WORLD NUCLEAR UNIVERSITY

SUMMER INSTITUTE 2019

# Networks for Nuclear Innovation

A Magazine containing the results achieved in the Network for Nuclear Innovation projects during the WNU Summer Institute 2019

# FROM WORLD NUCLEAR UNIVERSITY PRESIDENT

Nuclear electricity generation is growing globally, but it needs to grow faster if the world is to meet future energy demand and mitigate the effects of climate change. The major goal that we have set to achieve by 2050 is to generate 25% of global electricity with nuclear power. Challenges in the technological, regulatory, economic, and social levels of our industry must all be addressed to achieve this growth. In such an international industry, this requires strong international collaboration. Networking is a vital component of international collaboration, and I am delighted to see the central role the Networks for Nuclear Innovation has played in this year's Summer Institute.

Fellows are selected to participate in the Summer Institute in part due to their ambition and enthusiasm for the future of nuclear. The Networks for Nuclear Innovation groups this year produced high quality reports with serious recommendations for diverse aspects of the nuclear future. Information does not respect national boundaries, and I anticipate that the innovative ideas generated during the NNI will be carried forward by the Fellows into their 39 countries. I support the endeavours of these future leaders, and fully believe in their future successes.

Agneta Rising
President
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# ACKNOWLEDGEMENTS

The first edition of the Networks for Nuclear Innovations (NNI) magazine was completed at the Summer Institute 2016. The main concept is to compile the ideas that emerge from the Fellows collaborative work in a publication that could inspire future innovations and serve as reference for the continuous development of important topics in the nuclear area.

We are extremely impressed by the efforts the Fellows and Mentors dedicated to finalize the text within the Summer Institute timeframe, at the same time they were preparing their impactful oral presentation.

We are grateful for the NNI Magazine Editor, Alina Constantin, who made sure all the pieces were correct and in place for its timely publication. The digital version of the NNI magazines can be found at: www.world-nuclear-university.org

Patricia Wieland
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# FOREWORD

This year the Summer Institute attracted 82 Fellows representing 39 countries. They bonded in Romania and then gathered in Switzerland, under the close guidance of their mentors, to intensively work on the dedicated projects of the programme – the Networks for Nuclear Innovation. The thematic chosen reflects actual aspects of nuclear industry, which are or have to be driven even more by innovation, to cope with the global context of climate change and accelerated digitalization.

The Fellows developed ideas, concepts and practical solutions to promote innovation in their area chosen while addressing the Sustainable Development Goals. The presentation of their results achieved, during the closing day of the Summer Institute, called for reflection, adaptability and international cooperation. Institutional changes needed, short term, mid-term and long term perspectives, economical aspects and implementation ways were carefully studied by the teams. Some of the messages derived are captured in this brief introduction, being in the same time an invitation for the reader to carefully consider each of the projects described, engage in dialogue and disseminate the most feasible proposals.

Innovative nuclear reactors, the Gen IV and the small modular reactors can be the ingredients of a nuclear renaissance, having increased safety capabilities and ability to target specific customer needs.

In order to encourage the development of Gen IV reactors, it is needed to collaborate at international to consolidate the fundamental features of Gen IV design and simplify the process of validation.

When communicated nuclear energy outside the industry, the Fellows highlighted how important is to come from the same shared values to the social and ethical level in order to be understood and build solid partnerships based on trust. This is key in gaining more acceptance for nuclear and going towards the goals of the Harmony programme.

Different aspects and criteria have to be considered when assessing the feasibility of a nuclear project, this being the base of creating openness and support, as every country has its own particularities. A forum for providing technical advice on feasibility studies and sharing of information has been proposed by one of the teams.

People are a company's most important resource. Even with the most expensive and safest equipment and systems, high-performing organizations shall invest in their people and culture to truly achieve their vision and mission. In order to maintain a proper organizational environment, favourable to development and progress, periodical checks and assessments of the organizational health and state of the culture in the organization have to be performed.

