PROOF OF CONCEPT FUND

Development of hybrid electron accelerator system for the treatment of marine diesel exhaust gases

By

RIGA TECHNICAL UNIVERSITY

Center of High Energy Physics and Accelerator Technologies

Partners:

1. Institute of Nuclear Chemistry and Technology - INCT (Warsaw, Poland)
2. The European Organization for Nuclear Research - CERN (Geneva, Switzerland)
3. Fraunhofer Institute for Organic Electronics, Electron Beam and Plasma Technology - FEP (Dresden, Germany)
4. The University of Huddersfield, Accelerator Applications Group – UH (Huddersfield, UK).
5. ebeam Technologies Europe – ebeam (Flamatt, Switzerland)
6. Remontowa Marine Design – Remontowa (Gdansk, Poland)
7. Milgravja Tehnoloģiskais Parks - Riga Ship Yard - RKB (Riga, Latvia)
8. BIOPOLINEX Sp. z o.o.(Lublin, Poland)

Advisors (see ANNEX 1 for supporting documents):

1. Italian Coast Guard – ITCG (Genova, Italy)
2. American Bureau of Shipping - ABS (Houston, USA)
3. DNV GL (Oslo, Norway)

Background and Aims

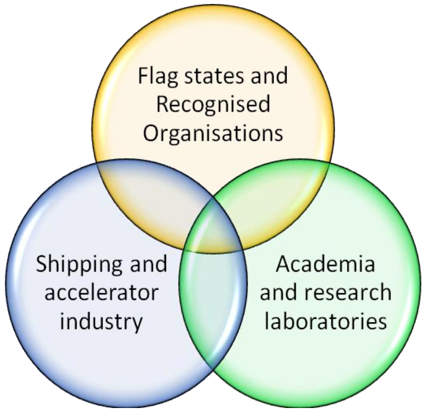
Air pollution is an important issue among present day society, with people living in big cities at the greatest risk of harm. Despite the fact that air quality has been improved significantly in comparison to the last century, especially thanks to introducing of pollution control installations at the fossil fuel power boilers, there is still a lot of room for improvement. According to WHO (World Health Organization), more than 80% of people living in cities and towns are affected by the air pollution which exceeds safe norms set by WHO with countries of low economic status suffering the most from toxic pollutants. Recently, there has been significant concern with the pollution from marine sources which currently utilize low quality diesel fuels. As a result, research and development projects have focused heavily on creating cost effective technology that can clean off gases with a high level of efficiency.

Exhausts from marine engines may contain nitrogen, oxygen, carbon dioxide and water vapor as well as nitrogen oxides, sulfur oxides, carbon monoxide, various hydrocarbons and complex particulate matter. The maritime transport usually uses heavy fuel oil (HFO) with a high content of sulfur, which naturally leads to the three main pollutants formation derived from shipping: nitrogen oxides (NO_X), sulfur oxides (SO_X) and particulate matters (PM). Around 15% of global NO_X and 5-8% of SO_X emissions are attributable to oceangoing ships. SO_2 and NOx emission as a smog component is a precursor to acid rains and it can have a negative influence on plant life as well as on wider ecosystems. Therefore, it is necessary to use a gas purifying method before releasing them into the atmosphere. To address the adverse impacts of sulfur and nitrogen oxides from shipping emission, the maritime sector is required to find highly efficient and low cost methods of gaseous pollutants removal. According to International Maritime Organization regulations (MARPOL Annex VI), there are two sets of emission and fuel quality requirements: global (progressive reduction in globally emissions of SOx, NOx and particulate matter) and more restrictive requirements dedicated to ships in deliberately established zones – Emission Control Areas (ECA). Outgoing methods are applied to remove NO_X or SO_2 separately. These technologies are divided into NO_X-reducing devices and SO_X scrubbers and their development is focused on process engineering aspects of such systems, including designing of apparatus, main dimensions, advantages/disadvantages as well as processes economy and cost analysis. The removal of nitrogen oxides is a difficult process, requiring the use of expensive catalysts. However, as international emissions regulations on nitrogen and sulfur oxides tighten, current removal methods are becoming increasingly insufficient. First of all, marine's scrubbing and denitration systems are expected to be compatible. NO_X reducing systems usually requires a high temperature of activation, close to 300^{o} C. Simultaneously, SO_2 solubility decrease at higher seawater temperatures. For this reason, equipment manufacturers are expected to provide guidance on the maximum sulfur content of fuel that can be consumed by an engine or boiler with a scrubbed exhaust, so that emissions remain within applicable limits, together with any seawater temperature limitations that may apply and, if applicable, the engine's NO_X certification limits. The main challenges for marine SCR applications are sulfur originated catatlyst deactivation resistance and very low efficiency at temperatures feasible for SOx scrubbing.

