LOW-MASS INFLATION SYSTEMS FOR INFLATABLE STRUCTURES

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Abstract

The use of inflatable space structures has often been proposed for aerospace and planetary applications. Communication, power generation, and very-long-baseline interferometry are just three potential applications of inflatable technology. The success of inflatable structures depends on the development of a low mass inflation system. This paper describes two design studies performed to develop a low mass inflation system. The first study takes advantage of existing onboard propulsion gases to reduce the overall system mass. The second study assumes that there is no onboard propulsion system. Both studies employ advanced components developed for the Pluto Fast Flyby spacecraft to further reduce mass. The study examined four different types of systems: hydrazine; nitrogen and water; nitrogen; and xenon. This study shows that all of these systems can be built for a small space structure with masses lower than 0.5 kilograms.

Introduction

The purpose of an inflation system is to successfully inflate an inflatable structure in a space environment. This design study performs two analyses each with its own major assumption. The first assumes an existing propulsion system onboard the spacecraft. The second assumes there is none. The former further assumes that the inflation system can run off an existing onboard propulsion system. It was for this reason that the four following inflation systems were studied: hydrazine; nitrogen and water; nitrogen; and xenon. The focus of this design study was on mass considerations while volume and complexity considerations were considered to a lesser extent. Each analysis is discussed in detail.

The inflation system consists of pressurant or pressurants (such as nitrogen and water), system components (such as valves and filters), tanks, and tubing. For this design study, the total of these four represent the total mass of the inflation system. Of the four inflation systems considered, the total mass is heavily dependent on the size of the space structure and the length in time of the mission. Nitrogen and xenon systems are the least massive for short missions and small structures. Hydrazine and nitrogen and water systems are the least massive for long missions and large structures. Hence, the final choice of an inflation system is mission dependent. However, unless mass is a critical design parameter, the nitrogen and xenon systems are recommended for their comparatively simple system design.

Major assumptions in the design study will first be discussed. A brief discussion of the inflation sequence follows, with the equations governing the pressure and volume of the inflatable structure. The four inflation systems will then be explained in detail for the design study that assumes an onboard inflation system followed by a summary of the propulsion system itself. A brief discussion of the differences between the two design studies is then discussed as are other important assumptions made. The mass, volume, tank impact, and tubing analyses follow and remaining open issues are listed. Lastly, recommendations and conclusions end the paper.

Major Assumptions

The major assumption made in the first design study is the existence of a propulsion system onboard the spacecraft. Indeed, it was this assumption that led to the design study of four inflation systems that could be run off the spacecraft's existing propulsion system: hydrazine; nitrogen and water; nitrogen; and xenon. This assumption was made primarily to save tankage mass, but also to significantly reduce the complexity

of the inflation system. A combined system would already have the hardware associated with loading, testing, monitoring, fluid pressure and temperature, etc. as part of the propulsion system. Such a combined system would have this hardware available to both the propulsion and inflation system without a mass penalty to the latter. The second analysis assumes there is no onboard propulsion system. This analysis results in slightly higher overall masses due to the addition of tanks and hardware.

The type of inflatable structure that was used as a baseline for this study is a concentrator such as that shown in Figure 1.
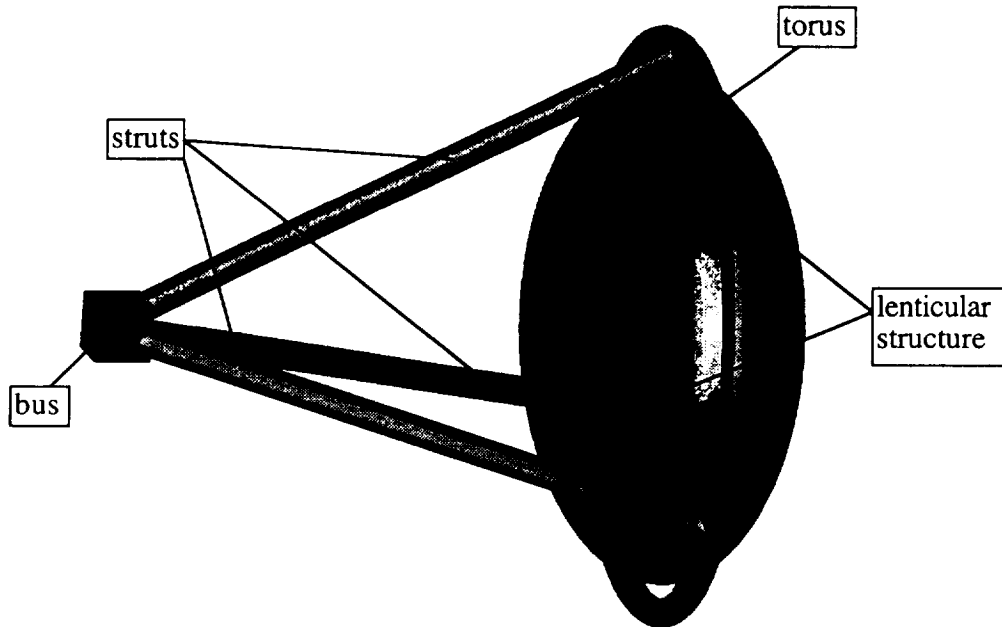

Figure 1. Inflatable Concentrator Used in this Design Study.

This structure could serve as an antenna or a solar concentrator. An inflation system that has been designed for this type of structure should be adaptable to any type of inflatable structure. The basic structure includes the lenticular structure with a transparent front surface and a reflecting back surface; a torus around the outer edge of the lenticular structure; and struts that connect the torus to a focal structure. The focal area, or bus, is where the spacecraft would be located.

The three parts of the concentrator that inflate are the struts, torus, and lenticular structure. The three primary values that were varied in both design studies were the diameter of the lenticular structure (D), the focal length over lenticular structure diameter ratio (f/D), and the length in time of the mission (t). Mission requirements size the structure. Although a concentrator might have a diameter of 25 meters, an f/D ratio of 1, and a 2 year mission time, a very-long-baseline interferometry experiment might have a diameter of 10 meters, an f/D ratio of 4, and a ten year mission time. Figure 1 illustrates a concentrator with a 15 meter diameter and an f/D of 1.

The assumption that the total mass of the inflation system does not include the mass of cables, electronics, and structure is significant. Furthermore, the total mass does not include the interface hardware.

Inflation Sequence

The actual inflation sequence for this type of structure is as follows:

1. Release a small amount of inflatant into struts, torus, and lenticular structure to start the deployment sequence.
2. Just prior to full erection (the amount of time it takes to do this is on the order of minutes), release gas into the torus and struts until the material reaches yield stress to rigidize (in the case of aluminum film) or near yield stress to remove wrinkles (for other types of rigidization methods).

3. Release gas into the lenticular structure to achieve near yield stress in the material to remove wrinkles. It should be noted that the inflation rate in this step has to be fast enough to overcame any initial leaks in the system or structure.
4. Vent the lenticular structure to a predetermined maintenance pressure.
5. Vent the torus and struts to space.
6. Maintain pressure in lenticular structure to compensate for losses in inflatant due to micrometeor holes.

The venting in step 5 removes inflatant from the structure that could leak out at a later time due to micro-meteor impacts. Such leaks would create forces and moments that would affect the structure's attitude and control.

Governing Equations

Equations that determine the volume and pressure needed for a concentrator with a paraboloid reflector and a transparent cone that holds the focus apparatus at the tip were used.[1] These equations are modified for a lenticular structure with two mated paraboloids and struts that connect the focal structure to the torus.

