DOI: 10.13009/EUCASS2023-928
Aerospace Europe Conference 2023 – 10TH EUCASS – 9TH CEAS

PERSEUS and Minerva: Firing tests

Arthur Berlet⋆ *and Stephanie Dreyer*⋆ *and Michel Duvergey*⋆ *and Sandra Boujnah*⋆†
⋆*ArianeGroup SAS*
arthur.berlet-dechauffour@ariane.group ; stephanie.dreyer@ariane.group ; michel.duvergey@ariane.group
⋆† *CNES*
sandra.boujnah@cnes.fr

Abstract

The PERSEUS (Projet Etudiant de Recherche Spatiale Europeen Universitaire et Scientifique) program launched, financed and managed by the Direction of Space Transportation of Centre National Etudes Spatiales (CNES) aims to make students discover the space field. Today, one of the stepping stone of the project is to launch the sounding rocket ASTREOS 1 by the end of May 2025. This bi-liquid rocket is equipped with the 5kN LOX/Ethanol MINERVA Engine. MINERVA engine, which has been designed some years ago by students in the frame of PERSEUS program, has been tested on the site of ArianeGroup SAS in Vernon in summer 2022, on the test facility P20. The objective was to assess the specimen regarding the necessary performances related to the launch of ASTREOS 1. Five firing tests were done in order to qualify the new test bench P20, to determine the performances of the engine and to choose between different configurations and materials for the thermal protection.

1. Introduction

Space field is today a growing sector of activities. Old and new actors coexist to answer the needs of the market. Indeed, the use of the space diversify and there are now used both for the private life, for the industry and for the state organisation. The multiplication of the needs lead to an acceleration of innovations, entrepreneurship and investments.

It is in this context that the Centre National des Etudes Spatiales (CNES) launched in 2005 the Projet Etudiant de Recherche Spatiale Europeen Universitaire et Scientifiques (PERSEUS). The objectives are to promote the space related jobs and to promote the innovation and the development of technological bricks. In practice students, under the coordination of professional from the space field (CNES, ArianeGroup, and Universities), develop technological bricks destined to be assembled to create something bigger. SERA (Supersonic Experimental Rockets ARES) rockets have been launched since the creation of the project. This project allows students to discover the space field, to make them aware about the problematics of the sector: ecological, financial and political. It also allows the students to improve their skills on spatial technologies.[1]

Today, the objective of the project is to launch a bi-liquid sounding rocket, liquid oxygen and ethanol (LOX/ETH) in a first step. The launch of this sounding rocket named ASTREOS is planned on the first 2025 semester at Kiruna, Sweden. It will be the first demonstrator with liquid propellants of the PERSEUS project. It will be equipped with the MINERVA rocket engine on which tests have been made on the historical site of ArianeGroup in Vernon, France. There were five firing tests done during the second semester of 2022, different combustion duration and different thermal protections have been tested. These tests have been made by students in apprenticeship or in internship and monitored by the ArianeGroup's teams.

2. Rocket Engine Characteristics

The tested engine on the Vernon site is the MINERVA S1a (Moteur INovant Experimental pour les Recherches sur les Vehicules Aerospatiaux). More Precisely, MINERVA is a family of engine which will welcome gradually improvements.
The specifications of the engine family are the following:

- Chamber Pressure : 20 bar

DOI: 10.13009/EUCASS2023-928

- Mixing ratio (MR): 1.4
- Vacuum thrust : 5kN
- Vacuum specific impulse : 295s
- Combustion time: up to 20s

Tests were conducted on the first generation of the MINERVA engine, the specifications of this version are the following:

- 7 tripled impact injectors
- Isolated chamber with an ablative internal thermal protection
- Engine design for a test facility: mass non optimised

Figure 1: Minerva S1a Engine

They are two types of ablative thermal protection (Internal Thermal Protection (PTI) + Throat): graphite carbon and composite carbon. The graphite thermal protection should be stronger but heavier than the composite thermal protection.
Due to the size of the Astreos Rocket, the choice has been made to use pressure fed technology to pressurise the propellants in the combustion chamber.

