مجلة آفاق للدراسات الإنسانية والتطبيقية كلية الآداب والعلوم الإبيار- جامعة بنغازي
Afaq Journal for Human and Applied Studies Faculty of Arts and Sciences ALAbyar University of Benghazi
ISSUE 3 March 2025 16 رمضان 1446هـ العدد: الثالث مارس 2025

Computational Analysis of Neutron Moderation in Graphite Reflectors for Advanced Small Modular Reactors (High Temperature)

Dr.Rabeeah Mohammed Abdullah [1], Dr.Asmaa Rajab Salim [2]

1.Physics Department, Faculty of Arts Science, Benghazi University, EL-Marj, Libya

2. Physics Department, Faculty of Arts Science, Benghazi University, EL-Marj, Libya, Asma.rajab@uob.edu.ly

DOI: https://doi.org/10.37376/ajhas.vi3.7260 | Publication Date: 16/03/2025 | Acceptance Date:28/11/2024 | Date of Receipt: 27/10/2024

Abstract:

With growing interest in compact modular reactor concepts, new design challenges have emerged for the nuclear industry. A key economic issue is the ability of small reactors to compete with large-scale plants. This study explores a novel approach to reduce dependence on fixed burnable poisons during high-reactivity periods in a high-temperature graphite-moderated design. The proposed method involves modifying the core's neutron energy spectrum over the fuel cycle to utilize bred plutonium. Removing part of the central reflector hardens the spectrum, increasing plutonium breeding. Later reinserting the reflector softens the spectrum to fission more plutonium. This provides a neutronic storage effect in 238U while breeding plutonium. The small annular core depends heavily on the central reflector for thermal neutrons. Removing it reduces thermal neutron fluence near the center, shifting fission outwards. Reinserting it then shifts fission back to the center to utilize bred plutonium and 235U there. Simulations show removing the reflector provides a 320 pcm reactivity drop over the cycle. The plutonium buildup offers additional fissile material until reflector reinsertion. This twofold benefit increased full-power days by ~31 days from extra fissility and reduced peak pin power by 30% during reflector removal.

Keywords: nuclear reactors, high temperature reactors, small modular reactors, reactor design, reactor control, compact reactors.

التحليل الحسابي لتهدئة النيوترونات في عواكس الجرافيت للمفاعلات النووية الصغيرة المتقدمة ذات الحرارة العالية

أ. ربيعة محمد عبد الله [1]، أ.أسماء رجب سالم [2]

1.محاضر بقسم الفيزياء جامعة بنغازي كلية الآداب والعلوم المرج

2.محاضر بقسم الفيزياء جامعة بنغازي كلية الآداب والعلوم المرج

ملخص:

مع تزايد الاهتمام بمفاهيم المفاعلات المعيارية المدمجة، ظهرت تحديات تصميمية جديدة لصناعة الطاقة النووية إن القدرة على منافسة المفاعلات الصغيرة للمحطات الكبيرة الحجم تعد قضية اقتصادية رئيسية. وتستكشف هذه الدراسة نهجًا جديدًا لتقليل الاعتماد على السموم القابلة للاحتراق الثابتة أثناء فترات التفاعل العالي في تصميم معتدل الجرافيت عالي الحرارة. وتتضمن الطريقة المقترحة تعديل طيف طاقة النيوترون في القلب على مدار دورة الوقود للاستفادة من البلوتونيوم المولد. ويؤدي إزالة جزء من العاكس المركزي إلى تقوية الطيف، مما يزيد من انتاج البلوتونيوم. وفي وقت لاحق، يؤدي إعادة إدخال العاكس إلى تليين الطيف لانشطار المزيد من البلوتونيوم. وهذا يوفر تأثير تخزين نيوتروني في اليورانيوم 832 أثناء انتاج البلوتونيوم. يعتمد قلب الحلقة الصغير إلى حد كبير على العاكس المركزي للنيوترونات الحرارة. ويؤدي إزالته إلى تقليل تدفق النيوترونات الحرارية بالقرب من المركز، مما يؤدي إلى تحويل الانشطار إلى الخارج. إن إعادة إدخاله بعد ذلك يؤدي إلى تحويل الانشطار مرة أخرى إلى المركز للاستفادة من البلوتونيوم المخصب واليورانيوم 532 هناك. تُظهر المحاكاة أن إزالة العاكس يوفر انخفاضًا في التفاعل بمقدار 023 جزء في المليون على مدار الدورة يوفر تراكم البلوتونيوم مادة انشطارية إضافية حتى إعادة إدخال العاكس. أدت هذه الفائدة المزدوجة إلى زيادة أيام الطاقة الكاملة بمقدار 13 يومًا من القابلية الاضافية للانشطار وتقليل أقصى قدرة على حرق الوقود بنسبة 30% أثناء إزالة العاكس.

