PROJECT SOURCE TO SOAR

Small Modular Reactors for Low-Carbon Electric Aircraft

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Gateways to Blueskies

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Motivation and Metrics

Motivation

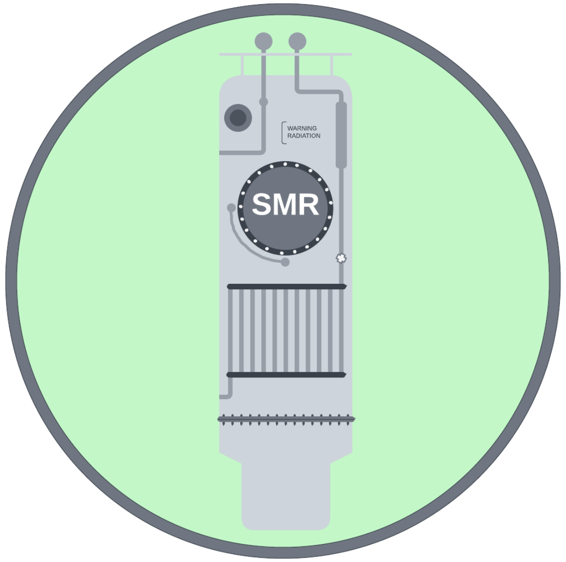
- Numerous factors will push aviation towards more sustainable fueling options:
  - Rising energy demands
  - Stagnant oil production
  - Global climate policy

