Investigation of Steady-state Neutronics and Negative Feedback Mechanisms in a UZrH Core

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Abstract

To investigate the steady-state neutronics and negative feedback mechanisms of a uranium-zirconium hydride (UZrH) fueled core, a numerical analysis is conducted based on the OpenMC code and the ENDF/B-VII.1 nuclear evaluation database, with the Pulsed Reactor of China(PRC) serving as the reference reactor. Initially, the computational model is validated against available zero-power physics experimental data, confirming its accuracy and reliability. Building on this, a detailed steady-state neutronics and negative feedback analysis is performed. Neutronic parameters such as the core effective multiplication factor (K eff), neutron flux distribution, core neutron energy spectrum, power distribution, and control rod worth are analyzed. A decoupling analysis method is proposed to quantify the individual contributions of key factors, including the fuel temperature effect and the moderator temperature effect. Subsequently, by comparing the combined effect of these individual factors with the comprehensive effect of all factors, the physical mechanisms that dominate the overall negative feedback are identified. The influence of the hydrogen-to-zirconium atomic ratio (H/Zr) on core reactivity is also analyzed under conditions of constant uranium content and enrichment. The results demonstrate that the established computational model and analysis method can effectively replicate zero-power physical experimental data and reveal the neutronic characteristics and dominant negative feedback mechanisms of the UZrH core.These findings can provide methodological support and data reference for the physical design, performance prediction, and safety assessment of UZrH reactors, thereby contributing to the technological development of advanced UZrH reactors.

Full Text

Preamble

Investigation Steady-state Neutronics Negative

Feedback Mechanisms in a UZrH Core

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Abstract

investigate steady-state neutronics negative feedback mechanisms uranium-zirconium hydride (UZrH) fueled core, numerical

analysis

conducted based OpenMC ENDF/B-VII.1 nuclear evaluation database, Pulsed Reactor China(PRC) serving reference reactor.

Initially, computational model validated against available zero-power physics experimental data, confirming accuracy reliability.

Building this, detailed steady-state neutronics negative feedback

analysis

performed. Neutronic parameters effective multiplication factor neutron distribution, neutron energy spectrum, power distribution, control worth analyzed. decoupling

method

proposed quantify individual contributions factors, including temperature effect moderator temperature effect.

Subsequently, comparing combined effect these individual factors comprehensive effect factors, physical mechanisms dominate overall negative feedback identified. influence hydrogen-to-zirconium atomic ratio (H/Zr) reactivity analyzed under conditions constant uranium content enrichment.

results

demonstrate established computational model

method

effectively replicate ero-power physical experimental reveal neutronic characteristics dominant negative feedback mechanisms core.

These findings provide methodological support reference physical design, performance prediction, safety assessment reactors, thereby contributing technological development advanced reactors.

Keywords

Uranium-zirconium hydride Steady-state neutronics; Negative feedback;

Temperature effect; Hydrogen-to-zirconium atomic ratio

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1. Introduction

Amidst global energy system' s low-carbon transition rapidly growing demand distributed power supply, micro-nuclear reactors emerged pivotal technological option supporting energy supply remote areas, island development, polar scientific expeditions, backup power important facilities, owing their modular design, transportable deployment, flexible power output range (typically [1-4].

However, widespread deployment micro-reactors non-traditional nuclear power plant sites imposes stringent requirements inherent safety, long-term autonomous operation capability, economic viability compared large commercial reactors. address challenge, micro-reactor designs centered uranium-zirconium hydride (UZrH) becoming frontier direction international advanced nuclear energy system research development [5,6]. advantages fuel' s unique physical properties, inherent safety mechanisms nuclear itself, historically proven exceptional safety performance demonstrated decades imilar research reactors [7,8]. utilizes zirconium hydride moderator, which homogeneously combined uranium integrated composite structure design endows following physical characteristic: trong negative temperature feedback characteristics, primarily arising effect temperature neutron reaction cross-section hydrogen, complemented Doppler effect U-238. characteristic enables autonomously reduce reactivity within milliseconds abnormal power temperature, achieving rapid power self-limiting self-stabilization. passive negative feedback mechanism constitutes physical basis "inherent safety" reactors [10,11], enabling withstand various design basis accidents, including uncontrolled reactivity insertion, coolant flow, ejection accidents, inadvertent control withdrawal, significantly reducing reliance external intervention complex safety systems.

Currently, plays important research, development, application reactor types micro-reactors.

Numerous international projects dedicated integrating system modern engineering solutions,

employing fully ceramic microencapsulated enhance operating temperatures fission product retention, optimizing geometry increase power density, introducing passive cooling technologies (e.g., pipes) simplify system configurations [12,13].

These advancements overcome limitations traditional reactors operational parameters, achieving higher thermal efficiency, longer refueling cycles, enhanced environmental adaptability. application perspective, new-type reactors electricity generation provide stable energy national defense technology, industrial heating, seawater desalination, hydrogen production.

Uranium-zirconium hydride reactors renowned their unique inherent operation attributes, physical basis which strongly negative temperature feedback [14-19].