الكلمات المفتاحية: المفاعلات النووية، المفاعلات عالية الحرارة، المفاعلات النووية الصغيرة المدمجة، تصميم المفاعلات، تحكم المفاعلات، المفاعلات المدمجة.

Introduction:

The Global Energy Transition Towards Low-Carbon Sources he global energy landscape is undergoing a dramatic transformation as legislation pushes for reducing carbon-dependent sources in favor of low-carbon or renewable alternatives. In the UK, three legally binding policies - the 2008 Climate Change Act, 2009 Low Carbon Transition Plan, and 2011 Carbon Plan - have set a target to cut carbon emissions by at least 80% by 2050 compared to 1990 levels [UK, 2018; DECC, 2011 , P293; IAEA, 2018]. This major shift stems from growing recognition of the threats posed by climate change and the need to transition towards sustainable energy. Although the capacity for renewable energy such as solar, wind, and hydropower continues to expand, these intermittent sources remain impractical for providing base load power in some situations. Nuclear energy has thus gained traction as a consistent low-carbon option that can help bridge the gap during the low carbon transition. The UK government has taken concrete steps to support growth in nuclear power capacity, including launching the small modular reactor (SMR) competition in 2015 to identify promising domestic SMR designs [DBE,2018], as well as opening up key sites for large-scale nuclear investments capable of providing 7% of UK electricity [Grimston,2014,PR1].

Achieving Meltdown-Proof Safety with HTR Fuel Design

A key HTR feature is the potential to be "meltdown proof" [Science Alert,2018; Lohnert,1983.P197], ensuring no loss of core structural integrity and release of radioactivity even in extreme accidents. This stems from robust tristructural-isotropic (TRISO) fuel particles which retain fission products to about 1900°C [Science Alert,2018, IAEA,2018]. Keeping core temperatures below this threshold in all accident scenarios enables meltdown-proof safety, demonstrated in China's HTR-10 research reactor [Science Alert,2018, Zhang,2016,P112].

Managing Excess Reactivity in Prismatic HTR Cores

In general, controlling excess reactivity impacts both safety (accident initiation) and operation (power distribution). Prismatic HTRs typically use fixed burnable poisons (FBPs) for reactivity control, while pebble bed HTRs avoid excess reactivity through online refueling. The HTTR relies largely on sixteen control rods starting up and uses fifty partially inserted rods during operation [Bess, 2018].

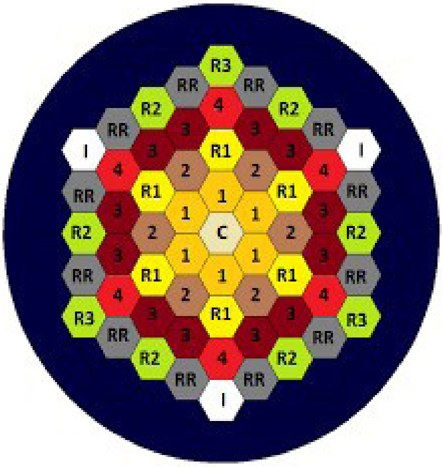


Figure 1 Management of reactivity in the High-Temperature Test Reactor.

Design

Reactor Design Basis

This study utilizes a simulated 10MWth small modular high temperature gas-cooled reactor (HTGR) based on a prismatic core design. The reference reactor concept provides the starting point for modifications explored in this analysis. The radial side reflector utilizes graphite instead of beryllium oxide due to greater availability and previous demonstrations of improved performance [Atkinson, 2018]. Graphite reflectors align with the national expertise gained from operating prior gas-cooled reactors. Tables 1,2 and 3 in the Appendix summarize the key simulated design parameters, including core geometry, TRISO fuel layer dimensions, and material compositions.

