Critical assessment of the safety of advanced manufacturing processes for internationally relevant SMR concepts - project overview

Martin Werz[1], Sven Sewalski[2], Linda Mally[3], Lisa May[2]

[1] Dr.-Ing., Material Testing Institute (MPA), University of Stuttgart, Stuttgart, Germany (martin.werz@mpa.uni-stuttgart.de)
[2] M.Sc., Material Testing Institute (MPA), University of Stuttgart, Stuttgart, Germany
[3] M.Sc., Institute for Materials Testing, Materials Science and Strength of Materials (IMWF), University of Stuttgart, Stuttgart, Germany

ABSTRACT

In many countries around the world, nuclear energy is being considered a long-term target technology or at least a bridge technology to replace fossil fuel power plants and reach international climate goals. In particular, small modular reactors (SMRs) appear promising, as they can be operated as a complement to renewable energy sources, thereby increasing energy security. For this reason, new reactor concepts are being developed internationally based, for example, on light-water reactor technology or high-temperature gas-cooled reactor technology. In order to maintain the competence with regard to the assessment of newly developed reactor concepts, the German Federal Ministry for Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV) is funding a research group at the Material Testing Institute (MPA), University of Stuttgart which runs under the administration of the German association for reactor safety (GRS). The aim of this research group is to build up far-reaching competences for the assessment of the safety of advanced manufacturing methods that are considered internationally by companies or research organizations to be used to produce SMRs. Therefore, the main manufacturing processes including Laser Powder Bed Fusion (LPBF), Wire Arc Additive Manufacturing (WAAM), Electron Beam Welding (EBM), Hot Isostatic Pressing (HIP) and Cold Spray (CS) coating are taken into account within the research group. Beside qualification of these manufacturing techniques the behavior of additively manufactured specimen under the influence of hydrogen, high-temperature stress, liquid metal corrosion, and dynamic behavior in the context of accident loading is investigated for different candidate materials. In addition, additively manufactured liquid metal heat pipes are used as a notional example to evaluate the impact of various advanced manufacturing processes on the functional and structural safety of such components. International networks and collaborations will be developed and strengthened during the course of the research project.

INTRODUCTION

New reactor types are being developed around the world. Instead of the construction of large power plants, which often take many years to build and become incalculably expensive due to delays, concepts for small modular reactors (SMRs) with outputs < 300 MWel are playing an increasingly important role [IAEA (2011), NEA (2020), USNRC (2020)]. Every two years, and most recently in 2020, the IAEA publishes an overview of almost all current SMR concepts. This "handbook" currently comprises 84 concepts from 17 countries and divides them into five categories: water cooled SMRs, high temperature gas cooled SMRs, fast neutron spectrum SMRs, molten salt SMRs and micro modular reactors [IAE (2020)]. Prominent exemplary SMR concepts are the reactors from Oklo Inc. (Aurora Powerhouse), Westinghouse Electric Company (eVinci) or Toshiba Energy Systems & Solutions Corp. (MoveleX).

Many of the SMR concepts that are currently being pursued worldwide are based on the established concepts of light water reactors [IAEA (2020)]. The processes, materials and damage mechanisms for light water reactors are very well understood. Unresolved issues for SMRs lie primarily in the new manufacturing processes that have yet to be established and in the monitoring and maintenance concepts that arise from the special boundary conditions of SMRs, such as size and accessibility. Additional concepts are being investigated that are based on Generation IV reactors or pursue completely new approaches - in some cases, concepts from the 1960s that have not yet been tested, or at least insufficiently tested in terms of safety, are revisited [IAEA (2020)]. These reactor types place completely different demands on materials and manufacturing qualities, e.g. due to higher temperatures and different cooling and working media, for which safety concepts must therefore be rethought [IAEA20]. These include, for example, microreactors whose nuclear fuel is in the form of a molten salt or liquid metal, as well as monolithic reactor cores in which the heat is transferred to a gaseous working medium such as helium via heat pipes [Lane (2022), Westinghouse (2022)].

