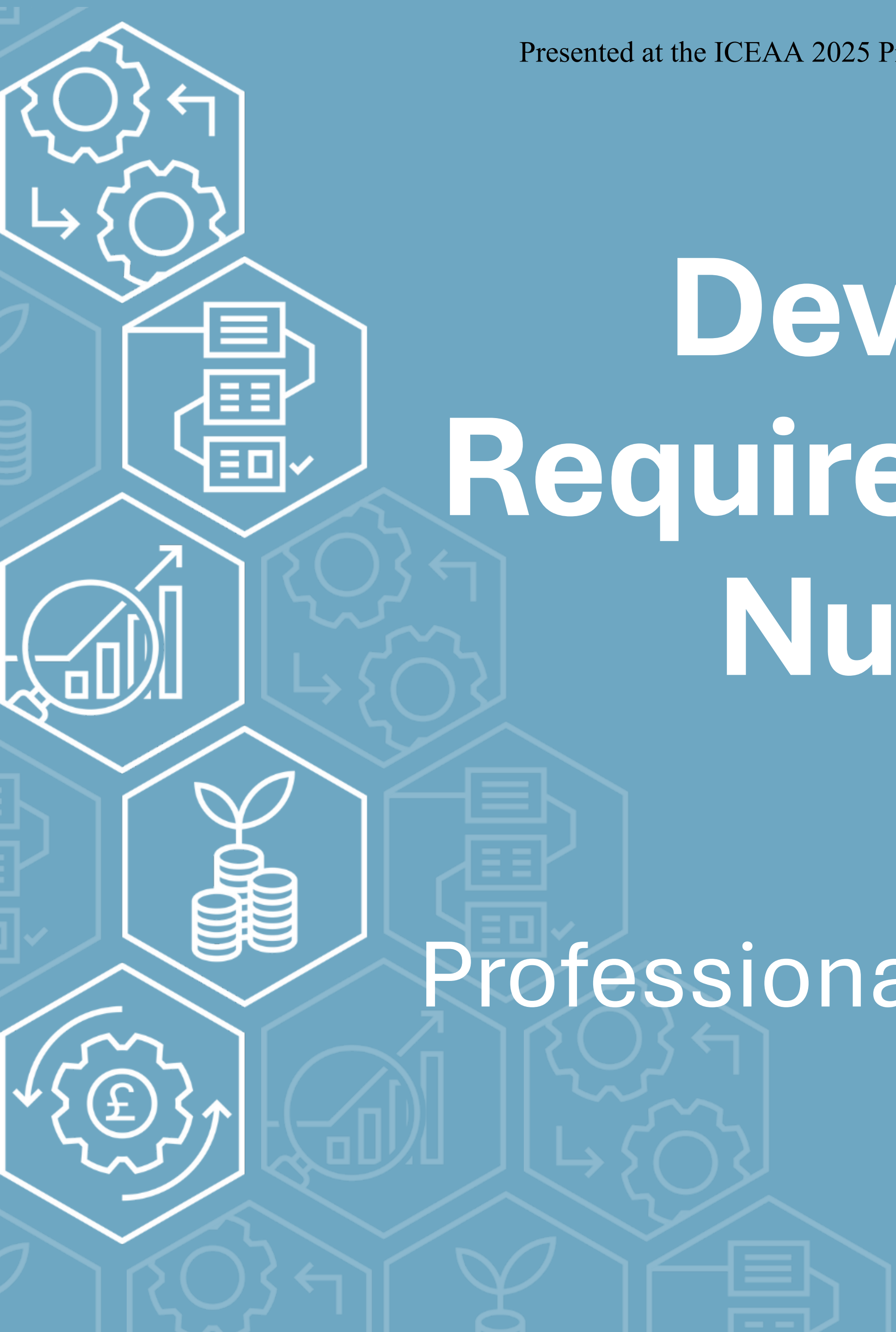


# Developing Cost Requirements for Small Nuclear Plants

ICEAA 2025
Professional Development & Training Workshop

Delivering clarity from complexity

SIRIUS ANALYSIS

# Nuclear Cost Estimating Experience

Fuel Route Engineer

Project Engineer

Cost Researcher

Head of Assurance

Cost Estimate Lead

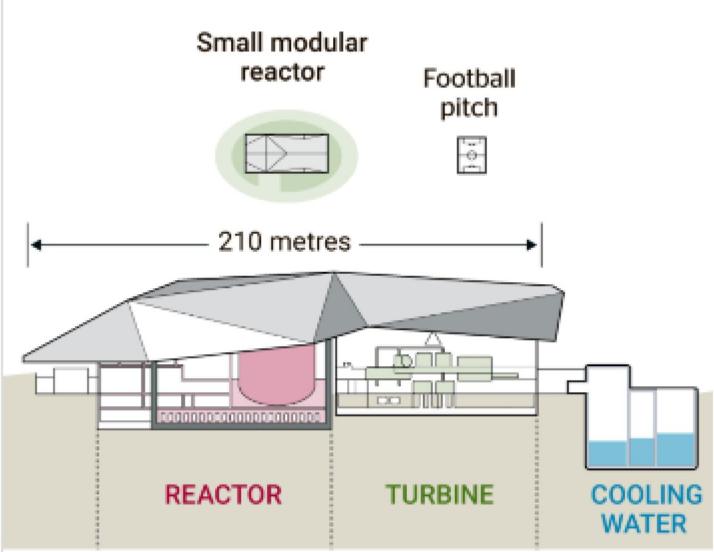
Principal Cost Consultant

Worked across the **lifecycle** of nuclear, from **early concept** to **construction** and **operations** of large reactors, through to **decommissioning** and **waste management**

