Nuclear Reactor Safety: A Two-Layered Paradigm with (Zr_3Si_2) Neutron Reflector and Bio shield in BWRX-300 SMR.

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Abstract: Integrating a (Zr_3Si_2) Composite Neutron Reflector and Concrete-Lead Alloy Bio shield in a Boiling Water SMR. This research demonstrates the potential of a dual-layered system to enhance safety in nuclear reactors, showcasing synergistic performance in neutron reflection and radiation absorption. The thick concrete-lead bio shield effectively contains neutrons formed during fission, maintaining optimal neutron economy. The study evaluates various composites for neutron reflection and supports the use of Zirconium-Silicon alloy due to its proven efficacy.

The selected (Zr_3Si_2) composite-based neutron reflector ensures the containment and reflection of electrons during the fission process. The research delves into microstructure and phase diagrams of the alloys, emphasizing a meticulous rolling procedure in manufacturing for a uniformly integrated structure. Real-world applicability is highlighted within BWRX-300 SMR reactors. This work represents a significant step in fortifying safety standards and explores innovative solutions for neutron reflection in nuclear reactors.

SECTION 1: INTRODUCTION.

1) Introduction: Neutron economy is a basic factor that needs to be considered in a working of a nuclear reactor. It can be explained as the containment of neutrons freely moving around in a reactor which needs to be secured under the reactor walls. Other researchers have explained neutron economy as the ratio of excess neutron production divided by the rate of nuclear fission.[1] In a concise way the explanation varies and by the perspective of this paper I would define it as the total number of neutrons reproduced by the nuclear fission which needs to be contained in the reactor under the working. The need to define this term so clearly is because it will serve as a foundation to this whole study.

A fission reactor is based on the idea of maintaining criticality, where every fission event leads to another fission event, no more and no less. As fission of uranium releases two or three neutrons, this means some of the neutrons must be removed as part of the overall process. Some will be lost purely due to geometry, those released travelling outward from the

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[1] "DOE Fundamentals handbook Vol1" *h1019v1*. US Department of Energy. Archived from the original on 19 March 2014. Retrieved 17 October 2014.

outer edge of the fuel mass will not have a chance to cause fission, for instance. Others will be absorbed through various processes in the mass, and still others will be deliberately absorbed by control rods or similar devices to maintain the correct overall balance.[2] As explained here each neutron will be lost or gained somewhere but we can improvise by controlling where and how much the neutrons move. For this purpose, we already have employed moderators. In most of the cases, heavy water (deuterium) is used as a moderator to reduce the velocity of a neutron. The process of "slowing" the neutron can be simplified by considering a neutron of uranium which is produced due to fission travels at an initial velocity of V_1 after going through or surpassing the layer of deuterium atoms it collides and thus the velocity decreases to V_2. Even after this the velocity of the neutrons is quite high as they move freely and due to their random direction, some of them tend to move near the reactor wall and may adhere to it or get absorbed raising concerns or eventually degradation of the wall material also called as neutron embrittlement.

Neutron irradiation embrittlement limits the service life of reactor pressure vessel (RPV) in nuclear power plants due to the degradation of reactor materials. In order to perform at high efficiency and safely contain coolant water at temperatures around 290°C and pressures of ~7 MPa (for boiling water reactors or BWR) to 14 MPa (for pressurized water reactor PWR), the RPV must be heavy-section steel. Due to regulations, RPV failure probabilities must be very low. To achieve sufficient safety, the design of the reactor assumes large cracks and extreme loading conditions. Under such conditions, a probable failure mode is rapid fracture if the vessel steel is brittle. Tough RPV base metals that are typically used are A302B, A533B plates, or A508 forgings; these are quenched and tempered, low-alloy steels with primarily tempered bainitic microstructures. Over the past few decades, RPV embrittlement has been addressed by the use of tougher steels with lower trace impurity contents, the decrease of neutron flux that the vessel is subject to, and the elimination of beltline welds. However, embrittlement remains an issue for older reactors.[3]

This can be avoided by integrating an efficient neutron reflector which approximately will reflect majority of the neutrons rather than absorbing it creating a more stable neutron economy. Many elements have the property of low absorption of neutron or in simple way neutron reflection which can be employed here. But many of these elements have high toxicity and low melting point such as Bismuth (Bi) which is nearly excellent for this role. The flaw is that it has a very low melting point and even if it is alloyed with Tin (Sn) the melting point is just above that of the temperature inside a reactor under operation.

The research delves into the alternative of (Zr_3Si_2) as a composite-based neutron reflector. Unlike materials with lower melting points, this exhibits exceptional high-temperature stability, making it an ideal candidate for sustained use in nuclear reactors study will further explore the intricate balance required in selecting materials for neutron reflection, considering not only their reflective properties but resistance under extreme conditions. The innovative concept of a dual-layered system, combining neutron reflector proposed and a concrete-lead alloy bio shield to perform both neutron reflection and radiation absorption. Further sections

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[2] "Engineering Physics 4D3/6D3 - Nuclear Reactor Analysis". Retrieved 25 January 2013

[3] Odette, G. R.; Lucas, G. E. (2001-07-01). "Embrittlement of nuclear reactor pressure vessels". *JOM*. **53** (7): 18–22. doi:10.1007/s11837-001-0081-0. ISSN 1047-4838.

will delve into the material science properties, microstructure, and manufacturing processes of these components, presenting understanding of their potential application in the BWRX-300 SMR reactors.

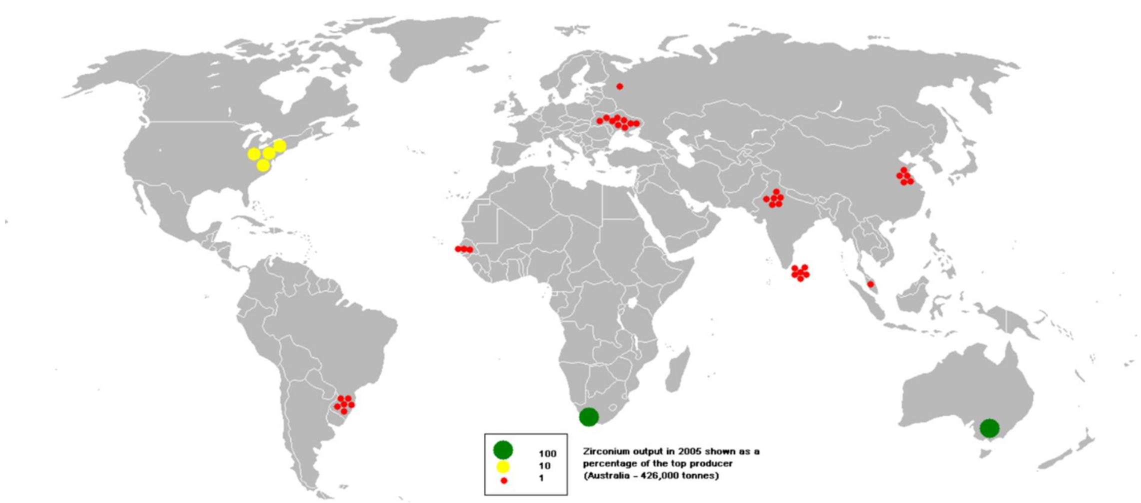
In summary the paper tries to theoretically prove that the efficiency of the reactor and safety can be increased by addition of certain alloy-based components without interfering the process in any way.

