# HEAT-PIPE NUCLEAR FUEL ASSEMBLY (HPNFA)

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March 11, 2025

## BACKGROUND

### Concept

The **Heat-Pipe Nuclear Fuel Assembly (HPNFA)** concept integrates **heat pipe technology** directly into the nuclear fuel assembly, enabling efficient heat transfer from the fuel rods to an external heat exchanger. By utilizing the phase-change properties of a sealed working fluid, heat is passively transported without the need for active coolant circulation, improving system simplicity and reliability. A **sealed nuclear fuel assembly** functions as a **monolithic heat pipe**, where the heat generated by nuclear fission is transferred to the heat exchanger through **evaporation and condensation** cycles. Unlike traditional reactor cores that rely on forced coolant flow, the **entire assembly acts as a self-contained heat transfer unit**, ensuring consistent thermal performance while minimizing dependence on external cooling systems.

### Advantages

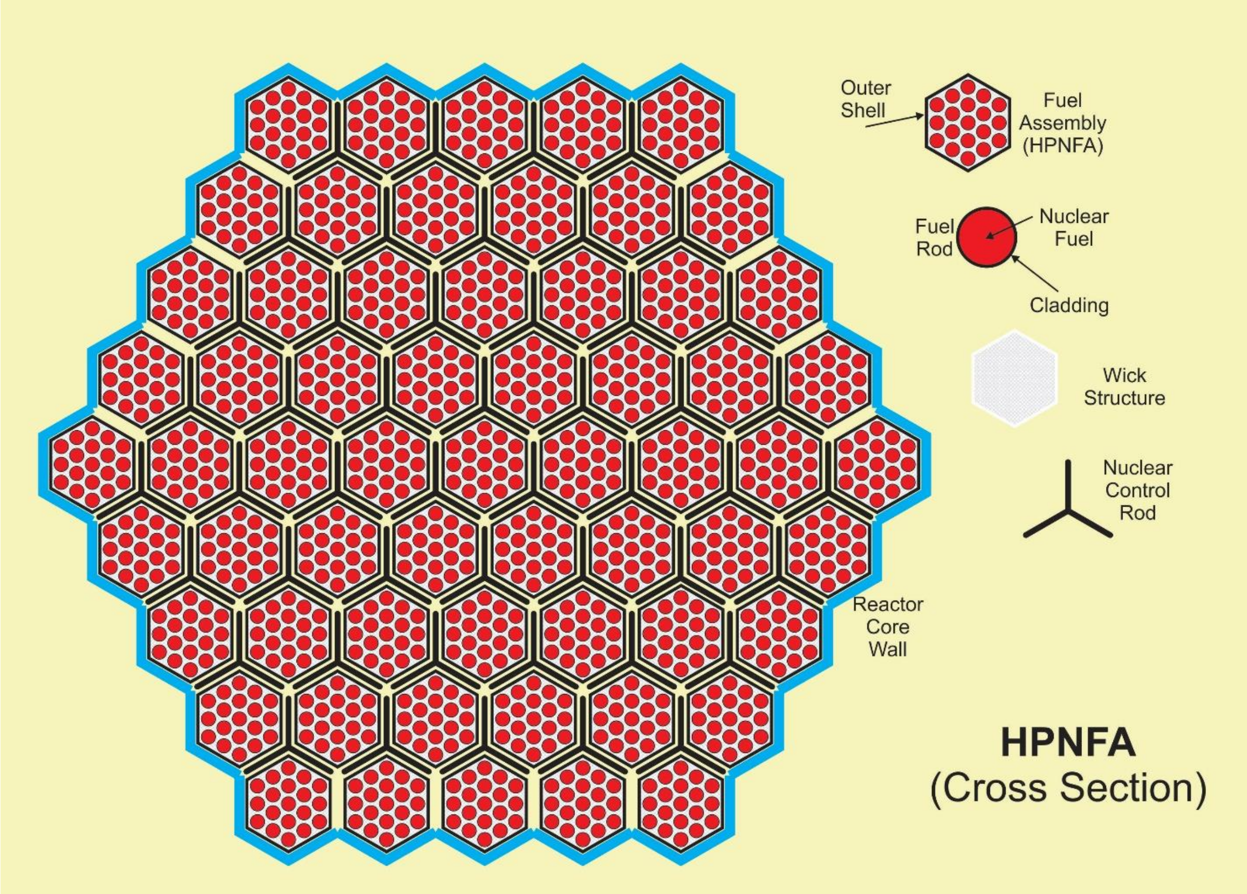
HPNFA design offers several advantages over conventional nuclear fuel assemblies, including **passive heat transfer**, which eliminates the need for coolant pumps and reduces overall system complexity. The **sealed structure enhances safety** by minimizing the risk of coolant loss. **High thermal conductivity** enables efficient and uniform heat distribution across the reactor core, improving operational stability. Additionally, **modularity and scalability** make the design well-suited for **Small Modular Reactors (SMRs)** and **space-based nuclear systems**. With **few moving parts**, HPNFA also ensures **long operational life and reduced maintenance requirements**.

