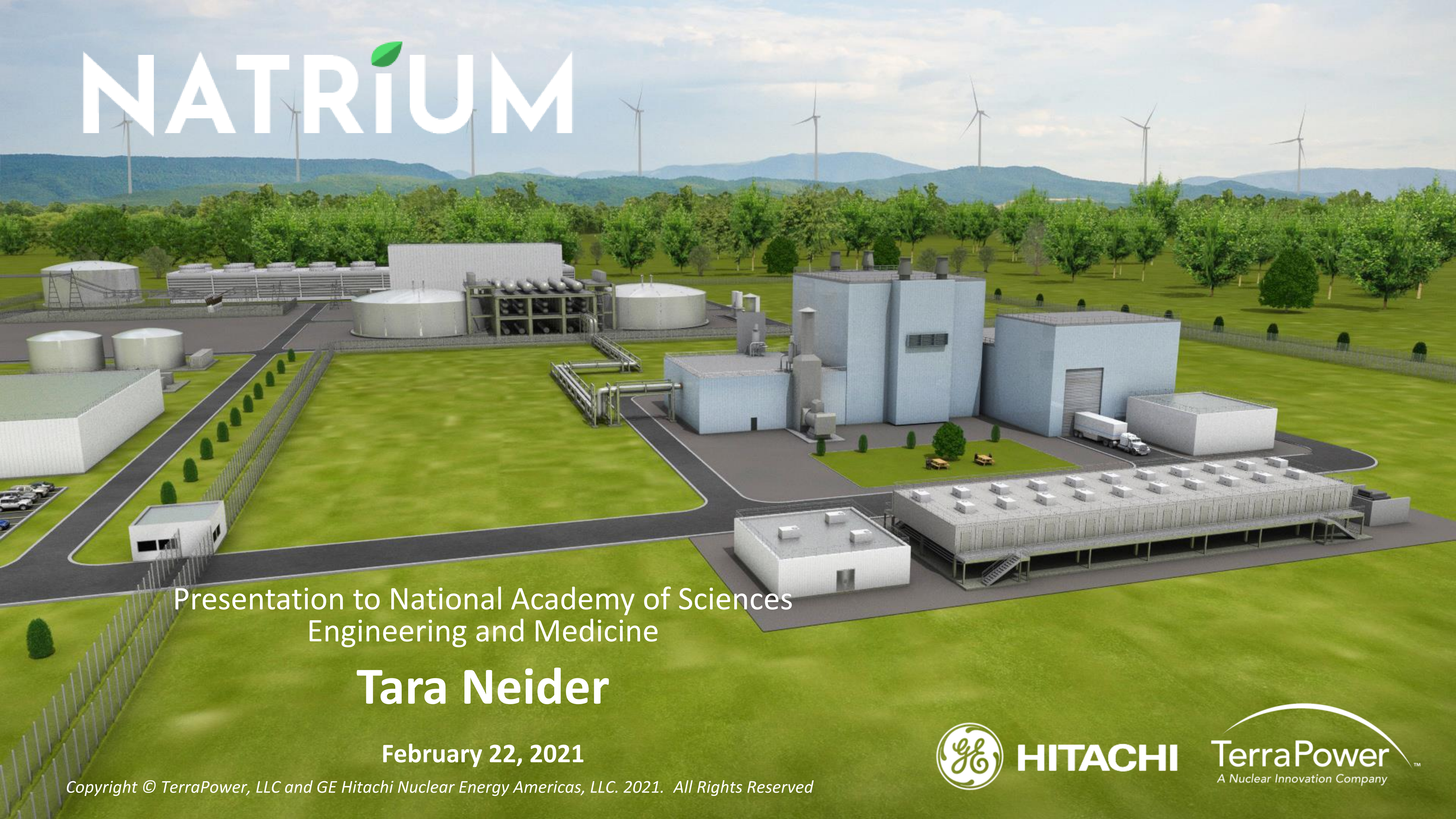


NATRIUM

Presentation to National Academy of Sciences Engineering and Medicine

Tara Neider

February 22, 2021

GE HITACHI

TerraPower™
A Nuclear Innovation Company

Natrium Roadmap – Ready for Demonstration

Mature commercial plant design

- Further establish compelling commercial case
- Focus on cost and economics
- Refine technology development needs

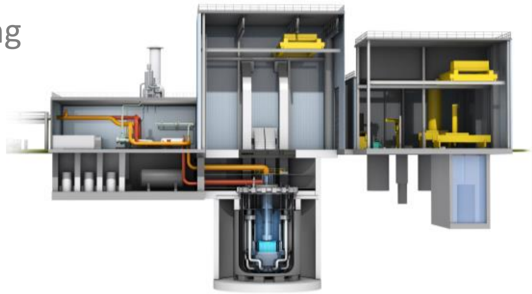
Develop IES technology & revenue modeling

U.S. NRC engagement

U.S. legacy SFR experience, PRISM and TWR development

1980s-2019

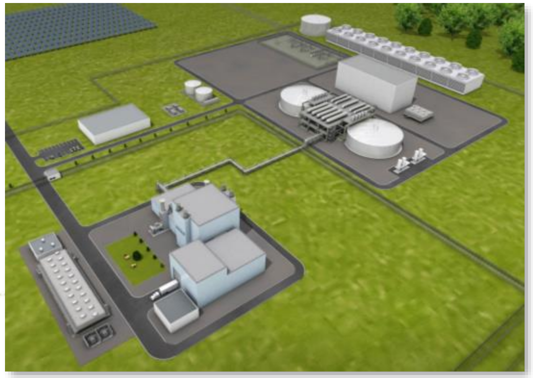
Pre-Demo Phase



Natrium Demonstration Plant (345 MWe → 500 MWe)

Commercial Plant Economics
+Energy Storage & Peaking Capability

2020-2027



Natrium Commercial Series I (345 MWe → 500 MWe)

