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Research Article

Modified CANDU Reactor MCR as an Early-Deployable Nuclear Workhorse

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Abstract

Safe, simple and soon deployable are the imperatives for each SMR concept today. Only this SMR has the potential to become a nuclear workhorse in the fight against climate change if it is available soon, in large numbers and deployable worldwide. Therefore the assessment of the usefulness of an SMR concept must not only relate to the reactor itself. Only a holistic view of the entire nuclear fuel cycle with the given SMR as the central part between the front-end and back-end can lead to viable decisions. The IAEA lists more than 120 SMR concepts in its Handbook 2022. Time pressure is forcing us to critical selection of a promising reactor concept and to combine innovative solutions with tried and established technical and administrative networks. Against this background, the Modified CANDU Reactor (MCR) is proposed as additional SMR design. The MCR has two obvious modifications compared to the well-known and globally proven CANDU design: a) spherical fuel elements (pebbles) with ceramic cladding b) vertical arrangement of the pressure tubes. Intended for the generation of heat and electricity close to the consumer, the construction of a plant with MCR is preferably carried out underground close to the surface. The Herrenknecht VSM-shaft-tunnel technology is planned for the construction of the structures. For the transportation of irradiated fuel elements, (extended) interim storage and final disposal, technologies are proposed (Initial Barrier; TRIPLE C) that have already been published elsewhere. In order to provide a basis for further scientific and technical discussions, an attempt was made to incorporate the MCR concept into the existing CANDU SMR TM design. The resulting combined "overlapping" concept has not yet been discussed with the CANDU developing and operating countries. The authors hope for a fruitful discussion and are looking for future cooperation with the CANDU SMR TM manufacturer (CANDU Energy Inc. Canada), as well as with the countries that traditionally use CANDU reactors (China, India, South Korea) and Norway in future maybe too.

Keywords

CANDU Reactor, SMR, Vertical Pressure Tubes, Ceramic Fuel Pebbles, Emergency Drop-Out, Underground-Construction

1. Introduction

You don't need to explain to any child in the world what a VW Beetle is. This ingenious car among the cars of the 20th century improved the living conditions of millions of people: a useful workhorse in everyday life and an inexpensive vehicle for leisure and travel.

No nuclear engineer anywhere in the world needs to be told what a CANDU reactor is. For decades this ingenious reactor concept has proven itself in many countries around the world.

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Humanity is facing now an existential challenge:

Supplying a growing population with sufficient energy while simultaneously meeting the climate protection targets.

The use of nuclear energy is indispensable for the transition to an emission-free energy supply. Hundreds, if not thousands of new plants for heat, electricity and desalination must be built in the next 3-5 decades.

Small Modular Reactors (SMR) will play an important role. Many interesting concepts – most of them futuristic- have been proposed. Only a few of them have been built and tested so far.

The basic requirements for mass deployment of SMR worldwide are:

1. simple
2. ultra-safe
3. early-deployable
4. compatible with established international rules and methods of fuel cycle.

No SMR concept meets all of these basic requirements, especially with respect to countries that are newcomers to the use of nuclear energy.

Why is the CANDU reactor a perfect favorite?

Two basic features are decisive:

1. the combination of natural uranium and heavy water, avoiding of uranium enrichment due to proliferation concerns
2. core design with pressure tubes, avoiding the manufacturing and transport of a heavy pressure vessel weighting hundreds of tons.

With a few modifications the CANDU reactor design has the potential to become the nuclear workhorse of the 21st century. The design of the Modified CANDU Reactor (MCR) is presented here to experts for critical review. The authors look forward to a fruitful discussion and possible future collaboration.

2. The Environment for the MCR: Fuel Cycle and Safety Goals

Every new reactor concept is subjected to a critical assessment according to established standards. The reactor design and the technical operating data alone are not sufficient for a decision on the basic suitability of a new SMR, especially for an intended mass production. It is advisable to assess the entire nuclear fuel cycle including fuel element production, reactor operation, interim storage and finally, the final storage of the spent fuel elements together with the necessary (overseas) transports.

Like all facilities for the utilization and handling of nuclear materials, the MCR has to fulfil general safety goals. With varying importance and priorities the same main safety goals apply for safety considerations of the MCR and its fuel cycle too:

1. ISOLATION: prevention of release of nuclear material into biosphere
2. CONTROL: prevention of unwanted criticality
3. HEAT REMOVAL: prevention of overheating
4. SHIELDING: prevention of irradiation with an overdose
5. PROTECTION: prevention of destruction, misuse, theft, unintentional intrusion

The fuel cycle of the MCR will be structured in a similar way to the fuel cycle of the light water reactors used today. Typical steps in the history of fuel elements are shown in Figure 1 [1].