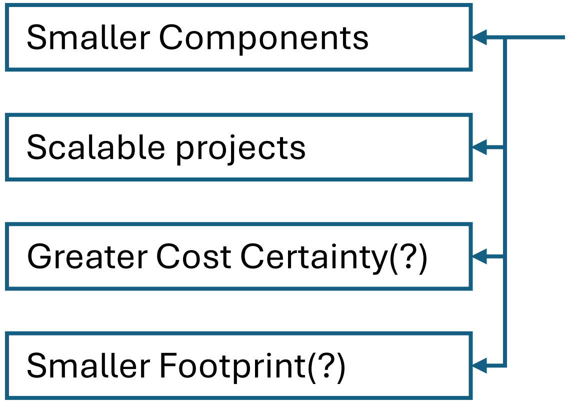
# Contents

# What are SMRs

- Smaller power output (under 600 MWe)
- Modular construction: Factory-built, assembled on-site
- Focus on PWR-type (Gen III+)
- 80+ designs at various stages of development



Small Modular Reactors | Rolls-Royce



Smaller Components

Scalable projects

Greater Cost Certainty(?)

Smaller Footprint(?)

The reactor | Hinkley Point C | EDF

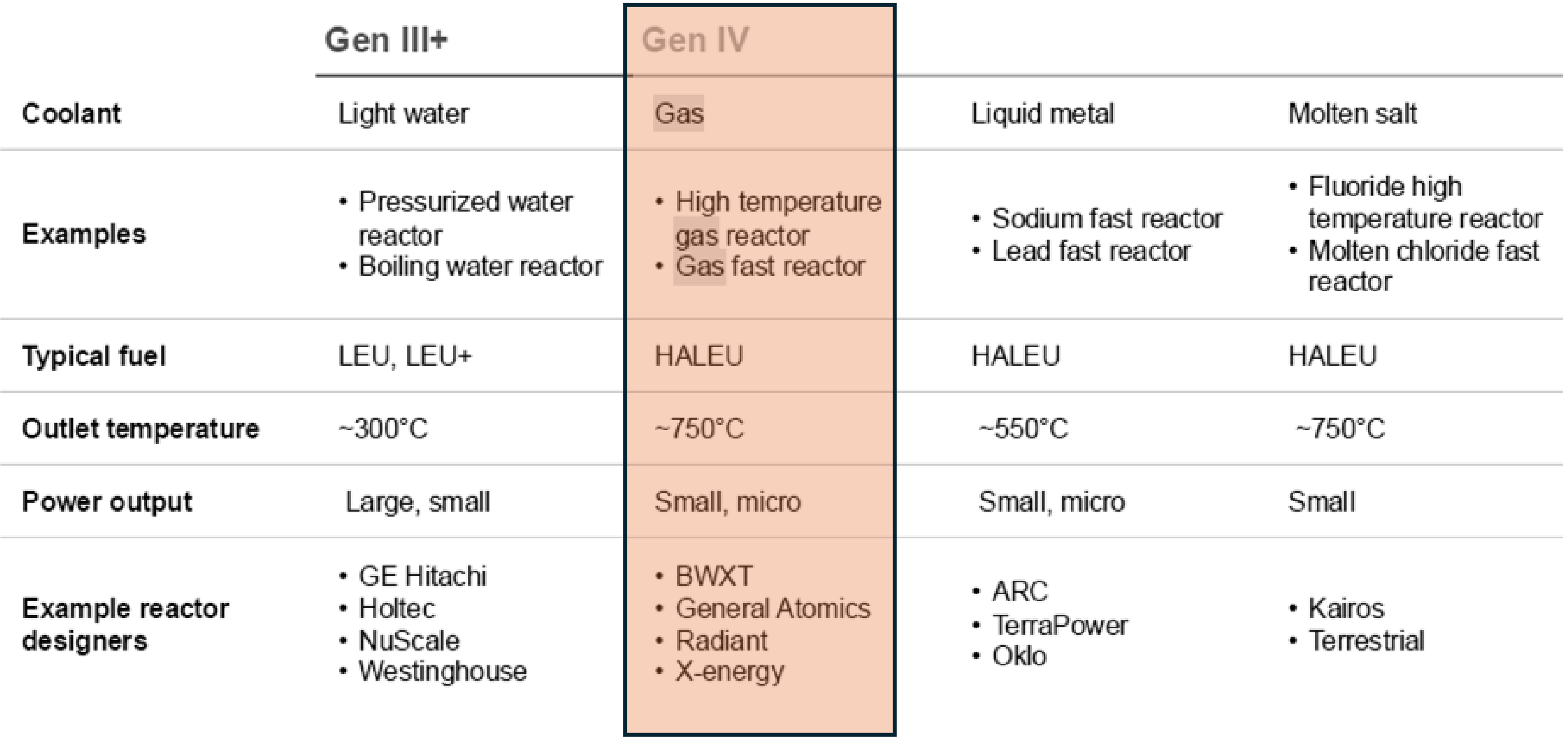
# Why are SMRs being developed?