Another message strongly reinforced was that creating and maintaining a valuable and well prepared human capital is crucial for nuclear but has also to keep the pace with the technology infusing now all aspects of people's life. Organizations have to be aware and prepared to allocate the needed resources while having a sound and adaptive strategy. Governments, academia, and nuclear industry stakeholders can join efforts to create an internationally connected nuclear industry network where individuals possessing qualifications needed are much easier identified, as well as shortages or surpluses of particular skills.

We hope that the reader will enjoy the content and find value in it.

Yours sincerely,

Alina Constantin

Editor-in-Chief

# STUDY OF "4 HARMONIZATION PROGRAMME" FOR ACHIEVING INTERNATIONAL COOPERATION IN GENERATION IV REACTORS

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**Abstract**

According to International Atomic Energy Agency (IAEA), an accessible, affordable, and sustainable energy source is fundamental to the development of modern society. Current scenarios predict a global demand for primary energy 1.5-3 times higher in 2050 as compared to today, and a 200% relative increase in the demand for electricity. The harmony program aims for at least 25% of world energy to be produced by nuclear to reduce the carbon footprint impact on the environment.

Generation IV International Forum (GIF) is seeking to develop more economical, sustainable and safe nuclear reactors, from their fuel cycles to decommissioning and waste treatment, and thus meet the world's energy needs. Research on the fourth-generation reactors is therefore needed for the realization of this programme. GIF proposed 6 reactor types as the future nuclear technologies which have clear advantages and technological advancements compared to reactors in use today, along with meeting the goals listed in this paper. There are breakthrough possibilities in the development of new generation nuclear reactors, where the life-time of the nuclear waste can be reduced to some hundreds of years instead of the present time-scales of a hundred thousand years.

The International Atomic Energy Agency has initiated an International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) in the year 2000. The main objective of INPRO is to help the world community to ensure that clean and safe nuclear energy is available to contribute in fulfilling the energy needs in the 21st century in a sustainable manner.

This paper analyses the technology, results, applications, and limitations of the GIF nuclear reactors. Also, review the use of nuclear energy for nonelectric applications especially in areas such as seawater desalination, hydrogen production, district heating and other industrial applications.

## 1. Introduction

With an ever-growing population of the earth and the aspiration of 10 billion people to better living conditions, there is no doubt today that demand for energy will continue to grow. However, a continuation of the current energy mix will be detrimental to the environment, and in particular to the global warming of our atmosphere. Demand for a safe, clean and efficient energy supply will therefore increase during this time too. Today, more than 400 nuclear power plants are in operation worldwide. They provide a large share of the Carbon Dioxide ($CO_2$)-free power supply. To continue to capitalize this advantage, new nuclear energy systems will be needed in the future.

Many nations, both emerging and industrial, therefore believe that increased use of nuclear energy will be needed to secure clean energy supplies. That's why they have teamed up for a Generation IV research and development programme to meet this challenge. Generation IV covers the entire system of nuclear energy, from extraction to disposal, including nuclear reactors and the nuclear fuel cycle. This work will focus on the six reactor systems selected from more than 130 concepts under the Generation IV programme and how to address the technology in order to know its availability at Industrial Level. The work will show whether the systems still meet today's requirements and why they lag behind the 2000 timetable. Section 2 of this study speaks about the history and the currents status of the Gen-IV technology and the nuclear reactor types that were proposed at the beginning of 2000. Section 3 contains the goals of the technology and the areas that were categorized.

An evaluation assessment is reflected in section 4, in order to know which technology is more suitable at the industry level from the proposed technology that was described. Within section 5 can be found the proposal of this study in order to achieve the international harmonization level and enhance the cooperation between existing organizations to achieve the commercialization of Gen-IV technology.

# 2. Background

## 2.1. History

The Generation IV research and development programme is an initiative launched in 2000. The goal is to advance research on nuclear energy systems that are needed after 2030 and that differ significantly from Generation III systems. The Generation IV International Forum (GIF) was established to develop and implement the program [1].