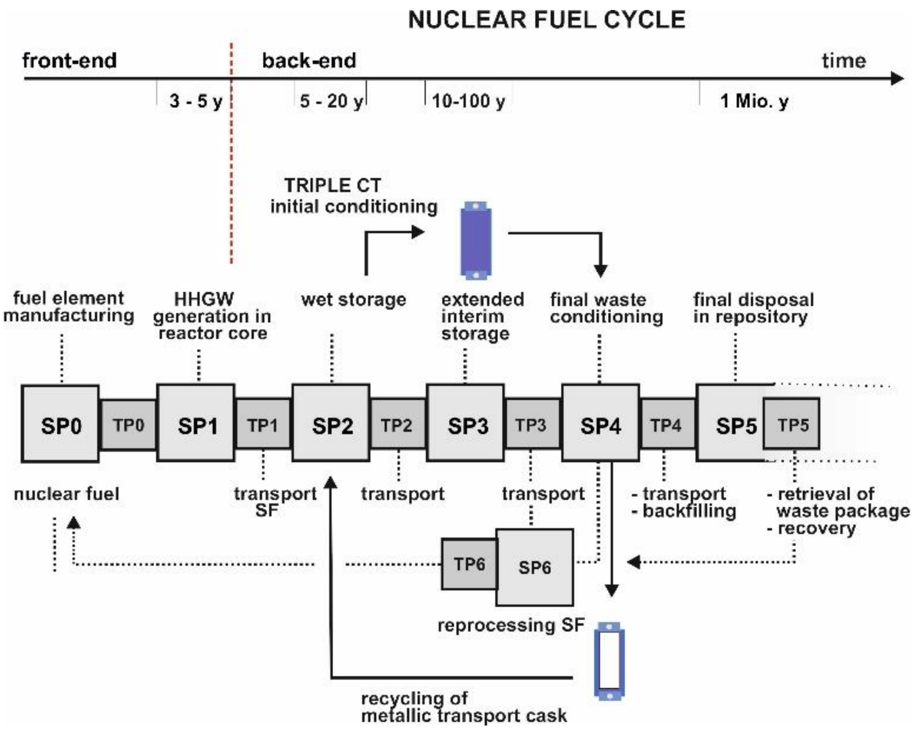

Figure 1. Fuel cycle, divided in Stationary Phases (SP) and Transport Phases (TP).

Considering the use and the user proximity of an MCR, a tailored set of appropriate safety measures has to be foreseen to guarantee ultimate safety over the whole lifecycle. The priority ranking of the safety goals may change from phase to phase.

3. Proposed Modifications of CANDU Design

In the pre-selection process, the CANDU concept showed the best match with the author`s design objectives. For the Modified CANDU Reactor MCR the CANDU® Small Modular Reactor (CSMR) serves as the role model. The well-known advantages do not need to be listed here [2-4].

So why are modifications proposed anyway?

The metallic cladding of the fuel is seen as a significant disadvantage. There are two strong arguments against metallic cladding:

1. Oxidation of overheated fuel element cladding in the event of a loss-of-coolant accident (LOCA), which leads to the generation of hydrogen (as the history of severe accidents has shown)
2. Loss of the long-term ISOLATION feature of the innermost retention barrier due to corrosion.

Today, innovative fuel elements should be ceramically encapsulated. But even with such fuel elements, the metallic pressure tubes remain as indispensable components. In case of a LOCA the pressure tubes can overheat, leading to hydrogen generation. As countermeasure it is proposed to remove the fuel elements as heat sources from the core (emergency drop-out), giving an ultra-safe walk-away core design. A spherical shape (pebble) is the best fuel element geometry for emergency drop-out and gravity-driven subcritical distribution in foreseen water reservoirs. This passive safety measure in turn requires a vertical arrangement of the pressure tubes. There were already earlier CANDU types with vertical pressure tubes (NRX, NRU) [5].

The proposed modifications to the CSMR therefore concentrate on two main measures:

1. Ceramic encapsulated spherical fuel elements (ceramic pebbles)
2. Vertical arrangement of the pressure tubes.

Underlying the structure of the fuel cycle (Figure 1) and the special requirements for an SMR, the main features of the MCR will be illustrated. At the same time, it becomes clear how the MCR fits into the established system of safeguards, waste management and final disposal.

4. Pebble Fuel Element; Pebble Manufacturing

Reactors with pebble bed are considered worldwide as a promising GenIV concept to solve the energy problem in the future, at least as part of bridge technologies. This reactor concept is applicable to Small Modular Reactors (SMR) as well as for hydrogen production on large scale with (V) HTR. But the fuel design has not changed since the invention of this reactor type even though severe deficiencies became obvious during the operation of two experimental reactors in Germany (AVR and THTR) [6]. The graphite sphere with incorporated TRISO particles represents the standard fuel design for pebble bed gas-cooled reactors till today. Obviously, these naked graphite spheres cannot be used in the chosen water-cooled CANDU concept.

Considerable progress during the past two decades has been made in ceramic technologies, especially in shape forming of components [7]. The latest step in shape forming development is 3D-printing [8], which has been applied to manufacture spheres with closed fuel chambers and open cooling channels.

Two different types of SiC encapsulated pebbles are considered appropriate for the MCR:

1. SSiC compact sphere (SSiC: pressureless sintered silicon carbide) (Figure 2)
2. SSiC sphere with coolant channels (Figure 3)

4.1. SSiC Encapsulated Compact Pebbles

The compact SSiC sphere (Figure 2) offers the advantage that no bonding process either for two halves or for a lid is necessary. This seamless technology results in a very robust and corrosion resistant product.

