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Test Bench for Key Components of Megawatt Class International Power and Propulsion System Ground Demonstration

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Abstract
Use of megawatt class international nuclear power and propulsion systems (INPPS) is considered in the frame of the DEMOCRITOS project. It will allow realizing new challenging near-Earth and deep space missions, which are hard to realize in other way. During the DEMOCRITOS activities, several demonstrators' concepts are being defined. Demonstrators are required for maturing technologies necessary for the development of spacecraft with INPPS. One of these concepts is a ground demonstrator, which includes the conversion, thermal management, power management and distribution and electric propulsion subsystems.

1. Introduction

The objective of the DEMOCRITOS project (Demonstrators for Conversion, Reactor, Radiator and Thrusters for Electric Propulsion Systems) (financed under the EU Horizon 2020 Research Framework Programme) is to investigate the necessary demonstration activities in order to mature technologies for megawatt class nuclear power

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and propulsion systems [1]. The project is a follow-on activity of the successful European-Russian cooperation in the frame of the MEGAHIT (Megawatt Highly Efficient Technologies for Space Power and Propulsion Systems for Long-duration Exploration Missions) project [2,3].
DEMOCRITOS project targets, for the long term, a 1 MWe nuclear-electric spaceship. This spaceship would be capable of realizing multiple new challenging space missions, which are hard to realize in other way. For example:

- Transport of multiple deep space exploration missions (e.g. asteroids, Mars and moons of Jupiter);
- Deflection of dangerous near-Earth objects like asteroids and meteorites as well as collection and removal of debris in Earth orbits;
- Building of Earth-Moon or Earth-Mars tug system;
- Use of nuclear power systems for planetary habitats and exploitation of planetary and asteroid resources.

The principle of the spaceship is the following [2,3]:

- A Fission reactor produces thermal power (3.3 MWth);
- A Conversion system (5 assemblies of 200kWe compressor+turbine+alternator + 1 redundant 200kWe assembly) converts this thermal power into electrical power (1MWe);
- This electrical power is managed and distributed by a Power Management and Distribution system (PMAD) to electric propulsion thrusters and other equipment.
- Radiators provide the rejection of the wasted heat from spaceship systems and evacuate it to space.

To develop this spaceship the DEMOCRITOS project proposes several demonstrators' concepts (see figure 1).
Demonstrators are required for maturing technologies necessary for the development of spacecraft with INPPS:

1. Ground Demonstrator or alternatively the DEMOCRITOS Ground Component;
2. DEMOCRITOS Core Component or Core Demonstrator;
3. Space Component or Space Demonstrator.

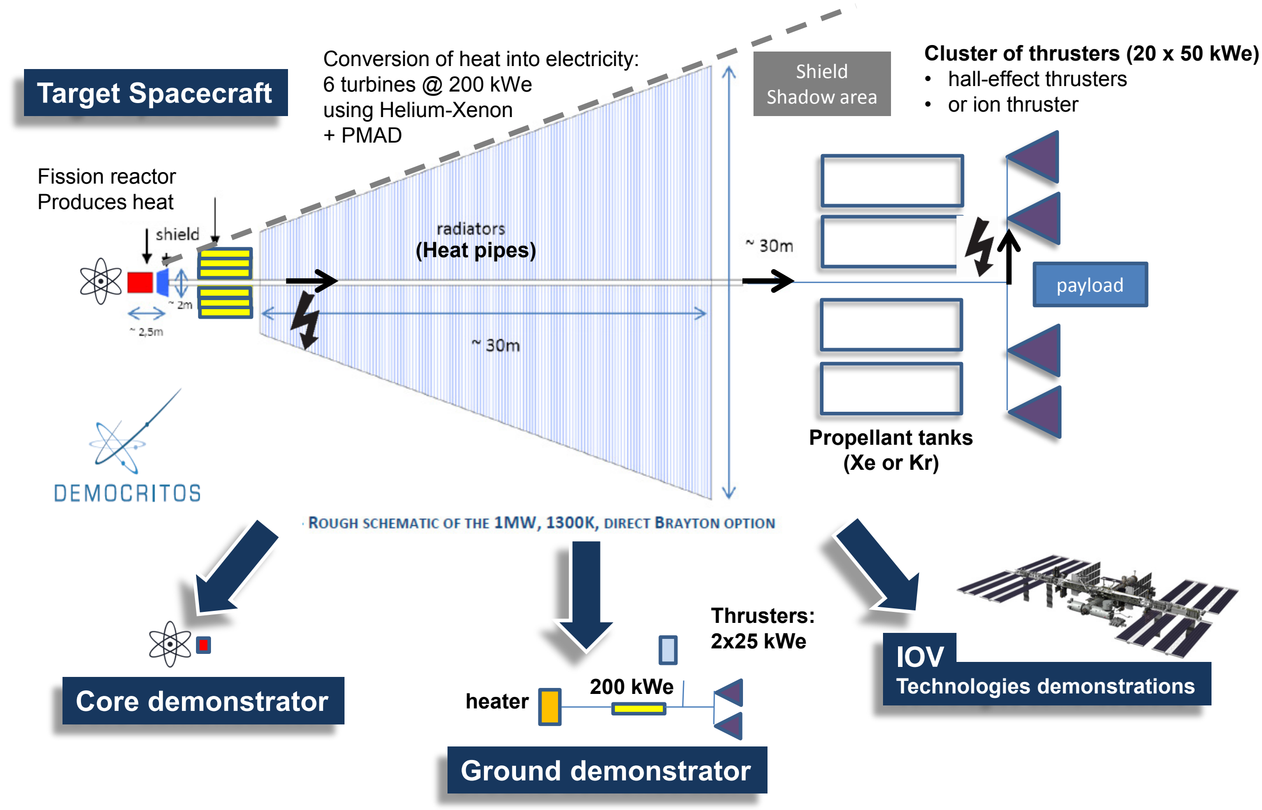

Figure 1: Spacecraft principle scheme (by courtesy of CNES).

One of these concepts is a ground demonstrator (GD), which includes the conversion, thermal management, power management and distribution and electric propulsion subsystems [4]. The main aim is to test the whole system end-to-end, in the most representative environment possible, with the clustered electrical thrusters linked to the electrical power generation. In the GD the nuclear core is replaced by a representative heater. The idea is to have a Core

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Demonstrator in parallel, in order to test everything related to the nuclear core. In-Orbit Demonstration / in-orbit Validation (IOD/IOV) of INPPS key technologies is foreseen after successful ground testing.

