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# INTERNATIONAL SYMPOSIUM ON ENERGY

Optimizing renewable energy: advanced strategies for enhanced efficiency and sustainability

## OVERVIEW ON THE STUDIES OF ADVANCED NUCLEAR TECHNOLOGIES AT THE FEDERAL UNIVERSITY OF MINAS GERAIS TOWARDS THE ENERGY TRANSITION

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### ABSTRACT

Currently, it is a reality that nuclear energy cannot be discarded in energy transition processes. Innovations in reactor design, including Small Modular Reactors (SMRs), microreactors and advanced materials, aim to improve safety, efficiency and waste management, leading nuclear energy to be a key part in any energy transition process for a clean and secure energy future. In this sense, the Department of Nuclear Engineering at the Federal University of Minas Gerais (DEN-UFMG) has further strengthened its research in order to contribute to safety and efficiency assessments of current and developing nuclear systems. This paper presents a history of DEN-UFMG and its role in the country as a workforce training agent in the area of Nuclear Engineering and the last contributions through research to advances in the area of nuclear reactor technology.

*Keywords: Energy Transition; Nuclear Power Plant; Small Modular Reactor; Nuclear Energy; GEN-IV*

### 1 INTRODUCTION

Brazil is part of several international agreements with the aim of reducing climate change resulting, in large part, from greenhouse gas emissions, especially from the burning of fossil fuels. Among the agreements signed to combat climate change, the most important is the Paris Agreement [1] with goals for reducing greenhouse gases (GHG) and increasing sustainable bioenergy aiming limiting global warming. Brazil also established the Climate Plan [2] and the National Climate Change Plan [3], which detail internal policies to achieve these goals, focusing on reducing deforestation, energy transition and sustainable development. This year, the country is hosting the 30<sup>th</sup> United Nations Conference on Climate Change (Conference of the Parties – COP30). The COP30, takes place between November 10<sup>th</sup> and 21<sup>st</sup>, 2025, in the city of Belém, capital of Pará, gathering world leaders, scientists, non-governmental organizations and civil society representatives to discuss the future of the planet, through actions to combat climate change [4].

In this context, the energy transition is fundamental in the planet's decarbonization process by promoting the replacement of highly emitting energy sources with clean sources with less environmental impact such as nuclear energy. Such energy source has provided new means of sustaining the progress of humankind. Fission reactors, in particular, represent a mature technology and are applied for generating electricity at hundreds of installations worldwide. However, the military applications, possibility of proliferation, the cost of energy production connected with system complexity and the fear of radiation have always been a challenge for the establishment of these technologies, as it has always been discussed [8].



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Then, the DEN-UFMG has further strengthened the researches in order to contribute to safety and efficiency assessments including Small Modular Reactors (SMRs), microreactors and advanced materials. This paper presents a history of DEN-UFMG, its role in the country as a workforce training agent in the area of Nuclear Engineering and its contribution through research to advances in the area of nuclear reactor technology to improve public trust and acceptance of this technology..

## 1.1 History and Activity in Nuclear Engineering

The activities of UFMG in the nuclear area are quite old and began in 1952 with the creation, at the School of Engineering, of the Radioactive Research Institute - IPR. In 1957, the Specialization Course in Nuclear Engineering was created, which trained specialists at postgraduate level. This course gave rise, in 1968, to the Postgraduate Course in Nuclear Sciences and Techniques, which was the first master's degree course in the area of Exact Sciences at the University. In the 1960s, in collaboration with the National Nuclear Energy Commission - CNEN, the TRIGA IPR-R1 nuclear research reactor was installed on the UFMG Campus. In 1972, the IPR was transferred to the Brazilian Nuclear Technology Company, created to comply with the Brazil-Germany Nuclear Agreement. Due to the divergence of purposes, it became unfeasible for the Nuclear Sciences and Techniques Course to remain within the IPR.

Thus, in 1978, the Department of Nuclear Engineering was created with the function of maintaining, within UFMG, the area of knowledge in Nuclear Engineering. Due to the strategic aspects of the options for generating electrical energy from various sources, including nuclear energy, it was a natural consequence to include the energy planning area in the course in 1989. In 1998, the area of concentration called Energy Planning was renamed Energy Engineering. At the end of 2005, with the approval of the doctorate level, the course was renamed as Program in Nuclear Sciences and Techniques (PCTN) and was organized into two main concentration areas: 1) Radiation Sciences and 2) Nuclear and Energy Engineering.

