AN OVERVIEW OF DEMISE CALCULATIONS, CONCEPTUAL DESIGN STUDIES, AND HYDRAZINE COMPATIBILITY TESTING FOR THE GPM CORE SPACECRAFT PROPELLANT TANK*

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Abstract

NASA's Global Precipitation Measurement (GPM) mission is an ongoing Goddard Space Flight Center (GSFC) project whose basic objective is to improve global precipitation measurements. It has been decided that the GPM spacecraft is to be a "design for demise" spacecraft. This requirement resulted in the need for a propellant tank that would also demise or ablate to an appropriate degree upon re-entry. This paper will describe GSFC-performed spacecraft and tankage demise analyses, vendor conceptual design studies, and vendor performed hydrazine compatibility and wettability tests performed on 6061 and 2219 aluminum alloys.

INTRODUCTION

NASA's Global Precipitation Measurement (GPM) project has the following objectives:

- Understand the horizontal & vertical structure of rainfall, its macro/micro-physical nature, and its associated latent heating.
- Train and calibrate retrieval algorithms for constellation radiometers.
- Provide sufficient global sampling to significantly reduce uncertainties in short-term rainfall accumulations.
- Extend scientific and societal applications.

The space-based portion of the mission architecture consists of a primary or core spacecraft and a constellation of NASA and contributed spacecraft as seen in Figures 1 and 2. The efforts described in this paper refer to the core spacecraft (hereafter referred to as simply GPM) which is to be fabricated at the Goddard Space Flight Center (GSFC). The core spacecraft is similar to the highly sucessful Tropical Rainfall Measuring Mission (TRMM) spacecraft but with enhancements to both instrumentation and global coverage. The core satellite mass is approximately 3200 kg. It is to be launched in 2013 from Japan aboard an H2-A rocket into a 65° inclination circular orbit of 407 km altitude. The primary instruments are:

1. Dual frequency Ku-Ka Band radar with approximately 4 km horizontal and 250 m vertical resolution
2. Multifrequency (7 band) radiometer with a frequency range of 10 – 183 GHz

NASA Policy Directive 8710.3 and NASA Safety Standard 1740.14 provide guidelines for the safe disposal of spacecraft that have completed their missions. One method for meeting End of Life (EOL) disposal requirements is to allow a spacecraft to simply reenter the atmosphere in an uncontrolled fashion. To be eligible for this option, the spacecraft must be designed such that it demises (ablates) to below a specified threshold. The threshold is set such that the chances of serious injury or death due to debris impact are minimized.

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The propellant tank or tanks of most spacecraft are constructed of materials such as steel or titanium which often survive reentry and are thus a significant source of debris. The GPM tank is required to completely demise during reentry. This paper describes the initial analytic and test efforts undertaken during the development of the GPM propellant tank.