Figure 1 contains the latest information on a status of GIF system arrangements and memoranda of understanding the system development timelines as defined in the original roadmap in 2002 and in the 2013 update.

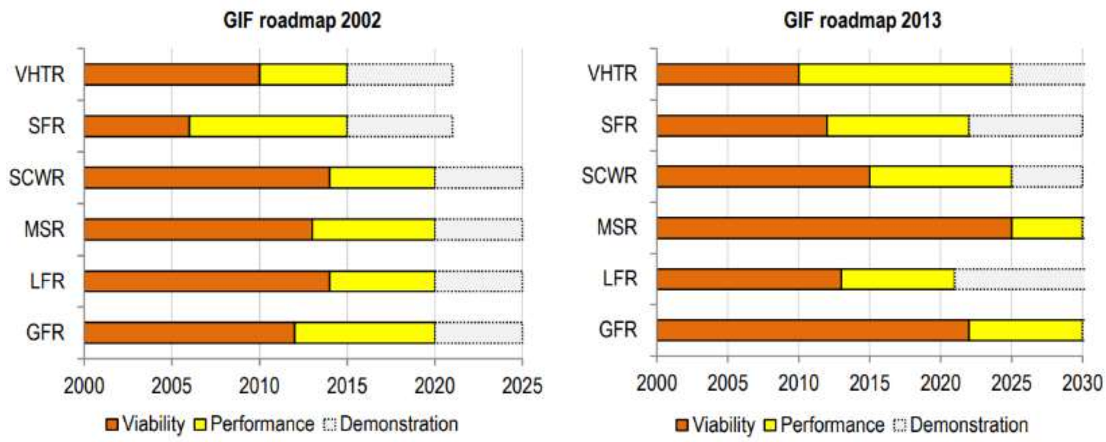


*FIG. 1. System development timelines as defined in the original roadmap in 2002 and in the 2013 update.*

The GIF formulated the development goals with 8 criteria, with several levels of sub-goals [2]. With these development goals, a worldwide survey was launched, in which more than 100 reactor concepts were submitted. Out of these, 6 systems were selected for follow-up: Gas-Cooled Fast Reactor (GFR), Lead-cooled Fast Reactor (LFR), Molten Salt Reactor (MSR), Sodium-cooled Fast Reactor (SFR), Supercritical-Water-Cooled Reactor (SCWR) and Very-High-Temperature Reactor (VHTR). The Technology Roadmap Update in 2013 has confirmed the choice of these six systems [3].

## 2.2. Current social-economic situation and environment

The ambitious technical goals of the Gen. IV programme can be divided into the following four policy objectives: (1) sustainability, (2) efficiency, (3) safety and reliability, (4) Proliferation barriers and physical self-protection.

On the basis of these political objectives, it is also easier to assess whether the provisions of the year 2000 are still up to date. Sustainability is generally a bigger issue than it was in 2000, especially for the topics of final disposal and fuel cycle. The energy market is more competitive than ever; with the development of renewable energies and state intervention, it is more important than ever to be able to offer energy at competitive prices. Safety continues to be a big issue at Nuclear Power Plants (NPPs).

The importance of reliability has greatly increased as a result of the expansion of renewable energies (wind / solar) and their unreliable feed-in and has also become more important from an economic point of view. At a time when global political turmoil and the threat of terrorism are on the rise, these goals are more relevant than ever. The targets set in 2000 are still applicable today, and some of them even meet the needs better than foreseen in 2000.

# 3. Goals of Generation IV

Eight technology goals have been defined for Generation IV systems in four broad areas which are sustainability, economics, safety and reliability, and proliferation resistance and physical protection.

These ambitious goals are shared by a large number of countries as they aim at responding to the economic, environmental, and social requirements of the 21$^{st}$ century. Table 1 lists the generation goals of Generation IV.