Currently, SCR catalyst mainly relies on V_2O_5–WO_3–TiO_2, but V_2O_5 is a kind of highly poisonous material and the active temperature is above 300^{o} C. The mechanism for deposit formation involves an undesirable parallel reaction (to the NO_X conversion) at the catalyst whereby sulfur dioxide in the exhaust is oxidized to sulfur trioxide (SO_3), which can then react with ammonia (used as an reagent in pure or urea solution form) to form ammonium sulphate and bisulphate. Such a process reduce the effective area and shorten the lifespan of the catalyst, with fuel-related hydrocarbon and particulate matter adding to the fouling. The spent catalyst which has to be replaced each 5 – 6 years , is a hazardous solid waste. As conditions deteriorate, NO_X reduction is impaired and more un-reacted ammonia will slip past the catalyst. This system may reduce the emissions of NO_X by more than 90%, (obligatorily requires comparatively low-sulfur fuel), with cost effectiveness of 873.5 $/ton and SOx emissions by 98% with 3115 $/ton in case of using seawater scrubbing. Researchers have indicated that the urea consumption of SCR system is 8.5% of the consumption of diesel oil, which will surely have a significant influence on size and weight of installation. Therefore, it is necessary to look for new cost effective solutions to remove both nitrogen and sulfur oxides with high efficiency simultaneously.

New, **hybrid technology** is based on the concept of combining two methods used to clean up the exhaust gases: Electron Beam (EB) and Improved Wet Scrubbing. This hybrid technology has a great potential to solve the emerging problem of marine industry, although it still requires research. Taking under consideration all of the advantages of the technology in comparison to other available methods, hybrid technology may become a promising and cost-saving option in the future marine market.

This is multidisciplinary and multi-industry project involving important stakeholders as indicated below.



Partners of the potential Consortium *inter alia* had two designated meetings where Project proposal was discussed in great detail:
1 December 2017 at CERN – https://indico.cern.ch/event/659434/
1 March 2018 in Genova at the premises of the Italian Coast Guard - https://indico.cern.ch/event/704222/

Participants

Lead Applicant RIGA TECHNICAL UNIVERSITY - Center of High Energy Physics and Accelerator Technologies - RTU		
Type of organization	**Country**	**ARIES Beneficiary**
University	Latvia	yes
Name of contact person	**Job title**	**E-mail**
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Partner #1 - Institute of Nuclear Chemistry and Technology - INCT		
Type of organization	**Country**	**ARIES Beneficiary**
Research institute	Poland	yes
Name of contact person	**Job title**	**E-mail**
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Partner #2 - The European Organization for Nuclear Research - CERN		
Type of organization	**Country**	**ARIES Beneficiary**
Research laboratory	Switzerland	yes
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Partner #3 - Fraunhofer Institute for Organic Electronics, Electron Beam and Plasma Technology - FEP		
Type of organization	**Country**	**ARIES Beneficiary**
Research institute	Germany	yes
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Partner #4 - The University of Huddersfield, Accelerator Applications Group – UH		
Type of organization	**Country**	**ARIES Beneficiary**

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Company	Switzerland	no
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Partner #7 - Milgravja Tehnoloģiskais Parks - Riga Ship Yard - RKB		
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Name of contact person	**Job title**	**E-mail**
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Partner #8 - BIOPOLINEX Sp. z o.o.		
Type of organization	**Country**	**ARIES Beneficiary**
Company	Poland	yes
Name of contact person	**Job title**	**E-mail**
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Technical Summary

Objectives

1. To conceptually proof the electron-beam accelerator application for the effective treatment of marine diesel exhaust gases.
2. To proof its technical feasibility within the simulated ship environment.
3. To demonstrate that the technology in question is capable to remove at the sufficient level SOx a NOx.
4. To provide realistic financial calculation on the cost of this technology to the ship-owner.
5. To engage and inform all relevant stakeholders during the project