### Applications

Potential applications include **advanced reactor designs** such as **microreactors, space reactors, and molten salt-cooled reactors**, where passive heat transfer can enhance efficiency and safety. HPNFA is also well-suited for **waste heat recovery systems** and **nuclear power reactors for lunar and Martian bases**, where **coolant loss represents a critical failure mode**.

## HEAT PIPE NUCLEAR FUEL ASSEMBLY DESIGN AND CONFIGURATION

A typical HPNFA consists of multiple fuel rods arranged in a hexagonal or square lattice, enclosed in a sealed, monolithic heat pipe.




**Design Components**

- Sealed Outer Shell – The fuel rods of the assembly are embedded in the porous wick structure filling a sealed metal casing, which acts as the outer wall of the heat pipe. This prevents the need for coolant circulation inside the fuel assembly.
- Nuclear Fuel Rods (Heat Source) – Inside the sealed assembly, uranium or mixed-oxide (MOX) fuel rods generate heat through fission.
- Working Fluid – A liquid metal (e.g., sodium, potassium, or lithium) is used inside the assembly to transfer heat efficiently. It undergoes phase change to absorb and transport heat.
- Wick or Capillary Structure – A porous metal wick (e.g., sintered metal or wire mesh) filling the inside of the assembly to return the liquid working fluid to the bottom of the assembly via capillary action.
- Heat Transfer Surfaces (Evaporator and Condenser Regions):
  - The evaporator region is around the fuel rods, where heat causes the liquid metal to evaporate.
  - The condenser region are is at the top of the assembly, where vaporized working fluid releases heat to an external system and condenses back into liquid.
- Passive Heat Transfer Process:

- The evaporated working fluid rises to the condenser regions.
    - It releases heat to an external heat exchanger (e.g., molten salt, supercritical $CO_2$, or gas).
    - The condensed liquid metal returns to the evaporator (fuel rods) via wick action.

**Alternative Configurations**
**Vertical (SMRs)**

- Heat naturally flows upwards to a high-efficiency condenser at the top.
- Best for modular SMRs and passive cooling integration.

**Horizontal (Alternative for Microreactors & Space Reactors)**

- Works in microreactors or transportable nuclear power units.
- Requires multi-directional vapor pathways but can be optimized for zero-gravity operation.

**Inverted Orientation (Possible for Space Applications)**

- Since wick-driven liquid return is gravity-independent, the assembly can operate upside-down.
- Useful for low-gravity or zero-gravity applications

**Direction of Heat Flow in a Vertical Reactor Core**
While capillary action ensures liquid return works in any orientation, a vertical core arrangement provides additional advantages:

- **Natural Convection in the Reactor Vessel:**
    - In most terrestrial SMRs, the heat exchanger (condenser) is placed above the core for efficient heat rejection.
    - This minimizes the need for additional mechanical pumping in the external cooling loop.
- **Lower Vapor Transport Resistance in a Vertical Tube:**
    - In a vertical orientation, vapor has an unobstructed pathway to rise, reducing transport resistance.
    - Horizontal systems require more complex multi-directional vapor flow channels.
- **Better Integration with Gravity-Driven Safety Systems:**

If external cooling is lost, gravity-fed passive decay heat removal is easier to design in a vertical configuration.