Energy Design Metrics

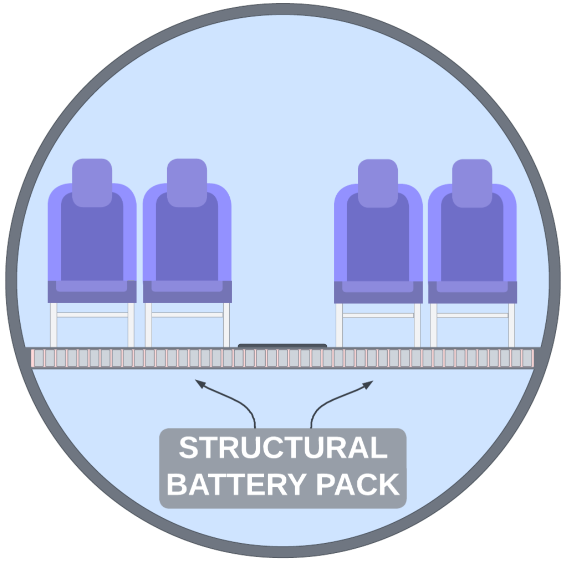
- Flexible
- Energy-dense
- Low-carbon

Proposed Lifecycle

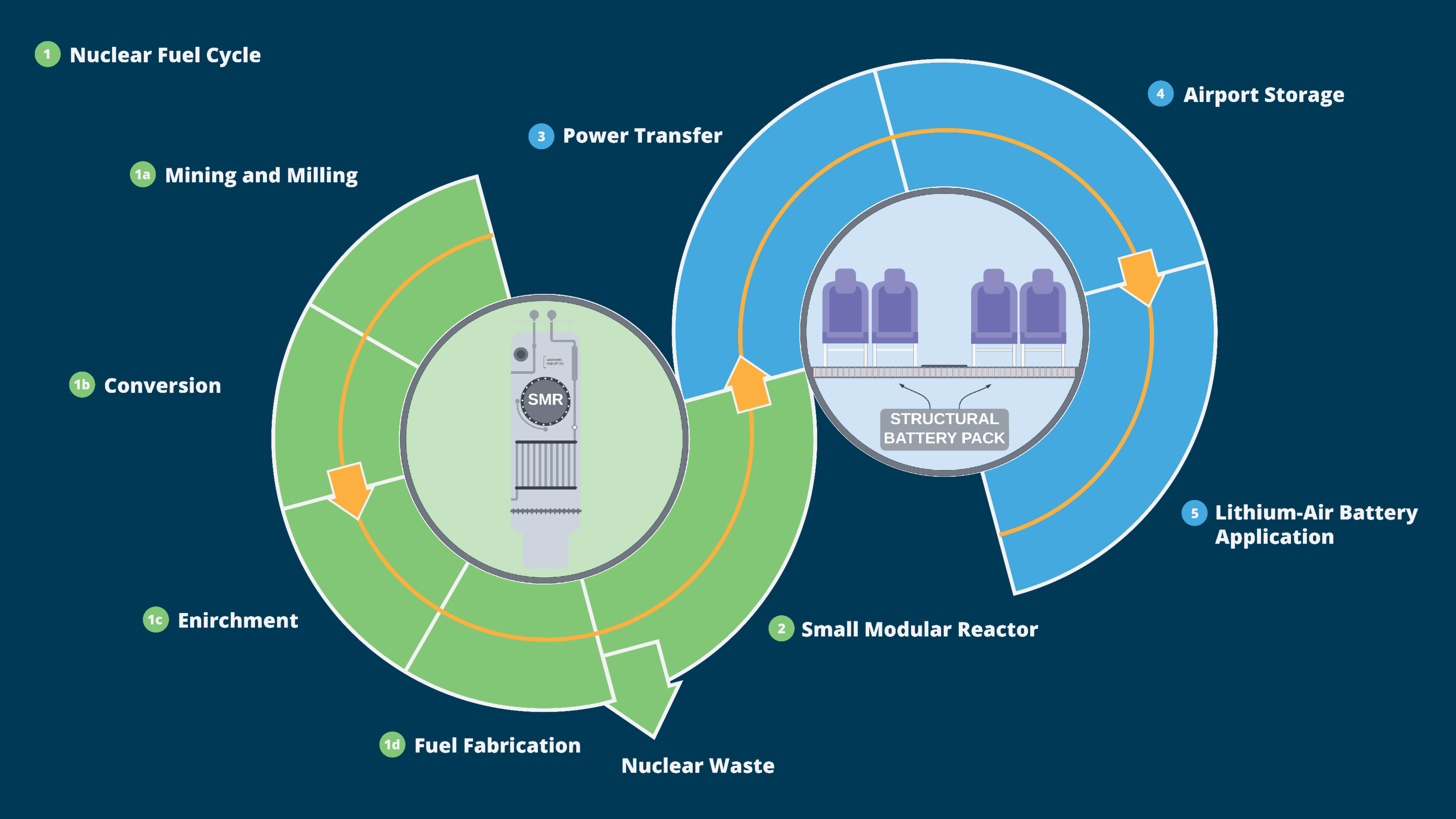
Lifecycle Overview: Electric Aircraft



Generation:
Small Modular Reactor



Storage:
Lithium Battery Chemistry



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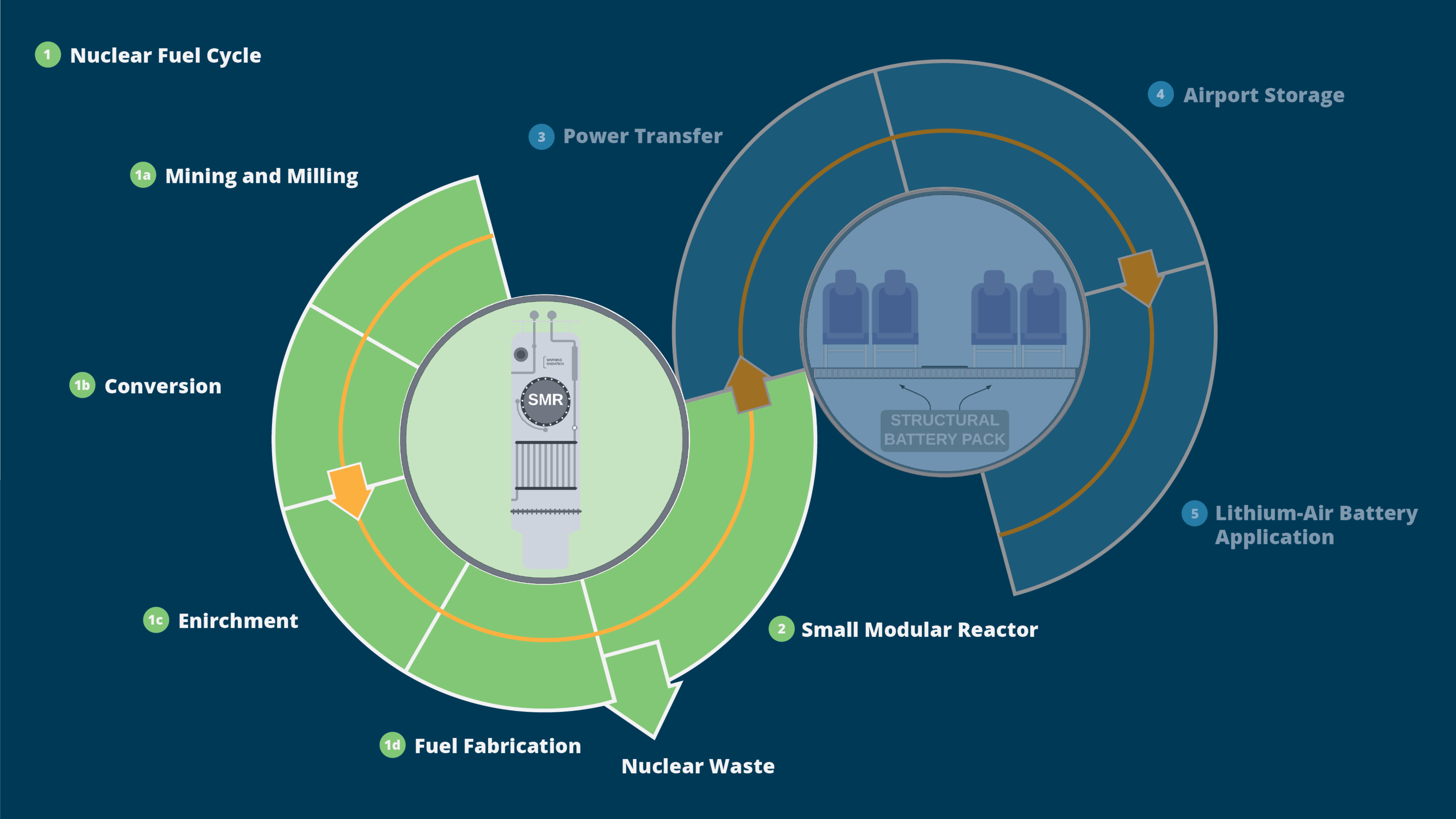
1a Mining and Milling
1b Conversion
1c Enrichment
1d Fuel Fabrication
Nuclear Waste
SMR
2 Small Modular Reactor
3 Power Transfer
4 Airport Storage
STRUCTURAL BATTERY PACK
5 Lithium-Air Battery Application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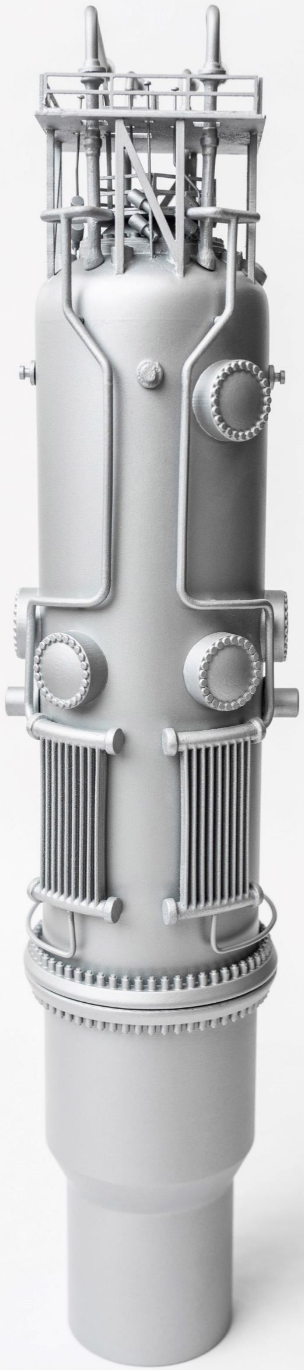
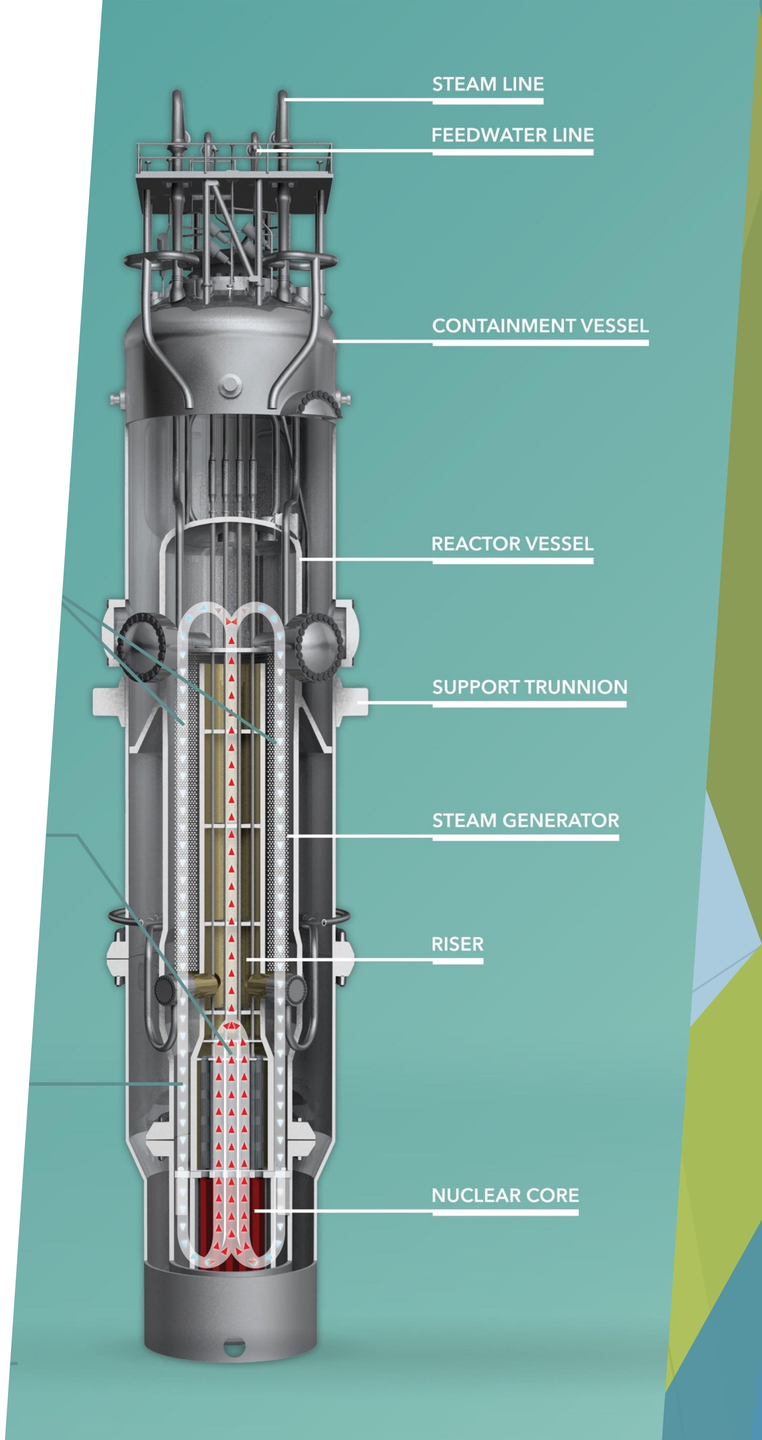