Although technological advantages reactors evident, design new-type reactors still faces critical challenges: their configurations, enrichments, hydrogen-to-uranium ratios, power densities often differ significantly those traditional similar reactors, which important changes their neutronic behavior, negative feedback efficacy, dynamic safety characteristics [20-23].

Currently, systematic experimental high-confidence analytical models lacking regarding spatiotemporal evolution neutron energy spectrum under design scenarios, compositional mechanisms negative temperature coefficient, response characteristics during transient conditions [24,25]. particular, systematic research needed quantitative magnitude core' s negative feedback, variation patterns temperature.

Therefore, study takes operational Pulsed Reactor China (designated reactor built 1991) reactor object, conducting numerical simulation analyses based OpenMC Monte Carlo ENDF/B-VII.1 nuclear evaluation database [26-29].

Employing processing

methods

tools, systematically investigate neutronic parameter characteristics negative feedback mechanisms.

Regarding neutronic parameters, multiplication factor neutron distribution, neutron energy spectrum, control worth power distribution characteristics analyzed.

Concerning negative feedback mechanisms, detailed quantitative

analysis

performed under gradually

varying temperature conditions. temperature effect moderator temperature effect decomposed individual factors, moderator water further decomposed investigate temperature effect cross-sections density effect. research outcomes clarify neutronic characteristics regularities reactor, elucidate negative feedback mechanisms contributions major factor, establish analytical

method

negative feedback effects reactors. paper deepens scientific understanding neutronic characteristics negative feedback mechanisms reactors. significance study twofold: hand, parameters regularities obtained provide direct guidance physical design new-type reactors, those micro-reactors, example, optimizing hydrogen-to-uranium atomic ratio improving arrangement djust negative feedback efficacy; other hand, established analytical

methods

validation offer reliable support eutron characteristics prediction, safety assessment, licensing new-type reactors, thereby advancing technology towards safer, economical, better adapted directions diverse application needs. contributes technological pathway inherent safety constructing future distributed low-carbon energy systems.

2.1. Structures

parameters reactor Safety

Analysis

Report Pulsed Reactor China provides detailed description structure materials reactor. reactor located bottom reactor pool, which surrounded octagonal reinforced concrete biological shield. components reactor arranged seven concentric circles, featuring vertical central channel horizontal tangential channel. second sixth circles outward, elements control arranged, while seventh circle contains graphite elements. comprises total elements control rods, which respectively safety compensati regulating pulse reactor utilizes rod-type elements control rods, light water

serving coolant moderator [31,32], graphite acting reflector [33]. equipped horizontal tangential channel vertical central channel, which utilized neutron irradiation experiments [34-36]. overall parameters reactor presented Table technical parameters reactor components shown Figure reactor.

Parameter name Unit Value

Uranium (U -235) loading of the core kg 3.5

Component Parameter Value Radial shielding layer components element

diameter Filling Helium enrichment Outer diameter Stainless steel cladding thickness Absorber length Control Absorber diameter Absorber material follower outer diameter Outer diameter Aluminum alloy cladding thickness Pulsed Absorber length Absorber diameter Absorber material Outer diameter Aluminum alloy cladding thickness Graphite element Graphite pellet diameter Graphite pellet length Pulsed operating state reactor.

2.2. Structures

modeling reactor study employs OpenMC three-dimensional modeling simulation

analysis

reactor. OpenMC open-source Monte Carlo particle transport

featuring continuous-energy, arbitrary three-dimensional geometry, nuclear processing capabilities, enabling accurate simulation neutron, photon, electron transport processes complex systems [37,38]. incorporates eigenvalue critical source, fixed source, burnup coupling calculation functions, supporting parallel computing multiphysics coupling interfaces [39,40]. field reactor physics, OpenMC widely applied neutronic analysis, full-core pin-by-pin detailed modeling, management analysis, conceptual physics design advanced reactors [41-45]. schematic diagram reactor structure shown Figure which illustrates core, graphite reflector, water, horizontal tangential channel, concrete structure. horizontal tangential channel through-pipe penetrating reactor concrete biological shield, average diameter length channel positioned below center height, starting located graphite reflector terminal outer concrete shield. layout schematic reactor presented Figure which shows arrangement elements, graphite elements, central channel, safety compensating regulating pulsed within structure, marking validation positions worth ring. axial profile provided Figure illustrating axial positions rods, control followers, barrel, graphite reflector, layer.

Schematic diagrams components reactor namely control rods, elements, pulsed structure shown Figure depicting axial material compositions arrangements.

Radial profile reactor.

Schematic diagram arrangement. Axial profile core.

Schematic diagrams components.

