ISO 9001: 2008
Quality Management System

European Astrotech

Compatibility of Welded Propellant Systems with New Green Propellants
Executive Summary Report (D2)

Preparation/Review	Name	Date, Signature
Prepared by:	S. Graham	05/02/2019
Agreed by:	C. Smith	05/02/2019
Accepted by:	A. Makaya (ESA)	Advenit Makaya Digitally signed by Advenit Makaya Date: 2019.04.02 22:20:56 +02'00'

Amendment Register

Issue	Sheet/Page	Description of Change	Date
DRAFT	*All*	*Initial Issue*	*05/02/2019*

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ESA Study on the Compatibility of Welded Materials with New Green Propellants

Abstract

The ESA study on Compatibility of Welded Materials with New Green Propellants was conducted by aerospace companys European Astrotech, Airbus, MOOG and TWI. This collaborative programme investigated the compatibility between a range of different propulsion system materials and welds and promising new green propellants. A review of the literature determined the most propitious combinations for experimental study. The two propellants chosen for experimental testing were High Test Peroxide (HTP) and LMP-103S. The testing involved a range of Titanium, Aluminium alloy and Stainless steel samples immersed into the chosen propellants at elevanted temperatures, in order to simulate exposure to propellants during spacecraft mission durations. The decomposition rates were measured, along with elemental and assay analysis of the propellants. The material properties of the samples were tested before and after immersion to determine any deletarious effects caused by propellant exposure. LMP-103S displayed good compatibility with all welded materials, but further work on Stress Corrosion Cracking is recommended. HTP was incompatibile with Titanium. This combination can be eliminated from further testing. HTP displayed some characteristiccs of incompatiblity with Aluminium alloy Al2060 and stainless steels SS316 and SS304, but more research into optimum passivation and cleaning processes is recommended for materials in contact with HTP. AlMgSc is recommended for further testing as it performed well in the majority of tests in this study.

1 Introduction

Hydrazine is a toxic and corrosive fuel that is dangerous to handle and store. Currently, it is the most commonly used propellant in satellite thrusters. In a quest to replace hydrazine with a more environmentally friendly fuel, ESA initiated the study of green propellants and propulsion systems that can provide better performance than hydrazine without the toxicity. These propellants could help lower costs by eliminating infrastructure needed for handling toxic fuels and reducing processing time, consequently making it less expensive, safer and easier to launch spacecraft. If a high-performance green propellant and propulsion system can be found, it is clear to see that using such propellants will make a big difference in increased mission performance at a reduced cost while keeping both the environment and the workforce safe from contamination.

This study investigated the compatibility of current and future materials and weld combinations with selected Green Propellants. The use of materials already used in propulsion systems will help minimize the modifications on current propulsion systems, thus reducing development costs. The material compatibility is vital in determining how the current propulsion systems must be adapted for green propellants. ESA initiated this study and approved the Test Plans. European Astrotech conducted the literature review, compatibility testing and propellant chemistry. TWI, Airbus and MOOG ISP provided the samples and performed the welding processes as well as the vast majority of the material testing.

The ESA study was divided into three distinct sections;

- A literature review of current green propellants, propulsion system materials and manufacturing techniques
- Selection of propellants, materials and weld combinations for experimental investigation
- Compatibility and materials testing

The findings of the literature review were used to identify the most promising green propellants, materials and weld combinations for experimental study. The experimental work followed the Test Plan which encompassed preparation and approval of the samples and the experimental test procedures. The results were reported in full in the Test Report, AD 1. Finally, details of each section of the program, including all supporting documentation, were presented in the Final Report, AD2. This document gives a condensed summary of that Final report. The first section summarizes the findings from the literature review. This is followed by a brief description of the test plan along with a summary of the most important results. The last section covers conclusions and recommendations.

2 Applicable Documents

The following documents, at the latest current issue, form a part of this issue to the extent specified herein.

Applicable documents are referred to in the text, in the form of ADx where x is the relevant identifying letter.

1. **EAL/TR/ESA/CWPSNGP-TR/001** Test Results from the Compatibility of Welded Propellant Systems with New Green Propellants

2. **EAL/FR/ESA/CWPSNGP/TN6/001** Final Report for the Compatibility of Welded Propellant Systems with New Green Propellants (TN6)

3 Literature Review

3.1 Introduction

The findings of the literature review were reported in March 2017 after a study period of 3 months. During that time some 60 papers and 30 other documents dealing with green propellants and relevant spacecraft materials were obtained and assessed. The aim of the study was to provide a list of applicable materials and weld combinations to test for compatibility with the most promising green propellants. Thus, at the end of the literature study, final trade off assessments were made into order to determine the best combination of propellants, materials and weld processes for experimental study. The two down selected propellants were High Test Peroxide (≥87.5%) and the Ammonium Dinitramide (ADN) based propellant, LMP-103S. These are described below along with brief justifications for their selection and trade off assessments against the green propellants that were reviewed.

3.2 LMP-103S

ECAPS (Ecological Advanced Propulsion Systems) in Sweden developed the ADN based monopropellant as essentially a pre-mixed bipropellant (fuel mixed with 60-65% ADN oxidizer) with high energy content. It is an aqueous solution of ADN oxidizer and is dissolved in water with methanol and ammonia as fuel components. The propellant is thermally and catalytically decomposed and ignited by a reactor which is preheated prior to operation.

LMP-103S has achieved proven flight status following the PRISMA mission. The system (including propellant and thrusters) has been demonstrated as an enabling technology for improved performance and enhanced volumetric efficiency. For small satellites the high-performance green propellant (HPGP) propulsion system has about a 32% higher ΔV capability over hydrazine. In addition, the propellant loading is simpler, less time consuming and significantly less hazardous. HPGP systems could also be used for de-orbiting due to the environmentally benign nature of LMP-103S.

It also has high stability in air and humidity and none of the propellant components are carcinogenic. The transportation restrictions are low.

3.3 Hydrogen Peroxide (≥87.5%)

High Test Peroxide (HTP) is the aqueous solution of H_2O_2 in concentrations greater than or equal to 87.5%. It has been used in rocket propulsion since the 1930s with many successful launches. Russia continues to use HTP in their space program and it still drives the turbo pumps on the boosters of the Soyuz orbital vehicle.

When used as a bipropellant with kerosene as the fuel, HTP can achieve Specific Impulses (I_{sp}) up to 350s. The higher the concentration of the peroxide the greater the potential to convert to oxygen and steam, the rate of decomposition also increases with higher temperatures and pH, thus, special care in handling and dedicated storage areas are necessary. HTP can form explosive mixtures and shock sensitive material with organic compounds. The higher concentrations of hydrogen peroxide can cause **B**oiling **L**iquid **E**xpanding **V**apour **E**xplosions (BLEVE) of the remaining peroxide. High Test Peroxide offers a reduction in toxicity compared to Hydrazine based propellants. It is widely available and has a high maturity level due to its longstanding heritage in the space propulsion.

3.4 Trade off Assessment with Other Propellants

There are a number of properties that are desirable for a monopropellant successor to hydrazine. The safety and hazard objectives must be acceptable by the US Department of Defence Ammunition and Explosives Hazard Classification Procedures. Other characteristics, which are important to consider for propellant evaluation and use include vapour pressure, viscosity, surface tension, compatibility, cost, ignitability and combustion temperature and behaviour over the chamber pressure range.

Combustion and ignition temperatures must also be considered in propellant down selection. In this respect LMP-103S is favorable. All green propellants reviewed in this study have significantly higher combustion temperatures compared to hydrazine. A summary of the most important performance characteristics of the five most promising new green propellants are presented in the table below.