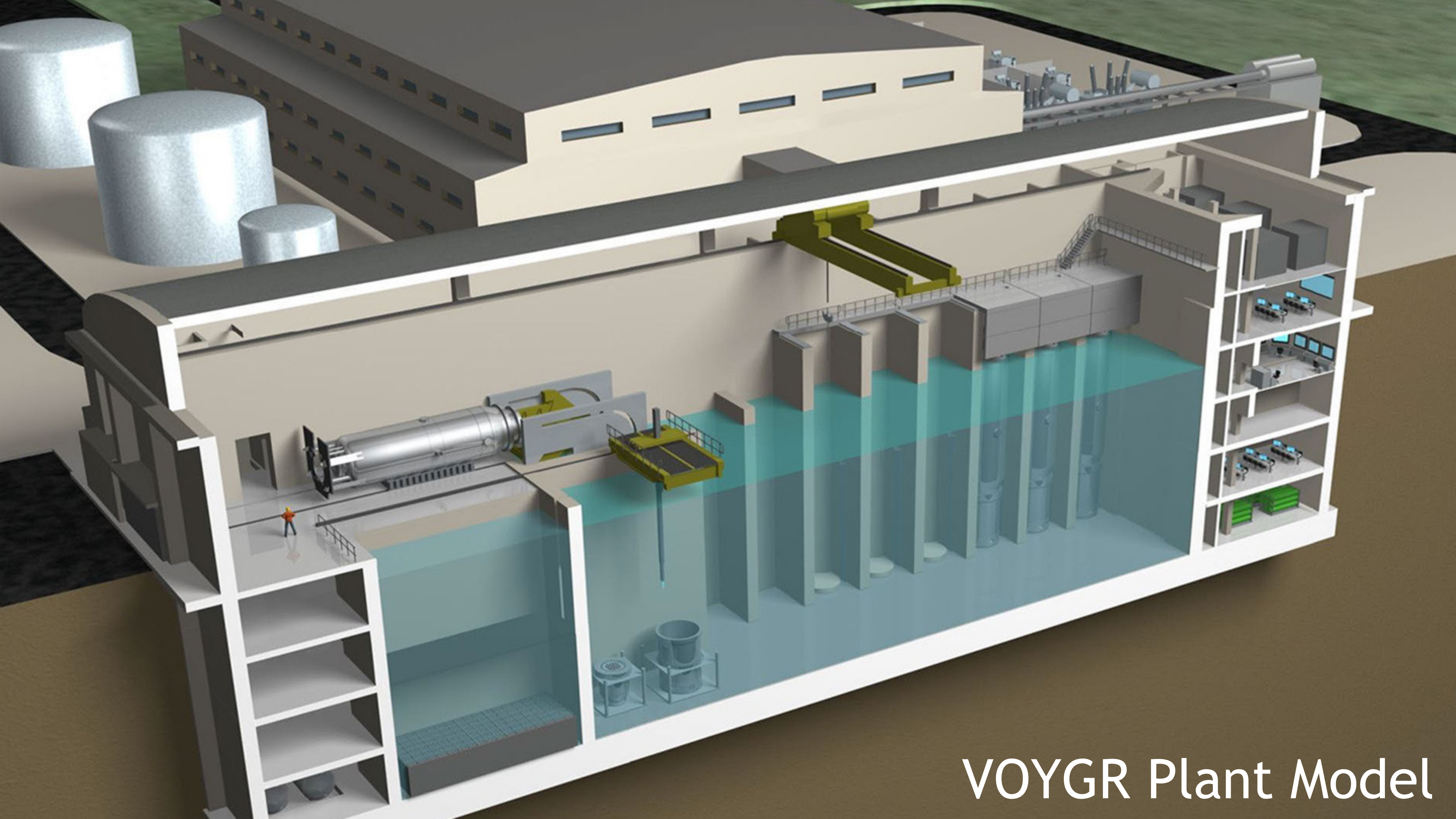
Small Modular Reactor System

- Small modular reactors (SMRs) represent miniaturized nuclear energy systems
- Integral design with lowered power output
- Integrated pressurized water reactors (iPWRs)
- Technologies with decades of industry experience

iPWR Working Principle

- Uranium-based fuel cycle modelled for construction of fuel rods
- Fission reactions heat primary water circuit
- Heat exchange occurs with a secondary water circuit, converting it to steam
- Steam generates electricity through a turbine





VOYGR Plant Model

Safety and Regulation

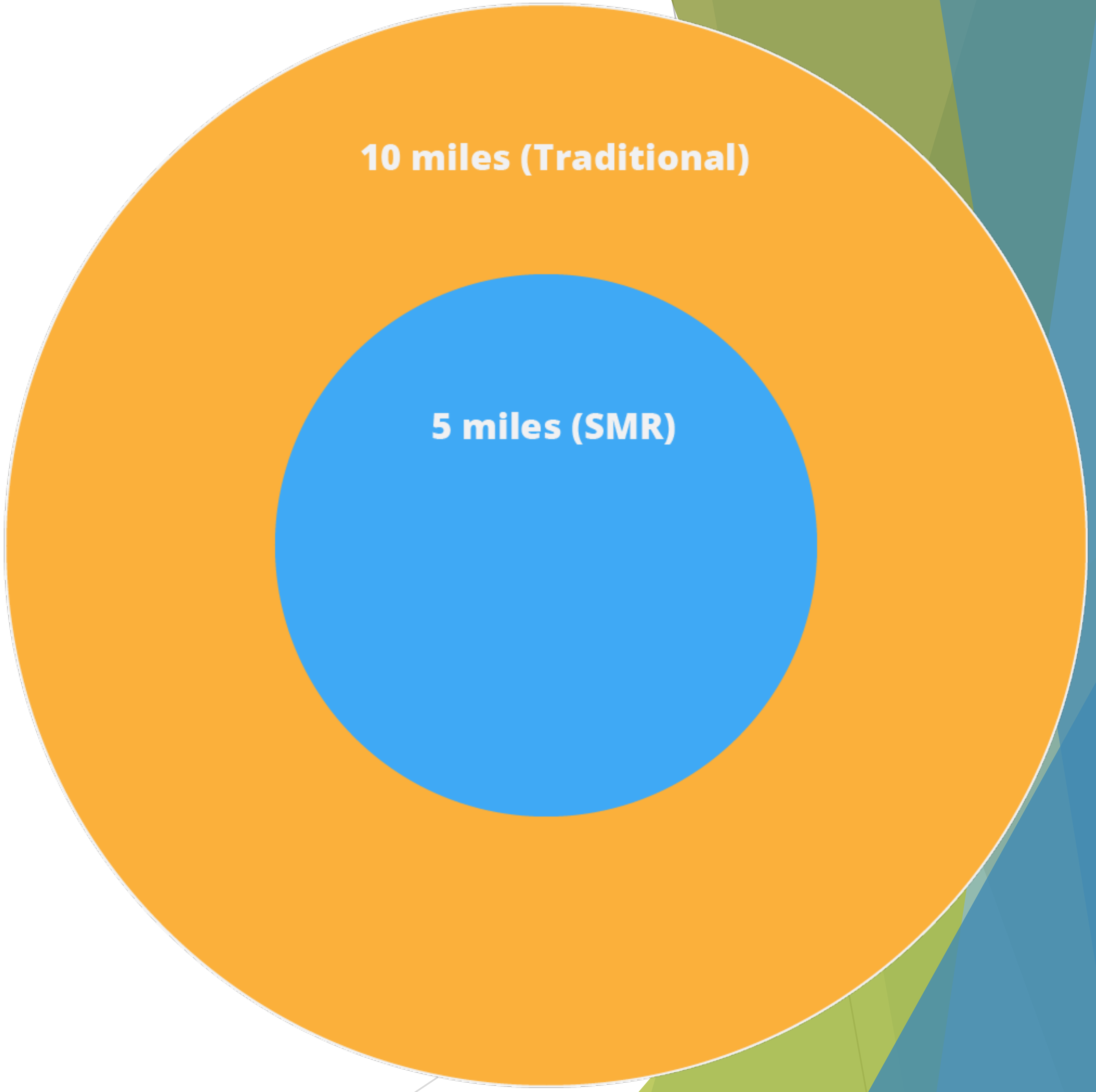
- Passive safety measures
- Industry experience gives confidence to stakeholders
- Engagement on safety is needed to increase public trust
- Nuclear waste represents a concern that must be monitored