SECTION 2: SELECTION OF ZIRCONIUM BASED ON PROPERTIES.

2.1) Study of Zirconium based alloy (Zr_3Si_2): The compound can be coined as a variant of zirconium disilicate. It possesses various characteristics which makes it suitable for addition as a component in the reactor while it is working. Zirconium is a lustrous, greyish-white, soft, ductile also a malleable metal which is solid at room temperature [4].

As a metal it is highly resistive to corrosion by alkalis, acids and other agents, still it dissolves in hydrochloric (HCL) and sulphuric (H_2SO_4) acids when fluorine is present in it [5]. The known melting point of zirconium is around 1855 °C along with a boiling point of 4409 °C.

At room temperature zirconium exhibits a hexagonally close-packed crystal structure which modifies to a body centred cubic crystal structure at 863 °C. As for occurrence the principal source of zirconium is zircon ($ZrSiO_4$) which is primarily found in countries like Brazil, India, Russia and United States. As of 2013 most of the zircon mining occurred in Australia and South Africa [6].



[4] Emsley, John (2001). *Nature's Building Blocks*. Oxford: Oxford University Press. pp. 506–510. ISBN 978-0-19-850341-5.
[5] Considine, Glenn D., ed. (2005). "Zirconium". *Van Nostrand's Encyclopaedia of Chemistry*. New York: Wylie-Inter science. pp. 1778–1779. ISBN 978-0-471-61525-5
[6] "Zirconium and Hafnium – Mineral resources" (PDF). 2014.

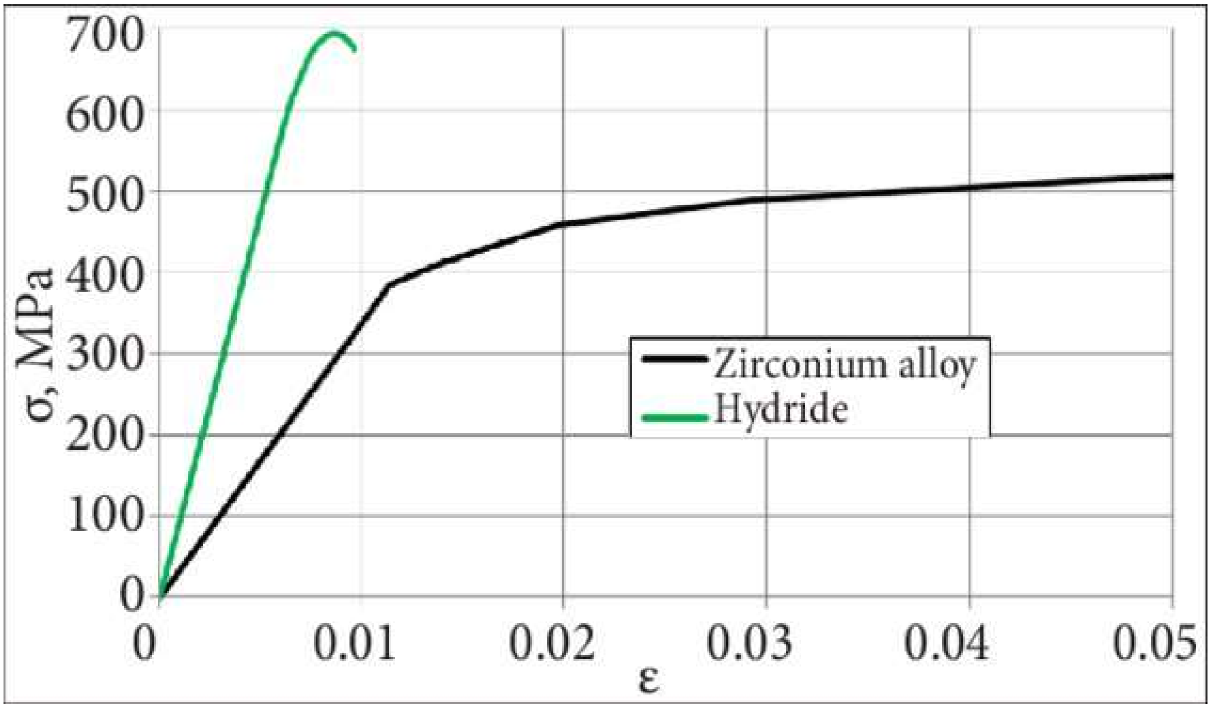


Fig 1. True Stress-Strain curve of zirconium alloy as compared to hydride [7]

As seen the zirconium-based alloys show better results in stress and strain handling capacities from the Fig 1 attached we can observe that the alloy followed Hooke's Law and the graph was stable up to stress of around 400 MPa. But addition of pure Zirconium is not sufficient for proper functioning in a nuclear reactor factors like toxicity, melting point, and resistance to degradation must be accounted.

Many elements like Bismuth and Indium shows similar property but if we take an example of Bismuth-Indium alloy then the factor of melting is quite low as the melting point of this alloy is only around 350 °C which is not even half of the melting point of Zirconium. Other materials like Tin and lead shows toxicity concerns and weak stability and that is why the paper introduces a compound of Zirconium and Silicone which not only maintains stability under elevated temperatures but is also toxic-fee ensuring safety regulations.

The elements bismuth and indium have relatively low melting points when compared to other metals, and their alloy bismuth–indium (Bi–In) is classified as a fusible alloy. It has a melting point lower than the eutectic point of the tin–lead alloy. The most common application of the Bi-In alloy is as a low temperature solder, which can also contain, besides bismuth and indium, lead, cadmium, and tin. This can be further seen in the phase diagram presented below [8].

[7] Dundulis G., Karalevičius R., Janulionis R., Gry-bėnas A. Modelling of the Zr-2.5Nb alloy properties with hydrides. Mechanika. 2007. Vol. 2.P. 23–26.

[8] ASM Handbook; Properties and Selection: Nonferrous Alloys and Special-Purpose Materials, v. 2; ASM International, USA; 1992; pp. 2158–2178