- Cost and schedule overruns
- Competitiveness in liberalised markets
- Security and energy independence
- Need baseload Electricity + Datacentres, hydrogen, heat, applications

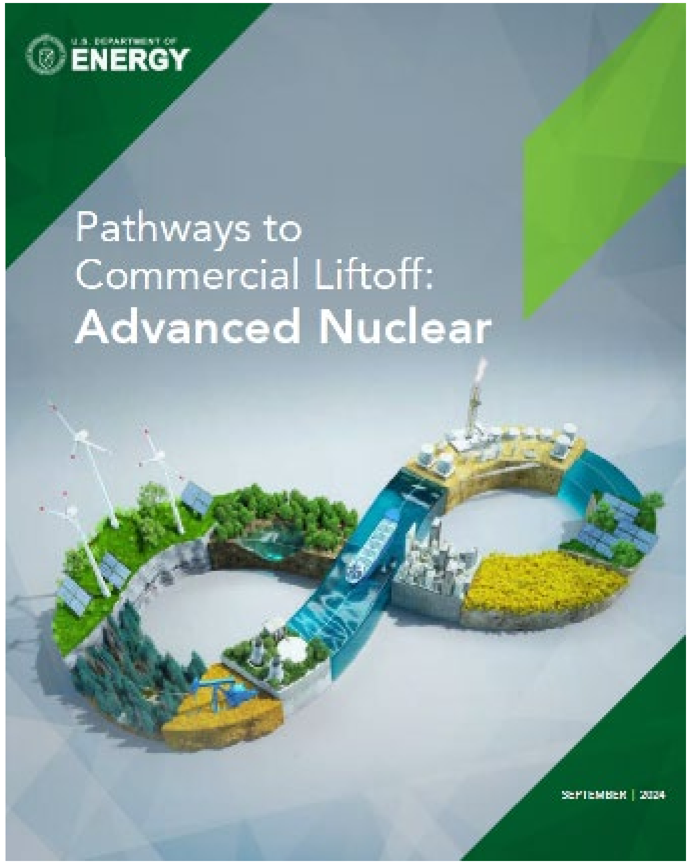
| Power Plant | Original Cost ($bn) | Current Cost ($bn) | Cost Overrun ($bn) | Original Completion Date | Actual/Expected Completion Date | Delay (Years) |
|---|---|---|---|---|---|---|
| Hinkley Point C | £18 (approx. $23) | £46 (approx. $59) | £28 (approx. $36) | 2025 | 2029–2031 | 4–6 |
| Flamanville EPR | €3.3 (approx. $3.6) | €13.2 (approx. $14) | €9.9 (approx. $10.4) | 2012 | December 2024 | 12 |
| Barakah (UAE) | $20 | $24 | $4 | 2017 | 2024 | 7 |
| Olkiluoto 3 (Finland) | €3.2 (approx. $3.6) | €8.5 (approx. $9.5) | €5.3 (approx. $5.9) | 2009 | 2023 | 14 |
| Vogtle 3 & 4 (USA) | $14 | $35 | $21 | 2016–2017 | 2023–2024 | 7 |

# Advanced Reactors

- Advanced Modular Reactors - AMRs
- High Temperature Gas-cooled Reactors (HGTRs)



| | Gen III+ | Gen IV | | |
|---|---|---|---|---|
| **Coolant** | Light water | Gas | Liquid metal | Molten salt |
| **Examples** | • Pressurized water reactor<br>• Boiling water reactor | • High temperature gas reactor<br>• Gas fast reactor | • Sodium fast reactor<br>• Lead fast reactor | • Fluoride high temperature reactor<br>• Molten chloride fast reactor |
| **Typical fuel** | LEU, LEU+ | HALEU | HALEU | HALEU |
| **Outlet temperature** | ~300°C | ~750°C | ~550°C | ~750°C |
| **Power output** | Large, small | Small, micro | Small, micro | Small |
| **Example reactor designers** | • GE Hitachi<br>• Holtec<br>• NuScale<br>• Westinghouse | • BWXT<br>• General Atomics<br>• Radiant<br>• X-energy | • ARC<br>• TerraPower<br>• Oklo | • Kairos<br>• Terrestrial |



U.S. DEPARTMENT OF ENERGY

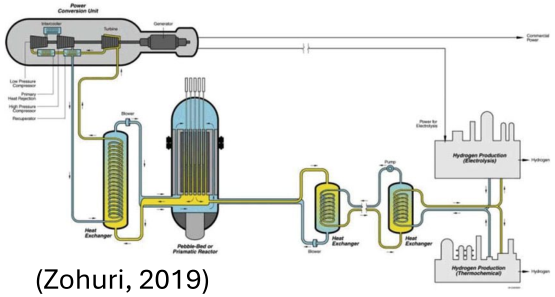
Pathways to Commercial Liftoff: Advanced Nuclear

SEPTEMBER | 2024

# High Temperature Gas-cooled Reactors

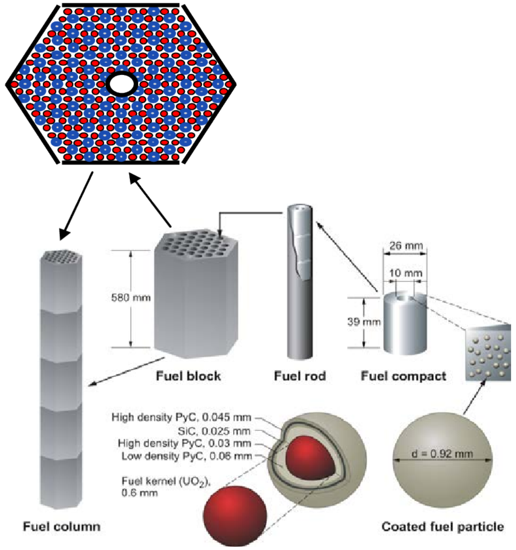
- Pressurised Water Reactors (PWRs): Most common nuclear reactors globally, using water as both coolant and moderator.
- High-Temperature Gas-Cooled Reactors (HTGRs): Advanced reactors using helium gas as coolant and graphite as moderator.
- HTGR Variants:
    - Prismatic Block: Fuel embedded in graphite blocks.
    - Pebble Bed Modular Reactor (PBMR): Fuel in spherical pebbles.


