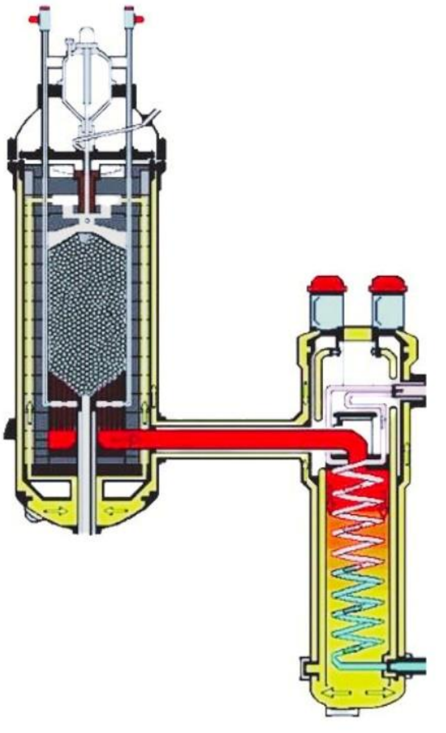
High-Temperature Gas-Cooled Reactor (HTGR) Workshop

18-20 March 2024
Online



Proceedings

MULTINATIONAL DESIGN EVALUATION PROGRAMME
Distributed: English text only

Proceedings of the Workshop on High-Temperature Gas-cooled Reactor (HTGR)

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Contents

List of abbreviations and acronyms

ARN	Nuclear Regulatory Authority (Argentina)
CNPE	China Nuclear Power Engineering Co., Ltd.
CPP	Chemical Process Part
DiD	Defence-in-Depth
FOAK	First-of-a-kind
GIF	Generation IV International Forum
HTGR	High-Temperature Gas-cooled Reactor
HTR-PM	High-Temperature Gas-Cooled Reactor-Pebble-bed Module
IAEA	International Atomic Energy Agency
MDEP	Multinational Design Evaluation Programme
Mozweli	Nuclear Engineering Ltd (South Africa)
NNR	National Nuclear Regulator (South Africa)
NEA	Nuclear Energy Agency
NNSA	National Nuclear Safety Administration (China)
NSC	Nuclear and Radiation Safety Centre (China)
NPP	Nuclear Power Plant
NPPS	Nuclear Power and Process Station
OKBM	OAO I. I. Afrikantov OKB Mechanical Engineering (Russia)
PAR	Passive Autocatalytic Recombiners
PC	Primary Circuit components
PSA	Probabilistic Safety Assessment
Rostechnadzor	Federal Service for Environmental, Technological and Nuclear Supervision (Russia)
RPV	Reactor Pressure Vessel
RSS	Reserve Shutdown System
RSWG	GIF Risk and Safety Working Group
SMR	Small Modular Reactor
SDC	Safety Design Criteria
TR	Technical Report
VHTR	Very High Temperature Reactor

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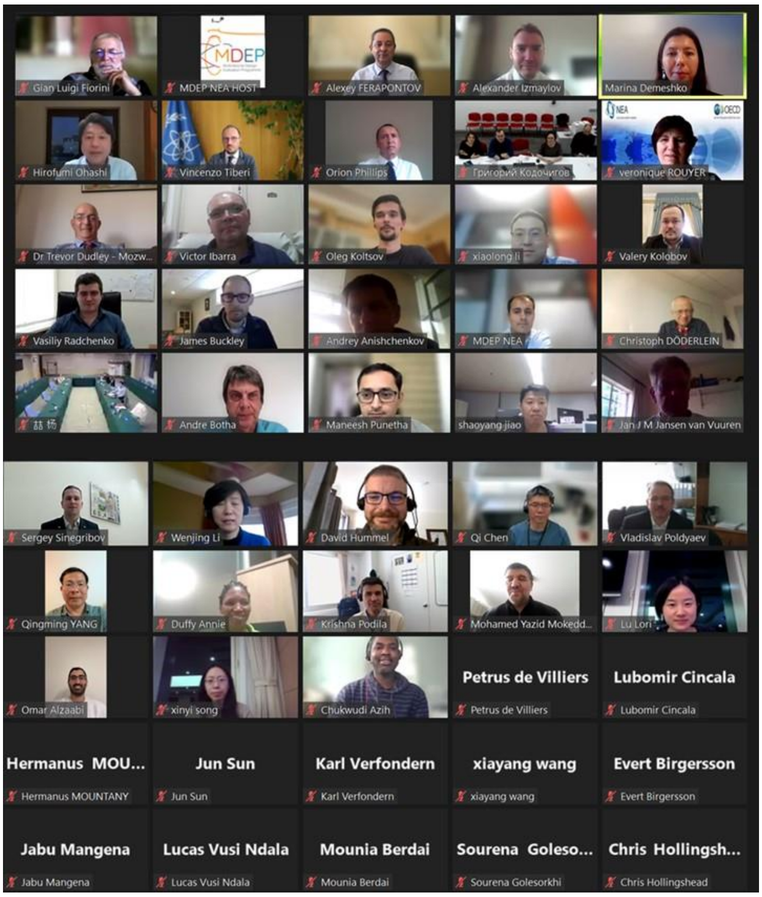
MDEP Workshop on
High-Temperature Gas-cooled Reactor (HTGR)

