FALCON advancements towards the implementation of the ALFRED Project

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Abstract. In the European context, the implementation of the Generation-IV vision for safer, more sustainable, economic and proliferation resistant nuclear energy systems is being pursued as long-term action of the EU's strategies for a sustainable scenario securing energy availability. ALFRED, the Advanced Lead Fast Reactor European Demonstrator, is supported by the European Sustainable Nuclear Industrial Initiative (ESNII) to implement the Gen-IV vision as the cornerstone for the deployment of innovative nuclear energy systems based on the European Lead-cooled Fast Reactor concept.. The evidences of unparalleled safety and competitiveness of the LFR technology have raised a worldwide attention by industry and opened the possibility for a shorter-term deployment, with lead-cooled Small Modular Fast Reactors (SMFR), as a promising option to address a market segment of increasing interest. This broad spectrum of potentialities for the LFR has oriented the efforts of the FALCON (Fostering ALFRED Construction) International Consortium towards extending the role of ALFRED also as a prototype of a lead-cooled SMFR, thereby addressing the objectives of industry both in the short- and long-term perspective.
A pan-European effort is required to accomplish the ambitious programme, supporting this twofold goal. A first action is being pursued by setting up a Distributed Research Infrastructure, including a Centre of Excellence on the heavy liquid metal technology. The Infrastructure will gather the most relevant facilities (both existing ones and planned ones) in the European landscape in order to provide an extensive support to the deployment of future LFRs. Moreover, thanks to the envisaged open access policy, the Infrastructure will reinforce the cooperation between academia, research, industry and safety authorities. The paper focuses on the phased Roadmap for the ALFRED Project implementation in its extended role, as well as on the vision for the Distributed Research Infrastructure, as an incubator for competences and ideas sustaining Europe in a leading position on the LFR technology.

Key Words: Fast Reactors, Lead technology, Demonstrator, Implementation Plan.

1. The European and International Context

The projection of worldwide energy needs, combined with global and local drivers for future development (e.g., security of energy supply, reduction of greenhouse emissions, diversification of energy sources, stable and competitive energy costs, support for nuclear industry, etc.), translates into an impressive increasing trend of nuclear net installed capacity and new builds. Although the nuclear energy will contribute to the overall electricity production for an almost constant 12%, projections towards 2040 [1] forecast an average increase in energy demand by a 37% worldwide.

In particular, the reduction of greenhouse gas emissions is one of the priorities of the European Union (EU), aiming at a reduction to 80-95% below 1990 levels by 2050 [2]. Nuclear power is considered to play a fundamental role in meeting the 2 Degree Celsius Scenario (2DS), elaborated by the International Energy Agency (IEA) [3]: worldwide projections show nuclear generation capacity should increase of at least a factor of two by 2050.

The European Union (EU) recognizes the contribution of nuclear energy as a safe, secure and sustainable technology providing electricity with a very limited environmental footprint at stable and comparatively low prices [4][5]. A number of EU Member States rely on its further inclusion in the evolving energy mix [6], nuclear innovation being promoted and supported through the Sustainable Nuclear Energy Technology Platform (SNETP) [7].

In order to reinforce the technological leadership for a safe nuclear energy generation, the Union Energy Package 2015 highlights the central importance of research and innovation. Europe shares the vision put forward by the Generation-IV International Forum (GIF) [8][9], which identified in sustainability, safety and reliability, economics, proliferation resistance and physical protection the four main areas of improvement for next generation innovative Nuclear Energy Systems (NESs).

The mandate for pursuing the maturity of breakthrough concepts fulfilling these four goals is assigned, through SNETP, to the European Sustainable Nuclear Industrial Initiative (ESNII) [10]. Thanks to the constant advancements in more than ten years of collaborative actions and experimental activities on Heavy Liquid Metal (HLM) coolants, the Lead-cooled Fast Reactor (LFR) technology gained the status of short-term alternative to Sodium Fast Reactors (SFRs) [11][12], having in ALFRED, namely the Advanced Lead-cooled Fast Reactor European Demonstrator, its cornerstone [13].