2. Ground Demonstrator components description

Generally, while performing ground tests of space technology prototypes, conditions of their operation in space (vacuum, temperature range, zero-gravity, cosmic radiation etc.) must be taken into account. However, there is no need of full simulation of all listed conditions for demonstration of these technologies. It is advisable to simulate only those conditions, which are of crucial importance for the provision of the operation of GD components.
The creation of the test bench on a basis of a huge vacuum chamber and placement of all GD components therein may be inexpedient due to large financial expenditures. Also this variant of the placement would require an arrangement of individual zones in the vacuum chamber for the testing of various Ground Demonstrator components, e.g. a zone for the testing of high-speed units must be separated from other zones to exclude the action of thermal radiation on other components (EP, radiator and others).
Therefore, the Demonstrator tests are proposed to be conducted with help of the test bench, consisting of several testing areas. Though, all GD components should remain linked together as much as possible.
1. The power conversion loop testing area (turbine, compressor, alternator, heat-exchangers etc.).
2. The electric propulsion (EP) testing area.
3. The power management and distribution (PMAD) system testing area.
4. The radiator testing area.

2.1 Turbomachine Unit

View of the turbomachine unit (TU) model (developed by ASL) is given in the figure 2.
Its main function is to convert heat coming from the test bench heater (650 kWth) into electrical power (200 kWe).
Sub-components are compressor, turbine and 2 alternators.
Overall dimensions are 1.2m×0.7m×0.7m.
The loop fluid: A gaseous mixture of He (36%) and Xe (64%). Inlet condition (hot side): P=13.7 bar, T=1300K.

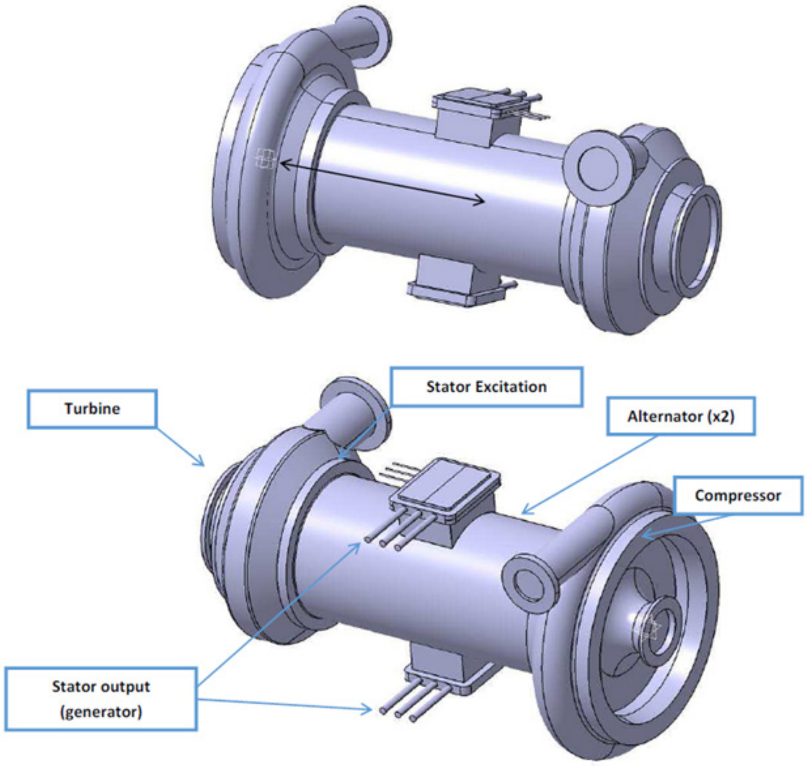

Figure 2: Turbomachine unit model (by courtesy of ASL).

Following configuration of the turbomachine unit the choice was made of a centrifugal compressor and an axial turbine. Alternator technology is based on «flux switch machine» architecture. For the purposes of a 200 kWe turbo-alternator, an axial turbine was designed. The reference conditions are given in Table 3. In order to estimate a first diameter of the rotor, a design rotational speed about 16000 rpm is selected. With a pressure ratio about 2, a single

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stage subsonic turbine is foreseen. As a high efficiency is required, a shrouded disk is requested and an additional outlet guide vanes is mandatory. Conversion loop main parameters are given in Table 1.

Table 1: Conversion loop parameters

Turbomachine part	**Compressor**	**Turbine**
Inlet pressure, bar	7.0	13,7
Inlet temperature, K	440	1300
Outlet pressure, bar	14	7,1
Outlet temperature, K	631	1041
Mass flow, kg/s	9,03	9,03

2.2 Radiator section

TAS-I experts proposed a two-stage radiator approach. The first stage is a high temperature radiator, with liquid metal or halide, and the second stage is water. The two-stage approach is necessary, as there is no single fluid able to function in heat pipes, with a given wide range of temperature. On the side of the conversion loop, between the inlet and outlet, the temperature decreases steadily from 643K down to 440K. On the side of the heat pipes, there is also a temperature gradient between inlet and outlet. The first heat pipe will "see" 593K, the last heat pipe will "see" 390K (see figure 3).

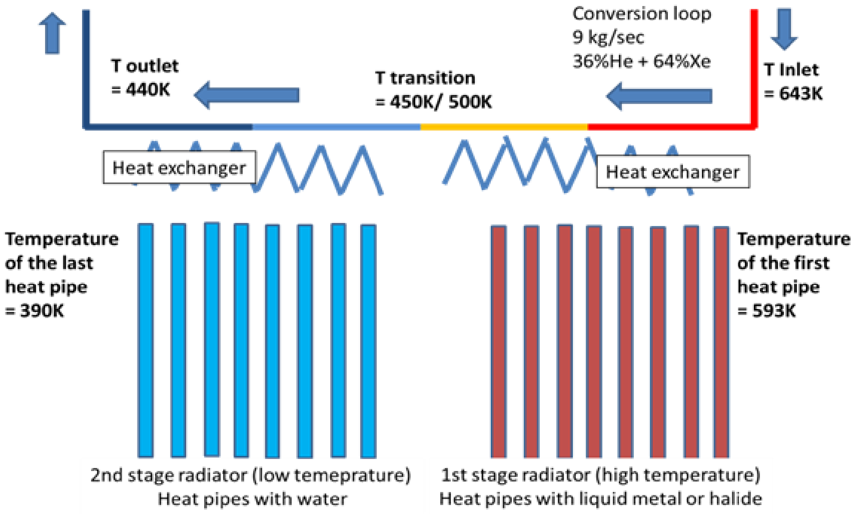

Figure 3: Two stage radiator scheme (by courtesy of TAS-I).

In the frames of ground demonstration much smaller radiators will be tested. The target is to test radiators of a surface between 1 and 3 square meters (1m x 1,5m, see figure 4).
Sub-components: Several heat pipes (probably 20), and a heat exchanger to link the heat pipes and the heat source (hot gas or electrical heater).