## 1.2 The Lines of Research in Nuclear and Energy Engineering

Linked to the lines of research "Technology of Nuclear Reactors and Fuel Cycles" and "Technological, Socio-Economic and Environmental Assessment of Energy Systems", the general area "Nuclear and Energy Engineering" acts as theoretical support and physical knowledge for the development of nuclear engineering and energy. The research line "Nuclear Reactor Technology and Fuel Cycles" also serves to support other lines that require theoretical training in neutron physics and particle transport, in addition to thermal hydraulics and nuclear reactor safety. Development of methods and techniques for using nuclear codes are also carried out and several studies are currently being developed related to the development of radioactive waste transmutation systems into hybrid systems. To carry out studies and investigations in this area, DEN-UFMG has computers with high processing power and several codes for neutronic, thermal hydraulic and energy planning analysis.

The researches follow global trends in the area involving IV generation systems (GEN IV), SMRs, microreactors, cogeneration and fusion. Currently, DEN-UFMG participates in the INCT (National Institute of Science, Technology and Innovation) for Modular and Innovative Nuclear Reactors, contributing to studies in the area of the research group Advanced Multiphysics Analysis of Hybrid Nuclear Systems and New Generation Reactors: Fusion-Fission, ADS (Accelerator-Driven System), GEN IV and SMRs [5].



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## 2 METHODOLOGY

As the purpose of this paper is to provide an overview of DEN-UFGM's research specifically focusing on advances in nuclear technologies, summaries of results that impact the role of nuclear energy in transition processes are being presented. The main topics considered were advances in studies on SMRs, microreactors, ADS, new materials and use of nuclear technology for cogeneration. For this study, a time window of the last 10 years was considered.

## 3 RESULTS AND DISCUSSION

As previously described, the DEN-UFGM research group “Advanced Multiphysics Analysis of Hybrid Nuclear Systems and New Generation Reactors” has focused its efforts on studying various nuclear technologies, which are characterized in a general way in Table 1.

*Table 1 – Nuclear Technologies: Characteristics and Possible Contributions to Energy Transition.*

| Tech-nology                          | Short Description                                                                                                                                                                                                                                                                                                                                                                                                                                     | Contribution for Energy Transition                                                                                                                                                                                                                                                                                                                                                                                                                                                    |
|--------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| ADS                                  | <ul style="list-style-type: none"> <li>- the concept of accelerator-driven systems (or hybrid systems) combines a particle accelerator with a sub-critical core;</li> <li>- most proposals assume proton accelerators, with beams of around 1 GeV energy;</li> <li>- the accelerator can be linear (linac) or a circular (cyclotron).</li> </ul>                                                                                                      | <ul style="list-style-type: none"> <li>- reducing long-lived radioactive waste through its transmutation into shorter-lived or stable radioisotopes;</li> <li>- enabling the generation of energy from abundant thorium fuel;</li> <li>- improved safety features due to their subcritical design and can facilitate a simplified nuclear fuel cycle, making nuclear energy a more sustainable and viable option for a low-carbon energy future.</li> </ul>                           |
| SMR                                  | <ul style="list-style-type: none"> <li>- smaller size and lower power output (generally under 300 MWe);</li> <li>- modular design for factory production and scalability;</li> <li>- passive systems and simplified designs,</li> <li>- flexibility in siting and applications;</li> <li>- shorter construction times and lower upfront costs compared to traditional large nuclear power plants.</li> </ul>                                          | <ul style="list-style-type: none"> <li>- stable and flexible power, zero GHG emission;</li> <li>- possible us to complement renewable energy sources like solar and wind, diversifying the energy matrix;</li> <li>- the modular design allows for lower costs and faster deployment and the smaller size makes them suitable for a wider range of applications, including remote communities and industrial heat.</li> </ul>                                                         |
| Micro-reactor                        | <ul style="list-style-type: none"> <li>- smaller size and lower power output (under 20 MWe);</li> <li>- passive safety features that prevent any potential for overheating or reactor meltdown;</li> <li>- small number of specialized operators.</li> </ul>                                                                                                                                                                                          | <ul style="list-style-type: none"> <li>- suitability for decentralized power, remote locations, and microgrids.</li> <li>- compact to easier portability, fast deployment, long operational periods without refueling (up to 10 years);</li> <li>- possible integration with renewables within microgrids;</li> <li>- ideal for emergency response to help restore power to areas hit by natural disasters;</li> <li>- ease removal from sites and exchanged for new ones.</li> </ul> |
| GEN IV and Ad-<br>vanced<br>Reactors | <ul style="list-style-type: none"> <li>- GEN IV reactors: the very high temperature reactors (VHTR) potentially can provide high quality process heat; fast reactors offer the possibility of burning actinides to further reduce waste and can breed more fuel than they consume;</li> <li>- use of TRISO (TRi-structural ISOtropic): structurally more resistant to neutron irradiation, corrosion, oxidation and high temperatures than</li> </ul> | <ul style="list-style-type: none"> <li>- significant advances in sustainability, safety and reliability, economics, proliferation resistance, and physical protection.</li> <li>- the very high temperature reactors (VHTR) potentially can provide high quality process heat; fast reactors offer the possibility of burning actinides to further reduce waste and can breed more fuel than they consume;</li> <li>- improved safety, and potential benefits for waste</li> </ul>    |