Propellant	Hydrazine	H_2O_2	NOFBX	LMP-103S	FLP-106	AF-M315E
I_{sp} (s)	230	153 (mono) 350 (biprop)	335	252	259	266
ρ (g/cm^3)	1.0037	1.440	0.720	1.240	1.362	1.46
ρ I_{sp} (gs/cm^3)	231	220.3(mono) 504(biprop)	241	312	353	388
Maturity level	TRL 9	TRL 7	TRL 6	TRL 7 + flight tested	TRL 7	TRL 5-6
Combustion Temperature (°C)	1120	2442	2727-3177	1608	1880	1893

Table 1: Comparison of Green Propellants with Hydrazine

From the data provided above, each propellant has been assessed and scored with a value of 1 (poor) to 5 (excellent) in each of the following categories;

- Maturity
- Handling
- Ease of Availability
- Available Data
- Environmental Friendliness
- Performance (I_{sp})

The table is as follows;

Propellant	**Maturity**	**Handling**	**Availability**	**Available Data**	**Environmental Friendliness**	**Performance**	**SCORE**
LMP-103S	4.5	3	5	5	3	4	24.5
H_2O_2 (HTP)	4	2	5	5	5	2	23
FLP106	4	3	4	2	3	4	20
AFM315E	3	3	1	3	3	4	17
NOFBX	3	4	3	2	5	5	22

Table 2: Final Comparison of Green Propellants

LMP-103S and H2O2 were chosen for this programme as they display the most promising characteristics and perform highest in the categories above.

3.5 Materials and Weld Selection

The Literature review surveyed the relevant materials (and material combinations) currently used in propulsion system components in launchers and satellites from propellant tanks to valves to thrusters. Materials and weld process in each element of the propulsion system were assessed in order to select the most relevant materials and weld types for this programme. Titanium and aluminium alloys are prevalent in propellant tanks, feed lines, pressure transducers, valves, and filters. Thrusters are manufactured from a variety of stainless steels, titanium alloys and specialized metals. The most relevant materials were selected for this study and are shown in the table below:

Notes for Table 3

1. At 40 degrees C
2. Current investigations show these to be potential tank candidate materials for demisable systems
3. Yes gives a score of 1, No gives a score of 5 and possibly gives a score of 3.

Material	LMP-103S Compatibility Class	HTP Compatibility Class	Typical Propulsion System Materials[3]	SCORE
Titanium and titanium alloys	1	2/3	Yes	4.5
Titanium G5	1	2/3	No	8.5
SS2343 (SS316L)	1	1 [1]	Yes	3
SS304L	1	1 [1]	Yes	3
SS347	1	1[1]	Yes	3
SS15.5	1	1 [1]	NO	7
CRES430	1	1	NO	7
Aluminium	3	1	Possibly[2]	7
Al Mg Sc Alloys	3	1	Possibly[2]	7

Table 3: Materials Trade off Matrix

- **Class 1:** Long term
- **Class 2:** Short term
- **Class 3:** Incompatible

From the scoring systems it was clear that the CRES stainless steels should be investigated as should titanium and titanium alloys (except titanium G5). This left some further stainless steels and/or aluminium/aluminium alloys to consider. Since 3 stainless steels were already included in the test matrix, and those remaining are not considered for use in propulsion systems, it was concluded that the aluminium and aluminium alloys were the most interesting since they provide a platform for the manufacture of HTP propulsion systems and a demisable material for tank manufacture.

It can be seen that HTP is best suited to use with treated stainless steels (those steels that have seen specific cleaning/pickling and passivating procedures) and aluminium. LMP-103S exhibits good compatibility with stainless steels and titanium but not aluminium. As such, it is necessary to perform some trade off in test materials in order to get a set of samples that will provide some meaningful data. For LMP-103S it was clear that those samples that consist of titanium, stainless steel and titanium/stainless steel transition joints should perform best, and these were suggested to be the backbone of the test matrix. For HTP aluminium and stainless steels seemed to be the best suited. However, to keep the test matrix cross comparable, some aluminium samples were included in the LMP-103S matrix (specifically tank samples that may be of relevance especially in the frame of demisable materials) and these were intended to be used to verify the compatibility status of aluminium against this propellant.

For HTP some titanium samples are included in the test matrix, again to give a cross reference against existing data and also to ensure the testing of materials against both propellants wherever possible. It should also be noted that the compatibility of the stainless steels with HTP diminishes with temperature and as such it was decided that any accelerated tests should be kept to 50 degrees C or below.

Three out of the six main welding methods were selected as the most commonly used to fabricate propulsion systems and therefore were chosen for this investigation, those being TIG, EB and FSW. Additive manufacturing was also chosen for consideration, due to the significant reduction in manufacturing times and costs.

The Test Material and weld combinations for both LMP-103S and HTP are shown below in Table 4 and 5 respectively. Additional characterization tests on the baseline materials are defined and justified in the following section on Sample Preparation.

Material sample	Type	Welding Technique
Ti6Al4V	Plate Tank sample	EB
Ti6Al4V	Tank sample	WAAM
Al2060	Tank sample	FSW
AlMgSc 5028	Tank sample	FSW
Al2060	Tank sample	EB
Ti3Al2.5V-Ti2.5V	Pipe Transition Joint	OTIG
Ti3Al2.5V-SS304	Pipe Transition Joint	RFW
SS316L	Pipework	TIG
SS347	Pipework	TIG
SS304L	Pipework	TIG

Table 5: Test Matrix for Immersion Testing in LMP-103S

Material sample	Type	Welding Technique
Ti6Al4V	Plate Tank sample	EB
Al2060	Tank sample	FSW
AlMgSc 5028	Tank sample	FSW
Al2060	Tank sample	EB
Ti3Al2.5V-Ti2.5V	Pipe Transition Joint	OTIG
Ti3Al2.5V-SS304	Pipe Transition Joint	RFW
SS316L	Pipework	TIG
SS347	Pipework	TIG
SS304L	Pipework	TIG

Table 4: Test Matrix for Immersion Testing in HTP

4 Test Plan

Samples and propellants were checked and certificated suitable for use in the experimental work by subjecting them to the following inspections:

- Log incoming sample
- Certificates of Conformance inspection against propellant specification
- Visual Inspection
- Propellant assay
- Conformance to weld specification drawings
- Storage of sample prior to issue for use

A clear process of weld manufacture was developed based on information from the literature review and requirements set by the Test Plan which involved a series of these welds exposed to systematic controlled testing with live propellants. In order to ascertain degradation of the welds and materials by the propellants, the welded test samples were then subjected to materials tests (fracture toughness, hardness, mass loss), burst testing to 4 x MEOP (in the case of pipework) and weld inspection (by means of sectioning, etching, polishing and inspecting).

4.1 Material Procurement

Table 6 lists the samples required, and these can be broadly broken down as follows;

a) Tank or Plate samples
These samples were subjected to fracture toughness tests, metallographic and hardness testing. For each material, 6 - 9 fracture toughness samples were required and 3 metallographic samples (one of which also doubled as the hardness sample).

b) Pipework samples
These samples are, as indicated, pipework samples, and they were subjected to burst testing, hardness testing and metallographic testing. For each material, 9 samples were required, with one being doubled as a hardness sample.
The provider of the materials samples is given under the column "Provider".