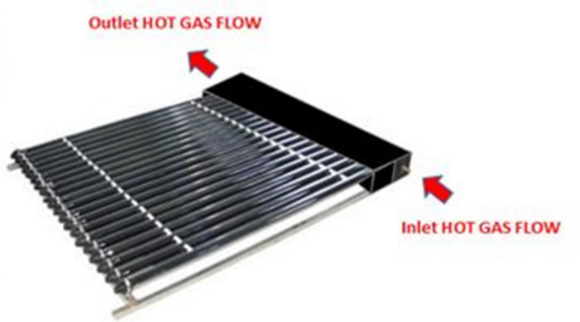

Figure 4: View of radiator section (by courtesy of TAS-I).

Fluids: There will be two kinds of radiator: a high temperature radiator, with heat pipes containing liquid metal that could be Halide (for example: TiBr4, AlBr3, SbBR3). The walls of the heat pipe could be made of Titanium or Superalloys. A low temperature radiator functions with heat pipes containing water.

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There is a second radiator in a separated test area. The objective of testing this radiator is to check whether it is able to reject the heat it contains into space, and this with correct efficiency and reaction time.
There would be two kind of tests:

- to test the heat collection capability: it is decided to test a small radiator coupled to the conversion loop, without necessarily being in vacuum conditions. Radiator would be coupled with a cold sink that would substitute the vacuum chamber and its shrouds. This radiator would be a water HP radiator section and it will be placed at the primary loop testing area nearby the vacuum chamber (see the paper subsection 3.2).
- to test the heat rejection capability, it is decided to test in parallel a small radiator standalone inside a vacuum chamber (see the paper subsection 3.3). There is no risk of bad interaction with the conversion loop and it is possible to choose the temperature that the radiator will "see". Therefore, both types of radiators will be tested: a liquid metal heat pipe radiator, and a water heat pipe radiator.

2.3 Power Management and Distribution

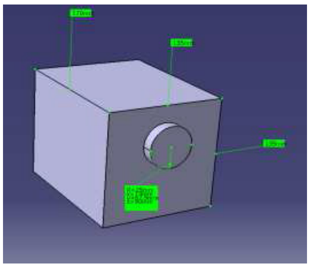
PMAD (developed by Safran Electronics & Defence) main functions are:

- Convert alternative current generated by the alternator to direct current;
- Deliver direct current to the electrical propulsion as well as to other electrical systems of the spaceship;
- Adapt power level to actual need;
- Deliver alternative current to the alternator in order to start it.

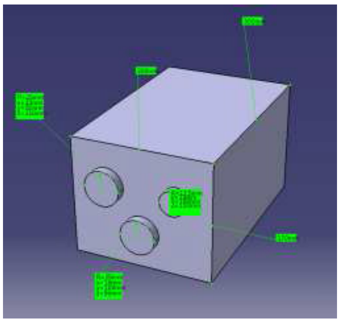
For GD, PMAD baseline architecture will be kept, with some modifications to take into account GD specificities:

- Single PMAD chain consisting of 5 units (see figure 5), sized for maximum power of 200 kW,
- Capability to transform into 540VDC, HVAC power delivered:
  a) Either by DEMOCRITOS electrical generator,
  b) Or by an external HVAC generator;
- Capability to distribute the available 540VDC power to 3 external loads:
  a) Either an Hall Effect Thruster cluster (maximum 70 kW under 540 VDC),
  b) Or a Grid Ion Thruster cluster (maximum 70 kW under 4500 VDC),
  c) And the balance of the available power being consumed by the Electrical Load System (ELS);
- Capability to trigger a manual emergency shutdown in case of failure of the PMAD control function.

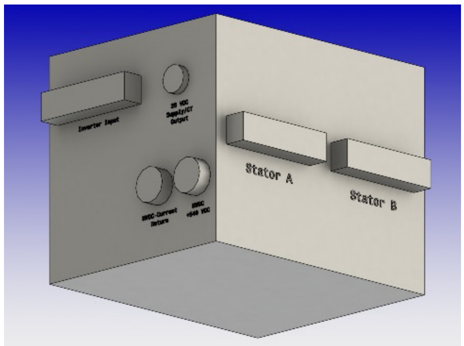
Control unit



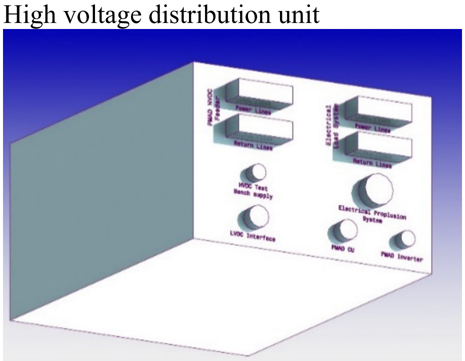
Inverter unit



Rectifier unit



High voltage distribution unit



Low voltage distribution unit

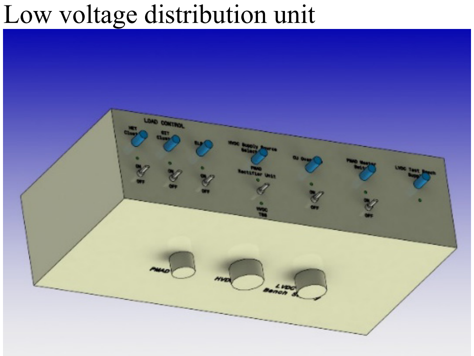


Figure 5: View of PMAD units (by courtesy of Safran Electronics & Defence).

PMAD units will be placed at the primary loop testing area nearby the vacuum chamber flange with TU cables outlet (see the paper subsection 3.2).

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Three test configurations (TC) are considered for ground demonstration:
TC 1 Alternator – PMAD integration.
TC 2 PMAD – Electrical Propulsion (EP) integration.
TC 3 Full integration: Alternator – PMAD – EP.
Whenever the Alternator is part of the TC, 2 main sub-phases are defined: Start phase and power supplying phase.

2.4 Electric Propulsion

The function of the electric propulsion is to produce thrust and to propel the spacecraft. For the Ground Demonstrator a cluster of two 25 kW electrical thrusters is proposed (see figure 6). Each thruster will have its own Power Processing Unit (PPU) and its own Propellant Management System (PMS). The cluster will be inside the test bench, and will need vacuum to operate properly.
A simulator of cluster of electrical thrusters, part of the test bench, able to work at 150 kWe in continuous mode. The test bench will be able to accommodate the two following types of electrical thrusters:

- Hall effect thruster (PPS20k from Snecma) (details in [5]);
- Grid ion thrusters (IT-500 from Keldysh) (details in [6,7]).

