EUROPEAN COMMISSION
EUROPEAN HEALTH AND DIGITAL EXECUTIVE AGENCY

HADEA.B – Digital, Industry and Space
B.4 – Space research

GENERAL PROJECT REVIEW CONSOLIDATED REPORT

Grant agreement (GA) number:	870506
Project[1] Acronym:	NEMESIS
Project title:	Novel Electride Material for Enhanced electrical propulSIon Solutions
Type of action:	RIA
Start date of the project:	01/10/2019
Duration of the project:	42
Name of primary coordinator contact and organisation:	Angel Post (ATD)
Period covered by the report:	from 01/10/2020 to 31/03/2023
Periodic report/Reporting period number:	Final
Date of first submission of the periodic report (if applicable):	30/05/2023
Amendments (latest AMD concerning description of the action)[2]	24/06/2022 (AMD-870506-4)
Date of meeting with consortium (if applicable):	20/03/2023 - 24/03/2023
Name of project officer:	Traian BRANZA
Name(s) of monitors:	– Stephane MAZOUFFRE • CNRS - ICARE

[1] 'Project' means the same thing as 'action'.
[2] Only amendments to the description of the action (DoA; AT21) are relevant for general project reviews since they always have to be carried out against the latest version of the DoA

1. Overall assessment

1. Overall assessment
Project has fully achieved its objectives and milestones for the period.
2. Significant results linked to dissemination, exploitation and impact potential
Project has delivered exceptional results with significant immediate or potential impact (even if not all objectives mentioned in the Annex 1 to the GA were achieved). All objectives and milestones have been fully achieved by the consortium in due time with very significant outcomes and many potential applications for a broad range of stakeholders due to the strong involvement of all NEMESIS consortium members. Thanks to extensive research, the use of state of the art chemical methods and advanced diagnostic techniques for material characterization, ATD is currently able to provide high-quality high-purity highly-stable C12A7:e electride material for a broad range of applications as electron emitter for cathodes and electrodes. The electride material developed, tested and validated by the consortium offers a low work function, below most of common electron emitting material available today on the market, a low emission temperature, stability in time with no degradation and the ability to operate with various chemical compounds and propellants for thrusters. When combined, the properties make the NEMESIS C12A7:e material unique and of great interest especially as it can furnish a large amount of electrons at a relatively low temperature with a moderate input power. As a consequence, the use of this material in industrial processes gives the possibility to reduce power consumption, to simplify system design, to increase the overall efficiency and to reduce operation cost. Furthermore, the synthesis of C12A7:e requires simple chemical compounds and precursors that are inexpensive and easy to find within Europe. Many applications can benefit from the discoveries and advances made in the NEMESIS project. First, C12A7:e can be used in cathodes and neutralizers of electric thrusters for satellites and spacecraft, as considered in the proposal. Its characteristics make it perfectly suitable and of great interest for low-power small thrusters of electrostatic type installed in Cubesats and micro-satellites that form constellations and mega-constellation for Earth observation, communication and IoT. This is especially the case for Hall effect thrusters and gridded ion engines, which at the present time dominate by far the electric propulsion market. Another specific features of the NEMESIS C12A7:e is the fact that it can operate with inorganic fuels alternative to xenon and krypton like Iodine (I_2) and ammonia (NH_3) as demonstrated in the project. This feature could make C12A7:e a game changer in the electric propulsion field and open new opportunities as xenon, the favorite propellant for Hall thrusters and ion engines, is becoming unaffordable, with prices above 10 k€/kg, when available, due to several factors. As there is no sign of improvements in the short term, C12A7:e could upset the space market by allowing the use of cheap and available propellants. In that case, thrusters and satellites manufacturers as well as operators and users would be affected, which represents a large set of possible stakeholders and a relatively big market. Second, C12A7:e can still be employed in cathodes yet for applications different from satellite propulsion. As investigated in NEMESIS, a new generation of high-efficiency cathodes/electrodes based on the new electride material could emerge for the field of energy production and storage. Indeed C12A7:e electrodes could be used for the production of hydrogen (H_2) and ammonia, two relevant, if not critical, energy vectors for the next decades or even centuries due the urgent need of decreasing carbon dioxide (CO_2) generation while increasing the amount of energy available for humans. The NEMESIS outcomes could provide ways to improve electrolysis processes needed to generate H_2 and NH_3. The use of C12A7:e could increase the efficiency, increase the system lifetime and decrease the production cost. Possible applications both in and out of the space field have been investigated in the NEMESIS project. In parallel, industrial property has been addressed through the registration of several patents, which protects consortium members and gives them opportunities in various industrial domains.
3. General comments
NEMESIS is a high-quality project with remarkable outcomes and findings. This is firstly due to the quality of the consortium and secondly to a large amount of work with careful thinking. I want also to emphasize on the fact that despite the COVID-19 pandemic and associated disorganization of the world in 2020 and 2021, all objectives have been achieved with a minor extension of only several months, which images the responsiveness and the strength of the consortium. The project includes several scientific and technological achievements. The main outcomes is certainly a high-quality high-purity highly-stable C12A7:e electride material (100 % purity, large electron concentration) that serves as electron