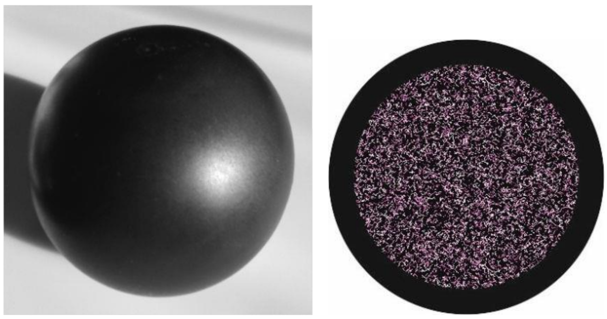

Figure 2. *Seamless compact SSiC sphere: accident-tolerant, disposal-preconditioned [8].*

The SSiC compact sphere makes unnecessary the manufacturing of TRISO-particles because its kernel consists of a dispersion of SSiC and fuel. The technology can be described in general as known ceramic technology. A comparison of production costs reveals that the ceramic technology is roughly 10 times less expensive than the TRISO technology.

4.2. SSiC Pebbles with Coolant Channels: DEXPRINT Technology

The temperature gradient from the centre of the sphere to the surface may be disadvantageous for some applications. The sphere with coolant channels exhibits an exchange surface for heat transfer around 3 times higher than a massive sphere of the same diameter. Dual extrusion 3D-printing technology (DEXPRINT@) allows to print simultaneously the surrounding cladding of SSiC and the uranium oxide fuel, dispersed in SSiC to the required concentration. The separating walls between channels and chambers exhibit a wall thickness of 0.9 – 1 mm, whereas the outer shell is 2.5 mm thick. The cross section of chambers and channels amounts to 4.9*4.9 mm^2. Due to the high flexibility of the 3D printing process all geometrical values can be adjusted to the respective needs.

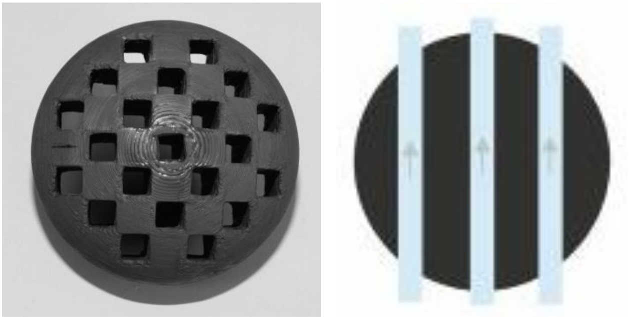

Figure 3. *DEXPRINT@ technology: SSiC sphere with coolant channels [8].*

Cylindrical and prismatic geometries are feasible as well, but the sphere is considered as optimal due to its flowability/moveability.

In a final step the fuel element gets a laser-engraved fabrication Safeguards Code (Figure 4). In terms of international nuclear material control, each pebble is one batch, which can be localized and traced in its history easily [7].

Figure 4. *Laser engraving: permanent traceability for nuclear material control [7].*

5. MCR Core Design

The MCR is a vertical pressure tube, heavy water reactor (in contrast to the CSMR with horizontal pressure tubes) taking advantage of long lineage of successful CANDU reactors. The reactor core consists of a vertical calandria housing a set of pressure tubes. The reactor coolant system consists of these pressure tubes, two steam generators, four primary circulation pumps plus interconnecting piping and headers. The calandria itself is filled with heavy water that surrounds the pressure tubes and provides neutron moderation. The vertical positioning of pressure tubes allows together with corresponding safety valves an emergency drop-out of fuel pebbles in case of loss-of-coolant (LOCA).

Gravity-driven the pebbles take a path into a subcritical geometry in a large volume water pool. The irradiated fuel bay is a robust, seismically qualified structure with a large volume of light water relative to the decay heat load of discharged fuel, providing many days of passive cooling in the event of a loss of active heat removal.

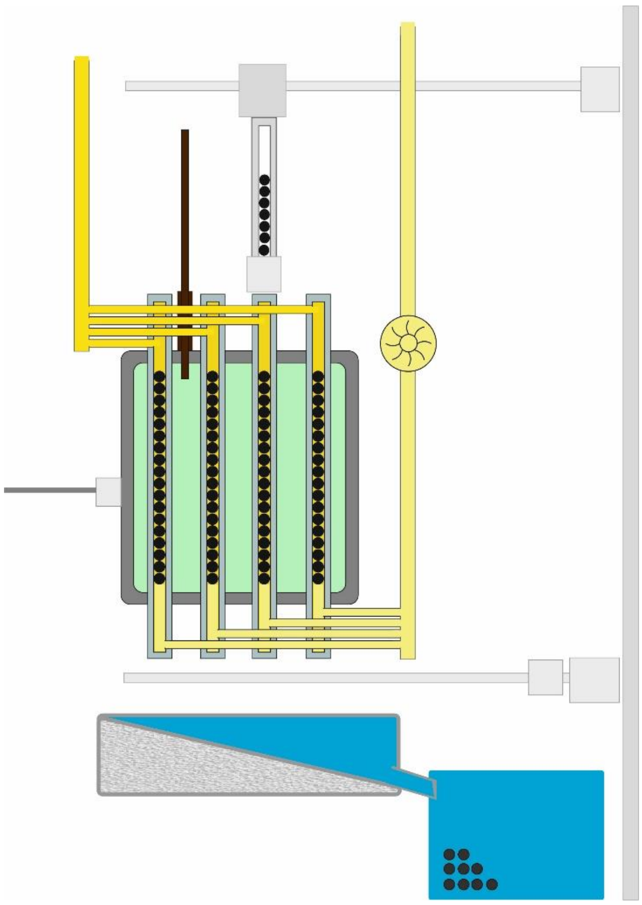

Figure 5. *MCR core arrangement with vertical pressure tubes, pebble fuel elements and emergency drop-out.*

