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The ARC-100 Advanced SMR

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The National Energy Strategy Objective – Achieve Significant Reductions in Green House Gas Emission

Nuclear energy is strikingly absent in many national discussions, even though nuclear energy use has avoided 19 gigatons of CO_2 emission in the US since 1995

New opportunities associated with advanced SMR development may lead to changes in the future perception and role of nuclear energy

A key motivation for ARC Clean Energy SMR development has been to address key issues associated with nuclear energy – safety, economics, proliferation, and adaptability for distributed energy networks

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ARC Clean Energy Technology Addresses Major Criticisms of Nuclear Energy and Provides Low Development Risk

- **Nuclear security and nonproliferation (a key motivation for ARC)** – 20-year core life without access to fuel
- **Safety** – Self protecting against all anticipated-transients-without-scram including station blackout and uncontrolled single-rod withdrawal
- **Fuel cycle and waste management** – Flexible options: once through with on-site cask storage, proven technology for fuel treatment and recycle
- **Economics** - Factory production and modular construction
- **Economic return -** <u>Load following capability</u> compatible with solar and wind distributed grids, use of waste heat and off-peak power applications
- **Low development risk** – Mature, advanced and demonstrated technology foundation (EBR-II)

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The ARC-100 Based on Demonstrated Technology Improved for the 21st Century

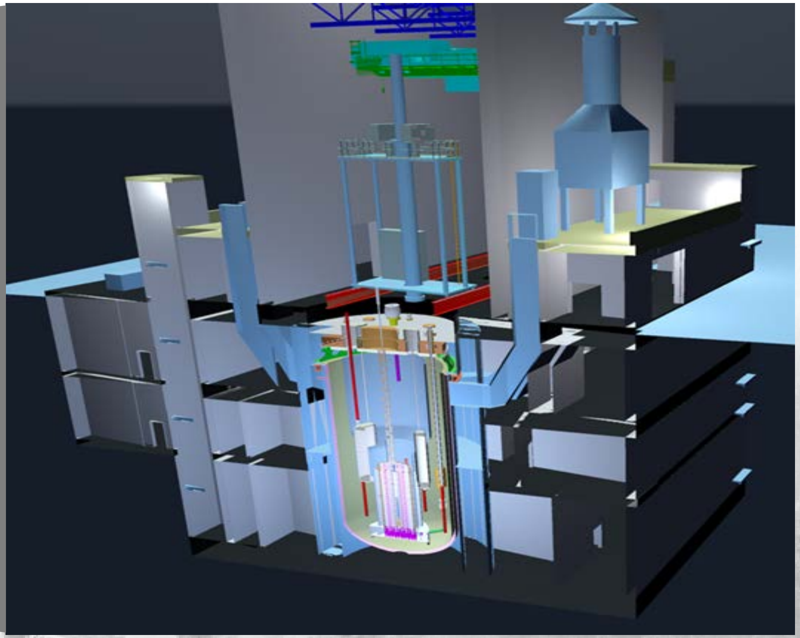
A modest scale up (5X) of the successfully operated (until mid 90's) EBR-II

EBR-II

20 MWe

- Sodium Cooled
- Metallic uranium alloy fuel
- Long 20 Year fuel cycle
- Low pressure pool type
- Inherent safety
- Redundant passive systems
- No need for emergency cooling
- Superheated steam BOP