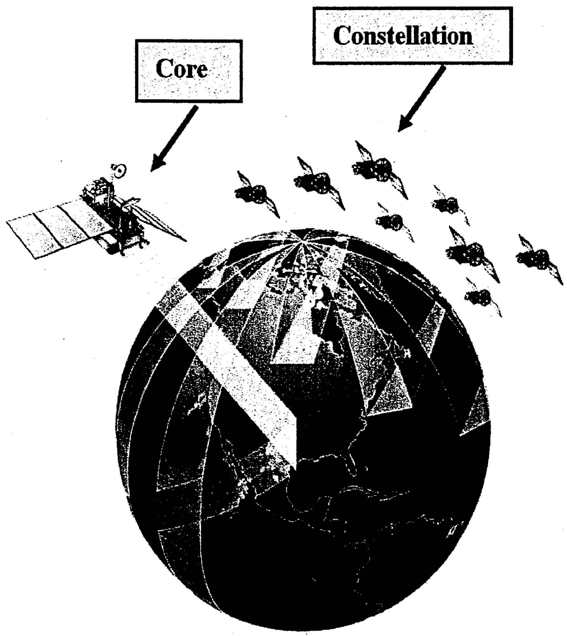


Figure 1. GPM Program Constellation

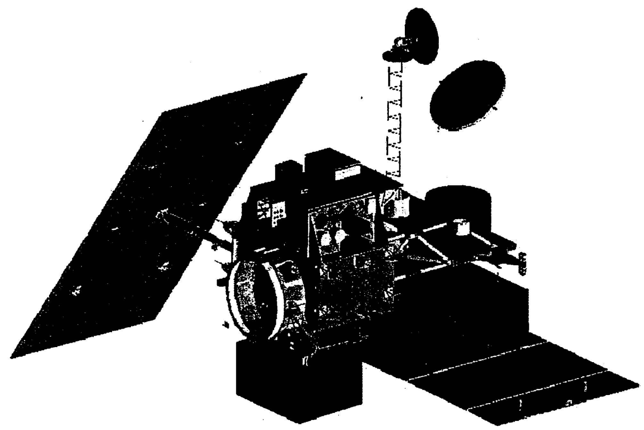


Figure 2. GPM Core Spacecraft Concept

RESULTS AND DISCUSSION

PART 1: INITIAL DEMISABILITY ANALYSES

The demisability of the GPM spacecraft including its tanks was assessed in the 2002 through 2004 time frame using the Object Reentry Survivability Analysis Tool (ORSAT) program. ORSAT is a NASA-proprietary software package written and maintained by NASA/Johnson Space Center. Simplistically viewed, the spacecraft and the objects that make up the spacecraft are treated by ORSAT as layers of an onion that ablate away as the spacecraft traverses the atmosphere. Simple shapes are used to represent actual S/C piece parts (plates, boxes, spheres, right circular cylinders, etc.). Objects may consist of multiple layers; however each layer must have constant thickness and material properties. It is often not possible to model the actual shapes and thicknesses of the spacecraft parts, but a mixture of judgment and parametrics have been shown to bound the solution and yield reasonable results. An object's thermal mass (the mass that must ablate) and aerodynamic mass (for ballistics) may differ which can help to offset the inaccuracies in the object models. The heat balance includes oxidation heating, radiative cooling, aerodynamic heating, convective cooling, and gas cap radiation heating. Outputs include demise altitude or if the object survives, demise factor, impact velocity, debris casualty area (DCA), and impact energy.

The first basic ORSAT analyses for GPM tanks were performed in 2002 and are reported in Reference 1. The GPM spacecraft was modeled as a generic tumbling aluminum box shell entering the atmosphere at an altitude of 120 km with a velocity of 7634 m/sec. The initial velocity and trajectory conditions for the tank parametric analyses were derived from the generic spacecraft model assuming a breakup altitude of 78 Km. The breakup altitude was chosen based on experience. The tank was modeled as a fragment which broke away from the spacecraft at the breakup altitude with a wall temperature of 300 K. The selected wall temperature was conservative in that it assumed no parent body heating. In all cases the tank was a 1.016 m (40 inch) OD sphere. The eight basic tank material cases studied are summarized in Table1.

A number of parameters in addition to materials and wall thickness were varied. These included oxidation efficiency (baseline = .5), initial altitude (BL = 78 km), initial wall temperature (BL = 300 K), emissivity (BL = .3). A summary of the results is contained in Table 2. Demise is defined as 100% ablation prior to 50 km altitude. For example, the highlighted item in Table 2 is an Al 2219 monolithic shell for which wall thickness up to 1.55 cm thick demise. The demise altitude was 60 Km when an oxidation factor of 0.5 was selected. The common parameters for this table are listed in the header.

Table 1. Initial ORSAT Study Case Definitions

Case	Liner Material / Thickness	Shell Material
1	N/A	Ti 6Al-4V, min 0.05 cm (0.0196 in)
2	N/A	Al 2219
3	N/A	Al 6061
4	N/A	CRES 304L, min 0.15 cm (.0590 in)
5	Ti 6Al-4V / 0.0762 cm (0.03")	Graphite Epoxy Composite
6	Al 2219 / 0.0762 cm	Graphite Epoxy Composite
7	Al 6061 / 0.0762 cm	Graphite Epoxy Composite
8	CRES 304L / 0.0762 cm	Graphite Epoxy Composite

Table 2. Initial ORSAT Study Result Summary
Emissivity = 0.3, Altitude = 78 km, Initial Temperature = 300 K

	Oxidation Efficiency	Case (Materials identified in Table 1)							
		1	2	3	4	5	6	7	8
% Demise or Altitude (km)	1.0		58	61			64	65	
	0.5	65%	60	65	82%		66	67	
Max. Wall Thickness (cm)	1.0		2.05	1.65			6.1	5.5	
	0.5		1.55	1.15			5.0	4.4	

None of the cases containing Ti or CRES demised for the conditions summarized in Table 2. In fact, none of the Ti or CRES tanks demised with even the most demise favorable combinations of parameters (not shown in Table 2). The debris casualty area for the undemised cases was 2.3 m^2. For reference, the goal for debris casualty area for the entire spacecraft is 8 m^2. These initial results indicated that a demisable propellant tank concept warranted further analyses for GPM. Although subsequent analyses would show that the initial analyses were optimistic in their estimate of maximum allowable wall thickness, it can be seen from the Table 2 results that the allowable wall thicknesses are well beyond the normal liner thickness for propellant tanks.

