COAUTHOR- A MoU to create a **CO**nsortium of **A**cademics from **U**niversities promoting the use of T**HOR**rium

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***Abstract*—This paper describes the Memorandum of Understanding (MoU) signed by the authors to create a future consortium of academics from universities to promote the utilization of thorium (COAUTHOR). Besides the description of the MoU, also results of the research conducted in each participating partner or collaborative work performed among them will be described. Finally, the future work planned in the framework of the MoU, will be discussed.**

Keywords—Thorium, Memorandum of Understanding, Universities, Consortium.

I. Introduction

Nuclear Energy, primarily to produce electricity and other use, and the enveloping Nuclear Technology, as inherited from the XX Century, constitutes a controversial issue for political and economic reasons. On the one hand, the energy source is promoted in several Countries and an unavoidable mean to ensure growth for the human civilization ad suitable living standard with reduced or no impact upon the environment, on the other hand it is abandoned or going to be abandoned in other Countries which did benefit of stable economic growth. Thorium is an emblem for such a situation: huge reserves are available all over the world (primarily India, Turkey, and Brazil, but not only) and its technological worth for exploitation in

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current generation of thermal fission reactors is demonstrated, on the other hand no industrial use is ongoing or planned for the near future (with an exception constituted by situation in India). Moreover, research on thorium utilization in nuclear reactors and associated fuel cycles has been of academic interest for many researchers around the world. These researches are being conducted to increase the natural resource utilization, reduces the radiotoxicity, and other criteria of sustainability, by using thorium in the present time advanced reactors (Generation III), as well for the future Generation IV, mainly in Molten Salt Reactors (MSR) and in hybrid fusion/ accelerators driven system. Here we are going to describe a MoU signed by the authors to promote the utilization of thorium as nuclear fuel, and shortly describe the research activities conducted by the MoU partners.

II. MEMORANDUM OF UNDERSTANDING-COAUTHOR

In the beginning of 2017, a Memorandum of Understanding was launched to establish the terms and understanding among academics to develop efforts together with their institutions, the international academic community, and the nuclear sector interested in the utilization of thorium in Nuclear Reactors and associated Fuel Cycle, to create a future Consortium of Universities, but open to other entities and representatives who share the same vision, to promote the utilization of thorium as nuclear fuel in Nuclear Reactors, hereby named as **COAUTHOR** (**CO**nsortium of **A**cademics from **U**niversities promoting the use of **THOR**rium) within two years. Since them twenty academics from all the world had already join the MoU.

Details of the MoU can be found in the webpage: https://sites.google.com/view/coauthor-mou/memorandum-of-understanding . To join the MoU any interested academic just need to send an e-mail to the present chairman, Prof. Jose Rubens Maiorino (joserubens.maiorino@ufabc.edu.br).

III. RESEARCH ACTIVITIES

Even before the MoU was signed by the partners, the Universities and Institutions participating in this paper were, or still are involved in Research related with the scope of MoU or related with it. Here the authors will shortly review these research activities in order to divulge their past and present activities.

A. *Federal University of ABC- Jose Rubens Maiorino*

The focus of the research at Federal University of ABC in the Engineering Center (CECS-UFABC) is on studies of the reactor physics of Advanced PWR by conversion studies to use (U-Th)O_2. The studies are conducted by simulations using Monte Carlo Codes (SERPENT; MCNP).

Recently, a study was made to study the feasibly to convert the AP 1000, to use U/Th oxide without any change in the plant, only changing the fuel pellets, with advantages such as a lower maximum linear heat density, eliminating the IFBA, reducing the soluble boron concentration, and even the possibility of an extended discharge burnup (>60,000 MWD/MTHM), although the in-core fuel management is ongoing. Although regarding the natural uranium resource consume is a disadvantage, in OTC fuel cycle, since AP-Th 1000 consumes more uranium, we note that by optimizing the production of ^{233}U, we expected that the concept could be used as producer of ^{233}U, and therefore the first step in a closed U/Th fuel cycle, by recycling the uranium(^{233}U; ^{235}U; ^{238}U) and use in the same reactor, in such way that the requirement of enriched ^{235}U is reduced and substitute by ^{233}U; ^{235}U recycled[1,2].

Also, in cooperation with University of Pisa and Amirkabir University of Technology a study to convert a Small Modular Reactor (SMR) with uranium core to the thorium mixed oxide core with minimum possible changes in the geometry and main parameters of SMR core was done [3]. This option is due to most of SMR are designed to strongly poisoned in the beginning of cycle and to have a long cycle. Thorium can be used as an absorber in the beginning of the cycle and also be used as a fertile material during the cycle, it seems to be a good option to use (Th/U)O2 as SMR's fuel. The main neutronic objectives of this study is achieving longer cycle length for SMR by using the minimum possible amount of burnable poison and soluble boron in comparison with reference core.