TABLE 1. Generation IV goals.

| Goals for Generation IV nuclear energy systems | |
|---|---|
| Sustainability-1 | Generation IV nuclear energy systems will provide sustainable energy generation that meets clean air objectives and provides long-term availability of systems and effective fuel utilization for worldwide energy production. |
| Sustainability-2 | Generation IV nuclear energy systems will minimize and manage their nuclear waste and notably reduce the long-term stewardship burden, thereby improving protection for the public health and the environment. |
| Economics-1 | Generation IV nuclear energy systems will have a clear lifecycle cost advantage over other energy sources. |
| Economics-2 | Generation IV nuclear energy systems will have a level of financial risk comparable to other energy projects. |
| Safety and Reliability-1 | Generation IV nuclear energy systems operations will excel in safety and reliability. |
| Safety and Reliability-2 | Generation IV nuclear energy systems will have a very low likelihood and degree of reactor core damage. |
| Safety and Reliability-3 | Generation IV nuclear energy systems will eliminate the need for offsite emergency response. |
| Proliferation Resistance and Physical Protection | Generation IV nuclear energy systems will increase the assurance that they are very unattractive and the least desirable route for diversion or theft of weapons usable materials, and provide increased physical protection against acts of terrorism. |

# 4. Evaluation assessment

After some two years' deliberation and review of about one hundred concepts, late in 2002 GIF announced the selection of six reactor technologies which they believe represent the future shape of nuclear energy. These were selected on the basis of being clean, safe and cost-effective technology, which means of meeting increased energy demands on a sustainable basis, while being resistant to diversion of materials for weapons proliferation and secure from terrorist attacks.

In addition to selecting these six concepts for deployment between 2010 and 2030, GIF recognized a number of International Near-Term Deployment advanced reactors available before 2015.

Tables 2 and 3 contain the specifications and fuel cycles of those six reactor technologies.

TABLE 2. Specifications of 6 Gen-IV reactor technologies [4].

| Type | Neutron spectrum | Coolant | Temperature (°C) | Pressure | Size (MWe) | Use |
|---|---|---|---|---|---|---|
| Gas-cooled fast reactors | fast | helium | 850 | high | 1200 | electricity & hydrogen |
| Lead-cooled fast reactors | fast | lead or Pb-Bi | 480-570 | low | 20-180<br>300-1200<br>600-1000 | electricity & hydrogen |
| Molten salt fast reactors | fast | fluoride salts | 700-800 | low | 1000 | electricity & hydrogen |
| Molten salt reactor - advanced high-temperature reactors | thermal | fluoride salts | 750-1000 | | 1000-1500 | hydrogen |
| Sodium-cooled fast reactors | fast | sodium | 500-550 | low | 50-150<br>600-1500 | electricity |
| Supercritical water-cooled reactors | thermal or fast | water | 510-625 | very high | 300-700<br>1000-1500 | electricity |
| Very high temperature gas reactors | thermal | helium | 900-1000 | high | 250-300 | hydrogen & electricity |

TABLE 3. Fuel cycle of 6 Gen-IV reactor technologies.

| Type | Fuel Cycle | Fuel |
|---|---|---|
| Gas-cooled fast reactors | Closed, on site | U-238+ |
| Lead-cooled fast reactors | Closed, regional | U-238+ |
| Molten salt fast reactors | Closed | UF in salt |
| Molten salt reactor - advanced high-temperature reactors | Open | $UO_2$ Particles in prism |
| Sodium-cooled fast reactors | Closed | U-238 & MOX |
| Supercritical water-cooled reactors | Open (Thermal) / Closed (Fast) | $UO_2$ |
| Very high temperature gas reactors | Open | $UO_2$ prism or pebbles |

+: with some U-235 or Pu-239

For the evaluation assessment of the current status of the proposed technology; the following aspects are forecast regarding the research conducted, with technical, safety and non-proliferation considerations taken into account.