3.1. Physical

model validation based experiments After completing modeling using reactor physics calculation codes, practice validate theoretical model against limited basic experimental measurement (such critical control positions, reactivity worth, etc.) before proceeding complex analyses physical characteristics [46-49]. 3.1.1. Validation critical positions Based critical control position measurement

results

documented Safety

Analysis

Report Pulsed Reactor China [30], OpenMC employed perform physical modeling core, criticality simulation calculations conducted [50,51]. ensure accuracy criticality calculations, simulation strategy configured total batches inactive batches particles batch verification

results

critical position calculations presented Table shown table, maximum deviation between effective multiplication factor calculated OpenMC measured critical positions 0.00289, which superior value reported literature [52]. reactivity maximum deviation absolute maximum tandard deviation 0.00006, indicating excellent agreement between simulation

results

experimental measurements. Critical position alculat alculat (standard deviation) safety compensating regulating pulsed compensating safety regulating pulsed regulating compensating safety pulsed pulsed compensating regulating safety Note: indicates (390mm) indicates bottom. reactor equipped control rods, namely safety compensating regulating pulsed arrangement control within

illustrated Figure Through simulation calculations, control fully inserted core, effective multiplication factor (with standard deviation 0.00005), shutdown margin measured shutdown margin zero-power physic experiments yielding deviation 1.25%, which indicates agreement superior deviation reported literature [52]. shutdown margin

results

demonstrate reactor' s shutdown system design satisfies safety requirement shutdown margin greater sufficient safety margin, confirming there criticality during reactor shutdown [53]. 3.1.3. Validation worth circle arranged seven concentric circles, central first circle being vertical central channel, elements located second sixth circles. analyzing reactivity worth elements different rings (i.e., reactivity change caused removing elements ring), support provided reactor operation refueling schemes. calculated measured values reactivity worth elements different rings presented Table alidation positions reactivity worth elements illustrated Figure During experimental measurements, reactivity worth element obtained measuring reactivity change element placed position compared element placed. calculation element worth, first critical position Table taken initial state 1.00057), elements successively replaced water cavities, element worth determined resulting change reactivity.

Comparison between calculated measured values table shows agreement, element worth gradually decreasing inner outer rings. because neutron generally exhibits decreasing trend inner outer regions, reactivity worth positively correlated neutron flux. position Calculated

result

(pcm) Measured

result

(pcm) tandard deviation) Deviation (pcm)

Third circle Fourth circle Fifth circle Sixth circle

3.2. Steady-state

neutronics

analysis

steady-state neutronics

analysis

core, primary focus neutronics behavior reactor under equilibrium conditions. objective verify nuclear safety characteristics operational performance design. parameters analyzed include neutron distribution, neutron energy spectrum, power distribution, control worth [54-57]. 3.2.1. Neutron distribution neutron defined number neutrons passing through (unit: n/(cm neutron distribution directly reflects intensity distribution nuclear reactions consequently corresponds power distribution within core. control reactor contain strong neutron-absorbing material. position insertion depth these control directly impact neutron [58]. immediate vicinity control rods, thermal neutrons heavily absorbed, causing sharp local decrease neutron forming local depression. multiple control inserted deeply, significant number neutrons absorbed, leading overall reduction neutron flux. neutron distribution crucial physical characteristic core, intrinsically linked reactor operational safety.

Therefore, necessary analyze neutron distribution under different control configurations.

Monte Carlo codes OpenMC commonly employed calculating neutron distribution [59-61]. study, OpenMC utilized perform detailed calculations neutron distribution critical states listed Table states control fully withdrawn fully inserted.

results

presented relative neutron distribution normalized source particle (unit: particles/(cm source particle)). visualization program generate plots calculated neutron distribution, shown Figure obtain absolute neutron

distribution units n/(cm these relative neutron

results

multiplied source strength (unit: specific operating power level.

Based layout safety rods, compensating rods, regulating rods, pulsed illustrated Figure calculated neutron distributions critical position align expectations. neutron exhibits overall decreasing trend center outward.

Neutron relatively lower positions control their surrounding areas, while higher control withdrawn control fully withdrawn, neutron distribution characterized central region peripheral region, displaying quarter-core symmetry.

neutron distribution Figure Caption: Critical position Critical position Critical position Critical position control fully withdrawn; control fully inserted. 3.2.2. Core neutron energy spectrum Analyzing neutron energy spectrum great significance, serves physical parameter connecting reactor' s "design objectives" "operational performance." directly determines reactor' s function, operational safety, economic efficiency, nuclear cycle characteristics [62]. comparing overall neutron energy spectrum characteristics under three conditions (ARI), critical state (taking critical position example), (ARO) macroscopic features neutron energy spectrum under typical operating conditions analyzed, providing insight proportion neutrons different energy levels.

These three control states correspond different total control withdrawal heights: state represents minimum withdrawal condition, critical state represents intermediate withdrawal condition, state represents maximum withdrawal condition. allows assessment impact control withdrawal height neutron energy spectrum. accurately reflect neutron energy spectrum characteristics possible, statistical region neutron energy spectrum selected within ring. overall neutron energy spectrum curves critical position states shown Figure quantify neutron energy spectrum across different energy intervals, spectrum divided three energy groups: thermal

group (0-1.0 epithermal group eV-0.1 MeV), group (0.1-20.0 MeV). neutron

results

these different energy groups presented Figure Table alculated standard deviation smaller observed Table total neutron highest state, followed critical state, lowest state. clearly demonstrates effective neutron absorption control rods.

Figure shows differences neutron energy spectra primarily manifested thermal neutron energy range, indicating absorbers control sensitive thermal neutrons.