B. *University of Pisa-Francesco D'Auria*

Although the Group of Nuclear Research at San Piero a Grado (GRNSPG), University of Pisa (UNIPI), presently is not directly involved with Thorium, it has cooperated with Federal University of ABC and Amirkabir University of Technology as described in III-A.

The GRNSPG-UNIPI, has a long tradition in Best Estimate (BE) system thermal-hydraulic codes (SYS-TH), Nuclear Reactor Safety (NRS), Deterministic Safety Assessment (DSA), Accident Analysis (AA) and the characterization of Thermal-hydraulic Phenomena (T-HP) [4]

Recently a list of 116 T-HP was derived [5], The T-HP list includes the consideration of Separate Effect Tests (SET) and Integral Effect Tests (IET) relevant in Reactor Coolant System (RCS) and Containment of Water-Cooled Nuclear Reactors. Each T-HP can be characterized by one or more parameters or variables which are part of numerical model Each T-HP can be characterized by one or more parameters or variables which are part of numerical models and constitute calculational results from system codes.

Moreover, the GRNSPG, participates in the FONESYS, SILENCE and CONUSAF projects run by some of the leading organizations working in the nuclear sector. The FONESYS members are developers of some of the major System Thermal-Hydraulic (SYS-TH) codes adopted worldwide, whereas the SILENCE members own and operate important thermal hydraulic experimental facilities. The two networks work in a cooperative manner and have at least one meeting per year. On the other hand, SILENCE addresses topics such as identification of current measurement needs and main gaps for further SYS-TH and CFD codes development and validation, definition of similar tests and counterpart tests in Integral Tests Facilities (including containment thermal-hydraulics) to be possibly conducted on Members' test facilities, scaling issue, and other subjects. These projects were founded by GRNSPG. CONUSAF is a new project submitted to the European Union and expected to be run in 2019 [6].

Finally, the experience of GRNSPG could be useful for the future COAUTHOR project, by accepting students from other participating countries at Pisa University and even for BE SYS-TH codes, Safety Deterministic Analysis collaboration of thorium reactor with the COAUTHOR colleagues.

C. *Federal Universiyty of Pernambuco- Fernando R. A. Lima and Carlos A.B.O. Lyra*

The activities of the UFPE team had as main motivation the feasibility of converting an advanced PWR reactor with UO2 core to (Th, U) O2 [1].

Presently, the UFPE team is conducting a safety study in the thermal-hydraulic area considering the neutronics results obtained by Stefani [1]. In this study, the safety analysis of the hottest channel of the AP1000 reactor using a CFX computational fluid dynamics code, ANSYS. is being analyzed.

D. *Military Engineering Institute- Claudio Luiz de Oliveira*

The Nuclear Engineering Section of the Militrary Engineering Institute has recently being involved with Thorium, and Master Thesis, were done to make an overview of thorium utilization in nuclear reactors, and review of the chemical, physical, mineral and nuclear properties of thorium, as well as an analysis of the conversion of the core of the Brazilian ANGRA II to use mixed oxide of uranium and thorium in various concentrations, allowing a preliminary assessment of the feasibility of the modification of the fuel, the resulting production of uranium-233, the emergence of protactinium and the poisons resulting from burning. All the calculation were performed using SCALE 6.1 [7,8,9].

E. *Nuclear and Energetic Research Institute(IPEN)- Paulo E.O.Lainetti*

Brazil has a long tradition of thorium technology, from mining of monazite to obtaining thorium with purity suitable for nuclear use. The first reports on the exploitation of monazite in Brazil date back to 1886, when Englishman John Gordon began exporting to the ore mined in the municipality of Prado, Bahia State to Europe, for use in lighting (incandescent gas lamps), before the advent electricity from the 1920s, when there was a decline in the consumption of monazite [10]. A typical Brazilian monazite contains 39% of cerium oxide, 5% of yttrium, 6% of thorium oxide and 0.3% of U_3O_8. In Brazil, monazite occurs mainly on the beaches of the States of Bahia, Espirito Santo and Rio de Janeiro [11]. In the late of 19th and early of 20th century, the interest in monazite increased owing to the use of thorium nitrate by gas mantle industries. Later, the use of lanthanide elements turned monazite into a much more important commodity than it was in pre-war years [12].