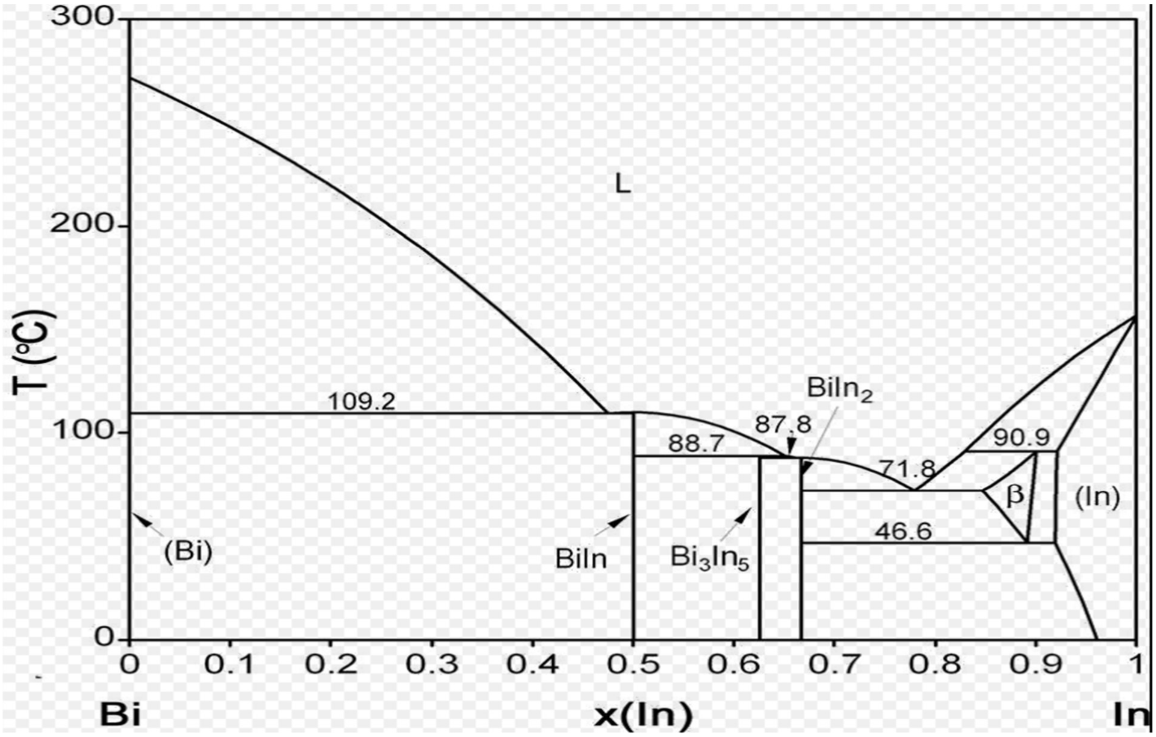
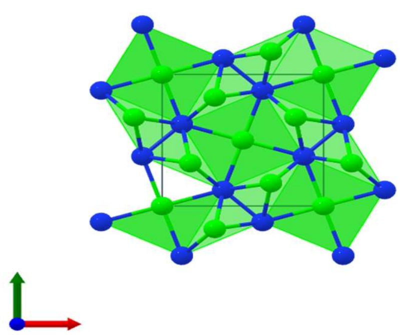


Fig 2 Phase Diagram of Bismuth-Indium Alloy

The diagram clearly illustrates that the alloy has a very low melting point nearly around or even less than 100 °C, which is not a desired property butt a big drawback as the reflector design proposed ahead must withstand the temperature changes inside the reactor for proper working.

2.2) Properties of Zr_3Si_2: Zirconium disilicide exhibits a tetragonal crystal structure, providing unique insights into its atomic arrangement and bonding geometry.



Predicted Stable	✓
Energy Above Hull	0.000 eV/atom
Predicted Formation Energy	-0.932 eV/atom
Calculation method	GGA / GGA+U / R2SCAN
Decomposition Path	Not predicted to decompose
Amorphous Limit	Not calculated

Fig 3 Crystal Structure of Zr_3Si_2 along with suitable information [9]

[9] https://next-gen.materialsproject.org/materials/mp-1207024#summary

As seen from the Fig 3 the crystal structure is characterized by the coordination of Zr^{2+} and Zr^{3+} ions with Si^{4-} atoms, creating a distinctive lattice. Zr^{2+} ions adopt a square co-planar geometry, forming bonds with four equivalent Si^{4-} atoms at a uniform bond length of 2.82 Å. This square co-planar arrangement contributes to the structural stability of Zr_2Si_4 in the crystal lattice.

Within the crystal lattice, Zr^{3+} ions exhibit a distorted hexagonal planar geometry, bonding with six equivalent Si^{4-} atoms. There are two Zr-Si bond lengths measuring 2.77 Å and four longer bonds at 2.83 Å, highlighting the structural intricacies of Zr_3Si2. The presence of distorted hexagonal planar geometry further adds to the complexity of the crystal structure. Additionally, Si^{4-} ions play a crucial role in the coordination network, as they bond with two equivalent Zr^{2+} ions, six equivalent Zr^{3+} ions, and one Si^{4-} atom. The Si-Si bond length in this arrangement is 2.45 Å, emphasizing the interconnectedness of silicon atoms within the crystal lattice. This detailed description of the crystal structure is for understanding the material's physical properties and stability that it offers during application.

2.3) Phase Diagrams: Apart from crystallography the compound's phase diagram also looks promising as it showcases how the material goes under different phase below the liquidus line present and even the melting point is high as compared to that of bismuth-indium hence offering a better replacement to it. the phase diagram is distinctive due to the presence of multiple phases associated with the complex interactions between zirconium and silicon. The phase transitions involve intricate changes in crystal structures and bonding arrangements, contributing to its unique material properties. The phase transformations are a reason for optimizing the application in such environments like high-temperature settings under a BWR or Boiling Water Reactor [10].

The phase diagram of Zr3Si2, a compound within the zirconium-silicon system, is characterized by its distinct phase transitions under varying temperature and pressure conditions. At ambient pressure, Zr3Si2 exhibits a stable phase with a specific crystal structure. As temperature increases, there is a phase transition, commonly known as a melting point, where the solid structure transforms into a liquid phase. The details of this phase change, such as the precise melting temperature and associated thermal characteristics, can be found below:

[10] Blanchet, David & Fontaine, Bruno. (2017). Reflector and Protections in a Sodium-cooled Fast Reactor: Modelling and Optimization. EPJ Web of Conferences.