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|-----|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|     | traditional reactor fuels;<br>- new fuel rod geometry proposals.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | management and advanced reactor operation.<br>- better efficiency in energy generation.                                                                                                                                                                                                                                                                                                       |
| ATF | <ul style="list-style-type: none"> <li>- ATF (Accident Tolerant Fuel) has improved material response when compared to traditional <math>\text{UO}_2</math> fuel cladding enveloped by zirconium-based alloys (<math>\text{UO}_2\text{-Zr}</math>) while providing the capability to maintain or exceed fuel performance during normal operations, operational transients, and design-basis accidents.</li> <li>- fuels such as <math>\text{U}_3\text{Si}_2</math>, <math>\text{U}^{15}\text{N}</math>, <math>\text{U}^{11}\text{B}_2</math>, UC, have special characteristics that improve economic performance over the standard <math>\text{UO}_2</math> fuel.</li> </ul> | <ul style="list-style-type: none"> <li>- Reduction of costs of fuel including fabrication, conversion, and mining;</li> <li>- Extension of operating cycles reducing, consequently, costs;</li> <li>- higher burnup fuel requires less uranium ore and this reduces the environmental impact of mining;</li> <li>- thermal conductivity 5 to 10 times higher than uranium dioxide.</li> </ul> |

## 3.1 SMR

The SMRs technologies have emerged as potential options for increasing the contribution of nuclear energy for the energy transition processes offering lower costs and faster deployment compared to traditional nuclear projects. The DEN-UFMG has turned its efforts to research on these new system proposals that, in fact, use the concepts and principles of consolidated reactor physics. A study focused on evaluating neutronic parameters and investigating actinide burning in a compact lead-cooled research reactor proposal, the European Lead-Cooled Training Reactor (ELECTRA), of small dimensions, low power (0.5 MWth), and the availability of freely accessible data. ELECTRA incorporates innovative features such as the use of nitride fuels and advanced cladding materials developed over the past 15 years. The analysis has provided insights into the performance and potential of this compact lead-cooled research reactor design [9]. The study employed the Monte Carlo N-Particle code, version 6 (MCNP6).

SEALER (SwEdish Advanced LEad Reactor) was also investigated. The entire primary circuit of the SEALER was modeled using the CFD software package ANSYS Fluent. The core was represented as a combination of porous media and heat sources, the pumps were represented as recirculating boundary conditions to account for momentum sources, and the steam generators were represented as porous media coupled with a temperature-dependent heat sink function for a detailed investigation of the thermal behavior in steady state operation [24].

DEN-UFMG has been studying a small fast sodium (SFR) reactor concept based on the 4S concept (Super-Safe, Small and Simple). The SFR/DEN preliminary project presented behavior according to data found in the literature for similar reactors. The design of the fuel is based on U-10Zr (10%w Zr) binary alloy, with HT-9 steel fuel rod cladding. The neutronic evaluation was performed using the MCNPX code. The MAs (Minor Actinides) generation was very low, almost exclusively of neptunium, while the generation of TRU was composed almost entirely of fissile isotopes, mostly plutonium, which is very advantageous [12]. Studies about a Stable Salt Reactor (SSR-W300) focusing on the neutronic behavior of various fuel compositions derived from PUREX (Plutonium–Uranium Redox Extraction) and UREX+ (Uranium Extraction Plus) reprocessing have been performed [22]. The MCNP6 code was used to evaluate the impact of different reflector thicknesses on neutron parameters and the performance of fuels. The results demonstrated that extending the refueling interval beyond the conventional 6 months to 8 months could enhance reactor performance and also that there is of SSRs to address growing energy demands through sustainable and efficient means [22].