3 yr. Construction
+Energy Storage & Peaking Capability

2027-2030s

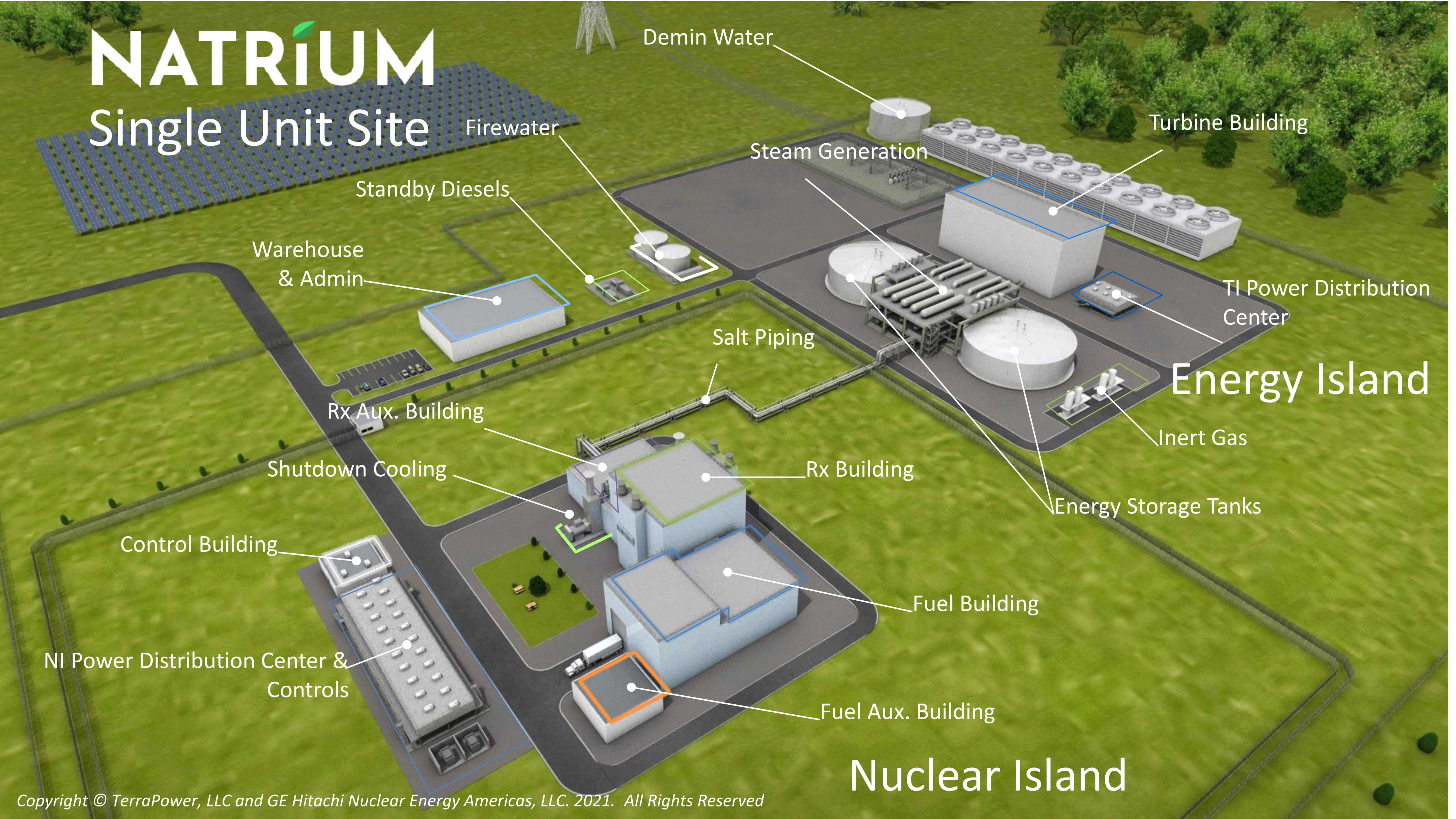
Commercial Series II+ (Up to GWe scale)

Commercial Series I Benefits
+DU Breed-and-Burn
+Potential UNF Recycling
+Potential Pu Disposition
+Zero-Carbon Process Heat

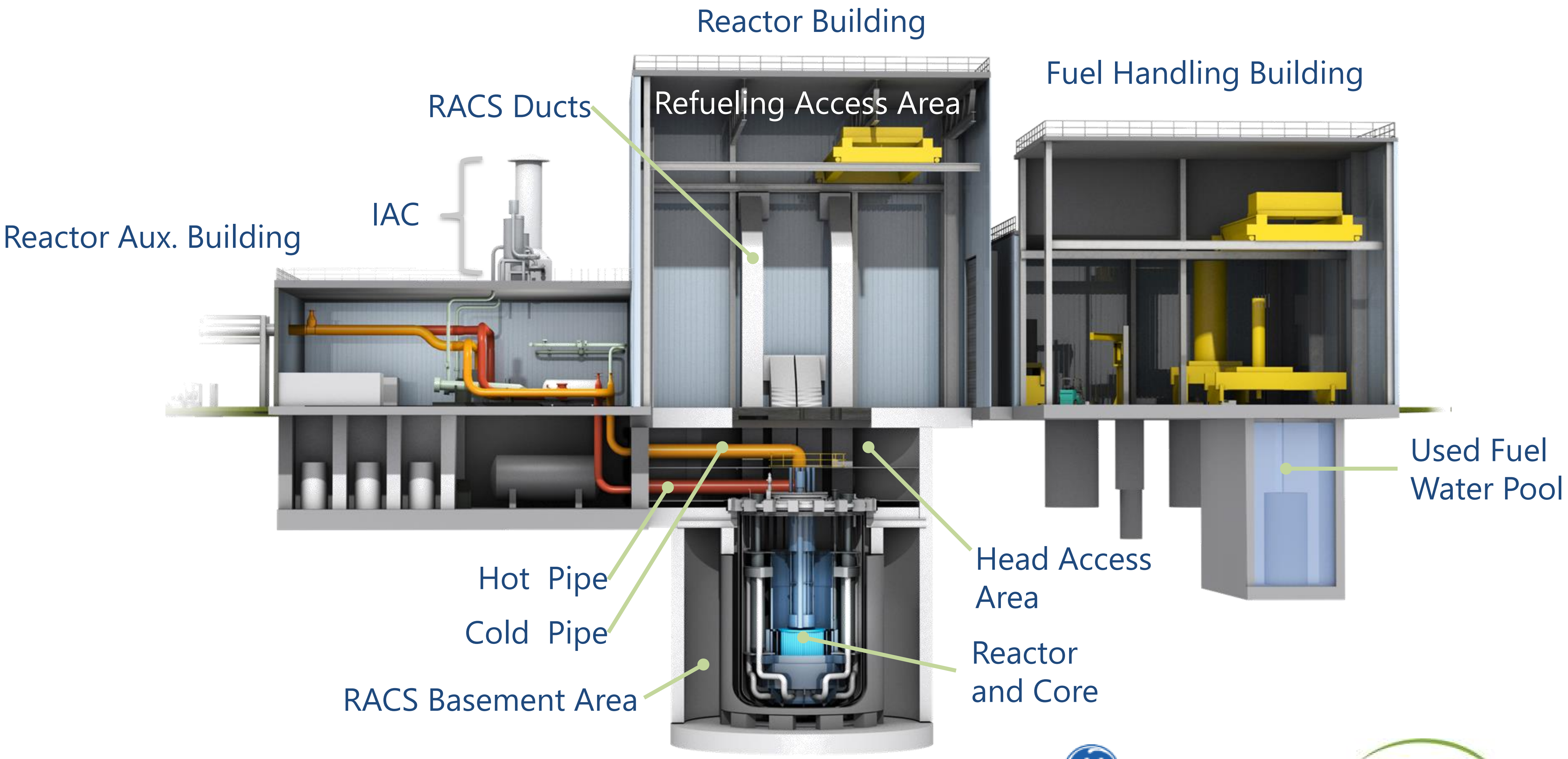
~2040s

What is Natrium™ Technology?