The next set of ORSAT analyses again employed parametric tanks but instead of a generic spacecraft the tanks were placed within a realistic model of the TRMM spacecraft and within the latest GPM configuration. All modeling was performed using ORSAT 5.5 (version dated 5/22/2002). Tank variables included materials, tank shape (sphere or cylinder), tank quantity (one or two), thicknesses for monolithic tanks, and thicknesses for composite overwrapped pressure vessel (COPV) metallic liners and COPV composite shells. Aerodynamic mass was also varied to better match the actual tank ballistics without affecting material thicknesses. A summary of the basic options is presented in Table 3. The outer location is the most favorable for demise as it is exposed to the ablating environment soonest. The mid position is a special case for which part of the propulsion module cylinder is removed to promote early heating. The innermost position is the most conservative for demise as this position is shielded by the spacecraft. The single tank configurations for all materials had a volume of 56288 in^3 and were exclusively analyzed in the aft position due to their length. Each tank of the two tank configurations had half the volume of the single tanks.

A total of 56 tank configurations were analyzed. None of the monolythic titanium tanks (t = .06" min) demised in any location with even the most favorable oxidation factor of 1.0. Similarly, none of the nine CRES 316/Graphite Epoxy COPV tanks were found to demise even in the favorable outermost position. The best case used a liner thickness of 0.010" and a composite thickness of 0.100" and had a demise factor of 80% using the nominal oxidation factor of 0.5. The monolythic aluminum tanks yielded the most suprising results. Unlike the initial demise study results which used a generic set of initial conditions, even relatively thin walled spherical tanks only demised at the outermost location. Increasing the aeromass of these tanks only improved demise altitude by 2 km. Limited results did seem to indicate that the cylindrical shaped aluminum tanks were more demiseable than sperical tanks of comparable thickness and mass. Cylindrical tanks are constrained to be right circular cylinders of constant thickness which do not account for the domed end of a real world tank. All of the large aluminum cylindrical tanks demised above 60 km except for the 0.4" thick tank, which demised at 51.1 km (marginal demise).

Table 3. Parametric Tank ORSAT Study, Summary of Basic Tank Options

*Small = 28144 in^3, Large = 56288 in^3				Number of Cases by Location in Propulsion Cylinder		
Shell Material	Construction	*Size	Shape	Outer	Mid	Inner
Titanium	Monolithic	Small	Sphere	2		2
Al 6061	Monolithic	Small	Sphere	6	3	6
Al 6061	Composite	Small	Sphere	12	3	12
Al 6061	Monolithic	Small	Cylinder	5		5
Al 6061	Monolithic	Large	Cylinder	10		
Al 6061	Composite	Small	Cylinder	6		6
Al 6061	Composite	Large	Cylinder	6		
CRES 316	Composite	Small	Sphere	9		
				Total = 56		

The aluminum lined composite tanks had liners ranging from 0.030" to 0.100" thick and composite layers from 0.025" to 0.100". All of these configurations demised in both the inner and the outer locations except for the 0.100/0.100" combination sphere, which did not demise in the inner location. As expected, the tanks located in the inner location demised at a lower altitude.

PART 2: GPM TANK STUDY AND POST-STUDY ORSAT ANALYSES

GSFC does not possess the expertise or software tools to produce conceptual tank designs of sufficient fidelity for configuration trade studies, realistic ORSAT analyses, or cost schedule and risk assessments. A GPM Tank Study procurement was initiated and all U.S. based tank vendors were invited to participate. The following was a list of "conventional" design variables the contractor could choose to include in their study efforts.

1. Materials: Aluminum alloys (6061 vs. 2219 etc), Full or partial overwrapped aluminum liner, Hybrid (i.e. metallic dome with overwrapped cylinder), All metallic
2. Number of tanks (single vs. dual tanks).
3. Mechanical interface (flange, tabs, bosses, etc).
4. Fabrication options (spun, formed, welded, machined, etc).
5. Shape (spherical, cylindrical).
6. Expulsion devices:
   a. Positive: diaphragm, bladder
   b. Surface tension devices ("PMD's"): vanes, sponges, traps, etc. Can include auxiliary external devices such as large filters or small tanks to hold maneuver propellant. Double ended tanks and acceleration aligned dual tanks may be considered with recommendations for any required extra valving.
7. Vendor recommended options

The goal of the study was not to arrive at an optimum or single recommended configuration but rather to study a broad spectrum of realistic concepts that highlight the strengths and weaknesses of possible solutions for GPM. Each of the four vendors who took part in the study proposed a variety of options for configurations. GSFC selected from the options proposed by each vendor such that the greatest diversity of information could be obtained. One of the vendors took a broad brush approach with less detail in its concepts. Its tank configuration options included monolythic aluminum (2219 vs 6061), hybrid composite (bare dome ends), composite, spherical, cylindrical, single or dual tank sets, variable aspect ratio for cylindrical tanks, surface tension expulsion (PMD), diaphragm expulsion, bladder expulsion, and vacuum or ambient pressure loading. Mass, cost, and production risk were the focus of comparison between configurations.