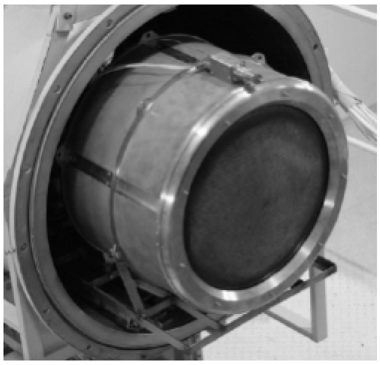

Figure 6: PPS20k (to the left, by courtesy of Snecma) and IT-500 (to the right) thrusters

Table 2: Electric propulsion thrusters and their parameters

Type of thruster	**PPS20k**	**IT-500**
Power, kW	20-35	20-35
Thrust, N	1 (design)	0,4 – 0,75
I_{sp}, sec	2500	7000
Main voltage	300-700	4500

Cluster overall dimensions: 1.5m ×1.5m × 0.5m.
Mass (for the clusters of thrusters): inferior to 250 kg.
Operating Propellant: Xenon and Krypton (Argon and Iodine tbd).
Two PPS20k cluster scheme and model (developed by CNES) are presented in the figures 7 and 8.

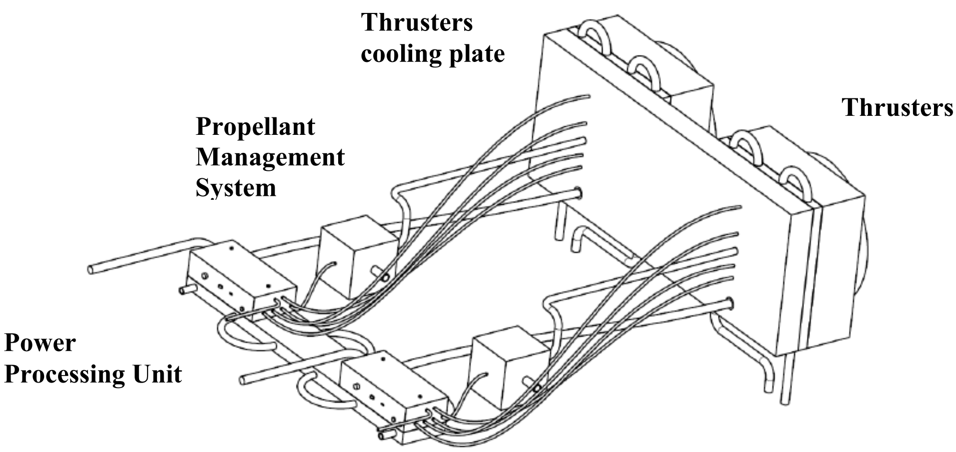

Figure 7: Scheme of cluster based on two PPS20k (by courtesy of CNES)

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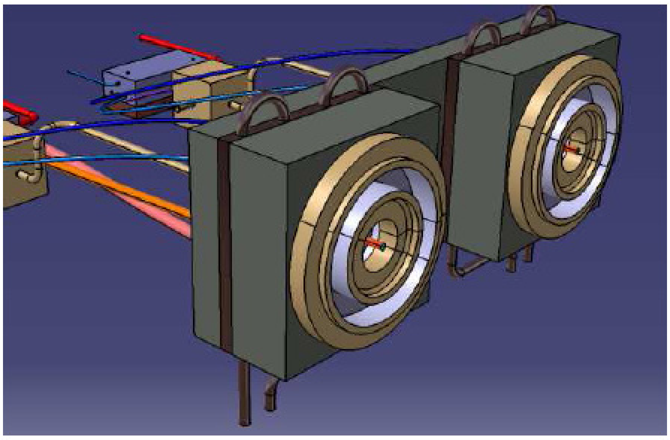

Figure 8: Model of cluster based on two PPS20k (by courtesy of CNES)

3. Ground Demonstrator Test Bench description

A plan of the GD test bench is given in the figure 9.

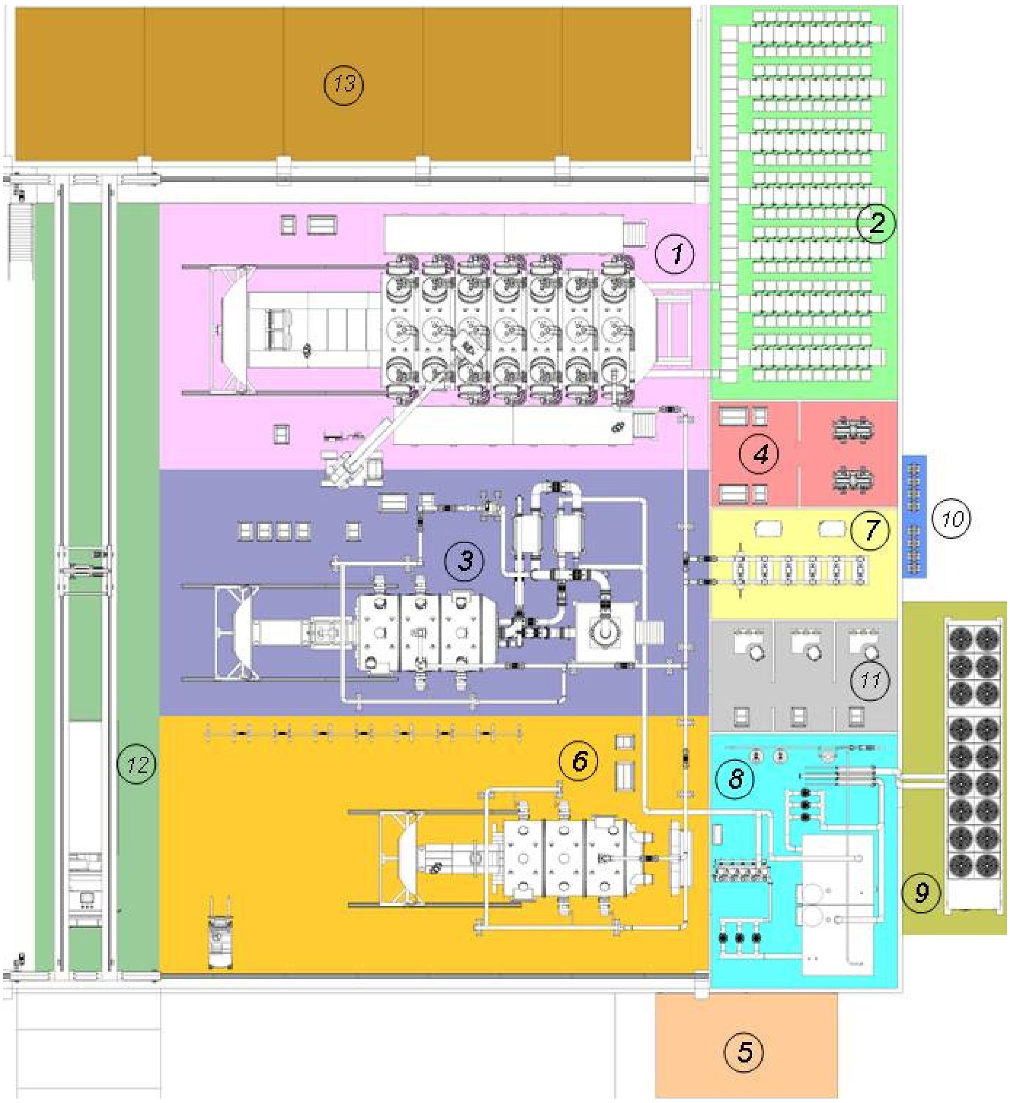

Figure 9: GD test bench plan

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By convention, production rooms can be separated into 13 areas. The main testing areas are as follows: 1 – the electric propulsion testing area, 3 – the primary loop testing area and 6 – the radiator testing area. The other areas are auxiliary and intended to carry technological and engineering equipment:

2 – The cryogenic pumps compressors testing area
4 – The GRH power supply and control system testing area.
5 – The parasitic load fuel element testing area.
7 – The forevacuum station area
8 – The recycling water supply and treatment system testing area.
9 – The recycling water supply cooling system area.
10 – The high pressure gas ramp area.
11 – The control desk room area.
12 – The handling area.
13 – The office rooms.

The 3-D view of the test bench is given in Figure 10. The area of the test bench (excluding the office rooms' area) makes up ~1400 m^2.

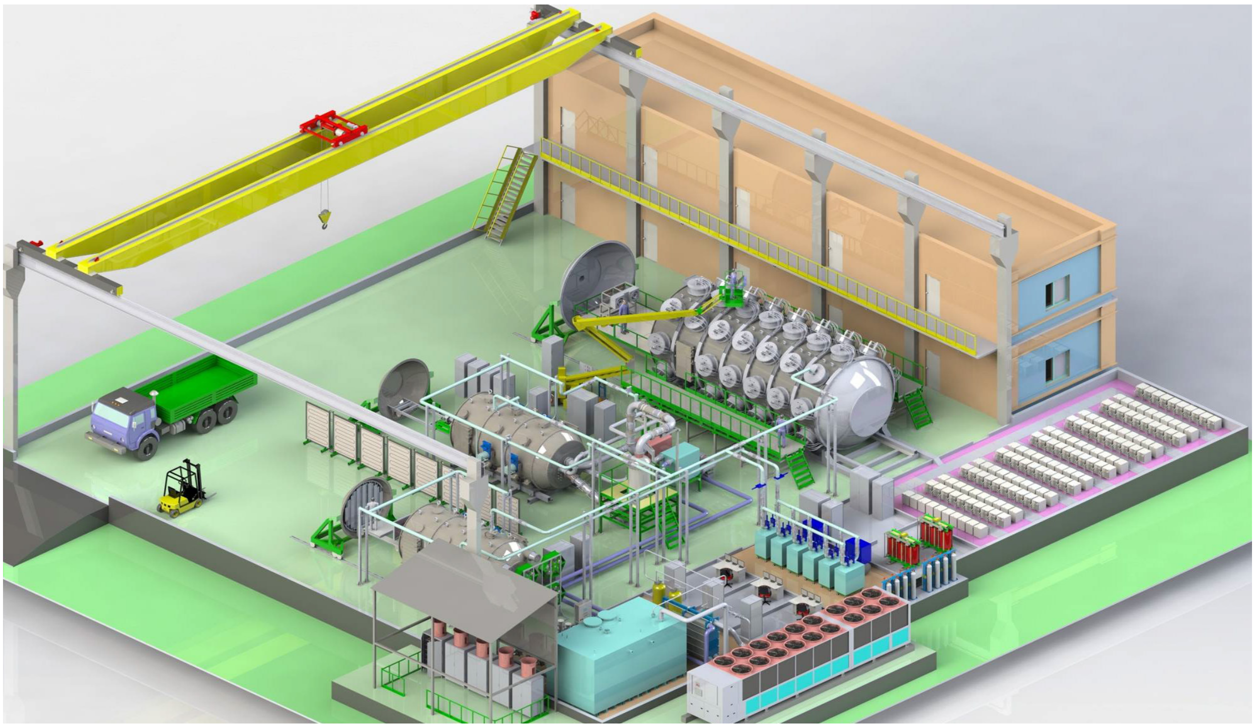

Figure 10: Test bench 3D view.

3.1 Electric Propulsion testing area

Plan of the EP testing area is presented in Figure 11. The area is composed of: 1 – the vacuum chamber, 2 – the loading system with the rolling cover and the interior technological service platform, 3 – the cryogenic pumps, 4 – the forevacuum pump pipe line, 5 – the exterior technological service platforms, 6- the EP, 7 – the EP propellant feed system, 8 – the EP power sources, 9 – the control system elements.

The vacuum chamber is comprised of several sections and two covers and it has the following overall dimensions: the diameter ~4.5 m, the length ~ 13 m. There are two flanges. One of them is fixed, while the other one is combined with the system of EP loading into the chamber and the interior technological service platforms. The closing and the opening of the chamber are made according to the kinematic scheme shown in the figure 12. In so doing, the driving wheel pair of the loading system moves on the track guides installed in the testing area floor, the driven pair – on the guides positioned inside of the vacuum chamber.

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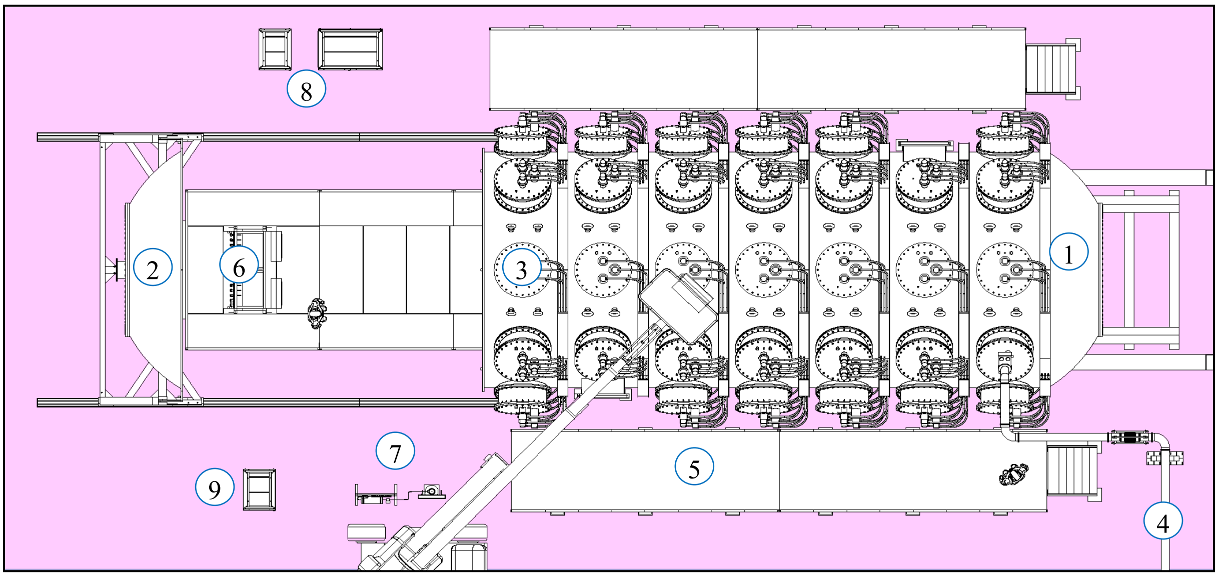

Figure 11: Plan of EP testing area.