Lenticular Structure
The equation for the pressure to achieve near yield pressure (p_1) in the lenticular structure is:

$$p_1 = \frac{2S_1 t_1}{R} \tag{1}$$

where:

$$R = D \cdot (0.48K + 0.11)$$

S_1 = yield stress of lenticular material

t_1 = thickness of lenticular material

D = lenticular structure diameter

$$K = 4\left(\frac{f}{D}\right)$$

f = focal length

The pressure needed to retain the shape of the lenticular structure is a function of the structure size:

$$P_m = \frac{2S_m t_1}{R} \tag{2}$$

where:

S_m = maintence stress of lenticular structure

The volume of the lenticular structure is:

$$V_1 = \frac{\pi D^3}{16K} \tag{3}$$

The mass (in kg) of inflatant needed to replace gas loss due to micro-meteor holes is:[2]

$$m = \sqrt{MW} p_m A \sqrt{\frac{\gamma}{RT}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}}} \frac{a}{2} t^2 \tag{4}$$

where:

MW = molecular weight of inflatant

p_m = maintenance pressure (in Pa)

A = projected area (in m^2) = $\dfrac{\left(\pi + \dfrac{K}{2} + \dfrac{5}{6K}\right)D^2}{8}$

γ = ratio of specific heats for inflatant

R = universal gas constant = 8314.3 $\frac{J}{kmol \cdot K}$

T = temperature of inflatant (in K)

$a = 1.08692462718E - 15 \; \frac{1}{s} \; \left(0.000343 \; \frac{cm^2}{m^2 \cdot yr}\right)$

t = mission time (in s)

Torus
The diameter of the torus is given by the equation:

$$d^3 = \frac{FS \cdot \left(\dfrac{2S_s t_t}{R}\right)D^4 K}{6E_t\left(\pi + \dfrac{2}{3}\right)t_t} \tag{5}$$

where:

FS = factor of safety (4 for this study)

S_s = stress to size torus

E_t = torus material modulus

t_t = thickness of the torus material

The volume of the torus is:

$$V_t = \frac{\pi^2 d^2 D}{4} \tag{6}$$

The pressure required to yield the torus is given by:

$$p_t = \frac{2S_t t_t}{d} \tag{7}$$

where:

S_t = yield stress of torus material

Struts
The strut material and diameter are assumed to be the same as the torus. Hence the pressure required to yield the struts is identical to the pressure required to yield the torus ($p_s = p_t$). The total volume of the struts is given by:

$$V_s = 3 \cdot \frac{\pi D d^2}{8}\sqrt{\frac{\left(K - \frac{1}{K}\right)^2}{4} + 1} \tag{8}$$

The '3' in Equation (8) signifies the number of struts in the concentrator.

In this design study the torus and struts were assumed to be made out of aluminum polyester film composite (S_t = 2.000E7 Pa; t_t = 6.350E-6 m). The elastic modulus of the torus is 5.860E9 Pa. The lenticular structure was assumed to be an aluminum polyester film composite with a slightly different make-up and properties (S_l = 7.750E7 Pa; t_l = 9.000E-6 m). The maintenance stress of the lenticular structure (S_m) and the stress to size the torus (S_s) are 3.447E5 Pa and 6.895E5 Pa, respectively.

Existing Propulsion System

As stated earlier, the first design study in this paper assumes an existing propulsion system onboard the spacecraft. Four different types of inflation systems were studied: hydrazine; nitrogen and water; nitrogen; and xenon.

Hydrazine System

The hydrazine pressurization system (shown in Figure 2) uses gases created when the liquid monopropellant hydrazine decomposes as an inflatant. Please note from Figure 2 that the latch valve LV1 and filter F1 (to the left of the dashed line) are normal parts of the propulsion system, but are shown here because they also perform a function in the inflation system.
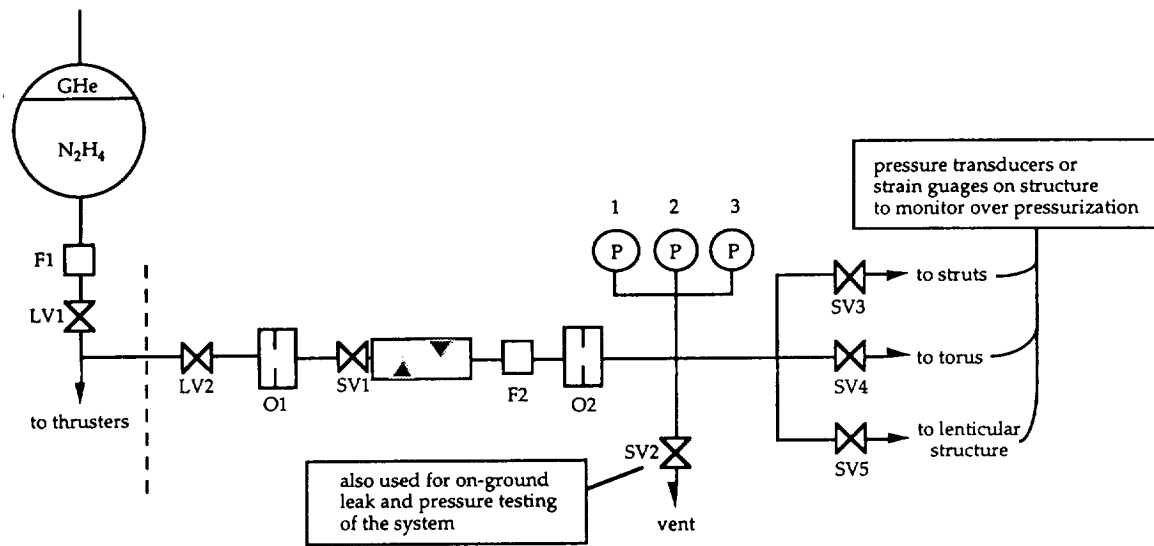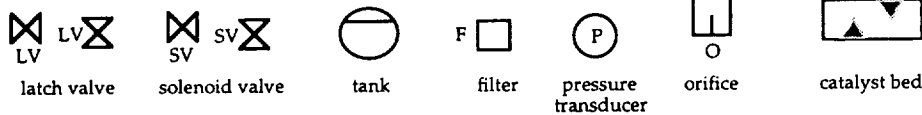

Figure 2. Hydrazine System Set-Up for an Existing Propulsion System.

After launch, when the propulsion system is activated, LV1 is opened to allow the flow of hydrazine out of the propellant tank. When inflatant is required, latch valve LV2 is opened, resulting in pressurized hydrazine filling the inlet of the gas generator (which is solenoid valve SV1 in conjunction with a catalyst bed). Flow control orifice O1 has the function of limiting the flow rate of propellant into the gas generator so that very small amounts of gas can be generated if desired. This is important during the initial inflation and later in the mission when maintenance pressure is required.

Inflatant gas is created when solenoid valve SV1 is opened and liquid hydrazine passes into the catalyst bed. Hydrazine decomposes in the following two-step reaction:[3]

$$3 \cdot N_2H_4 \rightarrow 4 \cdot NH_3 + N_2 + Q$$
$$4 \cdot NH_3 \rightarrow 2 \cdot N_2 + 6 \cdot H_2 - Q \tag{9}$$

While the first reaction is exothermic, the second is endothermic. The amount of ammonia (NH_3) that dissociates depends on, among other things, the length of the catalyst bed. Equation (9) can also be expressed as a function of the amount of ammonia dissociation, X:

$$3 \cdot N_2H_4 \xrightarrow{\text{cat}} 4 \cdot (1 - X) \cdot NH_3 + 6 \cdot X \cdot H_2 + (2 \cdot X + 1) \cdot N_2 \tag{10}$$
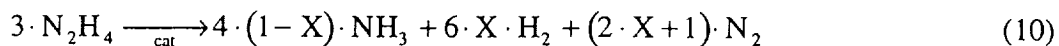
For an inflation system, it would be preferable to maximize the amount of dissociation possible, both because more moles of gas are created (thus requiring less hydrazine for the same inflation amount) and because the final temperature of the created gas is lower, reducing the task of cooling the gas once it is generated.

Once nitrogen, hydrogen, and possibly ammonia gas are created, they pass through filter F2 and flow control orifice O2 into a manifold, where the pressure of the gas is sensed by redundant pressure transducers (P1, P2, and P3). Note that three transducers are required to allow voting, in case one transducer fails. Different parts of the inflatable structure can be pressurized by opening SV3, SV4, and/or SV5.

Pressure transducers can also be mounted downstream of solenoid valves SV3 through SV5, or strain gauges could be mounted on the inflatable structure to indicate if the pressures are indeed at the correct level. In case of over-inflation, solenoid valve SV2 can be opened. SV2 is also used for relieving the pressure within the inflatable structure once it has already been rigidized.

It should be noted that no service valves are required for the inflation system because SV2 can be used for leak and functional testing of all up-stream components. It is assumed that leak testing of SV3 through SV5 can be performed prior to the final installation of the inflatable structure.

The mass of the various components used in the hydrazine system are summarized in Table 1.

Table 1. Mass Breakdown of Hydrazine System Set-Up.

