2015 International Nuclear Atlantic Conference - INAC 2015
São Paulo, SP, Brazil, October 4-9, 2015
ASSOCIAÇÃO BRASILEIRA DE ENERGIA NUCLEAR - ABEN
ISBN: 978-85-99141-06-9

TECHNOLOGY DEVELOPMENT FOR NUCLEAR POWER GENERATION FOR SPACE APPLICATION

Lamartine N. F. Guimaraes[1,2,3], Guilherme B. Ribeiro[1], Francisco A. Braz Filho[1], Jamil A. Nascimento[1], Guilherme M. Placco[1,2] and Saulo M. de Faria[2]

[1] Divisão de Energia Nuclear
Instituto de Estudos Avançados
Trv. Cel. Av. José Alberto Albano do Amarante, no. 1
12228-001 São José dos Campos, SP
guimarae@ieav.cta.br
Lamartine.guimaraes@pq.cnpq.br

[2] Instituto Tecnológico de Aeronáutica (ITA)
Praça Marechal-do-Ar Eduardo Gomes, 50
12228-900 São José dos Campos, SP, Brasil

[3] FATESF/UNIESP
Av. Siqueira Campos, 1174
Jacareí - SP 12.307-000

ABSTRACT

For a few years now, the TERRA project is developing several technology pieces to foster nuclear space applications. In this way, a nuclear reactor concept has been developed as a first proposal. Together, the problem of heat to electricity conversion has been addressed. A closed Brayton cycle is being built and a Stirling machine is being worked out and perfected. In addition, two types of heat pipes are being look at. One related with high temperature made of Mo13Re, an especial alloy. And a second one made of copper, which mainly could be used as a passive heat rejection. In this way, all major areas of interest in a micro station to be used in space has been addressed. A new passive technology has been inferred and is related with Tesla turbine or its evolution, known as multi fluid passive turbine. This technology has the potential to either: improve the Brayton cycle or its efficiency. In this paper, some details are discussed and some will be shown during the presentation, as the work evolve.

1. INTRODUCTION

For years now, the TERRA project [1,2,3,4] aims to develop technology pieces to foster nuclear space applications to fulfill Brazilian future interests and demands. The name TERRA is an acronym that, in Portuguese, means advanced fast reactor technology ("TEcnologia de Reatores Rápidos Avançados"). The TERRA Project has as a general objective, the development of critical technologies to generate electric energy to be used in difficult access environments, such as space and isolated regions, by means of nuclear power and high efficiency and reliable thermoelectric converters. The main lines of interest for the TERRA project are innovative fuel elements and reactor core concepts [5,6,7,8,19], heat to electricity conversion by means of thermo-cycles [3,4,8,9,10,19], core heat extraction and excess heat rejection by passive means [11,12,13,14] and innovative technologies, as for instance, the

Tesla turbine [18]. The objective of this contribution is to describe and discuss briefly the status of the development for each line and the next step.

2. TERRA PROJECT - FIRST FUEL ELEMENT AND CORE CONCEPTS

This section provides a general description of the first nuclear fuel element and reactor core developed. The Fig. 1 presents that concept, where the yellow dots represent high temperature heat pipes (made of Mo13Re) that conduct the nuclear heat to the Brayton cycle for electric generation. The red region is nuclear fuel, which consists of uranium nitride microspheres distributed in a lead medium. This mixture is set inside a hexagonal canisters, which walls are made of Mo13Re. The canister wall to wall distance is 12 cm, three hexagonal canisters are 36 cm wide, and its height is 37 cm. The blue circles are control barrels. The brown arch is a neutron reflector material. The barrel rotates around its axis, controlling the neutron population and the power, by allowing them to leak out of the system. This is still a rough neutronic concept, but a lot of calculation and developing effort were put into it. This concept requires refining and that means a new round of calculations.