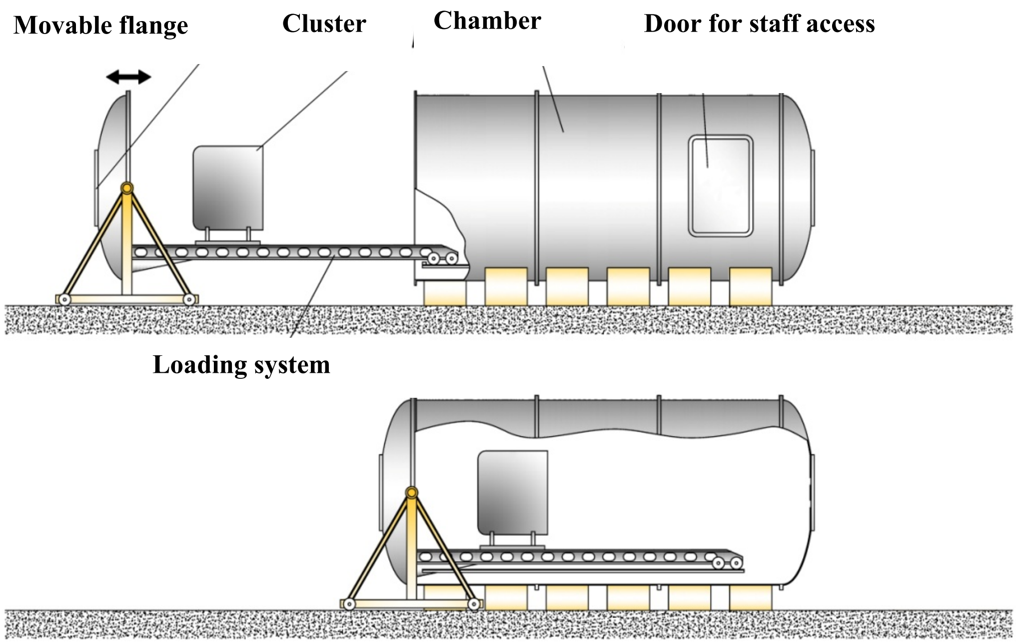

Figure 12: The kinematic scheme of the EP loading system.

3.2 Primary Loop testing area

Plan and model of the primary loop testing area are given in Figures 13 and 14, respectively. The primary loop testing area consists of: 1- the vacuum chamber, 2 – the loading system with the rolling cover, 3 – the turbomolecular pump with the vacuum seal, 4 – the forevacuum pumping manifold, 5 – Turbomachine, 6 – the gas resistance heater (GRH) (see figure 14), 7 – the heat- exchanger recuperator, 8 – the heat- exchanger cooler, 9 – the cooling water supply/discharge to the heat- exchanger cooler, 10 – the shut-off valve to cut off the vacuum manifold from the primary loop, 11 – control system elements, 12 – PMAD elements,13 – primary loop pipes.

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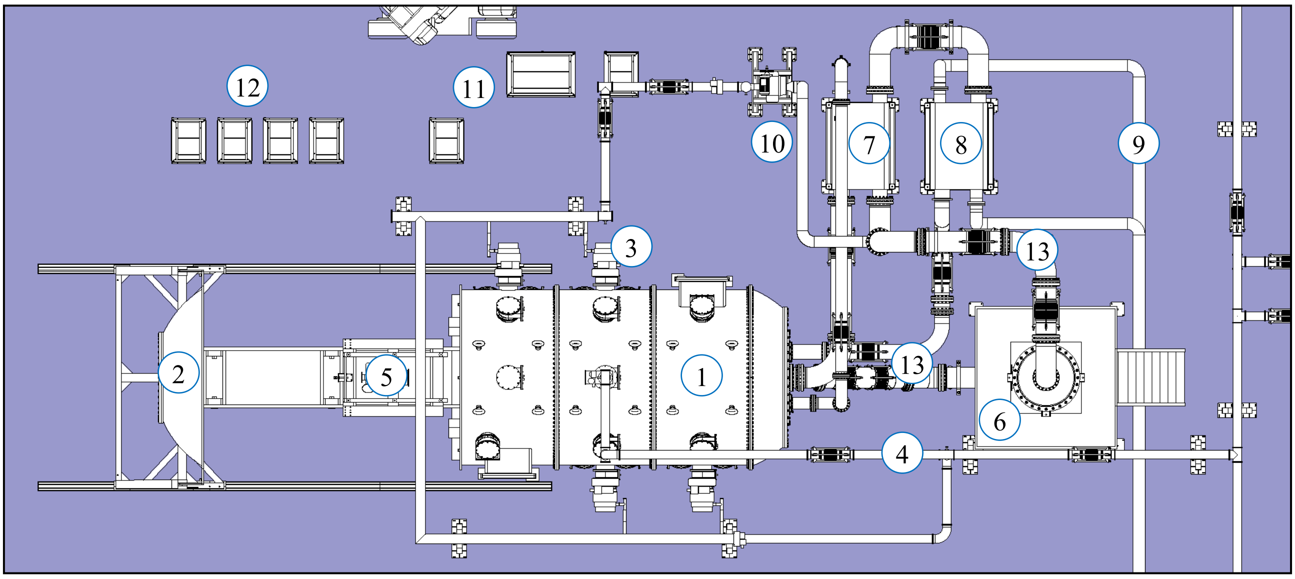

Figure 13: Plan of Primary loop testing area.