**Fuel Assembly Key Characteristics**

- A hexagonal assembly of 19 standard 9.5 mm diameter fuel rods embedded into the metal wick structure.
- Fuel rods are evenly spaced (12 mm pitch) to allow for efficient heat transfer to the wick.
- Fuel Assembly Length: 1.2 – 3.5 meters
- Diameter of Heat Pipe Fuel Assembly: 8 – 10 cm
- Power Output per Assembly: 100 – 500 kW

## BASICS OF HPNFA OPERATION

The proposed design integrates heat pipe technology directly into a nuclear fuel assembly, enabling passive heat transfer through phase-change mechanisms instead of relying on active coolant flow.

**Five-Step Heat Transfer Cycle**
This cycle passively moves heat without pumps or moving parts, enhancing reactor safety and efficiency.

1. The nuclear fuel inside the assembly produces heat.
2. Heat is absorbed by the liquid metal inside, causing it to vaporize.
3. The vapor carrying heat rises to the condenser section.

4. The heat is transferred to an external coolant, condensing the working fluid back to liquid.
5. The liquid metal returns to the evaporator region via wick structure.

**Heat Flow**
Heat flow in this system is still predominantly upwards due to the natural behavior of phase-change heat transfer in heat pipes.

**Phase-Change Heat Transfer Mechanism**
In a sealed heat pipe fuel assembly, heat transfer occurs via liquid-vapor phase change, not conduction alone. The key steps are:

**Evaporation at the Fuel Rods (Heat Source)**

- Heat from the nuclear fuel rods is transferred to the working fluid (e.g., sodium or lithium) in the wick.
- The working fluid boils and vaporizes, absorbing latent heat.

**Vapor Flow Moves Toward Cooler Region (Condenser Zone)**

- The generated vapor expands and moves towards cooler region (i.e., the condenser at the top).
- This movement is driven by the pressure difference between the hotter (evaporator) and cooler (condenser) zones, not gravity.
- Higher temperature/higher vapor pressure vapor naturally moves to lower pressure zones.

**Condensation at the Heat Exchanger (Heat Rejection Zone)**

- At the condenser region (top of the assembly), the vapor releases heat to the external heat exchanger (e.g., supercritical $CO_2$ or molten salt system).
- The vapor condenses back into a liquid, ready to be recirculated.

**Liquid Return via Wick Capillary Action**

- The condensed liquid is wicked back to the evaporator zone near the lower sections of fuel rods via capillary action.
- This process happens independent of gravity, meaning the system could also work in horizontal or even inverted orientations (e.g., space reactors).

**Temperature Ranges for Heat Pipe Fuel Assembly**

- Fuel Centerline Temperature: ~1800 K (Uranium dioxide core)
- Fuel-Cladding Interface Temperature: ~1200 K (Silicon carbide (SiC) or advanced steel cladding)
- Heat Pipe Outer Wall Temperature: ~900 K (Nickel-based alloy or ODS steel)
- Condenser Temperature: ~700 K (Supercritical $CO_2$ or molten salt heat exchanger)

The fuel and cladding temperatures predicted in the heat pipe fuel assemblies are comparable to existing LWRs and fast reactors, meaning fuel performance should remain within known limits.

## MODELING

**Thermal Modeling**
The key to this design is ensuring effective heat transport through the heat pipe mechanism. Below are the critical thermal parameters.

**Axial Temperature Distribution:**

- The bottom region (evaporator zone) experiences the highest temperatures.
- Heat is gradually removed as the working fluid vapor rises.

- The top region (condenser zone) is cooler, allowing the working fluid to condense.

**Radial Temperature Profile:**

- The center of the fuel rods is the hottest region, with heat spreading outward radially.
- The fuel-cladding interface maintains a stable temperature, ensuring material integrity.
- The heat pipe wick maintains a near-uniform temperature, preventing localized hot spots.

**Power Conversion Integration**

**Potential Heat Sink Options**

- Supercritical $CO_2$ Brayton Cycle: High efficiency (40-50%), compact, and ideal for SMRs.
- Molten Salt Loop: Works well with high-temperature reactors.
- Helium Gas Cycle: Can integrate with gas-cooled reactor designs.