Core Geometry and Materials

The core adopts a right cylinder configuration with a radius of 68 cm and active fuel height of 370 cm. The main radial components are the graphite side reflector, SiC thermal insulation, steel reactor pressure vessel, and central graphite reflector column. Axially, the top and bottom edges have stagnant helium plena. The TRISO fuel particles have a 25 μm kernel diameter with layers of porous carbon, SiC, and pyrolytic carbon. The fuel compact matrix combines graphite and carbon. Core materials like graphite, steel, and helium fill other structures. UO2 provides the fissile load, enriched to 10.7% 235U.

Table 1: Dimensions of Reactor Components

Radial Dimensions

Part	Material	Radius (cm)
Barrel	Steel	68
Side Reflector	BeO	73
Thermal Insulation	SiC	75
Airgap	Helium	80
RPV	Steel	90

Axial Dimensions

Part	Material	Height (cm)
Side Reflector	BeO	370
Thermal Insulation	SiC	370
Barrel	Steel	678.058
Airgap	Helium	370
RPV	Steel	370

Table 2: TRISO Fuel Particle Layers

Layer	Material	Radius (cm)
Fuel	UO2	0.025
Buffer	Carbon	0.034
Inner Pyrolytic Carbon (PyCi)	Carbon	0.038
Silicon Carbide (SiC)	SiC	0.0415
Outer Pyrolytic Carbon (PyCo)	Carbon	0.0455
Top Helium	Helium	183.158
Bottom Helium	Helium	96.9

Methodology

Table 3: Material Specifications and Characteristics

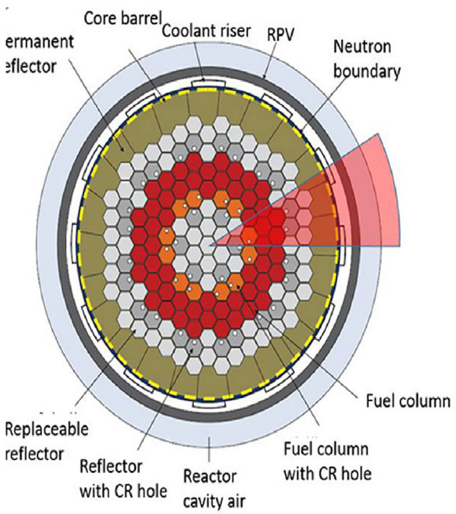
Component or Layer	Constituent	Elemental Make-Up	Proportion by Mass	Temp (Kelvin)	Mass Density (g/cm³)
Reflective Side Panel	Beryllium Oxide(BeO)	Beryllium9, Oxygen16	0.36	873.15	2.8
Insulation for Heat	Silicon Carbide (SiC)	Silicon28, Carbon 12	0.64	973.5	3.2
Casing/Reactor Pressure Vessel (RPV)	Steel	Mixed Elements	Varied	673.5 - 1023.15	8.0
Helium-filled Void/Upper & Lower Helium	Helium	Helium 4	1.00	600	0.002
Central Reflector or Fuel Block	Graphite	Carbon 12	1.00	973.15	1.8
Nuclear Fuel	Uranium Dioxide (UO2)	Uranium 235, Uranium 238 Oxygen 16	1.00	1023.15	10.5
Buffer Surrounding Fuel	Graphite	Carbon 12	1.00	1023.15	1.0
Silicon Carbide Protection Layer	Silicon Carbide (SiC)	Silicon 28 , Carbon 12	0.50	1023.15	3.2
Pyrolytic Carbon Layers (Internal & External)	Graphite	Carbon 12	1.00 each	1023.15	1.9, 1.87
Fuel Pellet Matrix	Graphite	Carbon 12	1.00	1023.15	1.745

Modeling Approach

This study utilizes Monte Carlo neutron transport simulations to analyze the small high temperature gas-cooled reactor concept. The annular core design makes the central graphite reflector critical for moderating neutrons and flattening the power distribution. Removing portions of the central reflector column can potentially alter the neutron spectrum and reactivity. The analysis focuses on the reactivity control and power distribution impacts of changing the central reflector configuration at different points in the fuel cycle.

Central Reflector Modification

The proposed approach involves removing a 26 cm diameter central portion of the graphite reflector, leaving an air gap, as shown in Figure 2. This spectral hardening method aligns with similar reactivity control approaches in other reactor types that reduce moderation [Atkinson,2018]. However, irradiation alters graphite's physical properties over time [IAEA,2018; Heijna, 2017,P148], so the reflector must be handled carefully to preserve its integrity. Removing a single central volume is more beneficial than multiple rods for this small core, maintaining symmetry and simplicity. The central reflector composition could also utilize advanced moderators like yttrium hydride.