3. Objectives and firing test plan

There are several objectives for the firing tests made In Vernon. First, the performances of the engine are characterised in resptect to the objective to fulfill the needs for the first flight of ASTREOS 1. In particular, the thrust needed on the ground is about 4.2kN to launch ASTREOS 1. The following information have been collected: chamber pressure, mixture ratio, specific impulse, flow rate, C* and Cf. Secondly, the ignition sequence is obtained in order to have the smoothest ignition. Finally, the two types of thermal protection have been tested to characterize their thermomechanical properties with visual control before and after the tests

Table 1: Firing test plan

	Test 1	**Test 2**	**Test 3**	**Test 4**	**Test 5**
Graphite Throat	X	X	X		X
Composite Throat				X	
Graphite PTI	X	X	X		X
Composite PTI				X	
Duration	5s	5s	5s	5s	20s

For the first three tests, the test facility has been validated, the graphite thermal protections has been tested and the parameters of the test has been known to have the optimal engine operating point. For the fourth test, the composite thermal protection has been tested. Finally, for the fifth test, a testing duration representative of the ASTREOS 1 fly duration has been accomplished. Flow check tests have been made before these firing tests to characterize the test facility. During those tests, the pressure rise in the LOX and ETH dome have been measured in order to build the ignition sequence of the engine.

DOI: 10.13009/EUCASS2023-928

4. Test results

In the following section, only the results of the two final tests will be considered, they are the most important regarding the performances and the question of the choice of the thermal protection for the engine. The test facility has been instrumented to measure the pressure in the combustion chamber, the LOX and ETH pressure at the inlet of the injectors, the flow rates and the engine thrust. The throat diameter was also measured before every test to assess the engine performances.

4.1 Test 4

4.2 Test Objectives

After having done three tests to characterise the test bench and to test the thermal protection in Graphite, a test with a composite configuration has been performed. The objective was to assess the possibility to use this configuration for the flight of Astreos 1. The thermal protection used is made of composite with carbon fiber and phenolic resin. It is lighter than a graphite configuration which is better for the rocket performances.
The test parameters are the following:

- Duration :5s
- D_{throat} = 50mm

With the experiences of the previous tests performed, the expected performances are the following

- F = 4.2 kN
- P_{ch} = 16.6 bar
- $\dot{m}$ = 2.23 kg/s
- MR = 1.4
- Combustion efficiency = 86%

The firing test sequences is presented in the following table, the ignition is possible with a ground igniter after the LOX injection.

Table 2: Firing test sequence

Time	Sequence
H0 -10s	Beginning of the firing sequence and engine sanitation
H0 - 7s	End of engine sanitation
H0 - Δt	Ethanol injection
H0	Liquid Oxygen injection
H0 + Δt_{tir}	End of Liquid Oxygen injection
H0 + Δt_{tir} + 0.1s	End of Ethanol injection
H0 + Δt_{tir} + 2s	Ethanol lines sanitation
H0 + Δt_{tir} + 5s	End of Ethanol lines sanitation
H0 + Δt_{tir} + 7s	LOX lines sanitation
H0 + Δt_{tir} + 10s	End of LOX lines sanitation

4.2.1 Performance results

The performances achieved on this test were:

- F = 4.014 kN
- P_{ch} = 14.1 bar
- $\dot{m}$ = 2.09 kg/s
- MR = 1.11

DOI: 10.13009/EUCASS2023-928

- Combustion efficiency = 90%

Those performances were calculated on a stabilised point. Moreover, the plots of the pressure chamber, the thrust but also the pressure in the LOX and Ethanol tanks are presented on figures 2 and 3. Indeed, there is no turbo pumps, the engine is pressure fed through the LOX and ETH tanks, the pressure in those thanks are important regarding the performances of the engine but it is mandatory to analyse them.

