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Welding and Testing of Propulsion Subsystem of PMM-Based Satellite Qualification Model

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The Brazilian National Institute for Space Research - INPE is developing a medium-sized (400 to 600 kg) satellite program based on Multi-Mission Platform - PMM. This platform corresponds to the satellite service module, containing: a propulsion subsystem, batteries, solar panels, transponders, onboard computers, sensors and actuators for attitude control, conditioning and power management unit, etc. It is the first satellite of the Brazilian Space Program imposing challenge to the development of propulsion system, which was the responsibility of the company Fibraforte™. This paper presents details of the welding phase and qualification testing of the propulsion subsystem which consists of piping and components made of commercially pure titanium (grade 2) and titanium alloy Ti 6Al-4V (grade 5). Details of welding parts with different joints (grade 2 with 2, grade 2 with 5, and grade 5 with 5) with wall thicknesses ranging from 0.4 mm to 0.9 mm are discussed. We present the use of equipment such as digital X-ray as an important ally in the analysis of the quality of the weld specimens during the determination of the correct set of welding parameters with orbital equipment with argon gas. We also refer to norms that were followed and procedures used by the Integration and Testing Laboratory - LIT where the activities were conducted.

Nomenclature

ACE = Attitude and Control Electronics
AIT = Assembling, Integration and Tests
AWFI = Advanced Wide Field Imager
AWS = American Welding Society
CP-Ti = Commercially Pure Titanium (Grade 2)
EMI/EMC = Electromagnetic Interference/Electromagnetic Compatibility
GPS = Global Positioning System
GTAW = Gas Tungsten Arc Welding
INPE = (Brazilian) National Institute for Space Research
ISO = International Organization for Standardization
LIT = Integration and Testing Laboratory
LNA = Low Noise Amplifier
MECB = Complete Brazilian Space Mission
MMP = Multi-Mission Platform
OBDH = On Board Data Handling
PCDU = Power Conditioning and Distribution Unit
PM = Payload Module

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PMM = *Plataforma Multi-Missao (*Multi-Mission Platform)
QM = Qualification Model
SADA = Solar Array Drive Assembly
SAG = Solar Array Generator
S-band = Frequency range from 2 to 4 GHz
SCD-1 = Data Collect Satellite-1
TCE = Thrusters Control Electronics
Ti 6Al-4V = Titanium alloy with 6% of aluminum and 4% of vanadium (Grade 5)
TIG = Tungsten Inert Gas

I. Introduction

IN 2001, the Brazilian National Institute for Space Research – INPE[§] started a space program called "*Plataforma Multi-Missao - PMM*" (Multi-Mission Platform - MMP). It consists in a nonspecific satellite service module that would be used in a family of middle-sized satellites of different missions. Initially foreseen to weight about 250 kg, the PMM would be joined with a payload model of comparable dimensions and weight, compounding satellites in the 500 kg Class. This platform corresponds to the satellite service module, containing the propulsion subsystem, harnesses, batteries, solar panels, transponders, onboard computers, sensors and actuators for attitude control, conditioning and power management unit, GPS receivers and antennas, etc.

The process of development and qualification of a space artifact requires that all its subsystems undergo a series of environmental tests in order to confirm compatibility with the flight conditions they will face. Thus, it is mandatory that a lot of tests be carried out, like vibro-acoustic testing, electromagnetic interference/compatibility (EMI / EMC) testing, thermal-vacuum testing, and so on.

The PMM has been the first spacecraft of the Brazilian Space Program imposing challenge to the development of the propulsion system, largely due to the challenge of welding titanium parts of small dimensions and thicknesses. Titanium pipes and parts must be qualified to get in contact with hydrazine under high pressure, which requires special attention. The design and responsibility for the propulsion system was charged to the Brazilian Fibraforte™ E.I.C.Ltda Company. The thrusters and fill/drain valves were also developed and constructed by Fibraforte™.

This paper presents details of the welding phase and qualification testing of the propulsion subsystem which consists of piping and components made of commercially pure titanium (grade 2) and titanium alloy Ti 6Al-4V (grade 5). Details of welding parts with different joints and with wall thicknesses ranging from 0.4 mm to 0.9 mm will be shown. We will present the use of digital X-ray equipment as an important ally in the analysis of the quality of the weld beads of the welded parts. It was very effective during the determination of the correct set of welding parameters with orbital GTAW[1] (Gas Tungsten Arc Welding) equipment.