The interest on the LFR technology is constantly growing also outside of Europe. In 2015 the Republic of Korea joined the GIF LFR Steering Committee, chaired by EURATOM. A Cooperation Agreement on the LFR technology and Safety was formalized between the LEADER Consortium [14], which initiated the ALFRED design, and ROSATOM-NIKIET, developer of BREST-OD-300 expected to be part of a pilot energy complex, under construction at the site of the Siberian Chemical Combine in the Tomsk region. Canada is showing growing interest in the LFR technology applications for remote areas, as proposed by LeadCold, a spin-off from the Royal Institute of Technology (KTH) in Stockholm, which was recently funded with 1.8 M$ by Essel Group Middle East. In October 2015, Westinghouse Electric Company applied for a Grant Agreement from the Department Of Energy, with a proposal based on an LFR concept.

2. A short-term deployment option for the LFR technology

Collaborative projects on research, development and design devoted to HLM coolants, both supported by EU Framework Programmes (FPs) and national programs [15], have significantly strengthened the relation between industries and research centres in the EU. The large databases of physical, chemical, thermal-hydraulic properties collected for the lead coolant in the last decade [16] have allowed designers to develop technical solutions that simplify the plant design, thus reducing capital cost, while simultaneously achieving inherent safety.

On the other hand, technical solutions have been fed back to laboratories, where they have been tested and proven, thus increasing their Technology Readiness Level (TRL) and overall supporting the near-term “deployability” of Lead Fast Reactor (LFR) technology. Although

further performance enhancement is possible, however requiring additional R&D efforts, the recent advancements on the LFR technology provide the necessary confidence on the feasibility to integrate technological solutions of high readiness level into a feasibly deployable lead-cooled reactor concept.

A key characteristic of the LFR technology is its inherent safety, which mainly results from the properties of lead as coolant. Its high boiling point, which exceeds 1700°C, allows for high temperature operation at atmospheric pressure without boiling concerns, facilitating the achievement of inherent safety [16], compared to pressurized systems. The lack of exothermic chemical reactions with air and water allows for full exploitation of passive engineered safety features and supports the implementation of multiple units at the same site through elimination of domino effects. Moreover, the excellent fission product retention capabilities of molten lead provide an inherent barrier to external radioactivity release, strengthening the Defense-in-Depth concept and supporting reduced emergency preparedness requirements, thus facilitating siting near populated or industrial areas.

Encouraged by the above intrinsic features, the LFR technology is considered an optimum candidate for a multi-unit site, as an essential competitive character of the SMR philosophy. The deployment of a lead-cooled Small Modular Fast Reactor (SMFR) could benefit from a significant export potential [18], in light of its compatibility with small remote electricity networks, intermittent energy sources and cogeneration applications [19]. Plant characteristics such as a high core power density, as well as design simplification offered by passive safety features and compact containment, represent important assets for compensating for the small design scaling factor and achieving economic viability.

In a context of general financial uncertainty, the recent experience with large NPPs, revealing construction costs and times far beyond expectations, is raising concerns by investors. A lower initial investment, which reduces financial barriers and investment risk, increasing plant affordability, would represent an attractive feature towards higher reliability for on-schedule and on-budget construction, if supported by smaller size and modular fabrication.

While First Of A Kind (FOAK) nuclear plants able to fully meet the Gen IV goals can be expected by late 2040s, lead-cooled SMFRs integrating high TRL design options are considered feasibly deployable in a shorter time-frame. Targeting the replacement of the current fleet of Gen-II reactors, as well as the rapid growth of electricity demand in emerging countries, is a key strategic aspect that is attracting political and industrial interest. The ALFRED Project, as small sized demonstrator of the LFR technology, can serve both purposes by paving the way for a lead-cooled SMFR FOAK, while showing the capability to meet the ambitious goals set forth by the GIF.

3. ALFRED Project and FALCON international Consortium

The ALFRED Project is supported by the FALCON (namely, Fostering ALFRED Construction) international consortium [20], established in December 2013. Ansaldo Nucleare (IT), ENEA (IT), ICN (RO) and CVR (CZ) have entered into the agreement to pursue the EU vision, aiming at bringing the LFR technology to industrial maturity. The Project envisages the realization of three main infrastructures at the Mioveni platform, in Romania:

- a European “Lead School”, providing certified Education and Training as well as dissemination services on HLM technology, as basis for spreading information, knowledge and best practices towards students, researchers and technicians willing to master this technology for application in innovative fields;

- a Centre of Excellence (CoE) on HLM, equipped with unique facilities offering services and opportunities for basic research, development of innovative components and full qualification of components and systems, in the perspective of bringing the European R&D and industry communities towards a leading position on innovation-intensive solutions;
- ALFRED (the Advanced LFR European Demonstrator), as an element of uniqueness of this Project, playing the role of European Technology Demonstrator Reactor (ETDR) of the LFR technology as envisaged in the Strategic Research and Innovation Agenda (SRIA) [13] and, in perspective, supporting the safe and sustainable operation of future commercial LFRs.