Item	Quantity (#)	Mass (g)	Total Mass (g)	Reference/Comments
catalyst bed	1	150	150	discussions with Olin Aerospace
filter	1	50	50	typical mass for capacity and flow rate assumed
heater	0	0	0	
latch valve	1	73	73	Pluto Fast Flyby latch valve[4]
manual valve	0	30	0	
orifice	2	10	20	Viscojet (Lee Company)
pressure transducer	3	10	30	Entran (Fairfield, NJ); no electronics
solenoid valve	5	7	35	Pluto Fast Flyby thruster valve[4]
		TOTAL MASS	358 g	

Nitrogen and Water System
The nitrogen and water system shown in Figure 3 assumes a cold-gas nitrogen system already exists which is regulated to produce relatively constant thrusts throughout the mission.
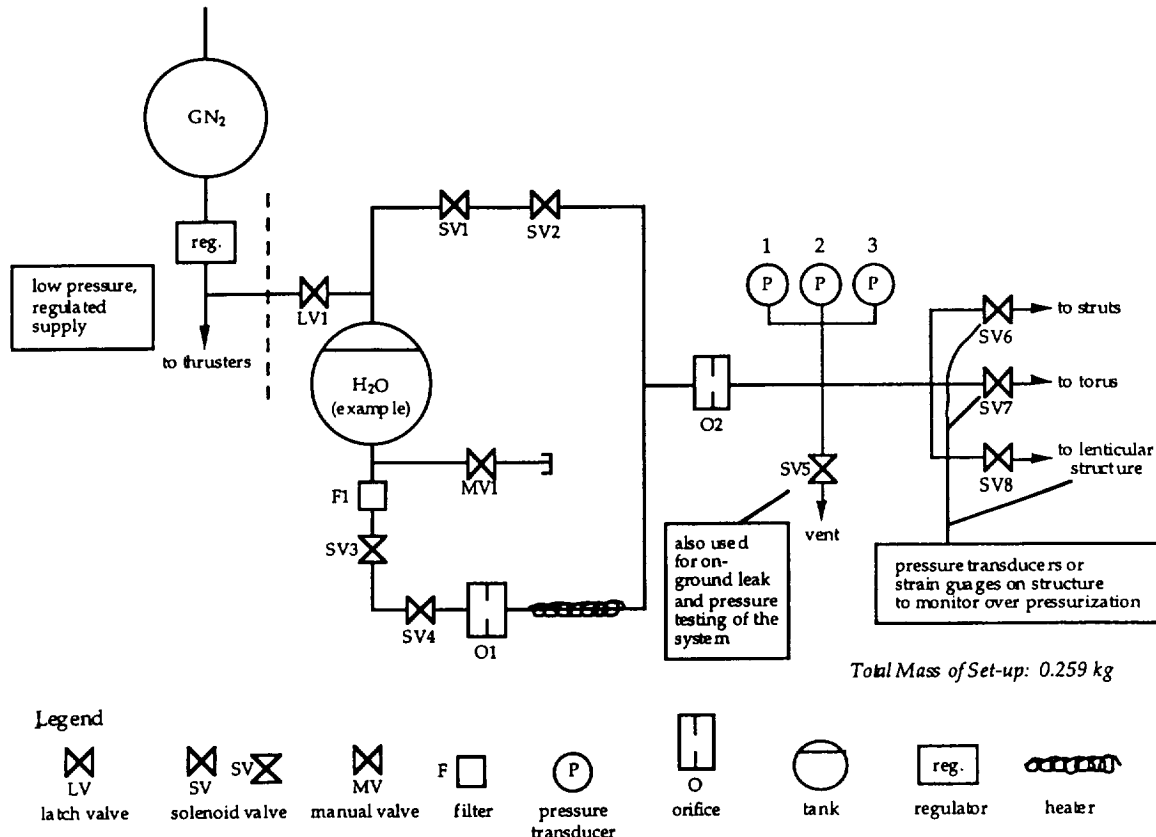
GN₂

reg.

low pressure,
regulated
supply

to thrusters

LV1

SV1 SV2

H₂O
(example)

1 2 3
P P P

to struts
SV6

O2

to torus
SV7

to lenticular
structure
SV8

F1

MV1

SV5

vent

SV3

also used
for on-
ground leak
and pressure
testing of the
system

pressure transducers or
strain guages on structure
to monitor over pressurization

SV4

O1

Total Mass of Set-up: 0.259 kg

Legend

LV
latch valve

SV SV
solenoid valve

MV
manual valve

F
filter

P
pressure
transducer

O
orifice

tank

reg.
regulator

heater

Figure 3. Nitrogen and Water System Set-Up for an Existing Propulsion System.

Figure 3 further assumes a regulated pressure high enough to yield the structure. A separate water tank is incorporated to take advantage of storing the inflatant gas as a liquid and thus minimizing tankage size and mass. The nitrogen and water system maximizes water use in the inflation process. That is to say, water is used as the pressurant up to its vapor pressure. The vapor pressure of water is a function of its temperature. The vapor pressure of water is 2333.14 Pa at 293 K.[5]

Note that although water was used in this study, any liquid with a high vapor pressure and density could be used. Freon would be an ideal choice but was not selected for this design study for environmental reasons.

After launch, latch valve LV1 is opened to pressurize the ullage of the water tank, which is assumed to be a normal bladder-type tank. When pressurizing gas is required, solenoid valves SV3 and SV4 are opened, allowing water to flow through flow orifice O1, after which it vaporizes due to the low pressure downstream of O1. A heater is likely required to keep the water from freezing, due to cooling caused by rapid pressure decrease.

Once the water is vaporized, it passes through flow orifice O2 into a similar manifold described for the hydrazine system. If pressures higher than the vapor pressure of water are required (such as to fully inflate the lenticular structure), high pressure gaseous nitrogen can be introduced directly into the inflatable structure by opening solenoid valves SV1 and SV2.

Manual valve MV1 is incorporated into the system to allow loading and testing of water system plumbing and tank. The mass of the various components used in the nitrogen and water system are summarized in Table 2.

Table 2. *Mass Breakdown of Nitrogen and Water System Set-Up.*

Item	Quantity (#)	Mass (g)	Total Mass (g)	Reference
catalyst bed	0	150	0	
filter	1	50	50	typical mass for capacity and flow rate assumed
heater	1	0	0	negligible mass
latch valve	1	73	73	Pluto Fast Flyby latch valve[4]
manual valve	1	30	30	VACCO (developed for the Ballistic Missile Defense Office)
orifice	2	10	20	Viscojet (Lee Company)
pressure transducer	3	10	30	Entran (Fairfield, NJ); no electronics
solenoid valve	8	7	56	Pluto Fast Flyby thruster valve[4]
		TOTAL MASS	259 g	

Nitrogen Only System

The nitrogen only system (sketched in Figure 4) works the same way as the nitrogen pressurization part of the nitrogen and water system, and has no water tank or associated hardware.
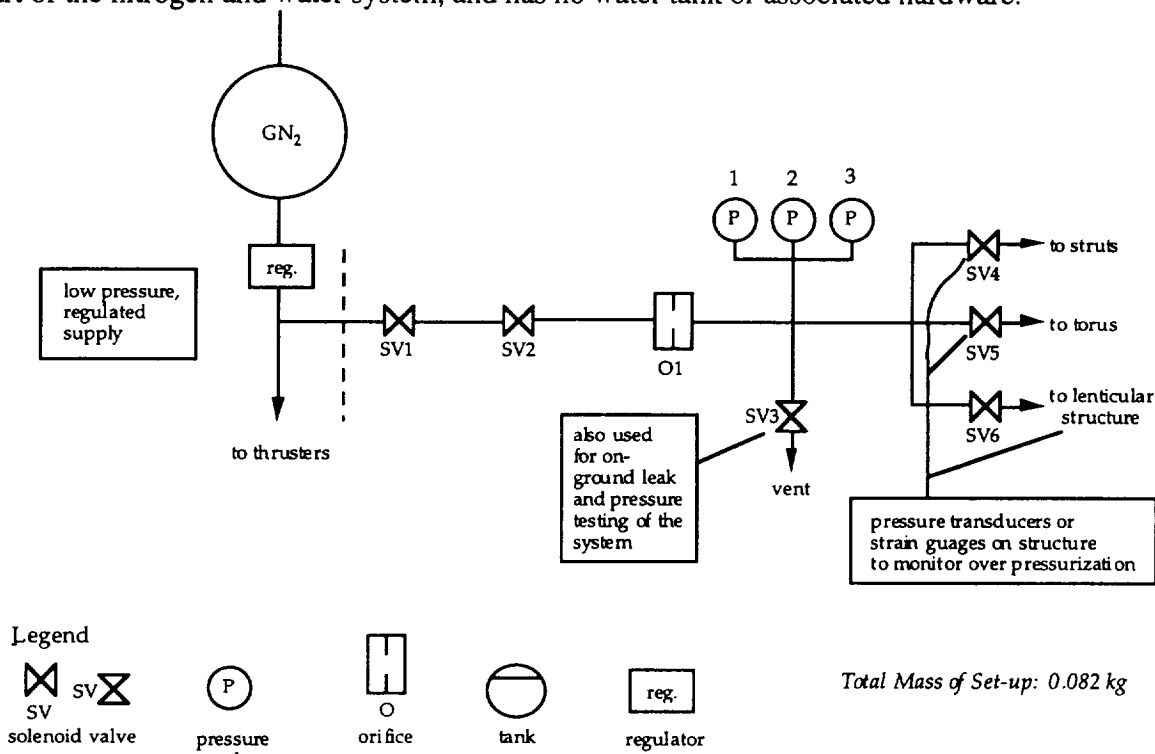

Figure 4. *Nitrogen Only System Set-Up for an Existing Propulsion System.*

The mass of the various components used in the nitrogen system are summarized in Table 3.