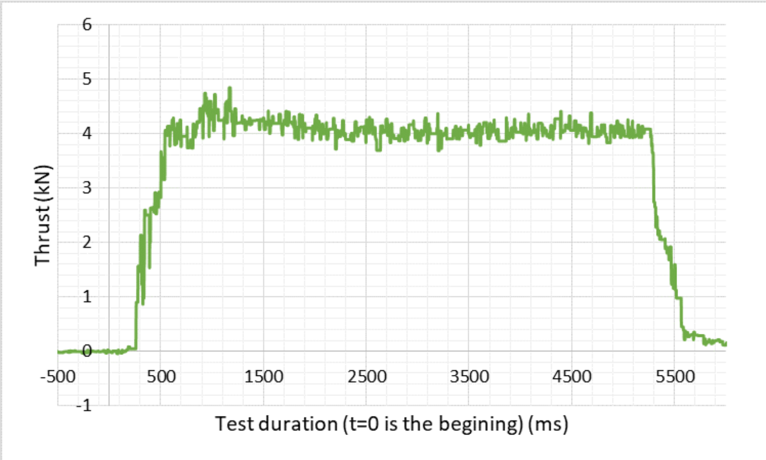

Figure 2: Engine thrust for the fourh test

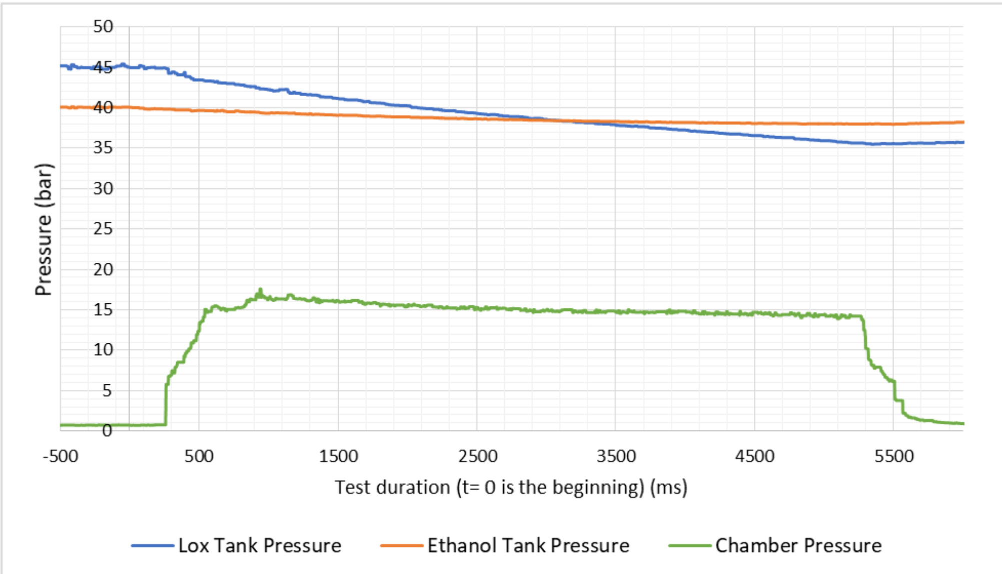

Figure 3: Pressure for the fourth test

The slow ignition is due to difficulty to have the pressurisation of the LOX dome that leads to have a slow increase of the pressure chamber. After ignition, there is a pressure around 15 bar in the chamber, however we have a decrease in the pressure of the LOX tank. This can explain also the little pressure drop that we have in chamber pressure. Nevertheless the thrust of the engine is enough regarding the expected performances for Astreos 1.

4.2.2 Results on the thermal protection

The major point for this test was to test the thermal protection in composite material. This protection consists of two parts:

- The Internal Thermal Protection (PTI) which protects the combustion chamber

DOI: 10.13009/EUCASS2023-928

- The throat which is composed of the throat itself but also the complete nozzle

For the composite materials there are two different technology used to manufacture the two parts. The throat is made of wires cylindrical wound then pressed while the PTI is made of wires wound in the way of the exhaust gazes.
So during this test the two materials were tested under the usual characteristics of the engine. The objective was to test the thermomechanical strength. A lot of information have been collected during the test. The results of the two material parts will be presented.
Two bright flashes have been observed during the test as shown on figure 4.

Figure 4: Bright Flashes during test 4

Moreover, during the test, several particles have been ejected in the hot gaz as shown in the figure 5

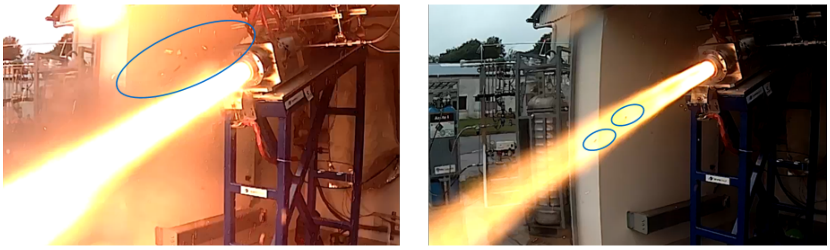

Figure 5: Particles observed during the test

Finally, the thermal protections were disassembled after the test and measurements of the ablation were made.

- For the throat, a maximal augmentation of the diameter of 3.3mm (53.3mm after the test and 50mm before the test) was measured. Moreover, we have a degradation of the circularity of the throat with somewhere some "flat revolution" surfaces which prove an asymmetrical degradation of the throat during the test.
- For the PTI, a maximal augmentation of the diameter of 3.2mm (105.6mm after the test and 102.4 before the test) has been measured. The circularity of the PTI has been conserved.