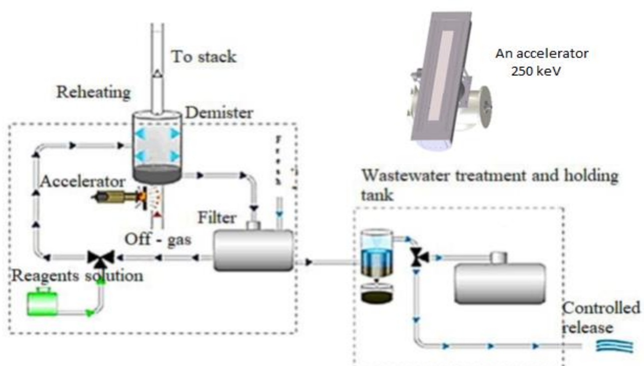
To achieve these objectives the following **main tasks** are identified within this project:

1. Effective project management, transparent coordination and targeted communication
2. Integration of the e-beam accelerator into the marine diesel engine exhaust flow system - in the simulated ship environment
3. Investigation of flue gas flow pattern and process parameter influencing on the removal efficiency of NO_x and SO_2 using computer simulation
4. Experiment measurements

Current status of the technology

A new emerging **hybrid technology** that couples the Electron Beam with the reduced size wet scrubbing methods may provide an answer to the reducing emissions from the marine shipping industry. There are two main stages involved: 1) SO2 and NOx oxidation during irradiation of wet gases by the Electron Beam from the accelerator and 2) the pollution products absorption into aqueous solution. Such a concept aims to enhance the advantages and minimize the limitations of each technology and achieve simultaneous removal of both pollutants e.g. the low removal efficiency when cleaning exhaust gases with high SO2 and NOx concentrations with only the EB and the low NOx removal efficiency with absorption, etc. The organic pollutants (VOC, PAH) may be destroyed in eb formed plasma as well. As the scrubbing solution is used salty water, easily obtainable by marine industry with the addition of the limited concentration liquid oxidant to scrub products of the reactions. Schematic diagram of the hybrid technology principles is presented below.

Technological units of the system are presented below, with the photo of an accelerator with linear cathode, which can be applied in elaborated solution.The closed loop water solution purification will be applied.
Hybrid technology is now at the level 4 in the Technology Readiness Level (there is 9 levels in this classification). This means that the technology was optimized in the laboratory level and is in the medium development phase.
The NOx removal of hybrid technology is higher than results obtained for SNCR – Selective Non Catalytic Reduction (only low concentration of NO can be treated), ozone injection, bioprocess and other plasmas methods (EB is more energy efficient than e.g. pulsed corona discharge). The SCR catalyst enables a very high removal efficiency for high NO initial concentrations, but the technology is very expensive and requires extensive amount of space. Furthermore, only NOx can be treated with this technology. The Hybrid eb method by contrast, enables a significant reduction of both pollutants in the limited reagent consumption and may assure organic pollutant destruction what may be required by new standards in the future.



Business Plan

Business development of this technology is directly dependent of this proof-of concept project – results of this project will demonstrate to the industry (ship owners, shipyards, engine manufacturers) and relevant stakeholders and decision makers, technical possibility of the electron beam accelerator application into the marine environment. Experimental results demonstrating sufficient efficiency of the SOx and NOx removal rates will be supported by the independent economic feasibility study. Very strong interest of the industry and stakeholders (including European Commission) was demonstrated in two preparatory meetings for this project (see links above and participants). To move-on maritime industry needs prof that this technology works on the marine diesel engine and is cheaper that currently available scrubber technologies. When it will be done, Consortium will be enlarged and direct funding from the industry supported by the European Community funding will be obtained. Therefore this proof-of-concept is crucial step to advance this promising accelerator technology societal application which could have enormous economic potential and very much needed solution to address the maritime environmental and air pollution problems.
One of the project partners – INCT is possessing European Patent application (see enclosed- EP17460063) related to said hybrid technology. Thus there is direct commercial interest of involved parties and Consortium members. The present value of the Patent application by INCT was evaluated by independent consulting company INVESTIN at some 540 000 EUR. The IP will be managed in the following manner, in case if the project will be approved:

- Partners IP shear of this patent will be proportional to their input to the PoC project.
- Any further IP, patents, inventions, etc - all what will be developed during the PoC and Consortium work will be equally distributed amongst Partners of Consortium
- Observers and Advisory entities are out of IP.