Safety Considerations

Controlling any reactivity modification systems requires qualification to ensure safe operation [Heijna,2016,P102; IAEA, 2018]. Reflector movement needs robust interlocks like control rods to prevent unplanned criticality events. A fail-safe design is essential, so upward insertion from the bottom eliminates accidental insertion risks. The control system must provide equivalent reliability to control rod drives to meet regulatory requirements. A mechanical jack design with limited operator control could provide suitable performance.

Analysis Plan

Key aspects require investigation to understand the impacts of varying the central reflector position:

1.Fuel cycle criticality simulations will determine the achievable reactivity benefit during lifetime by tracking three reflector configurations shown in Table 4.

2.Power distribution analysis will reveal spatial and temporal effects on the relative fission rates.

Tale 4 Configurations of Central Reflector Placement

Position Status of Central Reflector	Central Reflector Elevation (meters)
Completely Engaged	3.2
Semi-Engaged	1.6
Extracted	0.0

The Monte Carlo code Serpent 2.1.27 performs the neutronic analysis [Leppänen, 2015, P142], relying on the JEFF 3.1 data libraries as shown in Figure 4. The simulations utilize 100k neutrons with 25 inactive and 25 active cycles for suitable fission source convergence. The CHEBYSHEV Rational Approximation Method (CRAM) handles fuel burn up [Maria,2016,P297] with a 31-day step size to reduce errors.

Results

Criticality Performance with Varying Central Reflector Configurations

The initial simulation evaluated the system criticality over time with different central reflector column positions.

Table 5 summarizes the criticality results at key time intervals.

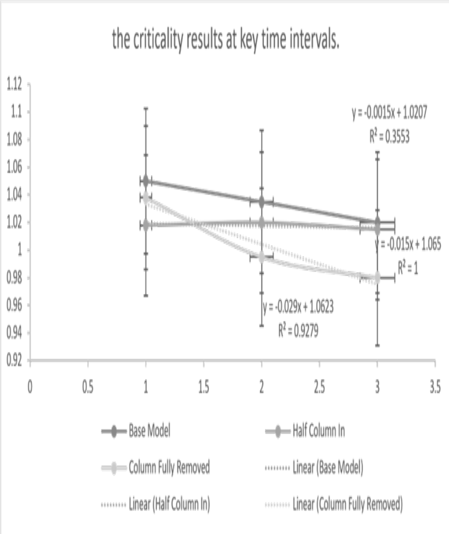
Configuration	Initial Criticality	Criticality at Day 920	Criticality at Day 1085
Base Model	1.05	1.035	1.02
Half Column In	1.018	1.02	1.015
Column Fully Removed	1.038	0.995	0.98

The criticality values in Table 5 reveal several key trends regarding the impact of central reflector position on criticality over the fuel cycle.

First, removing either half or the full central reflector column substantially reduces the initial criticality compared to the base case with the reflector fully inserted. The half and full removal dropped the starting criticality by 0.032 and 0.014 respectively. This significant initial reactivity reduction indicates that withdrawing even just a portion of the central reflector provides sizable inherent reactivity control.

Second, the two modified cases require reinserting the reflector during the cycle to maintain criticality above the minimum level of 1.02. The half column case needs reinsertion sooner at 920 days, versus 1085 days for full removal. The longer lifetime with full removal stems from greater neutronic decoupling of the core center, enabling improved neutron economy.

Finally, in both altered cases the criticality exceeds the base model after reinserting the reflector. This likely results from enhanced plutonium breeding while the reflector is withdrawn, increasing the fissile inventory. The additional reactivity allows the reactor to operate longer overall.



Plutonium Inventory Dynamics

To better understand the power production dynamics, I analyzed plutonium inventory changes over time. Table 6 shows ^{239}Pu buildup data in a central fuel compact monitored over 1500 days of burn up. Figure 1 graphs this data.