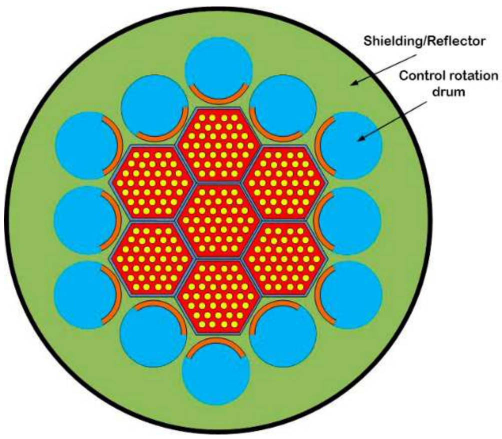


Figure 1: Core concept proposed for the space nuclear microreactor.

Fig. 2 shows an axial cut of one of the 7 canisters, it is important to observe that Mo13Re is used for structure definition and hold materials such as shielding (B4C) and reflector (BeO). Also, a gap is left empty to collect the gaseous fission products, this gap is called expansion chamber. All these material distribution plus thermal conditions such as heat pipe operating temperature of 1400 K, power transfer per heat pipe of about less than 5 kW, heat pipes made of Mo13Re and operating with Li. After an extensive neutronic calculations, the arrangement and measures for this conceptual fuel element and reactor core are obtained. Obviously, a second round of calculations must be performed including, for instance, the thermo-hydraulic effects for this configuration. Another consideration, and requirement, is a better Knowledge with the properties of the alloy Mo13Re. These are the next steps. Nevertheless, the (first) concept for fuel element and micro-reactor core are considered finalized. But it is clear that the work performed so far points the development to a promising direction.

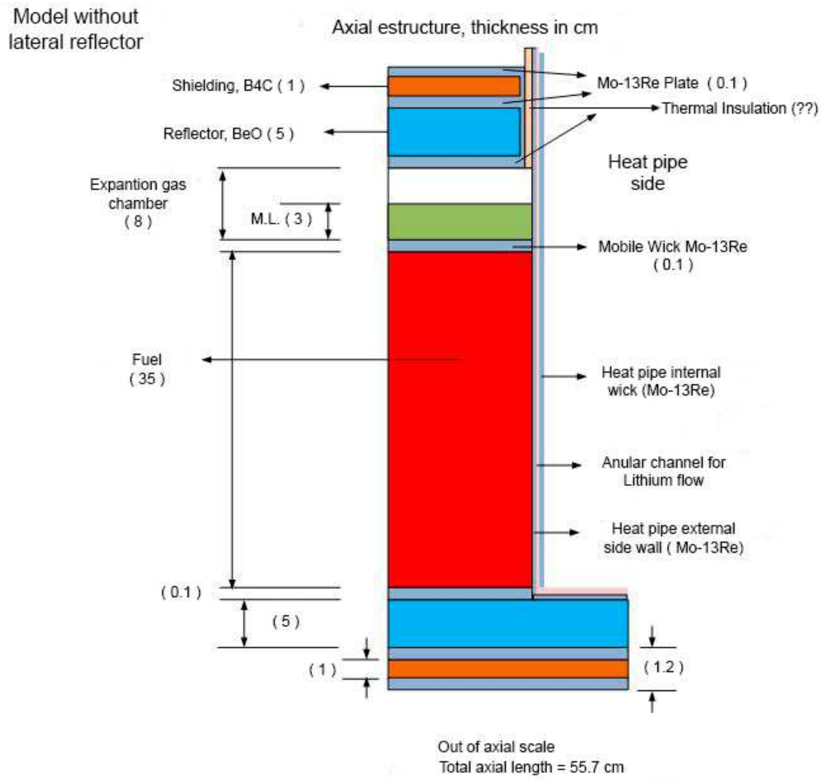


Figure 2: Core concept proposed for the space nuclear microreactor.