BWXT BANR – Image courtesy BWX Technologies, Inc.



(Zohuri, 2019)


(Strydam et al, 2014)



(Strydam et al, 2014)

# High Temperature Gas-cooled Reactors

## Historical HTGRs:

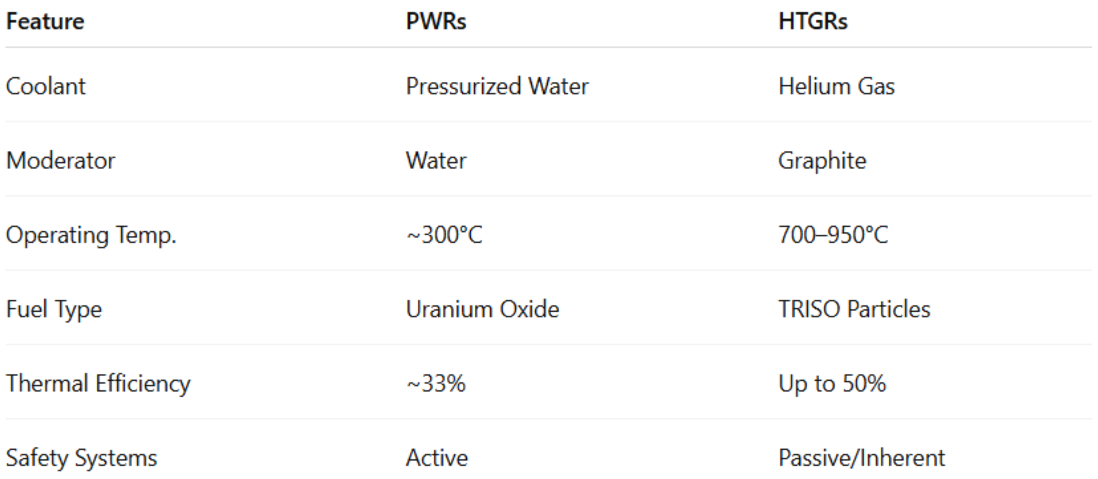
- Germany's THTR-300: Pebble bed reactor operational in the 1980s.
- Fort St. Vrain (USA): Prismatic block reactor operated from 1979 to 1989.

## Modern HTGR Projects:

- X-Energy's Xe-100: Modular pebble bed reactor under development.
- BWXT's mPower: Compact reactor design focusing on safety and efficiency.

## Applications:

- Electricity generation.
- Industrial process heat.
- Hydrogen production.



| Feature | PWRs | HTGRs |
|---|---|---|
| Coolant | Pressurized Water | Helium Gas |
| Moderator | Water | Graphite |
| Operating Temp. | ~300°C | 700–950°C |
| Fuel Type | Uranium Oxide | TRISO Particles |
| Thermal Efficiency | ~33% | Up to 50% |
| Safety Systems | Active | Passive/Inherent |

# Problem Statement

Nuclear has promised (and not delivered) low cost and schedule certainty, and there are limited examples of modern HTGRs. How can cost priorities be identified to development HTGRs for commercial success?

# Purpose of this Study

- Exploratory study to understand if expert judgement (non-cost professionals) can be utilised to develop cost priorities at the very early project stage.
- The best way to influence cost is to understand the drivers at an early stage.
- Cost analysts are usually not involved at the front end. But cost requirements are defined at this early stage.

# Estimates of HTGR Costs

| Document / Report Title | Year | Estimated Construction Cost | Reference Technology | Power Output (MWe [MWth]) | Country / Region | Source Link |
|---|---|---|---|---|---|---|
| INL Technical Evaluation (TEV-1196) | 2012 | $3.7 billion | NGNP HTGR (prismatic design) | 267 MWe (600 MWth) | USA | https://inldigital.inl.gov/TEV/TEV-1196.pdf |
| GTHTR300: Basic Design and Economical Evaluation (JAEA) | 2016 | ¥200,000/kWe (~$1,667/kWe) | GTHTR300 | 300 MWe (600 MWth) | Japan | https://jopss.jaea.go.jp/pdfdata/JAEA-Research-2016-014.pdf |
| University of Chicago / DOE NGNP (GT-MHR) | 2010 | $1,365/kWe (~$0.39B per module) | GT-MHR | 285 MWe (600 MWth) | USA / Russia | https://nuclear-economics.com/GT-MHR-cost-study.pdf |
| NucNet: China HTR-PM Construction | 2013 | ¥3 billion (~$476 million) | HTR-PM | 200 MWe (2×250 MWth) | China | https://www.nucnet.org/news/china-begins-construction-of-first-gen-iv-reactor |
| Cost-effective Advanced Nuclear (MIT/NGNP-SC-HTGR) | 2020 | $2.7B (FOAK), $5.5B (NOAK) | SC-HTGR (Areva Antares) | 250 MWe (625 MWth) | USA | https://web.mit.edu/canes/publications/reports/2020-cost-study.pdf |
| X-energy Xe-100 Project Announcement | 2021 | $2.4 billion (4-pack) | Xe-100 | 320 MWe | USA | https://www.x-energy.com/press-releases/xe-100-project-overview |
| U-Battery Concept Briefing | 2015 | £40–70 million (NOAK twin-unit) | U-Battery | 8 MWe | UK / Netherlands | https://www.ubebattery.com/resources/u-battery-overview.pdf |
| USNC MMR Overview | 2022 | no information available | USNC MMR | 5 MWe (15 MWth) | USA / Canada | https://usnc.com/mmr/ |

“FOAK” = First-of-a-kind;

“NOAK” = Nth-of-a-kind (mature deployment).