ARC-100



100 MWe

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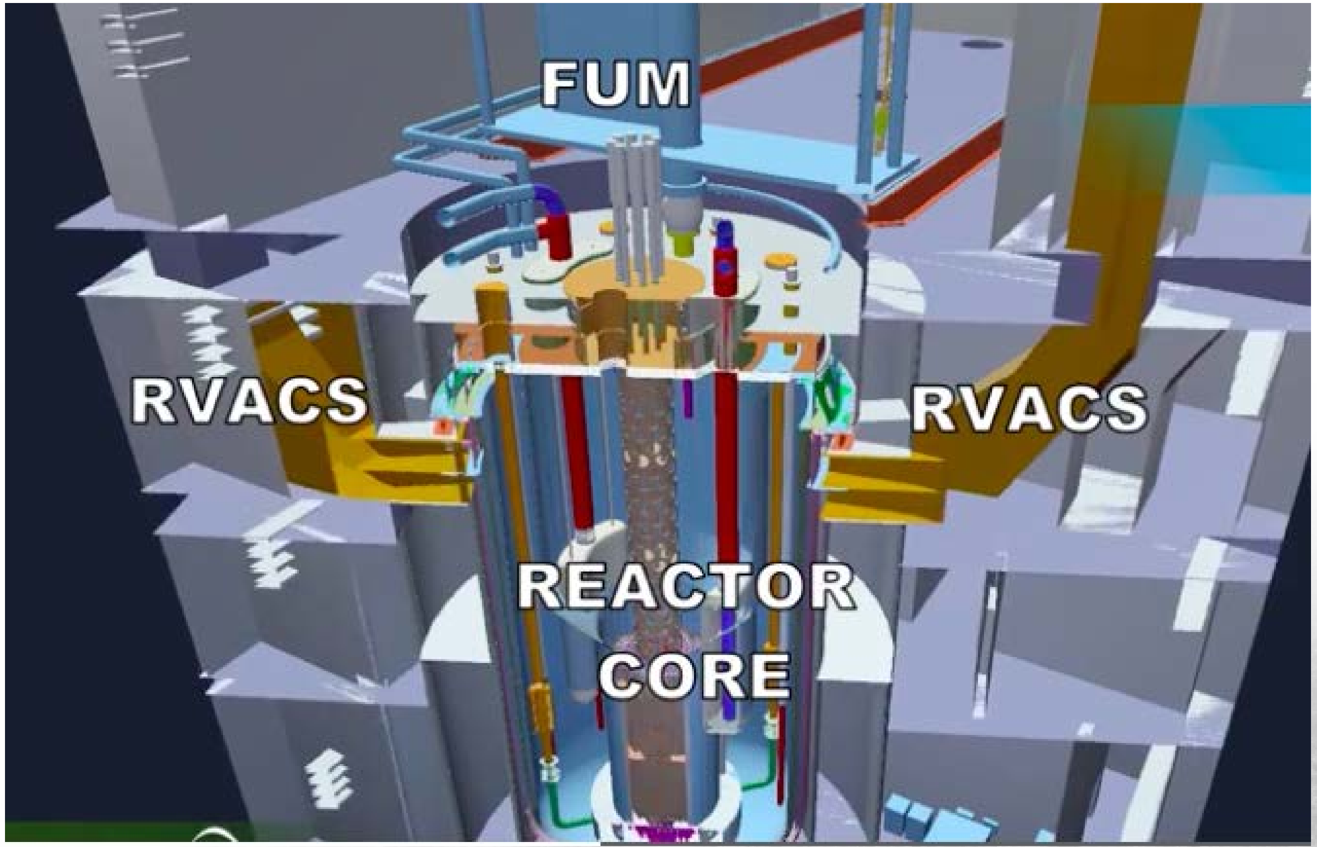
ARC-100 Parameters (Preliminary)

- Reactor power 286 MW_T, 100 MW_E
- Coolant Temperature, Inlet/Outlet 355^{o}C/510 ^{o}C
- Initial Heavy Metal Loading – 24.2 tones
- Fuel Metal- 3 zone (HALEU) 10.9%, 12.4%, 15.5%
- Cladding, Duct Material, assemblies upper and lower fittings Fuel HT-9
- Fueling Interval - 20 years
- Plant Life - 60 years
- Specific power density – 11.8 MW/t
- Average discharge burnup – 76.8 MWd/kg
- Approx. Reactor Vessel Size (includes core): 8 m diameter, 16.8 m height
- Approx. Core Dimensions: 2 m diameter, 3.75 m height, (fuel region 1.5 m)
- Cooling Pool containing primary pumps, intermediate heat exchangers (IHX), DRACS HX
- Steam Generator (baseline design) Helical coil, shell and tube, sodium to H_2O
- Thermal efficiency 38%