Table 4. Tank Study, Summary of Detailed Configurations

		Liner Thickness, inch	Hoop Wrap, inch	Helical Wrap, inch
1	Carbon/Al 6061, full wrap, thick liner	0.110	0.023	0.015
2	Carbon/ Al 6061, full wrap, thin liner	0.010	0.035	0.023
3	Carbon/ Al 6061, hoop wrap, (bare domes)	0.186	0.012	0.0
4	Carbon/Titanium, hoop wrap, (bare domes)	0.055	0.018	0.0
5	Carbon/ Al 6061, full wrap, medium liner	0.050	0.030	0.020
6	Carbon/Titanium full wrap	0.030	0.026	0.017
7	Carbon/ Al 6061, hoop wrap, (bare domes)	0.220	0.024	0.0
8	Carbon/ Al 2219, hoop wrap, (bare domes)	0.220	0.024	0.0
9	Carbon/Al 2219, full wrap	0.080	Tot = 0.063	
10	Carbon/Al 2219, full wrap, liner sized for vacuum	0.105	Tot = 0.063	
11	Zylon PBO/ Al 2219, full wrap, liner sized for vacuum	0.105	Tot = 0.055	
12	Zylon PBO/ Al 2195 (Al-Li), full wrap, liner sized for vacuum	0.105	Tot = 0.055	
13	Carbon/Al 6061, full wrap	0.050	0.040	0.025
14	Carbon/Al 6061, full wrap, non-yielding liner	0.050	0.110	0.054
15	M46J (High modulus) carbon /Al 6061, full wrap, non-yielding liner	0.050	0.075	0.036
16	M46J/Al 2219, 45% exposed dome, non-yield liner	0.050	0.075	0.036
17	M46J/Al 2219, 100% exposed dome, non-yield liner	0.130	0.063	0.0

The remaining three vendors provided a more limited number of concepts but with higher detail. A summary of the basic configurations produced can be seen in Table 4. In the case of COPV's, proprietary geometry and overwrap characteristic programs were used to arrive at realistic tank configurations. Finite element analyses were included with some of the concepts which helps to lend credibility to the thicknesses and mass estimates. The more detailed of the tank concepts produced included realistic increases in liner thicknesses in the boss and weld land regions. All of the detailed concepts used skirt mounts. Tab, flange, and polar mounts were not considered for the detailed concepts since they provided no mechanical integration advantages for GPM and are heavier to impliment for a GPM class tank. None of the concepts included a detailed PMD concept, but a place holder mass of 3 pounds was used. Taken as a whole, the designs produced by this study were very useful for assessing risk, bounding tank mass, conducting mechanical integration trades, and refining the ORSAT analyses with realistic configurations.

PART 2: POST TANK STUDY ORSAT ANALYSES

Table 5 summarizes the results of the ORSAT analyses that were conducted after the GPM Tank Study. Previous ORSAT analyses, the Tank Study, discussions with PMD experts, and refinements in the

Table 5. Post Tank Study ORSAT Results

	NOTES: Nominal Tank Volume = 50120 cu. in., single tanks, Vendor mass = mass without skirt, PMD, or tubes)	Al Liner t, inch	Over-wrap t, inch	Vendor Mass, Kg	ORSAT Total Tank Mass, kg	ORSAT Demise Alt., Km
1	ORSAT Case #51 from previous study	0.070	0.05	n/a	30.38	70.7
2	Generic COPV from tank study	0.030	0.039	13.0	14.11	73.5
3	#2 COPV, .019" composite (test thickness effect)	0.030	0.019	13.0	11.55	73.8
4	Table 4 Design 13 Mass=34.88 kg (Yielding .050" liner)	0.050	0.065	33.3	23.56	71.8
5	#4 with thicker liner to match liner mass	0.0725	0.065	33.3	30.45	70.0
6	Table 4 Design 15 (non-yield liner@.050", high modulus fiber>>thicker composite shell)	0.050	0.111	38.8	29.49	71.0
7	#6 with thicker liner to match liner mass	0.0725	0.111	38.8	36.40	68.9
8	Table 4 Similar to Designs 3, 17 , Cylinder wrapped only (bare Al domes), Ignore thin cylinder overwrap	0.160	0	55.9	48.98	63.2
9	Table 4 Design 9, Full Wrap, Non-Vacuum load	0.080	0.063	49.3	32.95	70.0
10	#9 with thicker liner to match liner mass	0.1175	0.063	49.3	44.62	66.8
11	#9, match liner and composite masses	0.1175	0.0977	49.3	49.19	65.7