Construction cost values are total overnight capital costs unless otherwise noted.

Each HTGR design is listed with no prioritization, including conceptual designs, demos and industry proposals since 2010.

# Expected Cost Drivers for HTGRs

1. Capital Cost and Construction Complexity - FOAK (First-of-a-Kind) HTGRs typically have high construction costs due to:
    - Novel reactor pressure vessel designs (e.g., for helium coolant systems).
    - Specialized materials (e.g., graphite moderators, ceramics).
    - Lack of standardized modular construction practices.
    - INL (TEV-1196) and MIT (SC-HTGR) cite capital costs of ~$3–5.5 billion, with significant cost concentration in non-recurring engineering and custom fabrication.

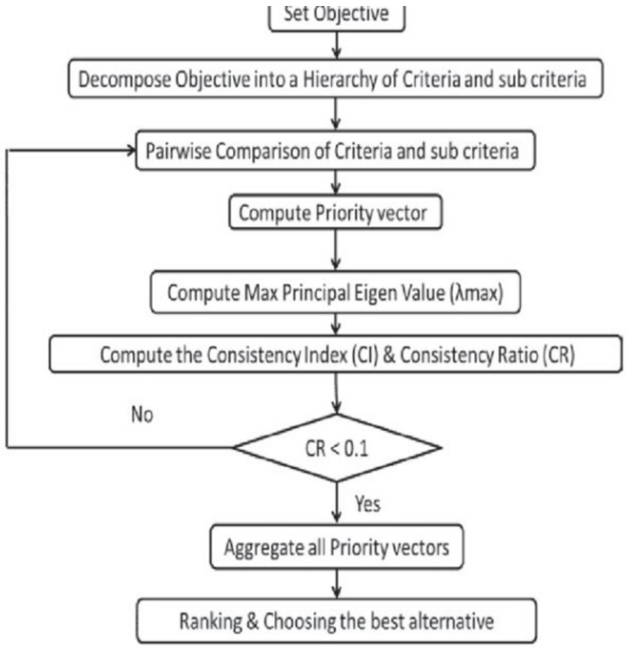
- 2. Fuel Supply and TRISO Fabrication - TRISO fuel is more complex and expensive to produce than standard LWR fuel. Several reports (e.g., GTHTR300, Xe-100 briefings) highlight:
    - Limited HALEU supply chain as a bottleneck.
    - High fabrication costs due to stringent quality assurance.
    - This affects both front-end fuel costs and availability for scaling.
- 3. Licensing and Regulatory Uncertainty - Regulatory frameworks (especially in the U.S. and EU) are still largely LWR-centric . HTGRs face additional costs for:
    - Prototype demonstration and safety validation.
    - Custom licensing paths, especially for micro-reactors or cogeneration HTGRs.
    - INL and NGNP documents emphasize this as a barrier to commercial deployment.
- 4. Financing and Schedule Risk - As with all nuclear projects, interest during construction (IDC) is a significant contributor to levelized cost. Delays due to unfamiliar supply chains, workforce training, or regulatory approvals exacerbate this. Several cost studies assume optimistic timelines (e.g., 3–5 years), which may not be realistic for FOAK units.
- 5. Supply Chain Immaturity - Many HTGR-specific components (e.g., helium turbomachinery, graphite core blocks) lack:
    - Volume production.
    - Qualified suppliers.
    - This leads to higher unit costs, longer lead times, and schedule unpredictability—especially for SC-HTGR and GT-MHR designs.
- 6. Operations & Maintenance - HTGRs have potential O&M advantages (e.g., fewer moving parts, passive safety), but:
    - Actual O&M cost reductions depend on staffing models, automation, and learning curve.
    - This was a secondary but acknowledged factor in GTHTR300 and Xe-100 evaluations.

# Method

# AHP Expert Elicitation

- Analytic Hierarchy Process (AHP) - structured decision-making method developed by Thomas L. Saaty in the 1970s at the Wharton School of the University of Pennsylvania.
- Designed to help individuals and organizations make complex decisions involving multiple criteria by breaking down the decision problem into a hierarchical structure.
- Decision-makers perform pairwise comparisons of the elements at each level of the hierarchy, assessing their relative importance or preference.
- Comparisons used to derive numerical weights or priorities for each element, facilitating a quantitative analysis of qualitative judgments.
- AHP has been widely applied across various fields, including business, government, healthcare, and engineering, to support decisions such as resource allocation, policy development, and strategic planning.

# AHP Expert Elicitation



1. **Identify Criteria and Sub-Criteria -** Develop a hierarchy of influencing factors e.g.
    1. **Technical Factors** (design specific elements, first of a kind differences, materials)
    2. **Regulatory Factors** (licensing, policy requirements)
    3. **Economic Factors** (capital costs, operating costs)
2. **Expert Elicitation:**
    1. Conduct structured interviews with nuclear industry experts.
    2. Gather insights on key differentiators between PWRs and HTGRs that may drive cost.
3. **Pairwise Comparisons:**
    1. Experts compare each factor against others in terms of importance.
    2. Assign relative importance scores using a scale (e.g., 1 to 9).
4. **Construct a Comparison Matrix:**
    1. Arrange expert evaluations into a matrix for analysis.
    2. Calculate weighted priorities for each factor.
5. **Compute Consistency Ratio (CR):**
    1. Check the reliability of expert judgments.
    2. Ensure CR < 0.1 for acceptable consistency.
6. **Determine Weighting Factors:**
    1. Derive the priority weights for each parameter.
    2. Identify the most influential cost-driving factors.
7. **Use AHP Output to prioritise cost requirements of the design:**
    1. The prioritised cost drivers inform the selection of analogous cost data.
    2. Establish how these parameters will guide HTGR cost projections