A safety analysis and risk assessment of SMR concepts was therefore commissioned and carried out by the German Federal Office for the Safety of Nuclear Waste Management. It was found that safety concepts for this and for components manufactured using new production technologies are still lacking [BASE (2021)]. It lists general principles for nuclear technology to ensure safety functions. In addition to the preference for inherently safe mechanisms, redundancies, passive systems and quality checks, the use of qualified materials, manufacturing and testing procedures and sufficiently tested equipment are listed in particular [BMUB (2015)]. For the assessment of nuclear activities in neighbouring and more distant countries, German government bodies are willing to maintain its expertise in this field and build up this expertise for new reactor types by critically observing global developments. The development and use of SMRs leads to the necessity to be evaluated in a discerning way. Although the plants are smaller and therefore contain less fuel, the risks inevitably add up with a large number of plants and accidents and incidents become more likely simply due to the growing number or plants that are expected to be in operation in the next years. The development of expertise for an independent safety assessment of these technologies is only possible in a cooperative dialog with relevant international partners. In order to actively participate in international developments, it is essential to not only deal with the topics theoretically, but also to produce the materials and investigate the manufacturing processes. For this reason, the German Federal Ministry for Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV) is funding the research group SiFeKo at the Material Testing Institute (MPA) which works in cooperation with the Institute of Nuclear Technology and Energy Systems (IKE) at the University of Stuttgart. The project runs under the administration of the German association for reactor safety (GRS). The aim of this research group is to build up far-reaching competences for the assessment of the safety of advanced manufacturing methods that are considered to be used to produce SMRs.

For the investigations, an SMR concept consisting of a monolithic block into which a large number of liquid metal heat pipes are inserted, a so-called solid state SMR, was selected as a case study. This concept is also used in a design developed by Westinghouse called eVinci. This reactor concept offers the opportunity to investigate many unresolved issues that are also relevant for a large number of other SMR concepts currently being pursued. The critical assessment of reactor safety in SMR plants is consequently covered in a representative and internationally broad manner using the example of the selected concept:

- New manufacturing processes are used here, for which the necessary manufacturing qualities and tolerances for manufacturing defects have yet to be defined. The production of the steel monoliths in particular is very complex.
- In addition, stresses that could occur during transportation of the reactors already loaded with fuel and possible accidents in the plants, which generate high dynamic loads on the components, must be considered.
- The operating temperatures of the reactors can reach up to 700 - 800 °C, which requires the use of other materials than those already established in light water reactors. Inevitably, phenomena such as creep must be considered when considering safety, which until now have only been known from conventional high-temperature applications.

- The influence of hydrogen on additively manufactured materials must also be investigated, as well as the influence of corrosion of liquid metal heat pipes by liquid metals at high temperatures.
- The heat transport in the additively manufactured heat pipes also plays a role here and is determined by simulations and experiments.
- Suitable non-destructive testing methods must be developed or adapted for the new material states resulting from the new manufacturing methods, which can prove the necessary structural integrity during production and in the event of failures. Another challenge here is the geometric compression, which is required by the concept on the one hand and simultaneously is made possible by modern CAD systems on the other.

SCIENTIFIC AND TECHNOLOGICAL GOALS

The aim of the research group is to build up extensive expertise in the safety assessment of new manufacturing methods that are considered for with the production of SMRs. In the cluster, a reactor type is closely examined from various angles in order to acquire knowledge about manufacturing additions, damage developments and effects and to be able to assess the safety of such plants accordingly. The overall scientific objective is to gain a comprehensive understanding of the processes in reactor types with liquid metal heat pipes and high operating temperatures from production to the end of their service life, with regard to the safety of the plant during operation and in the event of an accident. The project is divided into seven work packages. Each work package focuses on a specific research question and is described in more detail below.