Following conclusions can be derived from the observations and associated analysis: the fact that the throat is made by stacking carbon sheets that are compressed into a mould and that those sheets are compressed perpendicularly to the engine axis leads to have a shearing phenomenon of the sheets until the mechanical rupture. Concerning the carbon sheets of the PTI, they are stacked in parallel to the engine axis. This manufacturing difference leads to have an abnormal deterioration of the throat while for the PTI the question is still opened. To conclude, the definition of the throat has not been validated while the PTI one is suspended before deeper analysis and additionnal tests performed.

4.3 Test 5

After having done three tests to characterise the engine and the bench with the thermal protection in Graphite and an another test with the composite materials to test them, a long test was necessary to observe the performances of the engine during a firing time representative of the flight. The nominal time duration of the flight for Astreos 1 is 20 seconds. So a final test of 20 seconds and with the thermal protection in graphite has been done for final validation of

DOI: 10.13009/EUCASS2023-928

the MINERVA engine.
The test duration was 20s and the expected performances were the same as the ones for the test 4. The firing sequence was similar between test 4 and test 5.

4.3.1 Performance results

In this section, the engine performances for this test will be given. At the beginning of the test and after the ignition the performances were:

- F = 3.9 kN
- P_{ch} = 16.04 bar
- $\dot{m}$ = 2.2 kg/s
- MR = 1.47
- Combustion efficiency = 84.5%

Those performances were calculated on a stabilised point at two seconds after the ignition of the engine. Moreover, the plots of the pressure chamber, the thrust but also the pressure in the LOX and Ethanol tanks are presented on figure 6 and 7. Indeed, there is no turbo pumps, the engine is pressure fed through the LOX and ETH tanks, the pressure in those thanks are important regarding the performances of the engine but it is mandatory to analyse them.

