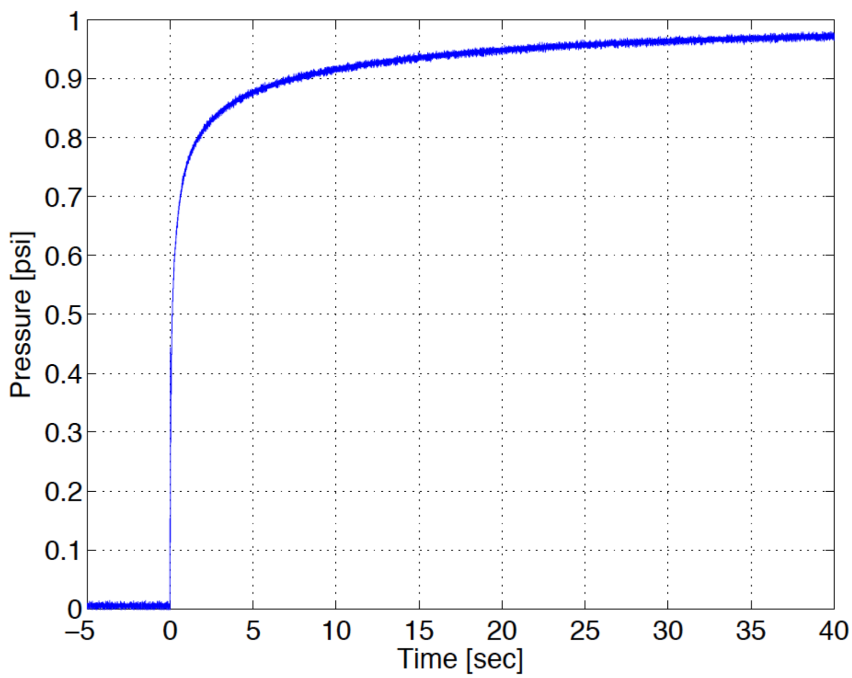


Figure 24: Absolute chamber pressure during the full functional test..

Assuming that the water in the methanol solution does not vaporize, the maximum possible pressure increase for a methanol saturation temperature of 20 °C is 6.72 kPa (0.98 psi). Per figure 24, the chamber did not reach this pressure until more than 40 seconds have elapsed from IA initiation. From this behavior, it is clear that the test represented an energy-limited system. If the IA and chamber had been heated prior to the test, as the PDD pack is heated in flight, it is likely that the rate of pressure increase would have satisfied the requirement levied on the IA.

IV. In-flight Performance

The inflation aid and ballute are heated prior to flight via heaters that are attached to the outside of the mortar tube. These heaters are powered through ground power and were not active during launch preparation, float, and flight. Thus, the PDD pack had to be heated to well above the deployment temperature in order to achieve that target 12-16 hours after the heaters were disconnected. A pre-flight test of the heating configuration was performed to obtain the correct starting temperature and heating time. Testing of the heaters and heating process prior to flight indicated that the inflation aid needed to start at a temperature of 80 °C in order to be at a temperature of at least 40 °C after 18 hours from power disconnect (the estimated time was 16 hours from disconnect to PDD mortar fire, with 2 hours of margin).[2] The testing also revealed that the mortar tube cools down significantly faster than that inflation aid, which is insulated by the ballute pack.

The first LDSD Supersonic Flight Dynamics Test (SFDT) occurred on June 28th, 2014 in Kauai, HI. Given the observed times for heating and cool down, the PDD system was heated for over 36 hours prior to the SFDT-1 flight to warm up the inflation aid to 80 °C. ballute mortar fire occurred roughly 12 hours after heater power disconnection. At the time of PDD deployment, the predicted IA temperature was 50 °C. The reconstructed SFDT-1 trajectory indicated that the PDD mortar fire occurred at a Mach number of 2.73, and a dynamic pressure of 429 Pa.[2] The deployment occurred at a geodetic altitude of 50 km.