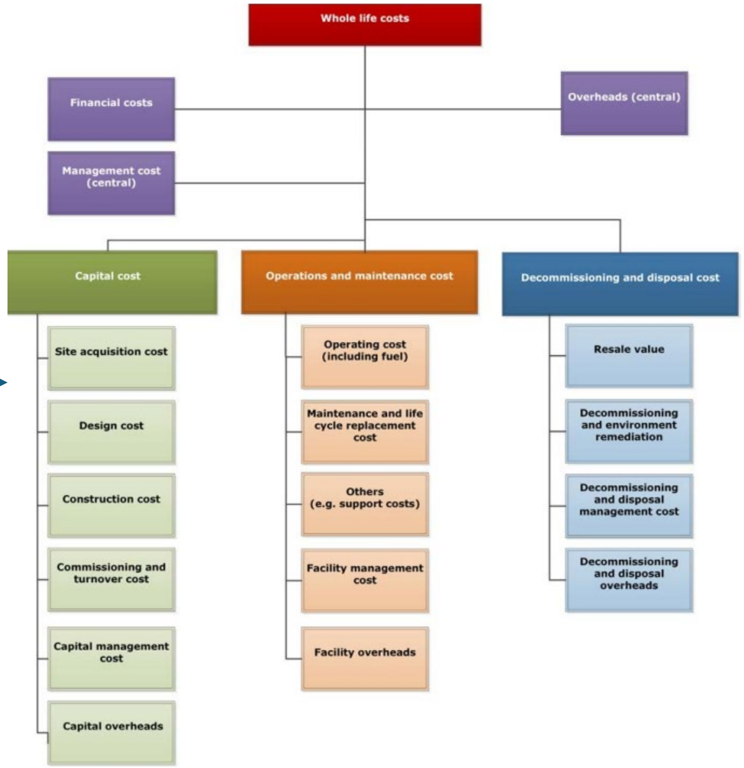
# Goal, Criteria, and Pairwise Comparison

**Goal (Top Level):** Prioritise HTGR drivers for Successful UK deployment

**Criteria (Second Level):** Based on categories identified in the Gen IV code of accounts

The questions in this interview are about the relative impact of key aspects of the nuclear power plant lifecycle on the successful deployment. Essentially you are thinking about which of the two items will are more important (relatively) on the deployment of the technology.

| Attribute |
|---|
| Number of technologies |
| Technology class |
| Deployment location |
| Financial environment |
| Regulatory environment |
| Fuels and fuel cycles |
| Main products |
| Reactor and balance of plant (BOP) fabrication concepts |
| Level of design definition |
| Level of cost definition |
| Fuel cycle material and service costs |



**Criteria (for Pairwise Comparison Table)**

**Development & Design**
conceptual design, safety case R&D, fuel qualification, regulatory engagement, and engineering.

**Financing & Construction Schedule**
Cost of capital, interest during construction, and financial risk tied to build time and delays.

**Capital Construction**
Physical plant build : site works, concrete, reactor components, instrumentation, and installation.

**Licensing & Regulatory Compliance**
Effort to gain approval, navigate safety review, and meet regulatory standards.

**Fuel Cycle**
Front-end (e.g. enrichment, TRISO fabrication), back-end waste handling, and availability of fuel infrastructure.

**Operations & Maintenance**
Running the plant: staffing, scheduled maintenance, inspections, and consumables over the lifecycle.

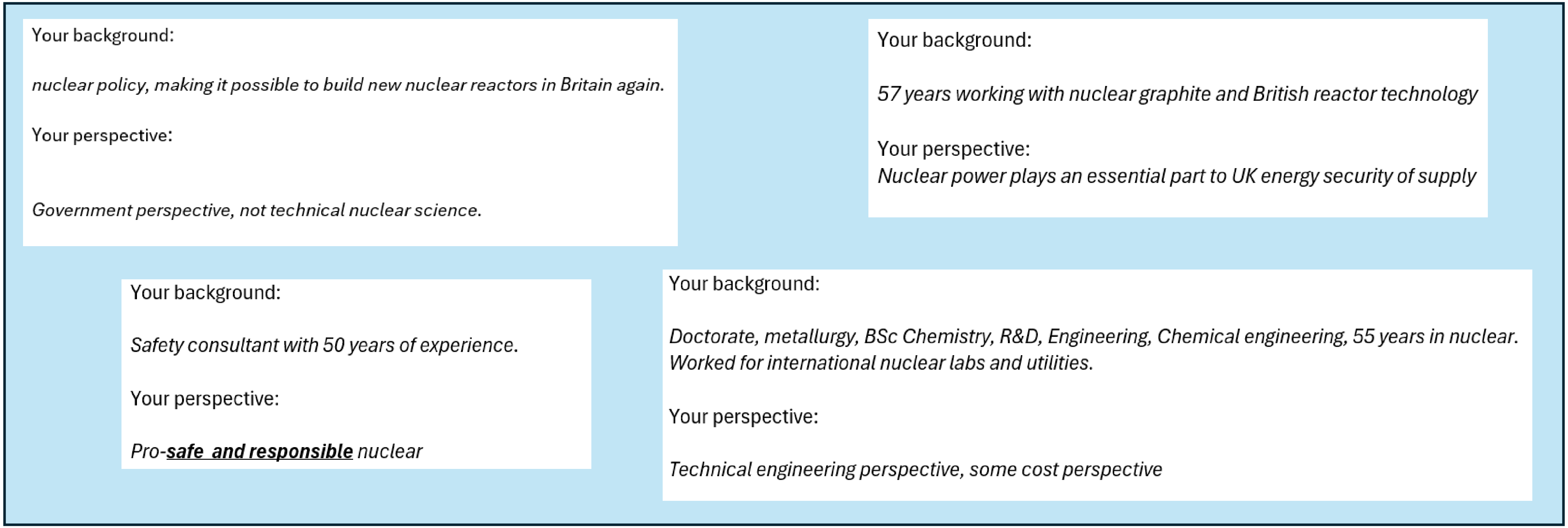
**Supply Chain & Industrialization Readiness**
Availability and maturity of suppliers, manufacturing capabilities, and ability to support scaling of design.