Furthermore, neutron energy spectrum Figure exhibits energy peaks, energies approximately After being produced fission undergoing propagation moderation within core, neutrons sufficiently thermalized, probable thermal neutron energy being forming first energy peak. second energy peak, average energy corresponds fission neutrons generated neutrons induce fission reactions U-235. indicates intense fission reactions within core. overall shape neutron energy spectrum curve reflects distribution pattern neutron energies within core. neutron energy spectrum different control withdrawal states.

Neutron

results

different energy groups.

results

different energy groups. source particle) source particle) source particle) Percentage Percentage Percentage Energy Group significance analyzing power distribution ensuring reactor operation: preventing burnout identifying avoiding local spots, improving reactor’ s average power output utilization through power distribution flattening

Taking state critical position power distribution characteristics within region analyzed,

results

presented represent three-dimensional power distribution accurately possible ensure rationality

analysis

processing, region divided small grids during simulation’ s generation process. specific dimensions directions resulting total 75,504 grids.

After completing three-dimensional power distribution calculation, summation normalization processes applied core’s axial radial directions separately, yielding power density distribution maps.

Figure subfigure shows radial power density distribution.

During processing, values summed along axial direction radial position normalized.

Considering control layout Figure withdrawal status critical position observed subfigure region highest power density location where safety fully withdrawn, while region lowest power density location where regulating pulse fully inserted.

Subfigure presents YZ-section power density distribution projection direction indicated arrow subfigure three elongated regions power density correspond, right, pulse vertical central channel, regulating Subfigure depicts radial average power distribution core.

Here, processing involved summing values axially within annular regions different radii normalizing. figure shows power density radial region radial water region.

Moreover, power density gradually decreases radius increases, which consistent neutron distribution characteristics core.

Subfigure illustrates axial average power distribution core.

Values radial grids different axial positions summed normalized axially. location axial power indicated figure.

Subfigure presents power peaking factors, where corresponds radial power peaking factor after axial summation, corresponds axial power peaking factor after radial summation,

corresponds overall power peaking factor. Subfigure shows frequency distribution power density within region.

Based statistics 75,504 grids (each volume excluding grids power density zero, number effective statistical grids 53,796. simulating million source particles, minimum power density eV/cm maximum power density eV/cm average power density eV/cm power density value highest frequency occurrence around eV/cm

power distribution characteristics critical position Figure Caption:

Radial average power density distribution; Power density distribution plane (X=0); Radial average power distribution core; Axial average power distribution core; Power peaking factors; Frequency distribution power density. 3.2.4. Control worth Analyzing reactivity worth reactor control essential ensuring reactor safety controllability. hand, verifies control provide sufficient shutdown margin safely rapidly reactor under operating condition. other hand, adjusting control allows precise compensation excess reactivity burnup tracking, enabling flexible regulation reactor power optimization neutron distribution. enhances nuclear utilization efficiency economic performance while ensuring nuclear safety Based typical critical positions reactor, study calculated integral worth safety regulating compensating pulse multiplication factors states control fully withdrawn fully inserted calculated.

results

presented Table calculated integral control worth values consistent previously published literature [52]. observed Table safety compensating symmetrically positioned followers attached their lower ends; consequently, their calculated worth values similar. regulating pulsed symmetrically positioned; however, regulating followers their lower ends, whereas pulsed

Therefore, worth regulating significantly greater pulsed fully withdrawn, adequate shutdown margin achieved control fully inserted. (standard deviation) Control withdrawn) inserted) Reactivity(pcm)

6 ARO

*Note: pulsed follower.

3.3. Analysis

negative feedback mechanisms negative feedback mechanisms based unique properties elements, enabling reactor operate either steady-state pulsed mode, thereby functioning adjustable strong neutron source.

U-ZrH fuel, which uranium homogeneously mixed primary moderator

results

large prompt negative temperature coefficient [67]. excess reactivity introduced (i.e., during pulsed operation), reactor power increases rapidly, quickly automatically decreases without causing element damage, endowing reactor unique inherent safety characteristics.

U-ZrH fuel, variations atomic ratio significantly influence multiplication factor provided uranium content enrichment remain unchanged. negative feedback reactor primarily originates temperature effects, resulting superposition temperature effect water temperature effect. 3.3.1. Effect atomic ratio Analyzing effect atomic ratio reactor

importance because enables precise balance between initial reactivity, burnup life, inherent safety through optimization zirconium hydride moderation capability. higher ratio enhances neutron moderation, thereby increasing extending life.

However, enhanced moderation reduces neutron leakage, which diminishes relative effectiveness control absorption consequently lowers control worth.

Additionally, ffect water temperature coefficient potentially induce hydrogen migration issues within fuel.

Therefore, essential ensure reactor maintains sufficient power operational cycle length while consistently preserving overall negative feedback characteristics structural stability fuel. study, quantitative effect small perturbation atomic ratio analyzed state critical position utilizes material atomic ratio precisely characterize effect atomic ratio,

analysis

range interval

results

presented Figure Table observed atomic ratio gradually increases, correspondingly increases, slope curve remaining approximately constant. indicates that, within certain range, incremental effect multiplication factor associated interval atomic ratio nearly identical.