The first mission that will use the PMM as its service module is the Amazonia-1 Satellite[2]. We will present an outline of this satellite too. The activities of AIT (Assembly, Integration and Tests) were conducted by the Integration and Testing Laboratory – LIT[3], which belongs to INPE. LIT's test facilities as well the welding laboratory and equipment will be presented. In this paper we will also refer to standards and guidelines that were followed and procedures used by the LIT staff.

II. The Multi-Mission Platform

The Multi-Mission Platform assembles all equipment that perform functions necessary for the survival of a satellite, regardless of the type of orbit, mission, or pointing, within plenty of limits. The outer dimensions of the PMM are just 1 m × 1 m × 1 m. Its external geometry is similar to a cube. It provides the necessary resources in terms of power, control, management of telemetries, telecommands and data transmission, to operate in orbit a payload module of about 280 kg. It has two wings of solar panels, located on opposite lateral faces. Figure 1 shows an exploded view of the Multi-Mission Platform PMM.

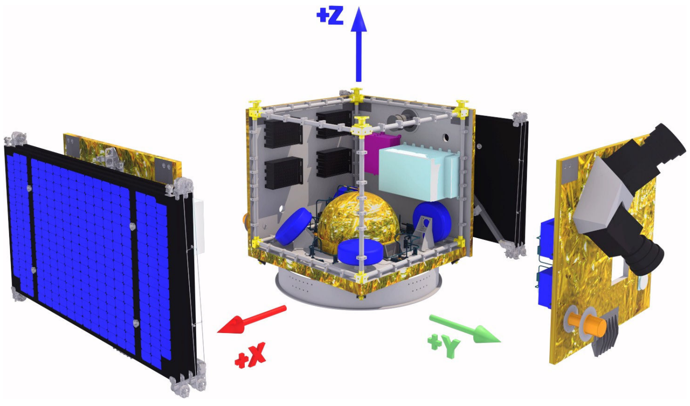

Figure 1. PMM Module. *This figure shows exploded views of the Multi-Mission Platform.*

[§] Available at URL: http://www.inpe.br/ingles/, Access in August, 2013.

The main subsystems which the PMM module contains are: propulsion, power, on-board computers, attitude control, communications, thermal control, harness, and structure. At the center of Fig. 1 one can see the bottom panel (-Z face) with the adaptation ring to the launch vehicle set underneath. On each corner of the "cube" there are columns of aluminum which, together with the side panels, form the structure. The great sphere corresponds to the propellant and pressurizing tank. Four reaction wheels are positioned at each corner of the bottom panel. Six 5-N thrusters are present, pointing towards the -Z axis. The whole propulsion subsystem is contained in the lower panel. The upper panel of PMM contains two magnetometers oriented within the structure. The coupling to the satellite payload module is done through this face.

The lateral panel positioned on the -X side contains the PCDU (Power Conditioning and Distribution Unit), GPS receivers, and one SADA device (Solar Array Drive Assembly), rotating equipment to which one solar panel wing is fixed. The SADA permits to position the solar panel so as to achieve a better energy obtainment.

The panel positioned on face +Y contains transponders, gyroscope, gyro unit electronics, LNA amplifiers, GPS antennas, a star sensor and an S-band antenna. The panel on face -Y contains four sets of batteries, an S-band antenna and two magnetotorque bars. The panel positioned on face +X contains the units OBDH (On Board Data Handling), ACE (Attitude and Control Electronics), TCE (Thrusters Control Electronics), a magnetotorque bar and another SADA device corresponding to the other solar panel wing.

III. The Amazonia-1 Satellite

The Amazonia-1 is a polar orbiting satellite that will produce images of the Earth every five days. It has an optical imager of wide target called AWFI (Advanced Wide Field Imager), with three bands in the visible spectral range, and one in the near-infrared band. This camera is able to observe an extent of 750 km with 40-m resolution.

Figure 2 shows an external view of what will be the Amazonia-1 Satellite. There it appears with its SAGs (Solar Array Generators) shut, in its launching configuration. In Fig. 3 the Amazonia-1 Satellite is seen deployed, as in orbit. Figure 4 shows exploded views of the Amazonia-1 Satellite Payload Module (PM).