Screen shot from “flyover” of the baseline system

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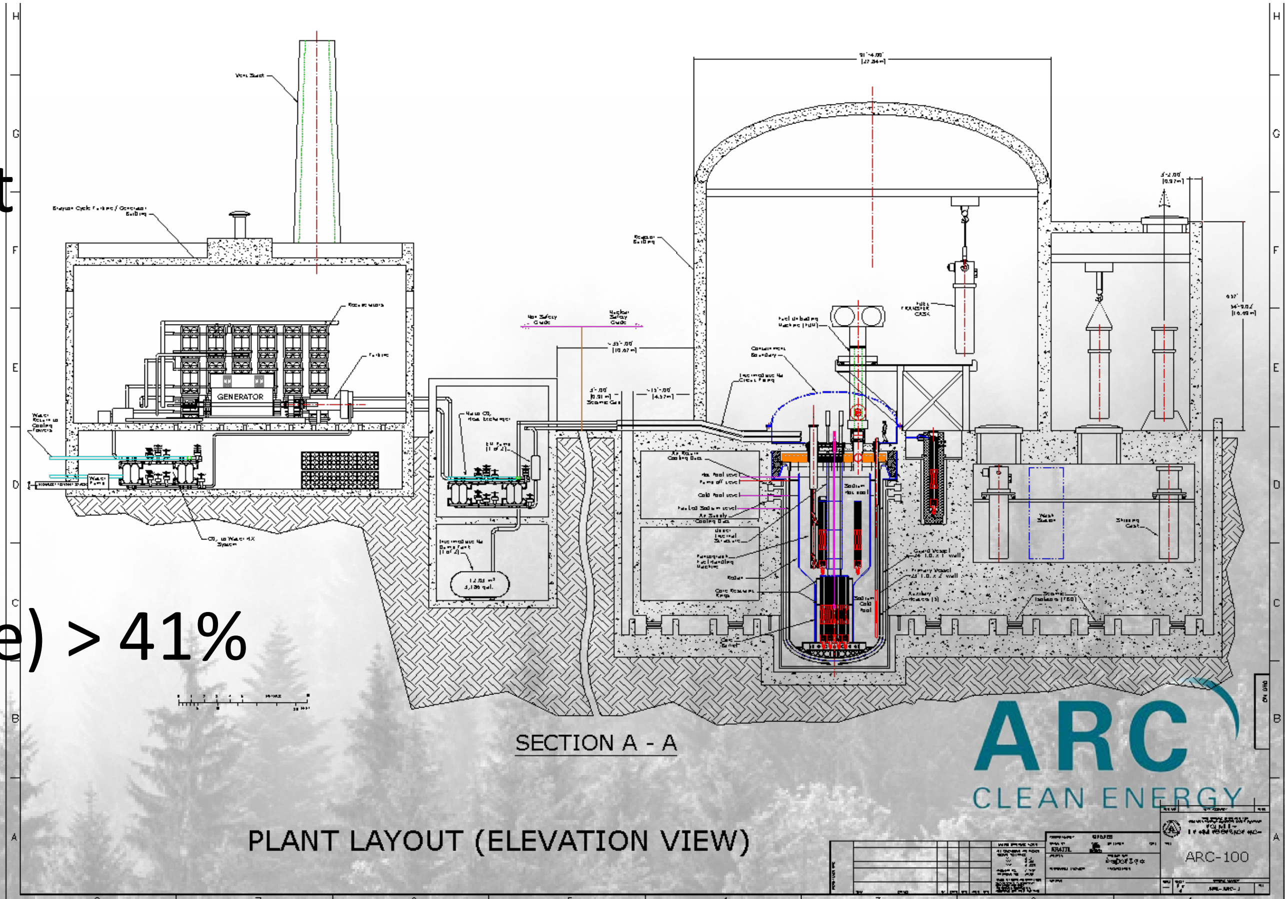
Two Designs Are Being Pursued

- New Brunswick Canada Point LePreau Generating Station is under consideration; $20M (Canadian) Grant from Canada
  - 100 MWe Rankine Cycle power conversion
  - Steam generator helical coil, shell and tube, sodium to H_2O, thermal efficiency 38%

- Advanced Design - $34.4M DOE Grant
  - Generic site
  - Seismic isolation
  - Brayton cycle, SCO_2 power conversion
  - Thermal efficiency (conservative) > 41%
  - 100 MWe , expandable to 200 MWe per unit



Nuclear Security and Proliferation Resistance of the ARC-100

ARC-100 Enhancements to Proliferation Resistance

- Sealed, heavily instrumented core (with possible remote monitoring) means low possibility of clandestine access to NM, and system misuse

- Hardened underground core

- 20 year fueling cycle reduces opportunity to access the core during refueling; transportation frequency of fresh/used fuel reduced