Table 3. *Mass Breakdown of the Nitrogen and Xenon System Set-Ups.*

Item	Quantity (#)	Mass (g)	Total Mass (g)	Reference
catalyst bed	0	150	0	
filter	0	50	0	
heater	0	0	0	
latch valve	0	73	0	
manual valve	0	30	0	
orifice	1	10	10	Viscojet (Lee Company)
pressure transducer	3	10	30	Entran Sensors and Electronics (Fairfield, NJ); no electronics
solenoid valve	6	7	42	Pluto Fast Flyby thruster valve[4]
		TOTAL MASS	82 g	

Xenon System
The xenon system works the same way as the nitrogen only system with the only difference being the use of xenon propellant instead of nitrogen. A xenon system is appealing for use in conjunction with an electric propulsion system. The mass of the various components used in the xenon system are summarized in Table 3.

Propulsion Tanks

As stated earlier, since the first design study assumes that an inflation system piggy-backs on the propulsion system, an existing propulsion system had to be used. Such an assumption would allow mass impacts of the inflation system on the spacecraft to be calculated provided reference tanks were available.

For this design study the propulsion systems proposed for the Pluto Fast Flyby and NASA SEP (Solar Electric Propulsion) Technology Application Readiness program (NSTAR) were used.[6] The hydrazine system assumed 24.34 kg of liquid hydrazine at initial pressure of 3.447E6 Pa (500 psi). The nitrogen and nitrogen and water system assumed 1.25 kg of gaseous nitrogen at 4.137E7 Pa (6,000 psi). The xenon system uses two tanks each holding 20 kg of supercritical xenon at 1.379E7 Pa (2,000 psi). Note that although the Pluto Fast Flyby and NSTAR programs may change their tanks, it does not affect this study since only a rough baseline was needed for tank impact analysis. This design study assumed T-1000 graphite/epoxy tanks with an aluminum liner for calculations involving nitrogen and xenon. Titanium tanks were used for calculations involving hydrazine or water.

A spreadsheet was used to calculate the resulting size and mass of these tanks. Table 4 summarizes this information.

Table 4.   Propellant Tank Information.

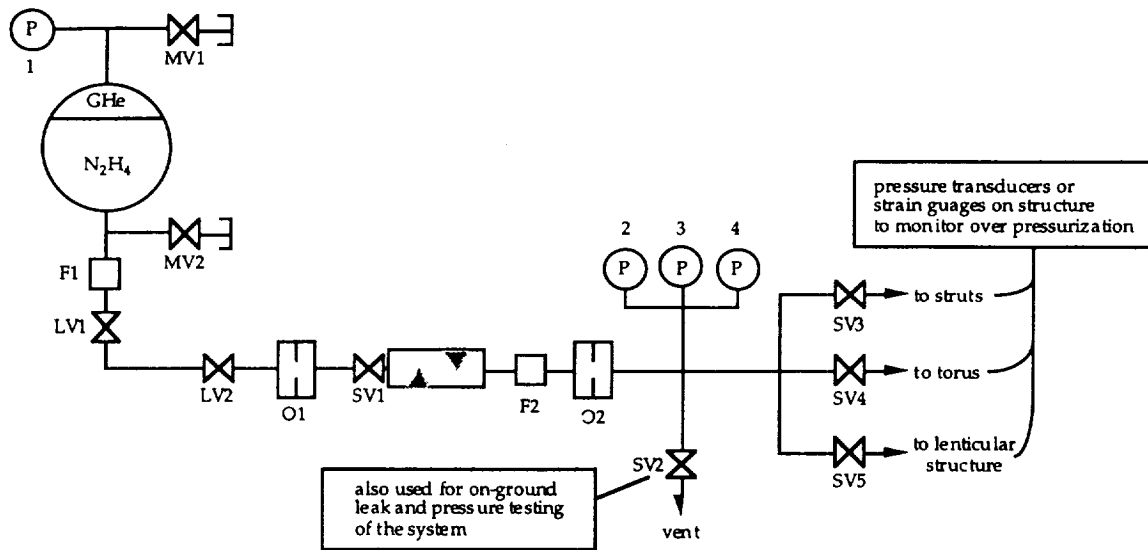| System	State	Mass of Propellant (kg)	Pressure of Propellant (Pa)	Initial-to-Final Pressure Ratio	Resulting Mass of Tank (kg)	External Tank Diameter (m)
Hydrazine	Liquid	24.34	3.447E6	3-to-1*	1.149	0.277
Nitrogen	Gas	1.25	4.137E7	120-to-1	0.679	0.178
Xenon (2)	Supercritical	20.00	1.379E7	40-to-1	1.135	0.271

* blowdown ratio for hydrazine

The nitrogen tank would be used in both the nitrogen and water system and the nitrogen only system. The former requires the addition of a water tank whose size depends on the amount of water needed.

No Propulsion System

The second design studied performed assumed no onboard propulsion system. This assumption affects the total mass in two ways. The first is that since there is no onboard propulsion system, there are no onboard tanks. Although tank impact is no longer an issue, entirely new tanks must be determined for each case. The second is the addition of components used to control the inflation process that were part of the propulsion system. Valves and transducers used to monitor the inflatant are part of the propulsion system in the first design study and must be added for the second design study. Both of these changes increase the overall mass of the system.

Hydrazine System
The hydrazine inflation system for a spacecraft with no existing onboard propulsion system is shown in Figure 5.

pressure transducers or
strain guages on structure
to monitor over pressurization

also used for on-ground
leak and pressure testing
of the system

Total Mass of Set-up: 0.551 kg

Legend

LV — latch valve   SV — solenoid valve   MV — manual valve   tank   F — filter   P — pressure transducer   O — orifice   catalyst bed
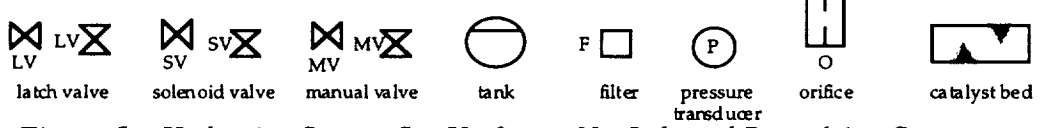
Figure 5.   Hydrazine System Set-Up for an No Onboard Propulsion System.

Figure 5 differs somewhat from Figure 2 through the addition of several components that were assumed to be part of the propulsion system in Figure 2. The manual valves MV1 and MV2 are used to load the ullage gas and propellant, respectively. These valves are also used in combination with other manual valves for leakage testing. The pressure transducer P1 is needed for monitoring the amount of propellant remaining in the tank. Filter F1 is needed at the outlet of the tank for contamination control. Such a filter protects down-stream valves from contamination that could lead to leakage. Table 5 summarizes the mass of the various components used in this system.

Table 5.   Mass Breakdown of Hydrazine System Set-Up.