These trend

results

provide reference optimized design atomic ratio reactors, ensuring cores possess sufficient excess reactivity while maintaining stable performance.

Effect atomic ratio multiplication factor (standard deviation) atomic ratio

3.3.2. F temperature effect ensure long-term stable operation prevent abnormal swelling early operating temperature controlled within [24].

Under severe accident conditions reactor, literature simulated maximum expected temperature achievable MARVEL micro-reactor Based analysis, safety tolerance limit ensure cladding remains undamaged. existence different temperature limits stems their different rationales: operating temperature limit primarily intended prevent microstructural changes within pellet (such swelling) caused excessive temperatures, which directly affects long-term performance itself. contrast, safety tolerance limit established reactor safety perspective, ensuring under extreme conditions, cladding material enclosing rupture excessive internal pressure, thereby preventing release radioactive materials [25].

Considering

analysis

aforementioned temperature limits, covering potential operating temperatures incorporating appropriate temperature gradient, study analyzes temperature effect within range (826.85 temperature interval fuel, temperature effect jointly determined eutron nergy ffect Doppler ffect, nergy ffect often playing dominant role. temperature zirconium hydride increases, probability increases neutrons within energy hydrogen atoms crystal lattice. elevated temperatures, neutrons acquire energy increasing their probability escaping fuel. reduces ratio neutron absorption within total absorption, higher neutron energy corresponds lower fission cross-section, thereby decreasing probability neutron-induced fission reactions consequently reducing reactivity. phenomenon termed eutron nergy ffect.

Concurrently, temperature rises, thermal motion nuclei (especially U-238) intensifies, leading broadening resonance absorption peaks (Doppler roadening) increase resonance absorption. reduces probability

neutron-induced fission reactions, further decreasing reactivity. other words, temperature effect exhibits negative feedback characteristics. study, temperature effect quantitatively analyzed adjusting temperature pellets within core.

results

presented Figure Figure Table average temperature during rated power operation

results

indicate that, other variables constant, multiplication factor gradually decreases temperature increases.

Moreover, within tolerance temperature range, variation trend multiplication factor temperature approximately linear.

Across entire temperature range, temperature coefficient remains negative, consistently below temperature increases, temperature coefficient initially decreases increases. minimum value region, approximately corresponds precisely temperature normal operating temperature fuel. enables exhibit favorable negative temperature feedback characteristics, ensuring operational safety.

Variation multiplication factor temperature

Variation temperature coefficient temperature Average temperature emperature coefficient Temperature (standard deviation) Reactivity (pcm) (pcm/ 3.3.3. Pool water temperature effect reactor, materials serve moderators: zirconium hydride within

matrix water. Here, water temperature treated independent variable discuss influence multiplication factor Similar reactor, pulse reactors based typically feature open-pool designs, where pressure considered atmospheric water temperature exceed Table presents typical temperatures water reactor their operating conditions. water density neutron cross-section hydrogen atoms significantly influenced temperature. temperature changes, impact water multiplication factor

results

combined effect neutron cross-section effect hydrogen density effect. water temperature increases, water density decreases, weakening neutron moderation capability. reduces proportion thermal neutrons, which unfavorable fission reactions between thermal neutrons U-235, constituting negative feedback effect [68]. time, water temperature increases, scattering cross-section hydrogen atoms increases. causes neutrons scattered absorbed fuel, thereby promoting fission reactions, constituting positive feedback effect.

Based above analysis, study decomposes water temperature effect density effect cross-section effect hydrogen atom, which opposing influences multiplication factor.

Using variable separation method, these opposing feedback effects analyzed individually, followed comprehensive

analysis

overall water temperature effect under their combined state cover various operating conditions reactor comprehensively possible, water temperature range selected (corresponding variation water density temperature shown Figure Starting temperature, gradient water density change respect temperature gradually increases temperature rises; higher water temperature, significant thermal expansion effect, faster density decreases increasing temperature. temperature effects water density changed without altering neutron cross-section, neutron cross-section changed without altering water density, shown Figure temperature effect

neutron cross-section water density changed simultaneously shown Figure which presents superimposed curve derived Figure maximum standard deviation calculating multiplication factor facilitate quantitative comparison, multiplication factors converted reactivity during processing. above

analysis

results, observed superimposed

result

considering water density neutron cross-section single factors slightly higher comprehensive

result

considering factors simultaneously. trends curves consistent, certain systematic difference exists, overall average difference relatively small reactivity value between curves.

Through aforementioned quantitative analysis, found moderator water reactor, comprehensive temperature effect exhibits positive feedback. contrast, temperature effect moderator water conventional light water reactors generally negative feedback, highlighting unique characteristic core. neutron moderation relies primarily itself secondarily water, whereas neutron moderation conventional pressurized water reactor relies solely water. means analyzing temperature effect water moderator, cross-section effect (positive feedback) dominates reactor, while density effect (negative feedback) dominates conventional pressurized water reactor.