**Expected Efficiency**

- Traditional Steam Rankine Cycle: ~33-38% efficiency
- Supercritical $CO_2$ Brayton Cycle: ~45-50% efficiency
- Direct Thermophotovoltaic Conversion: ~25-35% efficiency (future potential)

**Key Thermal Properties**

Operating Temperature Range: 500°C – 900°C

Thermal Conductivity of Working Fluid:

- Sodium: ~90 W/m·K (liquid), ~30 W/m·K (vapor)
- Lithium: ~50 W/m·K (liquid), ~20 W/m·K (vapor)

Heat Transfer Coefficient at Condenser Interface:

- Supercritical $CO_2$: 1,000 – 5,000 $W/m^2 \cdot K$
- Molten Salt: 300 – 1,500 $W/m^2 \cdot K$
- Helium Gas: 50 – 500 $W/m^2 \cdot K$

## OPTIMAL MATERIAL SELECTION

**Stability of Cladding Submerged in The Liquid Metal**

The stability of cladding depends on chemical compatibility, corrosion resistance, and mechanical integrity in the working fluid.

**Candidate Cladding Materials & Stability in Liquid Metal Coolants**

| Cladding Material | Maximum Stable Temperature (K) | Compatibility with Liquid Metals | Suitability for Heat Pipe Design |
|---|---|---|---|
| Zircaloy (Zr-based alloys) | ~1300 K | Reacts with sodium (Na), dissolves in lithium (Li) | ❌ Not suitable for liquid metal |
| Stainless Steel (316, HT9, or Ferritic-Martensitic) | ~1300 K | Good compatibility with Na, fair with Li | ✅ Suitable for Na but limited for Li |
| Nickel-Based Alloys (Inconel, Hastelloy) | ~1400 K | Excellent Na/Li compatibility | ✅ Best for heat pipe durability |
| Silicon Carbide (SiC/SiC composite) | ~1800 K | Resistant to Na, stable in Li | ✅ Best radiation and corrosion resistance |

| Cladding Material | Maximum Stable Temperature (K) | Compatibility with Liquid Metals | Suitability for Heat Pipe Design |
|---|---|---|---|
| Oxide-Dispersion-Strengthened (ODS) Steel | ~1400 K | Good Na/Li resistance, excellent high-temperature strength | ✅ Advanced high-performance option |

**Optimal Material Selection**

Based on thermal, radiation resistance, and longevity considerations, the best materials for the sealed nuclear fuel assembly with heat pipe integration are:

- Outer Casing: Nickel-based Superalloy (Inconel 718 or ODS Steel) – Provides high-temperature strength and radiation resistance.
- Fuel Cladding: Silicon Carbide (SiC) or Advanced Stainless Steel – Offers low neutron absorption and high corrosion resistance.
- Working Fluid: Sodium (Na) – Balances thermal conductivity, phase-change efficiency, and stability.
- Wick Structure: Sintered Tungsten or Niobium Mesh – Ensures capillary return of liquid metal over long operational lifetimes.
- Condenser Interface: Supercritical $CO_2$ Exchanger – Provides the best power conversion efficiency in SMR applications.

**Summary: Challenges and Solutions**

| Challenge | Solution |
|---|---|
| Fuel Rod Cladding Compatibility | Use high-temperature ceramics (SiC) to prevent fuel degradation. |
| Working Fluid Corrosion | Use advanced coatings (e.g., tungsten or molybdenum) for liquid metal containment. |
| Long-Term Wick Performance | Employ sintered tungsten or niobium mesh for reliable operation over decades. |
| Thermal Management in Shutdown | Integrate passive radiators or decay heat removal loops. |

## COST COMPARISON: TRADITIONAL VS HEAT PIPE NUCLEAR FUEL ASSEMBLIES

**Cost Estimates**
Traditional Fuel Assembly: $30,000 per assembly
Heat Pipe Fuel Assembly: $50,000 per assembly

**Benefits for Additional Costs**
The additional investment in heat pipe fuel assemblies provides the following benefits:

Passive Heat Removal (No Pumps Needed)
- Eliminates the need for active coolant circulation within the fuel assembly.
- Reduces LOCA (Loss-of-Coolant Accident) risks, enhancing safety.

Higher Efficiency & Advanced Power Conversion
- Traditional fuel assemblies require Rankine steam cycles (38% efficiency).
- Heat pipe assemblies enable Supercritical $CO_2$ cycles (~45% efficiency), boosting electrical output.

Improved Longevity & Fuel Utilization
- Traditional fuel assemblies have cooling limitations and uneven burnup.
- Heat pipes maintain uniform temperature, reducing fuel degradation and extending core lifetime.

Modular & Scalable Design
- Compatible with Small Modular Reactors (SMRs) and Space Reactors.
- Reduces maintenance costs due to no moving parts.