Material sample	Type	Welding Technique	Number of Samples required (Total)	Provider	Propellant
Ti6Al4V	Plate	EB	9 x FT, 3 x Met + Hv	MOOG	HTP/LMP
Ti6Al4V	Tank	WAAM	6 x FT, 2 x Met + Hv	Airbus DS	LMP
Al2060	Tank	FSW	9 x TT, 3 x Met + Hv	Airbus DS Material / Samples + Welding	HTP/LMP
AlMgSc5028	Tank	FSW	9 x FT, 3 x Met + Hv	Airbus DS Material / TWI Samples + Welding	HTP/LMP
Al2060	Tank	EB	9 x TT, 3 x Met + Hv	Airbus DS Material / Samples + Welding	HTP/LMP
Ti3Al2.5V-Ti3Al3.5V	Pipework	OTIG	3 x BT, 6 x Met (3 x Hv)	Airbus DS	HTP/LMP
Ti3Al2.5V- SS304	Pipework	RFW	3 x BT, 6 x Met(3 x Hv)	MOOG	HTP/LMP
SS316L	Pipework	TIG	3 x BT, 6 x Met(3 x Hv)	MOOG	HTP/LMP
SS347	Pipework	TIG	3 x BT, 6 x Met(3 x Hv)	MOOG	HTP/LMP
SS304L	Pipework	TIG	3 x BT, 6 x Met(3 x Hv)	MOOG	HTP/LMP

Table 6: Sample and Supplier Detail for Materials Sample

Notes:

EB: electron beam	WAAM: wire Arc Additive Manufacturing
OTIG: Orbital Tungsten Inert Gas	RFW: Radio Frequency Welding
FSW: Friction Stir Weld	FT: Fracture Toughness
TT: Tensile Test	BT: Burst Test
Met: Metallography	Hv: Hardness Testing

4.2 Sample Preparation

The materials and NDI tests were provided by Airbus, Moog and TWI as stated and consisted of;

- Propellant exposure effects on material properties (FT (tank samples only), Hardness (all samples))
- Weld inspection pre and post exposure (Metallographic Inspection – all samples)

EAL ascertained material degradation by performing

- Mass loss (all samples)
- Burst Tests to 4 x MEOP (Pipework)

The geometry, dimensions and surface treatment of the samples allowed for the requirements of the materials tests. For all processes, the steps taken to prepare the specimens were those considered to be representative of flight manufacturing conditions. In many cases, this was already the case (i.e for the titanium pipework and tank specimens provided by Airbus, which went through the same manufacturing process as flight components). Similarly for the stainless steel TIG welds provided by MOOG, the welds underwent a similar process to those used in their propulsion systems (Galileo/SAOCOM etc). For those new materials tested and weld processes developed, every effort was made to ensure that these developed processes mirrored existing processes for the handling and manufacture of flight components.

Any cleaning or passivation processes that were used prior to, or after, welding were also documented, either as reference documents in the WPS or as reference documents/steps in the test procedures. The passivation processes were selected based on the materials under test (i.e for stainless steels, a cleaning process, followed by welding, then a de-scaling (pickling) process, usually involving HF/HNO_3 followed by a passivation process (HNO_3) and rinse/dry). Titanium processes are well documented and were selected accordingly. For welds involving a transition between Stainless Steel and Titanium, a pickle step that is applicable to both materials was used, with the stainless steel part of the joint then subjected to a passivation (titanium processes are usually either an HF/HNO_3, or just an HNO_3 step).

Aluminium and stainless steel welds that were exposed to HTP underwent passivation using the methodology developed by Surrey satellite in AD [15] for their HTP thruster project. These processes had already been used for various aluminium and stainless steel samples and shown to enhance compatibility with HTP.

Welded pipe samples were exposed to propellant as per the proposed test matrix.

At the required sampling time the materials samples were drawn off test, decontaminated as per an agreed methodology (rinsed with deionised water, followed by a rinse with filtered IPA and then dried in a stream of filtered GN2 before a final drying under vacuum for a minimum of 8 hours), the welded materials were then dispatched to the materials test house for analysis.

After exposure the welded pipe samples were inspected for any obvious reasons for rejection. Welded pipe samples were carried forward for further testing. They underwent hydraulic burst testing at 4 x MEOP, where MEOP is defined as 24 bars as this is fairly nominal, and consistent with the Galileo program. Both pipe samples that were exposed to propellant and pipe samples that were not exposed to propellant underwent hydraulic burst testing. A comparison of burst test results between exposed and un-exposed samples gave an excellent indication as to whether exposure to propellant had an adverse effect on the properties of the weld.

In addition to the burst testing, welded pipe samples were sectioned, polished and etched such that the weld could be examined. Again, comparison of exposed and un-exposed samples helped to identify if any chemical attack of the weld occurred or if there were any other signs of weld degradation due to exposure to propellant. Sectioning, polishing and etching of the weld samples was an excellent way of assessing the compatibility of the welds with the propellant under test.

To make this assessment on the pipe samples, the location and function of the weld in the propulsion system must be understood and considered. For example, the weld may only be used in the propulsion system where it is only exposed to propellant for a limited amount of time. Factors such as this were considered when determining the compatibility of the weld. In addition, mass loss and hardness testing indicated further the compatibility of the material/weld combination and gave an idea of any corrosivity/porosity occurring at the weld interface.

For the tank samples fracture toughness was used in place of burst testing to determine any deleterious effects of propellant exposure – this is a measure of the ability of a material containing a crack to resist fracture, and is one of the most important properties of any material for many design applications; the change in the fracture toughness value, K_{Ic}. If the propellant inherently changes this value, the implication is that the propellant is attacking/corroding the material and weakening it. Mass loss and hardness testing was also performed on the tank samples giving a complete picture of any changes due to propellant immersion, and also a cross comparison with the pipework samples.

These tests (burst tests, fracture toughness) were deemed sufficient to determine the efficacy of the welds and, combined with the other material properties tested (hardness/mass loss), compatibility with the propellants themselves. In conjunction with the compatibility tests defined in section 6, this gave a broad picture of the potential of the materials/weld/propellant combinations for future use.

5 Test Sequence

5.1 Compatibility Test Programme

5.1.1 Introduction

The compatibility test program exposed the welds under investigation to live propellants LMP-103S and HTP. The elevated temperature of the test accelerated any reaction of the propellant with the materials and welds under test and this allowed "long term testing" to be carried out in short periods of time (by assuming the Arrhenius theorem is adhered to, the rate of reaction doubles with every 10 degree temperature rise. Thus, an increase in test temperature from 20 to 50 degrees ensured an 8 fold increase in the rate of reaction). This allowed data to be gathered that is relevant for long duration exposure in a short period of time. The test regime based on eight months exposure produced data relevant to a 5.33 year on-orbit exposure. The timeline selected was in accordance with medium duration science missions, and also encompasses launchers in as much as it would not be expected that a launch vehicle would be fuelled and left in a "hot" state for more than 3 months (this is the current maximum duration for the Vega upper stage, for instance).

The testing followed the ECSS guidelines. It ascertained the following parameters of the propellant;

- Decomposition
- Leaching
- Visual degradation
- Chemical Degradation

For each of the propellant/material/weld combinations a propellant sample was taken at the termination of the test to check for leaching of material into solution from the material, using ICP analysis. In addition, each propellant/material combination was subjected to a decomposition test over the 240 days, where pressure rise was monitored to determine the decomposition rate. The propellant was also sampled at the end of the 240 days in order to ensure no major deviations from the propellant specification had occurred, specifically in terms of its assay.

The elements for ICP analysis were selected based on the materials combination, thus a titanium alloy required the analysis of Ti, Al and V to determine any leaching of materials into the propellant, whereas CRES stainless steel required the analysis of Fe, Ni, Cr. Aluminium/lithium alloys needed Al/Li analysis. Control samples of propellant were analysed alongside the exposed propellant to provide a cross reference "blank" and remove any uncertainty due to trace levels of impurity dissolved in the propellant either during manufacture or storage.

In addition, visual inspection of the propellant determined if there was any change with respect to the control test – in particular looking for flocculence due to the formation of, for example, aluminium hydroxide in the HTP.

Pressure rise monitoring gives an excellent indication as to whether there is any incompatibility between the weld and the propellant and if there is decomposition severe enough such that the weld cannot be used in a propulsion system with the propellant under test. Combined with the post test assay and ICP testing, this is the most reliable of methodology to ensure compatibility of the propellant/weld combinations.