This passive safety feature can play an important role for the public and political acceptance, when a near-consumer site of the MCR is planned in a densely populated area.

6. Plant Construction: Safety and Low Cost: Underground Construction

The MCR design aligns with the concept of Defence in Depth, leveraging inherent safety features through the application of proven engineered systems with an emphasis on providing high reliability through a prudent mix of active and passive features. The overall MCR design philosophy is to reduce total unit energy cost by reducing specific capital cost, shortening the construction schedule, reducing operating, maintenance and administration costs and providing for plant life extension. In addition, MCR enhances or improves the traditional CANDU advantages including nuclear safety, low man-rem exposure, high-capacity factor and ease of maintenance. Proven systems, system parameters, components, and concepts are used, including proven technologies from other industries.

Recent developments have shown how important it is to protect nuclear facilities against terrorist attacks and military assaults. All safety-relevant components are arranged underground in Herrenknecht VSM shaft-tunnel structures (Figure 6) [9].

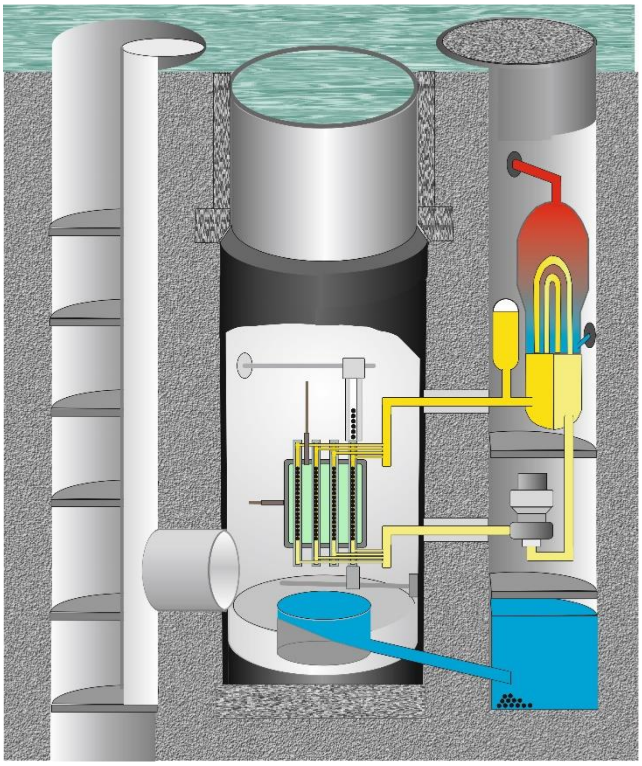

Figure 6. MCR facility layout with Herrenknecht VSM shaft-tunnel structures [9].

The MCR underground layout is arranged to minimize and achieve a short practical construction schedule. This is achieved by simplifying the layout, optimizing interfaces, reducing construction congestion, providing access to all areas, providing flexible equipment installation sequences and reducing material handling requirements.

Besides land-based sites, also marine-based application/desalination can be of future interest. It will be helpful, that the SSiC fuel cladding is resistant to corrosion in seawater too.

7. Waste Management

It is anticipated that the high radioactive waste produced over the MCR's 70-plus year lifetime will be stored in a dry storage facility after few years cool-down in a wet storage. This can be done on site or in a special interim storage facility.

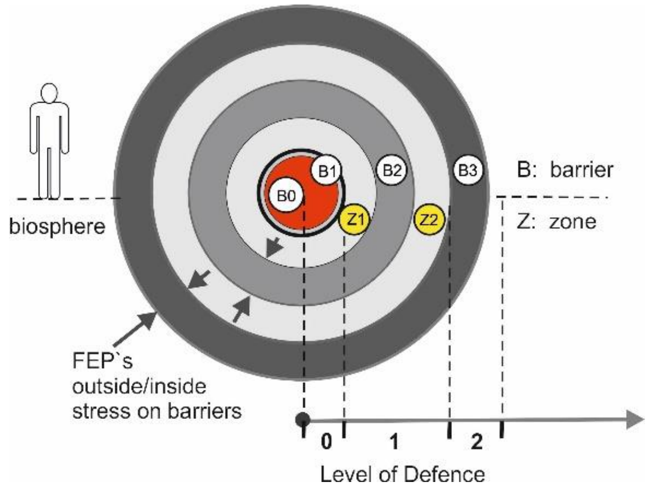

Figure 7. General scheme of a staggered defense system, consisting of passive barriers of a repository in phase SP 5 [1].