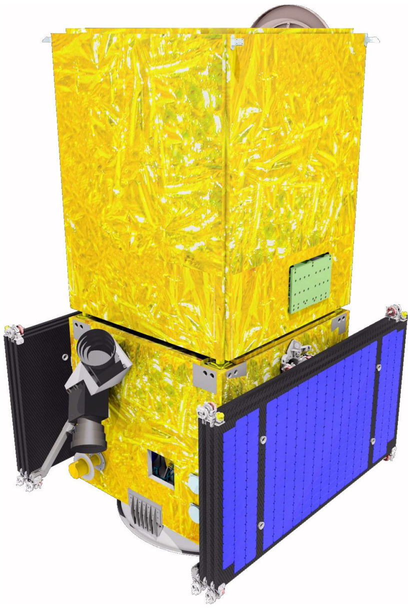

Figure 2. Amazonia-1 Satellite launching configuration. *External view of the assembled satellite with its SAGs shut, attached to the PMM module.*

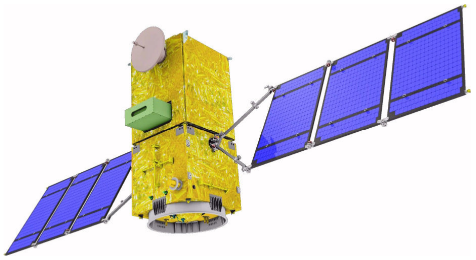

Figure 3. Amazonia-1 Satellite Deployed view. *External view of the satellite with its SAGs deployed as in orbit.*

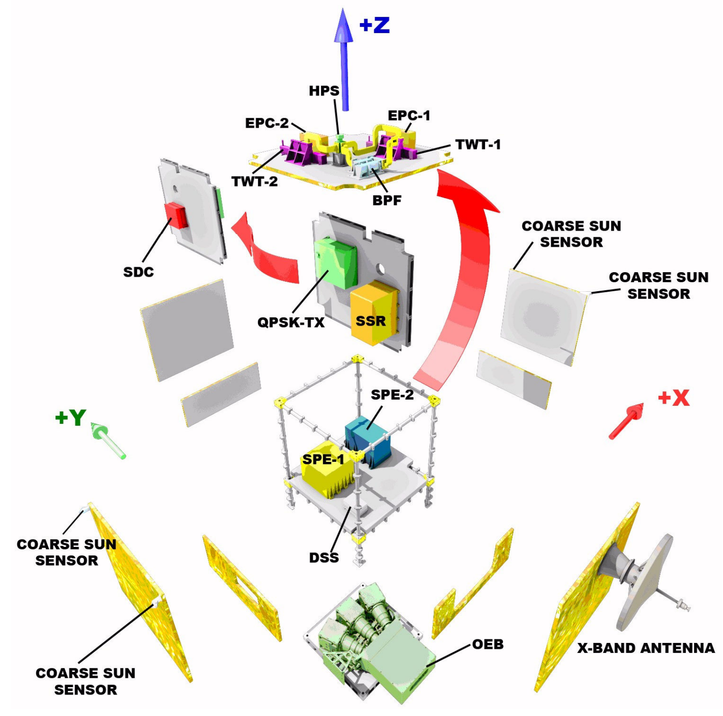

Figure 4. Amazonia-1 Satellite Payload Module. *This figure shows exploded views of the Amazonia-1 Satellite Payload Module.*

The fast revisit feature of the Amazonia-1 Satellite will permit improvement in deforestation warning data of the Amazon region in real time, by maximizing useful image acquisitions when the region is cloudy.

Scheduled to be launched between 2016 and 2017, the Amazonia-1 will also provide frequent images of Brazilian agricultural areas. As the first satellite of the modern modular concept of the PMM Program, the Amazonia-1 is being developed and is undergoing extensive qualification tests, along with its service module.

IV. Laboratory of Integration and Tests

The Integration and Testing Laboratory (LIT) of the Brazilian Institute for Space Research (INPE) was especially designed and built to meet the needs of the MECB (Complete Brazilian Space Mission) Program. Opened in 1987, LIT has been operating for 26 years in qualifying satellites and other space systems, their subsystems, equipment and components. Besides developing activities in the space branch, LIT is currently considered one of the most exquisite and powerful in qualifying industrial products requiring high reliability. This laboratory provides the means and skills to qualify products of the national industry and participates in programs of International Cooperation in the Space Sector, generating constant innovation and fostering the integration of human resources with the most modern and sophisticated technological means. Figure 5 shows a panoramic photo of LIT facilities in Sao Jose dos Campos – SP, Brazil.