New Manufacturing Methods

Discussions at international network meetings (e.g. Gateway for Accelerated Innovation in Nuclear GAIN) and workshops (e.g. U.S. NRC Workshop 2020) show that modern and advanced manufacturing processes play a central role in the future production of SMRs. Due to the modular design and reduced size of SMRs, factory production is possible with these concepts. Five key technologies in advanced manufacturing have currently been identified for the future production of components for new reactors. This includes Laser Powder Bed Fusion (LPBF, SLM) for small and complex parts, Wire Arc Additive Manufacturing (WAAM) for parts of the pressure vessel, Electron Beam Welding (EBW) for high wall thicknesses, Hot Isostatic Press (HIP) part manufacturing for large and complex parts and Cold Spray coating (CS) for austenitic corrosion protection layers [U.S.NRC. (2020)]. Combinations of different processes during production are supposed to be required for the manufacturing of larger structures, e.g. electron beam welding of HIP-manufactured parts [Gandy (2020)].

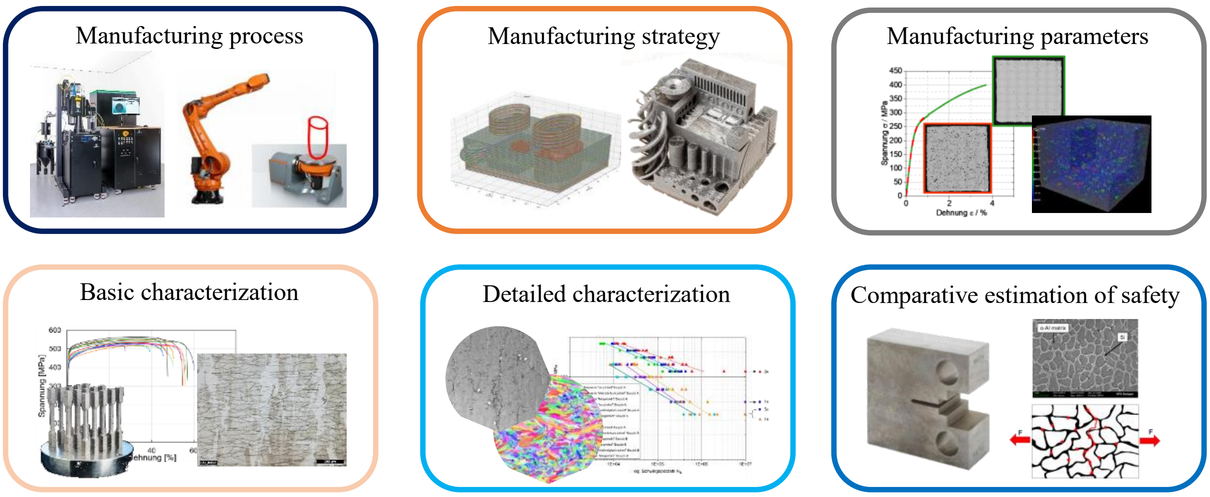

Figure 1: Applied methodology of characterizing advanced manufacturing processes.

In this work package, the influence of these manufacturing techniques on the safety of the considered SMR concept is evaluated. Therefore, possible imperfections, including their type, size, probability of occurrence, and, their impact on the structural integrity are analysed and quantified. Based on that, evaluation groups and admissibility limits are defined. Furthermore, a database for the safety assessment, particularly with regard to expected process variations in an industrial setting, is developed. Three different materials (316L, Inconel 718, 22NiMoCr3-7) are used to manufacture the specimen needed for this as well as all other work packages of the project. However, depending on which research question is followed only a subset of the mentioned materials is required.

As part of the BMUV project MeKomII (FKZ 1501596A), it was demonstrated that the reactor pressure vessel material 22NiMoCr3-7 can be processed using LPBF. Similar material properties to the conventional manufactured reference material could be achieved [Mally (2022)]. However, this raises completely new questions with regard to quality assurance and the safety of the components produce.

Liquid Metal Heat Pipes

The Westinghouse reactor concept investigated in this research project envisages the use of liquid metal heat pipes as a passive, redundant heat transfer system. Using the example of additively manufactured liquid metal heat pipes, the suitability of the manufacturing processes (LPBF, WAAM) for the production of safety-critical nuclear components will be demonstrated. Because of the thermodynamical background and wide experimental expertise IKE will test the additively manufactured liquid metal heat pipes for their overall functionality. Furthermore, the heat pipes will be quantitatively analysed and evaluated in detail with regard to their specific heat transfer characteristics on the basis of thermal parameters (e.g. thermal resistances, heat transfer rates).