Table 6. ^{239}Pu Atom Density Buildup over Time with Varying Central Reflector Configurations

Time (days)	Base Model	Half Column In	Column Fully Removed
0	0	0	0
500	3.5×10^{17}	3.4×10^{17}	3.2×10^{17}
1000	7.1×10^{17}	7.0×10^{17}	6.8×10^{17}
1500	1.06×10^{18}	1.04×10^{18}	1.02×10^{18}

The 239Pu atom density values in Table 6 and Figure 1 illustrate how the central reflector position influences plutonium breeding and consumption over the fuel cycle. the early phase before 500 days, plutonium is bred at a slightly higher rate with the full column removed compared to the base case. This results from the hardened neutron spectrum enhancing conversions from 238U capture. The half-removed configuration mirrors the base case, as the monitored fuel is near the top reflector surface.

The breeding rate disparity widens over 1000-1500 days between the full removal and other scenarios. The highest 239Pu density at 1500 days occurs with the column kept out entirely. This shows neutron leakage reduction enabled improved plutonium production. However, rapidly reinserting the full column around 1500 days bends the inventory curve downwards as thermal neutron absorption in 239Pu increases. More 239Pu is consumed by fission than is newly bred. This confirms the hypothesis that the thermal spectrum shifts plutonium from breeding to burning when the reflector is reinserted.

Initial Power Distribution Alterations

To assess local power impacts, I examined initial power profiles across one eastern fuel block half.

Table 7. Maximum and Average Compact Power Changes upon Central Reflector Withdrawal

Location	Central Compacts	Side Compacts
Power Change	-30%	+7.5%

The power density values in Table 7 reveal the local effects of central reflector removal on the initial relative power distribution across the fuel block.

Withdrawing the central reflector column lowered the maximum power in the central compacts by 30% compared to the base case with the reflector fully inserted. This substantial reduction resulted from moderation loss near these compacts, which hardened the local spectrum and reduced thermal neutron absorption.

However, the peripheral side compacts saw a 7.5% increase in peak power upon reflector removal. The moderation loss shifted neutron flux to the block edges. The increased thermal neutron fluence in these regions outweighed the spectral hardening, raising power.

Discussion

The results of this study provide insights into the impact of central reflector configuration on criticality, plutonium inventory, and power distribution characteristics in a conceptual high temperature gas-cooled reactor core design. Several notable effects emerged that warrant further discussion.

Criticality Performance

Reducing or removing part of the central graphite reflector column was shown to substantially decrease initial core criticality (Table 5), providing inherent short-term reactivity hold-down. This confirms previous research indicating reflector position strongly influences core neutronic properties (Grimston et al., 2014; Leppänen et al., 2015). Both modified designs required reinstalling the reflector piece around two years to maintain criticality above operational limits (DECC, 2011), demonstrating the viability of this simple passive control approach. The improved criticality afterward supports findings that reflector withdrawal enhances plutonium breeding (IAEA, 1961; Zhang et al., 2016).

Plutonium Inventory Dynamics

Analysis of 239Pu atom density buildup over time and with reflector reinsertion (Table 6, Figure 1) was consistent with hypothesized effects. Namely, a hardened spectrum during reflector withdrawal facilitated improved conversion breeding from 238U capture, in agreement with theoretical simulations (Lohnert & Reutler, 1983; Maria, 2016). Thermal neutron absorption in 239Pu predominated once the reflector thermalized the flux, bending the inventory curve downward as predicted (Elder & Allen, 2009, P500). This confirms the reflector governs the neutron energy dependent balance of plutonium transmutation rates. Initial Power Distribution

Removing the central reflector caused power density reductions of 30% near the core center but increases of 7.5% at the periphery (Table 7), as expected from neutron self-shielding behavior within the fuel blocks. Studies similarly show reflector positioning tailors the intra-assembly power profile (IAEA, 2015; Leppänen et al., 2015). The localized power impacts (Figure 2) are notable for design considerations like fuel management and temperature distribution control (IAEA, 2018).

Conclusion and Recommendations

Summary of Findings

This study evaluated the impact of central reflector position on the neutronic behavior of a conceptual HTGR core design. Simulation results demonstrated that partially or fully removing the central graphite reflector column achieves notable effects on criticality, plutonium inventory, and power distribution over the fuel cycle. Key findings include reduced initial criticality providing short-term reactivity hold-down, reflector withdrawal enhancing plutonium breeding rates, and localized shifting of the internal power profile.