PROCEEDINGS



1. Introduction

On 18-20 March 2024, MDEP hosted a brainstorming workshop on High-Temperature Gas-cooled Reactors (HTGRs), organized with engagement of international regulatory bodies and key industry stakeholders. This workshop, presented at a pivotal moment in the energy sector, gathered participants from diverse backgrounds to discuss the advancement of HTGR technology.

MDEP's role in facilitating this workshop is essential for fostering international collaboration and harmonisation in the development and deployment of HTGR technology. MDEP provides a unique platform for regulatory cooperation, information exchange, and the development of technical standards and best practices. By supporting early dialogue with industry and encouraging standardisation, MDEP aims to ensure that new reactor technologies meet the highest safety and environmental standards.

During the workshop, participants engaged in discussions on various aspects of HTGR safety. Especially in such important areas as: validation and verification of the codes, fuel safety, research needs, probabilistic safety assessment, defence-in-depth, materials selection and regulatory infrastructure.

The workshop's success **underscores** MDEP's commitment to ensuring the highest standards of safety and security in nuclear technology deployment. The insights gained will inform the establishment of a new working group within MDEP, aligning with efforts supported by the Generation IV forum and NEA to meet the growing demand for advanced nuclear technologies

2. Opening

Mr Alexey Ferapontov, the Chair of MDEP, the Vice Chairman of Rostechnadzor chaired the opening session. On behalf of the MDEP Management Board (MB), he welcomed all the participants and thanked the NEA and the involved colleagues for the organizing and preparing the workshop. He emphasized that the MDEP is a unique international initiative that have been bringing together the resources and knowledge of national regulators with over 16 years, fostering successful collaboration in the cooperative review of safety of new reactor designs, such as ABWR, AP1000, APR1400, EPR, HPR1000 and VVER type technologies, including new passive safety systems, first-of-kind components, innovative materials, new fuel designs, and much more. He indicated that the challenges of energy and environmental change can be overcome through the use of nuclear energy in the new field of energy-intensive technologies. The technology of HTGRs will play a key role in developing new spheres and extending the use of safe nuclear energy. The potential of this reactors will be useful in hydrogen production, production of methane gas mixture, long distance nuclear heat supply, oil production and so on. He stressed that the discussions of the workshop will be the basis for establishing a new working group dedicated to HTGR technology. This new HTGR working group under MDEP will be open for the new members, and will produce technical reports and common positions, that express the regulator's consolidated position. He highlighted the importance of all the topics covered by the workshop such as probably safety assessments of first-of-kind HTGR, verification and validation computer benchmark for HTGR, defence-in-depth principle and applicability for HTGR, etc. He also mentioned two aspects of the future main MDEP activities. The first one is the future MDEP workshop on Light Water Small Medium and Modular Reactors (LW-SMMR), which will be held in June in Turkey and will cover the most important issues related to regulation of SMRs. The other is the international nuclear safety assessment school, which is expected to be launched in 2026 and make a significant contribution to the development of the future MDEP activities related to capacity building of regulatory bodies.

Ms Veronique Rouyer, Head of the Division of Nuclear Safety Technology and Regulation of NEA, on behalf of NEA Director-General Mr William D. Magwood, IV made opening remarks. She thanked the MDEP Chair, and all the participants for attending the HTGR workshop. She noted that the global landscape of nuclear energy is undergoing significant change, with progress in licensing new and innovative reactors, particularly the HTGR type, pointing to a promising direction. While the regulatory process may vary among countries over time, we are united in our commitment to a higher understanding of safety and security in the deployment of this new technology. It is the shared commitment that forms the foundation of MDEP. And MDEP has played a crucial role in leveraging the resources and expertise of national regulator to assess new reactor design. The HTGR workshop convened today is more than gathering of experts; it serves as a platform for collaboration and forum for innovation. It is anticipated to create a synthetic effect affect and applying, applying collective efforts to meet the arising amount for advanced technology.