The development of the LFR technology, and, in particular, the deployment of ALFRED, has been continuously sustained also at national level in different countries, through endorsements and financial commitments. Italy played a major role in the European collaborative research projects since the early actions, developing significant expertise in HLM-cooled reactors design supported by several experimental facilities in the last 20 years. From 2005, Romania initiated R&D activities on LFR technologies, culminating in the political decision of hosting ALFRED at the Mioveni nuclear platform. Czech Republic included ALFRED among the national priorities of Research, Development and Innovation (RDI) [21][22], benefitting also from the Sustainable Energy (SUSEN) project [23] devoted to the development of Gen IV technologies.

The FALCON Consortium is continuously promoting the initiative, through the LFR provisional System Steering Committee in GIF and the ESNII Task Force, as well as taking direct contacts with potential industrial partners. Multiple universities, research centres, industries and other relevant European actors operating in the nuclear field (e.g. SRS, CRS4, IIT, CIRTEN in Italy; NRG in Netherlands; KIT and GRS in Germany; SCK•CEN in Belgium; Institut Symlog in France; KTH, Chalmers and LeadCold in Sweden) have signed Memoranda Of Agreement (MOA) with FALCON or expressed their interest in the initiative, further strengthening the LFR European community for an increased stability in a long-term program.

The short- and long-term scientific relevance of the ALFRED Project, as well as the social benefits deriving from it, have leveraged an increasing political interest towards the initiative, resulting in the achievement of three important milestones:

- On August 2015, as a consequence of the final consultation of Smart Specialization Strategy of Romania 3 region, «*The research, development and innovation activities dedicated to ALFRED are included in High technology Industry […] smart specialization […] of the region»*. ALFRED was considered a factor for economic growth, improved innovation, job creation, strengthening of RDI poles and creating the career opportunities for young talents.
- On May 2016, ANCSI (National Authority for Scientific Research and Innovation), as part of the Ministry of Education and Research, addressed a formal letter to the Ministry of European Funds in support to the ALFRED initiative, highlighting the technical and scientific relevance of the Project, the large interest of the scientific community, the support to include ALFRED as a Major Project in the Program for Operational Competitiveness.
- On January 2017, ALFRED was included in the Research and Innovation section of the 2017-2020 Romanian Government Program as a means to support the European partnership on the LFR technology and the development of the Gen IV reactors in the frame of the international partnership (EU, US, IAEA). The new government

committed to increase by 30% annually the national public budget for research and innovation actions. This will be translated into dedicated Priority Actions in the Romanian National Energy Strategy and Romanian National Research Strategy.

The Project represents a step forward in increasing Romania innovative performance and to help it to improve its status among the EU member states. The ALFRED demonstrator and the associated infrastructures allow research, development and innovation capacity improvement. By promoting the implementation of the ALFRED Project in Romania, the government will not only support and preserve the critical mass of knowledge and stabilization of educated young researchers in the country, but will also pursue a driving force which will attract talents from abroad, including those who left Romania. Finally, the Project will improve the induced economic activities through a relevant return of investment in the creation of new jobs in sectors such as accommodation, catering, recreation etc., contributing to increase the social welfare not only in the area, but in the South Muntenia Region in general.

4. Scientific and Strategic Vision

Together with all the strategic, economic and social advantages, , through the realization of ALFRED and all the supporting infrastructures, the aim is to create a unique set of research facilities allowing to address a number of scientific aspects and technological challenges. This will bring R&D to excellence in the field of HLMs towards their exploitation in various applications.