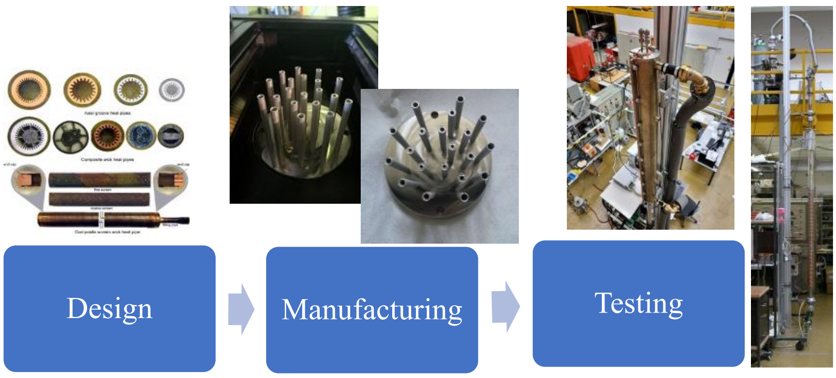

Figure 2: Steps of analysing additively manufactured liquid metal heat pipes.

Interaction of Hydrogen with New Manufacturing Processes

Hydrogen causes embrittlement in almost all metals and can be formed as a fission product during the radiolysis of water. This is a well-known phenomenon in light water reactors (LWRs). Although the Westinghouse eVinci concept does not rely on water for cooling or operating the microreactor, there are numerous SMR concepts based on LWR technology that are being vigorously pursued worldwide.

For this reason, the influence of hydrogen on the behavior of safety-critical, additively manufactured components is being investigated in this work package. The objective is to evaluate the hydrogen suitability of the respective materials and material states resulting from advanced manufacturing processes (LPBF, WAAM). The different sizes and distribution of porosity, dislocations, phase fractions, precipitation and anisotropy lead to the expectation that there might be significant differences in the hydrogen susceptibility than chemical equivalent casted or forged materials.

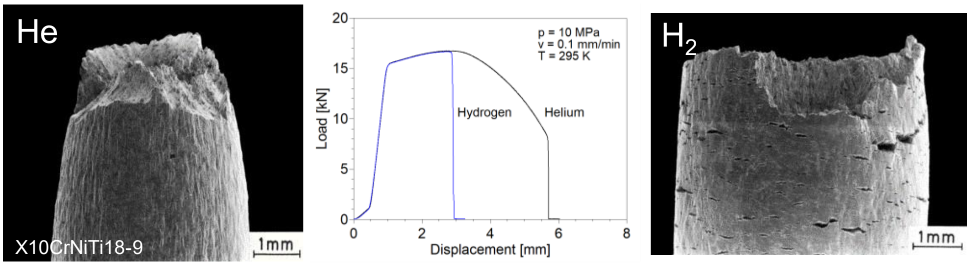

Figure 3: Load-Displacement curve of a tensile specimen after hydrogen embrittlement.

Non-Destructive Testing

Non-destructive testing (NDT) of structural parts of nuclear facilities during the production, the operation and after an incident is essential to ensure safety. However, established testing methods are not by default suitable for the reactor type and manufacturing methods considered in this research project. This is due both to the reactor design itself (different damage patterns, geometric complexity and limited accessibility) and on the other hand to the use of new manufacturing processes (size, number and orientation of imperfections, different material state such as grain size or anisotropy). It is therefore necessary to identify the relevant defect types and suitable NDT methods. The aim of this work package is to evaluate adapted test methods for SMR concepts, considering manufacturing imperfections and stresses under operational and fault conditions.