Figure 5. LIT Facilities. *Panoramic photo of the Laboratory of Integration and Tests.*

The first satellite fully assembled, integrated and tested at LIT was the SCD-1, which is a Data Collection Satellite, from the MECB Program, successfully launched in the U.S. in 1993, which still remains in activity.

A. LIT Testing Facilities

A twenty-thousand-square-meter constructed area houses clean areas, control rooms, data acquisition rooms, support labs, offices, training and meeting rooms, engine rooms and workshops, a modern auditorium with two hundred seats and an exclusive circuit for visits. All the means necessary for the complete sequence of assembling, integration and testing of satellites up to three tones are brought together within the same installation.

Among the means of testing available in LIT, we can point: electromagnetic compatibility tests, climatic tests, thermal shock tests, acoustic and vibration tests, space simulation tests by thermal-vacuum chambers, mass properties measurements and optical alignments, physical metrology, electrical metrology, laboratory of titanium welding, laboratory for spatial painting, laboratory for electronic components qualification and laboratory for contamination analysis. The testing environments are located in ISO-8 Class[4] clean areas (equivalent to the old FED.STD.209E Class 100,000), and ISO-7 Class (FED.STD.209E Class 10,000). Figure 6 shows a photo of LIT's Testing Hall.

Figure 6. LIT's High Bay Testing Hall. *ISO-8 Class LIT's Hall of Tests.*

B. Titanium Welding Laboratory[**]

LIT has a pipe welding laboratory for space systems, suitable for conducting welding of stainless steel and titanium. The environment is ISO-7 Class. It has instruments, tools, and accessories for the use and handling of inert gas used in the autogenous GTAW titanium welding process. The inert gas used is the 99.999%-purity argon.

[**] LIT24-LIT-00-MM-001, Laboratorio de Soldagem de Tubulacao de Sistemas Espaciais – private document.

The following is the main existing equipment in LIT's Welding Laboratory.

1. Microprocessor Controlled Power Supply

The welding lab is equipped with an Arc Machines™ Model HP-207A welding system, which is a pre-programmed / programmable 100 amp power supply and controller capable of welding tubing and thin wall pipes.

2. Orbital Tube Welding Head

Combined with the microprocessor controlled power supply comes an Arc Machines'™ Model 9AF-750HP, which is a high-purity orbital tube welding head. This head has high-temperature thermo-plastic housing and welds tubes from about 4.8 mm through 19 mm of outside diameter. Figure 7 shows LIT's microprocessor controlled power supply with the orbital tube welding head.

Figure 7. Orbital Welding System. *LIT's microprocessor controlled power supply Model HP-207A with the orbital welding head Model 9AF-750HP.*

3. Multiprocess TIG/Stick Welding Power Source and Torch

The welding lab has a multiprocess welding source Miller™ Model Maxstar 200DX. This piece of equipment is used for tack welding operations in order to immobilize the parts to be welded before application of the GTAW orbital head. The welder uses a conventional manual TIG torch (by Sumig™) in order to perform two diametrically opposite welding points.

4. Fitting and Squaring Machine

The welding lab has a Wachs™ Model FSE 1.0 electric machine for face milling and straightening tubes 3-25 mm in diameter.

5. Rigid Rod Endoscope

The welding lab has a Storz™ Model Halogen 250 Twin – 201133 20 Endoscope. This endoscope has rigid rod with diameter of 2.9 mm and a working length of 300 mm. It is used to visualize areas of difficult access, as the internal parts of the pipes.

6. Titanium Piping Cleaning System

Before being welded, the titanium tubes, parts and components are subjected to a pickling process, by acid attack. Afterwards, the titanium tubing must go through a cleaning process to remove residues of acid and particles. LIT's Welding Laboratory uses a pumping system which employs isopropyl alcohol filtering. The circulation of alcohol inside the pipes drags the particles that detach from their interior and from the interior of components. The cleaning process is monitored by counting the released particles up to a number which is below the acceptable limit. Figure 8 shows the cleaning equipment used in LIT's welding laboratory.