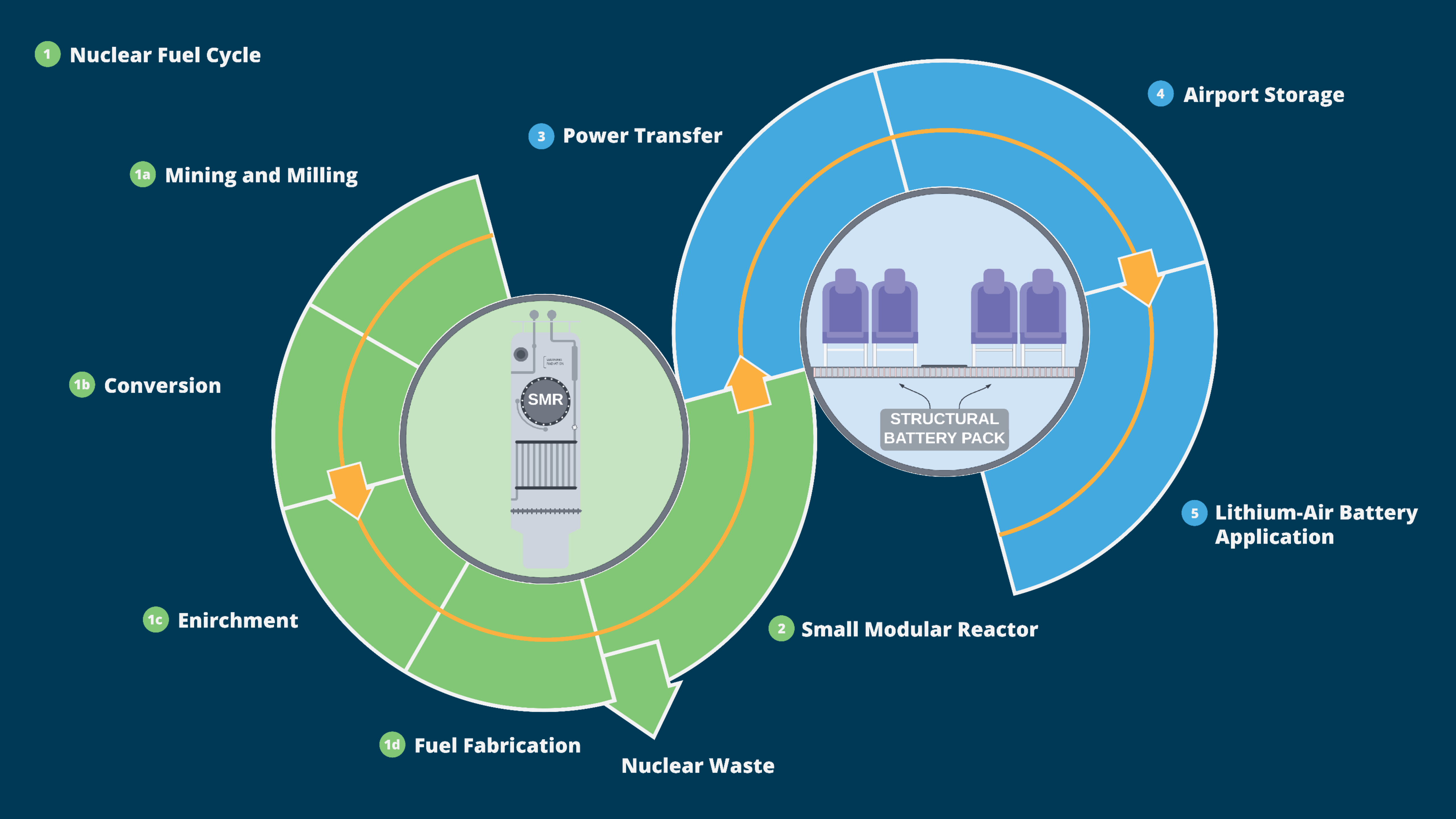
Economic Implications

- Studies have shown SMRs provide a decreased cost of electricity over conventional nuclear, favored through factors such as:
  - Mass manufacturing
  - Construction time
  - Co-siting

EPZ Case Study

- An Emergency Planning Zone (EPZ) defines the regulatory area around a nuclear reactor where protective actions must be taken in the event of an accident
- Lowered radiation exposure risks from SMR accidents can potentially reduce operational costs of these zones by up to $50 million dollars over the reactor lifetime





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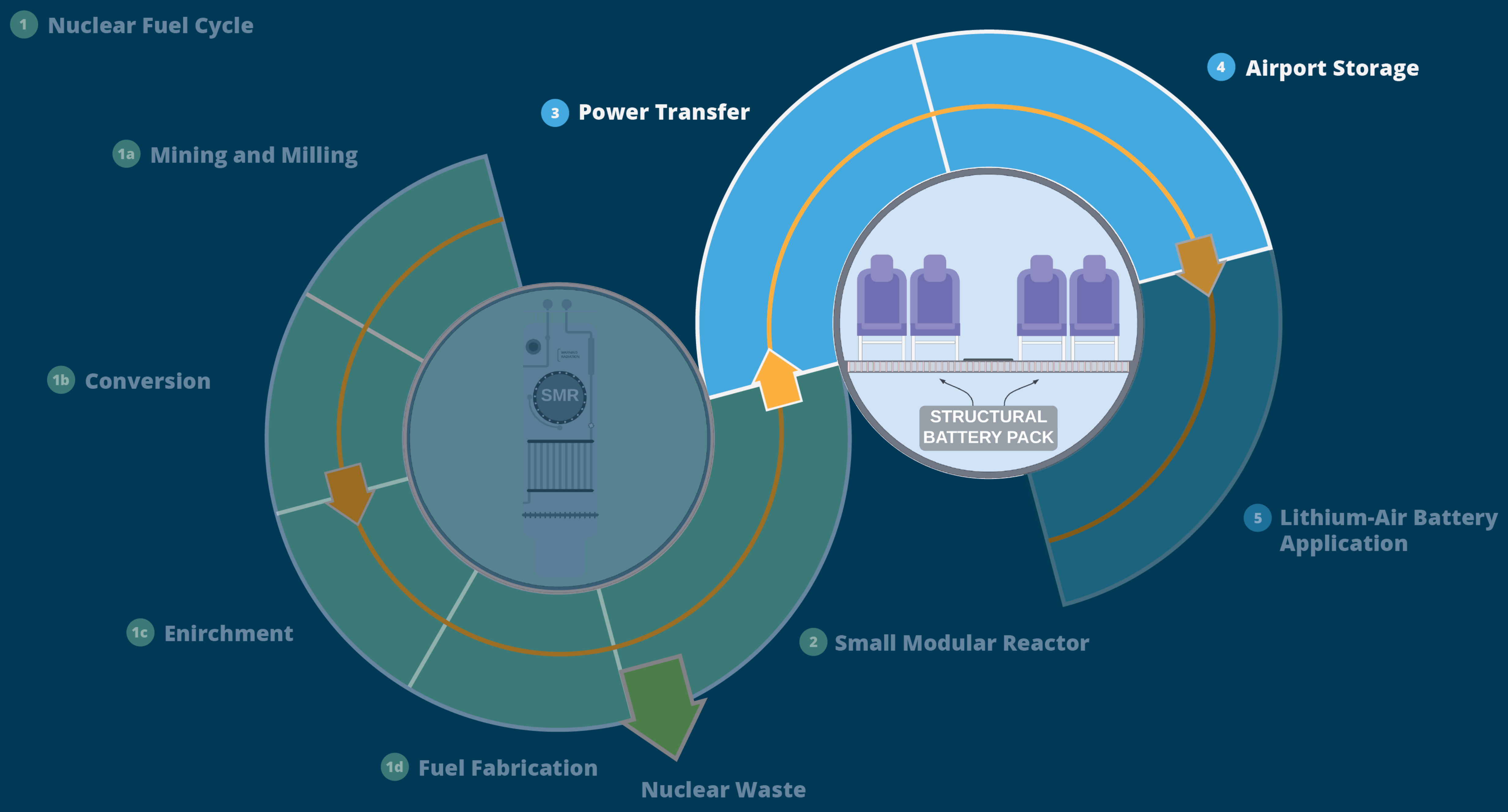