Item	Quantity (#)	Mass (g)	Total Mass (g)	Reference/Comments
catalyst bed	1	150	150	discussions with Olin Aerospace
filter	2	50	100	typical mass for capacity and flow rate assumed
heater	0	0	0	
latch valve	2	73	146	Pluto Fast Flyby latch valve[4]
manual valve	2	30	60	VACCO (developed for the Ballistic Missile Defense Office)
orifice	2	10	20	Viscojet (Lee Company)
pressure transducer	4	10	40	Entran (Fairfield, NJ); no electronics
solenoid valve	5	7	35	Pluto Fast Flyby thruster valve[4]
		TOTAL MASS	551 g	

Nitrogen and Water System
The nitrogen and water inflation system for a spacecraft with no existing onboard propulsion system is shown in Figure 6.
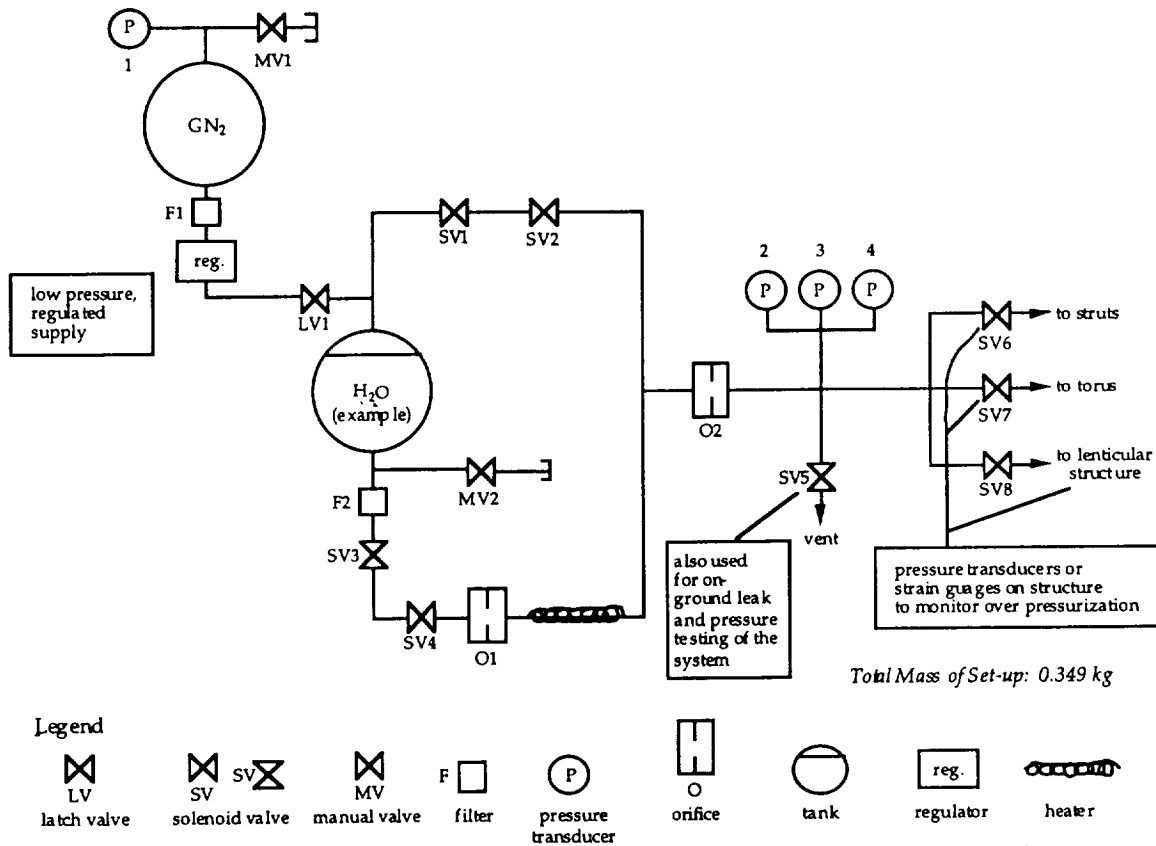
Figure 6. Nitrogen and Water System Set-Up for No Onboard Propulsion System.

The nitrogen and water system in Figure 6 adds several components to the schematic shown earlier in Figure 3. As with the hydrazine system, the pressure transducer P1 is added to monitor the amount of propellant in the tank. Only one additional manual valve, MV1, is needed for loading the propellant. Filter F1 is added for contamination control. Table 6 summarizes the mass of the various components used in this system.

Table 6. Mass Breakdown of Nitrogen and Water System Set-Up.

Item	Quantity (#)	Mass (g)	Total Mass (g)	Reference
catalyst bed	0	150	0	
filter	2	50	100	typical mass for capacity and flow rate assumed
heater	1	0	0	negligible mass
latch valve	1	73	73	Pluto Fast Flyby latch valve[4]
manual valve	2	30	60	VACCO (developed for the Ballistic Missile Defense Office)
orifice	2	10	20	Viscojet (Lee Company)
pressure transducer	4	10	40	Entran (Fairfield, NJ); no electronics
solenoid valve	8	7	56	Pluto Fast Flyby thruster valve[4]
		TOTAL MASS	349 g	

Nitrogen System
The nitrogen inflation system for a spacecraft with no existing onboard propulsion system is shown in Figure 7.
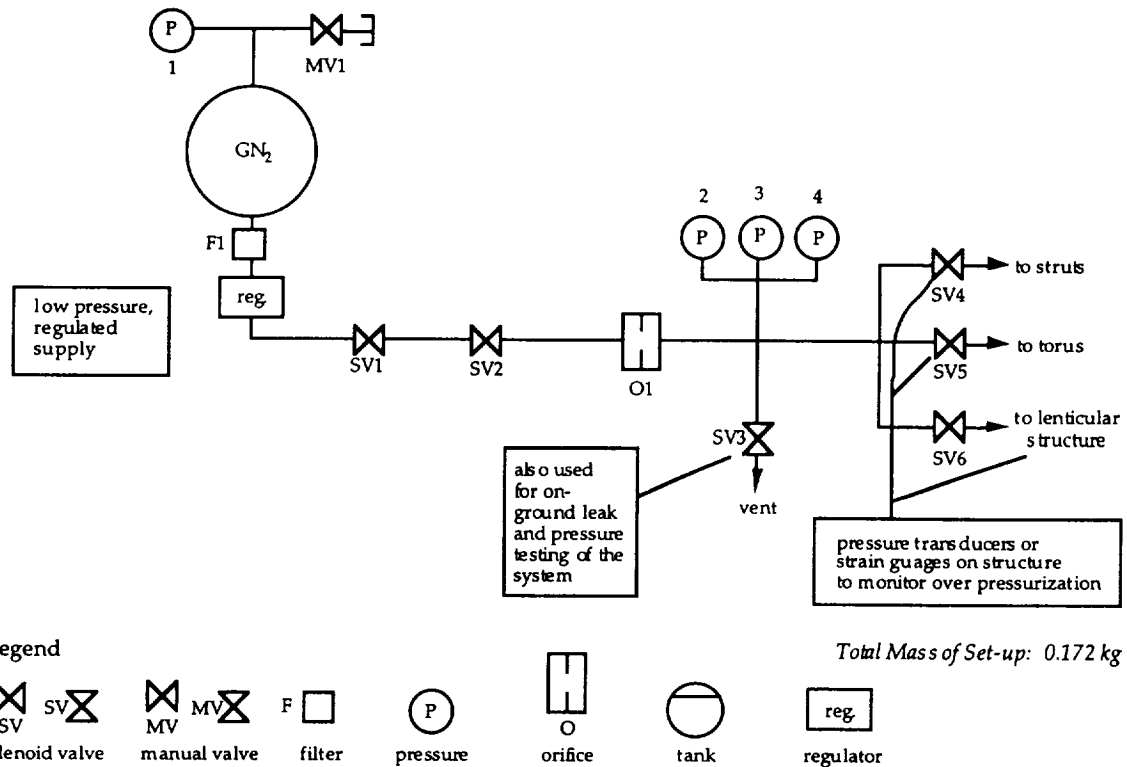
Figure 7.   Nitrogen Only System Set-Up for No Onboard Propulsion System.

The nitrogen system in Figure 7 adds three components to the schematic shown earlier in Figure 4. The pressure transducer P1, manual valve MV1, and filter F1 provide the same purpose as described in the previous nitrogen and water system. Table 7 summarizes the mass of the various components used in this system.

Table 7.   Mass Breakdown of the Nitrogen and Xenon System Set-Ups.

Item	Quantity (#)	Mass (g)	Total Mass (g)	Reference
catalyst bed	0	150	0	
filter	1	50	50	typical mass for capacity and flow rate assumed
heater	0	0	0	
latch valve	0	73	0	
manual valve	1	30	30	VACCO (developed for the Ballistic Missile Defense Office)
orifice	1	10	10	Viscojet (Lee Company)
pressure transducer	4	10	40	Entran (Fairfield, NJ); no electronics
solenoid valve	6	7	42	Pluto Fast Flyby thruster valve[4]
	TOTAL MASS		172 g	

Xenon System

The xenon system works the same way as the nitrogen only system with the only difference being the use of xenon propellant instead of nitrogen. The mass of the various components used in the xenon system are summarized in Table 7, above.

General Assumptions

In addition to the major assumptions stated earlier, the following general assumptions have been made in this design study. These assumptions apply to both design studies unless otherwise stated.