Though demonstration of those six concepts are planned to start from 2015 or 2020, those technical roadmaps were updated in 2013 to reflect the latest status of development and difficulty. Current technical situation of Gen IV is shown in Table 4. MSR and GFR are in the validity phase; validation of basic concepts and solving basic technical issues. The other four types are in the performance phase; evaluation of processes, phenomena, material and components in engineering scale or prototype scale. Especially, SFR and HTR (lower temperature than VHTR) type technologies are much more developed than others because of the experiences of construction and operation of reactors. There is no type which is reached in demonstration phase; detail design of system, License acquisition, construction and operation of reactors for implementation reactors which are industrial level.

TABLE 4. Technical situation of Gen IV reactors.

| Type | Status & Challenges | Construction & Operation |
|---|---|---|
| MSR | • Baseline concepts: MSFR, AHTR<br>• No system arrangements have been signed<br>• Main R&Ds:<br>liquid salt physical chemistry and technology | - |
| GFR | • The finalization of the design of a small experimental reactor<br>• The decision on launching the licensing process for the experimental reactor. | - |

| | | |
|---|---|---|
| SCWR | • Start of design studies for a prototype<br>• Main R&Ds:<br>Component tests, Qualification of computational tools and candidate materials, and Out-of-pile & in-pile tests for fuel assembly | - |
| VHTR* | • The construction and operation of HTR-PM<br>• Main R&Ds:<br>Main Thermal hydraulic safety experiments, Qualification of UCO-TRISO fuel, new grades of graphite for VHTR use, and Ni alloys for high temperatures | (HTR)<br>Peach Bottome 1, Fort St Vrain, THTR, HTTR, HTR-10, HTR-PM600 |
| SFR | • Constriction of demonstration reactors<br>• Main R&Ds:<br>Enhanced safety, advanced fuel development, used fuel handling, and economic evaluation, etc. | BN-600, BN-800, CEFR, PFBR, Phenix, SPX, EBR-II, Fermi, Monjy Joyo |
| LFR* | • Lead-cooled experimental reactor starts in 2020<br>• Preparing for higher-temperature designs<br>• Main R&Ds:<br>materials corrosion, a lead chemistry management, and fuel development | (Pb-Bi cooled)<br>experimental reactor, submarine reactors, |

* Not only to generate electricity, but also another potential of the reactors is investigated (i.e. generating hydrogen, industrial utilization of thermal, desalination of seawater) [3], [5].

Table 5 contains the safety features assessment for the six types of reactors of Generation IV. From the safety aspects in the table, it could be listed that the VHTR has clear inherent safety features, with no possibility of an off-site emergency. There are already several prototype projects in the world.

Although the SFR has some risk of positive reactivity insertion, it has enough safety margins. Besides, SFR has the prototype project and in China and Russia. SCWR has mature technology accumulation, which makes it easier during R&D, and the engineering safety features are proven.

LFR is a similar concept to the SFR, which will be some of reference. What's more, Lead has much better physical and chemical characteristics than Sodium, which means the LFR could have better safety features. The MSR and GFR has very good safety concept but has no any engineering experience, both of their safety needs to be proved in the future.

TABLE 5. Safety features assessment [6], [7], [8].

| TYPE | Inherent features | Passive systems and Emergency |
|---|---|---|
| VHTR | 1.Elimination of core melt and radioactivity release<br>2.Plutonium breeding and minor actinide burning | 1.Passive and inherent design features<br>2.Passive decay heat removal<br>3. Unnecessary off-site Emergency<br>4. Prototype project |
| GFR | 1.Lack of accident analysis<br>2. Fuel breeding and/or actinide management | 1. Fully passively safe GFRs are possible<br>2. Lack of engineering experience |
| SFR | 1.Reducing the radiotoxicity and actinide management<br>2.Operation in normal pressure with significant safety margins<br>3.Positive reactivity insertion might result in core damage | 1.Passive shutdown mechanism under R&D<br>2. Prototype project |
| LFR | 1.High thermal inertia and negative reactivity feedback of lead systems<br>2.No loss of primary coolant<br>3. Low chemical activity of Lead<br>4.Full actinide recycling | 1.Strong natural circulation characteristics<br>2.Passive decay heat removal systems<br>3. Reducing the requirements for off-site emergency |
| MSR | 1.Negative temperature and void feedback coefficients<br>2. The absence of in-core reactivity reserve<br>3.Minimization of radiotoxic nuclear waste | 1.A maximum of passive devices to cool the fuel<br>2.Passive draining of the core fuel into passively cooled geometrically noncritical tanks<br>3. Lack of engineering experience |
| SCWR | 1.Conservative design with high reliability and availability<br>2.Proven technology and quality assurance | 1.Automatic depressurization system<br>2.Gravity-driven core flooding system<br>3.Passive moderator cooling system |