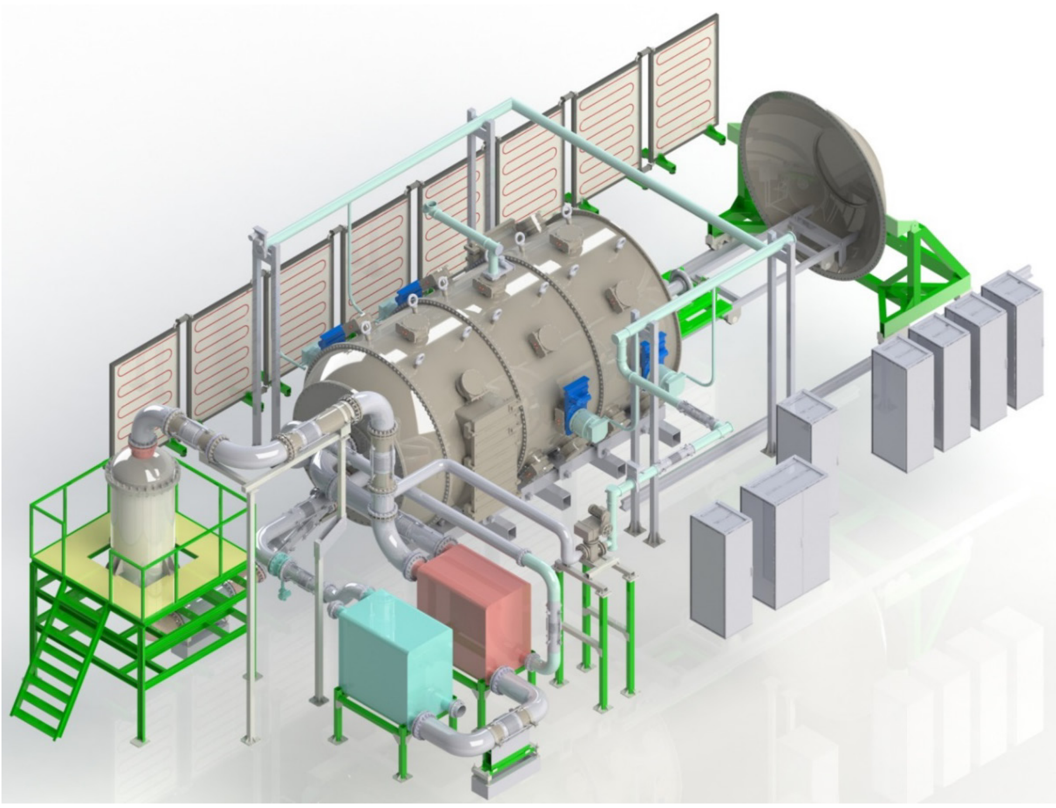

Figure 14: Model of Primary loop testing area.

The vacuum chamber consists of sections and flanges and has the following overall dimensions: diameter ~3 m; length ~ 5.5 m. Similarly to the chamber for EP testing, one flange is fixed and the other one is combined with the system of turbomachine units loading. The closing and the opening of the chamber are made according to the same kinematic scheme as for EP chamber (see figure 12).
The vacuum chamber has the following interfaces:

– the gaseous ones, through which the pipes for supply and discharge of the working fluid to the turbine and the compressor, positioned off the vacuum chamber, are connected with the turbomachine unit (TU) relevant pipes, themselves positioned within the vacuum chamber;

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– the high-power electric ones, through which the alternator-generated power goes to PMAD and the electric power from the start support system goes to the alternator for driving the TU shaft in the “motor” mode;

– the measuring ones, through which signals from TU transducers are transmitted to the bench control system;

– the hydraulic ones, through which the heat carriers are supplied and removed for TU parts cooling (if needed).

The vacuum chamber should be water cooled to remove heat power radiated by the TU surface and the pipes. Both the chamber sections, and the chamber flanges have to be cooled. The chamber should also have doors for the personnel access to the chamber for preparation to the TU testing after its loading to the chamber.

The scheme and photo of KeRC gas resistance heater [8,9] (simulating nuclear core) are given in Figure 15.

The heater functional parts are as follows:

1 – Cooled pressure-tight three lead-in wires (with powering the heater from three-phase supply); 2 and 9 – branch pipes for the inlet and the outlet of heated gas; 3, 5 and 13 – housings with water-cooling channels; 4 and 12 – the outer pressure-tight case, consisting of the cylindrical section and two ellipsoid-shaped covers; 6 and 8 – untight inner screens; 7 – the heat-insulation material layer; 10 – the inner cavity destined for gas heating; 11 – holes of the load-carrying flanges; 14 – untight tubes; 15 – electric buses.