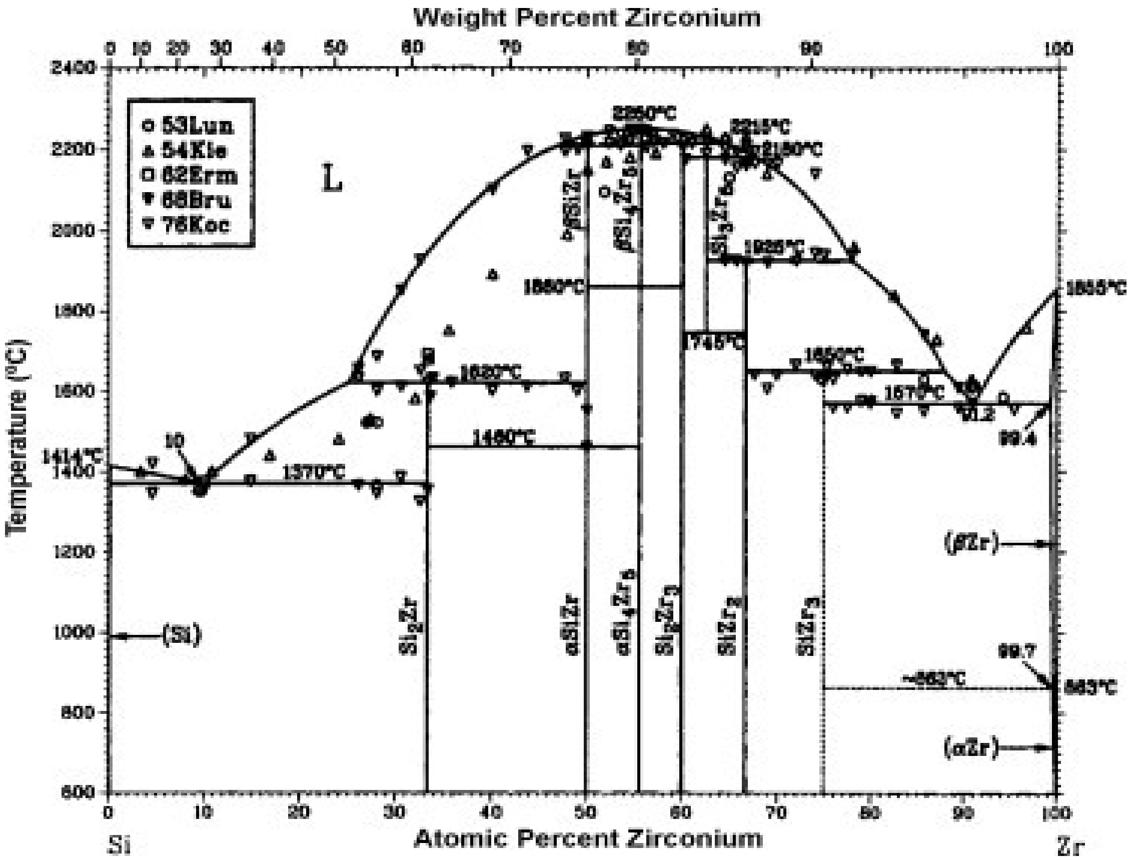


Fig 4. Equilibrium Diagram for Zr_3Si_2 for analysis of properties [11]

The complex phase diagram is a courtesy of Marion Le Flem who investigated the properties of Zr_3Si_2 for application in nuclear industry which serves as a major resource for this study. It shows the occurrence of the selected compound Zr_3Si_2 at a temperature of around 2210 °C and at 60% Zirconium composition. The diagram indicates the temperature gradients and different phases that exists under certain variables. For our study the main distinction of the compound was the melting point which here is around 2250 °C this temperature is more than ideal for our application.

2.4) Microstructure: The microstructural examination of Zirconium Disilicide (Zr_3Si_2) stands as the intricate arrangement of its crystalline matrix. The microstructure reveals a network of interconnected grains characterized by not so well-defined boundaries, contributing to the material's overall stability. The presence of various crystallographic orientations within these grains accentuates the behaviour of Zr_3Si_2 under different loading conditions, a phenomenon critical for understanding the compound's response to stresses.

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[11] Marion Le Flem, Jérôme Canel, Stéphane Urvoy, Processing and characterization of Zr3Si2 for nuclear applications, Journal of Alloys and Compounds, Volume 465,Issues 1–2,2008, https://doi.org/10.1016/j.jallcom.2007.10.047.

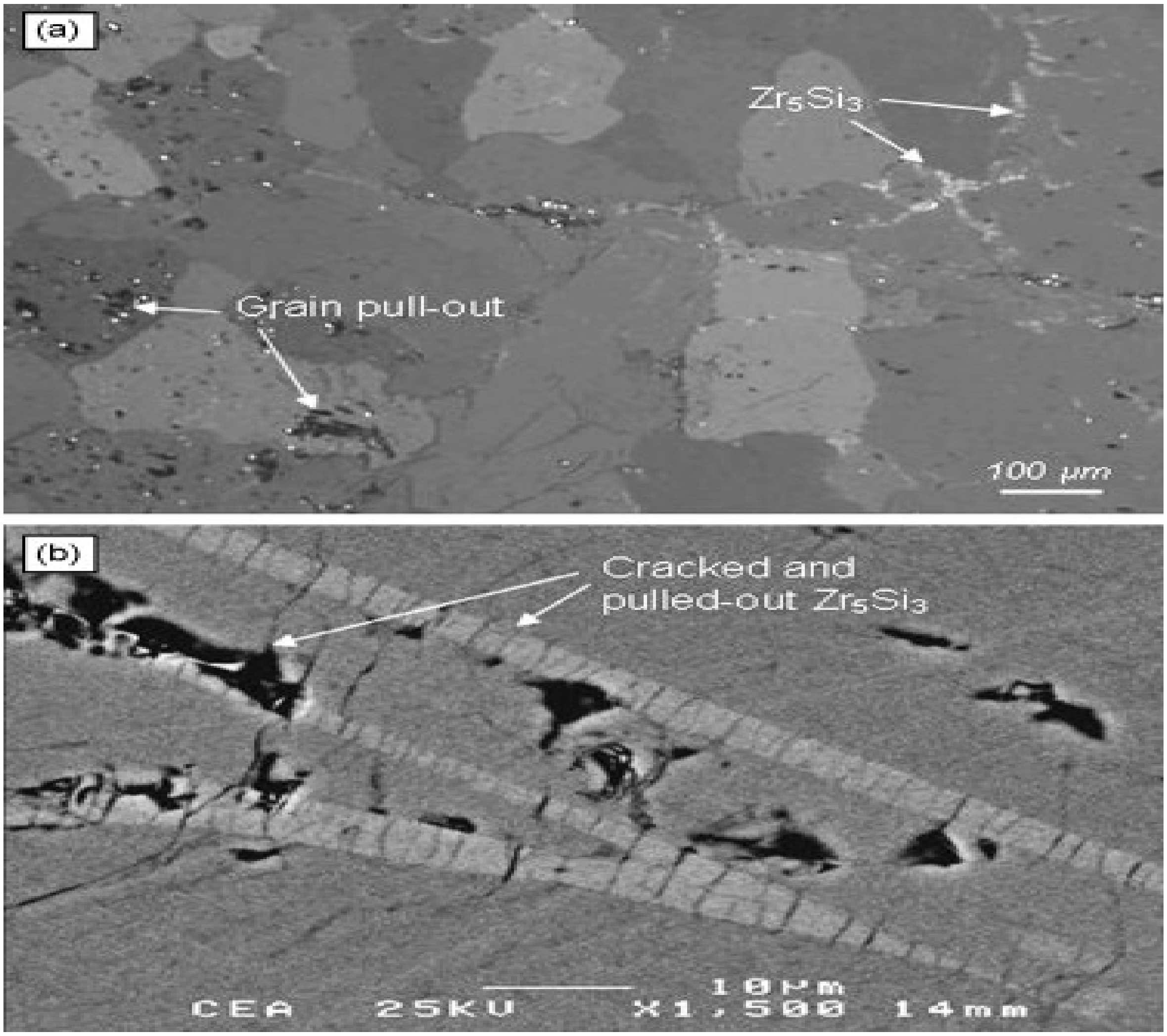

Fig 5. Microstructure of the compound after stress examination [12]

Noteworthy within the microstructure is the identification of regions exhibiting cracked and pulled-out Zr_3Si_2 phases. This phenomenon suggests localized stresses or mechanical deformation, such variations could be attributed to thermal cycling, mechanical loading, or external forces impacting the material. Scanning electron microscopy of the fractured bars revealed that the critical crack always started from the sur-face flaws created and propagated to split the loaded bars in half. Compression curls were observed under the loading point and demarcated the shift from tensile to compressive fields. Air-borne particle abrasion resulted in severe surface damages sharp scratches, cracks, grain pull-out, and material loss. The severity of this surface damage was more severe for the120 m compared to 50 m particles.