Figure 8. Titanium Piping Cleaning System. *Equipment for titanium piping cleaning by circulation and filtering of isopropyl alcohol.*

7. Pressure Gauge

There are some Magnehelic® Pressure Gauges by Hygro-Therm™, Model 195185-00 W21L, to monitor and control the argon pressure and flow during the GTAW welding processes.

8. Tungsten Electrode Sharpener

The welding lab has a SPS™ Tungsten Electrode Sharpener Model AFT-3500. It provides a quick and easy sharpening of tungsten electrodes, assuring high quality of taper for best arc stability, and improvement of the regularity of the geometry of the weld.

V. PMM Propulsion Subsystem Qualification

The whole qualification process of the Multi-Mission Platform comprises tests of all constituent parts of its QM (Qualification Model), including structure and subsystems, until the integration and testing of the flight model. As we said in the Introduction, this paper specifically focuses on the propulsion subsystem, regarding qualification of its titanium welding phase.

C. PMM Propulsion Subsystem

The propulsion subsystem is assembled on the PMM's bottom panel. A total of 6 thrusters cross to the flip side of this panel, as well as a spherical portion of the tank with the propellant piping. The components and pipes are manufactured in commercially pure titanium (CP-Ti Grade 2) and titanium alloy with 6% aluminum and 4% vanadium (Ti 6Al-4V Grade 5). The PMM employs titanium tubes of outside diameter equal to 6.35 mm and nominal thickness of 0.889 mm. Some components have inlet and outlet ports having the same outer diameter but with reduced thicknesses, respectively of 0.508 mm and 0.425 mm. Accordingly, we identified 5 different combinations of joints of parts, as summarized in Table 1.

Table 1. Sort of solder joins in titanium.

Kind	Joints (outside diameter 6.35 mm)	Thickness (mm)
1	CP-Ti with CP-Ti	0.889
2	CP-Ti with Ti 6Al-4V	0.889
3	Ti 6Al-4V with Ti 6Al-4V	0.889
4	CP-Ti with Ti 6Al-4V	0.508
5	Ti 6Al-4V with Ti 6Al-4V	0.425

The main parts of the of the propulsion subsystem are: tank of propellant/pressurizing gas (nitrogen); fill and drain valves; latching valves; pressure transducer; fuel filter; piping; thrusters; wiring and connectors; thermal insulation and heaters. The bottom mounting panel and supports for equipment and pipelines are considered as part of the structure subsystem of the platform. Figure 9 shows a view of the design of the PMM's propulsion subsystem. The development of the PMM Propulsion System was carried out by the Brazilian company Fibraforte™ Engenharia Industria e Comercio Ltda, partner of INPE in this Space Program.

The titanium tank, made of alloy Grade 5, has two environments separated by a flexible diaphragm, totalizing an internal volume of 60 liters. One of the spaces will contain the "hydrazine" propellant – N_2H_4.[5] The other space will contain nitrogen, which is the pressurizing gas to force the fuel to flow to the propulsion subsystem. It can be filled with a maximum of 45 liters of fuel. The internal pressure will be 22 bar at the beginning of life.

The tank has two ports (propellant and gas) of 6.35 mm diameter and wall thickness of 0.508 mm. In a similar manner to terminations of most satellite tanks, these endings are not threaded. Instead, they are welded to Grade 2 titanium pipes. Welded instead of threaded connections increase the reliability with respect to the occurrence of leaks. However, it imposes significant hardship and attention to welding the tank, since no rework is allowed in this part of the welding process. The constraint imposed by the tank diaphragm increased the difficulty in controlling flow and internal pressure of inert gas required for titanium welding. This was mitigated doing several welding trials on tube samples before performing the pipeline welding to tank ports.