**Decommissioning & End-of-Life Management**
Future dismantling, site remediation, and long-term radioactive waste disposal.

# Study Participants

4 Participants

Experts in nuclear technology, regulation and policy



Your background:

*nuclear policy, making it possible to build new nuclear reactors in Britain again.*

Your perspective:

*Government perspective, not technical nuclear science.*

Your background:

*57 years working with nuclear graphite and British reactor technology*

Your perspective:
*Nuclear power plays an essential part to UK energy security of supply*

Your background:

*Safety consultant with 50 years of experience.*

Your perspective:

*Pro-**safe and responsible** nuclear*

Your background:

*Doctorate, metallurgy, BSc Chemistry, R&D, Engineering, Chemical engineering, 55 years in nuclear.*
*Worked for international nuclear labs and utilities.*

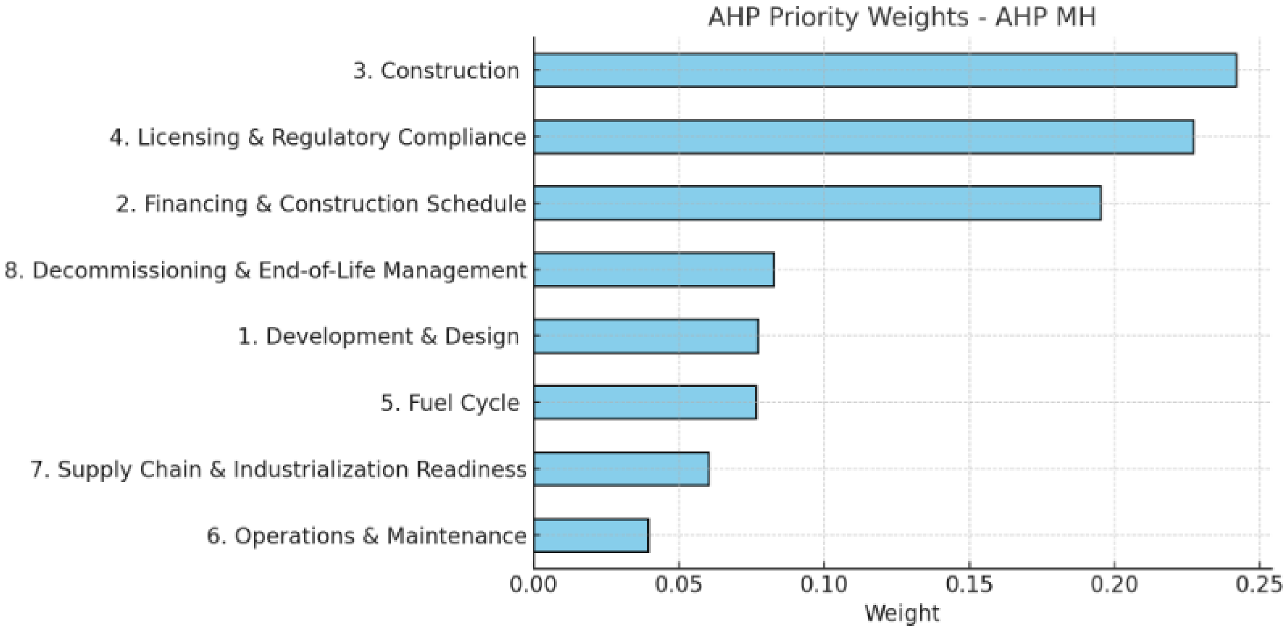
Your perspective:

*Technical engineering perspective, some cost perspective*

# AHP Analysis Results

| λ Max | CI | CR | Consistent? |
|---|---|---|---|
| 9.433 | 0.205 | 0.145 | ✗ No |
| 10.246 | 0.321 | 0.228 | ✗ No |
| 13.639 | 0.806 | 0.571 | ✗ No |
| 10.544 | 0.363 | 0.258 | ✗ No |

All four matrices have a **Consistency Ratio (CR) > 0.10**, meaning they fail the standard AHP consistency threshold. It's recommended to revisit and adjust pairwise comparisons to improve consistency.