In 1949, the chemical processing of monazite, to produce lanthanide chlorides and tri-sodium phosphate, was started at the Santo Amaro mill (Usina Santo Amaro - USAM that belonged to the company Orquima S/A), located in Sao Paulo city. The first phase of the monazite processing consists of the extraction, washing and drying of monazite bearing sands taken from beaches. Then, physical separation processes separate the four minerals: ilmenite, rutile, monazite and zircon. Owing to public pressure, economic and radiological problems, the chemical processing of monazite stopped in 1992 [13].

The production and purification of thorium compounds was carried out at IPEN for about 18 years. The raw materials used were some thorium concentrates obtained from the industrialization of monazite sands, a process carried out in Sao Paulo between 1948 and 1994 on an industrial scale by the company ORQUIMA, later NUCLEMON (acronym for Nuclebrás Monazita). The main raw material employed during the thorium nitrate production period was the thorium sulfate produced in ORQUIMA. The crystallized thorium sulfate was first transformed in thorium carbonate by addition of water, sodium carbonate and sodium hydroxide. Further, the carbonate was transformed in thorium nitrate by dissolution with nitric acid. To obtain high purity thorium nitrate, the most satisfactory process is purification by solvent extraction. The main product sold was the thorium nitrate with high purity (mantle grade), having been produced over 170 metric tons of this material in the period, obtained through solvent extraction. During the period of production, it was employed the solvent extraction in pulsed columns [14,15]. Aqueous solutions of highly purified thorium nitrate, $Th(NO_3)_4$, are used in the production of gas mantles. Welsbach mantles are made by impregnating cotton or synthetic fibers with a 25 to 50 percent solution of $Th(NO_3)_4$ containing 0.5 to 1 percent each of thorium sulfate and cerium nitrate. The added cerium nitrate improves spectral emission properties. Eventually, the impregnated fibers are treated with aqueous ammonia, producing thorium hydroxide, $Th(OH)_4$, and this compound is calcined to produce ThO_2 that, when heated, emits brilliant white light.

F. *Bahçeşehir University- Sümer Şahin, Hacı Mehmet Şahin*

The activities of the nuclear group, now at Bahçeşehir University, on the energy production have a long past going back to mid-70's. They cover large spectrum, which includes utilization of thorium and consequently ^{233}U in thermionic space craft reactors [16] fusion-fission (hybrid) reactors [17], CANDU reactors [18,19], fixed bed nuclear reactors , in high temperature reactors [20] and accelerator driven systems (ADS) [21].

It turns out that a ^{233}U fueled and $ZrH_{1.7}$ moderated thermionic space craft reactor will have minimum dimensions, whereas a ^{233}U fueled and a beryllium moderated thermionic space craft reactor will have similar dimensions as a ^{235}U fueled and $ZrH_{1.7}$ moderated thermionic space craft reactor.

Thorium fueled fusion-fission (hybrid) reactors will have higher energy multiplication factors than pure fusion reactors and they will produce simultaneously substantial quantities of precious ^{233}U fuel *in situ* for satellite critical reactors.

Thorium as mixed fuel with nuclear waste reactor grade plutonium and/or minor actinides will have considerably higher burn-up and longer plant operation periods than present conventional LWRs.

Graphite moderated high temperature reactors and also fixed bed nuclear reactors are suitable to burn thorium as mixed fuel.

The nuclear group at Bahçeşehir University intends to focus the investigation on thorium in fusion- fission hybrids and in ADS in the immediate future.

G. Harbin Engineering University(HEU)- Ming Ding

A small nuclear reactor physics group at College of Nuclear Science and Technology (CNST) of Harbin Engineering University (HEU) has worked on thorium utilization in block-type high temperature reactors (HTRs) cooled by helium or molten salt since 2011. Thorium firstly aims to be used in a long-life small block-type high temperature gas cooled reactor (U-Battery) in order to extend the lifetime and found that different types of the thorium/uranium fuels, like TMOX and seed and blanket (S&B), has an important influence on the multiplication factor and conversion ratio [22]. The S&B fuel block achieves a higher burnup because the spatial separation of thorium and uranium leads to a higher resonance escape probability, while the TMOX has a higher conversion ratio because of a more uniform distribution of the fissile isotopes.

Recently, the spatial separation effect of thorium and uranium between TMOX and S&B fuels was systematically analyzed based on a large block-type HTR from four level spatial separation levels: no separation, tristructural-isotropic (TRISO) level, channel level and block level [23]. Using a traditional two-step calculation scheme, lattice calculation, followed by core calculation, is used to get the neutronic performance of the equilibrium cycle, including uranium enrichment, mass of fuel, effective multiplication factor, and average conversion ratio. Furthermore, thorium fuel was also extended to the so-called advanced HTRs, that is, molten salt cooled HTRs [24]. Different driver fuels, like U-233, low-enriched uranium (LEU), reactor-grade plutonium (RGrPu), was studied and compared with weapon-grade plutonium (WGrPu) and weapon-grade uranium (WGrU).