The compatibility testing of the materials and propellants combinations are summarized in Tables 7 and 8 below. Each table details the material/weld combinations, the type of propellant, type of weld and the actual materials tests involved, the number of samples for testing and finally the task allocation – i.e. who produced the samples and who tested the samples.

COMMENTS FOR TABLES 7 and 8:

- Met is a metallographic inspection consisting of Sectioning, Etching, Polishing and Inspection of the weld
- Hv is hardness testing - this will be performed on one of the Met samples (as indicated by brackets).
- FT = Fracture Toughness
- TT = Tensile testing
- BT = Burst Testing

Material sample	Type	Welding Technique	Un-Exposed	N. samples for immersion testing during 8 months (equivalent to 5.33 years)	Task allocation
LMP 1- Ti6Al4V	Plate Tank sample	EB	3 x FT 1 x Met+Hv	3 x FT 1 x Met+Hv	- Immersion testing (EAL) - FT, Met and Hv testing (TWI)
LMP 2 - Ti6Al4V	Tank sample	WAAM	3 x FT 1 x Met+Hv	3 x FT 1 x Met+Hv	- Immersion testing (EAL) - FT, Met and Hv testing (TWI)
LMP 3 - Al2060	Tank sample	FSW	3 x TT 1 x Met+Hv	3 x TT 1 x Met+Hv	- Immersion testing (EAL) - Tensile Test (Airbus) - Met and Hv testing (Airbus)
LMP 4 - AlMgSc 5028	Tank sample	FSW	3 x FT 1 x Met+Hv	3 x FT 1 x Met+Hv	- Immersion testing (EAL) - FT, Met and Hv testing (TWI)
LMP 5 - Al2060	Tank sample	EB	3 x TT 1 x Met+Hv	3 x TT 1 x Met+Hv	- Immersion testing (EAL) - Tensile Test (Airbus) - Met and Hv testing (Airbus)
LMP 6 – Ti3Al2.5V- Ti2.5V	Pipe Transition Joint	OTIG	2 x Met (1x Hv) 1 x BT	2 x Met (1 x Hv) 1 x BT	- Immersion testing and BT (EAL) - Met and Hv testing (TWI)
LMP 7 - Ti3Al2.5V- SS304	Pipe Transition Joint	RFW	2 x Met (1x Hv) 1 x BT	2 x Met (1 x Hv) 1 x BT	- Immersion testing and BT (EAL) - Met and Hv testing (MOOG)
LMP 8 - SS316L	Pipework	TIG	2 x Met (1x Hv) 1 x BT	2 x Met (1 x Hv) 1 x BT	- Immersion testing and BT (EAL) - Met and Hv testing (MOOG)
LMP 9 - SS347	Pipework	TIG	2 x Met (1x Hv) 1 x BT	2 x Met (1 x Hv) 1 x BT	- Immersion testing and BT (EAL) - Met and Hv testing (MOOG)
LMP 10 - SS304L	Pipework	TIG	2 x Met (1x Hv) 1 x BT	2 x Met (1 x Hv) 1 x BT	- Immersion testing and BT (EAL) - Met and Hv testing (MOOG)

Table 7: Test Matrix for Immersion Testing in LMP-103S

Material sample	Type	Welding Technique	Un-Exposed	N. samples for immersion testing during 8 months (equivalent to 5.33 years)	Task allocation
HTP 1 - Ti6Al4V	Plate Tank sample	EB	n/a	3 x FT 1 x Met+Hv	- Immersion testing (EAL) - FT, Met and Hv testing (TWI)
HTP 2 - Al2060	Tank sample	FSW	n/a	3 x TT 1 x Met+Hv	- Immersion testing (EAL) - Tensile Test (Airbus) - Met and Hv testing (Airbus)
HTP 3 - AlMgSc 5028	Tank sample	FSW	n/a	3 x FT 1 x Met+Hv	- Immersion testing (EAL) - FT, Met and Hv testing (TWI)
HTP 4 - Al2060	Tank sample	EB	n/a	3 x TT 1 x Met+Hv	- Immersion testing (EAL) - Tensile Test (Airbus) - Met and Hv testing (Airbus)
HTP 5 - Ti3Al2.5V- Ti2.5V	Pipe Transition Joint	OTIG	n/a	2 x Met (1x Hv) 1 x BT	- Immersion testing and BT (EAL) - Met and Hv testing (TWI)
HTP 6 – Ti3Al2.5V- SS304	Pipe Transition Joint	RFW	n/a	2 x Met (1 x Hv) 1 x BT	- Immersion testing and BT (EAL) - Met and Hv testing (MOOG)
HTP 7- SS316L	Pipework	TIG	n/a	2 x Met (1 x Hv) 1x BT	- Immersion testing and BT (EAL) - Met and Hv testing (MOOG)
HTP 8 - SS347	Pipework	TIG	n/a	2 x Met (1 x Hv) 1 x BT	- Immersion testing and BT (EAL) - Met and Hv testing (MOOG)
HTP 9 - SS304L	Pipework	TIG	n/a	2 x Met (1 x Hv) 1 x BT	- Immersion testing and BT (EAL) - Met and Hv testing (MOOG)

Table 8: Test Matrix for Immersion Testing in HTP

6 Test Results Summary

A summary of the most important results are presented below. The test results are split between the two propellants tested starting with LMP-103S.

6.1 LMP Results

6.1.1 Propellant Testing

The propellant testing consisted of immersing the material/weld combination in the propellant under test for 8 Months (equivalent to 5.33 years on orbit assuming the Arrhenius Principle is adhered to). The pressure rise during the immersion period was measured alongside that of a control test. At the end of the test period the propellant was sampled for any dissolved metallics using the ICP technique as well as looking at any changes in the composition of the propellant if there was any significant decomposition seen over the period of the test

6.1.1.1 Propellant decomposition

Figure 1 illustrates the overall decomposition rates graphically. The pressure increase over time compared to the control sample indicates the propellant decomposition due to the same. The majority of the samples follow or are less than the slope of the control curve indicating no decomposition due to the material. Only two samples, Al2060 FSW and SS347, displayed curves steeper than that of the control, however both were very benign compared to that seen, for example, in hydrazine decomposition, and overall, although this was considered the least compatible of the weld/material samples alongside the AL2060 FSW, it still would not present a problem in terms of use in a propulsion system, even for a long duration mission.

Since no large decomposition of the propellant was observed no further testing of the propellant in terms of its assay was deemed necessary since even the largest decomposition rate seen would have produced changed in the propellant that would have been almost impossible to detect and certainly would have lain within the margins of measurement accuracy.

6.1.1.2 ICP Tests and Mass Loss

ICP analysis and mass loss tests determined any metal leaching into the propellant and corrosion of the parent material or weld, respectively. These results were scrutinized together into order to determine their significance. The ICP results are presented in Table 9. The results for Iron, Magnesium and Copper are highlighted in yellow as they were higher than the control. However, this were very low levels of dissolution, which would have no effect on the propellant or the sample/weld combinations. Since there was no mass change was detected in any of the samples, these levels of metal leaching were deemed insignificant.