Beyond the most straightforward impact on the extension of the scientific bases of the LFR technology, the outcomes of the research activities performed in the foreseen facilities can indeed be fully exploited for fundamental studies and technology validation in several other fields including fusion, solar power generation (concentrated solar power), hydrogen production, highly efficient electricity generation using liquid metal electrode solid oxide fuel cells, industrial applications (gas or steam turbines and heat exchangers used in various power generation systems) and aerospace applications.

Referring to the nuclear fission technology, the accessibility to ALFRED will allow industry, utilities and safety authorities – in close cooperation with research organizations and universities – to harmonically improve their preparedness on all operational aspects of future LFRs, as well as to investigate any possible improvement to the existing plants. The aim is the continuous improvement of the safety and sustainability of the European fleet of nuclear energy systems in a shared and top-level safety culture.

ALFRED, as a demonstration reactor, will significantly extend the European landscape with a key facility for testing in a relevant neutron field and operating conditions, opening a novel possibility in support to the qualification of new fuels and components [24]. This initiative will significantly promote the integration of materials research at European level allowing a step forward to achieve the main aim of EERA (European Energy Research Alliance), strengthening the scientific and technological bases, the competitiveness and the capacity to address the issues and challenges of fast-evolving technologies. Materials research will, in fact, tackle the fundamental topic of qualification of traditional nuclear materials in new environment and, in parallel, will allow advancements in the qualification of innovative materials, as a future pillar for the nuclear industry to continue in its safe operation.

The CoE will integrate unique facilities that are required to perform extensive investigations on all the aspects of HLM physics (notably, hydrodynamics and thermal-hydraulics in large and complex systems) and chemistry. This will provide the European scientific community with a platform allowing to achieve the excellence that is required to master the HLM

technology. Codes development and qualification will enhance the capability of licencing authorities to guarantee the licence of safer and more reliable systems for nuclear fast reactors.

The top-level facilities encompassed in the Project will allow the complete characterization and qualification of concepts, components and prototypical systems in a relevant environment, bridging the R&D world towards industry, in a synergic action aimed at the deployment of innovative solutions.

The design and operation of the facilities, as well as the preparation, commissioning and execution of the experimental programs envisaged in these, will also elevate the expertise in practical applications of the HLM technology, with a twofold potential for direct innovation building and the supply of R&D services.

The ALFRED demonstrator and the associated research infrastructures are expected – and will be promoted in order – to become the focal point attracting a critical mass of excellences working on the LFR technologies and science in more general aspects. The open cooperation and networking that will be stimulated through this pan-European hub, as well as the qualified support that will be provided to all interested organizations, comes in line with the European Research Area on fast reactors.

The realization and successful operation of ALFRED will increase the awareness of the potentialities of the LFR technology for the deployment of lead-cooled SMFRs and for the demonstration of compliance with the GIF vision. The industrial interest will progressively increase and, thanks to an open access policy, the acceptability of nuclear energy is expected to be improved, allowing in this way to maintain the nuclear energy source as an important contributor to the achievement of the envisioned secure and low-carbon European energy system.

The entire research infrastructure encompassed in the Project will be offered to the whole scientific and technical community, as a pan-European open access platform for basic to applied research on the Heavy Liquid Metals – and notably lead – technology. Existing and planned experimental facilities of the involved countries will be gathered in a Distributed Research Infrastructure (D-RI). It will be aimed at coordinating the European Research, Development, Qualification and Demonstration (RDQ&D) efforts on the lead, and HLM, technology and bring Europe to the forefront of advancement for the new generation of nuclear, and energy technology in general.

5. General Roadmap

In line with the main goals of addressing the energy needs through low-carbon emitting technologies and of meeting the GIF criteria for the next generation nuclear energy systems, FALCON members and associated partners share the target of a demonstration stage for ALFRED in the timeframe 2025-2030.

Due to the limited capacity of national programs and single organization initiatives, a shared roadmap has been developed and agreed at European level. The implementation of this roadmap will allow undertaking all the concerted actions addressing the urgent needs covering the following aspects:

- Improvement in the research infrastructure devoted to LFR technology development, qualification and demonstration, and translation of the main outcomes into feasible engineering solutions, manageable at industrial level;

- Enhanced integration of resources of financing at national and European level (European Structural and Investment Funds, Horizon-2020, National Programs,…), able to attract investments from the private sector;
- Development of a licensing framework for non-Light Water Reactors, starting from a robust demonstration and constantly improving the most advanced nuclear standards through the return of experience;
- A frame for integrate and attractive E&T programs for the new generation of scientists, seeking for open-access infrastructures and research reactors operated in a multi-cultural environment.