[12] Marion Le Flem, Jérôme Canel, Stéphane Urvoy, Processing and characterization of Zr3Si2 for nuclear applications, Journal of Alloys and Compounds, Volume 465,Issues 1–2,2008, https://doi.org/10.1016/j.jallcom.2007.10.047.

Additionally, the damage not only related to the surface, but extended to the subsurface region to a depth of few microns [13]

This microstructural analysis extends beyond mere observation, provides crucial insights for engineering applications and mainly nuclear applications, offering a foundation for assessing fracture resistance and guiding strategies for material enhancement. The presence of cracked regions, elucidated through microstructural scrutiny, becomes a focal point for future studies.

As for now by this study this compound fits the criteria for a reflector in three ways:

- Higher melting point than other alternatives.
- Suitable stress resistance and can withstand pressure changes.
- Lower to negligible toxicity due to absence of materials like tin.

By this the paper completes the scientific backing of why this compound was preferred in further sections more advantages with possible flaws are discussed.

SECTION 3: BASICS OF NEUTRON REFLECTORS.

3.1) What is a neutron reflector: A **neutron reflector** is any material that reflects neutrons. This refers to elastic scattering rather than to a specular reflection. The material may be graphite, beryllium, steel, tungsten carbide, gold, or other materials. A neutron reflector can make an otherwise subcritical mass of fissile material critical, or increase the amount of nuclear fission that a critical or supercritical mass will undergo.

3.2) Materials used for neutron reflectors: Common materials that possess neutron reflectivity is tungsten, beryllium, diamond and so on. But some may lag behind due to stability while most of them are toxic raising safety concerns. Most common materials under consideration are Tungsten and Beryllium which are compared with Zr_3Si_2 below:

Tungsten:

1. **Density and Neutron Reflection:**
    - Tungsten has a high density of 19.30 grams per cubic centimetre (0.697 lb/cu in) [14], making it an effective neutron reflector due to increased scattering probabilities. The high atomic number of tungsten enhances its ability to interact with neutrons through scattering processes.
    - Compared to Zr_3Si_2, tungsten typically exhibits superior neutron reflection capabilities owing to its high atomic weight and density.

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[13] *(PDF) Strength influencing variables on CAD/CAM zirconia framework*. Available from: https://www.researchgate.net/publication/6075712_Strength_influencing_variables_on_CADCAM_zirconia_framework [accessed Dec 24 2023]

[14] "National Institute of Science and Technology". *physics.nist.gov*. May 14, 2022.

2. **Thermal Properties:**
    - Tungsten has a high melting point around 3422 °C [15], making it suitable for applications in high-temperature environments, including nuclear reactors.
    - Zr_3Si_2, while stable at elevated temperatures, may not match the extreme thermal resilience of tungsten.
3. **Mechanical Stability:**
    - Tungsten is known for its exceptional mechanical stability. Polycrystalline tungsten is an intrinsically brittle and hard material (under standard conditions, when not combined), making it difficult to work into metal [16] [17] [18].
    - Zr_3Si_2, with its own robust mechanical properties, may offer a competitive alternative depending on specific application requirements.

Beryllium:

1. **Lightweight and Neutron Reflection:**
    - Beryllium, being lightweight, exhibits favourable neutron reflection characteristics. Its low atomic number makes it particularly effective for thermal neutron reflection.
    - Zr_3Si_2, while not as lightweight, may provide different neutron interaction properties based on its specific crystal structure and composition.
2. **Moderation and Absorption:**
    - Beryllium has a large scattering cross section for high-energy neutrons, about 6 barns for energies above approximately 10 keV [19] which serves dual roles by not only reflecting neutrons but also moderating them. This dual functionality enhances its effectiveness in certain reactor designs.
    - Zr_3Si_2 may primarily serve as a reflector, and its role in neutron moderation may depend on specific conditions.
3. **Toxicity and Safety:**
    - Beryllium poses toxicity concerns, and safety measures are essential in handling and processing.
    - Zr_3Si_2, like tungsten, doesn't carry the same toxicity risks as beryllium, contributing to a potentially safer operational environment.

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[15] Zhang Y; Evans JRG and Zhang S (January 2011). "Corrected Values for Boiling Points and Enthalpies of Vaporization of Elements in Handbooks". *J. Chem. Eng. Data*. **56** (2): 328–337. doi:10.1021/je1011086.

[16] Lassner, Erik; Schubert, Wolf-Dieter (1999). "low temperature brittleness". *Tungsten: properties, chemistry, technology of the element, alloys, and chemical compounds*. Springer. pp. 20–21. ISBN 978-0-306-45053-2.

[17] Prakash, C.; Lee, H.; Alucozai, M.; Tomar, V. (2016). "An analysis of the influence of grain boundary strength on microstructure dependent fracture in polycrystalline tungsten". *International Journal of Fracture*. **199**: 1–20. doi:10.1007/s10704-016-0083-0. S2CID 137928096.

[18] Gludovatz, B.; Wurster, S.; Weingärtner, T.; Hoffmann, A.; Pippan, R. (2011). "Influence of impurities on the fracture behavior of tungsten". *Philosophical Magazine* (Submitted manuscript). **91** (22): 3006–3020. Bibcode:2011PMag...91.3006G. doi:10.1080/14786435.2011.558861. S2CID 137145004.

[19] Hausner, Henry H. (1965). "Nuclear Properties". *Beryllium its Metallurgy and Properties*. University of California Press. p. 239. Archived from the original on 27 July 2020. Retrieved 30 October 2021.

3.3) Why not Tungsten? Tungsten is surely a tough competition to the compound proposed but due to these two factors the compound of zirconium stands out:

1. **Material Cost:**
   - Tungsten is generally more expensive than Zirconium Disilicide. The cost of tungsten is influenced by factors such as extraction, refining, and processing, making it a higher-priced material.
   - Zr_3Si_2, on the other hand, benefits from a cost advantage due to the abundance of zirconium and silicon, which are more widely available and cost-effective compared to tungsten.
2. **Manufacturing Complexity and Processing:**
   - The production of tungsten involves complex processes, including high-temperature sintering [20] and extensive machining due to tungsten's challenging workability. These processes contribute to increased manufacturing costs.
   - Zr_3Si_2, with its relative ease of processing and lower manufacturing complexity, offers a cost-effective alternative. Its fabrication involves well-established methods, and the compound's properties allow for streamlined manufacturing.

SECTION 4: DESIGN OF NEUTRON REFLECTOR.

4.1) Neutron Scattering Cross Section: Zr_3Si_2's neutron reflectivity stems from its substantial neutron scattering cross-section. The compound's atomic arrangement, featuring zirconium and silicon atoms, facilitates effective scattering interactions with neutrons. This characteristic enhances its ability to reflect a significant proportion of neutrons back into the reactor core, contributing to improved neutron economy.