Table 6 contains the rank categories in terms of safety that was used to categorize the technology. On the other hand, Table 7 points out the description of the proliferation issues of these technologies.

In fact, it is difficult to predict and compare Gen IV technologies in terms of proliferation risk. Currently, there is already an excellent international mechanism for non-proliferation for all the existing civil nuclear facilities, which definitely will be used for the Gen IV nuclear energy. For the breeding reactors, the risks of proliferation maybe higher during the reprocessing process, but it can be managed well under the current non-proliferation mechanisms.

TABLE 6. The safety rank

| RANK | TECHNOLOGY |
|---|---|
| Demonstration | VHTR, SFR |
| Performance | SCWR, LFR |
| Viability | MSR, GFR |

TABLE 7. Proliferation issues [3],[7]

| TYPE | DESCRIPTION |
|---|---|
| VHTR | Proliferation resistance |
| GFR | Risks in proliferation |
| SFR | Risks in proliferation |
| LFR | Risks in proliferation |
| MSR | No approach dedicated to liquid-fuelled reactors |
| SCWR | Proliferation resistance similar to BWR |

At the end of the evaluation assessment, it was found that the VHTR is the most viable technology to apply at the industry level. The evaluation shows that the technology has satisfied the early viability phase in the development project; as the developers have experience in construction and operation for high temperature reactors gained through their research and development programmes. It was learned that each country has a different VHTR concept and design; but at the same time has the additional application of the generation of hydrogen. It could be said that the high temperature is one of the challenges that needs to be studied more, in order to create a more mature technology.

## 5. Proposal

In order to encourage the development of Gen IV reactors, international collaboration is needed to consolidate the fundamental features of Gen IV design and simplify the process of validation. Based on the above investigation and discussion, NNI-6 group initiated a proposal called “4 Harmony” to achieve the target of harmonization with different international working groups to enhance the level of cooperation.

Many potential initiatives and projects were projected for Gen IV reactors; IAEA conducted the International Programme Innovative Nuclear Reactors Fuel Cycles (INPRO) programme and Generic Reactor Safety Review (GRSR) service; by the other side Organisation for Economic Co-operation and Development/ Nuclear Energy Agency (OECD/NEA) had Multinational Design Evaluation Programme (MDEP) evaluation programme; and World Nuclear Association (WNA) performed the Cooperation in Reactor Design Evaluation and Licensing (CORDEL) workgroup. GIF is an international specific forum that joins information about Generation IV reactors. Different organizations use different systematic languages but at the end, they are working in the development of Gen-IV technology.

A harmonization programme could be a good solution to join the existing organizations that are working in Gen-IV technology for the current development and deployment programs. The 4 Harmony initiative includes 4 levels and Figure 2 contains the main structure of the initiative.


*FIG. 2. The 4 Harmony Programme structure.*

The first one is Academic Training including neutronics, thermal hydraulics, materials, construction, and operation. It is required more human power who can understand deeply the knowledge and the development of the Gen IV technology. The World Nuclear University Summer Institute can be a good place to gather and spread the seed of knowledge.

The second level is Industrial consultant. An International Cooperation Convention among different consultants should be established to assist and support the design and regulation.

The third level is an international committee consisting of IAEA, NEA, WNA and GIF; they will work together to make a judgment on the limitations of the new design. A new design beyond the existing six concepts can get international recognition. This effort could strengthen the confidence of the industry and encourage more and more companies to invest in the Gen-IV areas.