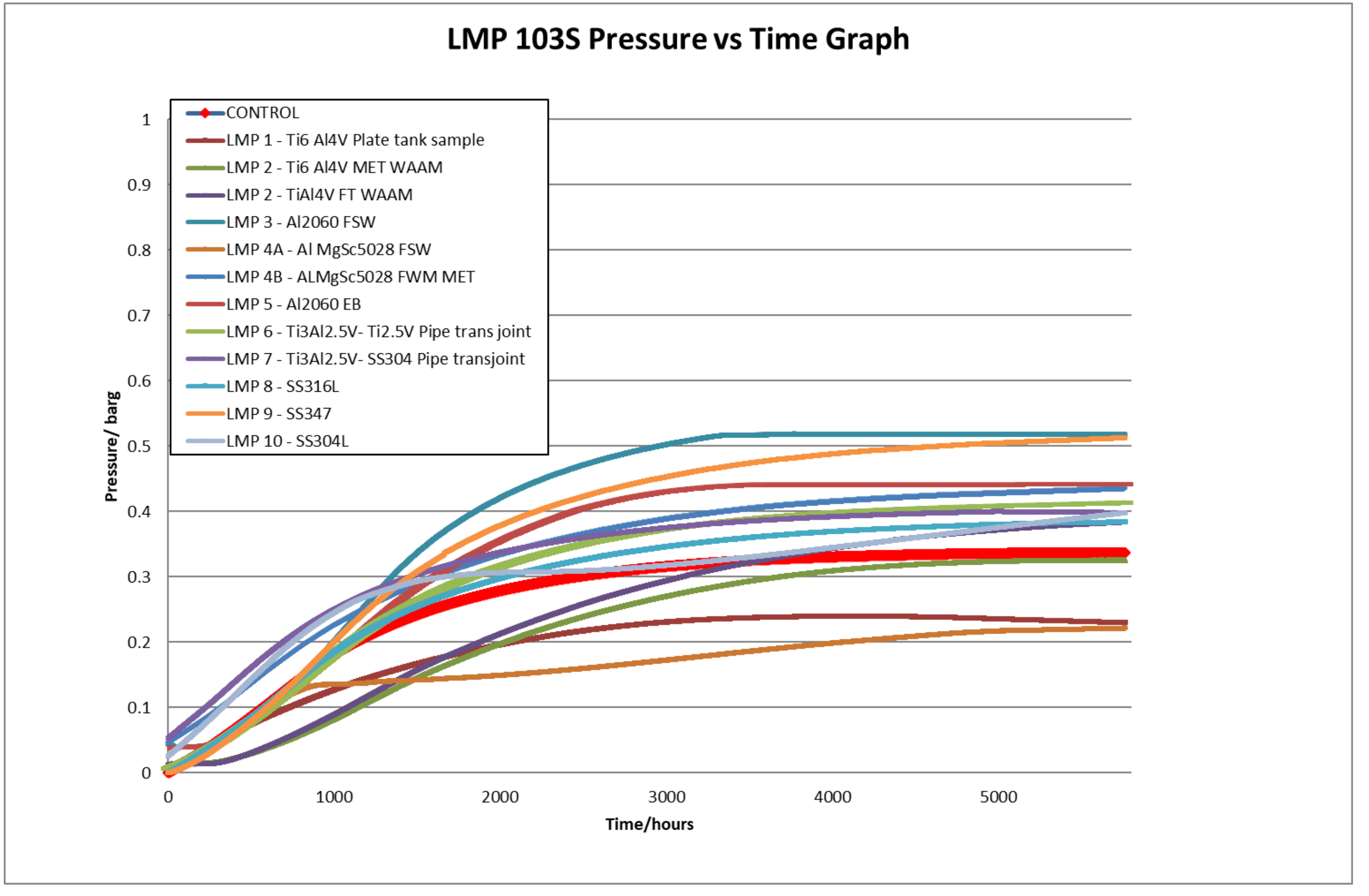

Figure 1: Decomposition Graph for LMP-103S against Test Materials

			Element, ppm											
Material sample	**Type**	**Welding Technique**	**Al**	**Mg**	**Sc**	**Fe**	**Cu**	**Ti**	**V**	**Ni**	**Cr**	**Mn**	**Mo**	**Si**
Ti6Al4V	Plate Tank sample	EB	<0.08	-	-	0.07	-	<0.009	<0.03	-	-	-	-	-
Ti6Al4V	Tank sample	WAAM	<0.08	-	-	0.04	-	<0.009	<0.03	-	-	-		-
Al2060	Tank sample	FSW	<0.08	-	-	<0.03	0.30	-	-	-	-	-	-	-
AlMgSc 5028	Tank sample	FSW	<0.08	0.1	<0.0002	<0.03	-	-	-	-	-	-	-	-
Al2060	Tank sample	EB	<0.08	-	-	<0.03	0.30	-	-	-	-	-	-	-
Ti3Al2.5V-Ti2.5V	Pipe Transition Joint	OTIG	<0.08	-	-	<0.03	-	<0.009	<0.03	-	-	-	-	-
Ti3Al2.5V-SS304	Pipe Transition Joint	RFW	<0.08	-	-	<0.03	-	<0.009	<0.03	<0.2	<0.03	<0.01	-	0.2
SS316L	Pipework	TIG	-	-	-	<0.03	-	-	-	<0.2	<0.03	<0.01	<0.4	0.1
SS347	Pipework	TIG	-	-	-	0.03	-	-	-	<0.2	<0.03	<0.01	-	0.2
SS304L	Pipework	TIG	-	-	-	<0.03	-	-	-	<0.2	<0.03	<0.01	-	0.2
Blank Sample (Control)			<0.08	0.05	0.0003	<0.03	<0.03	<0.009	<0.03	<0.2	<0.03	<0.01	<0.4	5.8

Table 9: LMP-103S ICP Results

6.1.2 Material Testing

6.1.2.1 Burst Tests

Burst testing was applied to both pre- and post- exposure pipe samples to pressures of 4 x MEOP (where MEOP is defined as 24 bars) in order to see if the welds failed under these conditions. All the pipework welds and transition joints performed with no problems at 96 bars with no visible deformation or bursting of the samples.

6.1.2.2 Weld Inspection, Visual Inspection and Metallography

Weld inspection consisted of sectioning the weld, polishing and etching and then examining the resulting prepared weld with microscopic inspection to determine any flaws that would, in normal circumstances, result in the weld being rejected. There were no structural defects in any of the samples and only minor discolouration of the stainless steel in Ti3Al2.5V-SS304. No evidence of superficial damage was observed for the samples immersed in LMP-103S. Immersion in LMP-103S seems to have only contributed to the oxide layer on the surface of the samples.

6.1.2.3 Fracture Toughness and Hardness Tests

This is a measure of the ability of a material containing a crack to resist fracture, and is one of the most important properties of any material for many design applications; the change in the fracture toughness value, K_{Ic}. If the propellant inherently changes this value, the implication is that the propellant is attacking/corroding the material and weakening it. There was no obvious effect of environmental condition on the value of fracture toughness for each material. The results are consistent for each material, across all environmental conditions.

Hardness tests consisted of a load being applied to the weld surface for a set duration. Pre and post exposure results indicated whether the weld had been adversely affected by exposure to the propellant. Although there is some hardness travel variation between immersed and non-immersed samples, this was not seen to be significant for any samples.

6.1.2.4 Tensile Tests

Although the samples showed changes in the average material properties measured during tensile testing, they were relatively small and would suggest that for all FSW and EB welded LMP103S immersed samples, there were only minor effects on the mechanical properties due to immersion in the propellant.

6.1.3 LMP-103S Summary Test Matrix

Table 11 below summarises all results obtained on samples immersed in LMP-103S. The most important results of each test are included. These are used to assess the level of compatibility between the propellant and material, putting the combination into one of the following three categories:

1. Compatible – There was little to no decomposition of the propellant due to the presence of the material. The propellant assay and composition was not affected by the material. The material displays no surface degradation due to immersion in propellant. There is no deleterious impact on the material properties post immersion.
2. Inconclusive – Some propellant decomposition may have occurred at the surface of the material and weld, especially at the beginning of the test. The material properties may not have been affected by immersion in propellant. Further investigation into surface preparation

of the material is advised before judging the compatibility of this propellant and welded material combination.

3. Incompatible – This material and propellant displayed rapid decomposition and corrosion of the material and weld surface. The propellant assay and composition was adversely affected by the presence of the material. The propellant has caused detriment to the physical properties and of the material and weld. This combination is considered unsafe for use.