emitter for cathodes and electrodes. This is for sure the best C12A7:e material in Europe and probably in the world. Along with the development of chemical methods for synthesis, purification and doping, the consortium was able to accurately measure chemical and physical properties of the material, a relevant task for industrial and commercial applications. The C12A7:e was tested in various environnement, with different systems and different types of gases (argon, krypton, xenon, nitrogen) and propellants (ammonia, iodine). During the project, different cathode architectures have been built, tested and optimized. Some use a flat disk C12A7:e emitter whereas others use a small cylinder into which plasma can be confined. Cathodes have all proven to operate without additional heating, i.e. in heaterless configuration, which improves the global efficiency. Moreover, the consortium tested with success heartless ignition applying a high voltage on the emitter. To sum up the main innovation outputs are the development of a high-quality C12A7:e material that acts as an efficiency electron emitter and low-power cathodes for electric thrusters.

The consortium provide an excellent C12A7:e material with remarkable properties. From this material efficient cathodes can be developed for Hall thrusters and ion engines. As demonstrated in the project, such cathodes can fire with alternative propellants like iodine and ammonia, which could revolutionize the space market as xenon, the main electric propulsion fuel, is becoming expensive and extremely rare. Iodine is of particular interest as, in addition to being affordable, it is heavy, easy to ionize and in solid state at room temperature. It appears as a very good alternative to xenon and krypton. In NEMESIS, two low-power Hall thrusters, the 50 W and 100 W Hall thrusters from Exotrail, have been successfully fired with iodine for several hours when equipped with a C12A7:e-based cathode. To the best of my knowledge this is a world first (iodine was previously used but the cathode was then fed with a rare gas to operate properly).

With no doubts all scientific and technological results are of great quality (not to write "of the highest"). This is in fact perfectly images by the achievements previously mentioned. Setups and tools were carefully designed and operated. Procedures have been written and followed. Lessons were learnt from one test/design to the next and leveraged. A good proof of the quality of the results is the large number of papers published in rank A journals (8 in total), of conference proceedings and of presentation in international symposia like the Space Propulsion Conference and the International Electric propulsion Conference. Another evidence of the high quality of the work as a whole is the transition from TRL1 to TRL4 (as expected at the beginning) despite the COVID-19 outbreak.

As already explained, the C12A7:e technology developed in NEMESIS will certainly have positive impacts in the space industry, especially in the field of electric propulsion for spacecraft and for the small satellite market by i) improving thruster performances (low energy consumption for the cathode) and ii) opening the way to the use of propellants like I2 or NH3 alternative to rare gases. As investigated by the consortium, C12A7:e electrodes could also have a great impact for non-space applications especially in the field of energy production as they could replace traditional electrodes for H2 and NH3 production.

The NEMESIS projet has led to the publication of several (8 in total) articles in high-level international scientific journals. Results have also been presented (and still will be) in many international conferences and symposia about space propulsion and aerospace and published in various conference proceedings. The community is therefore well aware of NEMESIS outcomes, advances and innovation.
Consortium members were well aware of the quality and potential of their results. Therefore they registered 8 patents to warrant IP rights

In a nutshell, NEMESIS was a great project and a profitable investment for the EU in terms of results and gain in knowledge.
As stated above results are exceptional and they will strengthen competitiveness and independence of Europe in the space and energy domains.

4. Recommendations concerning the period covered by the report

This report covers the entire project. There is then no specific recommendations. As previously mentioned NEMESIS is an exceptional project in my own opinion with relevant fundamental and technological outcomes that will certainly impacts the industry and the society in the coming years.

5. Recommendations concerning future work, if applicable

Here are a few recommendations for future and follow-up works:
- find a strategy for production of large amounts of C12A7:e
- improve cathode design and lifetime
- investigate deeper the pulse-mode cathode operation
- go on with operation with iodine and other alternative propellants; coupling with Hall thrusters

- coupling with ion engines
- test cathodes at high current (high power) with various fuels
- works on electrolysis for H2/O2 production
- publish new articles and present latest results in international symposia.