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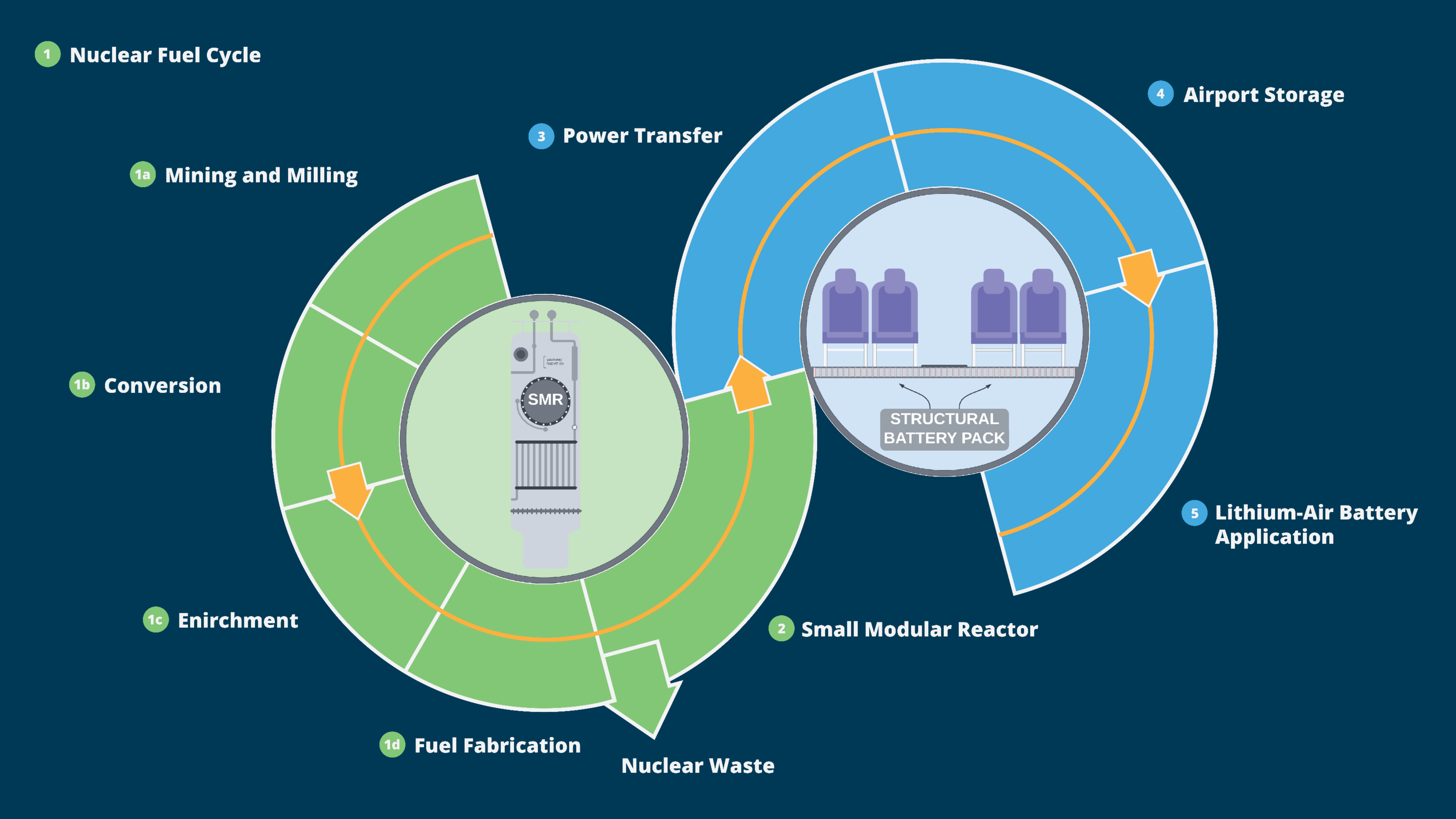
Power Transfer and Stationary Storage

- 5% projected energy loss across electricity distribution based on U.S. average
- Stationary storage at airport is incorporated for flexibility in supply and demand
  - Conventional lithium-ion batteries were modelled due to lessened constraints on energy density



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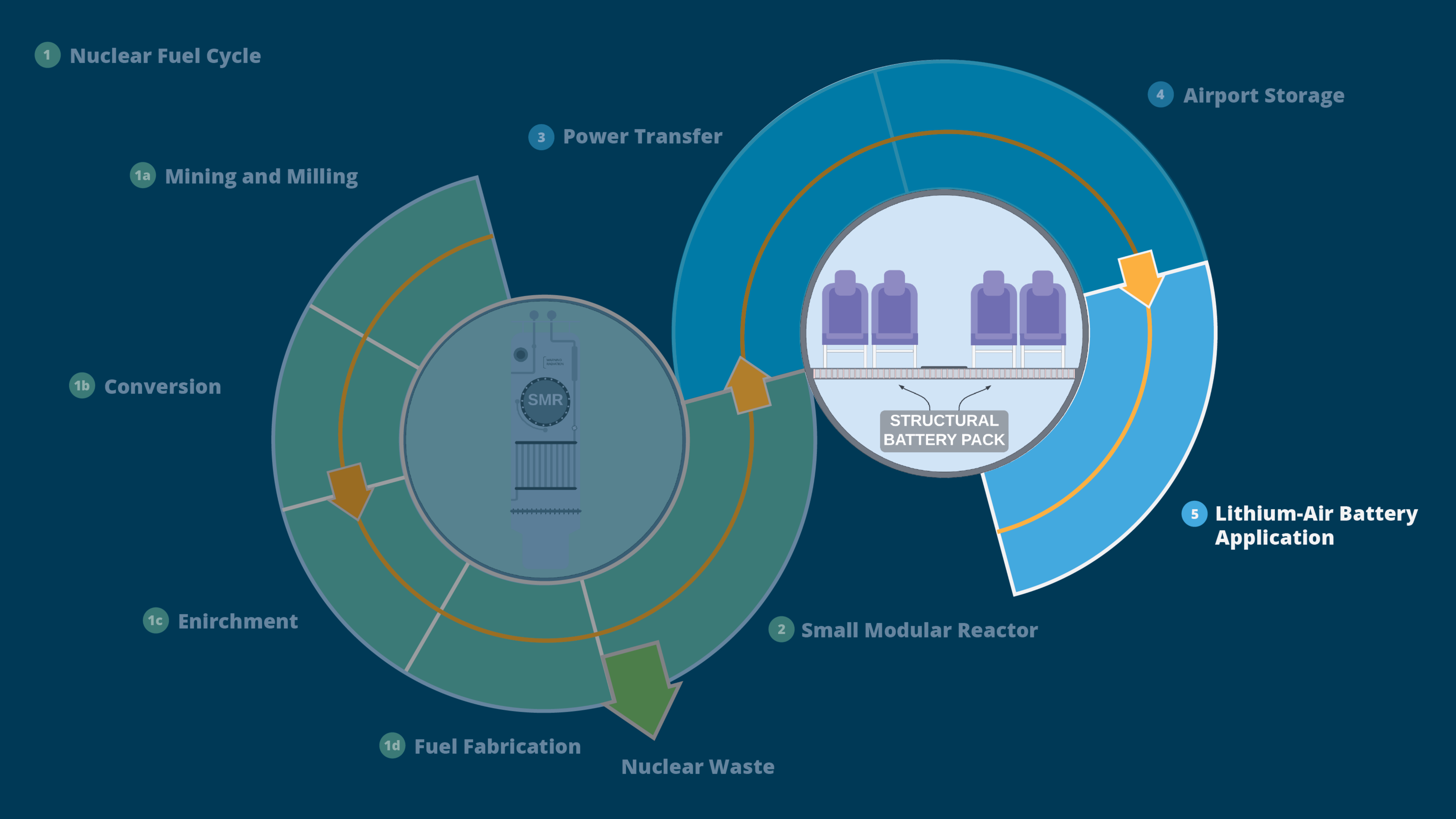