- Possible future designs could eliminate on site or in-facility fuel unloading machine

- If no fuel loading machine on site – significant reduction in capabilities for NM material diversion/theft

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ARC-100 Enhancements to Nuclear Security

- An actinide “soup” (with small presence of FP) exists throughout the system, high radiation and heat production (several thousand watts/kg) (Cm, Pu isotopes) no separated Pu and mix of Pu isotopes

- Throughout the system NM exists in unattractive form for WUM

- Poor bomb-making material (dedicated thermal reactor, U enrichment, “easier routes”)

- Hardened facility

- Used fuel (with high radiation) storage underground, extremely difficult to access

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ARC Fuel Cycle

Resource Utilization

- The ARC-100 Integrates smoothly into the existing uranium infrastructure
- The ARC-100 can operate in a once-through or recycle fuel cycle
- The ARC-100 can use fissile materials from existing used fuel stockpiles, thus extending the uranium resource (decreases uranium mining, conversion, enrichment requirements)
- Its use of HALEU requires changes in enrichment facilities (>5% U235) or down blending of HEU
- The ARC-100 reactor and recycle system can be sustained indefinitely if recycling is used

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ARC-100 Fuel Cycle Assumptions

- An open cycle is the currently planned approach

- The used fuel, after the 20-year cycle is over, would be stored within the facility to allow cooling, after which the fuel would be sodium washed and then be transferred to on-site dry storage

20-year fuel discharged isotopics)

For a core with 24 tons of HM and 3.2 tons of U235

U234	.001 MT
U235	1.6 MT
U236	.3 MT
U238	19.3 MT
Pu238	.004 MT
Pu239	1.03 MT
Pu240	.07 MT
Pu241	.003 MT
MA	.026 MT

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The Preferred Long-Term ARC-100 Fuel Cycle – Recover TRU and Use in New Fuel For Reconditioned ARC

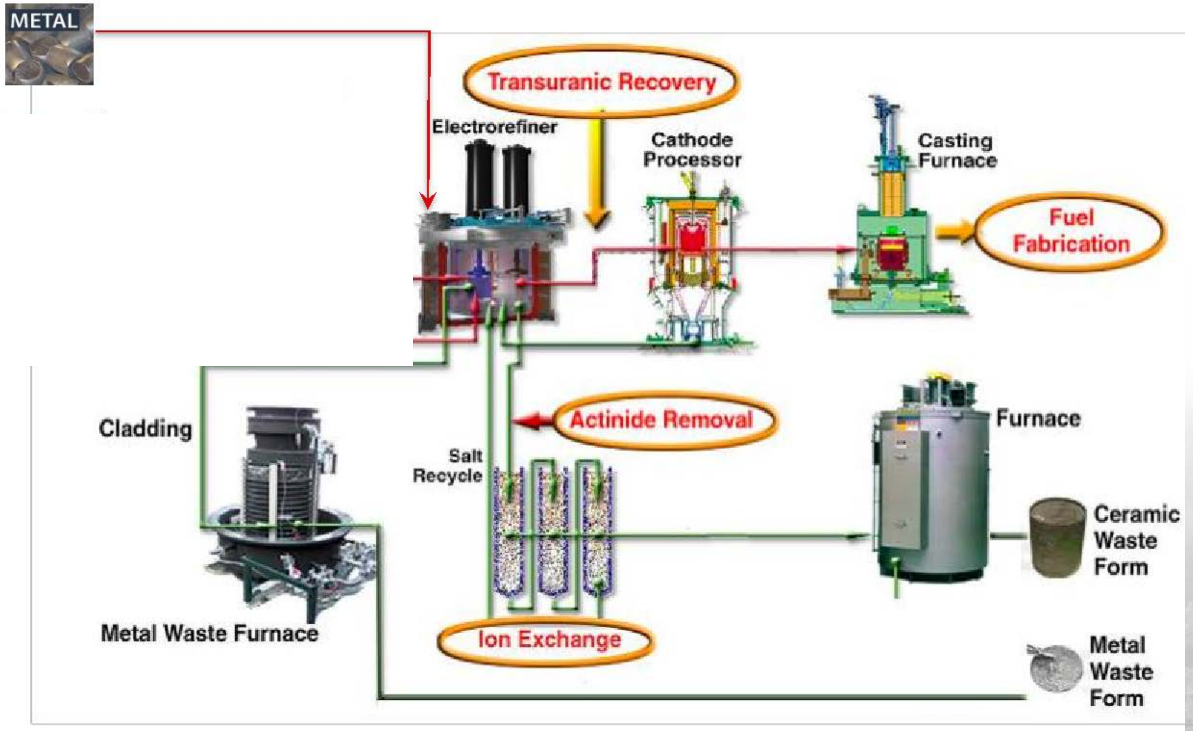
- The ARC-100 fuel, after 20-year operation, contains as much fissile content (Pu, U235) as BOL (U235 only)