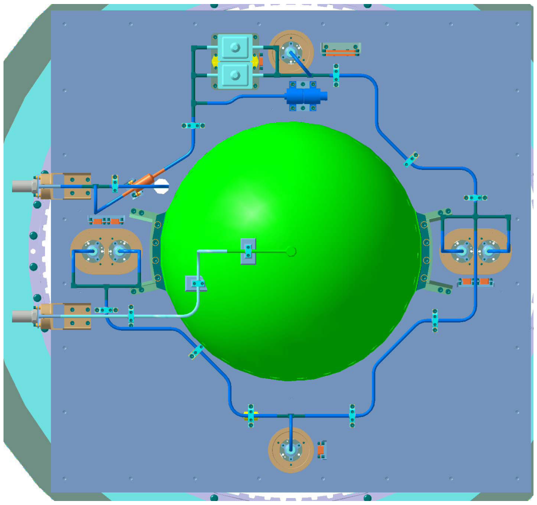

Figure 9. PMM Propulsion Subsystem. *Design view of the PMM's propulsion subsystem.*

As well, the latching valves, which control the hydrazine flow, are made of Ti Grade 5. Its nominal ends' thickness is 0.425 mm. This is the thinnest titanium wall in all the propulsion subsystem.

D. Welding of Titanium Tubes and Components

The ends to be fused must be previously made even to obtain perfect fit. Parts should be immobilized by fixation devices. To ensure that no misalignment happens during assembly and operation of the orbital head, they manually receive at least two tack welds, run in diametrically opposed positions of the joint.

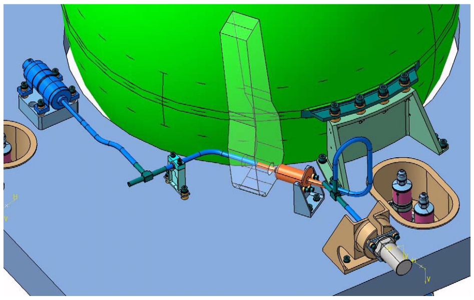

Figure 10. Orbital Head Insertion. *The soldering sequence must observe enough clearance to place the orbital head.*

The weld is autogenous, that is, there is no addition of filler metals. Only the original titanium or titanium alloy is present in the weld. Argon is injected inside the pipes, and in the region that surrounds the joint to be welded. Pressures and flow rates must be well controlled to obtain weld beads without imperfections, like convexities, concavities, pores, etc. It is an important concern to keep a proper and continuous flux of argon through the pipes and parts being welded, as well as an inert argon atmosphere around them.

The titanium tube joints to be welded should be located in rectilinear regions of the parts concerned with, at least 2 cm apart from any bends, folds or components, due to the need for inserting the orbital welding head. Figure 10 illustrates the insertion of the orbital head in such a manner. The soldering sequence has to observe enough clearance to place the orbital head.

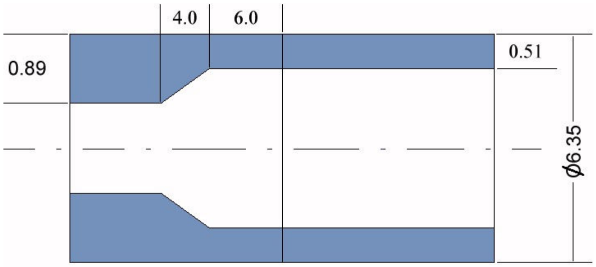

Figure 11. Transition Zone. *Detail of transition zone with different thicknesses to be welded, as between piping (0.89 mm) and tank (0.51 mm) extremities.*

For welding pipes with different thicknesses, it is necessary to provide a transition in the wall of the thicker tube, so as to enable that the weld bead formed by the fusion of parts occur as flat as possible, as recommended by welding Standards[6,7] and LIT procedures.[8] Figure 11 illustrates the strategy adopted by LIT to match the extremities of 0.889 mm thickness of the pipes with the tank ends of 0.508 mm to be welded together. A smooth transition region at the thicker side was adopted, in order to avoid sudden variations in pressure and increasing in local losses. It is important to mention that after cleaning the welded pipes and components, it is not recommended to introduce any objects that may cause some kind of damage or contamination to the inner part. Even the use of endoscopes should be avoided.

E. Specimens

The welded joints should instead be represented by specimens, which will go through several tests and inspections. The amount of specimens should be sufficient to allow the completion of all required tests. Furthermore, it is recommended to manufacture additional specimens to allow extra tests or re-testing, if necessary.

For the specimens, the thickness of the material should be the same as the one of the pipes and components to be welded. The shape and minimum dimensions of the specimens are specified by ISO 15614-5.[9] The minimum value of the length for specimens of thicknesses up to 1.6 mm is 50.8 mm.[8,10] The minimum length is 76.2 mm for thicknesses greater than 1.6 mm. Figure 12 shows a set of 26 specimens of all the 5 kinds presented in Table 1.