In the near future, some optimization algorithms are going to be developed to optimize the neutronic performance of thorium-fueled HTRs adopted S&B fuel blocks, like genetic algorithm, particle swarm optimization, shuffled frog leaping algorithm, etc., because the spatial arrangement of ThO2 and UO2 fuels in S&B fuel blocks generates an obvious effect on the neutronic performance, as the previous studies revealed.

H. Politecnico di Torino- Piero Ravetto

The researches of the NEMO (Nuclear Engineering Modelling) Group at Politecnico di Torino have been involved for many years in the development of models and methods for the simulation of advanced nuclear systems. Through the participation to various national and international projects, the group has contributed to studies for the assessment of new algorithms for the kinetics of source-driven systems and fluid-fuel reactors [25]. The classical factorization-projection approach has been consistently extended to include the possibility to simulate such systems, since standard methods do not allow to fully account for specific physical features, such as the dominance of the source neutron emission and the spatial displacement of delayed neutron precursors. Several applications have been carried out, including also the simulation of conceptual designs of thorium-fuelled reactors [26].

In recent times, efforts have been directed to the development of a computational tool, the code FRENETIC, for the multiphysics (coupled neutronics and thermal-hydraulics) of metal-cooled fast systems [27]. The code has been tested and benchmarked [28] and new numerical procedures have been incorporated to enhance the performance of the quasi-static approach [29]. The code can constitute a useful tool for the assessment of the stability and the behaviour of fast reactors in dynamic situations relevant for control and safety evaluations. On the educational side, students of the energy and nuclear engineering programs have been motivated towards the study of thorium-fuelled systems. Some final projects have now been completed and some are still under way. This can contribute to bring about a group of young engineers with competences in this field.

I. Nuclear Engineering Institute-Rubens Souza dos Santos

In Nuclear Engineering Institute (IEN) there are some researcher groups studying Innovative Reactor Concepts, aiming a secure use of the nuclear energy. These are such as Non-proliferate fuel, Reactor Safety Systems, use of Minor Actinides as Reactor Fuel to diminish the impact in final fuel disposal. Even in the Generation III Reactor Designers, some improvements have been studied in IEN, as Passive System in PWR as AP600.

However, the advances in our activities are centered in modeling transients in Subcritical Reactor Driven by External Neutron Source, as the ADS. They are computational programs based on Multigroup Diffusion Model and Reactor Point Kinetics Equations [30].

J. Royal Institute of Technology, KTH, Stockholm – Waclaw Gudowski

For many years Reactor Physics Department at KTH was involved in research related to the thorium based Nuclear Fuel Cycle.Studies have been performed on operation of the gas turbine-modular helium reactor (GT-MHR) with a fuel with thorium matrix. The major options investigated for a thorium fuel were a mixture with light water reactors spent fuel, mixture with military plutonium or with fissile isotopes of uranium. Consequently, three models of the fuel were investigated containing a mixture of thorium with ^{239}Pu, ^{233}U or ^{235}U in TRISO particles with a different kernel radius keeping constant the packing fraction at the level of 37.5%. This corresponds to the current compacting process limit. In order to allow thorium to act as a breeder of fissile uranium and ensure conditions for a self-sustaining fission chain, the fresh fuel contains a certain quantity of fissile isotope at beginning of life; this was called a triggering isotope. The small capture cross-section of ^{232}Th in the thermal neutron energy range, compared to the fission one of the common fissile isotopes (^{239}Pu, ^{233}U and ^{235}U), required a quantity of thorium 25–30 times greater than that one of the triggering isotopes in order to equilibrate the reaction rates. At the same time, the amount of the triggering isotope must be enough to set the criticality condition of the reactor. These two conditions were to be simultaneously satisfied. The necessity of a large mass of fuel forced to utilize TRISO particles with a large radius of the kernel, 300 μm. The results of the studies were published in [31,32,33]

Very recently our group has developed benchmarked and initially validated a nuclear fuel cycle simulator code – Fuel Advanced Nuclear Cycle Simulation Sweden Estonia (FANCSEE). The core physics of the code – solution of the burnup matrix exponential – is calculated using the state-of-the-art Chebyshev Rational Approximation Method. Libraries are separate for each fuel batch, fuel type as well as reactor type and are based on cross-sections calculated by Monte Carlo particle transport code Serpent 2.