B0 = fuel matrix
B1 = fuel cladding tube
B2 = disposal container,
B3 = enclosure relevant area of host rock
Z2 = buffer (bentonite)

Defense in Depth (DiD) has been developed to a special maturity in the safety philosophy for the design and the operation of nuclear reactors (SP 1). Redundancy, diversity, fail-safe and the consideration of failures from common source (common-cause-failure: common-mode- as well as common-event-failure) are well-established and self-evident safety principles of design.

The analysis of nuclear facilities of the back-end reveals that those principles are not applied consequently. This is valid as well for the ongoing repository planning in Germany. The regulation for repository safety requirement [10] states that the envisaged repository system has to guarantee *"... the safe enclosure of the radioactive waste passively and maintenance-free by a robust, staggered system of different barriers..."* for a period of proof of one Mio years. Legally binding specifications regarding redundancy and diversity of the so-called essential barriers of the repository are not defined. According to [10] "essential barriers" are such, which mainly ensure the safe enclosure of the radioactive waste.

On national as well as on international level, the concepts of final deposition show a serious disadvantage: the innermost barriers, consisting of metal (B1 and B2), don't fulfill the criteria of an essential barrier for phase SP 5 (Figure 7).

7.1. Safeguards: SSiC Encapsulation – Initial Barrier

In order to overcome this deficit and to make the inner levels of DiD to a fully integrated part of the safety concept of a repository system, the TRIPLE C concept has been developed. The decisive component consists of a ceramic waste container of pressureless sintered silicon carbide (SSiC). Details are presented in the research of J. Knorr, A. Kerber [1, 11]. The combination Z1 – B2 (ceramic potting compound and SSiC container) is denominated as Initial Barrier (Figure 8). [12].

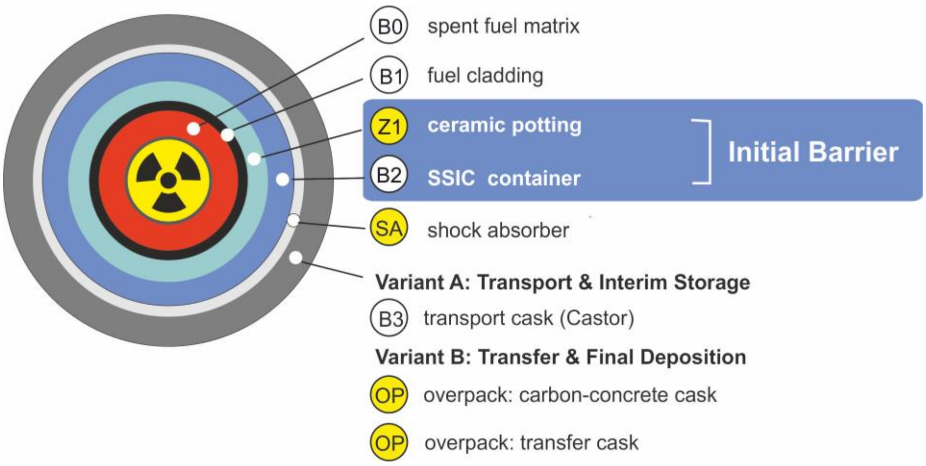

Figure 8. *Initial barrier Z1- B2 in the waste container according to TRIPLE C concept [12].*

The initial barrier represents a redundant and diverse component in order to fulfill the safety functions ISOLATION, CONTROL and HEAT REMOVAL.

At present it is assessed that

1. The Initial Barrier fulfills the criteria of an essential barrier for phase SP 5 [5].
2. The technical feasibility of manufacturing SSiC containers is given for all the existing shapes of waste; the transfer from lab-scale to industrial fabrication should be prepared now.
3. Hermetic sealing of the containers is feasible by the so-called Rapid-Sinter-Bonding (RSB) technology [13]; the transfer from lab-scale to industrial fabrication/qualification should be started now.

Following this concept, the spent MCR pebbles are filled in SSiC containers (Figure 9) [11], which are hermetically sealed [13] and laser-engraved with Safeguards ID code afterwards (Figure 10).

The advantages of the ceramic Initial Barrier shall be characterized by three obvious features: fixed solid geometry, impossibility of ingress of moderator substance (water) and the homogenously distributed neutron absorber fulfill the long-term stable safety function CONTROL (sub-criticality).

Figure 9. *Ceramic encapsulated pebble fuel elements in SSiC canister for deep-borehole disposal.*

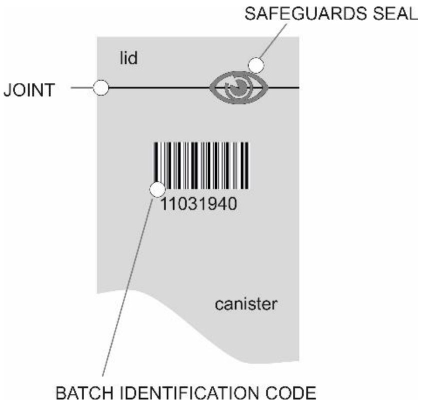

Figure 10. *SSiC canister with laser-engraved Identification Code and Safeguard Seal.*

7.2. Extended Interim Storage & Public Safety

It seems reasonable to take advantage of the ceramic Initial Barrier during an early stage of the back-end-cycle and not only for the final repository (SP 5) (Figure 11). This is feasible, because the Initial Barrier can be integrated, according to the TRIPLE C concept, into the final deposition package without modifications. The adaption to the specific conditions is realized by the outer material zones such as shock absorber, over-pack and buffer (Figures 7, 8).