Temperature Operating condition Temperature Operating condition

Variation water density temperature Temperature effects considering changes water density neutron cross-section

water temperature effect 3.3.4. Comprehensive negative feedback effect process reactivity analysis, using variable separation

method

analyze certain single-factor reactivity effects, interference effects often exist. comprehensive

result

considering multiple factors simultaneously slightly lower superposition multiple individual factors.

Understanding quantitative relationships these interference effects facilitates accurate reactor physics design.

results

water temperature effect described above exhibit pattern. entire core, analyzing comprehensive negative feedback effect often requires considering combined action temperature effect water temperature effect.

results

presented above, temperature effect exhibits negative feedback, while water temperature effect exhibits positive feedback.

During operation, positive feedback temperature effect water compromise operational safety reactor. because negative feedback effect temperature stronger positive feedback effect water

temperature. Additionally, temperature change pronounced water, ensuring reactor still possesses strong comprehensive negative feedback characteristics.

Taking operating conditions reactor example, reactor started achieve criticality power increases rapidly, temperature change approximately temperature negative feedback effect alone introduce approximately negative reactivity. maximum temperature change water approximately water temperature positive feedback effect alone introduce approximately positive reactivity.

Consequently, comprehensive negative feedback effect reaches approximately which sufficient rapidly transition reactor supercritical state subcritical state, thereby quickly reducing power. demonstrates exhibits strong negative temperature feedback characteristics, which constitute inherent safety

mechanisms of the UZrH reactor.

4. Conclusions

Through systematic steady-state physics analysis, study quantitatively reveals steady-state neutronics characteristics, negative feedback mechanisms reactor. employing single-factor separation method, contributions various physical effects quantified, explaining exceptional operational performance safety features.

After validating computational model established OpenMC accessible zero-power physical

results

reactor, neutronics parameters including effective multiplication factor neutron distribution, neutron energy spectrum, power distribution, control worth systematically analyzed. influence mechanisms factors atomic ratio, temperature effect, water temperature effect reactivity elucidated.

conclusions

follows: physical parameters calculated model established paper, including critical positions, shutdown margin, worth, agreement experimental

results

conform scientific laws. demonstrates accuracy

physical model terms structural dimensions material compositions, validates applicability OpenMC conducting physical analyses cores.

Through detailed steady-state neutronics analysis, found that: arrangement positions control directly affect neutron distribution, neutron distribution exhibits positive correlation power distribution. degree control withdrawal influences neutron energy spectrum, pronounced effect spectrum thermal neutron region. control fully withdrawn, possesses substantial excess reactivity; control fully inserted, sufficient shutdown margin achieved. safety worth exceeds meaning reactor shutdown accomplished using safety Within certain range atomic ratios (e.g., 1.7), multiplication factor increases almost linearly increasing atomic ratio. trend characteristic serve design reference reactors, ensuring possesses adequate excess reactivity.

Aiming unique negative temperature feedback mechanism reactor, decoupling

method

proposed. individual contributions single factors temperature effect water temperature effect quantified.

Subsequently, through comparison between superimposed single-factor effects comprehensive multi-factor effect, physical mechanism playing dominant core' s comprehensive negative feedback identified. pronounced negative temperature coefficient curve obtained. absolute value temperature coefficient reaches maximum temperature range, which coincides precisely temperature range during stable operation reactor, illustrating inherent safety characteristics. deconstructing water temperature coefficient cross-section effect density effect analysis, found temperature effect water exhibits positive feedback characteristics. contradicts requirement negative moderator water temperature coefficient conventional light water reactors.

However, strongly negative feedback characteristic temperature coefficient still ensures substantial comprehensive negative feedback effect core.

Based finding,

designing reactors utilizing fuel, range design constraints potentially expanded. facilitates meeting reactor design requirements special scenarios confined spaces rapid reactivity control.

Based study, areas requiring continuous improvement follows: current stage, modeling based mixed composition fuel, where temperatures nuclides within consistent. further decompose temperature effect Doppler ffect U-238, necessary separate nuclides UZrH. would enable individual adjustment nuclide temperatures, allowing investigation influence mechanisms

analysis

macroscopic characteristics refined level.

References

Black Shropshire Prospects nuclear microreactors: review technology, economics, regulatory considerations[J].

Nuclear Technology, 2023, 209(sup1): S1-S20. Vinoya Ubando Culaba State-of-the-art review small modular reactors[J].

Energies, 2023, 16(7): Michaelson Jiang Review integration small modular reactors renewable energy microgrids[J].

Renewable Sustainable Energy Reviews, 2021, Hjelmeland Hartmann Overview small modular advanced nuclear reactors their energy transition[J].

Transactions Energy Conversion, 2025, 40(3): Galahom Improving neutronic characteristics boiling water reactor using uranium zirconium hydride instead uranium dioxide fuel[J].

Nuclear Engineering Technology, 2016, 48(3): Evans Sweet Medvedev Uranium-zirconium hydride nuclear performance NaK-cooled MARVEL microreactor[J].

Journal Nuclear Materials, 2024, BOECK, Helmuth; VILLA, Mario.