3. BRAYTON CYCLE AS A HEAT TO ELECTRICITY CONVERTER

Several studies [8,16] suggest that closed Brayton cycles are very interesting heat to electricity converter for space nuclear micro-power plants that operates in the range of hundreds of kW up to a few MW. This range of power is exactly where a Nuclear Electric Propulsion (NEP) system operates. This is what the TERRA project is interested. In this way, a closed Brayton cycle is being built at the "*Instituto de Estudos Avançados – IEAv.*" Fig. 3 presents a schematic for the proposed closed Brayton cycle. Steady state values for temperatures, pressures and flow are presented. The closed Brayton cycle was designed based on the existence of the micro turbine NOELLE 60290. Based on the operation manual the maximum power delivered by the turbine is 27 kW and for a low efficiency Brayton cycle, around 9%, helped to define the maximum furnace thermal power at 300 kW. In addition, the specification of the turbine temperature operation of 650 ^{o}C, helped to define the maximum furnace temperature of 750 ^{o}C. This limit is also desirable because of the highest temperature supported by the SS-316L, which is the material used to build the hot source heat exchanger that is located inside the furnace. With the stablished boundary conditions, the heat sink load is calculated. A MATLAB program was produced with this procedure and helped to stablished the size of the heat sink heat exchanger.

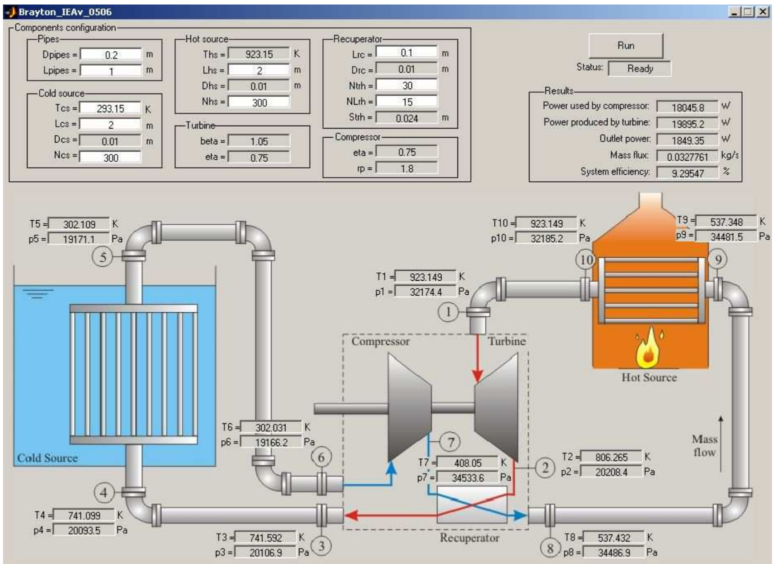


Figure 3: Closed Brayton cycle, schematic view with temperature, pressure and flow steady state values.

Fig. 4 shows how the closed Brayton cycle will be once it is built. At this time, the heat sink and its support is being built, the acquisition process for the temperature, pressure and flow sensors is on the way and a bid for a detailed design for an electric heat furnace is also set. It is important to say that initially a gas furnace was considered. A detailed design for the gas furnace was obtained, but it prove very difficult and incompatible with our acquisition process to procure that type of furnace. The predicted first operation of the Brayton cycle is 2018. This Brayton cycle will be a tool to help improve its design, to learn about control strategies, to test other working fluids, and test the heat pipe produced at IEAv.

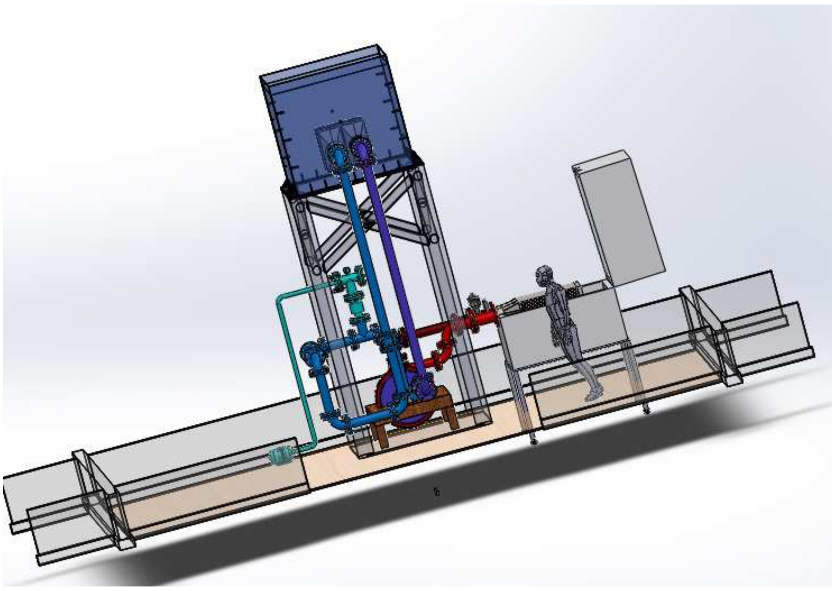


Figure 4: Closed Brayton cycle, how it is going to be built.