Mr Yingdong Hou, Deputy Director General of NNSA (China), on behalf of Mr. Baotong Dong, Director General of NNSA (China), made an opening remark. He thanked the NEA and MDEP for inviting NNSA to participate in the workshop. He indicated that China is actively promoting the construction and application of HTGR. The demonstration project of HTGR nuclear power plant at Shidao Bay, China has completed construction and is undergoing operational verification work. Meanwhile, China is also actively exploring the application of HTGR in the petrochemical industry. NNSA has carried out comprehensive supervision of the HTGR demonstration project and other small modular reactors, accumulated review experience and trained a professional review team. NNSA also has issued related guidance documents, safety review principles, technical insights and regulatory requirements. NNSA experts will positively participate in the HTGR workshop discussion and share their experiences and knowledge. He also emphasised that NNSA had a good cooperative relationship with NEA, during the activities of the HPR1000 Working Group and the VVER Working Group, the Chinese side has actively shared its experience and participated in the discussions, and he believed that on the basis of good cooperation among all parties, the cooperation in the HTGR Working Group will be smooth as well.

3. Main sessions

The workshop consisted of discussions among representatives of industry and of national regulatory authorities for nuclear safety dedicated to: Verification and validation (V&V) computer benchmarking for HTGRs, Fuel safety, Research needs relevant to HTGR, Probabilistic Safety Assessment (PSA) first-of-a-kind (FOAK) HTGR, Defense-in-depth (DiD) principles applicability to HTGR, Materials selection for HTGR reactor and primary and secondary circuit, and existing regulatory framework for addressing the specific safety requirements of HTGR.

3.1 Session 1: Verification and validation (V&V) computer benchmarking for HTGRs

The objective of this session was to share the experiences and knowledge about the verification, validation, and certification of computer codes used for HTGR design justification, as well as to explore interesting topics for further research by the MDEP working group.

Session Moderator: Trevor Herbert Dudley, Mozweli

Panellists: Jan J M Jansen Van Vuuren, Mozweli
Sergei Aleksandrovich Rogozhkin, OKBM

Verification and validation (V&V) computer benchmarking for HTGRs: Jan J M Jansen Van Vuuren, Mozweli

During the session, Mr. Jan J M Jansen Van Vuuren covered the topics including the Mozweli status, verification and validation of the code, reactor computational aspects, simulation model, the approaches for using codes to do deterministic and probabilistic analysis and the code benchmarking. He also highlighted the benefit of viewing benchmarking as a process, the high importance of experimental data for V&V, and the benefit of public material from IAEA to conduct V&V.

Computer Codes for HTGR, Verification and Validation: Sergei Rogozhkin, Ilya Fadeev, OKBM

Mr. Sergei Rogozhkin introduced the main stages of verification, validation, and certification of computer codes in Russia, as well as the progress on verification and validation of computer codes used for HTGR design justification. He also highlighted the importance of the information on the experimental data and benchmarks applied to validate the computer codes, as well as information on the planned experiments and the new ones in progress under the HTGR project.

Discussion

During the discussion it was highlighted that in the context of HTGR, benchmarking plays a critical role in ensuring the accuracy and reliability of computational codes. It should be viewed not as a one-time task but as an ongoing process. This approach allows for continuous improvement, aligning the benchmarks with evolving reactor technologies and updated methodologies.

The importance of experimental data in this process cannot be overstated. For Verification and Validation (V&V), experimental data acts as the foundation upon which computational models are compared and calibrated. Without high-quality experimental results, computational models run the risk of delivering inaccurate predictions, which can directly impact the safety and efficiency of HTGR systems. In this context, access to public material from the IAEA becomes a valuable asset.

One of the challenges highlighted in HTGR code development is the need for data integration with material properties when using computational models. Accurate material data — such as thermal properties, mechanical behaviour, and responses under reactor conditions — must be thoroughly integrated to ensure that simulations reflect in situ reactor environments.

While Artificial Intelligence (AI) has emerged as a promising tool in many technological fields, its role in HTGR benchmarking is currently limited to assisting in development rather than verification. The complexity of nuclear systems, coupled with the stringent safety requirements, makes it unlikely that AI will take on a significant role in V&V anytime soon due to the inherent challenges in verifying AI-generated results.

On the innovation front, digital twins are becoming increasingly important for developing HTGR simulators. By creating a virtual model of an operating reactor, digital twins allow for precise simulations of reactor operations. This technology not only enhances the design process but also aids in operator training by providing realistic virtual environments that mirror actual reactor conditions.

Finally, the Multinational Design Evaluation Programme (MDEP) is seen as a vital platform for HTGR developers worldwide. MDEP facilitates international collaboration, allowing developers to anticipate regulatory hurdles and share best practices. This collective approach ensures that HTGR technologies progress efficiently while maintaining the highest safety standards across global markets.