- Pyroprocessing would be used to recover TRU for fabrication into fresh fuel

- Metal fuel feed eliminates need for oxide reduction

  LWR oxide fuel also a potential feed for pyroprocessing

- 20-year fuel irradiation provides ample time (> 30 years) for a deliberate planning and development program



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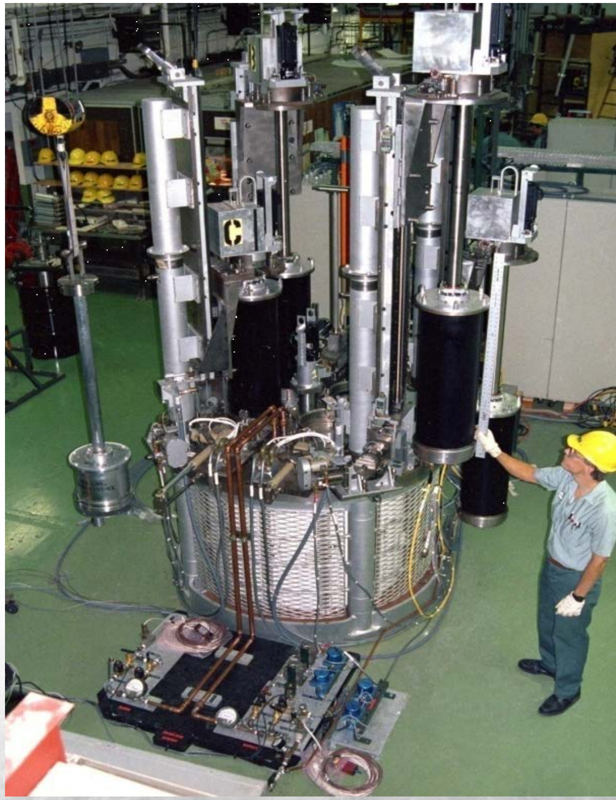
ARC Pyroprocessing Technology Status

- EBR-II fuel was processed and recycled to the reactor in the 1960s
- Pyroprocessing technology was developed at EBR-II in the 1980s and was proposed for used EBR-II fuel treatment following the shutdown of EBR-II
- A NAS committee charged with following its development found no technical barriers with the electrometallurgical technology for EBR-II fuel treatment
- Pyroprocessing of EBR-II continues today at the INL
- Major equipment components have been scaled to pre-pilot scale (multiple kgs)



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A 100 MT HM Facility Is Appropriate for Planning

- A beginning preconceptual design exists for a 100 MT facility (Chang, *Nuclear Technology* 2018)
- The design lays out major components and unit processing steps
- The preconceptual design report also includes facilities for security, waste management
- Material forms, flows, safety, safeguards assessment performed
- Salt waste generation has been estimated (Simpson 2011)
  - 15-20 MT/yr (ER salt, Na removed)
  - glass holding 10% salt waste - -140 MT
  - salt waste disposal in a salt repository -- 7 m^3 /yr for a 100 MT HM facility

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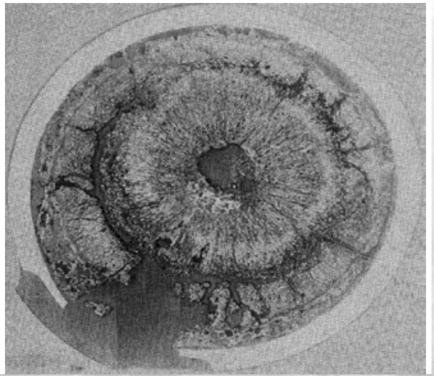
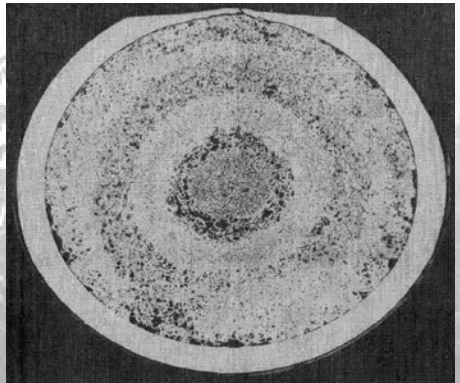
Safety of the ARC-100