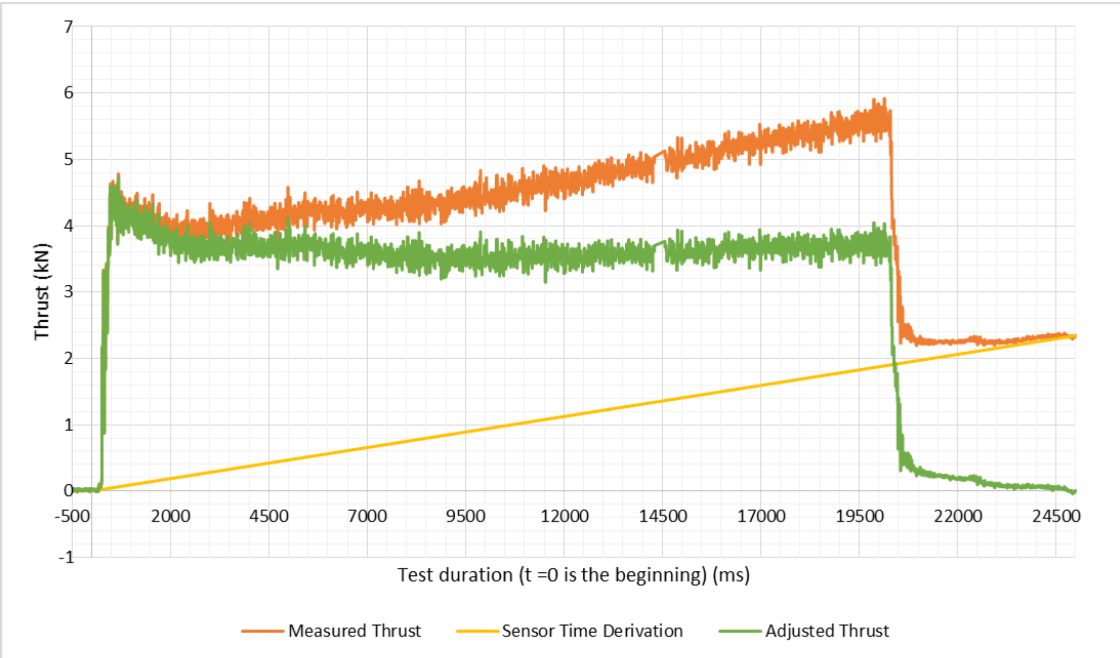

Figure 6: Engine thrust for the fifth test

DOI: 10.13009/EUCASS2023-928

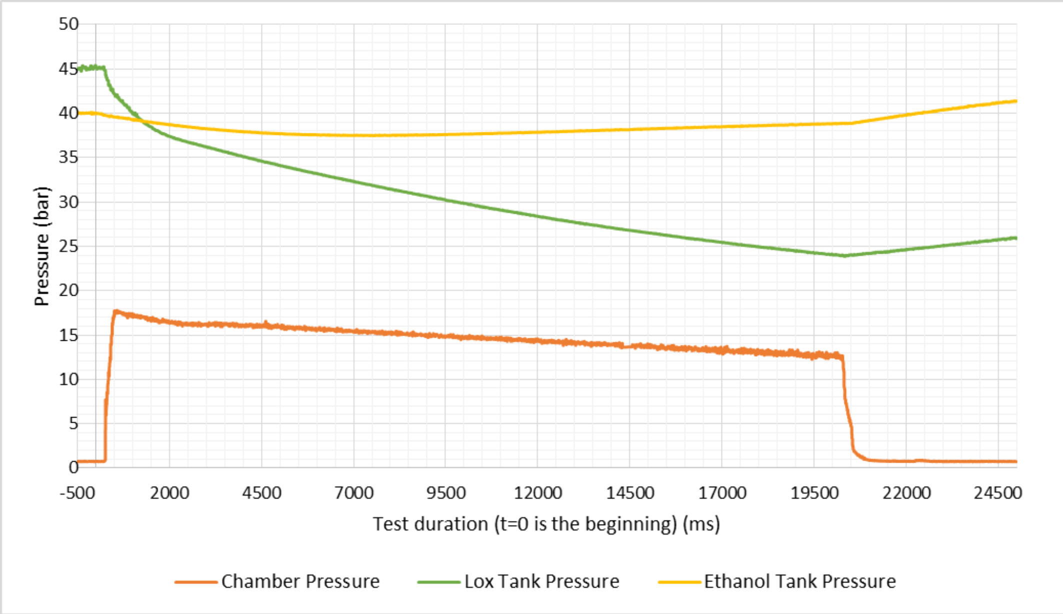

Figure 7: Pressure for the fifth test

To analyse the performances of the engine during this test, there are two problems to consider.
First, as it is visible on figure 6, there is a deviation of the thrust sensor, this leads to have an increasing thrust during the test while we know that it is not possible because the mass flow is constant (even a little bit decreasing at the end of the test) and the chamber pressure is also decreasing as shown on figure 7. As discussed with experts, the problem of deviation for this type of sensor is known and linear adjustement is possible to recover a good approximation of the thrust. After being adjusted, the thrust goes down to 3.9kN during the test with a 4.5kN peak at the ignition and a fast decrease of the thrust to 3.9kN. For the following test campaign, the objective will be to have a better thrust sensor to avoid this kind of deviation.
Secondly, there is a problem in the LOX tank pressure regulation system. Indeed, as it is shown on figure 7, the LOX tank pressure is decreasing and the regulation is not done correctly, this leads to have a decrease in the chamber pressure of 5 bar during the test (18 bar at the ignition to 13 bar at the end ot the test). The full potential of the engine is not developped. This is also a problem that needs to be solved for the next test campaigns.

4.3.2 Results on the materials

This test was the possibility to validate the thermochanical strength of the thermal protection during a long duration of test. It was also possible to test the injection plate for a long duration.
The results are good regarding our objectives for Astreos 1:

- For the throat, a maximal increase of the diameter of 3.4mm (53.37mm after the test and 50mm before the beginning of the test campaign) has been measured. This throat made four tests with a total of 30.6 seconds of test. There is also a split that cut the throat in two parts.
- For the PTI, a maximal increase of the diameter of 3mm has also been measured. There are longitudinal cracks on the PTI.

DOI: 10.13009/EUCASS2023-928

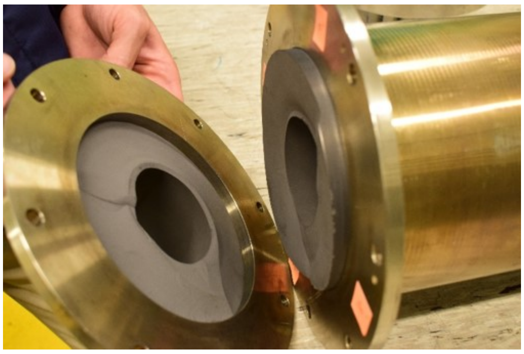

Figure 8: Split of the throat

The analyses lead to a validation of the definition of the thermal protection. Indeed, the ablation of the throat and the PTI is acceptable regarding the cumulative duration of the tests (30.6 seconds). The breakout of the throat is probably due to non coaxial dilation between the structure of the chamber and the structure of the throat as shown on figure 8. The cracks of the PTI are due to the fastening system which created to much constraints on the PTI.
This test was also the possiblity to test the injection plate for a long duration. It was a new injection plate.