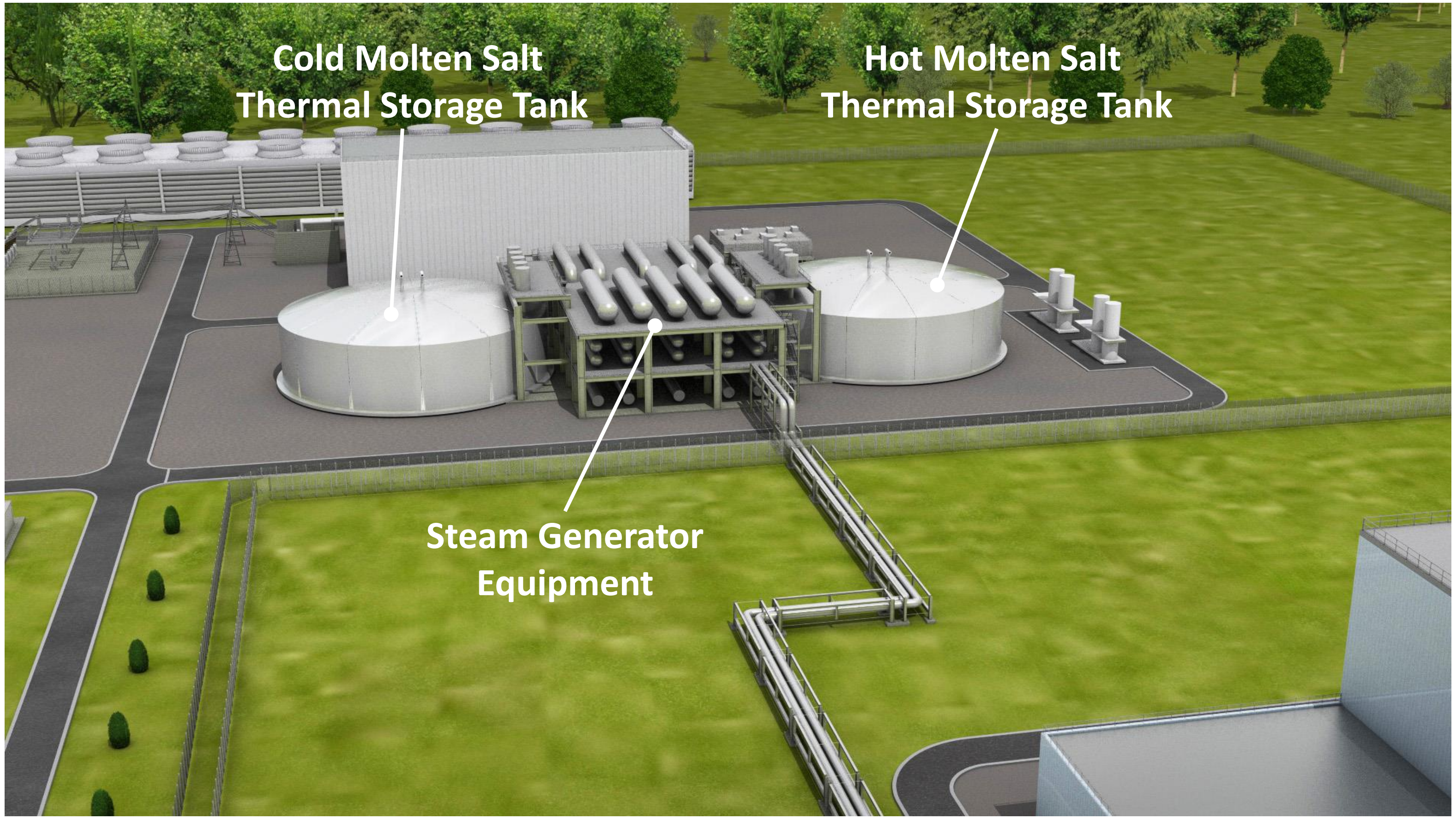
- A high readiness Sodium-cooled Fast Reactor (SFR) with the following benefits:
  - A ***new plant architecture*** that minimizes cost and construction time
  - ***Simpler, less costly safety systems*** compared to current generation reactors
  - Grid-scale ***energy storage*** to complement renewables
  - ***Fuel cycle flexibility*** that facilitates global export
  - ***Utility-scale decarbonization***


NATRIUM
Single Unit Site
Demin Water
Firewater
Turbine Building
Steam Generation
Standby Diesels
Warehouse & Admin
TI Power Distribution Center
Salt Piping
Energy Island
Rx Aux. Building
Inert Gas
Shutdown Cooling
Rx Building
Energy Storage Tanks
Control Building
Fuel Building
NI Power Distribution Center & Controls
Fuel Aux. Building
Nuclear Island

Reactor Building



Thermal Storage



Thermal Storage

- Number of tanks based on customer's energy need
- Steam generator trains based on size of turbines
- Turbine size based on customer's power need

Sodium Coolant and Molten Salt Properties

- 390-540°C Reactor Coolant Operating temperature
- 880°C Boiling Temperature
- 98°C Melting Temperature
- Sodium inventory -800 m^3 in reactor
- Operates at atmospheric pressure
- Molten Salt used for heat storage is the same as used for solar plants
- Temperature range 238°C – 621°C salt; 60 $NaNO_3$- 40 KNO_3

What is Different

Inherent Safety

Simple Nuclear Systems
- No sprawling nuclear piping and support equipment
- Exceptional heat transfer
- Passive air cooling
- Low pressure

Dramatic O&M Cost Reduction
- Less equipment to maintain
- Natrium Service Group

Architectural Innovations

Decoupled
- Bulk of plant constructed & operated without nuclear practices

Simple Nuclear Buildings
- 20 vs. 105 $\frac{m^3}{MWe}$ nuclear concrete

Simple Nuclear Construction
- Steel sided buildings
- Below ground reactor
- Minimal engineered backfill

Efficient Construction Layout
- High degree of parallel work

Staffing
- 65 – 125 staff

Flexible
- 8%/min ramp rate

Adjacent Industries

Concentrated Solar Power
- Energy storage in molten salt
- Steam generator & salt pump technology

Argonne Integral Fast Reactor
- 30 years of EBR-II operation
- Proven inherent characteristics

Tunneling
- Vertical cut excavation

Combined Cycle Gas Turbine
- Construction approaches
- Aggressive staffing
- Fast burst power ramping

Safety

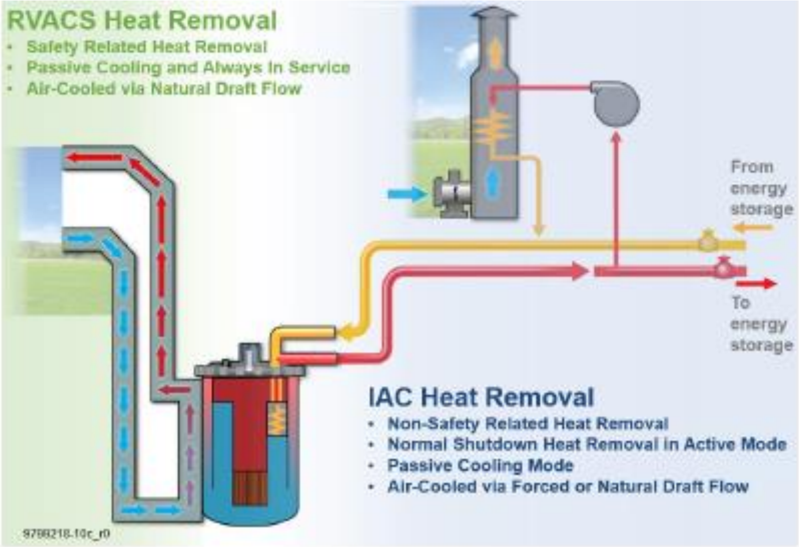
- Low-pressure pool reactor with no piping or fittings below the surface of the pool
- Guard vessel prevents loss of coolant if reactor vessel were to leak
- Fuel material compatible with coolant. Minor fuel cladding breaches are benign where the fuel material is not chemically reactive with the coolant.
- Sodium absorbs many of the released fission products, especially iodine and cesium. Sodium's affinity for fission products also limits the inventory that reaches the cover gas.
- Reactor cover gas operates at essentially atmospheric pressure so there is little to no driving force for a release.
- Intermediate coolant, by static head alone, is at a slightly higher pressure than the primary coolant.
- The only systems connected to the primary coolant boundary, cover gas and sodium cleanup, are automatically isolated by passive fail close valves.

Reactivity Control

- Non-safety related reactor control system acts as a buffer to prevent the need for a scram. It detects abnormal operation and initiates a runback via motor driven insertion of neutron absorbing control rods to achieve a softer shutdown than a scram.
- Safety related reactor protection system exists to initiate a scram should the reactor control system fail or a properly initiated runback fails to prevent the reactor from reaching a scram setpoint. The high reliability scram function is initiated by removing electrical power to an electromagnet, resulting in passive gravity insertion of all control and standby rods into the core.
- The core is designed with a negative temperature and power coefficient that is strong enough such that the reactor can accommodate anticipated transients without scram for events such as a loss of primary flow, loss of heat sink and uncontrolled rod withdrawal. The natural feedbacks are self regulating and will always find a low power level at which the production and heat removal are in balance.