mechanical design of the propulsion module led GSFC to baseline a single tank configuration. Unlike real world tanks, cylinders modeled in ORSAT are limited to uniform material thicknesses. The tank configurations modeled included thickening of the liner and composite layers to assess sensitivity to thicker regions in the tank and to increase the overall mass of the tank. Even so, in all cases except for the generic COPV, the mass used by ORSAT is less than the mass estimated by the vendor for any given tank. This is predominantly due to the thickening of the actual tank concepts at the inlet/outlet bosses and at the weld land. The analyses are conservative in terms of demise in that lower mass is unfavorable for ballistics. Additionally, during an actual reentry the thicker sections of the tank will be exposed to two sided heating after the thinner sections of the tank demise; thereby greatly increasing the rate of demise of the thicker sections. The only tank which fails to demise above 65 km is the 0.160” thick hybrid aluminum tank (#8). This is not a likely configuration for GPM as it is far too massive and does not exhibit substantial performance, cost, or risk benefits. For purposes of the GPM mass budget, a tank similar to #6 in Table 5 was baselined. The mass baseline also includes the mass of incorporating a bladder (aluminum PMD is the goal) and the mass of a skirt.

The demise of generic PMD elements was assessed by placing thin strips of aluminum (up to 0.05" thick) and titanium (up to 0.03" thick) and thin tubes of the same materials and thickness within tank #2 of Table 5. The aluminum simulators demised readily. Some of the titanium simulators demised although the results were mixed. It was decided that an all aluminum PMD was the lowest risk approach for achieving a 100% demisable tank.

One of the Tank Study vendors proposed exploring the use of passively activated demise aids. The device would cut the tank with an aerothermally activated exothermic pyrotechnic device. The tank would be thus be exposed early in its reentry to two-sided heating which would accelerate demise. A variety of compounds that were energetically comparable to thermite were tested first on 0.06" thick titanium and aluminum plates and then on overwrapped tubes. The titanium plate was consistently breached by linear charges whereas the aluminum plate was not always breached. It is suspected that that the ability of the aluminum to conduct away heat also allowed it to survive in some cases. The tests on overwrapped tubes did not show promise as executed in this limited trial. Although the results were less than conclusive for application to tanks, techniques could be adapted which would use exothermic reactions to aid a spacecraft's demise. One method would be to use a device to expose the interior of a box or even to "unzip" a spacecraft to expose its interior components to heating earlier in a reentry.

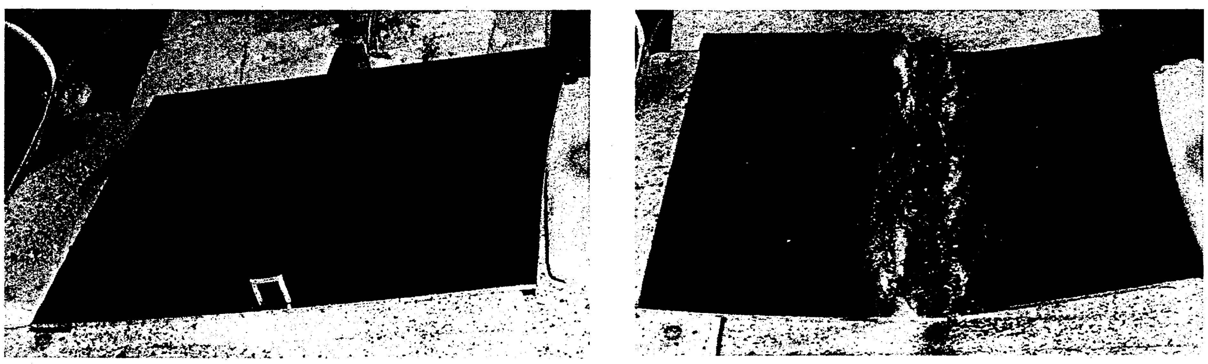


Figure 3. Exothermic Device On .06" Al 6061 Plate

PART 3: ALUMINUM/HYDRAZINE COMPATIBILITY AND WETTABILITY TEST

Hydrazine is compatible with very few materials for long-term missions such as GPM's. Compatibility depends not only on the metal alloy chosen but also on detailed characteristics such as heat treatment, manufacturing methods, and final configuration of the item. Although aluminum is generally considered compatible and wettable with hydrazine, a variety of literature sources give mixed results on both counts. Corrosion and film formation problems with aluminum were noted in the past as well.

Capillary strength as measured by contact angle plays an important role in the proper functioning of a surface tension PMD. For porous elements, the propellant when in contact with the tank/PMD surfaces must have a capillary strength across the liquid/gas interface that is adequate to prevent gas from entering the closed part of the PMD under the acceleration and flow environments of the mission. The propellant when in contact with the tank/PMD surfaces must also have an adequate capillary strength to retain propellant in sponge elements of the PMD and to provide the required propellant flow rates along valid communication paths. A gap between two surfaces (vane and wall) can be used to transport propellant. Again the propellant is retained in the gap by the capillary strength across the liquid/gas interface. A non-zero contact angle degrades the capillary strength that can be achieved across the liquid/gas interface. The larger the angle, the more the capillary strength is degraded. PMD's may be designed for higher contact angle; however, it is still required that the contact angle used for design be consistent and repeatable even after exposure to hydrazine. Contact angle depends on the propellant, surface material, surface finish and cleanliness of the surface. Figure 4 illustrates the contact angles for hydrazine on two aluminum coupons subjected to different cleaning procedures.