TRIGA reactor characteristics. Vienna University Technology, KHAN, Neutronics

analysis

initial TRIGA reactor. Nuclear Engineering Design, 2011, 241.5:

Simnad alloy: properties TRIGA fuel[J]. Nuclear Engineering Design, 1981, 64(3):

Olander Greenspan Garkisch Uranium zirconium hydride properties[J].

Nuclear Engineering Design, 2009, 239(8): Simnad Foushee elements pulsed TRIGA research reactors[J].

Nuclear Technology, 1976, 28(1): Coupled neutronic-thermal mechanical

analysis

medium temperature cooled reactor. Nuclear Engineering Design, 2024, LIANG, medium temperature cooled reactor.

Annals Nuclear Energy, 2022,

WANG, Lianjie; CHEN, Bingde; Dong. Reactivity temperature coefficient evaluation uranium zirconium hydride element power reactor.

Nuclear Engineering Design, 2013, PRADO SOUZA, Gomes; MESQUITA, Zacarias.

Measurements isothermal, power temperature reactivity coefficients IPR-R1 TRIGA reactor.

Progress Nuclear Energy, 2011, 53.8: HENRY, Romain; JAZBEC, Experimental determination calculation temperature reactivity coefficients TRIGA reactor.

International Conference Nuclear Energy Europe-NENE Nuclear Society Slovenia, Bled, Slovenia Ljubljana, RABIR, Mohamad Hairie.

Measurement power temperature reactivity coefficients TRIGA reactor.

Nuclear Engineering Design, 2013, BADEA, DAGAN, BROEDERS, Validation TRIGA reactivity coefficients.

Actinide and Fission Product Partitioning and Transmutation, 2007, 451.

HOSAN, Iqbal; SONER, KABIR, Khorshed Ahmad. Calculation Temperature Coefficient, Reactivity Temperature TRIGA Research Reactor.

EVANS, Jordan PARISI, Carlo. Optimizing Hydride Stability U-ZrHx Nuclear Fuel:

Goldilocks Radius Nuclear Science Engineering, 2024, SHIXIN, ZHENG, Youqi.

Study Neutronics Properties Zirconium Hydride Moderator Reactor.

International Conference Nuclear Engineering. American Society Mechanical Engineers, V002T02A022.

MERK, Bruno; FRIDMAN, Emil; Frank-Peter. moderation layer improve safety behavior sodium cooled reactors.

Annals Nuclear Energy, 2011, 38.5: MERK, Bruno. distributed moderating material improved thermal stability applied enhance feedback effects cores.

Science Technology Nuclear Installations, 2013, 2013.1:

Olander Konashi Yamawaki Uranium-zirconium hydride fuel[M]//Comprehensive Nuclear Materials:

Second Edition. Elsevier, 2020: Ensor Thermal

analysis

uranium zirconium hydride using lead-bismuth operating temperatures[D].

Massachusetts Institute Technology, Lorenzo, OpenMC

Analysis

TRIGA Reactor Temperature Reactivity

Coefficients. Proceedings International Conference Nuclear Energy Europe (NENE2023).

MIRA, Mohamed, OpenMC-based high-fidelity model Moroccan TRIGA research reactor.

Progress Nuclear Energy, 2024, MIRA, Mohamed, Development, Validation, Comparison OpenMC-Based Transport-Depletion Model Moroccan TRIGA MCNP6.

Nuclear Technology, 2025, Lorenzo, OpenMC Model Validation TRIGA Reactor.

Proceedings International Conference Nuclear Energy Europe (NENE2023).

Nuclear Power Institute China. Safety

Analysis

Report Pulsed Reactor China [M].2015. PARAJON, Huerta; ABAD, BERMEJO, review neutron moderator materials: neutronic performance radiation effects.

Physics Procedia, 2014, BAXTER, David Neutron moderator development research energy neutron source.

Physics Procedia, 2012, BAKER, Graphite neutron moderator reflector material.

Nuclear Engineering design, 1971, 14.3: Whitney Alvarez Investigation, design

analysis

neutron facility University Texas TRIGA Reactor[J].

Journal Radioanalytical Nuclear Chemistry, 2008, 276(3):

Craft Installation neutron facility Geological Survey TRIGA Reactor[J].

Nuclear Technology, 2014, 185(1): Rasito, Permana Ilham Characterization neutron gamma beams tangential TRIGA reactor using Monte Carlo methods[C]//Journal Physics:

Conference Series. Publishing, 2021, 1772(1): ROMANO, OpenMC: state-of-the-art Monte Carlo research development.

Annals Nuclear Energy, 2015, ROMANO, FORGET, Benoit.

OpenMC monte carlo particle transport code. Annals Nuclear Energy, 2013, ELLIS, Matthew, Preliminary coupling Monte Carlo OpenMC multiphysics object-oriented simulation environment analyzing doppler feedback Monte Carlo simulations.

Nuclear Science Engineering, 2017, 185.1: ROMANO, Recent developments OpenMC Monte Carlo particle transport code.

Proceedings international conference physics reactors-PHYSOR LABOSSIERE-HICKMAN, Travis FORGET, Benoit.