By focusing on these key areas—benchmarking as a process, integration of experimental data, and international cooperation—HTGR developers can push forward with more reliable, safer, and standardised reactor designs.

3.2 Session 2: Fuel safety

The objective of this session was to clarify the safety objectives of the HTGR fuel, and to share the experiences and knowledge about the key safety properties of HTGR fuel and the necessary regulatory approaches to guarantee the fuel safety, as well as exploring interesting topics for further research by the MDEP working group.

Session Moderator: Trevor Herbert Dudley, Mozweli
Panellist: Orion Phillips, NNR

Fuel safety requirements: HTGR, Orion Phillips, NNR

Mr. Phillips introduced the concept of the TRISO Fuel, as well as the safety requirements relevant to its design, manufacture, qualification, and application. He highlighted that the safety objectives of the TRISO Fuel is to adequately maintain its integrity to contain fission products under operating and accident conditions; the key safety properties of the TRISO Fuel, including mechanical, geometrical, and chemical properties, should be properly managed and regulated for both irradiated and un-irradiated fuel; the performance of the fuel under normal and accidental conditions is the key to the safety of the HTGR/SMR; It is essential that the design, fabrication and qualification of the fuel is adequately and properly regulated by the regulatory body to ensure that the fuel meets the required high level of safety performance; The HTGR fuel qualification requires from several months to beyond one year on average; There are special safety considerations for TRISO fuel fabrication facilities.

Discussion
In the context of fuel safety, particularly for HTGR and TRISO fuel, ensuring that the fuel can adequately contain fission products under both operating and accident conditions is paramount. The primary safety objective of TRISO fuel is to maintain its integrity throughout the reactor's lifecycle, preventing the release of radioactive materials and ensuring reactor safety during normal operation as well as in extreme scenarios like accidents.

Key safety properties of TRISO fuel—such as its mechanical strength, geometrical precision, and chemical stability—need to be carefully regulated. This applies to both irradiated and un-irradiated fuel, as any deviation from safety standards could compromise its performance. Proper management of these properties ensures that the fuel can maintain its containment capabilities under different operational stresses.

The fuel's performance during normal and accident conditions is critical for the overall safety of HTGR reactors and Small Modular Reactors (SMRs). Since fuel integrity directly impacts the reactor's safety margins, comprehensive testing is required. It is essential that the design, fabrication, and qualification of TRISO fuel are thoroughly regulated by the appropriate regulatory bodies to guarantee the fuel meets the high safety standards expected of modern nuclear reactors.

The qualification process for HTGR fuel is time-consuming, often taking several months to over a year. This extensive period is necessary to ensure that every aspect of the fuel's performance is thoroughly validated before it is deemed safe for use in reactors. Additionally, special safety considerations must be given to TRISO fuel fabrication facilities, where the complex process of fuel production is carried out under stringent safety protocols to prevent any potential hazards during manufacturing.

3.3 Session 3: Research needs relevant to HTGR

The objective of this session was to share the experiences and knowledge about the R&D for the design of the HTGR, as well as to find out the interesting topics for further research by the MDEP working group.

Session Moderator: Tatiana BOGDANOVA, Rostechnadzor
Panellist: Grigorii Kodochigov, OKBM

R&D for Design Substantiation of a Nuclear Process and Power Station with HTGR: Igor Marov, Grigorii Kodochigov, OKBM

During the session, Mr. Grigorii Kodochigov covered the following topics, including the General Information on the Design of HTGR in Russia, the status of R&D for RSS absorber elements and burnable absorber compact, the status of R&D for Fuel, the status of R&D for Reactor-Grade Graphite, the status of R&D for High-Temperature Materials, the status of R&D for the Chemical Process Part, the status of R&D for Hydrogen Safety, and the regulatory provisions for the NPPS Design with HTGR and CPP. He also highlighted the importance of the cooperation of key equipment developers, and the integrated programme for analytical and experimental development for the design of the HTGR.

Discussion

Research on High-Temperature Gas-cooled Reactors (HTGR) has been significantly advanced through wide-scale R&D efforts focused on several critical areas. One of the key areas is the testing of technology aimed at the production of fuel and the manufacturing of essential components for the reactor core. These components must withstand high temperatures, which necessitates further work on materials, particularly high-temperature-resistant materials and reactor-grade graphite. Additionally, the verification and qualification of computer codes for safety and operational modelling have been a vital part of this research. In the context of the HTGR's layout, the reactor is located 200 metres from the hydrogen production plant. Thus, hazards related to hydrogen production are considered as external factors in safety assessments. Further, in terms of severe accident analysis, graphite oxidation has been studied under controlled assumptions, such as no flame involvement and a temperature ceiling of 680°C, which prevents severe burning. Calculations related to potential radiation release during severe accidents have indicated that the exposure levels would not be significant enough to necessitate evacuation of the population. It was also noted that hydrogen diffusion is considered possible only when microdefects are present or in unsealed sections of the structure. Additionally, potential helium leakage/loss has been thoroughly analysed, and design adaptations have been made to ensure containment and safety.