The long-lasting goal is that one international Gen-IV cooperation agency will emerge to implement the common guideline based on consensus and common values for the design technology.

Figure 3 represents a flow chart process to develop an International Cooperation programme; it proposes the junction and international cooperation between organizations. After the selection of the evaluation assessment, this proposal could be applied to know the availability and capability of the technology at industry level. Harmonization with International Standards is a key point in the development of GIF if it is pursued, it could open a channel for International Standardization and regulation which is an important benefit. INPRO project will judge the capability and sustainability of the fuel cycle process of the design proposal, based also on the criteria of GIF. After this, it

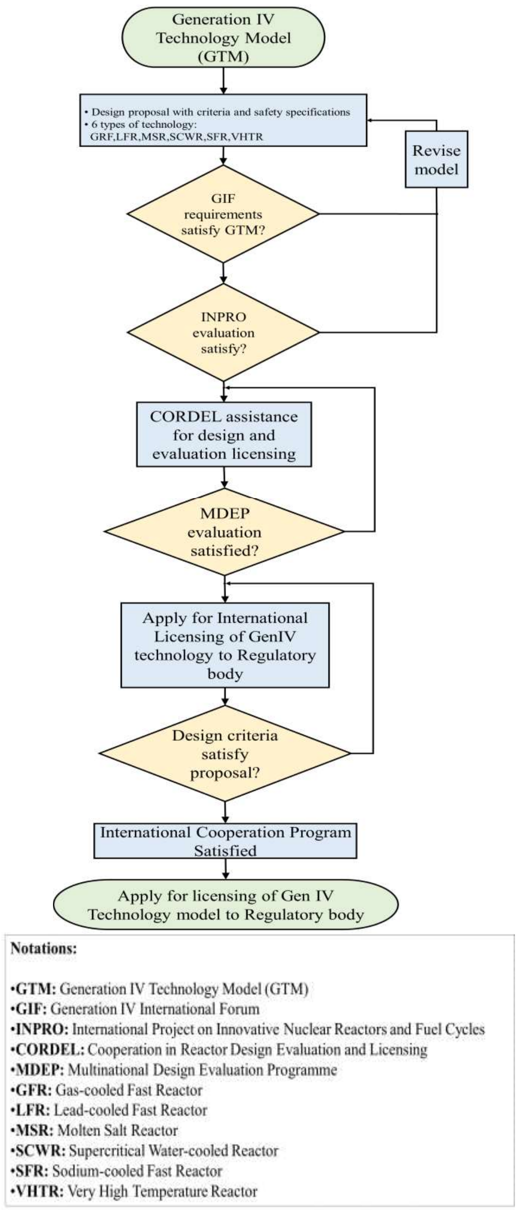


*FIG.3. Development process for international*

will pass the results to MDEP. MDEP could be a strategy for proposing international guidelines that could contain the general criteria for design and safety specifications.

MDEP could be a system controller in this process because it could develop innovative approaches to evaluate the resources and knowledge of national regulatory authorities reviewing new reactor designs. At the end, the final information could support the submission documentation to the National Regulatory Authority for License; it that way the reactor model could be commercialized.

# 6. Conclusion

After reviewing the original proposal of Gen IV and its background, we conclude that Gen IV is not a reactor type, but gives the direction of reactor technology development. Gen IV should meet goals from the aspects of sustainability, economics, safety & reliability, non-proliferation.

Safety and proliferation features of Gen IV are related to the current technical situation. Each type needs to be improved in technological challenges but a deep understanding is needed and supporting evidence before relying on only technical point to build high safety and non-proliferation reactors.

Before the implement of Gen IV NPP, international cooperation is essential on Research, Operation, Regulator, Human resource, etc. It was proposed the "4 Harmony" initiative has the potential to strengthen the connection between existing international organizations and working groups.

**ACKNOWLEDGEMENTS**

We would like to express our great appreciation and gratitude given by World Nuclear University and our respective governments, organizations and companies their assistance and support given during the planning and development of this paper.

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