The high radioactive waste is encapsulated in the SSiC canister after removal from the wet storage facility (SP2). These can then be placed immediately in transport containers (e. g. of the Castor type), which are stored underground on site or in an appropriate facility for (extended) interim storage.

8. Long-term Safe Disposal of High Radioactive Waste: TRIPLE C Concept

In phase SP4, the waste is conditioned by coating the Initial Barrier with additional layers of material for final disposal. The Initial Barrier does not have to be opened for this purpose (Figures 11, 12). It is assumed that in the future the ceramic Initial Barrier will become an integral component of each final deposition waste package, no matter which additional material zones will be applied later for completion of the technical barrier respectively under which geological conditions the final deposition will happen.

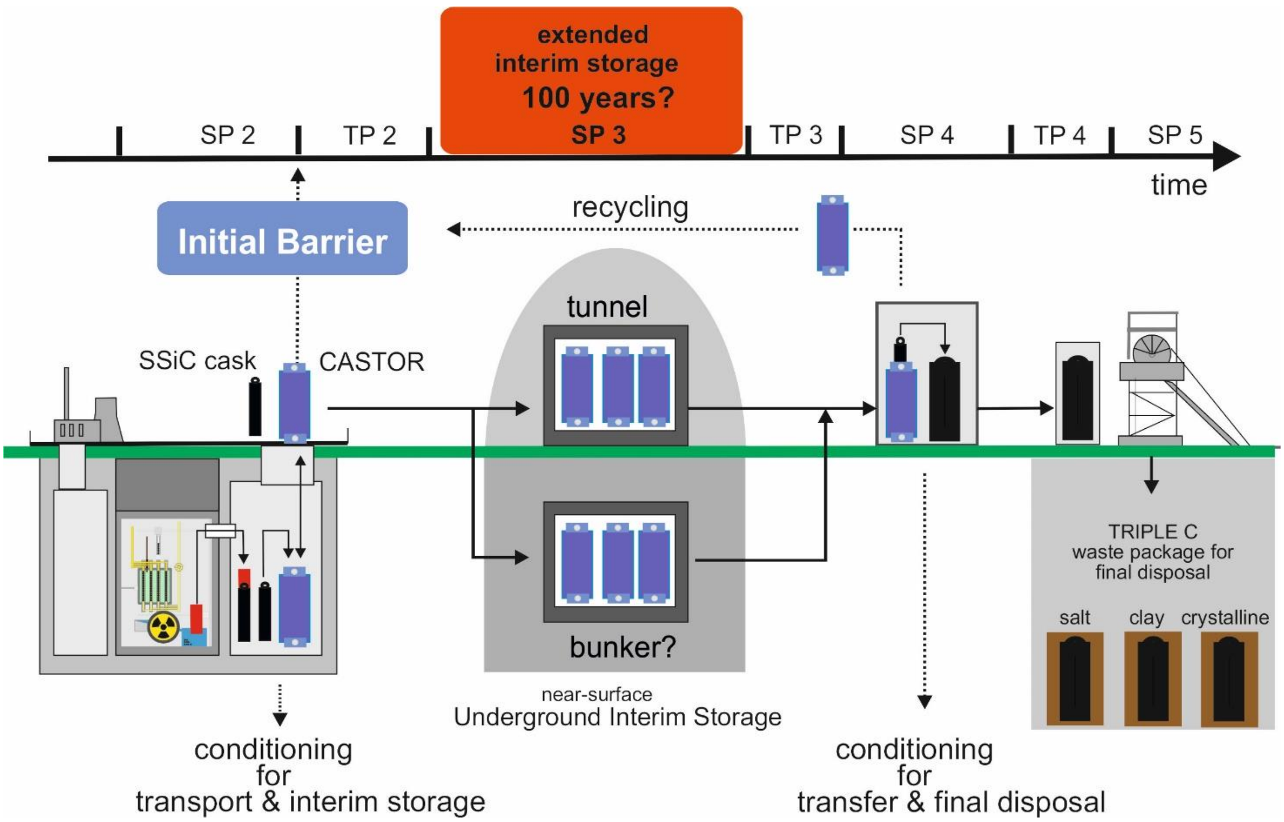

Figure 11. *Making the Initial Barrier at an early stage of the back-end fuel cycle [7].*