### 3.2 ATF

After the accident at the Fukushima Daiichi Nuclear Power Plant, every aspect of nuclear plant operations was studied, including the existing uranium dioxide fuel pellets enveloped by zirconium based alloys. The development of advanced fuel design concepts - Accident Tolerant Fuels (ATF) was made a higher priority and accelerated by combining recent operating experience with worldwide research and development. Several ATF designs are being developed to enhance safety [7]. These ATF concepts have been categorized as either near-term or long-term based on the anticipated implementation time to full core deployment. Near-term concepts include those that maintain the existing  $\text{UO}_2$ -Zr fuel design or that use previously used iron-based cladding materials with relatively minor changes. Longer-term, or subsequent concepts, significantly change the fuel system by replacing the fuel pellet and/or cladding with materials that have not previously been reviewed and approved for use in commercial nuclear reactors; thus, these concepts are anticipated to need more modeling and testing to support their licensing and deployment.

In this way, studies have been developed at DEN-UFMG to evaluate the feasibility of replacing Zircaloy-4 with SiC HNS and FeCrAl (KANTHAL) claddings. Among the several obtained results, it has been shown that the substitution of Zircaloy 4 by such alloys presented respectively similar and better thermal responses, as in steady state as in transient situations (channel blockage, LOFA (Loss Of Flow Accident), and LOCA (Loss Of Coolant Accident) [10, 11, 14].

### 3.3 Advanced Reactors

Advanced reactors are next-generation nuclear systems with significantly improved features including passive safety systems, reduced waste, higher thermal efficiency, potential for modular construction, and expanded applications beyond electricity generation to include process heat, hydrogen production, and desalination. DEN-UFMG has developed several investigations considering GEN-IV reactors. The 10 MW pebble bed high temperature gas cooled reactor (HTR-10) has been simulated using the RELAP5-3D code [15] as well as the LS-VHTR (Liquid-Salt-Cooled Very High-Temperature Reactor). The LS-VHTR is proposed to operate at 2400 MWth, and it is cooled by liquid  $\text{Li}_2\text{BeF}_4$  (Flibe) salt [16]. The HTR-10 is cooled by helium gas, moderated by graphite and uses Uranium spherical fuel elements (TRISO). The upper part of the reactor core has a cylindrical geometry and the lower part is cone-shaped. Experiments and calculations prove the better efficiency of these systems compared to conventional ones. The use of TRISO particles in the fuel elements of these reactors and different types of coolants increase heat transfer as well as operational safety.

As an advance it is possible also to mention the transition from a solid geometry to an annular geometry with characteristics that allow the increase of the power density. This occurs because of the reduction of the conduction thickness, which improves from peak fuel temperature to melting, and also because of the increased heat transfer surface area which improves the margin of safety for Departure from the Nuclear Boiling Ratio (DNBR). In a study developed at DEN-UFMG, a typical four loop PWR plant has been selected to be loaded only with annular rods. The thermal hydraulic conditions were calculated using the VIPRE (Versatile Internals and Component Program for Reactors) subchannel code and also the STHIPR-1 (*Simulação Termo-Hidráulica de Reatores de Pesquisa*) is a subchannel code that has been developed at the DEN-UFMG [13].

The Advanced CANDU Reactor (ACR-700) has also been studied in DEN-UFMG [25]. It presents slightly enriched uranium as fuel, which is cooled by pressurized light water and moderated by heavy water. Its core features a central structure called the



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calandria with 292 pressure tubes, each with 12 CANFLEX fuel bundles arranged in a line. The CANFLEX, in turn, has 43 fuel element rods arranged in three rings coaxial to a central rod. In the study, the CANFLEX bundle was successfully modeled using CFD tool [25].

### 3.4 ADS

In the process of energy transition, the Accelerator Driven Systems (ADS) can be considered as an option since they provide a method to manage and reduce long-lived nuclear waste and have the option to use thorium as a fuel, contributing to a sustainable, low-carbon energy supply [6]. In this sense, DEN-UFMG has invested efforts in researching these systems, and also in those based on fusion and hybrid fusion-fission (FFH) [17, 18, 19, 20, 21]. A FFH reactor is a fusion reactor combined with a layer of nuclear fuel from fission plants such as LWRs. These types of reactors will produce fissile material by capturing neutrons in fertile material (such as  $^{238}\text{U}$  and  $^{232}\text{Th}$ ) or transmuting minor actinides of high radioactivity and long-term half-life [17]. In a recent work, a hybrid modular system based on the SEALER has been analyzed modifying the original reactor core to design the subcritical system for actinides transmutation. The study demonstrated that the possibility of the hybrid system transmuting different reprocessed fuels: oxide-based spiked with thorium and depleted U ((TRU,Th)O<sub>2</sub> and (TRU,DU)O<sub>2</sub>) and also nitrides spiked with the same elements (TRU,Th)N e (TRU,DU)N [20].

### 4 CONCLUSIONS

This paper presented a brief history of DEN-UFMG and its most recent research efforts in nuclear technology to strengthen public acceptance of nuclear energy in an energy transition process in Brazil.

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