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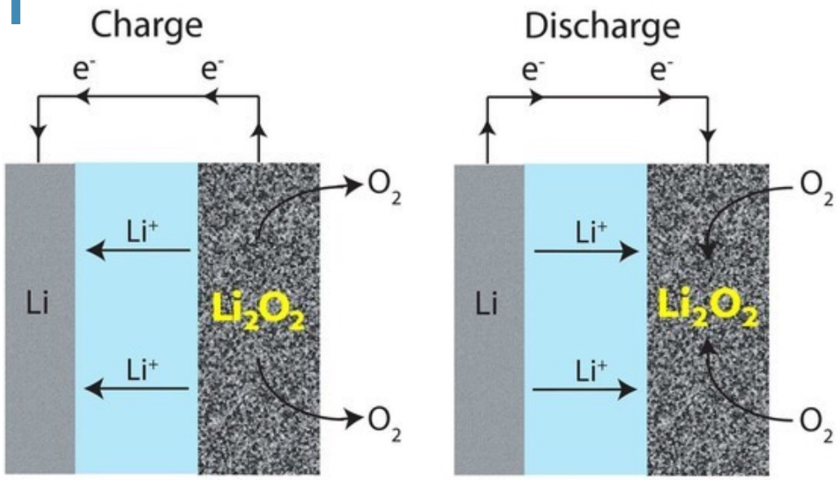
What is Lithium Air

- High theoretical energy density
- Sustainable energy storage
- High efficiency in energy transfer



Attribution: Wikipedia user Na9234

NONAQUEOUS LITHIUM AIR

- Electrolytes have a wider electrochemical stability window
- Higher energy density computed in comparison to Solid State and Aqueous type
- Necessity of pure oxygen

During discharge, Lithium ions are oxidized at the anode

↓

Releases electrons and creating Lithium cations

↓

These cations then travel through the electrolyte and react with oxygen

↓

Forms Lithium peroxide and generates electrical energy

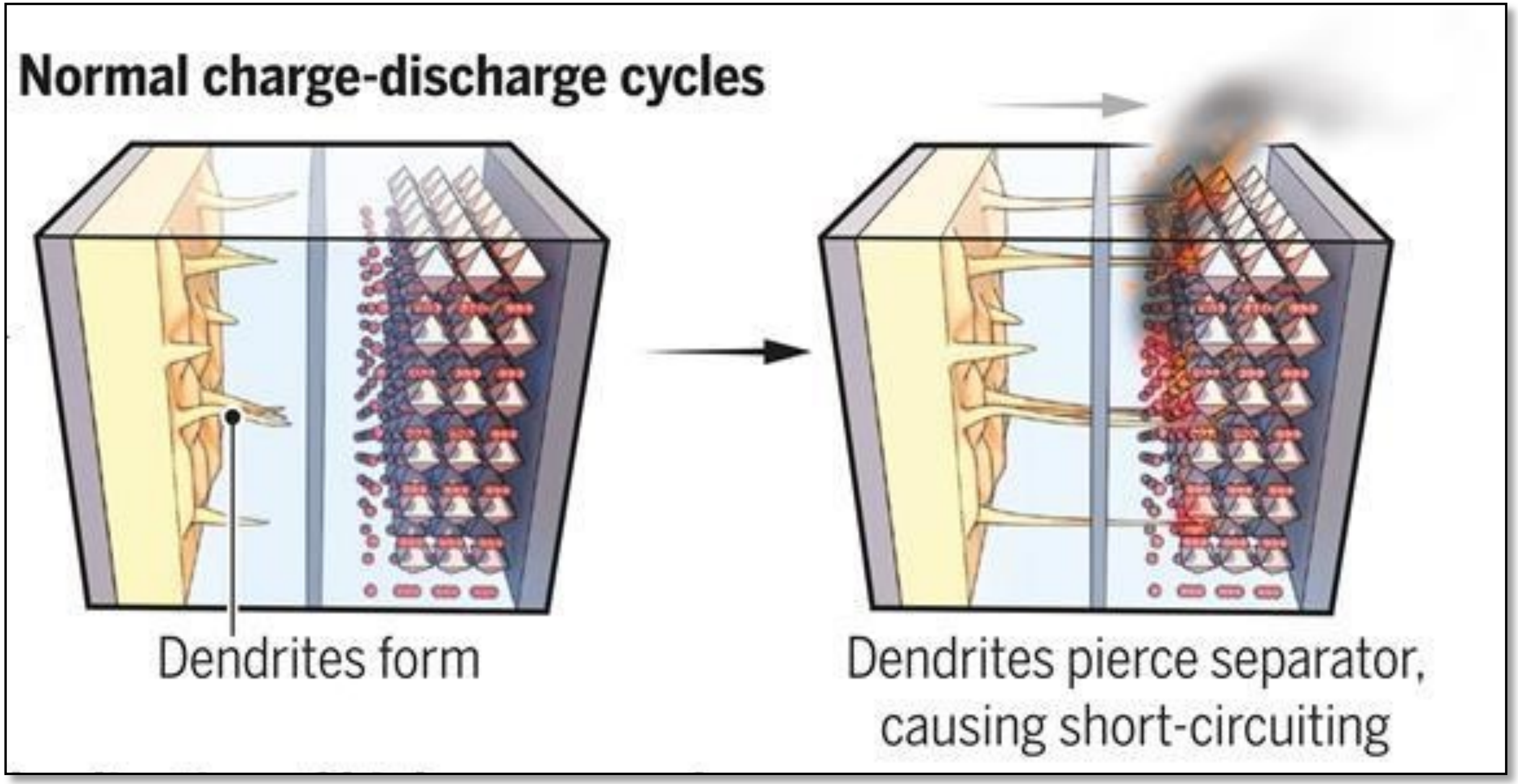
Lithium-Air: Current State

- A proven concept, with many labs confirming theoretical energy densities and creating prototypes
  - NIMS and Softbank Corp
  - Illinois Institute of Technology (IIT) and U.S. Department of Energy's Argonne National Laboratory
- Requires further research and development
  - Expand the number of rechargeable cycles
  - Decrease safety risks
  - Improve supply chain readiness