This extensive **research** highlights the focus on safety, material integrity, and operational reliability as essential components in the ongoing development of HTGR technology.

3.4 Session 4: Probabilistic Safety Assessment (PSA) first-of-a-kind (FOAK) HTGR

The objective of this session was to share the experiences and knowledge about the regulatory requirements of the PSA and the review practices of the PSA for HTGR, as well as to find out the interesting topics for further research by the MDEP working group.

Session Moderator: Tanju Sofu, Argonne National Laboratory, USA/GIF representative
Panellist: Yu Gong, NSC

Application of PSA in high-temperature reactors: Yu Gong, NSC

Mr. Gong introduced the regulatory requirements of the PSA in China, as well as the review practices of PSA for the HTR-PM. He pointed out the potential application areas of the PSA in the future. He also highlighted that since the deterministic safety requirements for HTGR have not been fully established, the PSA can play a more important role in the design and licensing of HTGR with the support of deterministic method and engineering/expert judgement; the PSA can also be used in the demonstration of safety objectives, categorisation of event sequences in different plant states considered in the design, selection of important beyond design basis accident sequences and design extension conditions, demonstration of design alternatives, safety classification of structures, systems, and components, and evaluation of defense-in-depth (DiD) adequacy; To issue practical regulatory principles and to have a clear regulations for defining the safety objectives and the boundary conditions by the regulatory body could be the meaningful measures to facilitate the design and commissioning of the HTGR. To define reasonable metric for consequences (dose limit at the site boundary, as well as cumulative risk targets such as the annual dose and/or the risk for early/latent fatalities) could be a good input for performing PSA and demonstrating the safety of the HTGR design; The risk analysis addressing the HTGR passive system reliability or failure should not be neglected.

Discussion
Since the deterministic safety requirements for HTGRs have not been fully established, PSA (Probabilistic Safety Assessment) can play a more significant role in their design and licensing, with support from deterministic methods and expert engineering judgement. PSA can be utilised to demonstrate safety objectives, categorise event sequences across different plant states considered in the design, and select important beyond design-basis accident sequences and design extension conditions. Additionally, PSA can aid in demonstrating design alternatives, the safety classification of structures, systems, and components, and the evaluation of defense-in-depth (DiD) adequacy.

To facilitate the design and commissioning of HTGRs, it is crucial for regulatory bodies to issue practical regulatory principles and clear guidelines for defining safety objectives and boundary conditions. Furthermore, defining reasonable metrics for consequences, such as dose limits at the site boundary and cumulative risk targets (e.g., annual dose or the risk of early/latent fatalities), would be beneficial for performing PSA and demonstrating the safety of the HTGR design. Lastly, the risk analysis of HTGR passive system reliability or failure must not be overlooked, as it is a critical aspect of ensuring reactor safety.

3.5 Session 5: Defence-in-depth (DiD) principles applicability to HTGR

The objective of this session was to emphasise the Defence-in-depth (DiD) principles, and to share the considerations about the application of the Defence-in-Depth Principle in the design of the HTGR, as well as to find out the interesting topics for further research by the MDEP working group.

Session Moderator: Vincenzo Tiberi, IAEA
Panellist: Andre Botha, NNR

Defence-in-Depth (DiD) Principle for the HTGR: Andre Botha, NNR

Mr. Botha introduced the regulatory requirements on the Defence-in-Depth in South Africa, as well as the considerations about the application of the Defence-in-Depth Principle, including the safety functions, the levels of DiD, the barriers, the accident prevention, and the accident mitigation. He also highlighted the importance of maintaining the concept of defence-in-depth in the design of the HTGR and recommended that the design shall prevent the challenges to the integrity of physical barriers, failure of one or more barriers, failure of a barrier because of the failure of another barrier and the possibility of harmful consequences of errors in operation and maintenance, as far as is practicable.

Discussion

There were differing views on the application of Defence-in-Depth (DiD) for HTGRs: whether to maintain the principle as currently defined (with 4 levels concerning design, including severe accident conditions) or adopt a different approach tailored to HTGRs. In the first case, a case-by-case discussion would be needed to account for the design's specificities, such as the types of accidents considered at each DiD level. The second approach could introduce a new structure with varying levels or sublevels, and potentially different requirements for their independence.