- An operational temperature of 293 K (20 °C) throughout. The temperature of the spacecraft is kept high enough such that the hydrazine and water do not freeze.
- The dissociation of hydrazine to be 90% (X = 0.9).
- A factor of safety of 4 in the calculation of the torus diameter.
- An existing tank was used with the exception of the water tank (first design study).
- A burst factor of 2 for tank calculations involving water and hydrazine; a burst factor of 1.5 for tank calculations involving nitrogen and xenon.
- A 15% fitting factor in tank calculations.
- A 10% margin in the hydrazine and water tank masses for the bladder.
- Pressure monitoring of the propellant in the tanks is performed by the propulsion system (first design study). Temperature transducers have negligible mass.
- The gaseous nitrogen put out by the cold-gas system is regulated to 3.447E5 Pa (50 psi). This pressure was randomly selected to allow tank sizing. Hence, the initial-to-final pressure ratio is 120-to-1 for nitrogen while 40-to-1 for xenon.
- A 33.3% initial ullage volume for hydrazine and a 6% initial ullage volume for water.
- 20% mass margins for liquids (hydrazine and water) and 50% mass margins for gases (nitrogen and xenon). Such margins account primarily for leakage. They also take into account the scenario in which more pressurant is needed during the initial inflation than originally calculated. A larger margin is required for a gas since it leaks more easily than a liquid.

Mass Analysis

The ideal gas law relates the pressure and volume of a gas to its mass and temperature:

$$PV = mRT \tag{11}$$

where:

$$P = \text{pressure}$$
$$V = \text{volume}$$
$$m = \text{mass}$$
$$R = \text{gas constant}$$
$$T = \text{temperature}$$

Equation (11) can be rewritten in terms of the mass:

$$m = \frac{PV}{RT} \tag{12}$$

Equation (12) and deviations on Equation (12) were used throughout this design study in determining the amount of pressurant needed for various stages of the inflation process. For example, the mass of nitrogen required to fully inflate the lenticular structure of a 10 meter power antenna (f/D = 1) would be:

$$m = \frac{(68.719 \text{ Pa})(49.087 \text{ m}^3)}{\left(296.749 \frac{J}{kg \cdot K}\right)(293 \text{ K})}$$

$$m = 0.0388 \text{ kg}$$

The equation governing the amount of pressurant in kilograms needed for maintenance was stated earlier in Equation (4). Continuing with the example earlier, the amount of nitrogen (to three digits) needed to maintain the pressure (0.306 Pa determined from Equation (2)) for 5 years would be:

$$m = \sqrt{28.016 \tfrac{kg}{kmol}} \, (0.306 \text{ Pa})\left(66.874 \text{ m}^2\right)\sqrt{\frac{(1.4)}{\left(8314.3 \tfrac{J}{kmol \cdot K}\right)(293 \text{ K})}}\left(\frac{2}{(1.4)+1}\right)^{\frac{1.4+1}{2(1.4-1)}} \cdot \frac{a}{2} \cdot t^2$$

$$m = 0.642 \text{ kg}$$

Where a is $1.087E\text{-}15 \text{ s}^{-1}$ (defined below Equation (4)) and t is $1.578E8$ s (5 years). It is apparent from Equation (4) and the calculation above that a significant portion of the total mass for long missions is replacement gas.

Volume Analysis

After summing the mass for the inflation steps and maintenance, the resulting volume (V) is determined for liquids (such as hydrazine and water) by rewriting the definition of density (ρ):

$$V = \frac{m}{\rho} \tag{13}$$

Note that xenon is supercritical at $1.379E7$ Pa and 293 K. That is, xenon at this pressure is neither a liquid nor a gas, but a state in between the two. The density of xenon at this pressure and temperature is assumed to be 2012.7 kg/m^3.[7] The volume of xenon was calculated using this value in Equation (13).

The equation of state is used for gases (such as nitrogen):

$$p = \rho RT \tag{14}$$

With Equation (13) substituted in, Equation (14) reduces to:

$$V = \frac{mRT}{p} \tag{15}$$

Further continuing with the nitrogen example, for a total mass (including margins) of 1.233 kg, the resulting volume at $4.137E7$ Pa (6000 psi) would be:

$$V = \frac{(1.233 \text{ kg})\left(296.749 \tfrac{J}{kg \cdot K}\right)(293 \text{ K})}{(4.137E7 \text{ Pa})}$$

$$V = 0.00259 \text{ m}^3$$

A final resulting internal tank volume can be obtained by applying the initial ullage volumes defined earlier (120-to-1 in the case of nitrogen).

Tank Impact Analysis

A spreadsheet was used to determine the impact that such an internal volume increase would have on an existing tank. As stated earlier, propellant amounts from the Pluto Fast Flyby and NSTAR design were assumed. The mass and diameter of these tanks were calculated by using the spreadsheet and were summarized in Table 4.

The mass and diameter of tanks were also calculated with the internal volume increase of the inflation pressurant. The mass and diameter impact is quite simply the difference between these two values. For the nitrogen example, the mass and diameter of the tanks with the pressurant included are 1.268 kg and 0.244 m, respectively. Hence, the mass impact would be 0.589 kg (1.268 kg - 0.679 kg = 0.589 kg). The diameter impact would be 0.046 m (0.224 m - 0.178 m = 0.046 m).

It should be noted that if the tanks for the propulsion system are larger (that is, if more propellant is required than documented here), then the mass impact of the inflation system is smaller (a smaller percent change in the tank size required). Also, it is typical for flight projects to select tanks which are "off-the-shelf" to save money. This means that often tanks that are too large are selected. If the mass total of the pressurant required for the inflation system is small enough that the gas can be loaded into the selected tank without affect, then no tankage mass impact would result.

Tubing Impact Analysis

A rough estimate of the mass of tubing that would be required for such an inflation system was also carried out. The design parameters of the 0.01 inch tubing are summarized in Table 8:

Table 8.   Tubing Design Parameters.

Material	Stainless Steel
Length	2 m
Outer Diameter	0.003175 m (0.125 in)
Inner Diameter	0.002667 m (0.105 in)

The volume of the tubing is calculated to be:

$$V = \pi \left(\frac{d_o}{2}\right)^2 l - \pi \left(\frac{d_i}{2}\right)^2 l$$

$$= \pi \left(\frac{0.003175\ m}{2}\right)^2 (2\ m) - \pi \left(\frac{0.002667\ m}{2}\right)^2 (2\ m)$$

$$V = 4.66170E\text{-}6\ m^3$$

Recalling the density of stainless steel to be 8000 kg/m³, the mass of this tubing can be calculated to be:

$$m = \rho V$$

$$= \left(8000\ \tfrac{kg}{m^3}\right)\left(4.66170E - 6\ m^3\right)$$

$$m = 0.03729\ kg$$

Mass Totals

Existing Propulsion System

The sum of the masses of the set-up components, the total pressurant required, the tank impact, and the tubing equals the total mass of the inflation system. This value represents the amount of mass that would need to be added to an existing propulsion system onboard a spacecraft. This value can be obtained for any system or configuration using the spreadsheet developed for this design study. Recall that this mass total does not include electronics, cables, and structure. Figure 8 plots the total mass as a function of lenticular structure diameter for a 5 year mission with a structure having an f/D ratio of 1.
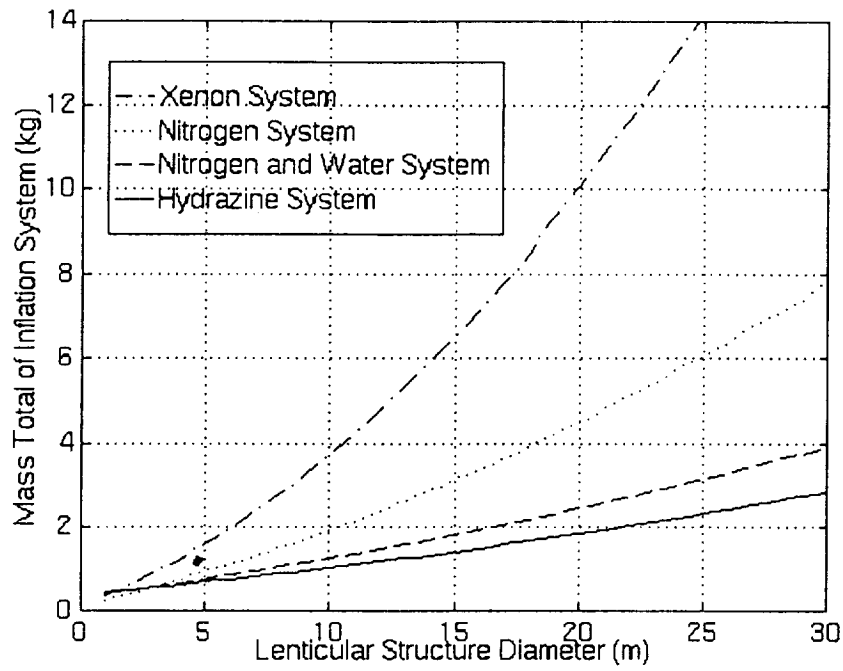
Figure 8. Mass Total for an Existing Propulsion System as a Function of Lenticular Structure Diameter
(f/D = 1 and t = 5 years).