The actual pressure inside the ballute was not monitored during deployment. However, using the anticipated temperature of the inflation aid at 12 hours of cooling, the Mach number at ballute deployment, and the ambient pressure at the deployment altitude, the IA was predicted to supply at least 99% of the expected ballute internal pressure during the SFDT-1 flight. The ballute inflation process, from line stretch to full inflation, is shown in figure 25. In figure 25, the IA appears to have triggered just prior to 162.44 s, as evidenced by the sudden inflation and lobing at the nose of the ballute without presentation of the ballute inlets. Complete inflation occurred in approximately 0.56 seconds. Given that the predicted inflation pressure was significantly higher than the requirement of half of the ballute internal pressure, it is likely that the time required reach the required pressure was significantly shorter than 0.4 seconds, and the inflation requirement was satisfied.

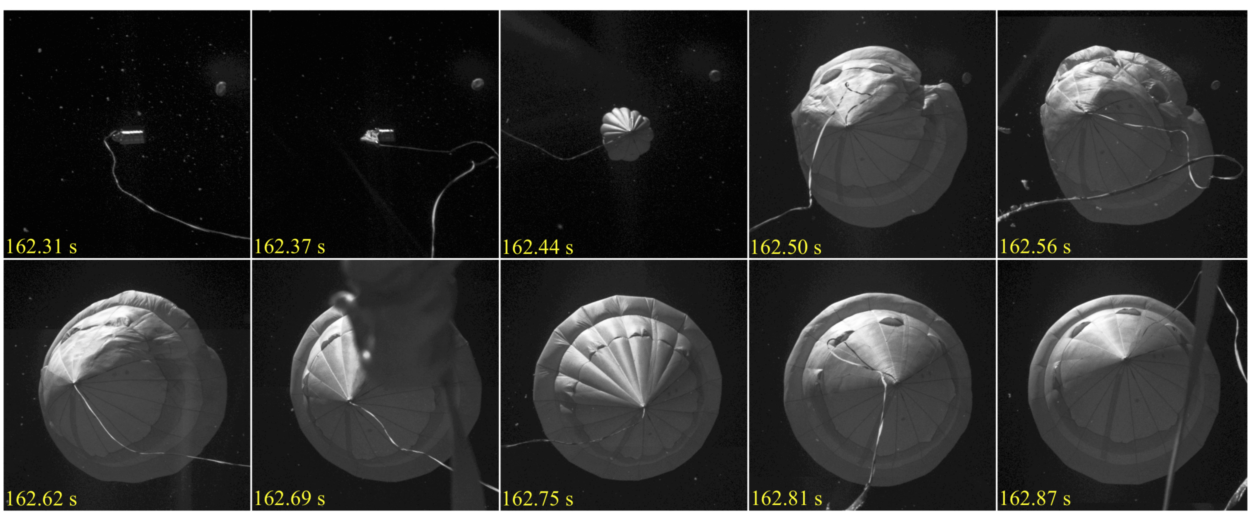


Figure 25: Ballute inflation sequence with the reconstructed time from drop in each image. Ballute inflation occurred in approximately 0.56 seconds.

V. Conclusion

The Inflation Aid represents a new implementation of a technology that was successfully demonstrated in aerodynamic decelerators more than 40 years ago. While tailored for the requirements of LDSD, the design of the device is easily scalable for use in other applications. The amount of methanol, the fraction of water in solution, the temperature of the device (and its target vessel) may all be adjusted. By changing these parameters, the rate of pressurization, the amount of gas, and the corresponding pressure increase may be tuned to specific requirements. The methanol evaporation process is self-regulating. As the pressure in the vented cavity increases to the vapor pressure of the methanol at a given temperature, the evaporation stops. This gas generating technique poses less risk of hardware damage due to over-pressurization. The methanol gas cools off as it expands, reducing the risk of hardware damage caused by the hot gases of combustion-only gas generators.

The unique mechanical activation design of this device, and its all-metal construction make it less susceptible to accidental activation due to electrostatic discharge (ESD) or electromagnetic radiation. Activation via tension in the trigger lanyard ensures that the device is only discharged once the ballute reaches the correct bag-strip condition, and not during the high acceleration environment experienced during mortar fire or line-stretch events. The rigid nature of the IA housing allows it to be packed within the PDD bag without risk of rupture, and to serve as the structural link between the riser and the ballute, thus reducing the overall PDD system mass.