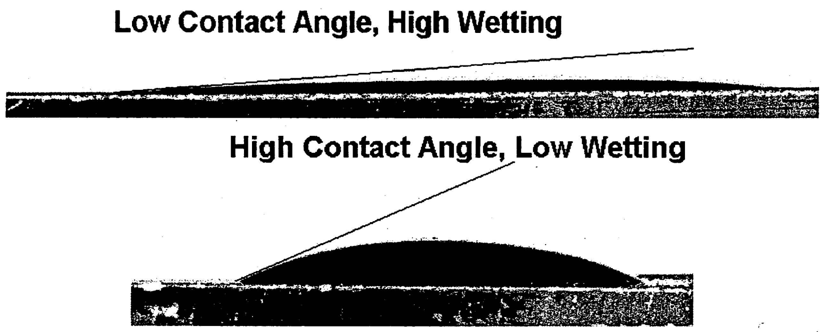


Figure 4. Contact Angle, Hydrazine with Aluminum in GN2

Data characterizing both hydrazine/aluminum compatibility and hydrazine/aluminum contact angle is scarce and is often contradictory. As a result of vendor recommendations from the GPM Tank Study, GSFC contracted with Hamilton Sundstrand Space, Land & Sea (HSSLS) to perform long term compatibility and wettability testing on Al 6061 and 2219. Angeles Crest Engineering Incorporated (ACEI) performed the bulk of the technical effort including authoring the final report and the Hamilton Sundstrand Rockford, Illinois facility provided laboratory facility and personnel support.

Hydrazine elevated temperature immersion tests were performed on a total test lot of 15 coupons composed of both Al 6061 and 2219 samples. HSSLS provided the test samples. All samples were subjected to a carefully controlled and documented standard cleaning and pre-treatment procedure. Both parent and weld material were tested. All regular (non-reference) test samples were 0.5 X 1.5 X 0.050 inches and had a small area 0.25 inch from one end that was perforated with 5 holes of either 0.015" or 0.030" diameter. The holes were mechanically drilled. Laser drilling was attempted, but resulted in a ring of debris around the holes. Consequently laser drilling was not deemed practical. Welded samples consisted of two parent metal pieces that were welded together. The Gas Tungsten Arc Welding Process (GTAW), also called the Tungsten Inert Gas (TIG) process, with Argon or Argon/Helium gas was used to join the two pieces. With the exception of adjustments to account for metal thickness, this process would be used for production welding. A reference sample of cylindrical shape with rounded ends was included in the tests to assess the effects of edges on the samples. All samples were immersed in ultra-pure hydrazine (procured from Arch Chemical Company) in glass vials (one sample per vial) and aged at 160°F for up to 84 days. The glass vials were covered with thin transparent membranes that would bulge or rupture in the event of gas generation due to hydrazine decomposition. The vials were sealed with plastic screw-on caps. Witness samples of hydrazine without metallic samples were also included. Samples were withdrawn at 4 days, 46 days, and 84 days. The equivalent ageing was calculated to be 0.38, 4.4, and 8 years, respectively based on an activation energy of 13900 cal/mole. The common test features are summarized in Table 6. The sample matrix can be found in Table 7.

SEM analysis and contact angle photography were performed on the samples prior to aging. Samples were weighed before and after immersion tests and surface chemistry analysis was performed after the tests. Pre- and post-test chemical analysis of the test hydrazine were also performed. Any particulate matter in the hydrazine after the tests was collected and analyzed.

The samples were dried in a nitrogen environment without rinsing. Photographs of contact angle of hydrazine on the aluminum surface of the samples were taken as drops of hydrazine were placed on sample surfaces after the immersion tests. The aged samples were in a nitrogen environment during the contact angle imaging.

	Table 6. Common Test Features
1	Material stock was same as that to be used in manufacturing flight PMD'
2	Metal samples were manufactured via processes that are as close to actual processes as possible.
3	Post machining processes followed manufacturing processes for PMD.
4	Samples were subjected to the fluids to be used in preparing and testing the flight tank.
5	Hydrazine was ultra pure grade from Arch Chemical Company. Pre- and post-test assay was performed.
6	Contact angle observation of all samples was conducted pre- and post-immersion in a GN2 environment.
7	Surface examination was performed post-immersion and for non-immersed samples.