Lithium-Air: Safety

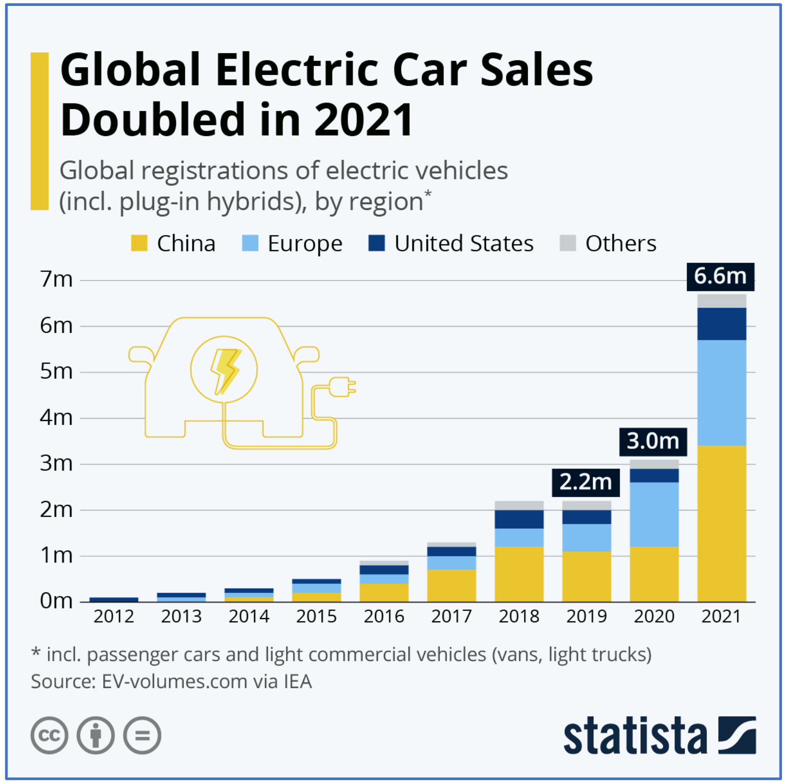
- Oxygen Tank Usage
- Calibration & Management
- Electrical Safety

Lithium-Air: Safety



Lithium-Air: Political, Social, Economic Impacts

- Environmental benefits and potential of a growing market
- Electrical cheaper than Jet-A
- Education, transparency, and detailed safety measures
  - Ensure good relations with the public
- Structural integration of the batteries into the floor of an airplane



*Rapid market growth of electric automobiles

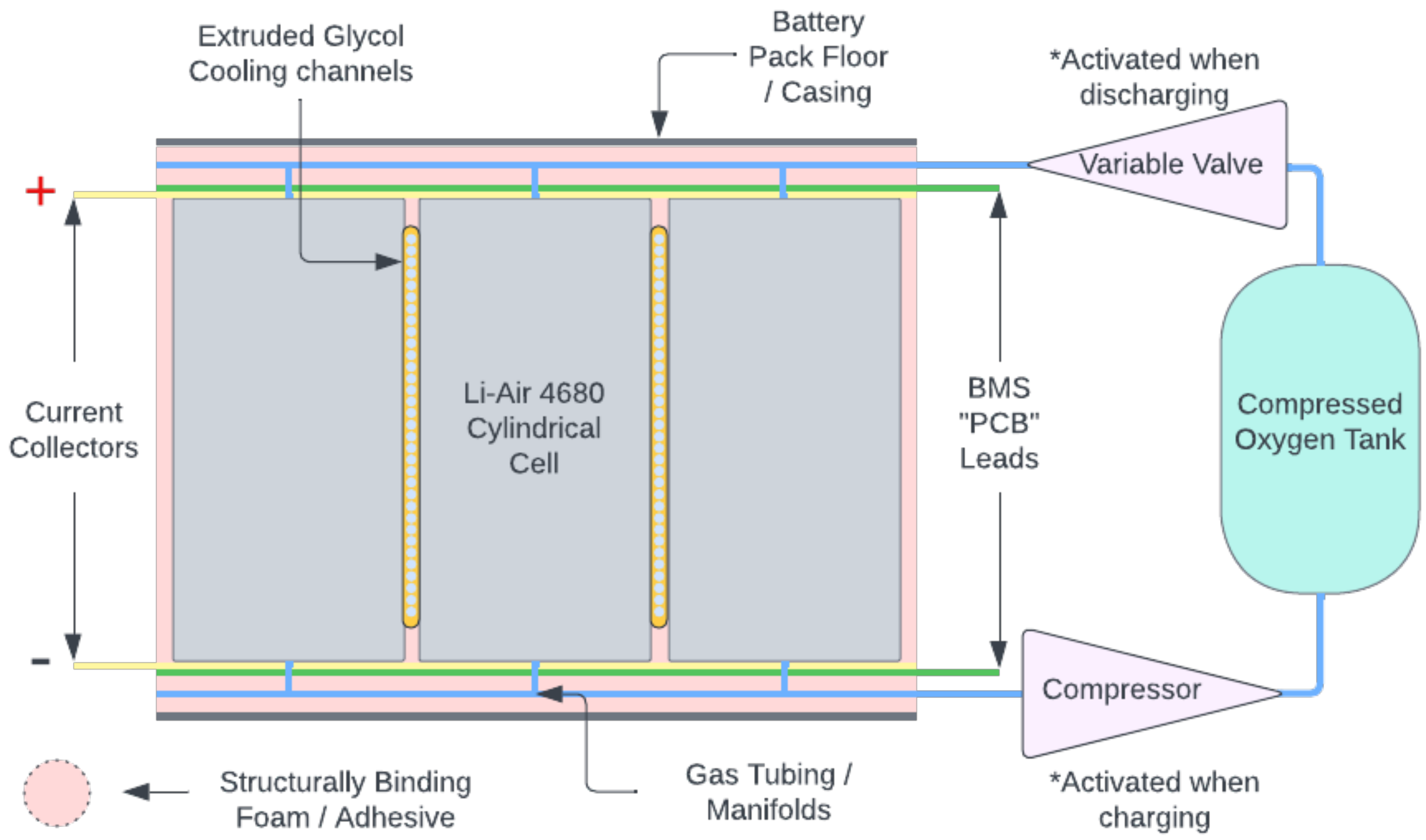
Courtesy of Tesla, Inc.

Lithium-Air: Structural Pack

- Integrated battery management system
- Fire retardant foam material
- Structurally sound

4680 Cylindrical Batteries

- Tabless design
- Greater thermal management
- Less resistance
- Reduce the number of cells needed
- Increased density
- Ease of manufacturing