It was noted that the public might not be receptive to varying basic safety principles for different reactor designs. Most discussions centred around the 4th level of DiD and the definition of a severe accident for HTGRs. The potential for severe accidents in HTGRs was acknowledged to be low probability, and a definition based on fuel temperature (T>1600°C) was proposed.

The role of passive systems was also discussed, with emphasis on the need to assess their reliability. A specific issue regarding nitrogen injection in the containment in case of air ingress was raised. One designer pointed out that if the amount of air is insufficient to promote graphite oxidation and potential TRISO fuel failure, nitrogen injection is unnecessary. However, if the air volume is significant, nitrogen injection would be ineffective, and an alternative solution would be required.

3.6 Session 6: Materials selection for HTGR reactor and primary and secondary circuit

The objective of this session was to share the experiences and knowledge about the principles, the approaches, and the practices of the material selection for the HTGR reactor and primary and secondary circuit, as well as to find out the difficulties and interesting topics for further research by the MDEP working group.

Session Moderator: Alina Constantin, IAEA
Panellist: Shaoyang Jiao, CNPE

The investigation of material selection and performance for gas-cooled micro-Reactor Pressure Vessel (RPV): Shaoyang Jiao, CNPE

Mr. Jiao introduced the design concept of mobilised GCMR, the design input of RPV, RPV material selection principle, the work for material selection analysis, and the verification of material performance of the selected 316H. Based on the data collected from the verification process for 316H, he concluded some initial results: The stress rupture of 316H with specific melting method was higher than the values stipulated in the code; The carbide precipitated along grain boundary after 7000 hrs at 550℃, whereas no brittle phase precipitated, thus the thermal ageing effect is not sensitive; The irradiation damage at the required fast neutron fluence (0.01dpa) can be negligible; The corrosion effect in the helium with impurities in certain range can be negligible; The high temperature environment affects the lifespan of the materials and components, thus its operational lifetime is significantly shorter than for Pressurized Water Reactors (PWR).

Discussion

The design concepts of the mobilised Gas-Cooled Modular Reactor (GCMR) include several critical aspects, particularly focusing on the design input for the RPV, the principles of RPV material selection, and the comprehensive process of material selection analysis. This process ultimately led to the verification of the material performance of the chosen 316H stainless steel alloy.

Key initial results from the verification of 316H include:

- Stress Rupture: The stress rupture performance of 316H, manufactured using a specific melting method, exceeded the values prescribed in the applicable codes.
- Carbide Precipitation: After 7,000 hours of exposure at 550°C, carbide precipitation was observed along the grain boundaries, but no brittle phase formed, indicating that thermal ageing effects were not particularly sensitive in this environment.
- Irradiation Damage: The damage caused by irradiation at the required fast neutron fluence (0.01 dpa) was deemed negligible.
- Corrosion: The effect of corrosion in helium with impurities within a specified range was considered negligible.

Additionally, it was noted that the high-temperature environment and radiation fluence impact the lifespan of the materials and components in GCMRs, leading to a significantly shorter operational lifespan when compared to that of PWRs. This underscores the importance of selecting materials capable of withstanding these conditions to ensure the safety and reliability of the reactor.

3.7 Session 7: Existing regulatory framework for addressing the specific safety requirements of HTGR

The objective of this session was to share the experiences and knowledge about the regulatory framework including the regulatory body, the rules & criteria, and the regulatory practices for regulating the HTGR, as well as to find out the interesting topics for further research by the MDEP working group.

Session Moderator: Alexander Izmailov, SEC NRS

Panellists: Hirofumi Ohashi, JAEA
Sergey Sinegribov, SEC NRS

GIF VHTR Safety Design Criteria: Hirofumi Ohashi, JAEA

Mr. Ohashi introduced the background and the process of developing Safety Design Criteria (SDC) for the specific Gen-IV systems – Very High Temperature Reactors (VHTR) by Generation IV International Forum (GIF), the VHTR safety principles, and the VHTR Safety Design Criteria revisions. He also highlighted the reference requirements included in the VHTR SDC for the safety design of structures, systems, and components consistent with high-level GIF safety goals and RSWG safety approach.

Existing regulatory framework for addressing the specific safety requirements of HTGR: Sergey Sinegribov, SEC NRS

Mr. Sinegribov introduced the Legal and Regulatory Framework of the Russian Federation, the Authorized Body of State Safety Regulation, the SEC NRS Activities, the Federal Rules and Regulations in the Field of Atomic Energy Use, the specific characteristics of the HTGR regarding the fuel, the core, the heat transfer, and the accident progression. He also highlighted that to regulate the safety of prospective HTGRs, it is necessary to consider their specific features in terms of nuclear fuel, core configuration and system of heat removal, specific accident sequences, and the impact of the technological part.