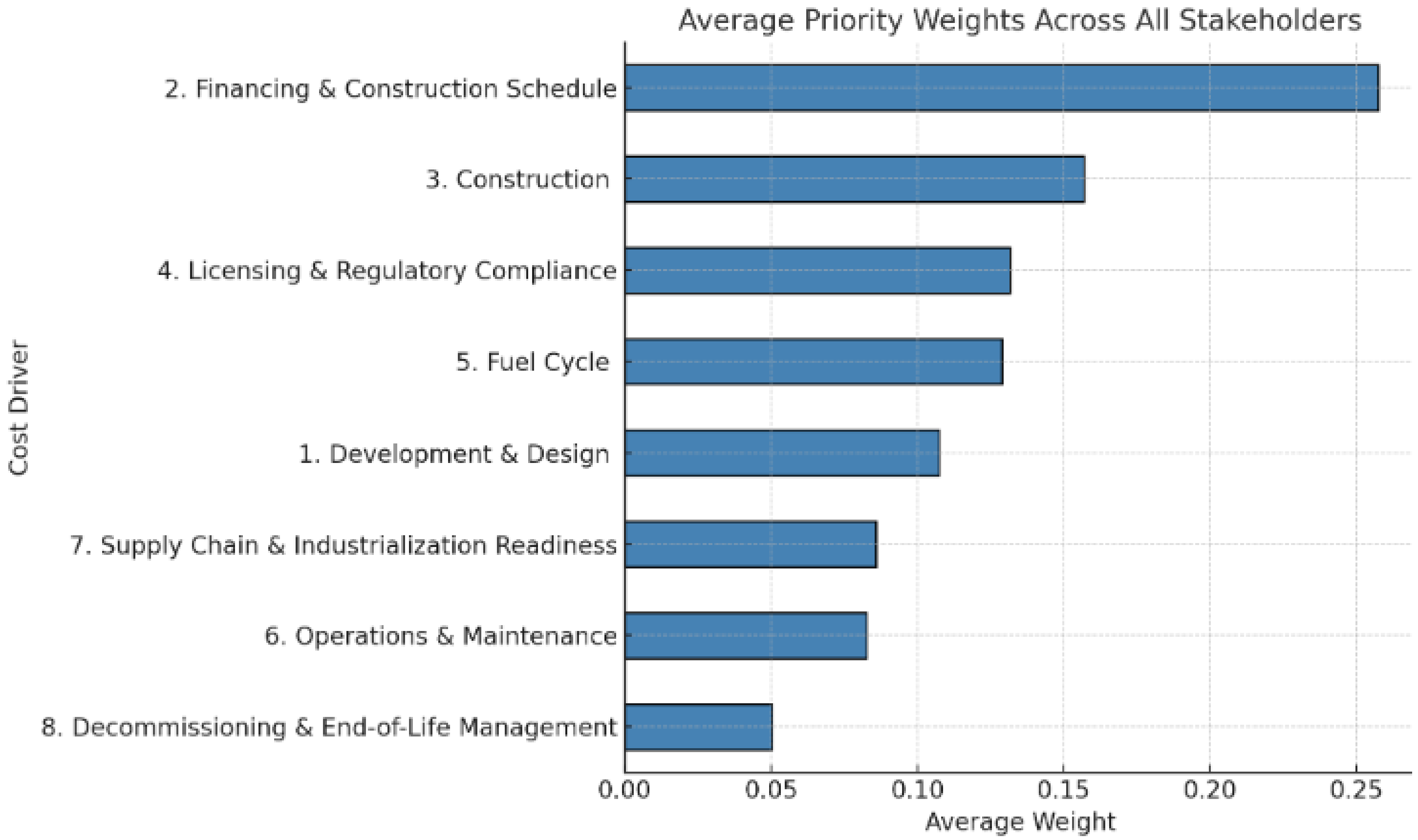
# AHP Analysis Results

- General agreement on Decommissioning as lowest priority, similarly on Development and Design costs
- Several areas lack consensus with some agreement on financing, construction
- Disagreement on licensing and O&M

**Comparison Of Priority Weights Across AHP Analyses**

# Consolidation and Consensus

- Further work to obtain consensus – workshop or revised scorings
- In this instance simply took an average (not recommended)



# Qualitative Statements

"Design for decommissioning upfront for public acceptance"

"No domestic capability to produce the graphite to required quality grade"

"Waste management during operational life more of a challenge"

"Commercial viability linked to need for co-generation (beyond electricity generation)"

"Financing costs and construction risk tied directly to cost uncertainty"

"PWR has been successfully commercially deployed"

"Reduced need for Emergency Planning Zone – opens more sites, and improved safety."

# Summary

- AHP is a useful method for establishing consensus and consistency when prioritising multiple criteria.
- Some level of prioritisation could be achieved at the early stage with limited cost information – in this case.
- Qualitative statements can support workshopping and developing consensus– to support multi-criteria decision-analysis approaches.
- Validity is limited to the very front end of FOAK projects.
- Further verification of the method and applicability required.

# Challenges

- Assessing level of expertise – What constitutes an expert? How available are experts.
- Consistency of analysis and verifying the output (does this really bring more confidence to the cost approach?)
- Resource intensiveness (not a quick process!)
- Changing views as development proceeds – can change the cost prioritisation faster than design can be developed.
- Resource intensive potentially – High level analysis easy, any detail is difficult
- Assumes criteria are independent - In reality, nuclear cost factors are often interdependent. E.g. Construction Schedule affects Financing Costs, Licensing Risk can delay Development & Design or increase Capital Cost.
- Over-Reliance on Expert Judgment - method is heavily reliant on subjective input from experts: Biases, inconsistency, and fatigue can distort results.
- Limited in Complex Systems AHP structures decisions in a strict top-down hierarchy (Goal → Criteria → Alternatives). May oversimplify decision contexts where feedback, loops, or dynamic relationships exist.

# Next steps – Test Network Approaches

- Analytic Network Process. A generalisation of AHP that does not assume independence among elements. Allows for network-based relationships between criteria and sub-criteria.
- ANP enables you to model mutual influence: e.g., how “Financing” depends on “Schedule,” which in turn depends on “Supply Chain.”
- Relationships expressed through a network model, not a strict hierarchy.
- Better suited to multifactor nuclear cost environments, where drivers co-evolve.
- For example, HTGR fuel cost is not just a fixed input — it's tied to supply chain maturity and licensing uncertainty.
- Network approach also opens up opportunities to verify with Bayesian methods.

# Thank you

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