From Figure 8 it is apparent that the total mass of the inflation system increases dramatically with lenticular structure diameter. This is especially pronounced for the xenon and nitrogen systems. While these systems are the least massive for small diameters, they are the most massive for large diameters. The difference in mass totals between systems for small structures can be attributed the higher overall component mass for the hydrazine and nitrogen and water system. This difference is not noticeable for large structure since the mass totals of the inflatant and tanks, on the order of kilograms, overshadow the mass total of the components, on the order of grams. The hydrazine and nitrogen and water systems display a competitive mass for all sizes. Figure 9 plots the total mass as a function of time of mission for a structure having a 25 meter lenticular structure diameter and an f/D ratio of 1.
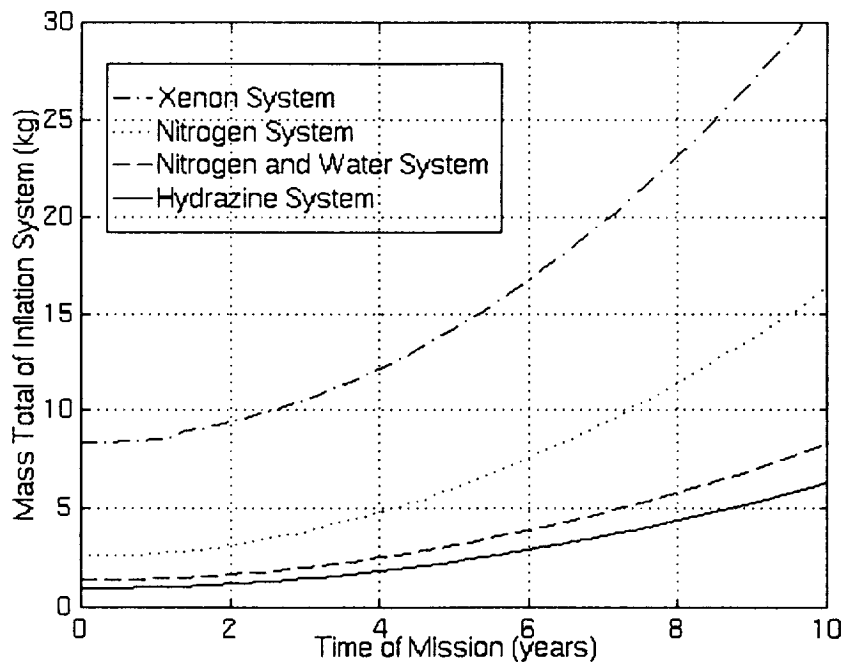

Figure 9. Mass Total for an Existing Propulsion System as a Function of Time of Mission
(f/D = 1 and D = 25 m).

Figure 9 illustrates the affect the time of mission has on the total mass of the inflation system. As the time increases, more pressurant is needed to replace gas lost through leakage. As in Figure 8, the xenon and nitrogen systems are more massive than the hydrazine and nitrogen and water systems. This can be attributed mostly to the molecular weight of the pressurants and the resulting tank impact. Figure 10 plots the total mass as a function of f/D ratio for a 5 year mission of a structure with a 25 meter lenticular structure diameter.
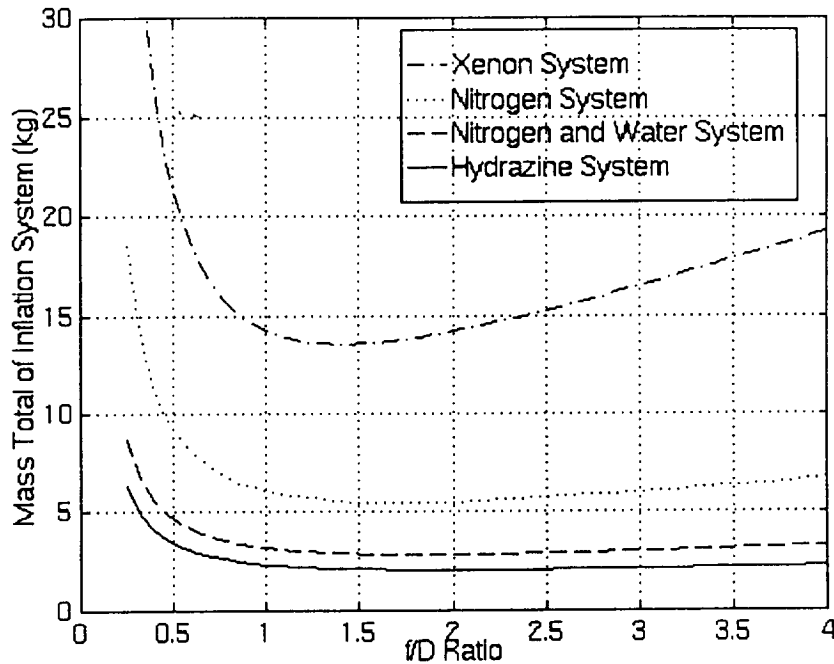

Figure 10.   Mass Total for an Existing Propulsion System as a Function of f/D Ratio
(t = 5 years and D = 25 m).

Figure 10 illustrates the effect the f/D ratio has on the total mass of the inflation system. It appears that for each system there is an "optimal" f/D for a given diameter. For example, the "optimal" f/D is in the region of 2 for the hydrazine system. Although this is interesting, it is not particularly useful. Mission objectives will decide the f/D ratio as opposed to mass considerations. Once again the xenon and nitrogen systems are more massive than the hydrazine and nitrogen and water systems.

No Propulsion System

The sum of the masses of the set-up components, the total pressurant required, the tank(s), and the tubing equals the total mass of the inflation system. This value represents the amount of mass that would need to be added to a spacecraft which has no existing onboard propulsion system. This value can be obtained for any system or configuration using a modified spreadsheet developed for the first design study. Recall that this mass total does not include electronics, cables, and structure. Figure 11 plots the total mass as a function of lenticular structure diameter for a 5 year mission of a structure having an f/D ratio of 1.
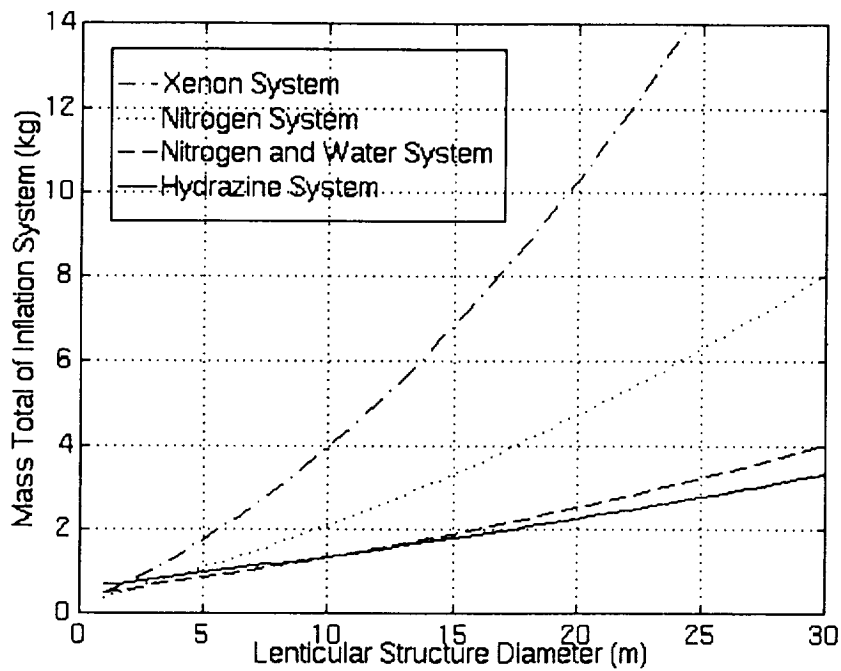
*Figure 11. Mass Total for No Onboard Propulsion System as a Function of Lenticular
Structure Diameter (f/D = 1 and t = 5 years).*