Cooling

- 3 Defense in Depth Features
  - Reactor Air Cooling (Inherent) designed to remove all decay heat (SR)
  - Intermediate Air Cooling Heat Removal
    - Non-Safety Related Heat Removal
    - Normal Shutdown Heat Removal in Active Mode
    - Passive Cooling Mode
    - Air-Cooled via Forced or Natural Draft Flow



Challenging Licensing Issues for Commercialization

- Review Time is biggest issue; We are confident in our design and licensing strategy but guidance on non-LWR licensing is incomplete; Positions being developed now and requirements could change.
- PRISM Pre-licensing Safety Evaluation used as basis for Natrium development; outstanding issues addressed

HITACHI TerraPower

Technical Challenges for Commercialization

- HALEU Supply
- Development of Supply Chain for critical components
- Our Development program includes significant testing and qualification, particularly in areas of low TRL.
- Ready for demonstration with improvements to lower commercial costs.

Natrium Team Committed to 7-year Time Frame

PSAR/CPA in 30 months (Phased Approach)

FSAR/OLA by 54 months

First Safety Concrete 48 months

Construction Complete 78 months

Fuel Cycle and Waste Management

Pavel Hejzlar

ADVANCED FUEL CYCLE

- Natrium™ fuel and advancements over established technology
- Towards long-term potential on the path to supply flexibility and sustainability
- HM flow once-through Natrium cycle
- Differences for initial operation of Natrium DEMO
- Fuel Development Program
- Special transportation considerations

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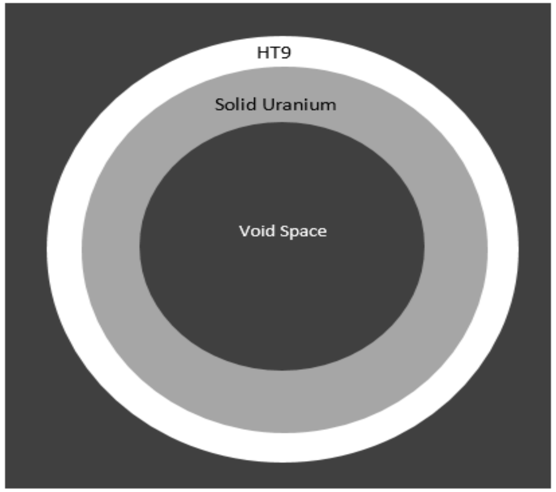
Natrium Fuel

- Advancements over traditional U-Zr fuel with sodium bond

  - Uranium metal annular fuel with helium filled central pore
  - Sodium bond eliminated
  - Fuel-Cladding Chemical Interaction (FCCI) barrier
  - Advanced ferritic-martensitic steel cladding with reduced void swelling
  - Ability to achieve average burnups of up to 200 MWd/kg



As fabricated (schematic)

Irradiated

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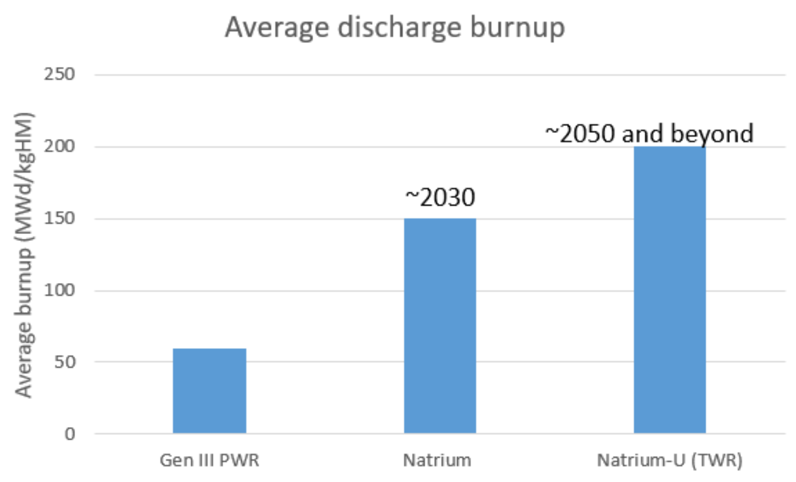
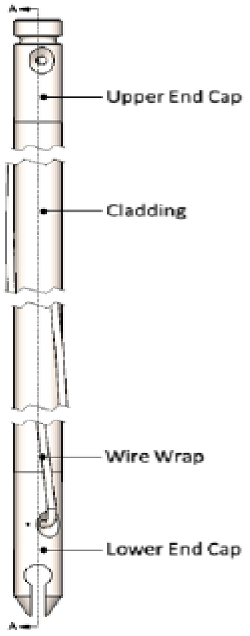
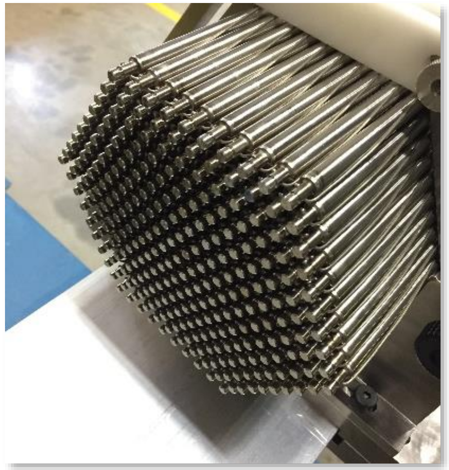
Natrium Fuel (Con't)

- Advancements in burnup will be in discrete stages to minimize risk
  - Natrium DEMO with advanced fuel will operate with 16.5% enriched U reloads to 150MWd/kg
  - Additional planned fuel advances will lower reload enrichment below 10% and increase fuel burnup in later Natrium units (~2050)
  - Increasing fuel burnup capability to 200 MWd/kg enables Natrium Ultimate (Natrium-U) operation with natural or depleted uranium reloads (full breed and burn mode, also called TWR) – beyond 2050