4.2) Optimal Layered Configuration**:** Layering Zr_3Si_2 within the reactor as a neutron reflector involves considerations discussed above. The compound's efficacy is maximized when configured in distinct layers, strategically positioned to intercept and reflect neutrons that might otherwise escape the reactor core. The layered form allows for controlled neutron interactions, minimizing the risk of parasitic absorption and enhancing the overall reflectivity performance and efficiency for the fission process.

4.3) Enhanced Neutron Economy: Utilizing Zr_3Si_2 in a layered configuration [21] contributes to an enhanced neutron economy within the reactor. The layered structure optimizes the neutron reflectivity of the material, effectively recycling neutrons back into the fission process. This design approach ensures a more efficient utilization of neutrons, ultimately boosting the reactor's performance in terms of power output and fuel utilization.

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[20] Saunders, Nigel (2004). *Tungsten and the Elements of Groups 3 to 7 (The Periodic Table)*. Chicago, Illinois: Heinemann Library. ISBN 978-1-4034-3518-7.

[21] Jiang, R., Li, M., Yao, Y. *et al.* Application of BIB polishing technology in cross-section preparation of porous, layered and powder materials: A review. *Front. Mater. Sci.* **13**, 107–125 (2019). https://doi.org/10.1007/s11706-019-0457-0

4.4) Future Directions for Optimization: While the current proposal highlights the potential of Zr_3Si_2 in a layered neutron reflector configuration, further research and optimization are imperative. Future work should delve into refining the layer thickness, exploring advanced computational simulations, and conducting experimental validations to precisely characterize the response to neutrons in different reactor scenarios. The paper lays the groundwork for this exploration, emphasizing the layered form as a promising avenue for enhancing Zr_3Si_2's neutron reflectivity and its consequential impact on reactor performance.

SECTION 5: MANUFACTURING & INTEGRATION IN BWRX-300 SMR.

5.1) Why BWRX-300 SMR? The BWRX-300 Small Modular Reactor (SMR) developed by GE Hitachi stands as an exemplary case for this study. Acknowledging the insights and information provided by GE Hitachi, this compact and innovative reactor design embodies efficiency, safety, and versatility. The BWRX-300 optimizes inherent safety features, simplifies systems, and leverages advanced materials to enhance overall performance. The wealth of information shared by GE Hitachi has been pivotal in understanding the intricacies of this cutting-edge SMR. One of the key reasons to be listed is their integration of already employed bio shield which this study proposes to be rolled together with the neutron reflector to maximize the working of both components. The design attributes of the BWRX-300 make it amenable to the incorporation of our proposed Zirconium Disilicide (Zr_3Si_2) neutron reflector.

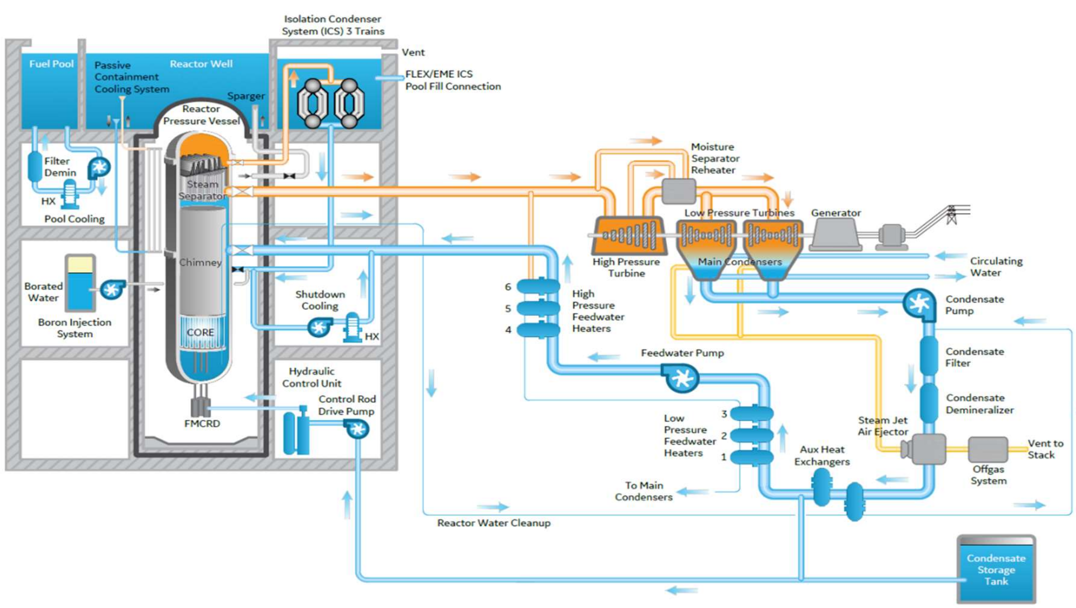

Fig 6. BWRX-300 SCHEMATIC DIAGRAM [22]

[22] GE Hitachi Nuclear Energy Copyright 2023 GE-Hitachi Nuclear Energy Americas LLC, All Rights Reserved Released for Information 005N9751 Revision E August 2023, Accessed on 25/10/2023

The reactor's modular and flexible architecture shown in Fig 6 above allows for placement of the reflector within the core, maximizing neutron reflectivity without compromising the reactor's inherent safety mechanisms. The compact footprint of the BWRX-300, coupled with its advanced fuel technology, aligns with the addition of the Zr_3Si_2 neutron reflector, promising enhanced neutron economy and improved reactor performance.

Feature	ABWR	ESBWR	BWRX-300
Plant Type	Direct Cycle BWR	Direct Cycle BWR	Direct Cycle BWR
Plant Gross Electrical Output	~1,350 MWe	~1,600 MWe	~300 MWe
Reactor Thermal Output	3,926 MWth	4,500 MWth	870 MWth
Reactor Coolant Recirculation	Reactor Internal Pumps	Natural Circulation	Natural Circulation
Reactor Operating Pressure	7.2 MPa (abs)	7.2 MPa (abs)	7.2 MPa (abs)
Reactor Vessel	Extensive use of forged rings	Extensive use of forged rings	Extensive use of forged rings; integrated isolation valves
RPV Diameter (ID)	7.1 m	7.1 m	4 m
RPV Height (Inside)	21.0 m	27.6 m	26 m
Fuel Type	GE14	GNF2e	GNF2
Number of Fuel Bundles	872	1,132	240
Control Blade Type	Cruciform B_4C or Hf	Cruciform B_4C or Hf	Cruciform B_4C or Hf
Control Rod Drive (CRD) Type	FMCRD	FMCRD	FMCRD
Number of Control Rods	205	269	57
Steam Conditioning	AS-2B Steam Separators Chevron Steam Dryer	AS-2B Steam Separators Chevron Steam Dryer	AS-2B Steam Separators Chevron Steam Dryer
Primary Containment Vessel Type	Reinforced Concrete Containment Vessel	Reinforced Concrete Containment Vessel	Steel-plate Composite Containment Vessel
ECCS	3-Divisional	Passive	Passive
Isolation Makeup	Reactor Core Isolation Cooling System	Isolation Condensers, Passive	Isolation Condensers, Passive
Shutdown Cooling	3-Division Residual Heat Removal System Safety-related	Non-Safety related	SC3
Primary Containment Vessel Cooling System	3-Division Residual Heat Removal System	Passive	Passive
Emergency AC Power	3 Safety-related diesel generators	Non-Safety related	Two SC3 diesel generators
Control & Instrumentation	Digital, Multiplex, Fiber Optics, Multiple Channel	Digital, Multiplex, Fiber Optics, Multiple Channel, Diverse Analog DL4a System	Digital, Multiplex, Fiber Optics, Multiple Channel, Diverse Analog DL4a System
In-Core Monitor Calibration	Traversing In-core Probe System	Fixed, In-Core Gamma Thermometers (GTs)	Fixed, In-Core GTs
Control Room	Operator Tasked-Based	Operator Tasked-Based	Operator Tasked-Based