The idea behind FANCSEE is to create a user-friendly, easy to use, graphically controlled software which allows to quickly implement, change and simulate complex scenarios. It has the ability to track up to 1307 nuclides over up to 8599 years. The target users would include researchers, policymakers and students.

The code is controlled through pre-defined objects which represent facilities in a nuclear fuel cycle – reactors, mines, fuel factories, waste repositories, enrichment and reprocessing plants. Every object has a list of corresponding parameters – for example, reactor power, fuel or reactor type, enrichment, processing capacity, "First In First Out" or "Last In First Out" reprocessing order. Calculation timestep can be set between 1 and 120 days. Results of mass, radioactivity and radiotoxicity of sets of isotopes, selected by the user, can be plotted directly with Grace plotting tool or exported as MATLAB script files. Currently available libraries are for Boiling Water Reactor ABB-III, Pressurized Water Reactor (PWR) Vodo-Vodyanoi Energetichesky Reaktor (VVER), PWR Mixed Oxide and Uranium Oxide fueled reference Nuclear Energy Agency assemblies.

Current development is focused on implementation of new reactor types exploiting the thorium based nuclear fuel cycle. Work is in progress [34].

K. Federal University of Minas Gerais (UFMG)- Claubia Pereira

The Nuclear Engineering Department (DEN) at UFMG has been participating in thorium research activities since 1965, when the Thorium Group was created by Federal University of Minas Gerais/Radioactive Research Institute in collaboration with France with the purpose to develop nuclear reactors capable to use thorium as a nuclear fuel [35].

However, the DEN/UFMG continues their research activities in the nuclear fuel cycle (NFC), safety analysis and thermal-hydraulics with a research group (Claubia Pereira (head researcher), Antonella L. Costa, Carlos E. Velasquez, Clarysson A. M. da Silva, Maria Auxiliadora F. Veloso and Ricardo Brant Pinheiro). The NFC emphasis has been studying different non-proliferation reprocessing techniques such as UREX+, GANEX, TRUEX, DIAMEX and SANEX, which recover transuranic (TRU) nuclides. The studies focus on the use of the different reprocessed spent fuel spiked them with thorium on different type of reactors: PWR, PHWR, GEN-IV reactors, ADS and Fusion-Fission System (FFS) [36-41]. The studies show the thorium behavior on different systems, under the irradiation of different neutron spectra and for different nuclear fuel composition. Besides, the DEN/UFMG has been developing research on the utilization of (Th, TRU) O_2 and (Th, U) O_2 on PWR like Angra 2 at different fissile material concentration and development a methodology to assess the use of different cross section libraries for a LWR pin lattices with thorium applications using U-233, U-235, Pu-239, Pu-241 as fissile material . To develop these works the DEN/UFMG has been development expertise working with different nuclear code such as MCNP, MCNPX, SCALE, NJOY, MONTEBURNS, ORIGEN, CFD, RELAP, PARCS etc. The DEN/UFMG is continuously working with their research on thorium as a nuclear fuel and contributing with paper works.

L. Universidad de Talca – Claudio Tenreiro

At our institution the focus has been the training of new engineers on nuclear reactor technology that incorporate Th as part of the fuel matrix, including the utilization of TMOX. Another goal it has been to integrate multinational groups regarding specific topics, such as development of ADSR systems, in configuration for a subcritical systems and spallation targets. The main tool of analysis has been the well known MCNP family codes as well as Fluka. The research also was aimed to include the model of nuclear waste burning as part of an NPP country program. The later as evaluating perspectives of introducing NPP's within an existing energy matrix but considering the nuclear waste problem in a wider sense, in this case, based on ADSR's, so burning rates scenarios were considered as part of the basic research. An example of the result of such collaborations is shown on reference [42].

IV. Future Activities and CONCLUSIONS

This paper has presented the MoU to create COAUTHOR, which is going to happen at the 19th International Conference on Emerging Nuclear Energy Systems (ICENES 2019), 6-9 October in Bali Indonesia (http://portal.fmipa.itb.ac.id/icenes2019/). Also, we had showed that we have researches of quality and diversity in several types of Reactors using Th as energy vector, as well as in different fields, neutronics, thermal hydraulics, safety analysis, etc. to gather academics with a common objective, that is to promote the use of Th, and be co-authors of its industrial use in a near future.

Finally, we expect that by presenting this paper would be a motivation for other academics to join COAUTHOR, and together we could define coordinated projects to achieve ours purpose.

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