Pins arranged in hexagonal assemblies surrounded by a duct



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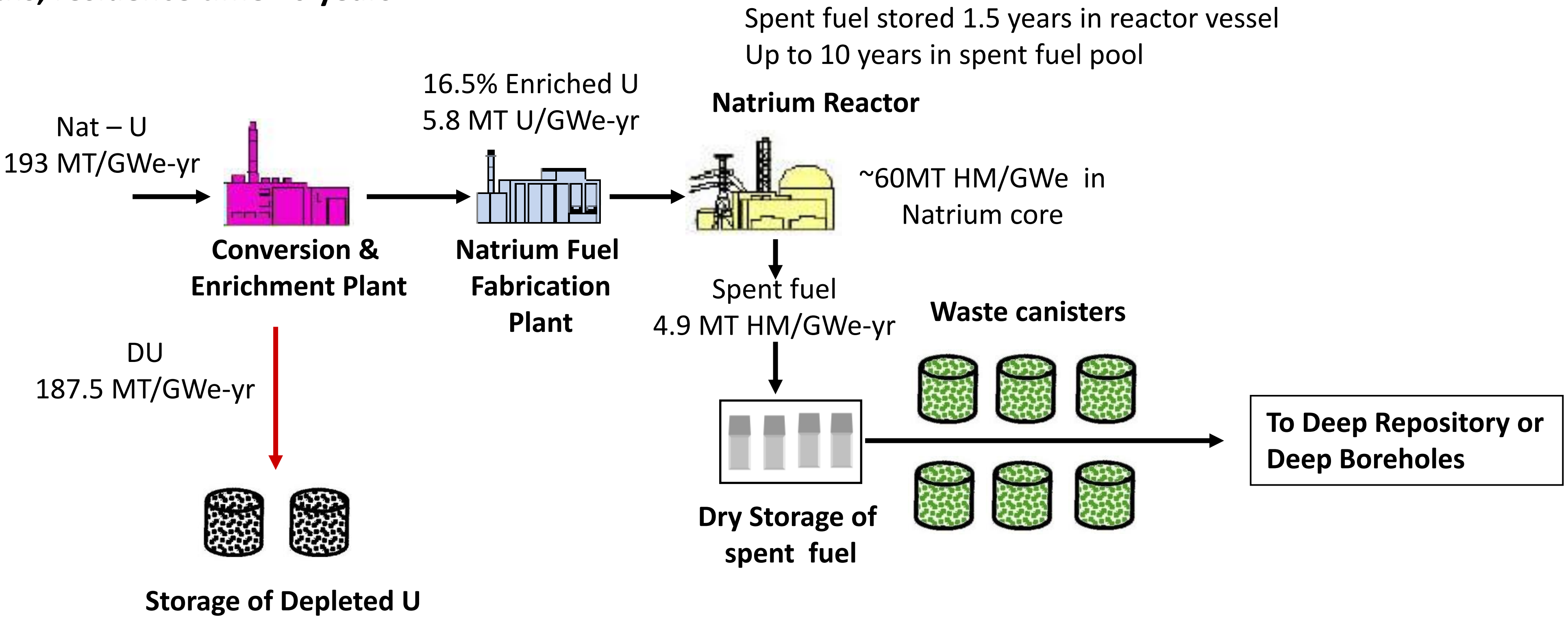
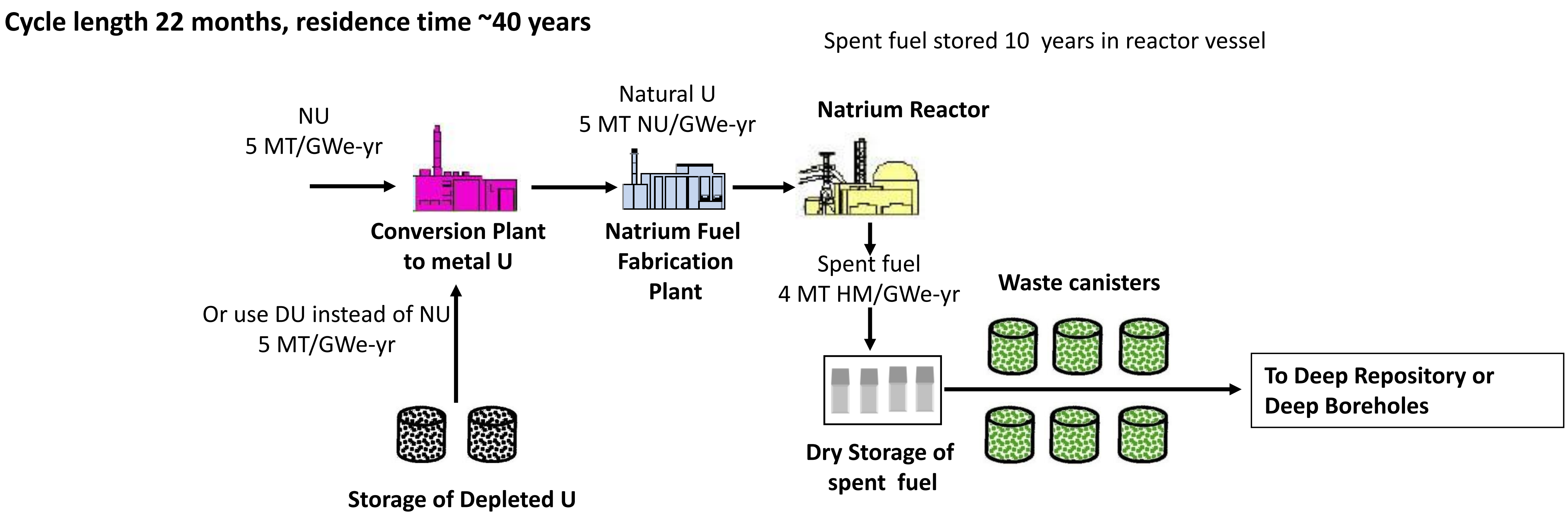
Natrium Fuel Cycle with Advanced Fuel

Cycle length 18 months, residence time 10 years



- Simple once-through cycle, no reprocessing

Natrium-U Fuel Cycle with Advanced Fuel



- No need for enrichment for reloads
- Can use depleted uranium waste as feed

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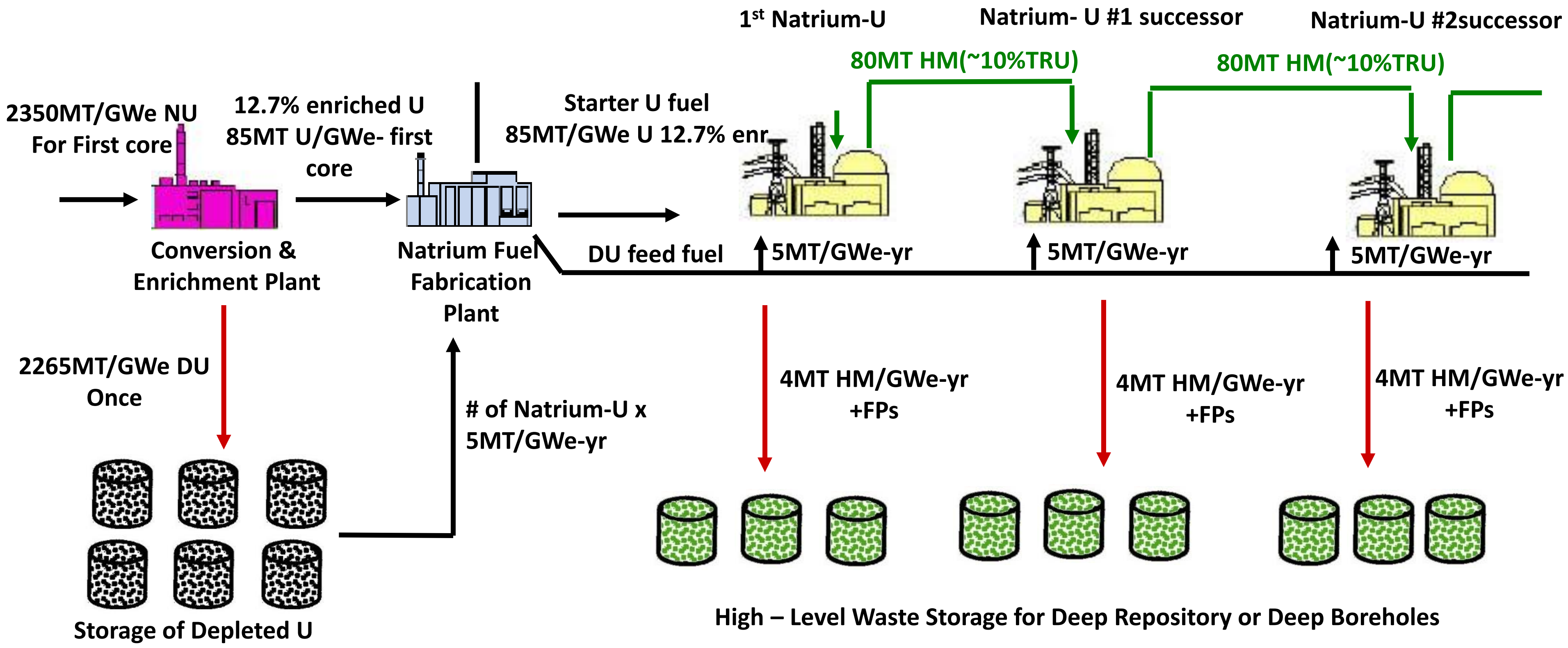
Natrium-U Fuel Cycle Using Successor