Note that during the NEMESIS project the consortium created an Innovation Management Board with several recognized experts to investigate perspectives and applications in the space field and in other fields in order to go beyond NEMESIS. I find this a very good strategy to prepare the next step and the future. This is quite unusual in European project. Therefore it must be acknowledged.
A direct consequence of the work of the IMB is the fact that 3 follow-up projects have already been awarded and 2 collaborations with the industry are running.

2. Objectives and workplan

1. Is the progress reported in line with objectives and work plan as specified in the DoA? If there are significant deviations, please comment.	Yes
All milestones were achieved. All deliverables have been submitted and validated. I want to mention they all are of high quality in terms of structure and content. Moreover all deliverables were accessible to the Referee before the final meeting. Objectives have been reached and even exceeded There was a weak impact of the COVID-19 pandemic due to access restrictions for some laboratories and delays in parts/ components procurement. All teams found solutions and ways to minimize impacts and delays during this perturbed period. Deviations and delays mostly concerned cathode testing. Thanks to additional efforts and a strong involvement of all consortium members no impact is noticed at the end of the NEMESIS program.	
2. Are the objectives of the project still scientifically and /or technologically relevant?	Yes
Objectives and achievements have been described and commented in details in the previous sections. Objectives are very scientifically and technologically relevant and sound. On a scientific viewpoint, the NEMESIS project brings new results and new insight into high-quality C12A7:e electride ceramic production methods and characterization. The NEMESIS project delivers at the end a large amount of new, useful and consolidated data. On a more technological standpoint, the consortium has developed and qualified high-efficiency electride-based cathodes for electric propulsion devices able to operate with a large family of propellants. Those cathodes will certainly find other applications in the field of energy production and storage. NEMESIS will consolidate the independence of Europe in high-tech and strategic fields with respect to foreign countries like China, Russia and the USA.	
3. Are the critical implementation risks and mitigation actions described in the DoA still relevant?	Yes
The COVID pandemic and crisis was unpredictable. The consortium acted the right way so there is no impact at the end of the research program.	
4. Have the pilots/case studies started to showcase innovative results as described in the DoA?	Yes
The NEMESIS project is full of innovative results thanks to careful reasoning, good organization, good communication and information exchange, good management and proper work sharing.	
5. Have the ethics deliverables due for the current period been adequately addressed and approved?	Not applicable
NA	
6. Have the comments and recommendations from previous project reviews been taken into account?	Yes
Consortium members accounted for comments and advises. This is part of the success of NEMESIS.	