Selected physics benchmarks OpenMC. Transactions American Nuclear Society, 2017, Development OpenMC/Trivac two-step scheme reactor neutronics analysis.

Annals Nuclear Energy, 2023, ANGELINA, Tsania Eksa, Neutronic

Analysis

Radial Direction Heterogeneous Configuration Thorium Fuel.

Journal Physics: Conference Series. Publishing, DALINGER, Maximiliano, High-Fidelity Modelling Molten Reactor. arXiv preprint arXiv:2507.04129, BISWAS, Sushanta; SAHADATH, Hossain; ANANYA, Nazia Rahim.

Neutronic Evaluation Light Water Reactor-Based Small Modular Reactor Transuranic Comparison Different Configuration Mixed Oxide Fuel.

Journal Nuclear Engineering Radiation Science, 2023, LABABSA, Djahid; MAZROU, Hakim; BELGAID, Mohamed.

Performance evaluation validation OpenMC criticality

analysis

MTR-type research reactor. Annals Nuclear Energy, 2024, LABABSA, Djahid, Cross-Verification validation steady-state research reactor neutronic models using OpenMC MCNP5 Codes: foundation advanced coupled simulations.

Annals Nuclear Energy, 2025, ISLAM, Saad; MOTALAB, Mohammad Abdul. model development verification Monte Carlo simulation.

Annals Nuclear Energy, 2025, ALHARBI, Abdullah NIMMAGADDA, Jyothier WATSON, Justin Validation OpenMC advanced graphite-moderated/reflected reactors: insights benchmarking UFTR.

Annals Nuclear Energy, 2026, ZHANG, Tengfei, Studies calculation models ASTRA critical facility benchmark using OpenMC.

Annals Nuclear Energy, 2021,

ZHAO, Zelong; Validation SNAP-10A reactor criticality

experiment

benchmark based OpenMC. Radiation Physics Chemistry, 2025, Qi-Dong, Physical

analysis

reactor based power physical experiments. Shams Engineering Journal, 2025, 16.11:

BOUSTANI, Ehsan; HASSANZADEH, Mostafa. Neutronic design investigation liquid injection-based second shutdown system typical research reactor using MCNPX.

Nuclear

Science and Techniques, 2018, 29.3: 33.

Wanbin, Neutronics

analysis

TRIGA reactor benchmark experiments SuperMC3. Nuclear Engineering Technology, 2019, 51.7:

CANDALINO, Robert Wilcox. Engineering

analysis

enriched uranium using improved

zirconium hydride cross sections. 2006. PhD Thesis.

Texas A&M University.

ISLAM, Saad; MOTALAB, Mohammad Abdul.

Analysis

TRIGA MARK-II benchmark IEU-COMP-THERM-003 Monte Carlo OpenMC.

Journal Bangladesh Academy Sciences, 2024, 48.2: NCHEZ SANZ, Effect hydrogen distribution UZrHx physical parameters TRIGA reactor.

Thesis. Univerza Ljubljani, Fakulteta matematiko fiziko.

KAMYAB, Raheleh. Sensitivity analyses different neutron absorbers safety parameters research reactor.

Nuclear Engineering Technology, 2014, 46.4: Jiankai, Experimental validation fidelity Monte Carlo neutron transport model graphite exponential pile.

Progress Nuclear Energy, 2022, PRASETYA, Fajri, Neutronic

analysis

withdrawal TRIGA reactor control using OpenMC program.

Annals Nuclear Energy, 2025, CHHAM, Neutronic thermal hydraulic

analysis

irradiation channels inside Moroccan TRIGA research reactor core.

Applied Radiation Isotopes, 2016, ABOU-JAOUDE, Abdalla; ERICKSON, Anna; STAUFF, Nicolas.

Design mixed-spectrum reactor improved proliferation resistance long-lived applications.

Journal Nuclear Cycle Waste Technology, 2018, OKAWA, Tsuyoshi; NAKAYAMA, Sinsuke; SEKIMOTO, Hiroshi.

Figure 11

Figure 1: Figure 11

Figure 14

Figure 2: Figure 14

Design study power flattening sodium cooled large-scale CANDLE burning using thorium fuel.

Energy conversion

management, 2012, 53.1: ZHANG, ZENG, Mechanical operational strategy designed CPR1000 nuclear power plant.

Nuclear Engineering Design, 2017, HAIFENG, Benchmarking verification control effects using codes throughout modeling rod-drop experiment.

强激光与粒子束 2018, 30.5: Ung-Soo; SEONG, Poong-Hyun. Development application axially variable strength control power maneuvering pressurized water reactors.

Nuclear technology, 2003, 141.2: PRADO SOUZA, Gomes; MESQUITA, Zacarias.

Measurements isothermal, power temperature reactivity coefficients IPR-R1 TRIGA reactor.

Progress Nuclear Energy, 2011, 53.8: ZAIN, Jamal, Validation DRAGON4/DONJON4 simulation

methodology

typical calculating reactivity feedback coefficient neutron flux.

Results

Physics, 2018,

Figures

Figure 15

Figure 3: Figure 15

Figure 16

Figure 4: Figure 16

Figure 18

Figure 5: Figure 18