- First set of Natrium-U reactors in the fleet Natrium-U uses enriched fuel for initial core loading and reloads are DU or NU
- Subsequent Natrium-U Natrium-U reactors in the fleet can utilize end of life core from previous Natrium-U reactors for startup; with depleted or natural uranium reloads
- No recycling of Natrium-U spent fuel; core at end of plant life just transferred to new unit



Initial Operation for Natrium DEMO

- Initial Natrium DEMO core and first several cycles will use established U-Zr sodium bonded fuel to enable earlier start at reduced technical risk
- Irradiation program with ATR/BOR-60 set the foundations for LTA program of advanced fuel
- Advanced fuel will be fully qualified in Lead Test Assemblies during initial operation of Natrium DEMO
- Added design margin used for DEMO fuel to ensure FSAR can support LTA program
- Hence, lower burnup due to FCCI limit and larger heavy metal reload throughout
  - 13.7 MTU/GWe-yr (18.5% average enrichment)
  - Cycle length 12 months
  - Advanced fuel allows 2.5 times reduction of fuel use and thus lower fuel cost
- Initial operation on U-Zr fuel will take ~ 6-8 years, then transition to advanced high burnup fuel

Note: If advanced fuel could be qualified in time in JOYO or VTR, Natrium DEMO could start on advanced fuel

Fuel Development Program in Support of Natrium

Legacy Data Collection	Compilation and analysis of archived DOE test data
Commercial Fabrication Process	Commercial scale fuel and material production
FCCI Barrier Development	Fabrication and testing
ATR Fuel Tests	Metal fuel irradiation
Transient Behavior	Transient performance of HT-9 clad fuel pins (TREAT)
HT9 Optimization and Testing	Ion Irradiation and BOR-60 Materials Testing

TerraPower has been doing testing, production development and irradiation for a long time (since 2009)

Exceptional Natrium Fuel Cycle Flexibility

- Natrium commercial fuels allow for a game changing, economically attractive, once-through fuel cycle (currently preferred option)
  - Simple cycle
  - Still allowing good sustainability
  - No need to develop two technologies at the same time (reprocessing and reactor)
  - Avoids reprocessing costs and proliferation concerns associated with closed cycles
  - Avoids short-term releases from reprocessing losses and leaks
- Natrium can support a closed fuel cycle if desired
  - High burnup capability allows less frequent reprocessing and less losses than reactors with lower fuel burnups

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Special Considerations Related to Transportation

- The extreme simplicity and high burnup fuel of once-through cycle minimizes the number and type of shipments
  - Especially on back end, there is only one shipment of high dose fuel versus several for reprocessing based systems
- Fresh fuel transportation casks have to be licensed for HALEU with higher fissile content and different assembly shape/size
- Will use dry storage and transportation casks for spent fuel as LWRs, but
  - License needs to be revised to account for different assembly shape, heat load and fissile content

RESOURCE UTILIZATION

Uranium utilization and path towards sustainability on planetary scale

Path to Excellent Uranium Utilization Without Need for Reprocessing

- Factors for high uranium utilization
  - High burnup for advanced fuel
  - 9 percent point higher net electrical efficiency
  - **Future Natrium-U plants can run on natural or depleted uranium with up to 30 times higher resource utilization**
    - Only the first plant requires an enriched initial core loading
    - Successor plants use last cores from predecessor plants for initial core

Comparative Table versus PWR

	Natrium	Natrium U	Gen III PWR
Burnup (MWd/kg)	150	200	60
Net plant efficiency	41%	41%	33%
Eq. fuel efficiency (MWhr-e/kg U)	1500	2900	484
Nat. uranium use (kg/MWhr-e)	**24**	**0.6**	**20**

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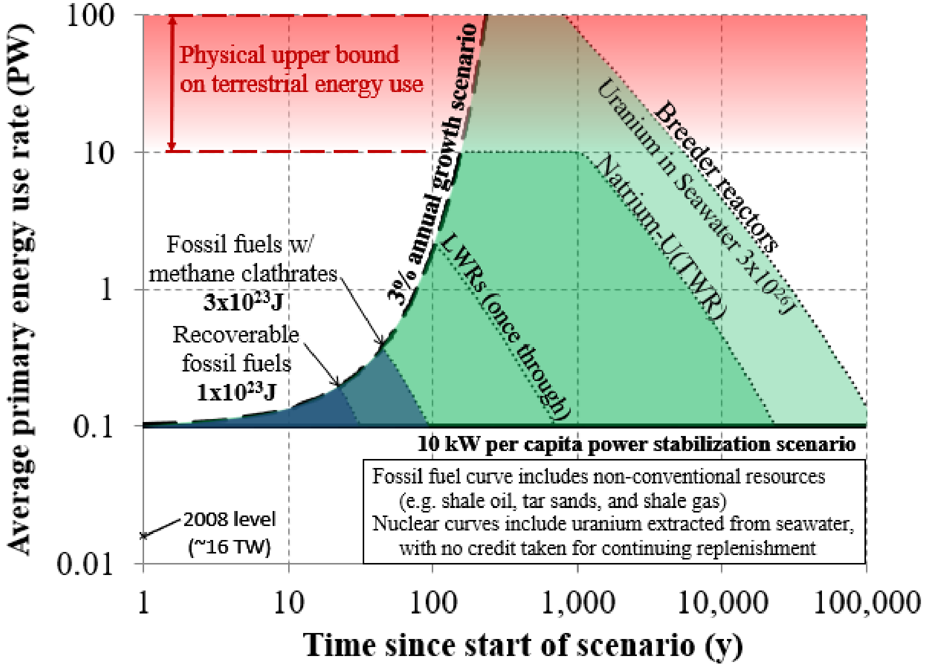
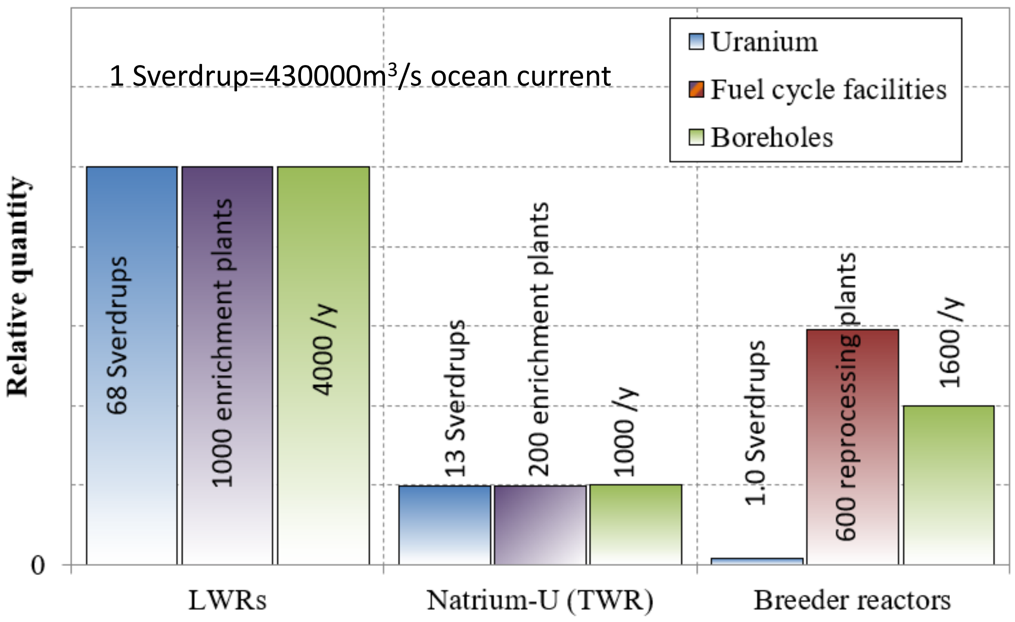
Can Natrium support long term sustainability on planetary scale?