Table 7. Test Matrix and Results for Aluminum/Hydrazine Compatibility Testing

	Material	Hole	Weld	Equiv Age	Surface Chemistry	Average Contact Angle, (Spread)
1	6061	.015	X	8	No Surface chemistry change	28 (21 – 34)
2	6061	.030	X	8	No Surface chemistry change	/
3	6061	.015	X	4.4	No Surface chemistry change	26 (15 – 36)
4	6061	.030	X	8	Decrease in Mg content	17 (17 – 19)
5	6061	.015		8	No Surface chemistry change	24 (22 – 26)
6	6061	.030		8	Decrease in Mg content	/
7	6061	.015		4.4	Decrease in Mg content	/
8	6061	.030		8	Decrease in Mg content	20 (18 – 23)
9	6061	.030		.38	No Surface chemistry change	37 (30 – 40)
10*	6061	n/a		8	No Surface Analysis	/
11	2219	none	X	8	No Surface Analysis	30 (28 – 31)
12	2219	none	X	4.4	Decrease in Cu content	31 (28 – 35)
13	2219	none		8	No Surface Analysis,	21 (15 – 27)
14	2219	none		.38	No Change in Cu	38 (34 – 42)
15*	2219	n/a		8	No Surface Analysis,	/

* rounded reference cylinder

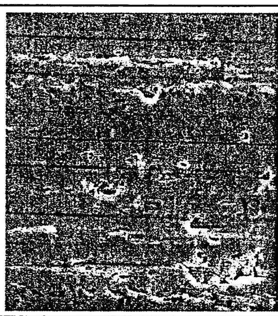
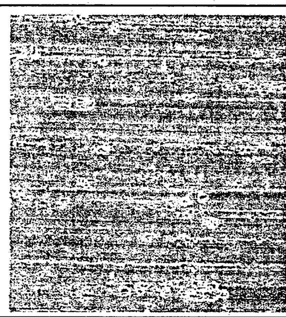
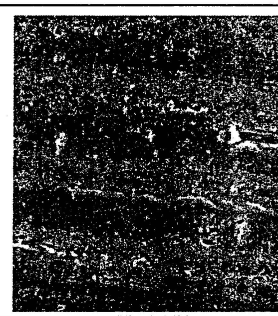
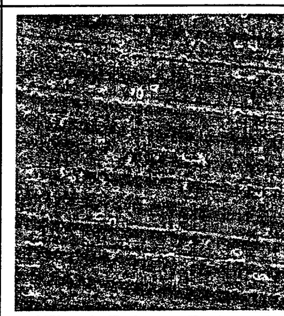
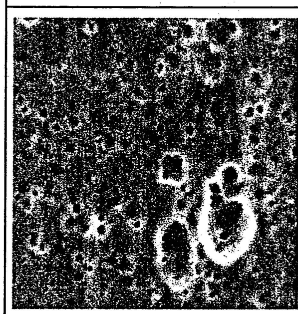
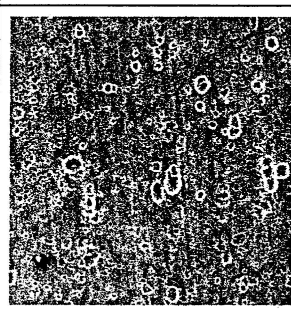
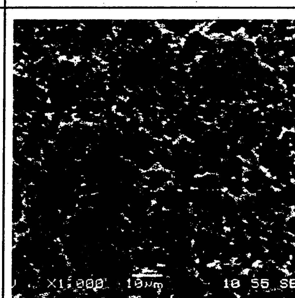
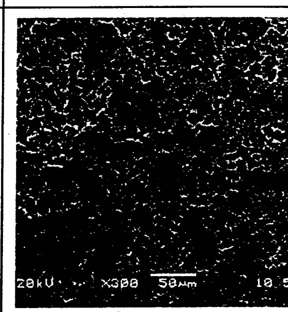
Post-immersion characterization of the samples included SEM photographs of the sample surfaces. The SEM analysis determination of the surface chemistry of the samples used the energy dispersive spectroscopy method. The surface chemistry after ageing for each sample is compared to that of the unaged samples in Table 7. Samples 1 through 10 are Al 6061. Samples 1, 2, 3, 5 and 9 show no significant changes in surface chemistry relative to the initial Al 6061 surface chemistry. Samples 4, 6, 7, and 8 show a decrease in magnesium content, but this is not considered to be a problem. Samples 11 through 15 are Al 2219. Sample 12 shows a decrease in Copper content while sample 14 does not. This could indicate leaching of copper from the surface of the Al 2219 sample. It is not known whether such leaching would be a serious problem, but it is of concern. It may be preferable not to use Al 2219 for extended exposure to hydrazine. Samples 10, 11, 13, and 15 did not have surface chemistry analyses.