4. STIRLING MACHINES AS AN OPTION FOR LOW POWER NUCLEAR SPACE SYSTEMS

The Stirling machine is considered to be the choice option for low power nuclear systems [9,10,11,12,13,14], either fission or radioactive decay based systems. By low power nuclear systems it is understood those generating thermal power in the range of hundreds watts to hundreds of kW. This is the case of the Radioisotope Thermal Generator - RTGs problems with the Pu238 shortage [15], that is driving the development of Advanced Stirling Thermal Generator - ASTG [16,17] or the development of fission power systems to reach the upper boundary of the previous range [11]. Fig. 5 shows the parts of a Stirling machine built at IEAv. This machine is a free piston type. Unfortunately, the power piston was built with a flaw. It did not fit tight; therefore, it was not generating power. This problem is being worked out. Together with this, an induction linear generator is being designed to be coupled with this Stirling machine. This induction linear generator is based on samarium-cobalt (Sm-Co) magnets. It is expected that this system be operational by the end of the year. A demonstration movie will be made of this coupled system by the time of the presentation of this paper.

Figure 5: Stirling machine built at IEAv.

5. HEAT PIPE DEVELOPMENT AND BUILDING

Heat pipes are considered part of the TERRA project in one of two possibilities. The first possibility is to extract heat from the reactor core. The extracted heat will be directed to the thermal cycle, assumed a closed Brayton cycle. The second possibility is to use heat pipes to dissipate the residual heat not used by a thermal cycle, in other words, be the heat sink. In the first hole, to extract heat from the reactor core, the heat pipe must be a high temperature one. In other words, it must stand temperatures around 1400 K, and operates on this level of temperature. This limits the choices of the alloy for the heat pipe metal tube. The TERRA choice is Mo13Re. In addition, it requires a proper working fluid. In this case, the choices are Na, NaK, Li and Ta [20]. In spite of the fact that Ta presents very interesting thermal properties, it creates a serious handling problem due to its highly toxic nature. The others present more manageable handling. Therefore, experimentation choices are heading towards those. A few pipes of Mo13Re were acquired for these tests.

In the second role, heat pipes are used as a passive heat sink. In this way, the heat pipes are made of copper, with copper porous media and water as a working fluid. That is what is planned for most concepts [1,8,19]. Recently, the usage of the copper heat pipe has been expanded [10,11,12,13,14]. In this case, copper heat pipes started to be considered as nuclear core heat extractor. It conducts heat from the nuclear core to a set of Stirling machines. The concept was proven right, and works for low power, as defined here, above.

Fig. 6 shows a concept of the workings of a general heat pipe. The yellow tube represents the metal pipe, the external arrows indicate the inlet and the outlet of heat from the pipe view point. The grey tick wall inside the pipe represents a porous media. The working fluid spreads inside this porous media. As the heat enters the pipe, the working fluid is vaporized and drives itself to the other extremity. Where it gives up its heat content and coalesce into a liquid inside the porous media. Capillarity pumping effect bring the liquid back to the hot extremity and the process starts again.