Work Plan and Risk Analysis

Work Package #1 (leader RTU): Project management, Coordination and Communication

Partner	Responsibility / Task	Expected outcome
RTU	1.1. Overall project **coordination and management**. Monitoring activities - ensuring that partners are timely following their responsibilities and verification of effective use of the received funding	2. Project kick-off meeting during ARIES annual meeting in Riga – May 2018 3. Quarterly coordination meetings via Vidyo platform 4. Mid-term review meeting during 2nd ARIES annual meeting in 2019 5. Project closing meeting in 2020
RTU	1.2. Coordination and Communication with relevant **stakeholders**	1. Relevant stakeholders (e.g. shipping companies, Class Societies, engine manufacturers, European Commission, EMSA, IMA, Interatnko; "Scrubbers" Group; Bimco) are directly informed about the project and its results – at least during or following the above mentioned meetings
RTU + all	1.3. Final project report	1. At the end of the project final report is compiled and made available to the relevant stakeholders

Work Package #2 (leader RTU): Integration of the e-beam accelerator into the marine diesel engine exhaust flow system - in the simulated ship environment

Partner	Responsibility / Task	Expected outcome
RKB	2.1. To provide with marine diesel **engine** (in-kind contribution)	1. Functioning marine diesel engine is made available at the Riga Ship yard (e.g. on dry-dock or shore facilities). 2. Adequate marine fuel (e.g. heavy fuel) is provided.
ebeam	2.2. To provide with electron **accelerator** (in-kind contribution)	1. Appropriate accelerator and all supporting systems are made available and are delivered to the Riga Ship yard
RTU INCT FEP ebeam RKB CERN Remon-towa UH	2.3. **Mechanical and electrical design** as well as technical integration of the **process vessel** with an accelerator provided 2.4. Design of the exhaust gas **cooling elements** based on the operational conditions 2.5. Design and integration of the control and **monitoring devices**	1. Design and drawings of the process vessel is provided to RTU and RKB based on the inputs received form the Partners 2. Design of the exhaust gas cooling elements is provided to RTU and RKB based on the inputs received form the Partners 3. Design and integration of the control and monitoring devices is provided to RTU and RKB based on the inputs received form the Partners
INCT FEP ebeam CERN UH	2.6. Different materials resistant for corrosion used for **accelerator windows** and **air curtain** for protection accelerator window to be studied	1. The most appropriate material and design is identified for accelerator windows and air curtain
RTU RKB Remon-towa INCT FEP CERN UH	2.7. **Production and manufacturing** of the process vessel, along with integration, supporting and control elements	1. All components are manufactured and assembled on the engine 2. Accelerator is installed on the process vessel 3. Accelerator windows and curtains are installed 4. Electrical and control elements are installed
INCT RTU UH	2.8. **Installation** of the flue gas measuring devices	1. Measuring devices are provided and installed on the prototype
All	2.9. **Assembly and testing** of all the components	1. Prototype is made ready for the tests

Work Package #3 (leader INCT): Investigation of flue gas flow pattern and process parameter influencing on the removal efficiency of NOx and SO2 using computer simulation

Partner	Responsibility / Task	Expected outcome

INCT	3.1. CFD (computer fluid dynamics) computer simulation will be used to model the **gas flow dynamic** inside the process vessel.	1. Process parameters, experimental - such as gas temperature, flow rate, droplet size, L/G ratio of droplet; based on modeling - process vessel dimension influence on removal efficiency of SO2 and NOx are investigated using MATLAB and KINETIC. 2. Relevant reports are provided in the form of the scientific papers
UH FEP	3.2. Dosimetry – analysis of the electron penetration and distribution in the process vessel by using Mote-Carlo simulations	1. Relevant analysis is made available and reports are provided in the form of the scientific papers 2. The system on ship operational safety conditions are evaluated.