Higher Safety Margin for Decay Heat Removal
- Heat pipes continue functioning even after shutdown, preventing overheating.
- No reactor coolant pumps or emergency cooling systems required.

**Final Consideration**
- The extra costs are justified by the increase in efficiency, passive safety, and longer fuel lifespan, making heat pipe fuel assemblies an excellent choice for advanced SMRs and next-generation reactors.
- If long-term operational savings (maintenance, fuel efficiency, accident prevention) are factored in, the total cost of ownership could become lower than traditional reactors.

**HPNFA PRODUCTION COSTS**
The primary reasons for the high cost of heat-pipe-based fuel assemblies compared to traditional nuclear fuel assemblies are:

**Complex Manufacturing & Advanced Materials**
**Heat Pipe Integration:** Unlike traditional fuel rods, each heat pipe fuel assembly requires:
- Precision-sealed casings to prevent coolant loss.
- High-performance working fluids (e.g., sodium or lithium) that must be purified and safely encapsulated.
- Wick structures (sintered tungsten or niobium mesh), which are more difficult to fabricate than standard fuel rod claddings.

**Advanced Cladding (SiC or ODS Steel):** Silicon carbide or oxide-dispersion-strengthened (ODS) steel is more radiation-resistant but significantly costlier than traditional Zircaloy.

**Lower Production Scale & Lack of Mass Manufacturing**

- Traditional fuel assemblies benefit from high-volume production (~100,000+ rods per year), reducing per-unit costs.
- Heat pipe fuel assemblies lack mass production infrastructure, keeping costs high.

**Higher Development and Certification Costs**

- Regulatory Hurdles: New nuclear fuel types must pass extensive licensing and safety tests before deployment.
- Testing & Prototyping Costs: Experimental heat pipe assemblies require extensive material testing, irradiation studies, and failure analysis.

**Reducing Costs**

The following will reduce the cost gap between heat pipe fuel and traditional fuel assemblies:

**Mass Production & Standardization**

- Factory Fabrication: Moving to automated, high-volume production of heat pipe assemblies (similar to traditional fuel rods) will significantly reduce per-unit cost.
- Standardized Designs: Establishing modular, interchangeable components for different reactor types will simplify manufacturing and licensing.

**Alternative Materials & Simplified Construction**

- Replace High-Cost Materials:
    - Wick Structure: Instead of tungsten/niobium, investigate cheaper sintered steel or ceramic alternatives.
    - Cladding: Use nano-coated stainless steel instead of pure SiC, balancing cost and performance.
    - Working Fluid: Explore low-cost molten salt blends instead of pure sodium or lithium.

**Advanced Manufacturing Technologies**

- Additive Manufacturing (3D Printing):
    - Can directly print wick structures inside the casing, reducing fabrication complexity.
    - Can optimize fuel-to-coolant interfaces for better heat transfer efficiency.
- Robotic Assembly: Reducing manual labor costs in precision sealing and filling of heat pipes.

**Leveraging Space & Defense Funding**

- Government agencies (e.g., NASA, DOE, DARPA) are investing in nuclear-powered space reactors and compact military reactors.
- Joint funding & cost-sharing programs can help scale up heat pipe reactor R&D.

**Incremental Deployment in Specialized Reactors**

- Instead of immediately replacing all fuel assemblies in a 300 MW SMR, heat pipe assemblies could first be deployed in microreactors or hybrid fuel-core designs.
- Dual-fuel designs (some heat pipe assemblies, some traditional rods) can allow gradual cost reduction while testing real-world performance.

If the above cost reduction strategies are implemented, the projected unit cost of heat pipe nuclear fuel assemblies could drop from $50,000 to around $30,000 - $35,000, bringing them closer to traditional fuel assembly costs while retaining their advantages.

**Projected Cost Reductions**

**Year Projected Unit Cost (USD)**

- 2025: $50,000 per assembly (current cost)
- 2030: $40,000 per assembly (20% reduction from mass production scaling)
- 2035: $27,200 per assembly (additional 15% reduction from material optimizations)
- 2040: $16,646 per assembly (final 10% reduction from additive manufacturing & automation)

Assuming the above predictions, by 2040, heat pipe fuel assemblies could become cheaper than traditional fuel assemblies ($30,000 each), making them cost-competitive while retaining their efficiency and safety advantages.