The preparation of the joints of specimens must follow guidelines,[11] in accordance with the Preliminary Welding Procedure Specification,[8] and under the general conditions of welding, which should provide welding positions and limitations for angles of tilt and rotation, so that the specimens remain in compliance with the Norm EN ISO 6947.[11]

Figure 12. Specimens. *Set of specimens of the five kinds presented in Table 1.*

The welding is considered qualified if the discontinuities of the weld beads are within the limits established for the class of quality of the specimens in question. In our case it is a Class A, referring to projects that require high demands, because if the weld fails, there may be failure in the main system and consequent loss of the project. This class is intended for projects of high pressure vessels, aerospace vehicles, pressure tubes, pipes of steam turbine, shown in AWS D17.1: 2001.[6,7] The welding procedure and testing of the specimens must be witnessed by a competent examiner from the welding and applicable testing area.

The specimens should go through the non-destructive testing and inspections shown in Table 2. Some of them, subsequently, have to suffer destructive test. The most important one is the tensile essay where the specimen is pulled until rupture, in order to evaluate the solder resistance.

Table 2. Non-destructive tests and inspections.

Item	Kind of Test / Inspection
1	Visual inspection
2	Measure of the width of the weld bead
3	Checking for concavities or convexities
4	Determination of thickness variation in the region of the weld
5	Determination of surface pores or other defects (internally using endoscope)
6	X-ray by at least two images with rotated specimen
7	Leakage test, using helium leak detector equipment
8	Pressure test
9	Inspection of the coloration of the weld

Figure 13. Special Specimens. *Set of 8 specimens of kind "1" (Table 1) to investigate late welding after pickling and cleaning the titanium samples.*

Figure 13 shows a set of eight specimens of kind "1" according to Table 1. This series was welded in order to better evaluate the acceptable time between the pickling and cleaning process of titanium tubes, its long-term storage and late welding, many days after the cleaning process. After the tubes were pickled with acid attack and cleaned, they were placed in plastic bags, filled with argon and sealed. The last subset of these specimens was welded 3 weeks after they had been packaged in argon. The welds were perfect, given the non-occurrence of contamination and oxidation in an inert atmosphere, proving that, if necessary, pickled and clean tubes can wait several days to be welded without any harm to a successful welding. No additional stripping must take place in order to avoid the thickness reduction that occurs in these processes.

F. Welding Programs

To carry out the welding of various types of joints described in Table 1, four different welding programs were qualified to attend to the five types of joints to be welded. Each program defines over 50 parameters. Basically those parameters are related to currents, voltages, pressures, times, electrode specification (composition, spacing and angle), flows, and operating modes. The set of all these parameters will determine the good result of the welding, the bead width, coloration, absence of dimples, porosity, convexities, cracks, etc. Table 3 shows the matching of these programs to the unions to be welded.

Table 3. Welding Programs for Titanium Joints.

Joints (OD = 6.35 mm)	Thickness (mm)	Program Number
CP-Ti with CP-Ti	0.889	P-18
CP-Ti with Ti 6Al-4V	0.889	P-18
Ti 6Al-4V with Ti 6Al-4V	0.889	P-19
CP-Ti with Ti 6Al-4V	0.508	P-23
Ti 6Al-4V with Ti 6Al-4V	0.425	P-17

G. Examinations with Digital X-Ray Equipment

LIT has a digital X-ray system, that allows radiographic inspection of specimens and welded parts of dimensions compatible with the access window of the equipment. This test medium was very valuable during the process of obtaining the welding programs referred above. It is possible to change, in real time, the intensity of the X-ray beam, the angle of incidence, the zoom level and other parameters of the apparatus, enhancing the images obtained, coloring them artificially, and improving contrast in regions of interest.

Figure 14 shows the image of Ti Grade 2 tubes that were welded for preliminary tests with the purpose of validation of images. They have original thickness of 0.889 mm, with reduction of about 50% in the welded region. One of them has a through hole of 0.6 mm. The other has a 0.2 mm punch (not through) in the region of the weld bead. It is possible to investigate the lack of pores and imperfections in the region of the weld, since the equipment has enough resolution to see small harmful defects.