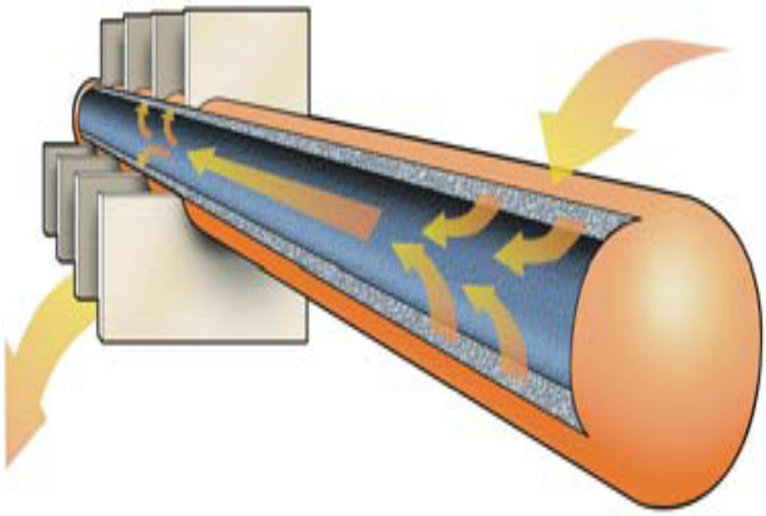
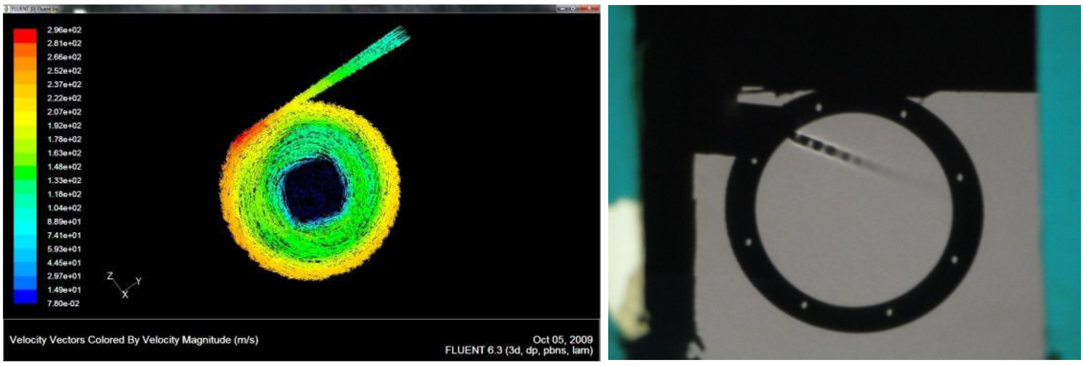


Figure 6: Heat pipe schematic.

6. TESLA AND PASSIVE MULTI FLUID TURBINE DEVELOPMENT

Nicola Tesla, a man that is more widely known for his inventions in electricity and magnetism than his works in fluid mechanics, invented the Tesla turbine. The Tesla turbine has discs instead of blades. The working fluid flows tangent to the discs and transfer momentum through the viscous forces. The discs are connected by its center to an axis, which turns as the discs turns. Fig. 7 presents an example on how this effect is achieved. In Fig. 7a presents a simulated velocity field for an air flow. In Fig. 7b, a photo of air wave front is presented. In this photo, the discs are removed from its place. The Tesla turbine is a very attractive technology to be applied in space. It adds a very little pressure drop to circuits, requires very little maintenance, and it may operate with any fluid. For the space application the use of this turbine may be performed in one of two ways: in series with an ordinary gas turbine in a Brayton cycle helping to increase its efficiency; and as a stand alone in a Brayton cycle. Whichever way, a lot needs to be done to characterize this type of turbine and understand its basic operation principles when related to other components in a closed cycle. The expectation is to have this fundamental work performed in time for the inauguration of the Closed Brayton Cycle, where these ideas may be tested as matter of fact. Meanwhile, three turbines were built at IEAv. Fig. 7b shows the shell of the second turbine. The first turbine was used for concept demonstration. The front and back walls were made of transparent polymer, which allows for the observation of its interior. This first turbine operates with air, at room temperature, and was able generate enough revolutions to generate 55 W and turn on a car head light bulb. The second turbine was made of stainless steel. It generated an excess of 65,000 rpm, and because it was made of metal it withstand temperature effects. It was run with room temperature air and saturated steam. The analysis of this turbine generates the thesis of Placco [18]. Some of the results of this work are presented in another contribution of this Meeting. Also, the workings of this second turbine inspired the building of the third turbine, which presents a new system to distribute flow through the discs inner spaces. This concept was tested with an open air circuit and works quite satisfactory. It was attempted to use the third turbine in a close steam cycle. But it leaked. It was concluded that this turbine was not prepared to operate in closed circuits. Nevertheless, the new distribution fluid flow system was worth a patent, which was deposited in 2013. Fig. 8 shows a Rankine cycle workbench built to produce vapor to test the turbine in a closed, heated cycle. Later, the third turbine was substituted by the second one, with which results were produced [18]. Nevertheless, the third turbine was used in an open loop experiment that, through the rotation control of the turbine and its electric power generation, turned on a sequence of LED bulb lights. Fig. 9 presents the setup of this experiment. It is important to mention that during the patent request preparation, it was realized that the new concept represented by the third turbine trigger a change of name. The new name is Passive Multi Fluid Turbine (PMFT). It is worth mention that along the development of this turbine, the unfortunate Fukushima accident happened. A very peculiar fact occurred along the whole trend of events during the accident and that was the availability of great amount of steam and no electricity generation. That is exactly a situation that may be easily handle by the PMFT. The PMFT is designed to remain in a passive state and may produce energy by simply passing steam through it. Placco, Guimaraes and dos Santos entertained this idea in [21]. This idea requires further study and development but looks promising.