- Scenarios assume support of 10B people with energy use as in US (~330GJ/y or ~10kW time average power), range between zero and 3% consumption growth
- 10PW considered as physical bound since it begins to approach total energy earth receives from the sun
- Fast spectrum reactors (both breeders with recycling and Natrium-U operating in B&B mode) can achieve this goal when uranium from seawater is used

Range of scenarios available with energy sources



Fuel cycle requirements in 3% growth scenario



Source: Petroski R. & Wood L., Sustainable, Full Scope Nuclear Fission Energy at Planetary Scale, Sustainability, 2012, 4, 3088-3123

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NUCLEAR WASTE MANAGEMENT AND DISPOSAL

- Key nuclides in spent Natrium fuel in various groups
- Decay heat differences from spent PWR fuel impacting disposal
- Disposition option for spent Natrium fuel
- Other waste streams

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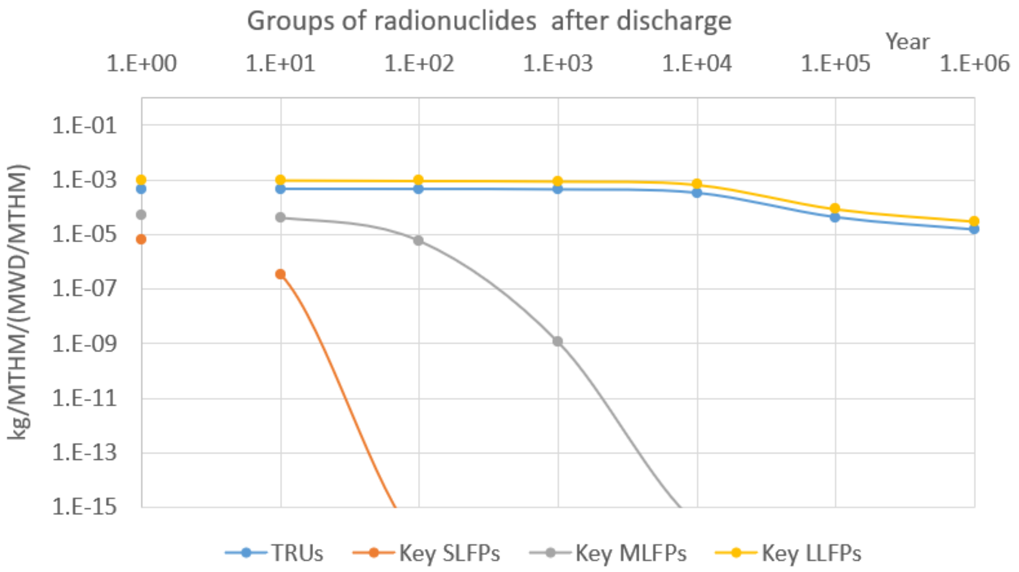
Spent Natrium Fuel

- SNF is in the form of metal fuel ferritic–martensitic steel cladded pins in a hexagonal assemblies
  - ~4.7m tall assembly with a duct ~16cm flat-to-flat
  - active fuel height is ~1.2m for Natrium and 2m for Natrium-U
- After washing assemblies from sodium, ~10 years storage in spent fuel pool, dry storage and transported in transport canisters to final disposition
- Mass of HM per GWE-yr shown in previous slides
- SNF isotopic composition as function of decay time, can be sent under NDA

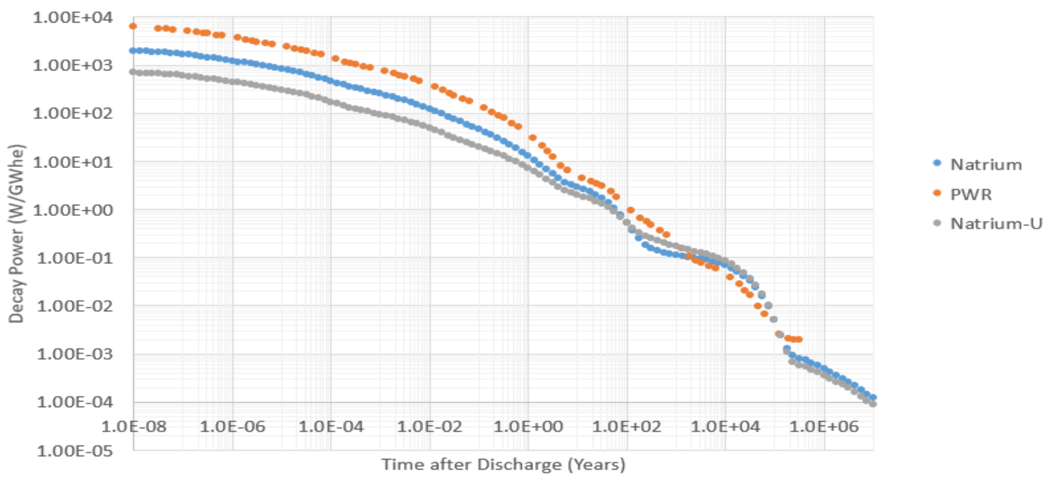
- Key transuranics: Pu239, Pu240, Np237, Pu238, Pu241, Am241, Pu242, Am243
- Key short-lived FPs: Pm147, Ce144, Ru106, Nb95, Zr95, Sr89, Rh106,I131
- Key Medium-lived FPs: Cs137, Sr90, Sm151, Eu155
- Key Long-lived FPs: Cs135, Tc99, Zr93, I129, Pd107, Sn126, Se79



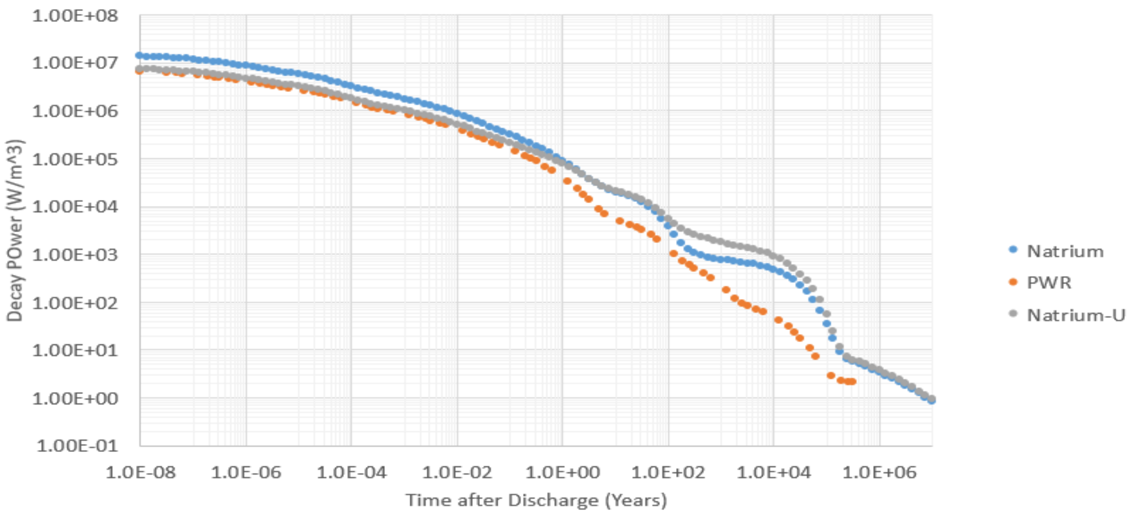
Decay heat differences from LWR spent fuel impacting disposal