Material Behavior Under High Temperature Stress

Certain new SMR concepts are designed for operation at higher temperatures than previously common light water reactors. Therefore, high-temperature materials are utilized for new reactor designs which have previously been used in high-temperature or very-high temperature reactors (HTR/VHTR) [IAEA (2020), Nuclear Innovation 2050 (2019)]. The need for reliable material properties and data is a key issue in the development of HTR technologies and is particularly important for areas where safety aspects and structural integrity are of critical relevance. High temperature reactors are already in operation in Japan (HTTR) and China (HTR-10), offering unique opportunities to qualify new high temperature precursor technologies and design codes [Fütterer (2014)]. In particular, additive manufacturing of high-temperature resistant materials provides open questions in terms of properties and component integrity [Kuo (2017)].

To ensure the safe use of additive manufactured components in high temperature reactors, the behaviour of these components must be determined and verified for relevant load scenarios. AM materials often do not have comparable properties to conventionally manufactured components. relevant materials, in particular nickel alloys, for VHTR that are operated at temperatures above 650°C are currently still in the qualification phase. Materials based on Fe, such as ferritic/martensitic steels, are intended as claddings or core housings for the range with lower operating temperatures up to max. 650 °C [Nuclear Innovation 2050 (2019)]. A comparative database for nuclear applications is therefore available for these two material groups, which are used to compare the properties and performance with the materials produced in the AM process during the project. The selected materials will be qualified under relevant loading scenarios, e.g. LCF tests, tensile tests, creep and creep fatigue tests, etc. Their microstructure will then be studied to gain insight into the damage mechanisms that occur. This will allow the development of assessment criteria and the adaptation of design and assessment concepts. The overall objective of this work package is to evaluate safety-relevant, additively manufactured components for use in a high-temperature reactor.

Dynamic effects under operating and accident loading condition

Dynamic loads in nuclear facilities occur primarily under accident or beyond-design conditions, where the effects are associated with sudden speed, pressure, and temperature changes. Such loads can result from either external hazards like earthquakes and aircraft crashes or internal hazards like hydrogen-oxygen aggregation explosions. Material properties can change significantly under dynamic loading due to local adiabatic temperature increase. Further influences result from the materials anisotropy, phase transformations or ageing. While the deformation and failure behavior of conventionally manufactured components of nuclear facilities under dynamic and highly dynamic loads is well known, novel manufacturing processes can lead to a significant shift of these properties. Therefore, this work package aims to determine suitable material and failure models for additively manufactured components, hence, contributing to the safety assessment of advanced manufactured SMRs under dynamic loading.

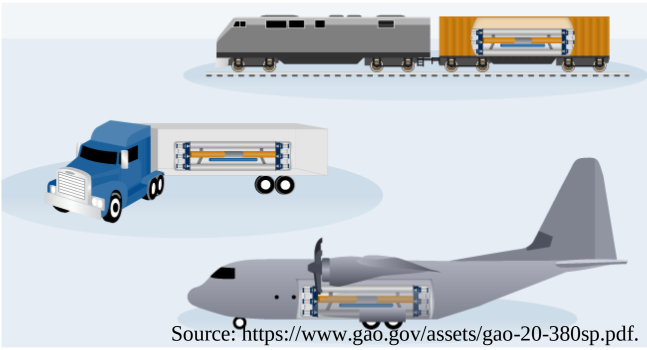

Figure 4: Transportation possibilities of microreactors

In a first step, dynamic effects under operation and accident conditions are to be analysed based on literature. Since SMRs are intended to be centrally manufactured, assembled and then transported to their deployment site additional hazards need to be considered which might not affect conventional nuclear power plants. Further, the Westinghouse micro reactor eVinci is being developed to be deployed in remote communities, catastrophic areas or for military use [IAEA. (2020)]. Then, requirements for the material of additively manufactured SMR components, based on an evaluation of the previously identified incident spectrum, are to be defined and material properties to be experimentally determined. Subsequently, suitable material models for describing the material behaviour and failure will be established and validated with the conducted experiments. Last, the numerical analysis of selected dynamic load cases will be used to assess the safety of additively manufactured safety-relevant components of the Westinghouse eVinci concept.