3. Impact

1. Does the work carried out contribute to the expected impacts detailed in the DoA?	Yes
As already explained, the space propulsion area, the satellite market and the energy sector (especially H2 generation) will be positively impacted by results and achievements of the NEMESIS project.	
2. Does the work carried out follow the plan detailed in the DoA to enhance innovation capacity, create new markets opportunities, strengthen competitiveness and growth of companies, address issues related to climate change or the environment, address industrial and/or societal needs at regional level or bring other important benefits for society? Give information on the relevant innovation activities carried out (prototypes, testing activities, standards, clinical trials) and/or new product, service, reference materials, process or method (to be) launched to the market, if any.	Yes
The NEMESIS outcomes and results, especially C12A7:e-based cathodes, will surely strengthen the competitiveness of the European space industry, especially the electric propulsion and the small satellite areas. First, new high-performance cathodes /neutralizers will soon be available for electric thrusters (already at TRL 4). These cathodes will be able to operate with standard propellants like xenon and krypton and solid and liquid propellants, eg iodine and ammonia, as well. So one can expect the propulsion market to be drastically modified as iodine is a serious and promising alternative to xenon as fuel for EP devices. C12A7:e cathodes could quickly replace traditional LaB6 cathode and avoid the dependence on lanthanum, a rare Earth element. The overall impact on the European space industry is very important. Europe would first be more independent with a more robust propulsion sector. The impact on the job market would be positive at all levels with new products (i.e. iodine-fed EP devices) and new opportunities. The satellite market would be impacted with great consequences and benefits for the society. For instance, one can imagine in the near future fully independent European satellite constellations for Earth observation, communication and defense. The energy sector could also be positively impacted, especially the hydrogen industry as C12A7:e electrodes could replace traditional metal or carbon electrodes for H2 production by electrolysis of water. With no doubt this sector will play a great role in the near future and C12A7:e could be a key element to favor Europe and to make its energy production/storage efficient, safe and secure.	
3. Does the work carried out contribute towards European policy objectives and strategies and have an impact on policy making?	Yes
Outcomes of the NEMSIS project will certainly make European EP systems more secure in critical fields like space access and energy. This is well illustrated in the propulsion domain. The cathode/neutralizer is a very critical component for electric thrusters. Currently cathode emitters rely on supply from foreign countries like China and Russia. So the European space industry will become more independent with in addition more advanced and more efficient products.	
4. Does (or will) the work carried out have an impact on SMEs?	Yes
SMEs and startups are nowadays pillars in the space sector (see the consortium composition) along with large groups. The core of the NEMESIS project, i.e. the high-quality C12A7:e compound, is produced by a SME. Low-power electric thrusters and small-size satellites are mostly produced by SMEs and startups. The work performed in the frame of NEMESIS will then impact many SMEs and startups through Europe with certainly positive implications on the job market in the space industry. NEMESIS outcomes will also by a runoff effect have positive consequences for large groups and big companies. Effets could be similar in the energy sectors as SMEs and startups play a major role in H2 and NH3 production.	
5. Have the beneficiaries reached gender balance at all levels of personnel assigned to the action? If not, have the reasons been explained in the periodic report?	Partially
The consortium was since the beginning aware of gender issues in research, especially in Physics and Engineering. One must keep in mind than the male-to-female ratio remains around 5/1 in Europe despite efforts and incentives measures. The space sector is unbalanced at all levels although appreciable progress can be observed. The NEMESIS consortium members did their best to achieve balance in the research teams. However, a 1:1 ratio could not be reached despite efforts when recruiting PhD students and students.	

4. Implementation

1. Has the project been efficiently and effectively managed?	Yes
The consortium really acted as a whole thanks to efficient management and interaction/communication strategy. A direct evidence is the weak impact of the COVID-19 pandemic on the project schedule an outcomes despite lab shutdown and delays in supply. All aspects of the project (material development, cathode development, experiments with various propellants, with various cathode design, with thrusters) were linked, coordinated and optimized in a good manner. Reports and technical notes (deliverables) are all of high quality. Without an efficient management, NEMESIS would not have provided so many results with extensive dissemination. Once more I want to acknowledge the creation of an Innovation Management Board with the goal to investigate perspectives and applications in the space field and in other fields in order to go beyond NEMESIS. This was a very good strategy to prepare follow-up studies, projects and contracts and also to critically analyze NEMESIS progress and results.	
2. Is the management of the project in line with the obligations of beneficiaries (including ethics and security requirements, risk and innovation management if applicable)?	Yes
The management of the project was in line with the obligation of beneficiaries.	
3. Is the contribution of each beneficiary in line with the work committed in the DoA? (applicable only to multibeneficiary projects)	Yes
Each beneficiary follows the path described in the work program with minor deviations always justified and always in the right direction. Each beneficiary had its own tasks and work line, however, strong interaction and exchanges between beneficiaries were noticeable, hence great achievements.	
4. Have the beneficiaries disseminated project results (foreground) in scientific publications as planned in the DoA (including the deposition of publications in open access repositories)? Do they include a reference to EU funding?	Yes
Several articles have been (or will be soon) published in rank-A scientific journals. Open access publication policy was followed. Several conference proceedings have already been published. Works and achievements have already been presented in several international symposia and conferences about space propulsion. 8 patents have been prepared to protect the IP. Reference to the NEMESIS project is included. The community is therefore well aware of NEMESIS results, findings and advances.	
5. Have the beneficiaries disseminated and communicated project activities and results by other means than scientific publications (social media, press-release, the project web site, video/film, etc) as planned in the DoA? Do they include a reference to EU funding?	Yes
Communication and dissemination activities were very good and done mostly through the website as well as social media. A few articles have been published in magazines and print media. I want also to report on the organisation by the University of Giessen of the first international workshop on C12A7:e in October 2022 in the frame of the NEMESIS program. This is another great achievement and a perfect way to communicate and create links.	
6. Has the plan for the exploitation and dissemination of the results (if required) been updated and implemented as described in the DoA, in particular as regards intellectual property rights? Is it appropriate?	Yes
The plan for the exploitation and dissemination of the results is well implemented considering the many patents and the IPR rights.	