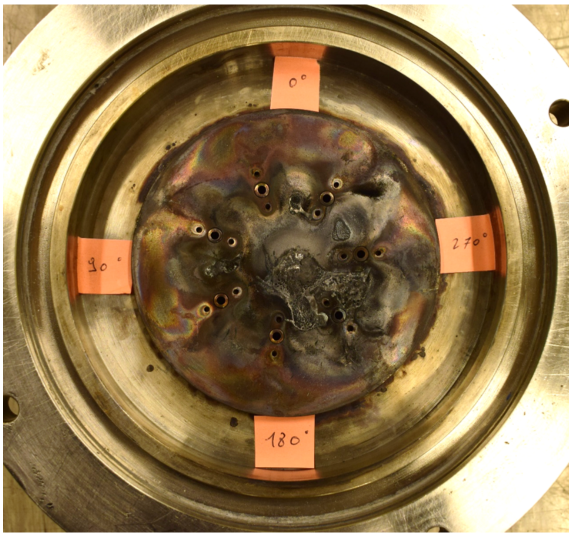

Figure 9: Injection plate

We are pretty satisfied about the extent of degradation of the plate.It has melt a little but regarding the test duration of 20 seconds, the defintion has been validated. However the degradation is asymetric, it is probably due to the position of the engine during the test, the engine is inclined on the test bench.

5. Global analysis and future prospects

Five firing test have been made during the summer 2022. It was the first tests of the MINERVA engine after a failure that leads to the destruction of the engine in 2017 and the first test campaign peformed on ArianeGroup test area in Vernon. The main objectives were to validate the performances of the engine regarding the necessary performances for Astreos 1 and to validate the thermomechanical strength of the thermal protections.

For the first point, the performances have been accepted for the flight of Astreos but there are to main points that will need to be treated before the next test campaign. First, the observed deviation of the thrust sensor has to be treated, the idea is to change the system to avoid this deviation during the firing sequence for the long test duration. The second point is about the pressure drop in the LOX tank, indeed, as it is visible on figure 7, there is a continuous pressure drop in the LOX tank which leads to a pressure drop in the combustion chamber and that minimizes the performances of the engine. So the full potential of the engine is not developped but this is a good indicator for the flight Astreos 1. Indeed,

DOI: 10.13009/EUCASS2023-928

we know that the pressure regulation will not be perfect and that we will have a pressure linear pressure drop in the LOX tank and the Ethanol tank. On the test facility it is not a normal situation, the pressure regulation should maintain the pressure in the tanks. It will be interesting to have a better regulation for the LOX tank and to see what are the real performances of the engine.

After the 5 tests, the engine performances have been validated by the CNES for the launch of Astreos 1. The performances obtained on the test bench are enough to make Astreos 1 flight with safety. However to have more performances for the rocket and to improve further, the CNES has developped a lighter engine: they worked on the engine structure without changing the fonctionnal parts. This new engine will be tested in Vernon in 2023 to validate the definition and to use this definition for the flight of Astreos 1. The second point is that, a new definition for the composite thermal protections will be developped with a partner of the PERSEUS project. So to increase the performances of Astreos 1, because the composite materials are lighter, new firing tests will be done to test the thermomechanical strength of the new definition. Those are the two main future prospects. Looking further ahead, MINERVA will receive a lot of new technology as explained in [2]: Pintle injector; regenerative chamber, igniter.On a longer time horizon the LOX/LCH4 could be used as propellants. The test facility in Vernon will be used to test these technologies.

6. Conclusion

In conclusion, five tests were made on the MINERVA engine on the test bench in Vernon. The engine developped by students reached the expected performances during a long duration test and the definition has been validated the Astreos 1 flight. However the definition of the composite materils have not been validated during the tests. Those tests made with students in apprenticeship or internship were a great opportunity for them to discover what a fire test was, the procedures and the necessary associated system.

References

[1] R. Bec, C. Bernard-Lepine, K. de Groote and F. Amouroux - PERSEUS A Nanosatellite Launch System Project Focusing on Innovation and Education -2nd EUCASS 2007
[2] Jean-Noel Chopinet and Marco Galeotta - Minerva, igniting the future: a PERSEUS Story - EUCASS 2022