The level of compatibility was assigned based on the results from the propellant and material tests described above. The overall judgment was made by EAL propulsion engineers and chemists. The grades do not correspond to classical compatibility standards, but rather serve as a guideline for compatibility based on the outcome of the tests. Only the results of significant relevance to the compatibility grade are tabulated overleaf.

LMP-103S Summary Test Matrix

Material sample	Type	Welding Technique	Propellant Decomposition	Propellant Assay	ICP	Mass Loss	Burst Test	Weld Inspection	Visual Inspection/ Metallography	Fracture Toughness	Hardness	Tensile Strength	Compatibility Grade
LMP 1- Ti6Al4V	Plate Tank sample	EB	<Control	No change	OK	No change	Pass	n/a	No defects	Immersion had no effect	Immersion had no effect	n/a	1
LMP 2 - Ti6Al4V	Tank sample	WAAM	<Control	No change	OK	No change	Pass	n/a	No defects	Immersion had no effect	Immersion had no effect	n/a	1
LMP 3 - Al2060	Tank sample	FSW	Control +0.2bar	No change	0.3ppm Cu = 10x blank	No change	Pass	n/a	No defects	Immersion had no effect	Immersion had no effect	Minor reduction due to immersion	1
LMP 4 - AlMgSc 5028	Tank sample	FSW	<Control	No change	0.1ppm Mg = 2x blank	No change	Pass	n/a	No defects	Immersion had no effect	Immersion had no effect	n/a	1
LMP 5 - Al2060	Tank sample	EB	Control + 0.1bar	No change	0.3ppm Cu = 10x blank	No change	Pass	n/a	No defects	Immersion had no effect	Immersion had no effect	7.9% reduction due to immersion	1
LMP 6 – Ti3Al2.5V-Ti2.5V	Pipe Transition Joint	OTIG	Control + 0.05bar	No change	OK	No change	Pass	n/a	No defects	Immersion had no effect	n/a	n/a	1
LMP 7 - Ti3Al2.5V-SS304	Pipe Transition Joint	RFW	=Control	No change	OK	No change	Pass	Some discolouration of SS	No defects	Immersion had no effect	n/a	n/a	1
LMP 8 - SS316L	Pipework	TIG	Control + 0.05bar	No change	OK	No change	Pass	No defects No discolouration	No defects	Immersion had no effect	n/a	n/a	1
LMP 9 - SS347	Pipework	TIG	Control +0.2bar	No change	OK	No change	Pass	No defects No discolouration	No defects	Immersion had no effect	n/a	n/a	1
LMP 10 - SS304L	Pipework	TIG	Control + 0.05bar	No change	OK	No change	Pass	No defects No discolouration	No defects	Immersion had no effect	n/a	n/a	1

Table 10: LMP-103S Results Summary

6.2 Hydrogen Peroxide Results

6.2.1 Propellant Testing

6.2.1.1 Propellant Decomposition

The decomposition results are detailed below with Figure 2 illustrating the overall decomposition rates graphically. Propellant testing also included assay analysis which reflected the decomposition results.

As expected, all samples containing Titanium were highly incompatible with HTP. All three Titanium samples exhibited rapid decomposition and reached very high pressures in the test vessels. These tests were terminated early on safety grounds.

Al2060 FSW tank sample and SS347 exhibited rapid decomposition and also had to be terminated. These faired a little better in HTP than the titanium, but still exhibited a rapid pressure rise and decomposition of the HTP. It is interesting to compare Al2060 FSW to the Al2060 EB welded sample which faired much better, indicating that the FSW may be the cause of the rapid decomposition observed.

The assay for Titanium, Al2050 FSW and SS347 were ≤ 65%. This is consistent with the very rapid pressure rise and decomposition, confirming reaction with the metal sample.

The other stainless steel samples, SS316 and SS304 exhibited a rapid decomposition initially but flattened out to a much shallower rise, comparable to the control test. This indicates that either some contamination on the surface of the weld/metal sample may have been responsible for the initial accelerated pressure rise or that the surface or the weld itself (or both) became passivated over the initial immersion period.

AlMgSc measured similar to the control giving confidence in the material/weld combination with HTP.

6.2.1.2 ICP Tests and Mass Loss

The ICP analysis and mass loss tests were anlaysed together into order to determine their significance, similarly to the LMP-103S results. The ICP results are presented in Table 11. All samples displayed higher levels of one or more dissolved metallics compared to the control, showing in all cases there was some corrosion of the weld or parent material. The highest concentrations of metallics were Ti, Al and V in the Titanium samples. These ICP results, mass tests and decomposition rates indicate attack of the material by HTP in all of the Titanium samples.

The stainless steel samples showed traces of Fe, Ni, Cr and mass losses which indicated some corrosion by the HTP. The 316 sample also showed some signs of Silicon and Molybdenum and it may be that some Si-Mo grease had contaminated the surface (which would also affect the decomposition rate). Mn, Cu, Ni, Sc and Mg were only present in very low concentrations. As these ppm levels would not affect the propellant or material, they were deemed insignificant.