Work Package #4 (leader INCT): Experimental measurements

Partner	Responsibility / Task	Expected outcome
INCT RTU FEP UH CERN	4.1. Experimental measurements and data recording regarding continuous testing of integrated system with the diesel real off gases flow	1. Output parameters like: temperature, flow velocity and gas mixing, window conditions etc are measured and data are recorded
INCT RTU	3.3. Analysis of the experimental results	1. Relevant analysis is made available and along with the conclusions are provided for the final project report

Work Package #5 (leader BIOPOLINEX): Economic analysis

Partner	Responsibility / Task	Expected outcome
BIOPOLINEX	5.1. To conduct a comprehensive business / economic / financial analysis from the point of view of the end user of the technology / installation	1. Relevant analysis and report is made available to the Consortium
BIOPOLINEX	5.2. To conduct a business / economic / financial analysis from the point of view of the plant manufacturer	1. Relevant analysis and report is made available to the Consortium
BIOPOLINEX	5.3. To assess the investment profitability based on discounted cash flows, NPV, IRR ratio as well as the payback period. 5.4. To calculate the break-even point for key financial parameters and to conduct the sensitivity analysis.	1. Relevant analysis and report is made available to the Consortium

Risk assessment and mitigation

The most relevant risks of the project are assessed below, followed by the proposed mitigation measures.

Project Risk Assessment Matrix - RISK FACTOR			
	LOW	**MEDIUM**	**HIGH**
Technological		- Proven state of the art - Some previous facility or site application - Some proof of application testing required	

Interference with other operations of the Partners		- Potential impact from other shipyard operations (e.g. dry-dock operations) - New interfaces must be established and managed in-situ	
Safety aspects		- shipyard is area of increased safety risks. Although there are well established they are not know to the research staff to be involved	
Visibility and Stakeholder involvement		- Major stakeholders are identified - Stakeholders neutral but interested in progress updates - Regular information sharing and communication outreach required	
Funding		- Two year duration - Detailed estimate but not yet validated - resources are not committed yet	
Time/schedule			- Compressed schedule - Activities developed only to conceptual level (some invalidated assumptions) - Resources uncommitted
Logistics and transportation		- components designed and delivered in several entities in various countries	
Quality requirements	- no specific quality requirements identified for the proof-of concept		
Number of key participants		- there are 4 key participants	
Scientific project management and participation	- Proven track record of key Partners and resources human resources immediately available		
Regulatory involvement	- At proof of concept stage no specific permits are needed, no specific certification is required		

Time/schedule risk is having HIGH probability and detrimental consequence to the project. To mitigate this following measures are envisaged:

- Compressed schedule - project manager has to engage all partners at very early stage of the project and detailed time schedule has to be developed respecting milestones and deliverables. Regular coordination meetings are foreseen. Partners are experienced in such projects and could back-up each other easily; however this has to be properly managed. Regular information exchange is critical to identify any potential problems at very early stage. Advise of the relevant stakeholder is available.
- Activities developed only to conceptual level (some invalidated assumptions) – this mostly concerns accelerator integration in the diesel engine exhaust tract. Appropriate mathematical modeling is envisaged in the WP2 and WP3, still it will require carefully project manager oversight and peer-review which is available in the consortium.
  If it will appear that some of the Partners could not deliver or will not be in position to deliver, by decision of simple majority of Consortium, after warning, this task could be (along with the relevant resources) given to another Partner or third party. This possible, since consortium is structured in the way that there is overlapping expertise and technological capabilities (e.g. two shipyards, two potential accelerator suppliers, etc).

– Resources uncommitted – this is mostly related with in-king contributions of the Partners. This will be mitigated within the Consortium agreement, where exact value and amount of this contribution will be established and agreed.

Other risks are identified as MEDIUM or LOW significance. These risks individually are not critical to the project and standing alone are not posing a threat. They are addressed in the relevant WP's and are clearly identified. However, if these risks occurring at the same time or overlapping they might became of HIGH significance. Therefore, this risks have to be made clear to all the partners and involved personnel and regularly monitored by the relevant WP leaders and project manager. Who will allocate designated staff member to follow risk assessment during the project and in case of need ad-hock meeting of the Partners could be set-up.

Milestones & Deliverables

Length of this project is 2 years (it will be completed by 31st January 2021).