There was no significant residue or precipitate in the aged hydrazine from any sample vial. There were no any indications of the formation of any film on the samples. There was no evidence of aluminum in the hydrazine from any sample. Additionally there was no chemical indication of hydrazine decomposition for any of the samples. No indications of bulging or deformation of the vial membranes were seen for any of the samples. There was no significant change in sample weight due to ageing. It is possible that the corrosion and film formation problems noted with aluminum in the past are due to impurities in Mil-spec grade hydrazine. This would suggest that highly refined hydrazine should be preferred for use with aluminum tanks.

Sharp edges and corners can change chemical reactions compared with plain surfaces. Sample 10 (Al 6061) and sample 15 (Al 2219) were both cylindrical in shape with rounded ends and were aged for 84 days. These samples were included to provide non-edged datum samples to compare to the standard coupons for edge effects. Edge effects could also have been visually detected on the samples with holes. No indications of edge effects of any kind were seen in any of the test observations or data. The geometries of the holes including their edges were not changed by immersion in hydrazine.

Typical SEM photographs for both unaged and aged samples are shown in Table 8. There were no indications of residue, film formation, or noticeable pitting or deterioration of any of the surfaces of either Al 6061 or Al 2219 samples. All of the aged Al 6061 samples have a similar appearance regardless of the time of ageing except sample 3 which looked like an Al 2219 sample. There may be a very slight increase in the apparent density of surface roughness in the aged Al 6061 samples relative to the unaged sample. The SEM photographs for the Al 2219 samples show a noticeable increase in surface texture roughness of the aged samples relative to the unaged sample. Although the roughness may appear to be significant, it is not severe enough to be considered an issue. All of the aged Al 2219 samples have a similar appearance, except sample 12 which looked like the Al 6061 samples.

Table 8. SEM Results

Unaged Al 6061, SEM, 1000x	Unaged Al 6061, SEM, 300x	Unaged Al 2219, SEM, 1000x	Unaged Al 2219, SEM, 300x
			
aged Al 6061, SEM, 1000x	aged Al 6061, SEM, 300x	aged Al 2219, SEM, 1000x	aged Al 2219, SEM, 300x
			

Contact angle photographs of for both unaged and aged samples were taken for both drops of hydrazine and drops of water. Both air and nitrogen environments were used for some of the unaged samples. The contact angle photographs were shot immediately after a drop was placed on the sample (initial) and again after a drop had been on the surface for more than three minutes (settled). Aged sample results for samples 1 through 9 and samples 11 through 14 are included in Table 7. None of the aged contact angles were sufficiently low or consistent enough to confidently design a reliably functioning PMD. This was an unexpected result. It had been reported that hydrazine will wet Al 6061 surfaces with contact angles of less than 5 degrees for highly prepared surfaces. The majority of the contact angles were greater than 25 deg with a high of 42 deg for the hydrazine drops. Both Al 6061 and 2219 had one contact angle measurement of 15 degrees. There did not seem to be a trend based on ageing time or alloy.

A companion paper describes additional work that was carried out to define a practical process to produce Al 6061 surfaces that consistently wet to contact angles less than 5 deg both before and after long term exposure to hydrazine.

SUMMARY AND CONCLUSIONS

The GPM core spacecraft is part of a GSFC follow-on mission to the highly successful TRMM. GPM is a "design for demise spacecraft." The flow down of this requirement to the propulsion subsystem necessitates a demisable tank design. A GPM Tank Study was initiated to assess a broad spectrum of realistic tank concepts that highlight the strengths and weaknesses of possible solutions for GPM. The results of this study were used for configuration trade studies, realistic ORSAT analyses, and cost-schedule-risk assessments. Demise analyses were conducted that indicated that traditional monolithic titanium and steel tanks as well as newer COPV designs lined with these materials will not demise. Aluminum lined COPV's placed within accurate models of the GPM spacecraft were shown to demise and thus this class of tank with an aluminum PMD was baselined for GPM. A long-term accelerated ageing test of aluminum coupons in hydrazine simulating over 8 years of life was conducted. Al 6061 and 2219 were both tested and both showed long term compatible. The surface texture of the Al 2219 coupons after ageing was rougher than that of the Al 6061 however the roughness was not to a degree that would cause concern. Contact angle tests to gauge the wettability of hydrazine with aluminum were conducted as part of the compatibility tests. The contact angles were significantly higher than theoretically expected and than reported in some literature sources. The values of the contact angles were also inconsistent with a wide range of values. A companion paper to this one describes additional work that was carried out to define a practicable process to produce Al 6061 surfaces that consistently wet to contact angles less than 5 deg both before and after long term exposure to hydrazine.

REFERENCES

1. Internal Memo "Parametric Study of a Demisable Propulsion Tank", Josephine San, Goddard Space Flight Center code 571, GN&C Systems Engineering Branch, October 16, 2002

2. Internal Memo "GPM Mission Propulsion Tank Study", Scott Hull, Orbital Debris Engineer, Goddard Space Flight Center, code 571, March 18, 2003