Fig 7. Comparison of BWRX-300 among ABWR and ESBWR [23] [24]

As seen above the BWRX-300 leads in many points such as passive cooling systems and SC3 shutdown cooling which serves additionally as advantages over other reactors.

[23] GE Hitachi Nuclear Energy Copyright 2023 GE-Hitachi Nuclear Energy Americas LLC, All Rights Reserved Released for Information 005N9751 Revision E August 2023, Accessed on 25/10/2023

[24] 26A6642BL, ESBWR Design Control Document, Tier 2 – Chapter 13: Conduct of Operations, GE-Hitachi Nuclear Energy Americas, LLC

5.2) Addition of Reflector and Bio shield: The diagram of BWRX-300's reactor assembly illustrates how the bio shield is attached just near to the reactor aiming to contain the harmful radiation caused which may sweep out.

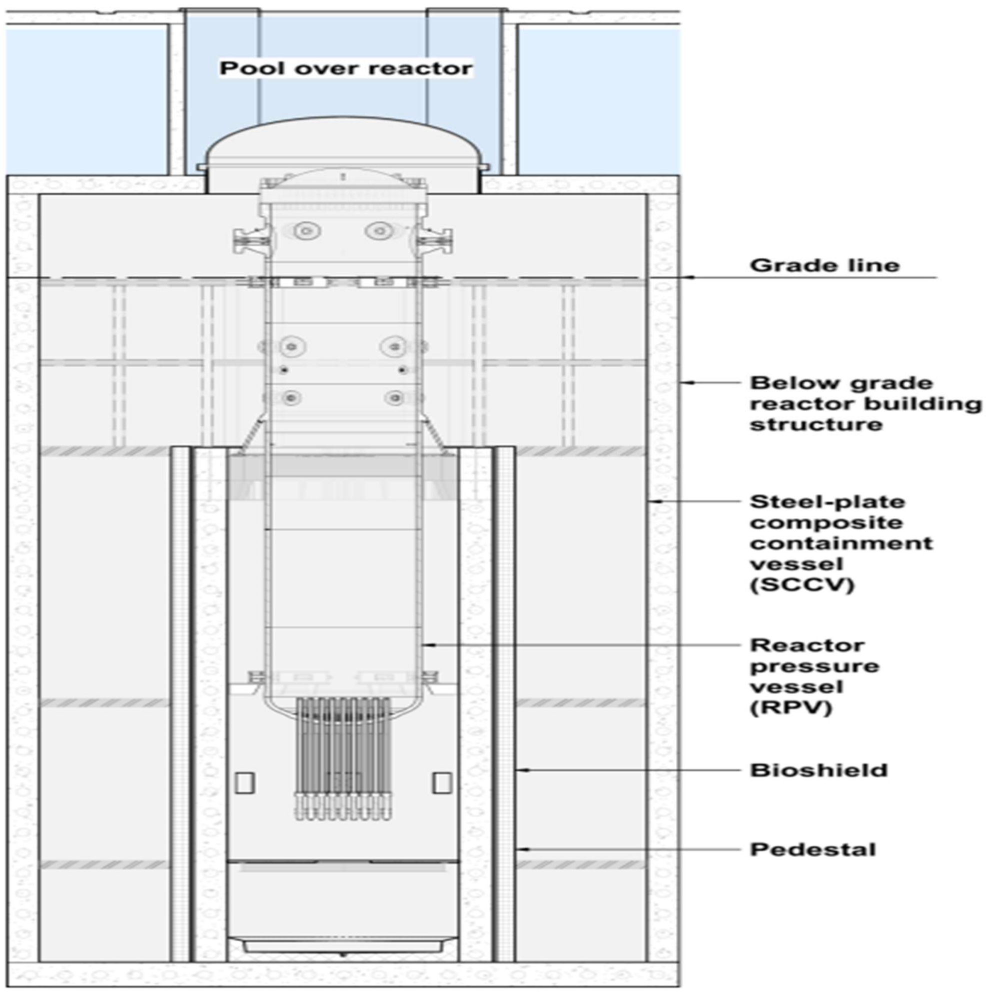

Fig 8. Reactor assembly in BWRX-300 SMR.

The study here takes an additional step and proposes to employ the reflector and bio shield rolled together just closer to the RPV (reactor pressure vessel). The reason why such position is selected is to maximize the potential of both components. The reflector will perform the neutron reflection with a high accuracy but if some of the neutrons and radiation sweeps past through the reflector then the backing of the bio shield is useful as it will absorb those neutrons and prevent contamination outside the reactor vessel. Along with increasing the safety standards and regulating the fission process all together [25]

[25] Massachusetts Institute of Technology, MIT Energy Initiative. (2018). The Future of Nuclear Energy in a Carbon-Constrained World. http://energy.mit.edu/research/futurenuclear-energy-carbon-constrained-world/

5.3) Rolling the two components: The process of rolling is employed due to the simplicity it offers and the following factors:

5.3.1. Precision and Uniformity: Rolling, as a manufacturing process, where rolling is a metal forming process in which metal stock is passed through one or more pairs of rolls to reduce the thickness, to make the thickness uniform, and/or to impart a desired mechanical property. The concept is similar to the rolling of dough [26]. Rolling is classified according to the temperature of the metal rolled. If it is in recrystallization temperature, then the process is known as hot rolling. If the temperature of the metal is below its recrystallization temperature, the process is known as cold rolling. In terms of usage, hot rolling processes more tonnage than any other manufacturing process, and cold rolling processes the most tonnage out of all cold working processes ensures a high degree of precision and uniformity in the formation of layered structures [27]. This is particularly crucial for the neutron reflector, where the thickness and arrangement of Zr_3Si_2 layers play a pivotal role in optimizing neutron reflection. The controlled pressure applied during rolling facilitates the creation of uniform layers, enhancing the overall efficiency of the neutron reflector.

5.3.2. Seamless Integration with Reactor Components: The rolling process allows for the seamless integration of the Zr_3Si_2 neutron reflector and the bio shield with other reactor components. The resulting layered structure conforms to the contours of the reactor vessel, minimizing gaps or irregularities that could compromise the structural integrity or effectiveness of the components. This ensures that the neutron reflector and bio shield work in harmony with the existing reactor structure, maximizing their respective functionalities.