(a) (b)

Figure 7: (a) Shows the velocity field flowing tangent to a disk. (b) Shows a photo of an air wave front as seen by shadow visualization technique.

Figure 8: Rankine work bench to test the Tesla turbine.

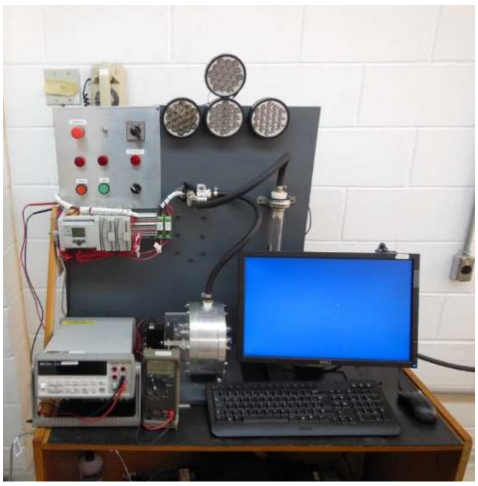


Figure 9: Test of the Passive Multi Fluid Turbine (an evolution of the Tesla turbine).

7. CONCLUSIONS

The first concept for nuclear fuel and reactor core is almost finalized. A final report is being prepared and more detailed info will be published elsewhere. The next steps involve identifying problems, refining the concept and including thermal hydraulic effects. The important issue at this point is that a first concept was produced, with that a scheme of codes was assembled and a specific nuclear data library was put together.

For the Brayton cycle there is a delay of three years, unfortunately. The reason for that was due to the choice of a gas furnace as the heat source for the Brayton cycle. The gas furnace proved to have an inconsistent acquisition process. A new detailed electric furnace project is being procured. In spite of that fact, the Brayton cycle did not changed significantly. Only the thermal source has changed. The expected date of first operation is the end 2018.

The Stirling machine presents great potential for low power nuclear systems. Not only for the fission ones, but also for the radioactive decay ones. And in the second case, there is even the possibility to use Americium heat source instead of the Plutonium. It is the intention, as soon as possible, to launch one of this machine, to perform a post flight analysis of the Stirling machine. This launching will be without a nuclear thermal source.

At this moment, the Heat Pipe Laboratory is acquiring the material required to build Mo13Re heat pipes. A furnace that can generate 1000 ^{o}C is available at the Lab and it is expected to have the first heat pipes of this material by the end of next year. As for the copper heat pipes the assembly process is going on, at a proper pace. In this case, it is expected the first tests by the end of this year.