## TESTING VIABILITY AND PERFORMANCE OF HPFNA: EXPERIMENTAL STUDY

The experiment proposed below aims to evaluate the thermal performance, structural integrity, and operational reliability of a Heat-Pipe Nuclear Fuel Assembly using electrically heated rods to simulate nuclear fuel rods.

### OBJECTIVES OF THE EXPERIMENT

- Assess heat transfer performance of the heat pipe system under steady-state and transient conditions.
- Evaluate temperature distributions (axial & radial) in the fuel assembly.
- Measure thermal efficiency and effectiveness of heat removal at different power levels.
- Analyze wick performance in different orientations (vertical vs. horizontal).
- Identify potential failures such as dry-out, wick degradation, or liquid metal loss.

### EXPERIMENTAL SETUP

#### Heat Pipe Fuel Assembly Test Module

The test assembly will replicate a single HPNFA assembly with electrically heated rods to simulate nuclear fuel rods.

**Key Components:**

Electrically Heated Rods (Simulating $UO_2$ fuel rods)

- Material: High-grade stainless steel or Inconel tube with an embedded resistive heating element.
- Size: 9.5 mm diameter (typical PWR fuel rod size).
- Power Output: Adjustable from 5 – 300 kW to simulate different reactor conditions.

Heat Pipe Structure

- Working Fluid: Sodium or lithium (sealed within heat pipe).
- Wick Material: Sintered tungsten or niobium mesh.
- Outer Casing: Nickel-based alloy (Inconel 718) or SiC composite.

Heat Exchanger System (Condenser Zone)

- Cooling Medium: Supercritical $CO_2$ or molten salt loop.
- Heat Exchanger Type: Liquid-to-air or liquid-to-liquid exchanger for controlled heat rejection.

Instrumentation and Data Acquisition

- Thermocouples: Placed along the fuel rods, wick, and condenser to measure temperature gradients.
- Pressure Sensors: To monitor vapor pressure inside the heat pipe.
- Heat Flux Sensors: To measure heat transfer rate at various sections.
- Flow Sensors: To analyze liquid metal return rates in the wick.
- Infrared Cameras: For real-time thermal mapping.

**STEADY-STATE THERMAL PERFORMANCE**
Objective: Measure steady-state temperatures and heat transfer rates under different power levels.

Procedure:
- Set heater rods to 50%, 75%, and 100% power levels.
- Measure temperature profiles along the heat pipe.
- Compare heat flux in evaporator and condenser zones.

**TRANSIENT RESPONSE AND OVERLOAD TESTING**
Objective: Evaluate heat pipe performance during power surges and shutdowns.

Procedure:
- Rapidly increase power input to simulate reactivity changes.
- Observe heat pipe response time and vapor flow dynamics.
- Perform an emergency shutdown to measure cooldown rates.

**WICK PERFORMANCE IN DIFFERENT ORIENTATIONS**
Objective: Test capillary return efficiency of the wick under different orientations.

Procedure:
- Vertical orientation test (Gravity-assisted liquid return).
- Horizontal orientation test (Capillary-driven liquid return).
- Inclined orientation test (Simulating core angles in microreactors).

**DEGRADATION AND LIFETIME TESTING**
Objective: Simulate long-term operation and identify material degradation effects.

Procedure:
- Cyclic heat loading over 1000 hours.
- Material analysis (X-ray diffraction, SEM, chemical tests) after prolonged exposure to sodium/lithium.
- Check for wick erosion, oxidation, and working fluid loss.

**EXPECTED RESULTS**
- Uniform temperature distribution along the heat pipe indicates effective thermal transport.
- Rapid heat transfer in transient tests confirms high thermal conductivity.
- Stable liquid return rates in the wick confirm orientation-independent operation.
- No dry-out or fluid loss over time suggests long-term viability.

**DATA ANALYSIS AND VALIDATION**
- Compare experimental heat transfer performance to theoretical heat pipe models.
- Use Computational Fluid Dynamics (CFD) simulations to validate experimental data.
- Correlate thermal efficiency and heat removal rates with power input.

## CONCLUSIONS

HPNFA is a highly innovative concept that enhances passive safety, heat transfer efficiency, and modularity. It could revolutionize next-generation nuclear reactors, particularly for remote and space applications.