In the implementation of the roadmap, Romania will benefit from a longstanding tradition of more than 45 years in a successful nuclear power program, which includes the operation of two CANDU reactor units in Cernavoda (from 1996 and 2005, respectively). Therefore, Romania will benefit from a national preparedness deriving from the existing nuclear programme [25]. However, the country will have to deal with the main milestones related to the introduction of a new technology, namely the LFR, required for the development of the ALFRED project [15]:

1. Comprehensive recognition and identification of the national commitments and obligations,
2. Adequate preparation of the national infrastructure needed for construction,
3. Reinforcement of all the necessary competences and capabilities needed to regulate and operate the demonstrator, as an innovative nuclear reactor, safely and securely over its life-cycle (including the management of fuel cycle and radioactive waste).

The ALFRED roadmap is thought in synergy with the above aspects at European and National level. It is based on a phased approach (Viability, Preparation, Construction and Operation phases), and includes the main actions of different nature, which are carried out in parallel and tailored on the specific phases of the ALFRED life-cycle. A schematic view of the roadmap, including the main Milestones (M), phases description and main outcomes is proposed in FIG. 1.

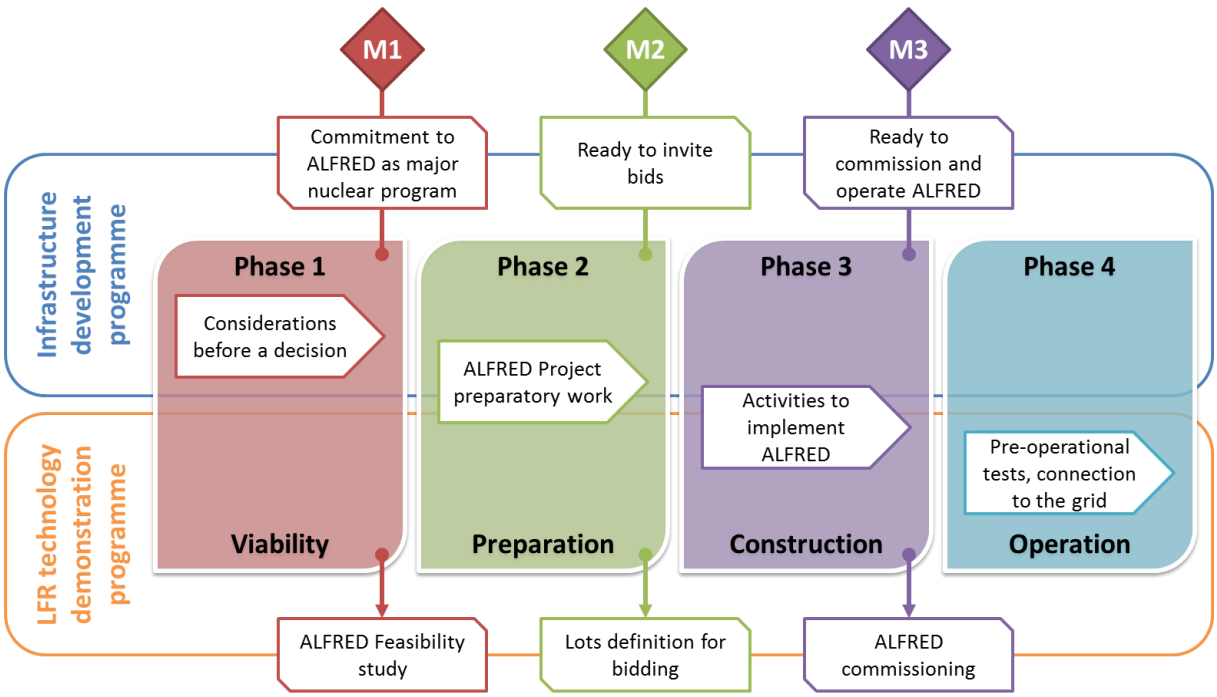

FIG. 1. ALFRED general roadmap.