Discussion
GIF has developed SDC specifically for VHTR systems. These criteria are aimed at setting reference safety requirements for the design of structures, systems, and components that are consistent with GIF's high-level safety goals and the safety approach of the Risk and Safety Working Group (RSWG). The VHTR SDC addresses the unique safety principles and design features inherent to VHTR technology to ensure safe operation, prevent hazardous events, and establish effective mitigation procedures and organisational processes for handling any events that do occur.

It's important to note that while the SDC provides a strong safety framework, removing or weakening requirements could negatively impact public perception regarding the safety and trustworthiness of these advanced reactors. Moreover, there is ongoing work related to accident analysis, which will require additional data to fully support the safety case for VHTR systems.

These safety design efforts are essential as the world continues to explore advanced nuclear technologies with higher safety and efficiency standards.

3.8 Session 8: Conclusion

The objective of this session was to discuss and define the key insights and challenges and recommendations from each session to support the selection of the topics for further researched by the MDEP working group in the future.

Session Moderator: Alexey Ferapontov, Rostechnadzor
Panellists: Presenters and moderators of all the sessions

Regarding verification and validation (V&V) computer benchmarking for HTGRs, the key identified challenges and recommendations are:

- Need of very good computer software representations of physical models and of mathematical equation simplification.
- Challenges regarding the applicability of verified Gen-III Codes and limitations on Generation IV Reactor Verified codes.
- All programmes used for justifying and ensuring the safety of nuclear facilities must be certified.
- The challenge and need of obtaining new experimental data aimed at verification and validation of computer codes for HTGR (e.g. thermo-hydraulics, neutron physics, etc.).
- Simulation of behaviour of materials and phenomena over long periods of time as a key challenge.
- Challenge of analysing system behaviour when subjected to extreme conditions.
- Benefit of using shared databases of codes.
- Simulation of physical characteristics for fuel elements as a challenge.
- Need for international collaboration in code benchmarking.

Regarding fuel safety, the key identified challenges and recommendations are:

- To define an adequate and proper procedure for the regulation of design, fabrication, and verification of the fuel by the regulatory body.
- To apply the PSA method in the safety assessment for the design and manufacture of the fuel to improve the regulatory capacity in the regulation of the new fuel.

- To collect, share and analyse the fuel test results to have a better understanding of the fuel behaviour to improve the safety of the fuel at the international level.
- Develop safety strategy for accident management.
- Need to investigate on special accidents for TRISO fuel.
- It might be interesting to do a benchmark on the differences in material properties between prismatic fuel and pebble fuel.

Regarding research needs relevant to HTGR, the key identified challenges and recommendations are:

- The main challenge for R&D area is the need of further developments for the consequent safety justification of a new NPP.
- Relevant R&D should be continued with focus on the appropriate high-temperature resistant materials, reactor-grade graphite, verification of calculation models, consideration of uncertainties and thorough safety analysis of a new NPP.
- There are minor differences in the results of irradiation tests for prismatic reactors fuel and pebble fuel. It might be interesting to clarify those.

Regarding Probabilistic Safety Assessment (PSA) first-of-a-kind (FOAK) HTGR, the key identified challenges and recommendations are:

- It is strongly recommended for the regulator to establish clear safety objectives, the HTGR-specific requirements for PSA (such as the format and content of the probabilistic safety assessment report), and adequate consequence metric for quantifying the risk to facilitate the design and commissioning of HTGR.
- It was proposed to establish a component reliability database for HTGR SSCs at the international level to facilitate the further development of HTGR.
- To study and define the severe plant conditions and a list of accidents considered in the PSA of HTGR will be of common interest to both the designers and the regulators.
- It was recommended to initiate benchmark models for comparison of the computer programs used in the PSA for HTGRs

Regarding Defense-in-depth (DiD) principles applicability to HTGR, the key identified challenges and recommendations are:

- A key challenge is to harmonise regulatory frameworks from a technology neutral standpoint (as far as possible). This includes the difficulty to define a DiD approach that is applicable to different technologies and designs.
- Regarding HTGRs, a challenging point is to analyse how the different roles of the barriers can affect DiD.
- The definition of a severe accident and 'practically eliminated' situations for HTGRs remains a source of debate.
- A difference of views also remains regarding the need of an emergency planning zone for HTGR versus eliminating the need for offsite emergency response.
- The products of other international platforms such as the IAEA SMR regulators forum or the Generation IV international forum is a good starting point to be considered by MDEP, especially the work related to DiD.
- The definition of a risk-informed approach as a combination of DSA and a PSA developed following the logic of DiD was suggested.