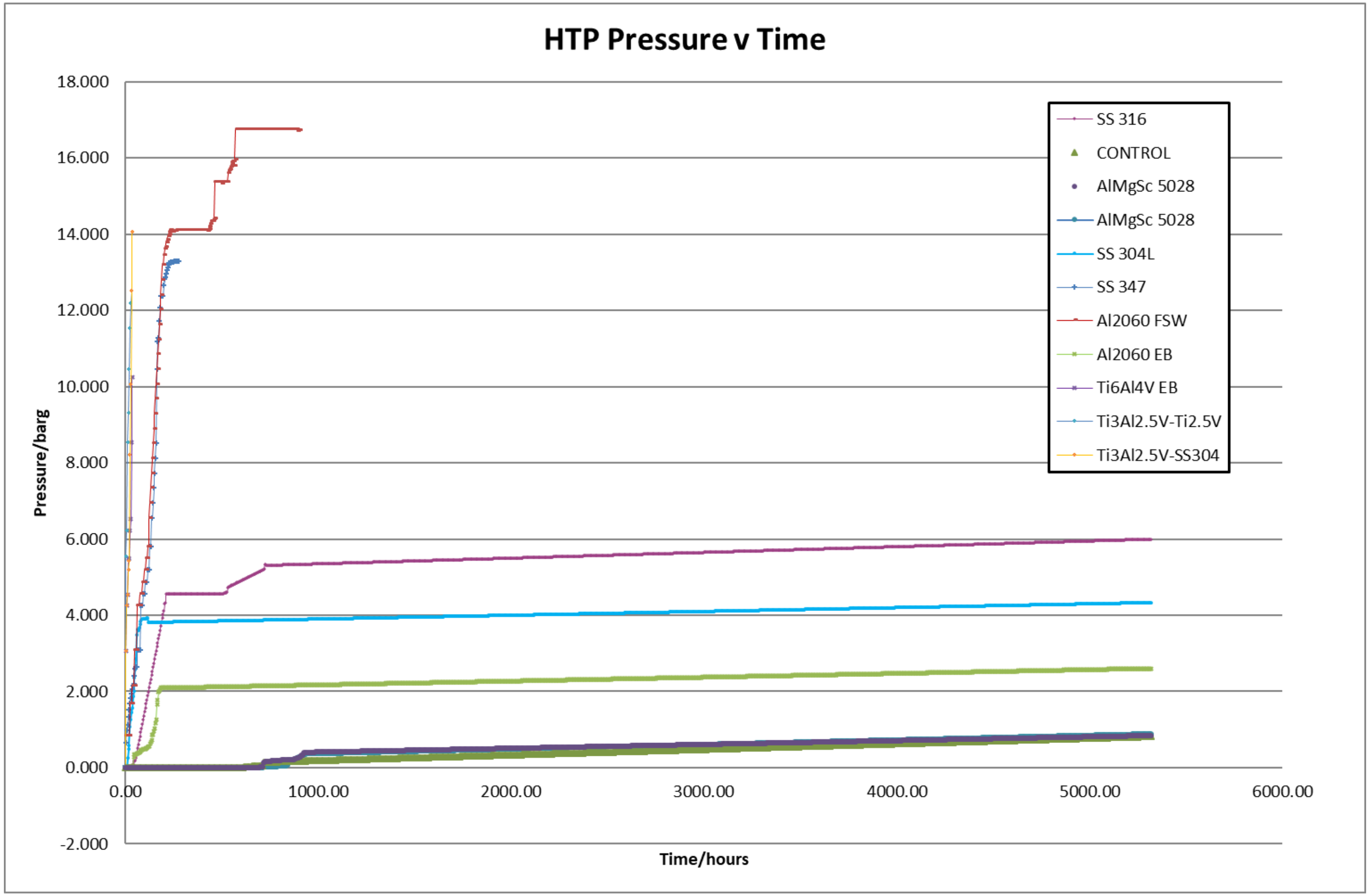

Figure 2: Decomposition Graph for HTP against Test Materials

			Element, ppm											
Material sample	**Type**	**Welding Technique**	**Al**	**Mg**	**Sc**	**Fe**	**Cu**	**Ti**	**V**	**Ni**	**Cr**	**Mn**	**Mo**	**Si**
Ti6Al4V	Plate Tank sample	EB	11	-	-	-	-	240	1.7	-	-	-	-	-
Al2060	Tank sample	FSW	10	-	-	1.5	0.04	-	-	-	-	-	-	-
AlMgSc 5028	Tank sample	FSW	9.0	1.4	0.002	0.2	-	-	-	-	-	-	-	-
Al2060	Tank sample	EB	19	-	-	1.2	0.04	-	-	-	-	-	-	-
Ti3Al2.5V-Ti2.5V	Pipe Transition Joint	OTIG	1.4	-	-	0.3	-	0.009	<0.03	-	-	-	-	-
Ti3Al2.5V-SS304	Pipe Transition Joint	RFW	2.5	-	-	0.4	-	81	1.8	0.1	0.1	-	-	-
SS316L	Pipework	TIG	-	-	-	1.0	-	-	-	<0.2	6.1	0.03	0.8	0.78
SS347	Pipework	TIG	-	-	-	1.1	-	-	-	0.2	7.0	0.07	-	-
SS304L	Pipework	TIG	-	-	-	0.55	-	-	-	0.3	2.1	0.11	-	0.5
Blank Sample (Control)			1.1	0.36	<0.0002	0.68	<0.03	0.1	<0.03	<0.2	0.1	0.07	<0.4	0.61

Table 11: ICP results for HTP Immersion

6.2.2 Materials Testing

6.2.2.1 Burst Tests

All pipework passed the burst test after exposure to HTP.

6.2.2.2 Weld Inspection, Visual Inspection and Metallography

The weld inspection did not display any structural defects, however there was discolouration of the steel in the pipework samples. Visual inspection of the FSW AlMgSc 5028, EBW Ti6Al4V and WAAM Ti6Al4V samples was undertaken, followed by metallographic examination under a microscope. The FSW AlMgSc5028 samples in HTP resulted in superficial damage in form of pitting. More severe pitting effects were noted on the Ti6Al4V and the transition weld (Ti -Ti) samples.

6.2.2.3 Fracture Toughness and Hardness Tests

There was no obvious effect of environmental conditions on the value of fracture toughness for each material. No discernible effects on hardness testing due to immersion in the HTP can be found when compared to the non-immersed samples, although HTP seemed to give a very slight increase in hardness when compared to the unexposed samples in the titanium to titanium OTIG weld samples (Ti3Al2.5V- Ti2.5V).

6.2.2.4 Tensile Tests

Minor effects on the Al2060 samples were observed with some reduction in ductility in the Al2060 EB welded sample.

6.2.3 HTP Summary Results Matrix

All HTP results are summarized in the table below. The most important results of each test are included. These are used to assess the level of compatibility with the propellant and grade the material as one in one of the following three categories: The most important results of each test are included. These are used to assess the level of compatibility between the propellant and material, putting the combination into one of the following three categories:

1. Compatible – There was little to no decomposition of the propellant due to the presence of the material. The propellant assay and composition was not affected by the material. The material displays no surface degradation due to immersion in propellant. There is no deleterious impact on the material properties post immersion.
2. Inconclusive – Some propellant decomposition may have occurred at the surface of the material and weld, especially at the beginning of the test. The material properties may not have been affected by immersion in propellant. Further investigation into surface preparation of the material is advised before judging the compatibility of this propellant and welded material combination.
3. Incompatible – This material and propellant displayed rapid decomposition and corrosion of the material and weld surface. The propellant assay and composition was adversely affected by the presence of the material. The propellant has caused detriment to the physical properties and of the material and weld. This combination is considered unsafe for use.

The level of compatibility was assigned based on the results from the propellant and material tests described above. The overall judgment was made by EAL propulsion engineers and chemists. The grades do not correspond to classical compatibility standards, but rather serve as a guideline for compatibility based on the outcome of the tests. Only the results of significant relevance to the compatibility grade are tabulated overleaf.

HTP Summary Test Matrix

Material sample	Type	Welding Technique	Propellant Decomposition	Propellant Assay (%)	ICP	Mass Loss (%)	Burst Test	Weld Inspection	Visual Inspection/ Metallography	Fracture Toughness	Hardness	Tensile Strength	Compatibility Grade
HTP 1 - Ti6Al4V	Plate Tank sample	EB	10 bars in 36hrs Terminated	<65	11ppm Ti 240ppm Ti 1.7ppm V	0.14	Pass	n/a	Discolouration Corrosion	Immersion had no effect	Immersion had no effect	n/a	**3**
HTP 2 - Al2060	Tank sample	FSW	16 bars in 572hrs Terminated	<65	10ppm Al 1.5ppmFe 0.04ppm Cu	0.52	Pass	n/a	Discolouration Pitting	Immersion had no effect	Immersion had no effect	Minor effects due to immersion	**3**
HTP 3 - AlMgSc 5028	Tank sample	FSW	=Control	79	9ppm Al 1.4ppm Mg 0.002ppm Sc	0	Pass	n/a	Discolouration Pitting	Immersion had no effect	Immersion had no effect	n/a	**1**
HTP 4 - Al2060	Tank sample	EB	2 bars in 160 hrs followed by rate = control	70	19ppm Al 1.2ppm Fe 0.04ppm Cu	0.27	Pass	n/a	Discolouration Pitting	Immersion had no effect	Immersion had no effect	Decrease in ductility due to immersion	**2**
HTP 5 - Ti3Al2.5V-Ti2.5V	Pipe Transition Joint	OTIG	14 bars in 36hrs Terminated	<65	1.4ppm Al	4	Pass	n/a	Discolouration Pitting	Immersion had no effect	Slight increased compared to unexposed	n/a	**3**
HTP 6 – Ti3Al2.5V-SS304	Pipe Transition Joint	RFW	14 bars in 36hrs Terminated	<65	2.5ppm Al 81ppm Ti 1.8ppm V 0.1 Ni	0	Pass	No defects Some discolouration of SS	Discolouration Pitting	Immersion had no effect	Immersion had no effect	n/a	**3**
HTP 7- SS316L	Pipe Transition Joint	TIG	4 bars in 100 hrs followed by rate = control	68	1.0ppm Fe 6.1ppm Cr 0.8ppm Mo 0.78ppm Si	0.60	Pass	No defects No discolouration	Discolouration Pitting	Immersion had no effect	Immersion had no effect	n/a	**2**
HTP 8 - SS347	Pipework	TIG	13 bars in 276 hrs Terminated	<65	1.1ppm Fe 0.2ppm Cr 7.0ppm Cr	0.64	Pass	No defects No discolouration	Discolouration Pitting	Immersion had no effect	Immersion had no effect	n/a	**2**
HTP 9 - SS304L	Pipework	TIG	4 bars in 70hrs followed by rate =control	72	0.3ppm Ni 2.1ppm Cr	0	Pass	No defects No discolouration	Discolouration Pitting	Immersion had no effect	Immersion had no effect	n/a	**2**

Table 12: HTP Results Summary

7 Conclusions

1. This study succeeded in identifying the compatibility of ten commonly used welded materials with green propellant LMP-103S and nine with the green propellant HTP. The welded materials were duplicated so that the same materials were tested in each propellant, with the exception of a Ti6Al4V tank sample welded by Wire Arc Additive Manufacturing, which was already known to be incompatible with HTP and therefore was only tested with LMP-103S. The 8 month exposure time at elevated temperature equated to 5.33 years on-orbit, which is correspondent with relevant mission durations.