Figure 11 displays a similar trend to Figure 8. The mass total is slightly higher for all cases. Once again, the most promising mass totals are those of the hydrazine and nitrogen and water systems. Figure 12 plots the total mass as a function of time of mission for a structure having a 25 meter lenticular structure diameter and an f/D ratio of 1.
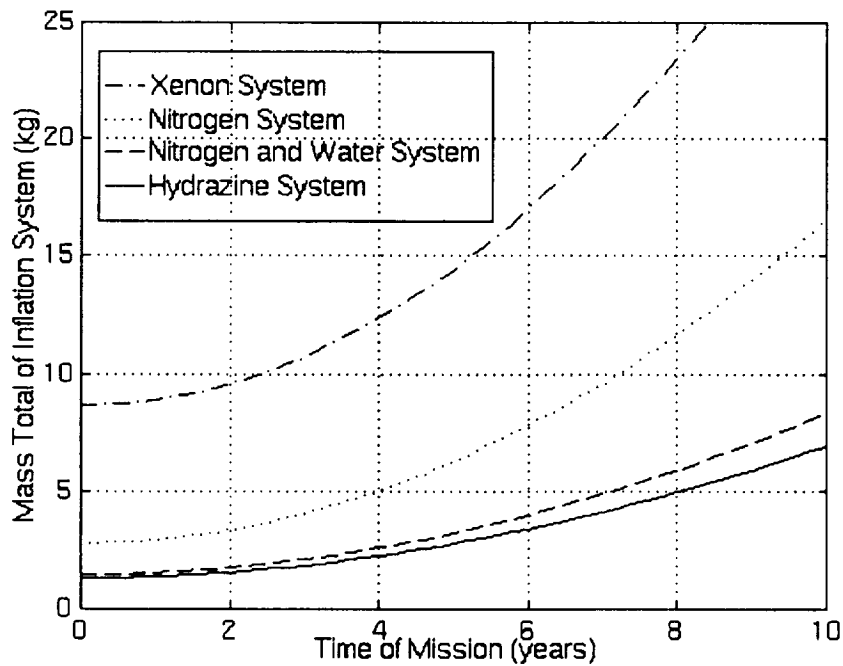

*Figure 12. Mass Total for No Onboard Propulsion System as a Function of Time of Mission
(f/D = 1 and D = 25 m).*

Figure 12 illustrates a similar trend to Figure 9 with slightly higher masses. Figure 13 plots the total mass as a function of f/D ratio for a 5 year mission of a structure with a 25 meter lenticular structure diameter.
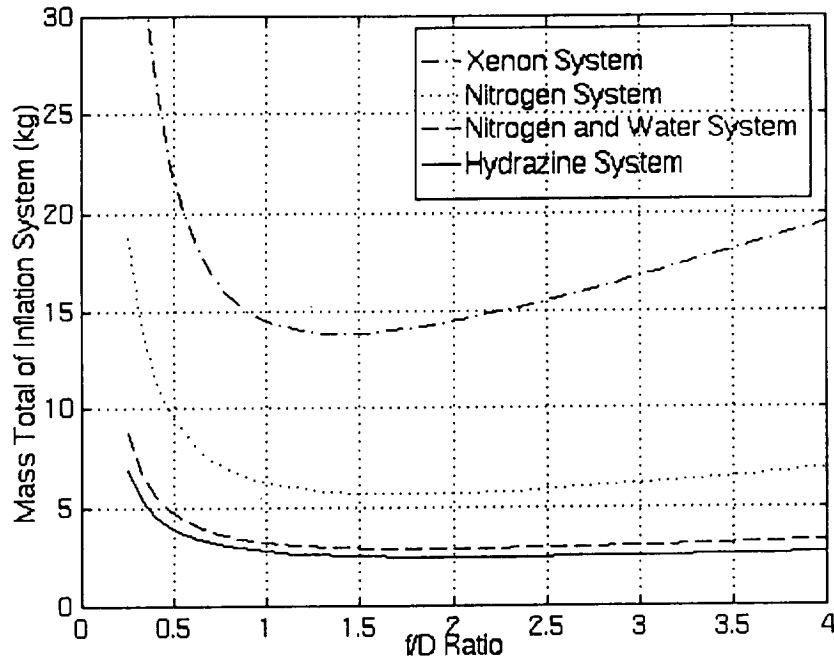
Figure 13. Mass Total for No Onboard Propulsion System as a Function of f/D Ratio
(t = 5 years and D = 25 m).

As with the previous plots, the mass total for no onboard propulsion system displays a similar trend to the mass total for an existing onboard propulsion system.

Open Issues

Although each inflation system is different, all have open issues that must be addressed prior to their selection and answered during the development of the inflation system. These issues are summarized for each of the four systems below:

All Systems
- Should the gas flow-control orifice and vent (O2 and SV2 in Figure 2 for example) be downstream of the isolation solenoid valves (SV3, SV4, and SV5 in Figure 2 again)? If so, then three times more solenoid valves are needed. One reason to do this is over-pressure control in case of thermal ratchet (current design allows venting of only one system at a time unless all systems are at the same pressure).
- Will it be possible to generate small enough bursts of pressurant during the maintenance stage of the mission?
- The absorptivity in the wavelength of interest of the gas used to maintain the shape of the lenticular structure.

Hydrazine System
- Can the gas generator itself supply controlled and repeatable pulses of gas when the demand is very small (during the maintenance phase of the mission)?
- Is a catalyst bed heater required? Can the catalyst bed survive the thermal shocks associated with pressurization without being heated to some high temperature first? Will sufficient catalysis occur for very small pulses unless the catalyst bed is heated?
- Will the catalyst bed be poisoned due to long residence time of exhaust gasses caused by the downstream orifice?
- Does the gas coming out of the gas generator have to be actively cooled, or is thermally shorting the tubing to the spacecraft structure enough?
- What is the compatibility of the inflatable structure material with ammonia and possibly hydrazine vapor? This includes the structure material as well as any epoxies or other adhesives used.
- Will ammonia or hydrazine vapor condense on the inflatable structure? If so, what then?

- How well can we get the hydrazine to decompose, especially during maintenance pressure phase when the amount of hydrazine to decompose is very small? At this stage, what amount of ammonia dissociation should be assumed?
- Do we need an orifice up-stream of the gas generator (O1 in Figure 2)?

Nitrogen and Water System
- Compatibility of inflatable structure material with water vapor.
- Will there be a problem of water condensing on the inside of the structure if it gets cold? What is the consequence of this happening? Can the inflated structure be kept warm enough?
- Is single point failure possibility of water tank outlet valve acceptable? If it leaks, the system fills with water to some extent. Will this freeze when the downstream solenoid valves open?
- How much mass can be saved by thermally shorting the water tank outlet tubing to the tank itself?

Xenon System
- Xenon thrusts require very pure xenon to prevent erosion of the thruster points. Can the xenon point of use purity requirement be maintained with hydrocarbons present in the inflation system? Will out-gassed hydrocarbons from the inflatables permeate into the propulsion system?

The actual inflatable structures have many open issues that are beyond the scope of this memorandum.

Recommendations and Conclusions

The two design studies performed attempted to be conservative in mass calculations. That is, mass margins of 20% for liquids and 50% for gases are probably excessive. The design studies revealed three areas of the analysis process that could use improvement. An accurate method of determining leakage would be needed for more accurate overall mass totals. A more accurate tank sizing spreadsheet is needed for improved tank calculations. The current spreadsheet is sufficient for this study yet becomes increasingly inaccurate for larger tanks. Lastly, a more realistic estimate of the tubing mass is needed.

Although this paper dealt primarily with mass considerations, reliability considerations are in many ways as important. There is a much higher chance of failure through leakage in any of these inflation systems than a single-point failure. However, such a single-point failure could occur in one or more of the many valves in a particular inflation system. By minimizing mass (redundant devices) there is an increased chance of failure. Hence, the trade-off with having a low mass inflation system is an increased chance of overall failure. Although the nitrogen and water system displays some of the most promising mass totals, it is a complex system. The hydrazine system also displays promising mass totals but the complexity of this system also raises the question of reliability. There is a potential for something to wrong in such complex systems. The nitrogen and xenon systems, although more massive for many conditions, are simple and reliable in comparison.

It is also important to recall the assumptions made in this analysis. If the operating temperature of the spacecraft is lower than 293 K, all four systems will be more massive. The nitrogen and water system will be most affected by temperature since the vapor pressure of water decreases significantly with decreased temperature. The assumption of near complete ammonia dissociation in the hydrazine system is also worth mentioning. In all likelihood, 90% ammonia dissociation would be possible but an assumption of 40% to 90% might be more realistic. A lower ammonia dissociation would not only raise the overall mass of the hydrazine but also further magnify the open issues surrounding the hydrazine system.

In general, the choice of an inflation system will depend on mission objectives. While a short and small mission would favor the nitrogen system, a large and long mission would favor the hydrazine system. If mass is not a crucial constraint in design, it is recommended the nitrogen or xenon system be used for their simplicity and reliability.

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