Liquid Metal Corrosion

Depending on the application scenario, heat pipes filled with alkali metals can be used both in normal operation and as part of the emergency cooling system, thus contributing both actively and passively to the safety of modern nuclear power plant types such as an SMR. For conventional manufactured heat pipes and the corresponding drawn tube material states there is already comparatively profound knowledge about liquid metal corrosion. However, for the behaviour of material states produced by laser powder bed fusion there is no operational experience regarding liquid metal corrosion and corresponding degeneration mechanisms. Potassium or sodium, can lead to corrosion phenomena such as localised corrosion, liquid metal embrittlement and high-temperature corrosion and, in the worst case, to component failure due to critical erosion rates or cracking. Therefore, the corrosion behaviour of additively manufactured heat pipes must be studied in advance to ensure safety both in normal operation and in the event of an accident. The aim of this work package is consequently to develop a test methodology to evaluate these effects and their impact on safety. For this, a suitable test setup for determining material characteristics under the influence of liquid potassium and high temperature will be developed based on an extensive literature research. After the design, manufacturing and assembly the test setup will be evaluated using a sample material.

In the beginning, the literature research is focused on the determination of mechanical material properties under the influence of liquid metal and the resulting demands on the test setup. Further, the necessary adaptations with regard to corrosion and embrittlement resistance need to be defined. Afterwards, the test setup is to be developed considering further aspects like the handling of the liquid potassium prior and after an experiment, the electrolytical properties of liquid metal or the prevention of an undefined contamination of the potassium. The safe operation of the new test concept is of high relevance. It is therefore necessary to analyse and incorporate various safety-related concerns, such as the liquid potassium fire hazard, into an appropriate safety concept. After the manufacturing and assembly of the test setup experiments with simple specimen are performed to evaluate the test methodology. Last, material properties for specimen surrounded by air and then liquid potassium under different temperature loading are determined.

CONCLUSION

In order to build up extensive expertise in the safety assessment of SMR components produced using advanced manufacturing techniques, the research cluster is divided into seven interlinked work packages. Each examines different safety aspects of the selected SMR concept.

Central to this is work package 1 "New Manufacturing Methods", which produces samples for all experiments that will be conducted in this research project using advanced manufacturing processes. These are LPBF, WAAM, EBM, HIP and CS. By developing special test specimens for the various manufacturing processes, it will be possible to assess the robustness of the processes and thus the subsequent safety of manufactured components in the future. The results of the basic mechanical characterization of the three considered materials (22NiMoCr3-7, 316L, Inc718) are combined with the results of work package 4 in order to provide a comparative assessment of the effect of the manufacturing processes on the formation of imperfections and thus the quality of the specimen.

Work package 2 “Liquid Metal Heat Pipes” aims to investigate additively manufactured heat pipes. After selecting suitable metallic structural materials and designing the specimens, a heat pipe test rig is developed. The test program includes experiments in which the temperature-dependent heat transfer characteristics for stationary and transient operating conditions are determined by varying application-oriented thermal boundary conditions and the heat pipe orientation. Particular attention is paid to the evaluation and classification of the results obtained in comparison with literature data and our own previous test results for conventionally manufactured heat pipes.

The findings derived from work package 3 " Interaction of Hydrogen with New Manufacturing Processes" on the material properties in hydrogen in combination with the respective manufacturing process are to be incorporated into the safety assessment. Based on this, the 2nd project phase envisages a dynamic iteration process for the safety assessment of varying manufacturing parameters (such as laser intensity and hatch distance).

The NDT investigations of work package 4 "Non-Destructive Testing" are of particular importance since testing concepts must be reconsidered and procedures adapted for new reactor concepts that are manufactured using advanced production processes. In the case of SMRs, the high density of components in the plants poses additional challenges, as accessibility for NDT can be significantly restricted. The aim of the NDT sub-project is to evaluate current developments and adaptations of test procedures for new reactor concepts, taking into account the safety challenges posed by new manufacturing processes and components.

In the context of work package 5, the behavior under high temperature stress is determined for the selected materials in accordance with the load and production parameters. The degradation mechanisms are analysed and the simulation techniques as well as evaluation criteria are explicitly adapted for AM components on the basis of existing procedures. For this purpose, (non-linear) finite element calculations are used for the design of high-temperature components.