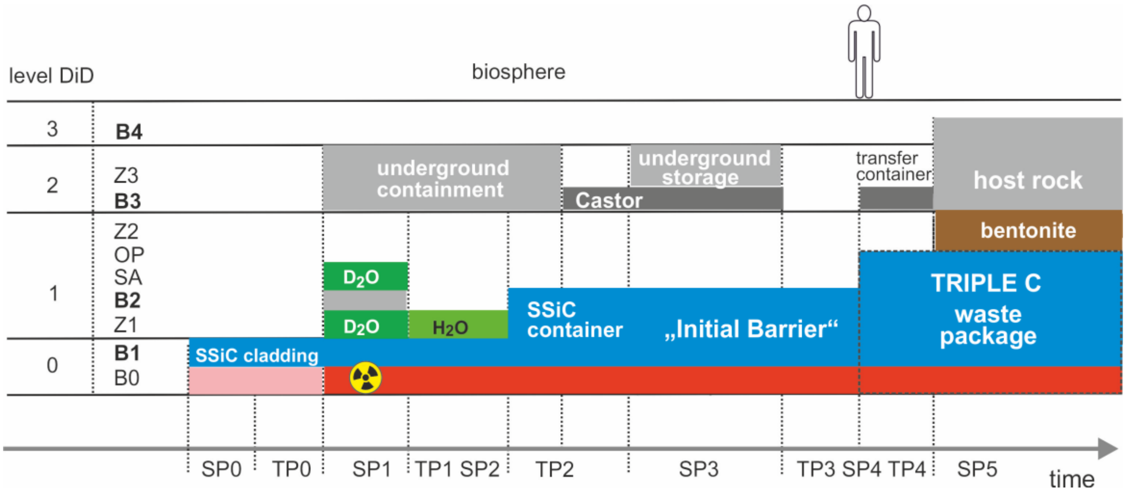

Figure 12. TRIPLE C: Successive construction of a three-stage ceramic retention barrier.

Once the high-level waste is placed in the Initial Barrier, it is not necessary to know what the repository container will actually look like later after 100 years of interim storage or in which host rock it will be emplaced [14, 15].

The all-ceramic version of the disposal container (TRIPLE C, Figure 13) envisages a container made of carbon concrete as the overpack [5]. It is the best long-term retention barrier presented so far.

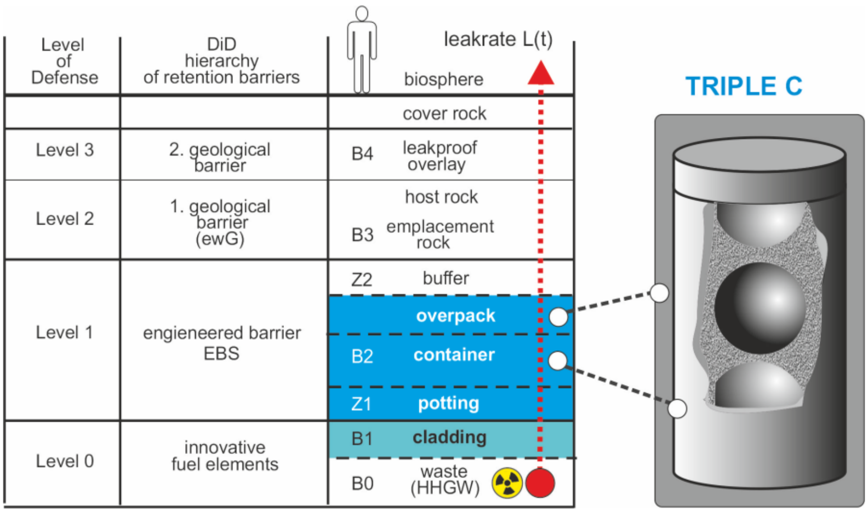

Figure 13. TRIPLE C waste packages for all types of host rock: salt, clay, crystalline [5].

In summary, the presented MCR seems to be a SMR variant with a high chance of success at manageable costs. The properties of the innovative fuel elements and the presented fuel cycle counter the usual killer-arguments that the disposal of the high radioactive waste has not been clarified. The preparatory work for the project planning of a MCR demo-plant, its licensing and construction could begin.

9. Summary

Safe, simple and soon deployable are the imperatives for each SMR concept today. Only this SMR has the potential to become a nuclear workhorse in the fight against climate change, if it is early-deployable, can be produced in large numbers and is deployable under different conditions world-wide. From this follows that the assessment of the usefulness of an SMR concept can not only relate to the reactor itself. A technically feasible SMR is pointless, if it does not fit in the present international system of rules, institutions and methods. Compatibility with the fuel market, Safeguards, transportation, waste management and final disposal are just as important as a challenging reactor design. Only a holistic view of the entire nuclear fuel cycle can lead to viable decisions.

The mass use of SMR`s must not inadmissibly increase the proliferation risk. Natural uranium is therefore the preferred fuel presently. Additionally, avoiding flammable graphite as moderator/reflector material almost inevitably leads to the choice of a heavy-water moderated SMR type, necessarily with high pressure in the first circuit. Heavy components like pressure vessels are difficult to manufacture, to transport and almost impossible to repair. That's why a pressure tube reactor type is favoured. This inevitably leads to the CANDU reactor as the basic type of consideration. The proposed MCR is a merger of our ideas in the CSMR concept.

All past major accidents involve failure of fuel cooling, last but not least with the risk of hydrogen generation and hydrogen explosions. Sites near to the consumer require ultra-safe reactor designs. Three new safety measures characterize the MCR: a) SSiC encapsulated fuel elements b) pebbles as fuel geometry c) emergency drop-out of pebbles from vertical pressure tubes. In the event of LOCA, fuel elements would drop-out (removal of heat sources out of core) and cool-down in light-water reservoirs (subcritical storage geometry), making the reactor walk-away safe.