The various images thus obtained helped in the preparation of different welding programs. Once these programs were established, specimens with all combinations of joints to be welded were made.

Final approval of the welding was performed by a company specialized in obtaining X-ray images and analyzing them, contracted to issue reports concerning welded joints. This company has experts, qualified and certified by the AWS-Brazil (American Welding Society) and the SNQC (National System of Qualification and Certification), for Non-Destructive Testing.

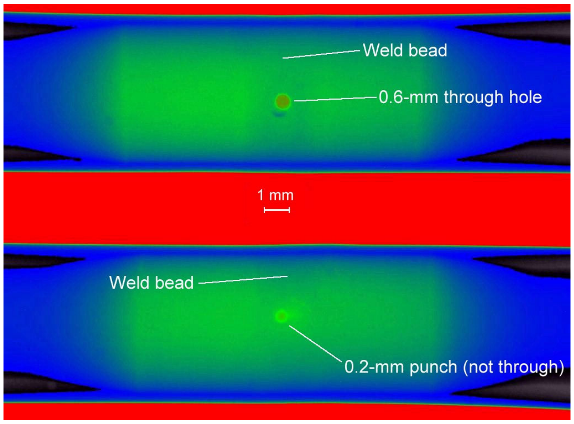

Figure 14. Digital X-Ray Image. *Example of X-ray image of specimens of titanium tubes Grade 2, with thickness reduction near the welded joints. Colors were artificially applied to increasing contrast.*

VI. Conclusion

The propulsion subsystem of the qualification model of PMM was fully integrated and successfully tested. The development of the PMM Propulsion System was carried out by the Brazilian company Fibraforte™ Engenharia Industria e Comercio Ltda, partner of INPE in this Space Program. The subsystem passed through pressure, burst pressure, vacuum, thermal cycling, vibration, and acoustic tests at qualification levels.

Leak tests were performed, with the subsystem filled with helium and placed inside a space simulation chamber at high vacuum ($\leq 1\times10^{-5}$ mbar) and room temperature. Leakage measuring was performed through the mass spectrometer installed in the vacuum chamber. The reading, measured in mbar·ℓ/s, was below the allowable limit of 1×10^{-3}, proving the tightness of the subsystem.

Shot tests of the thrusters were carried out, with the tank filled with hydrazine and nitrogen, in the Combustion and Propulsion Laboratory of INPE, located in Cachoeira Paulista. The thrusters have successfully reached the specified value of 5 N.

Figure 15 shows a photo of the qualification model of the propulsion subsystem developed and tested at INPE. Skin heaters for thermal control as well as wiring and electrical connectors are already installed.

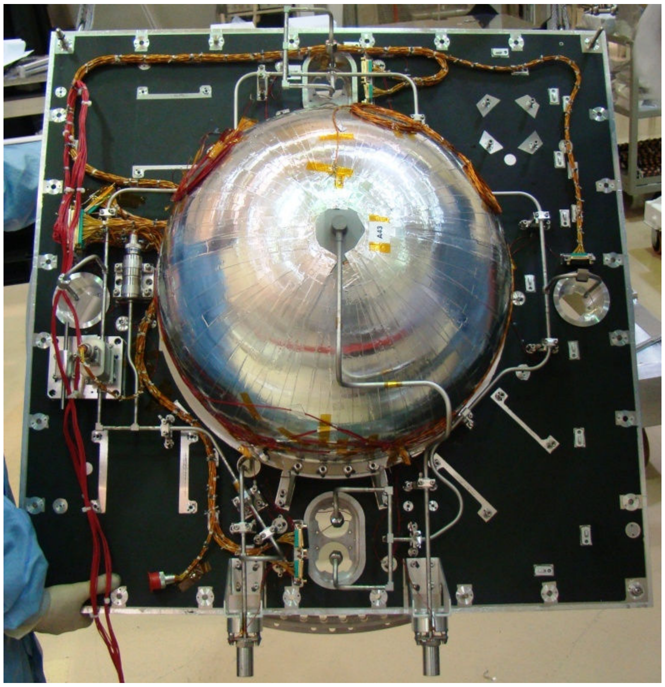

Figure 15. Propulsion Subsystem. *Qualification Model of the PMM Propulsion Subsystem, assembled and tested at INPE.*

Acknowledgments

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[11] ISO 6947:2011, Welding and allied processes – Welding positions.