7. Has the data management plan (DMP) (if required) been updated and implemented? Is it appropriate?	Yes
Data was managed by ATD for the consortium.	
8. Have the proposed institutional changes been appropriately promoted?	Not applicable
NA	

5. Resources

1. Were the resources used as described in the DoA and were they necessary to achieve its objectives? If there are deviations from planned budget, have they been satisfactorily explained? Have they been used in a manner consistent with the principle of sound financial management (in particular economy, efficiency and effectiveness)?	Yes
To the best of my knowledge, the resources were necessary and have been appropriately used to achieve the objectives. The deviations are fully justified due to i) the COVID-19 pandemic context and ii) the changes that had to be implemented while dealing with such novel, complex and state-of-the-art technological developments.	

Annex 1

Expert opinion on deliverables

Deliverable number	Deliverable name	Status	Comments
D1.1	Web site available	Accepted	
D1.2	Data Management Plan	Accepted	
D1.3	Selection of Innovation Management Board	Accepted	
D1.4	IPR protection and Exploitation Plan	Accepted	
D1.5	Report period 1	Accepted	
D1.6	Selection of 4/5 SMEs and projects outside the space market	Accepted	
D1.7	Selection of 4/5 SMEs and projects for further developments in space applications	Accepted	
D1.8	Final Report	Accepted	
D1.9	Report period 2	Accepted	
D2.1	Preliminary design report	Accepted	
D2.2	First NACES HW delivery to UPM	Accepted	
D2.3	NACES cathode test plan and procedures	Accepted	
D2.4	Report of NACES cathode characterization and electron emission	Accepted	
D2.5	Report on endurance tests	Accepted	
D3.1	Presentation of compatibility matrix	Accepted	
D3.2	Provision of cathode design parameters	Accepted	
D3.3	First C12A7:e- HW delivered to JLU	Accepted	
D3.4	First NACES cathode HW delivery to JLU	Accepted	
D3.5	Selection of best propellant candidate for endurance testing report	Accepted	
D3.6	Cathodes performance and endurance analysis report	Accepted	
D3.7	Cathodes minimun TRL4 qualification report	Accepted	

Deliverable number	Deliverable name	Status	Comments
D4.1	Miniature C12A7:e- samples first deliveries	Accepted	
D4.2	Full test report of miniature samples performances and comparison with LaB6	Accepted	
D4.3	Miniature samples C12A7:e- next deliveries	Accepted	
D4.4	Full cathode 5A characterization report with LaB6 comparison	Accepted	
D4.5	Full micro-cathode 1A characterization report with LaB6 comparison	Accepted	
D4.6	Report of cathode with a C12A7:e- emitter, and comparison with LaB6	Accepted	
D4.7	Report of heater-less cathode with C12A7:e- emitter, and comparison with LaB6	Accepted	
D4.8	Full test report on miniature C12A7:e- cathode test with Exotrail 50W & 100W HETs, and comparison with LaB6	Accepted	
D4.9	Full test report on C12A7:e- heater-less cathode test with Exotrail 50W & 100W HETs, and comparison with LaB6	Accepted	
D5.1	Summary information on thruster, cathode, and interfaces requirements for testing	Accepted	
D5.2	Lifetime test report	Accepted	
D6.1	Test requirements summary	Accepted	
D6.2	Test plan and test procedures	Accepted	
D6.3	Test procedures and facility adaptation plan	Accepted	
D6.4	Final report with ULP test results	Accepted	

Annex 2

Expert opinion on milestones

Milestone number	Milestone name	Achieved	Comments
MS1	Website	Yes	Validated
MS2	Intellectual Property Rights protection Plan	Yes	Validated - 8 patents submitted
MS3	NACES characterization and endurance tests	Yes	Validated
MS4	Material characterization and performnce	Yes	Validated - high-quality C12A7:e material is now available in Europe
MS5	Cathodes characterization under different propellants and selection of best propellant candidate	Yes	Validated - Xe, Kr, Ar and N2 as propellants
MS6	Ultra Low Power (ULP) cathode performances	Yes	Validated
MS7	Miniature cathode tested	Yes	Validated
MS8	Cathodes endurance tests under selected alternative propellant	Yes	Validated - Iodine and ammonia successfully tested
MS9	Miniature Hall Thruster Performance	Yes	Validated - Coupling successful with a 50 W thruster
MS10	Cathodes operated under alternative propellant TRL4 level achieved	Yes	Validated - TRL4 reached
MS11	HET operated with iodine lifetime	Yes	Validated - World first. Open the way to the next generation of Hall thrusters