In order to become a nuclear workhorse, standardized design is a key aspect for the MCR. Cost could kept be low because of central construction, shipyard-methods and the use of steel with minimal concrete, minimizing expensive on-site work too. For land-based sites, underground construction minimizes cement/concrete consumption for shielding and protection against military and terroristic attacks. Marine-based applications for floating desalination units should be considered too.

Abbreviations

SMR	Small Modular Reactor
MCR	Modified CANDU Reactor
SPx	Stationary Phase x
TPx	Transport Phase x
LOCA	Loss of Coolant Accident
(V)HTR	Very High Temperature Reactor
SiC	Silicon Carbide
SSiC	Pressureless Sintered SiC
DEXPRINT	Dual Extrusion 3D Printing
DiD	Defense in Depth
TRIPLE C	Threefold Ceramic Encapsulation

Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] J. Knorr, A. Kerber: TRIPLE C waste container for increased long-term safety of HHGW disposal in salt, clay and crystalline, atw, Vol. 66 (2021) I Issue 4, July, p. 54-62.

[2] CANDU SRM TM, Candu Energy Inc., IAEA SMR booklet 2022 p. 19 ff.

[3] IAEA Platform on SMALL MODULAR REACTORS AND THEIR APPLICATIONS; Annual Report 2023.

[4] C. Pistner et al.: Sicherheitstechnische Analyse und Risikobewertung einer An wendung von SMR-Konzepten (Small Modular Reactors), Wissenschaftliches Gutachten im Auftrag des Bundesamtes für die Sicherheit der nuklearen Entsorgung (BASE) Darmstadt, März 2021, urn: nbn: de: 0221-2021030826028.

[5] The Essential CANDU, A textbook on the CANDU Nuclear Power Plant Technology Editor-in-Chief Wm. J. Garland, University Network of Excellence in Nuclear Engineering (UNENE) ISBN-0-9730040, Canada 2014.

[6] R. Moormann, A safety re-evaluation of the AVR pebble bed reactor operation and its consequences for future HTR concepts, Berichte des Forschungszentrums Juelich, Juel-4275, ISSN 0944-2952.

[7] J. Knorr, A. Kerber, R. Moormann, „Upgrading (V) HTR fuel elements for generation IV goals by SiC encapsulation", Kerntechnik 77 (2012) 5, p. 351-355.

[8] J. Knorr, A. Kerber: Progress in ceramic technologies for SSiC encapsulation of nuclear fuel; atw Vol. 69 (2024) 3 p. 37-42.

[9] S. Frey Herrenknecht AG, D-77963 Schwanau-Allmannsweier, Info-Material zur VSM-Technik/Kosten (grobe Richtwerte), private communication, September 2021.

[10] Verordnung über Sicherheitsanfor-derungen an die Endlagerung hochradioaktiver Abfälle (EndlSAnfV) Referentenentwurf 17.07.2019 Deutscher Bundestag.

[11] A. Kerber, J. Knorr: SiC encapsulation of high level waste for long-term immobilization, atw International Journal of Nuclear Power, 1/2013 p. 8-13.

[12] J. Knorr, A. Kerber: Ceramic Initial Barrier/Keramische Initialbarriere für innovative Zwischen- und Endlagerung von hochradioaktivem Abfall, atw Vol 67(2022) Issue 2, March, p. 54-61.

[13] A. Kerber, J. Knorr, Joining Silicon Carbide Components by Rapid Sinter Bonding, Paper submitted to Nuclear Science USA, Weimar, / Dresden April 2024.

[14] J. Knorr, A. Kerber, Basics &Arguments for the SSiC Initial Barrier as integral part of each waste package for high radioactive waste final disposal, Conference Paper, Workshop "Behältermaterial", Karlsruhe 22.-23. März 2023.

[15] Y. Zhao, et. al: SSiC Nuclear Waste Canisters: Stability Considerations During Static and Dynamic Impact, atw Vol 66 (2021) Issue 5, September, p. 42-49.

Biography

Juergen Knorr: Prof. Knorr has been Professor of Nuclear Technology at the Technical University of Dresden (Emeritus since 2006). He received his doctorate in physics/nuclear technologies. From 1975 to 1992, Prof. Knorr was responsible for the planning, construction and operation of the AKR-1 training reactor in Dresden. From 1993 to 2000, Prof. Knorr was President of the German nuclear society KTG e. V. and also board member of the European Nuclear Society. The cooperation with SiCeram GmbH on the application of high-tech ceramics in the nuclear sector began in 2003.

Albert Kerber: Since 1998, Dr. Albert Kerber has been co-owner and managing director of SiCeram GmbH in Jena, specializing in high-performance ceramics. After studying chemical engineering, he completed his doctorate at the Technical University Karlsruhe. The collaboration with Prof. Knorr began in 2003 and focuses on the application of high-tech ceramic materials in the nuclear sector, particularly for innovative solutions in the field of nuclear waste and fuel elements. Today, Dr. Kerber is site manager of Qsil Ceramics GmbH in Jena.