Dynamic effects on SMR components under operating and accident loading conditions are investigated in work package 6. Based on literature an incident spectrum is identified and eventually evaluated to define material requirements for additively manufactured SMR components under dynamic load. Suitable material models for the description of the material behaviour and failure will be established and experimentally validated. Afterwards, chosen dynamic load cases will be numerically analysed. Based on that, the safety of additively manufactured safety-relevant nuclear components will be assessed.

Last, the influence of liquid metal corrosion on the safety of additively manufactured SMR components is investigated in work package 7. Here, a suitable test methodology for the evaluation of corrosion effects in conjunction with an appropriate test setup is developed. Material characteristics under influence of liquid potassium and high temperature will be gained.

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REFERENCES

Albert, M. (2020). *“Vision of Advanced Manufacturing Technology (AMT) Use in the Nuclear Industry”,* https://www.nrc.gov/docs/ML2034/ML20342A035.pdf

Bundesamt für die Sicherheit der nuklearen Entsorgung (BASE). (2021). *“Sicherheitstechnische Analyse und Risikobewertung einer Anwendung von SMR-Konzepten (Small Modular Reactors)“,* BASE-001/21

Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit (BMUB). (2015). *“Sicherheitsanforderungen an Kernkraftwerke“* https://www.base.bund.de/SharedDocs/Downloads/BASE/DE/rsh/3-bmub/3_0_1.html, last accessed 28.12.2023

Frew, B.; Gandy, W. (2020). *“Approach to Codifying New Manufacturing Methods (e.g., PM-HIP, LPBF, EBW)”*, https://www.nrc.gov/docs/ML2034/ML20344A113.pdf

Fütterer, M. A. et al. (2014). *“Status of the very high temperature reactor system”,* Progress in Nuclear Energy 77 (2014) 266-281

Gandy, D. W. (2020). *“PM-HIP and Electron Beam Welding Development for Nuclear Applications”,* NRC Public Workshop on Advanced Manufacturing Technologies for Nuclear Applications, https://www.nrc.gov/docs/ML2034/ML20342A377.pdf

IAEA. (2020). *“Advances in Small Modular Reactor Technology Developments”,* A Supplement to IAEA Advanced Reactors Information System (ARIS)

IAEA. (2021). *“Protection against Internal Hazards in the Design of Nuclear Power Plants”,* IAEA Safety Stand-ards, Specific Safety Guide No. SSG-64, International Atomic Energy Agency, Vienna

Kuo, Y.-L.; Horikawa, S.; Kakehi,K. (2017). *“Effects of build direction and heat treatment on creep properties of Ni-base superalloy built up by additive manufacturing”,* Scripta Materialia, Volume 129, 2017, Pages 74-78, https://doi.org/10.1016/j.scriptamat.2016.10.035.

Lane, H. (2022). *"U.S. Nuclear Industry Perspectives on Advanced Manufacturing Technologies"*, https://www.nrc.gov/docs/ML2034/ML20342A037.pdf

Mally, L.; Werz, M.; Weihe, S. (2022). *"Feasibility Study on Additive Manufacturing of Ferritic Steels to Meet Mechanical Properties of Safety Relevant Forged Parts". Materials* 2022, *15*, 383. https://doi.org/10.3390/ma15010383

Nuclear Energy Agency (NEA). (2020). *"Unlocking Re-ductions in the Construction Costs of Nuclear: A Practical Guide for Stakeholders",* Nuclear Technology Development and Economics, NEA no. 7530.

Nuclear Innovation 2050. (2019). "*An NEA initiative to accelerate R&D and market deployment of innovative nuclear fission technologies",* ANNEX 6: Advanced structural materials for GenIV systems

United States Nuclear Regulatory Commission (U.S.NRC.). (2020). *"NRC Public Workshop on Advanced Manufacturing Technologies for Nuclear Applications",* https://www.nrc.gov/docs/ML2033/ML20336A004.pdf

Westinghouse. (2022). *eVinci™ Microreactor*, https://www.westinghousenuclear.com/new-plants/evinci-micro-reactor, last accessed 28.12.2023