6. The Viability Phase

The initial Phase in the development of the ALFRED Project involves European and National considerations and planning before a firm decision is taken. The Viability Phase is aimed at increasing the overall Project maturity, as needed to enter into the subsequent Preparatory Phase. The scope of the Viability Phase is categorized in 5 main areas (governance and management; research, development and qualification; safety and licensing; engineering and design; human resources and E&T), intended to systematically tackle all the needs for a smooth execution of the preparatory work for ALFRED construction. The activities will be focused on the following main objectives:

- Preparation of the general frame for the establishment of an International Consortium. The actions are aimed at defining priorities, opening new partnerships, promoting optimal cooperation and joint programming for the implementation of the initiative, through strategic management and governance, financial seeking and technical work.
- Actuate the R&D program through experimental activities focused to the achievement of TRL 5 for all technological aspects which are necessary to support the design, including materials, components and main design choices, through existing infrastructures, as well as new facilities under design and construction, gathered into a pan-European D-RI.
- Completion of the Basic Design, implementing all R&D evidences, achieved during the technology assessment that is performed in parallel, through the support of National R&D programs on key topics.
- Finalization of the Site characterization process and related studies being the current reference location identified in the Romanian nuclear site of Mioveni.
- Preliminary dialogues with regulatory body and safety authorities for the definition of a stepwise informed approach to siting and licensing.
- Creation of a Centre of Excellence on HLM as key infrastructure supporting education and training of the specific competences and implementation of human resources E&T programmes by launching open access to the HLM CoE and increasing international participation to ongoing experiments.

The total budget required for the Viability Phase is estimated in about 200 M€. Based on projections, approximately 10% to 20% of the total budget will be covered through national programs and EURATOM projects, dedicated to the development of the LFR and HLM technologies. Therefore, at this development stage, the ESIF contribution plays a key role in obtaining significant advancements in the short term. The successful implementation of the viability phase is dependent on the firm commitment of ALFRED as a Major Project in Romania, which is expected to lead to a fund injection of the order of 150 M€.

7. Concluding Remarks

Innovative nuclear energy systems, with breakthrough concepts belonging to a new generation of nuclear technologies (Generation-IV), have the potential to meet the highest performances in terms of sustainability, safety, proliferation resistance and economics. The vision for a near future benefitting of new Lead Fast Reactors as clean, resource effective, safe and economic – hence sustainable – innovation-intensive power sources has been the driving force for the pan-European efforts which eventually led to the ALFRED Project.

Lately, the implementation of European deployment strategies of Gen IV technologies is being postponed towards the 2050s. Although a longer term perspective may lead to a reduced industrial interest, the intrinsic and passive safety features of the LFR design make it

an optimum candidate for the SMR segment. The ALFRED reactor is being revised to meet the goal of a feasibly deployable lead-cooled SMR concept, based on technologically-ready solutions and compatible with the short term global needs related to de-carbonization and security of energy sources. FALCON is considered the proper incubator for the concept development and will be a pole of attraction for partners interested in the HLM technology.

Europe, and Romania as hosting country, will benefit from scientific and strategic advantages for having ALFRED realized along with all the facilities required to support its development. In particular, facilities from member countries will be gathered under a pan-European D-RI aimed at addressing the R&D priorities, supporting the licensing process and assisting the industrial partners in the development and qualification of materials, components, instrumentation, for the short-term deployment of the LFR technology.

The scientific and social benefits deriving from the implementation of the ALFRED Project have leveraged an increasing political interest towards the initiative. ALFRED is being included in the main strategic documents of the Romanian National Energy Strategy and Romanian National Research Strategy. Multiple actions are on-going to meet the main milestone of the first phase of the ALFRED roadmap, namely the Viability Phase, i.e. the Romanian firm commitment to ALFRED as a Major Project.

The path selected by the FALCON international consortium, set by Ansaldo Nucleare (IT), ENEA (IT), ICN (RO) and CVR (CZ) in support to ALFRED development, is fully based on pan-European collaboration. The development of ALFRED, as demonstrator of the LFR technology for a short-term deployment of lead-cooled SMFRs and for long-term Gen IV goals, is an invaluable opportunity for Europe in general, and for the development of emerging member states, in particular. However, due to its innovative nature, it also requires huge investments in order to overcome the technological gaps, confirm the potentialities of the technology to consolidate the industrial interest and launch it into market deployment.

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