This technology is readily available for current and future NASA work. While the device design is new to the large parachute community, it has been successfully tested and implemented in the LDSD supersonic parachute system and flown on a supersonic flight dynamics test. Future large parachute systems or deployable systems can now take advantage of this technology to increase their robustness and save on their system mass.

Appendix

Table 4: Ambient Conditions at Potential Ballute Deployment Altitudes

Altitude	Temperature	Pressure	Confidence
Ground	20 °C (260.5 K)	101325 Pa (14.7 psi)	Nominal
45 km (148,000 ft)	−7.1 °C (266.1 K)	143 Pa (0.021 psi)	95% low
50 km (164,000 ft)	−1.5 °C (271.7 K)	76 Pa (0.011 psi)	Nominal
55 km (180,000 ft)	−12.7 °C (260.5 K)	40 Pa (0.006 psi)	95% high

Table 5: Properties of Methanol and Water at Nominal Design Point

Property	Mixture	Methanol	Water
Molecular Formula		CH_4O (CH_3OH)	H_2O
Gas Constant (J/kg-K)		259.5	461.5
Saturation Temp (°C) @ 40 Pa		-57.7	-2
Mass Ratio	100%	75%	25%
Liquid Mass (kg)	0.353	0.265	0.088
Volume (cc) @ 20 °C	411	335	111
Density (g/cc) @ 20 °C	0.859	0.792	0.998
Freezing Temp (°C)	-107	-97.6	0

Table 6: Energy Calculation Parameters for Unheated Deployment Conditions

Property	Value	Units
Ambient Pressure	40	Pa
Deployment Temperature, T_{deploy}	276.15	K
IA Properties		
Mass, m_{IA}	2.2	kg
Methanol Contact Efficiency, η_{IA}	0.1	
Specific Heat Capacity, $C_{p,IA}$	0.9	kJ/kg-K
Ballute Properties		
Mass, m_b	10	kg
Methanol Contact Efficiency, η_b	0.1	
Specific Heat Capacity, $C_{p,b}$	1.44	kJ/kg-K
Methanol Properties		
Heat of Vaporization, $\Delta H_{v,CH_4O}$	1144	kJ/kg
Mass, m_{CH_4O}	0.265	kg
Saturation Temp, T_{sat,CH_4O}	215.46	K
Specific Heat Capacity, C_{p,CH_4O}	2.641	kJ/kg-K
Water Properties		
Mass, m_{H_2O}	0.088	kg
Heat of Fusion, $\Delta H_{f,H_2O}$	334	kJ/kg

Table 7: Energy Calculation Parameters for Heated Deployment Conditions

Property	Value	Units
Ambient Pressure	40	Pa
Deployment Temperature, T_{deploy}	313.15	K
IA Properties		
Mass, m_{IA}	2.2	kg
Methanol Contact Efficiency, η_{IA}	0.1	
Specific Heat Capacity, $C_{p,IA}$	0.9	kJ/kg-K
Ballute Properties		
Mass, m_b	10	kg
Methanol Contact Efficiency, η_b	0.1	
Specific Heat Capacity, $C_{p,b}$	1.44	kJ/kg-K
Methanol Properties		
Heat of Vaporization, $\Delta H_{v,CH_4O}$	1197	kJ/kg
Mass, m_{CH_4O}	0.265	kg
Saturation Temp, T_{sat,CH_4O}	215.46	K
Specific Heat Capacity, C_{p,CH_4O}	2.420	kJ/kg-K
Water Properties		
Mass, m_{H_2O}	0.088	kg
Heat of Fusion, $\Delta H_{f,H_2O}$	334	kJ/kg

Acknowledgements

The Jet Propulsion Laboratory, California Institute of Technology directs the Low Density Supersonic Decelerator project, under a contract with the National Aeronautics and Space Administration.

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