- Decay heat per unit of electricity produced lower than PWR first ~2000 yrs but higher afterward due to higher content of TRU and LLFPs
  - Bump driven by decay of Pu239
- Natrium-U fuel produces more energy than Natrium fuel, hence lower decay heat per GWhe
- Natrium decay heat per active spent fuel volume is higher over whole decay time
  - Due to higher power density
  - Shorter fuel height
- Natrium-U has lower average power density than Natrium shorter fuel

Natrium vs PWR Decay Heat per GWhr-electric



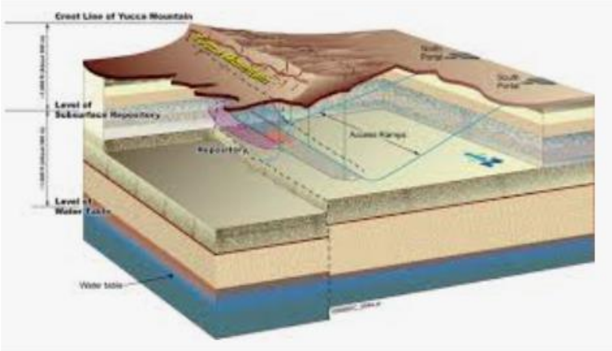
Natrium vs PWR Decay Heat per Active Spent Fuel Volume



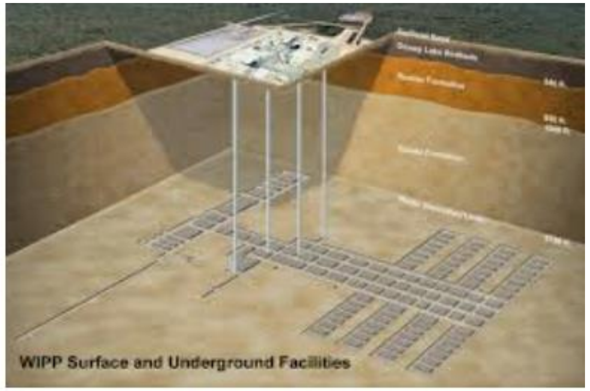
Disposal options for Natrium fuel in US

- Volcanic tuff type repository
  - Even though Natrium generates ~3 times less spent fuel volume than LWR, space in volcanic tuff repository is ~same as for LWR because these repositories are decay heat limited
- Salt bed type repository
  - Due to high conductivity of salt beds, temperature peak is lower and occurs earlier - Natrium fuel would require ~70% less space than LWR
- Deep borehole or horizontal drillhole
  - One assembly per canister
  - Natrium would require ~70% less boreholes than PWR spent fuel
  - If geology favorable, could potentially be drilled on plant site avoiding transportation
- Need for Natrium and all advanced reactors including LWRs in the US – permanent geological repository or deep borehole/horizontal drill holes
  - Encouraging to see successful progress on ONKALO Deep Geological Repository in bedrock in Finland (first full scale in-situ test completed and heading to integrated test, fuel placement expected this decade)

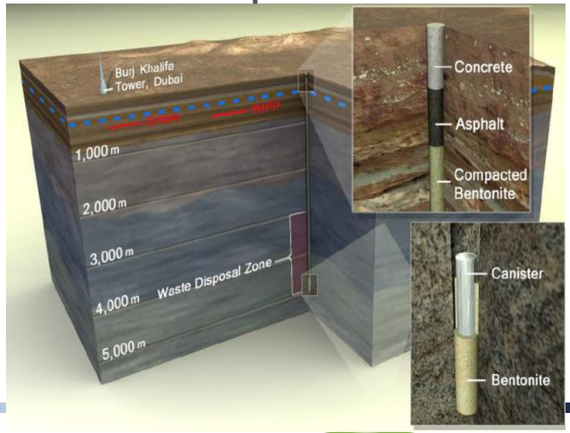
Volcanic tuff repository (e.g. Yucca Mt.)



Salt bed repository (e.g. WIPP in NM)



Deep borehole



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Other waste streams from Natrium reactor

Note: These are very preliminary estimates

- **During Normal Operation**
  - Based on experience with FFTF operation majority of low-level liquid waste comes from washing of spent fuel assemblies. Expected low-level waste projections are:
    - LLRW liquid ~1.5m^3 per year.
    - LLRW solid ~ 11-12m^3 per year
      - ~3-4m^3 of spent fuel pool resin from the filtration/ion-exchange system
      - ~1m^3 of spent fuel pool particulate from filtration system
      - ~7 m^3 of miscellaneous waste
- **After decommissioning**
  - Primary sodium (~800m^3) to be stored for decay and reacted to stable sodium compounds (technologies routinely performed around the world) and expected to be disposed as LLW (Class A or B)
  - Natrium DEMO will have additional sodium (~380 m^3) from intermediate sodium loop with much less activity – same treatment as above
  - Activated primary (2-4m^3) cold traps containing tritium and Cs and Cs traps (2-4m^3) and secondary cold traps containing tritium will require storage with decay, special treatment before disposal as Greater than Class C waste
  - ~80 MT of steel reflectors and other RV irradiated internals are expected to be disposed as LLW (Class C) waste
  - ~70 MT of irradiated control rods over 60-year plant life are expected to be disposed as LLW (Class C) waste, some portions may be segregated to Class B

NUCLEAR SECURITY AND PROLIFERATION RESISTANCE

Excellent proliferation resistance

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High Proliferation Resistance

- One of main motivations for development of TWR from the beginning in 2006
- **No reprocessing and ultimately with Natrium–U substantial reduction of enrichment facilities - two most likely diversion paths for proliferators**
  - If Natrium-U exported to other nations all subsequent reloads natural U, hence no need (or excuse for) enrichment facility
  - Simple once-through fuel cycle reduces likelihood of diversion of fissile materials
  - Fuel assemblies are tagged and easily accountable
  - 3 times fewer assemblies per GWe-yr than LWRs, less transportation of materials
- Very high average discharge burnup fuel
  - High self-protection from radiation dose for a long time
  - TRUs remain mixed with uranium and lanthanides
  - High content of Pu240 satisfying 1998 US-Russia Pu Management and Disposition Agreement (PDMA) requiring Pu240/Pu239>10 wt% (11% for Natrium and 22% for Natrium-U).
- LLNL nuclear security review indicates this approach is significant advance towards increased proliferation resistance

OVERALL SUMMARY OF NATRIUM ATTRIBUTES

- **Simple nuclear system for competitive clean energy production**
- **Excellent safety**
- **High flexibility in power production**
  - Dispatchable power and price following
  - Process heat
  - Integration with renewables
- **High flexibility in fuel cycle**
  - Early startup to start generating clean power and address CO_2 reduction soon
  - Step-wise fuel advancement to increase burnup while decreasing enrichment until ultimately allowing operation in future units on NU or DU reloads
  - Up to 30 times better uranium utilization possible than LWR allowing long-term sustainability without need for reprocessing
  - Significantly reduced waste volume of spent fuel
  - If recycling desired, Natrium can support it at reduced cost due to less frequent reprocessing
- **Excellent proliferation resistance**

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