A new Passive Multi Fluid Turbine is starting to be designed. The first one could not be used in a closed cycle for two reasons, it could not be properly lubricated and it leaked. These two reasons must be handled appropriately, and require retrofitting. Hence, the necessity of a new design. Also a retrofit of the Rankine test bench is required. The steam generator requires a new design. Its volume size must be increased and the output valve must be of better quality. It was manual in the previous design. An automated valve with a fine flow control must be used to guarantee a truly constant pressure at the turbine inlet. This was a flaw of the previous work bench. It is expected that the qualification of the new turbine will be ready by the time the Brayton cycle will have its first operation. This is highly desired once the Passive Multi Fluid Turbine must be tested in the Brayton cycle to prove its capability in space applications.

An event worth to mention is the participation of the principal investigator of the TERRA project in the DEMOCRITOS initiative. The DEMOCRITOS initiative is an European Union effort at designing demonstrators for a realization of a nuclear electric propulsion for the European roadmaps MEGAHIT & DiPoP. This effort is included in the H2020 broader program. This European program looks at a full spaceship which includes nuclear power unit, science package, ionic propulsion and several other topics. It includes members from France, Germany, Italy, Sweden, Portugal, England, Russia, and now Brazil. This participation is only possible because of the recognition of the work realized at the TERRA project. The TERRA project at this moment is focus on the power unit of a spacecraft such as the one desired by the European DEMOCRITOS program. This international interaction is refreshing and reaffirming of the research activities designed for the TERRA project, it vindicates those activities.

ACKNOWLEDGMENTS

Most of the resources for the TERRA project comes from COMAer. Nevertheless, certain funds were originated from CNPq, CNPq/AEB and FAPESP. The authors are grateful for this support and acknowledge it, with great satisfaction.

REFERENCES

1. Projeto TERRA, http://portal.ieav.cta.br/enu/?page_id=43 (2015).
2. L. N. F. Guimarães, G. P. Camillo, G. M. Placco, A. G.,Barrios Jr., J. A. Do Nascimento, E. M. Borges, P. D. C. Lobo, "Basic Research and Development Effort to Design a Micro Nuclear Power Plant for Brazilian Space Application", *Journal of the British Interplanetary Society*, **Vol. 64**, pp.1 - 6 (2012).
3. L. N. F. Guimarães, G. M. Placco, N. B. Marcelino, A. G.,Barrios Jr., E. M. Borges, J. A. Do Nascimento, "Power Conversion on the Brayton Cycle Loop of the TERRA project," *Proceedings of Nuclear and Emerging Technologies for Space 2013*, Albuquerque, NM, USA, February 25-28, 2013. Vol.1. pp. 6747-1 - 6747-8 (2013).
4. L. N. F. Guimarães, N. B. Marcelino, G. M. Placco, J. A. Do Nascimento, E. M. Borges, A. G.,Barrios Jr., "Heat-Electricity Convertion Systems for a Brazilian Space Micro Nuclear Reactor," *Annals of the International Nuclear Atlantic Conference - INAC 2013*, Recife, PE, Brazil, November 24-29, Vol. 1. pp.1 – 11 (2013).
5. J. A. Do Nascimento, L. N. F. Guimarães, S. Ono, P. D. C. Lobo, "Advanced Micro-Reactor for Space and Deep Sea Exploration: a Scientific Brazilian Vision," *Annals of International Nuclear Atlantic Conference - INAC 2011*, Belo Horizonte, MG, Brazil, October 24-28, Vol.1. pp.1 – 12 (2011).
6. S. Ono, L. N. F. Guimarães, J. A. Do Nascimento, "Coupling Between ANISN-BR and Citation Programs for Burnup Calculations of Fast Micro-Reactor," *Annals of the International Nuclear Atlantic Conference - INAC 2013*, Recife, PE, Brazil, November 24-29, Vol. 1. pp.1–12, (2013).
7. J. A. Do Nascimento, L. N. F. Guimarães, S. Ono, "Fuel, Structural Material and Coolant for an Advanced Fast Micro-Reactor," *Journal of the British Interplanetary Society*, **Vol. 67**, pp.381-389 (2014).
8. R. Taylor, "Prometheus Project Final Report," National Aeronautics and Space Administration, Jet Propulsion Laboratory, California Institute of Technology, Passadena, CA, USA, 982-R120461, (2005).
9. L. S. Mason, S. R. Oleson, C. R. Mercer and D. T. Palac, "Nuclear Power System Concepts for Electric Propulsion Missions to Near Earth Objects and Mars," *Proceedings of Nuclear and Emerging Technologies for Space 2012*, The Woodlands, TX, USA, March 21-23, 2pp., Paper 3066 (2012).
10. L. S. Mason, M. Gibson and D. Poston, "Kilowatt-class Fission Power Systems for Science and Human Precursor Missions," *Proceedings of Nuclear and Emerging Technologies for Space 2013*, Albuquerque, NM, February 25-28, 7pp., Paper 6814, (2013).
11. M. Gibson, M. Briggs, J. Sanzi, M. Brace, D. Poston, D. Dixon, "Heat Pipe Powered Stirling Conversion for the Demonstration Using Flattop Fissions (DUFF) Test,"