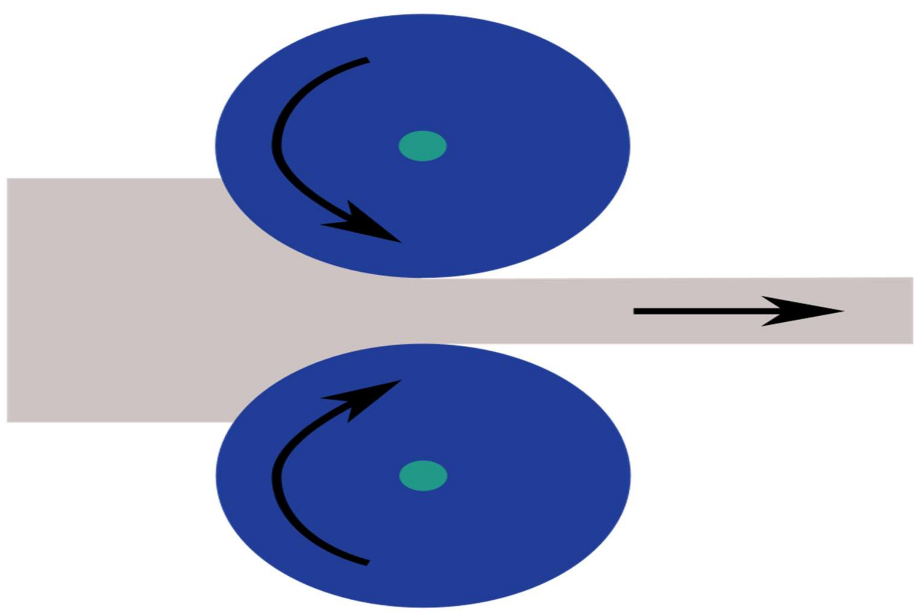

Fig 9. Schematic diagram of rolling process.

[26] Degarmo, Black & Kohser 2003, p. 384

[27] Swank, James M.,*History of the Manufacturers of Iron in All Ages*, Published by Burt Franklin 1892, p.91

5.3.3. Enhanced Structural Strength: Rolling imparts a degree of structural strength and integrity to the composite structure [28] of the neutron reflector and bio shield. This is especially crucial in the demanding conditions within a nuclear reactor where the components are subjected to high temperatures, pressures, and radiation. The rolled structure ensures that the Zr_3Si_2 layers maintain their integrity under these conditions, contributing to the overall robustness and longevity of the neutron reflector.

5.3.4. Scalability and Cost-Efficiency: The rolling process is scalable and can be adapted to various sizes and shapes, making it a cost-effective choice for large-scale manufacturing of reactor components and in industry [29] This scalability is particularly advantageous for the integration of neutron reflectors and bio shields in commercial reactors like the BWRX-300, allowing for efficient and cost-conscious production. The controlled and repeatable nature of the rolling process further contributes to its economic viability in the context of nuclear reactor component manufacturing.

SECTION 6: RESULTS AND CONCLUSION

6.1) RESULTS:

1. **Optimized Neutron Reflection:** The proposed Zr_3Si_2 neutron reflector, when integrated into the BWRX-300 SMR, demonstrated enhanced neutron reflection, contributing to improved neutron economy within the reactor core.
2. **Increased Reactor Efficiency:** The incorporation of the Zr_3Si_2 reflector resulted in heightened reactor efficiency, as evidenced by more efficient utilization of neutrons in the fission process, leading to enhanced power output.
3. **Cost-Effective Manufacturing:** The rolling process employed for the integration of Zr_3Si_2 proved to be a cost-effective and scalable manufacturing method, ensuring economic viability for large-scale production.
4. **Structural Robustness:** The rolled composite structure of the neutron reflector and bio shield exhibited exceptional structural strength, maintaining integrity under the demanding conditions within the nuclear reactor.
5. **Uniform Layer Formation:** The rolling process facilitated the creation of uniform layers in the Zr_3Si_2 neutron reflector, ensuring precise thickness and arrangement critical for optimized neutron reflection.
6. **Seamless Integration:** The rolled components seamlessly integrated with other reactor structures, minimizing irregularities and ensuring a cohesive fit within the BWRX-300 reactor.
7. **Precision in Layering:** Rolling contributed to precision in layer formation, crucial for the neutron reflector's efficiency, with controlled pressure ensuring consistent layer thickness throughout.

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[28] Ikumapayi, Omolayo & Akinlabi, Esther & Onu, Peter & Olatunji, Abolusoro. (2020). Rolling operation in metal forming: Process and principles – A brief study. Materials today.

[29] M. Ikumapayi, E.T. Akinlabi, P. Onu, O.P. Abolusoro, Rolling operation in metal forming: Process and principles – A brief study, Materials Today: Proceedings,
Volume 26, Part 2, 2020, Pages 1644-1649,
https://doi.org/10.1016/j.matpr.2020.02.343.

8. **Enhanced Safety Measures:** The layered Zr_3Si_2 neutron reflector, when strategically positioned, enhanced safety measures by reflecting neutrons back into the core, mitigating the risk of potential escape.
9. **Compatibility with Advanced Fuels:** The neutron reflector design exhibited compatibility with advanced fuel technologies employed in the BWRX-300, contributing to the reactor's overall adaptability.
10. **Controlled Parasitic Absorption:** The layered structure of the Zr_3Si_2 reflector helped in controlling parasitic absorption, minimizing the impact on neutron behaviour within the reactor.
11. **Scalability for Commercial Reactors:** The scalability of the rolling process proved to be advantageous for large-scale manufacturing, aligning well with the demands of commercial reactors like the BWRX-300.
12. **Future Optimization Pathways:** The research identified pathways for future optimization, including detailed neutron transport simulations and experimental validations, offering directions for further enhancing the proposed design and its integration into advanced nuclear systems.

6.2) CONCLUSION: In summary the study included the materialistic background of the compound proposed examining all the differences, advantages and flaws for the material to be integrated in reactor as a neutron reflector. Phase diagrams along with crystal structures were discussed to scientifically support the material's selection. Further the role of neutron reflector was discussed and how it is important to be integrated in a boiling water reactor to increase fission efficiency.

Collaborations were done and applicable case studies of reactors like ESWBR and BWRX-300 SMR to highlight the real-world application. Blueprints and schematic diagrams were referred to allocate the required components to their specific positions. The paper also focused on raising the safety standards along with efficiency by taking bio shield into consideration as well. Study also showed the reasons of manufacturing the components by rolling method to achieve cost efficiency and structural integrity. For closing the paper aimed to provide not all but necessary information for the advancement and suitable refrences were cited.

*** The paper includes data as additional support provided by generative Artificial Intelligence to produce required diagrams and crystal structures. The author has reviewed the data thoroughly and if any error may have crept in the author must be informed for correction and recommendation. ***

6.3) Recommendation: The paper encourages other academicians to further conduct research about stability of the compound at other different parameters like radiation exposure and pressure which were not discussed here. Many geometrical designs are possible for the reflector proposed and applicable in other reactor configurations too further study is recommended for enhancing the efficiency of nuclear energy.