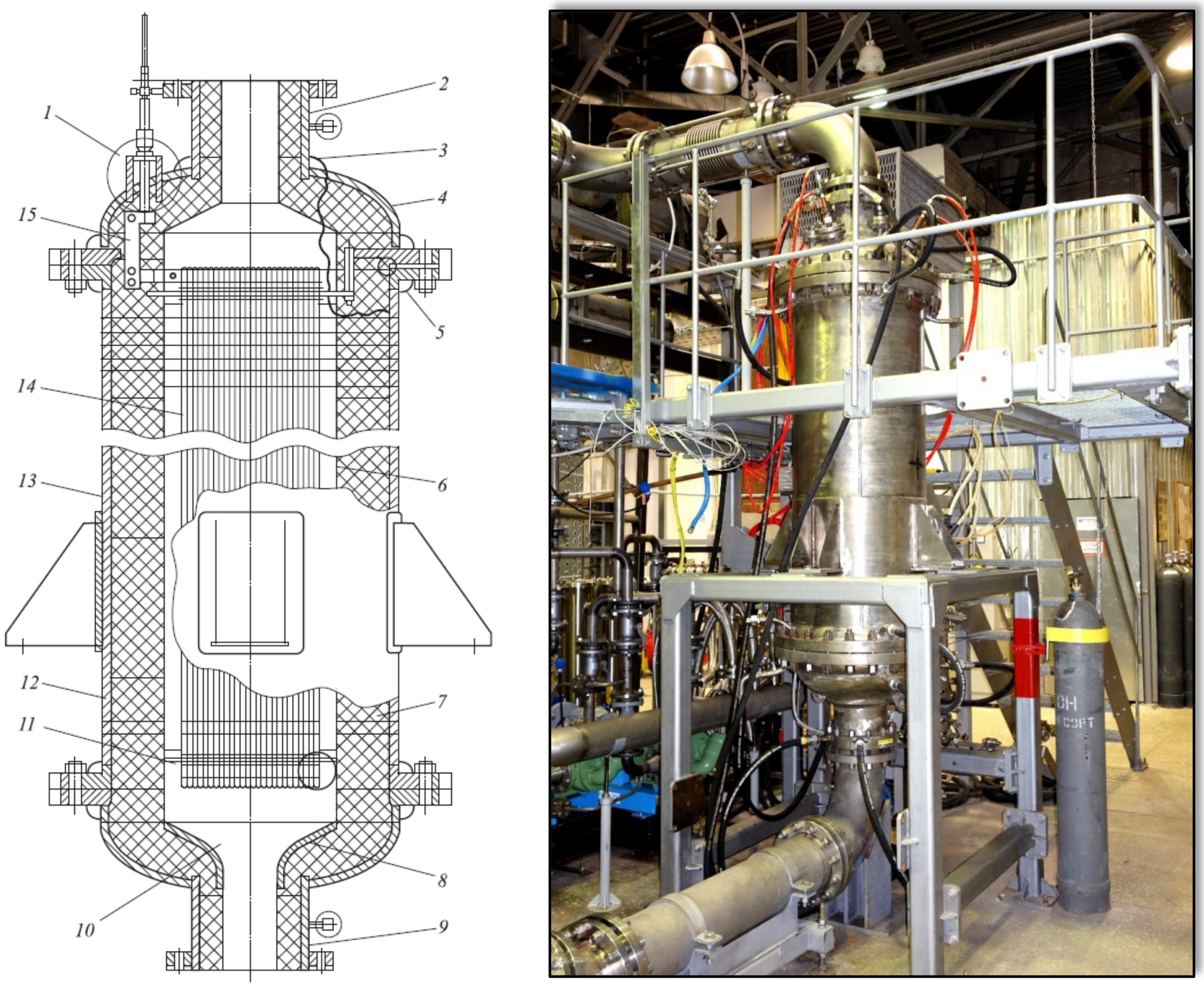

Figure 15: Scheme and photo of KeRC GRH.

3.3 Radiator section testing area

The radiator testing area is shown in Figure 16. It consists of: 1 – the vacuum chamber, 2 – the loading system with the rolling cover, 3 – the turbomolecular pump with the vacuum seal, 4 – the forevacuum manifold, 5 – the radiator panel, 6 – the optical input, 7 – the solar simulator, 8 – elements of solar simulator power supply and control system, 9 – the radiator panel assembly.

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The vacuum chamber design resembles that of the vacuum chamber for primary loop testing and consists of sections and covers and has the characteristic dimensions: the diameter ~3 m and the length ~5.5 m. The closing and the opening of the chamber are made according to the same kinematic scheme as for EP chamber (see Figure 12).

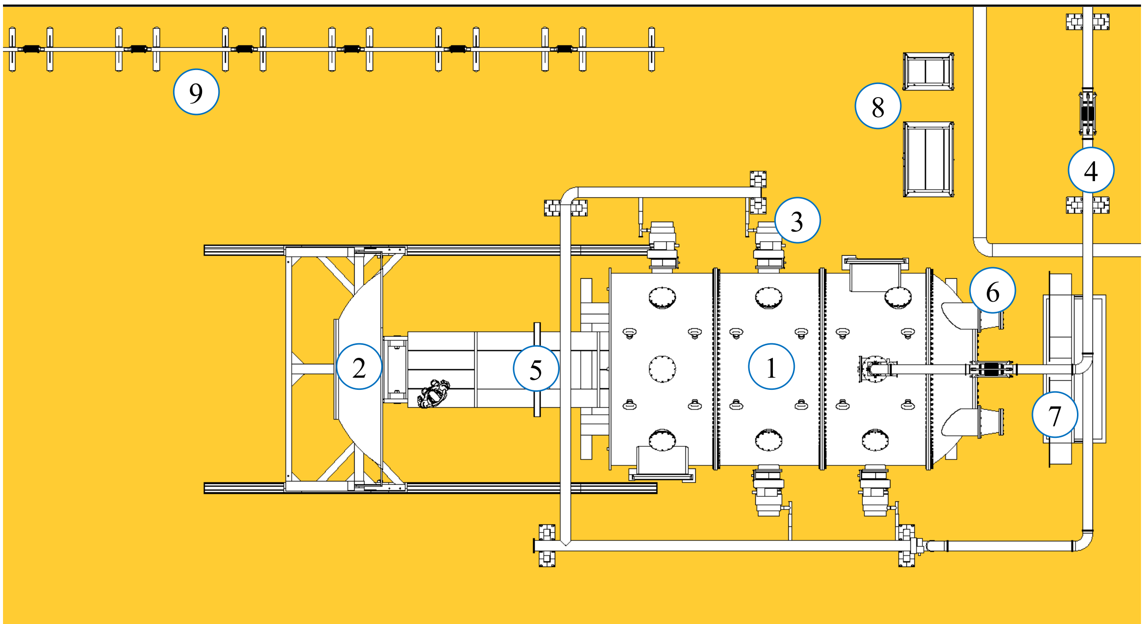

Figure 16: Plan of Radiator testing area.

Unlike the vacuum chamber for primary loop testing, this chamber is equipped with a supplementary cylindrical shield cooled down to cryogenic temperatures. Liquid nitrogen can be used as a cooling agent. The flanges are also fitted to the cryogenic shields. The chamber is equipped with the four optical inputs for projection of luminous flux on a mirror system installed inside the chamber. The luminous flux is supplied by a four groups of lamps of the solar simulator mounted in the immediate vicinity of the chamber fixed flange. This design of the solar simulator is analogous to constructions used in existing benches [10].

4. Conclusion

The preliminary design of the test bench for the Ground Demonstrator (GD) testing in all modes and range of characteristics is described in this paper. As of today, there is no existing test bench in the world capable of testing the GD as a whole system. KeRC has test facilities with capabilities that are close to the required ones. If the KeRC test bench is to be modified in a proper way, the GD could then be tested, albeit with some limitations. European partners could also optimize GD components design and characteristics to facilitate their testing at KeRC. Since new test bench development would be quite expensive in comparison with existing facility modification and GD components design optimization, it is proposed to use the current KeRC test facility for GD testing.
The follow on of the international cooperation will enable the development and testing of the ground demonstrators at the subsystem and system levels. Successful ground demonstration will be the key towards the realization of new ambitious international space missions.
Besides the space demonstrator, international activity has already started. The preliminary design (phase 0) for a 1MW class NEP enabled spacecraft for missions to Europa and Mars was produced by DEMOCRITOS consortium partners with the participation of NASA and JAXA specialists during a Concurrent Engineering study workshop organized by DLR Institute of Space Systems at Bremen in September 2016 [11].
The participants of the workshop expressed their strong opinion that nuclear power in space will be indispensable to reach the next level of solar system exploration. Taking into account the financial, technological and programmatic challenges related to missions using nuclear electric power systems to the Europa moon and Mars the experts believe that such missions could only be done with a concerted effort of several interested space powers (as it was the case for the International Space Station).
In accordance with the United Nations Committee for the Peaceful Uses of Outer Space (COPUOS) regulations [12,13], the transport, launch and operations of nuclear systems in space have to be safe and not cause any danger to life on Earth.

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