Proceedings of Nuclear and Emerging Technologies for Space 2013, Albuquerque, NM, February 25-28, 9pp., Paper 6812, (2013).
12. D. I. Poston, D. D. Dixon, P. R. McClure, M. A. Gibson, "A Simple, Low-Power Fission Reactor for Space Exploration Power Systems," *Proceedings of Nuclear and Emerging Technologies for Space 2013*, Albuquerque, NM, February 25-28, 11pp., Paper 6965, (2013).
13. D. I. Poston, P. R. McClure, D. D. Dixon, M. A. Gibson, "The DUFF Experiment – What Was Learned?," *Proceedings of Nuclear and Emerging Technologies for Space 2013*, Albuquerque, NM, February 25-28, 12pp., Paper 6967, (2013).
14. D. Dixon, P. R. McClure, T. E. Beller, D. I. Poston, M. A. Gibson, and S. D. Bagg, "The DUFF Experiment – Why and How," *Proceedings of Nuclear and Emerging Technologies for Space 2013*, Albuquerque, NM, February 25-28, 5pp., Paper 6968, (2013).
15. S, D. Howe, T. Ring, D. Crawford, J. Navarro, "Economical Production of Pu-238," *Proceedings of Nuclear and Emerging Technologies for Space 2013*, Albuquerque, NM, February 25-28, 5pp., Paper 6700, (2013).
16. G. R. Schmidt, D. H. Manzella, H. Kamhawi, T. Kremic, S.R. Oleson, J. W. Dankanich, L. A. Dudzinski, "Radioisotope Electric Propulsion (REP): A Near-Term Approach to Nuclear Propulsion," *Acta Astronautica*, **Vol. 66**, pp. 501-507, (2010).
17. R. G. Lange, W. P. Carroll, "Review of Recent Advances of Radioisotope Power Systems," *Energy Conversion & Management*, **Vol. 49**, pp393-401, (2008).
18. G. M. Placco, "*Caracterização de Uma Turbina de Tesla Operando em um Ciclo Rankine*," Dissertação de Mestrado, Instituto Tecnológico de Aeronáutica, São José dos Campos, SP, Brazil, 101pp. (2014).
19. F. Jansen, W. Bauer, F. Masson, J. M. Ruault, J. C. Worms, E. Detsis, F. Lassoudiere, R. Granjon, E. Gaia, M. C. Tosi, A. S. Koroteev, A. V. Semenkin, T. Tinsley, Z. Hodgson, C. Koppel, L. N. F. Guimarães, "DEMOCRITOS Demonstrators for Realization of Nuclear Electric Propulsion of the European Roadmaps MEGAHIT & DiPoP IEPC-2015-91079," Joint Conference of 30th International Symposium on Space Technology and Science, 34th International Electric Propulsion Conference and 6th Nano-satellite Symposium, 10 pp. Hyogo-Kobe, Japan, July 4 – 10 (2015)
20. N. B. Marcelino, "Tubos de calor em reatores rápidos," Relatório Interno ITA/IEAv, pp. 90, (2014).
21. G. M. Placco, L. N. F. Guimarães, R. S. dos Santos, "Passive Residual Energy Utilization System in Thermal Cycles on Water-Cooled Power Reactors," *Annals of the International Nuclear Atlantic Conference - INAC 2013*, Recife, PE, Brazil, November 24-29, Vol. 1. pp.1–10, (2013)