Aircraft Feasibility

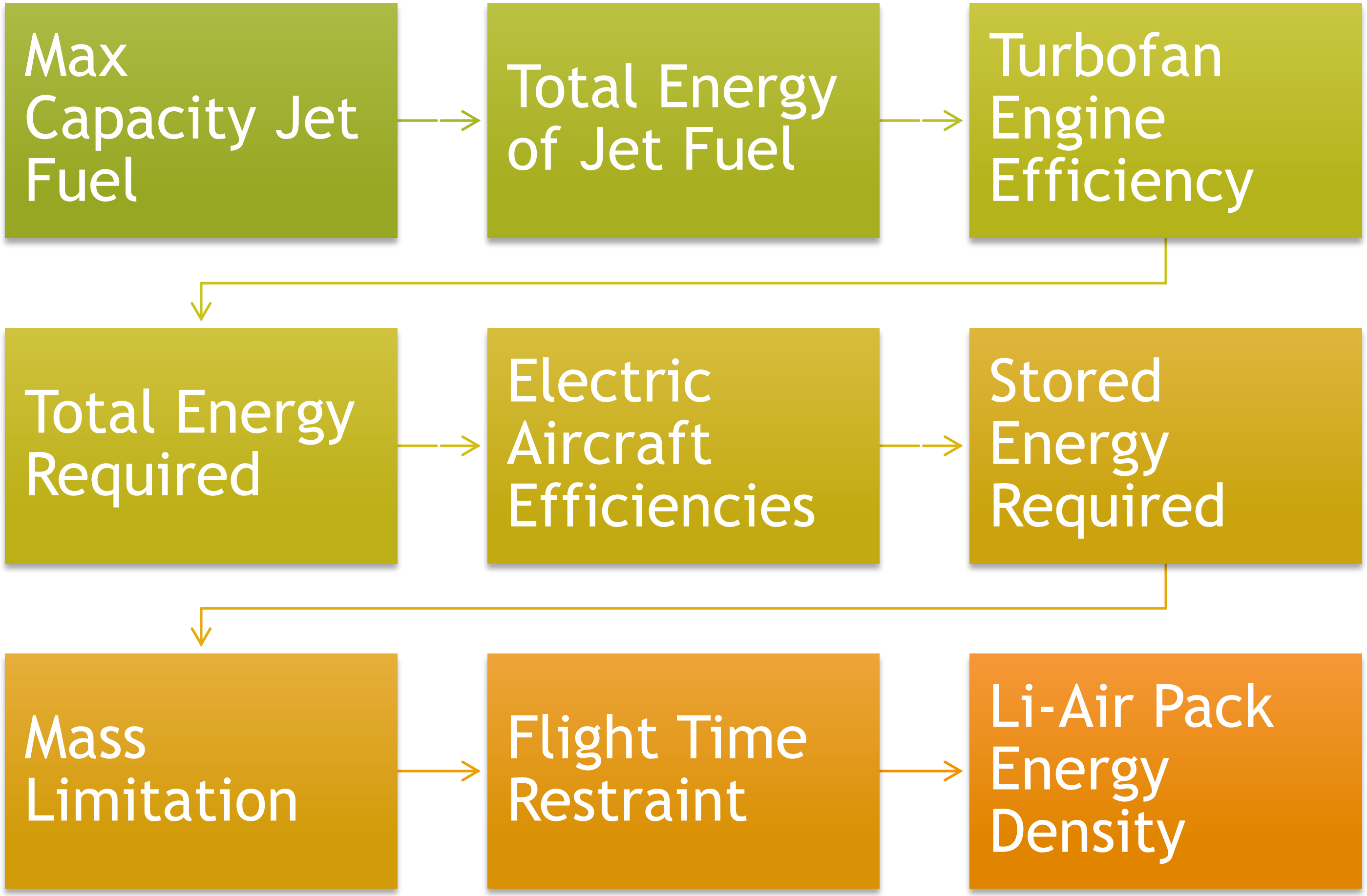
Aircraft Feasibility: Overview

- Target Aircraft
  - Boeing 737-700
- Compare Li-Air to Jet-A
  - Estimating Electric Capabilities from B737-700 Capabilities
- Prove plausibility
  - Compare Li-Air Performance

Aircraft Feasibility: Boeing 737-700

- Standard Regional Passenger Plane
- Max 149 Passengers
- Total Takeoff Weight of 56,240 kg
- CFM International Turbofan engines
- 0.785 Mach Cruise Speed
- Carries 26,020 L Jet-A (~21,000 kg)
- First flight in 1997

Lithium-Air Methodology



Aircraft Feasibility: Lithium-Air Estimates

	Li-Air Cylindrical Cell Density	Theoretical 4680 Structural Pack Density	Theoretical Usable Energy Storage	Aircraft Range (Cruising Speed)	Flight Time
Low Estimate	2210 Wh/kg	1536 Wh/kg	23.46 mWh	762 km	0.92 hours
Theoretical Estimate	5200 Wh/kg	3614 Wh/kg	55.20 mWh	1,788 km	2.16 hours
Required Estimate	4805 Wh/kg	3340 Wh/kg	51.01 mWh	1,656 km	2 hours

Aircraft Feasibility: Comparison to Jet-A

	Energy Density	Max Energy Capacity	Effective Energy Efficiency	Estimated Energy Usage	Max Flight Time (MTOW)
Li-Air	3,340 Wh/kg	51.01 mWh	64.5%	25.5 mW	2 hours
Jet-A	12,000 Wh/kg	248.8 mWh	50%	32 mW	7.5 hours
Li-Ion	270 Wh/kg	4.12 mWh	68%	24.2 mW	0.17 hours

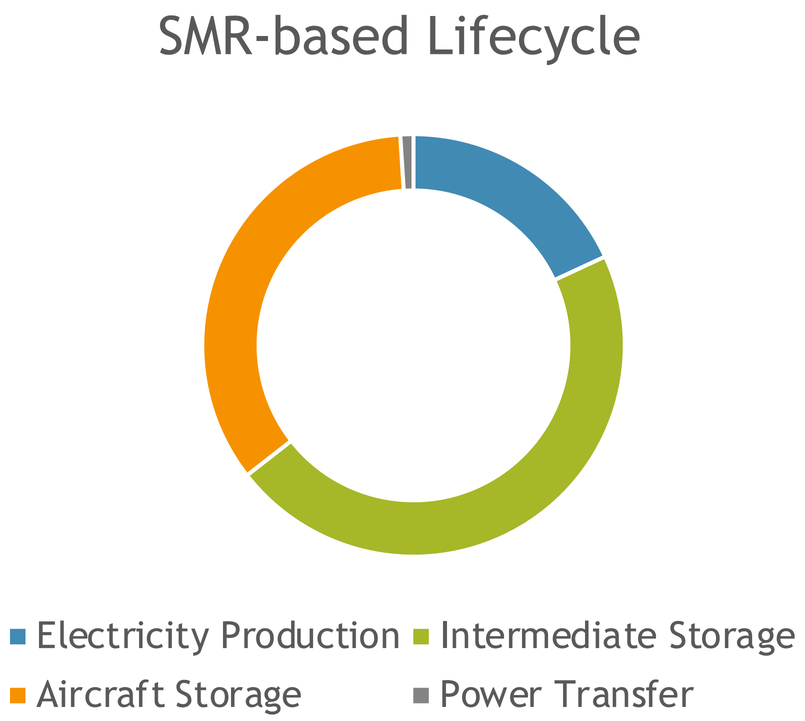
Impact and Readiness

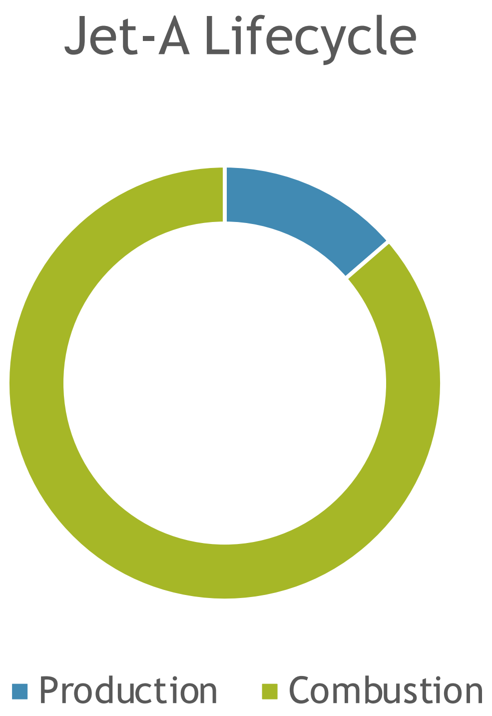
Climate Impacts: Comparison to Jet-A

- Life cycle assessments (LCAs) were analyzed in order to estimate climate impacts, with a functional unit of 1 kWh of energy delivered to the aircraft

Electricity Production	Power Transfer	Intermediate Storage	Aircraft Storage
LCAs on NuScale and Westinghouse modules	Efficiency loss based on US average	LCA on li-ion stationary storage	LCA on li-air battery system for electric vehicles
- Uranium fuel cycle - SMR construction, operation, and decommissioning	- Increased generation of electricity	- Material Production - Battery Production	- Material Production - Battery Production

Climate Impacts: Comparison to Jet-A





Climate Impacts: Comparison to Jet-A

SMR powered electric aircraft compared to convential jet fuel (g CO2 eq/kWh energy delivered)

Technology Readiness Levels

Component	Current TRL	Predicted 2050 TRL	Supply Chain Readiness 2050 TRL
Li-air Battery Chemistry	3	8 / 9	5
Small Modular Reactor - iPWR	7	9	7
Small Modular Reactor - iMSR	4	7	5
Stationary Lithium Storage	9	9	9
Battery Management System	7	9	8
4680 Cylindrical Battery Cells	7	9	9
Electric Passenger Airplane	4	9	5

Key Points

Flexible

- Small modular reactors provide flexibility in deployment

Energy-dense

- High-density lithium-air batteries show feasibility of design

Low-carbon

- Proposed lifecycle delivers greatly-reduced overall climate impact over conventional fuel

GATEWAYS TO BLUESKIES

Thank you!

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