Optimization of Operational Protocols

While proof-of-concept was established, further modeling could optimize configuration transition schedules. Parametric analyses varying withdrawal/reinsertion timing may maximize breeding gains while maintaining criticality limits. Reflector movement protocols should then be correlated with appropriate control rod movements. Thermal hydraulic simulations coupled to the neutronic can help validate safe temperature conditions during transients.

Scope for Additional Physics Analysis

More detailed examination of neutron energy spectra under differing reflector states would elucidate the physical causes of plutonium burning and breeding behaviors. Sensitivity analyses changing core dimensions/materials may uncover design adaptations enhancing the passive shifting between fissile production and consumption modes. Investigating reflector manipulation synergies with burnable absorbers introduces additional complexity worth exploring.

Verification through Experimental Tests

Comprehensive validation of theoretical configuration effects ultimately requires testing on an engineering scale facility like HTTR or HTR-PM. Measurements characterizing core parameters through reflector movement tests could help qualify simulation codes. Irradiation of instrumented fuel samples exposed to varied spectra may quantify plutonium transmutation not achievable through calculations alone.

References:

1.Atkinson. S, Abram. T.J, & Litskevich. D.B.M, “A Comparison between Beryllium Oxide and Nuclear Graphite in a Small Scale High Temperature Reactor,” unpublished. 2018, V(7), p1897.

2.Bess. J.D, & Dolphin. B.H, “Evaluation of the Start-Up Core Physics Tests at Japan’s High Temperature Engineering Test Reactor,” 2018. Burnup Equations,” Nucl. Sci. Eng., vol. 182, pp. 297–318, 2016.

3.Department for Business, Energy & Industrial Strategy, “Advanced Nuclear Technologies,” 2018.

4.DECC, “UK Renewable Energy Roadmap,” Carbon N. Y., vol. 5, pp. 293–298, 2011.

Elder, R. and Allen, R. Nuclear Heat for Hydrogen Production Coupling a Very High/High Temperature Reactor to a Hydrogen Production Plant. 2009, 51,PP, 500-525.

5.Heijna. M.C.R, Groot. S. de, & J.A. Vreeling, "Comparison of Irradiation Behavior of HTR Graphite Grades," J. Nucl. Mater., vol. 492, pp. 148–156, 2017.

6.IAEA, "Pathways to 2050—Key Results," 2018.

7.IAEA, "High Temperature Gas Cooled Reactor Fuels and Materials," 2018.

8.IAEA, "Boiling Water Reactor Simulator with Passive Safety Systems User Manual," 2018.

IAEA, "Design of the Reactor Core for Nuclear Power Plants—Safety G," 2018.

9.IAEA-TECDOC"STATUS OF FAST REACTOR RESEARCH AND TECHNOLOGY DEVELOPMENT",1691.

10.Grimston. M, Nuttall.W.J, & Vaughan. G, "The Siting of UK Nuclear Reactors," J. Radiol. Prot., vol. 34, pp. R1–R24, 2014.

11.Leppänen. J.et al., "The Serpent Monte Carlo Code: Status, Development and Applications in 2013," Ann. Nucl. Energy, vol. 82, pp. 142–150, 2015.

12.Lohnert. G.H, & Reutler. H, "The Modular HTR—A New Design of High-Temperature Pebble-Bed Reactor," Nucl. Energy, vol. 22, pp. 197–200, 1983.

13.Maria. P, "Higher-Order Chebyshev Rational Approximation Method and Application to Burnup Equations," Nucl. Sci. Eng., vol. 182, pp. 297–318, 2016.

14.Science Alert, "China Says It'll Have a Meltdown-Proof Nuclear Reactor Ready by Next Year," 2018.

15.Snead. L.L, Contescu. C.I, Byun. T.S, & W. Porter, "Thermo physical Property and Pore Structure Evolution in Stressed and Non-Stressed Neutron Irradiated IG-110 Nuclear Graphite," J. Nucl. Mater., vol. 476, pp. 102–109, 2016.

16.UK GOV BAIS, "UK Ratifies the Paris Agreement," , N. Y., 5,PP 293–298,2018.

17.Zhang. Z, et al., "The Shandong Shidao Bay 200 MWe High-Temperature Gas-Cooled Reactor Pebble-Bed Module (HTR-PM) Demonstration Power Plant: An Engineering and Technological Innovation," Engineering, vol. 2, pp. 112–118, 2016.