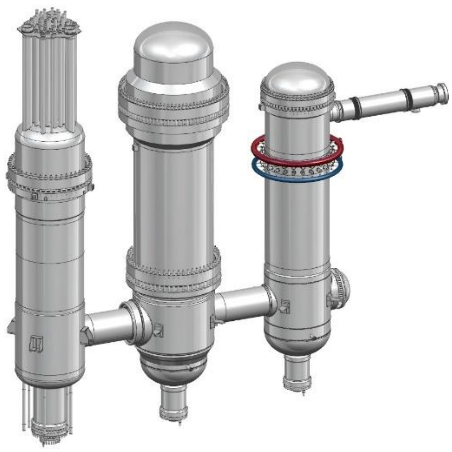
- Incorporating to regulations full functional independence of DiD levels instead of independence as far as feasible has also been proposed.
- It was proposed that MDEP should establish regulatory expectations for safety classification of plant equipment at different Defence-in-Depth levels.
- Proposal to develop a system of requirements/ classification of equipment based on DiD levels.

Regarding Materials selection for HTGR reactor and primary and secondary circuit, the key identified challenges and recommendations are:

- According to the widely used ASME III-D5 code for material selection, it lists limited types of materials that can be used in HTGR, which has limited the development of HTGR.
- It is suggested to develop a guideline at the international level for the introduction and verification of new materials for HTGR.
- Due to the high temperature design properties of HTGR and the special requirements for the material, it is highly recommended to initiate benchmark on the material selection to have more knowledge about different options of materials for HTGR.
- Clear guidance on safety grade classification for the structure systems and components for HTGR reactors is required for designers and regulators.

Regarding existing regulatory framework for addressing the specific safety requirements of HTGR, the key identified challenges and recommendations are:

- It is necessary to take into account specific features in terms of nuclear fuel, core configuration and system of heat removal, specific accident processes, impact of the technological part.
- Need to amend regulatory framework for the Nuclear Power and Process Station (NPPS) with HTGR design development.
- Gaining experience in licensing of a new type of nuclear power stations operated for power and process sector remains one of the main objectives.
- Since some regulators do not accept the principle of dynamic containment, this has to be part of discussions during the licensing and pre-licensing process.
- A difference of views also remains regarding the containment systems and practical elimination, which will require more discussions, especially between GIF and MDEP.
- Further discussion on containment vs confinement can help to develop the methodology and best practice to determine the radionuclide inventory of the primary circuit, and further the potential radioactive dose to the public. The discussion should consider IAEA TECDOC requirements.



4. Closing remarks

Mr Alexey Ferapontov, the chairman of MDEP, the Vice Chairman of Rostechnadzor chaired the closing session.

Mr Alexey Ferapontov thanked NEA Director-General Mr William D. Magwood, IV for his continued support and personal involvement in MDEP activity and invited him to make a closing remark.

Mr William D. Magwood thanked Mr Alexey Ferapontov for the efforts as the chairman of both HTGR workshop and MDEP and congratulated the success of 3-day HTGR workshop and the very valuable discussion, which had over 300 register participants from all over the world. He indicated that HTGRs are one of the most important advanced technology areas being worked on. While dealing with the need around the world to reduce CO_2 emissions, one of the most difficult to abate areas will be the replacement of fossil fuels using in chemical processes and industrial processes that need high temperature heat. HTGR do this extraordinary well. So, to get make progress we're going to have to work more globally. MDEP's entire purpose is to make it possible for nuclear safety technology experts to coordinate activities to have a more global approach to these technologies, so they can be deployed around the world. The discussions of HTGR workshop are extremely important. It shows the value of MDEP as a continuing platform for cooperation. And finally, he highlighted that we are going to have many more opportunities like this to continue this kind of collaboration, this kind of engagements as we go forward to future, particularly in the area of HTGR safety.

Mr Alexey Ferapontov then made a conclusion remark. He expressed the gratitude to the secretary of MDEP, to all the colleagues from NEA and other countries involved in the preparation of this workshop, and to all the participants who actively participated in the event. He highlighted the significant role of this workshop. During the sessions, we got important feedback from participants with various news and up to date actual information on projects development. It has also brought in the position of industry and regulators closer together in a certain way, which is also necessary. He also highlighted that the common factors are that our further solution lines within the framework of cooperation in MDEP. Time during working within existing groups has led to a more consistent approach to safety relation, ensuring that the highest safety standards are met in all MDEP countries, which is the main value of MDEP and will be a main goal of the HTGR working group.