Name	**Description**	**Estimated delivery month**
Deliverable 1 RTU	Project kick-off meeting is organized	M0
Deliverable 2 RKB	Functioning marine diesel engine is made available at the Riga Ship yard	M2
Deliverable 3 INCT	Drawings regarding system integration and concept design of air courtain system. Collaboration on the accelerator selection.	M3
Milestone 1 *all*	– Design and drawings of the process vessel is provided to RTU and RKB based on the inputs received form the Partners – Design of the exhaust gas cooling elements is provided to RTU and RKB based on the inputs received form the Partners – Design and integration of the control and monitoring devices is provided to	M6
Deliverable 4 ebeam	Appropriate accelerator and all supporting systems are made available and are delivered to the Riga Ship yard	M8
Deliverable 5 RTU; RKB; INCT Remontowa	– All components are manufactured and assembled on the engine – Accelerator is installed on the process vessel – Accelerator windows and curtains are installed – Electrical and control elements are installed	M10
Deliverable 6 INCT; RTU; UH	Measuring devices are provided and installed on the prototype	M11
Milestone 2 *all*	Prototype is made ready for the tests	M12
Deliverable 7 RTU	Mid-term review meeting is organized – progress report	M12
Deliverable 8 INCT	Computer simulation of flue gas flow pattern and process parameter influencing on the removal efficiency of NOx and SO_2. Evaluation of the electron accelerators feasibility for the system.	M18
Deliverable 9 UH; FEP	Dosimetry – analysis of the electron penetration and distribution in the process vessel by using Mote-Carlo simulations	M20
Deliverable 10 BIOPOLINEX	Economic analysis is concluded and results are provided to the Consortium	M22
Deliverable 11 INCT	Experimental results of process vessel flow conditions and testing of window protection system. Elaboration of the design assumptions for the industrial systems including relevant accelerator design conditions	M23
Deliverable 12 RTU	Project closing meeting is organized	M23-M24
Deliverable 13 RTU + all	Final report is compiled and made available to the relevant stakeholders	M24

Resources (Budget)

On the day of project application total budget of the Project is estimated of 112 500 EUR. This does not include in-kind contribution of the Partners – as it is indicated in the budget table below:

- Requested contribution from the ARIES Proof-of-Concept fund is 50 500 EUR
- Own contribution of the Partners (in-cash) is 62 000 EUR

Project budget will be used to cover the costs arising from the aforementioned Work Packages. Detailed distribution of the estimated costs is provided in the table below:

- personal costs of the Partners
- Material/Equipment
- Services from industry.

Significant part of the project will be formed by the in-kind direct contributions of the Partners. Value of the in-kind contributions is to be agreed within the subsequent Consortium agreement.
All costs are indicated in EUR.

Estimated project budget

Partner	**Person-months**	**Personnel costs (person-months * monthly salary)**	**Material/ Equipment/ joint test cost**	**Total costs (personnel costs + material/equipment)**	**contributions of the Partners**		**Requested contribution from the ARIES PoC**
					in kind	**in cash**	
Lead Applicant RTU	24	48 384	10 000	58 384		10 000	30 000
Partner 1 INCT	20	28 580	8 000	36 580		5 000	8 000
Partner 2 CERN	3	In-kind	0	0		10 000	0
Partner 3 FEP	3	6 000	0	6 000		5 000	2 000
Partner 4 UH	1.5	3 000	0	3 000		2 000	2 000
Partner 5 ebeam	3	In-kind	In-kind	In-kind	Providing ebeam accelerator to the project	0	0
Partner 6 Remontowa	5	In-kind	In-kind	In-kind	Design of the of the process vessel. Simulation of the engine room	10 000	0
Partner 7 RKB	10	In-kind	In-kind	In-kind	Providing marine engine and facilities + engineering, construction and manufacturing of the components+ security	5 000	0
Partner 8 BIOPOLINEX	5	8 500	0	8 500		15 000	8 500
		94 464	**18 000**	**112 464**		**62 000**	**50 500**

Total value of the project **112 500 EUR**

ANNEX 1 – Letters of Support

Letter	Company/Institution	Signatory	Date
	Italian Coast Guard - representing Italian Flag	Admiral Nicola CARLONE	31.03.2018