2. Propellant compatibility tests, which followed ECSS guidelines, allowed the determination of the degradation of the propellant due to the interaction with the welded materials

3. The extensive materials testing determined any degradation of the welds and material due to propellant exposure

4. The propellant testing consisted of 3 main tests: propellant decomposition, ICP analysis and propellant assay

5. The materials testing consisted of the following tests: mass loss, burst test, weld inspection and metallography, fracture toughness, hardness and tensile testing.

6. Conclusion on the LMP-103S results are presented below
    a. There was no significant decomposition of the LMP-103S over the test duration with any of the materials tested. The decomposition rates for most of the samples were less than or similar to that of the control. The highest propellant decomposition rate occurred with the Friction Stir Welded Al2060 tank sample. Although this is considered the least compatible of the weld/material samples alongside the AL2060 FSW, it still would not present a problem in terms of use in a propulsion system, even for a long duration mission.

    b. The ICP analysis determined any leaching of metallics into the propellant, which could potentially weaken the material and cause problems for catalyst beds. The most significant dissolved metallic in LMP-103S was 0.3ppm of dissolved copper from the Al2060 alloy. This could indicate depletion of the copper content in the alloy. However, since Al2060 samples performed well in the material tests and there was no mass loss, this result is not concerning.

    c. The material testing of the materials immersed in LMP-103S was encouraging. The visual inspection and metallography showed no noticeable effects to the weld. There was some discolouration of the Ti-SS pipe transition joint. There were no problems during the burst test, hardness, tensile tests or fracture toughness indicating the immersion of the samples in LMP-103S had no obvious adverse effects with respect to any material properties.

   d. From the points above the compatibility of the ten chosen materials with LMP-103S is deemed excellent.

7. Before concluding on the Hydrogen Peroxide results, it should be noted that Titanium and hydrogen peroxide was known to be incompatible and therefore the extreme results of the titanium samples were expected.

   a. The three titanium samples (Ti6Al4V Plate Tank Sample EB Weld, Ti3Al2.5V - Ti2.5V – Pipe Transition Joint OTIG, Ti3Al2.5V - SS304 – Pipe Transition Joint RFW) had to be taken off test within 1 week of testing on safety ground. The pressure within the test vessels exceeded the safe limits within 36 hours indicating rapid propellant decomposition. Yellow precipitate and corrosion of the material samples was also present. It is clear that titanium is highly incompatible with HTP. The ICP, assay and mass change results also testify to this conclusion.

   b. The Al2060 Tank Sample FSW faired a little better in HTP than the Ti6Al4V, but still exhibited a rapid pressure rise and decomposition of the HTP, reaching 16 bars in 572 hours; the test was allowed to continue for a short period after, but was then terminated, again on safety grounds. It is interesting to compare this to the Al2060 EB welded sample which faired much better indicating that the FSW may be the cause of the rapid decomposition observed. The high levels of Al displayed in the ICP results indicate some attack on the alloys by the HTP.

   c. The AlMgSc 5028 Tank Sample FSW exhibited a decomposition rate that was measured almost identical to the control sample, indicating that little decomposition of the HTP was occurring due to the presence of either the material or the weld itself. Two separate samples were tested, giving confidence that the material/weld combination is indeed a good match with HTP. The ICP results displayed increased levels of Al, Mg and Sc in the propellant indicating some corrosion of the weld and material by HTP. The visual inspection and metallography showed evidence of superficial damage in the form of pitting. However there was no mass change or difference in the fracture toughness.

   d. The stainless steel pipework samples (316L, 347L and 304L) all exhibited a rapid initial pressure rise. The most extreme decomposition rate was exhibited by SS347 which had to be terminated before the end of the test duration on safety grounds. The decomposition rate did appear to slow after approximately 280 hours, but there was still visible bubble generation on the surface of the 347 material. The 316 exhibited a rapid decomposition rate initially. After 200 hours the rate slowed to that comparable to the control. This indicates that either some contamination on the surface of the weld/metal sample may have been responsible for the initial accelerated pressure rise or that the surface or the weld itself (or both) became passivated over the initial immersion period.

8 Recommendations

1. LMP-103S displayed good compatibility with all materials selected in this study. In terms of compatibility, this is the most favourable candidate to use for replacement of hydrazine in spacecraft propulsion systems. Other advantages noticed while carrying out the experimental were its ease of handling and storage.

2. Titanium should not be used in HTP propulsion systems.

3. Al2060 alloys could be compatible with HTP after surface treatments with a lower concentration of Hydrogen Peroxide. After initial rapid decomposition, the rate levelled off to the same as the control indicating passivation of the surface eventually occurred. Further experimental work is needed to determine how different surface treatments affect Al2060 compatibility with HTP.

4. The stainless steel samples 316 and 304 may be compatible if given a longer pre-exposure to HTP prior to loading proper. The decomposition tests indicate the surface became passivated during the initial immersion period. Further work on how different surface treatments affect stainless steel compatibility with HTP is recommended.

5. AlMgSc performed well in the majority of the tests in this study. It displayed good compatibility with HTP and LMP-103S. This material should be considered for future applications with green propellants.

9 Further Work

Whilst LMP-103S has displayed good compatibility with all materials/weld combinations, and HTP with some, the testing here was by no means extensive. In fact, the object was to provide a broad-brush screening of available welding techniques and materials in order to identify those of interest and, indeed, to actively eliminate those that do not warrant further investigation.

It is clear that more research should be invested in determining optimum passivation and cleaning procedures for materials in contact with HTP, as it does seem that some materials would exhibit mush better results at least in terms of decomposition if these can be perfected.

Stress corrosion cracking tests must be undertaken across the board to ensure this is not an issue with LMP-103S and HTP, and longer-term compatibility trials would certainly be beneficial on the selected candidates for further investigation. If this were the case, a lower test temperature for HTO would also be of use (even though this would require longer test periods to duplicate an extended on-orbit time, since it is clear that at the 50 degrees C temperature employed was not conducive to compatibility and that some runaway was possibly taking place, certainly with some of the stainless steels, which could imply much better compatibility at lower temperatures (40 C or below).

Bearing in mind all of the above, the recommendations for further work would be;

1. Down selection of the materials/welds compatible with LMP-103S to those that are most likely to come on line in propulsion systems in the near future.
2. Down selection of the materials/welds compatible with HTP to those that are most likely to come on line in propulsion systems in the near future.
3. Stress Corrosion Cracking Testing of the materials/welds combinations identified in items 1 and 2, above.
4. Extended immersion testing of those materials selected in items 1 and 2 to increase confidence in long term orbital applications; HTP to be tested at lower (~40°C) test temperatures. Further materials tests to be undertaken on the samples during, and at the end of, test.