The Use of Na-Bonded Metal Fuel Is An Important Contributor to ARC's Enhanced Nuclear Safety

- Metal fuel physics characteristics offer distinct advantages for overall system safety (over oxide fuel)
- No fuel-coolant interaction issues
- Extensive data base from EBR-II and FFTF bound normal ops and accidents -
    - Over 150,000 metal fuel pins irradiated during the 30-year life of EBR-II obtaining 20% burnup in lead assemblies
    - Fuel compositions - Uranium-zirconium and uranium-zirconium plutonium over a range of plutonium concentrations, with and without addition of MA
    - Peak cladding temperatures to 620ºC
    - Tests also included run beyond cladding breach (RBCB) for both metal and oxide fuels -



Oxide RBCB
9% burnup



Metal RBCB
12% burnup

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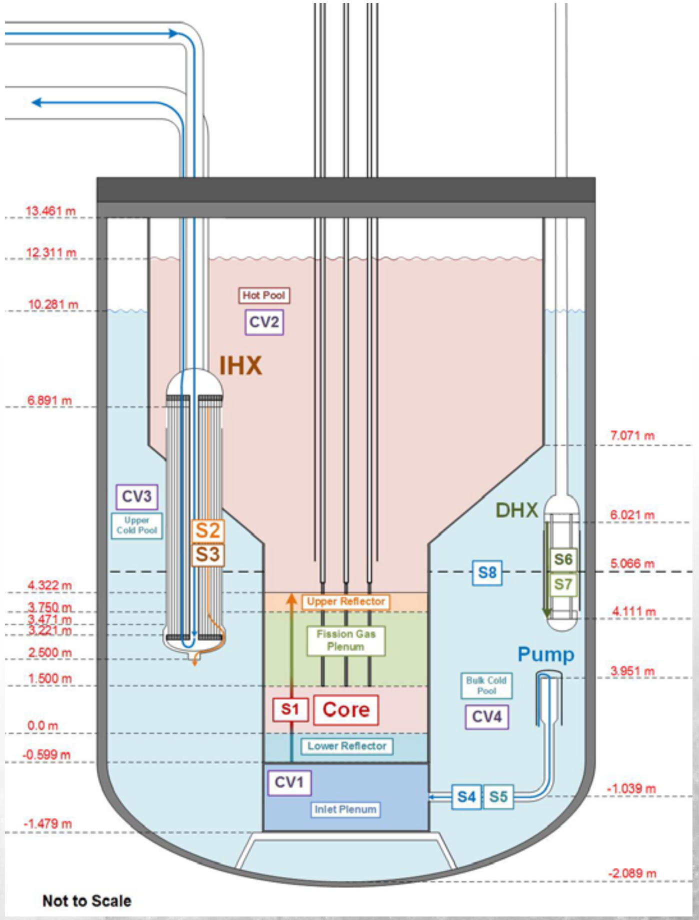
The ARC-100 has Large Operating Safety Margins and Natural Circulation

- **Ambient pressure primary system**
  - Coolant operates at 355-510^{o} C , boils at 900$^{o\,C}$
  - No stored mechanical energy, eliminates LOCA driving force
- **No potential for H_2 generation**
  - Elimination of $Zr/UO_2/H_2O$
  - Metallic alloy fuel, steel cladding
- **Small temperature rise in metallic fuel**
  - Thermal conductivity 10X oxide fuel
  - Reduced stored energy
- **In Addition**
  - Natural circulation – long term cooling
  - DRACS – continually operating
  - Fully independent RVACs

No Long term need for offsite or emergency AC power systems



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EBR-II Data : Two transient tests shown below provided benchmark development of transient analysis for the ARC-100

Loss of Flow Without Scram

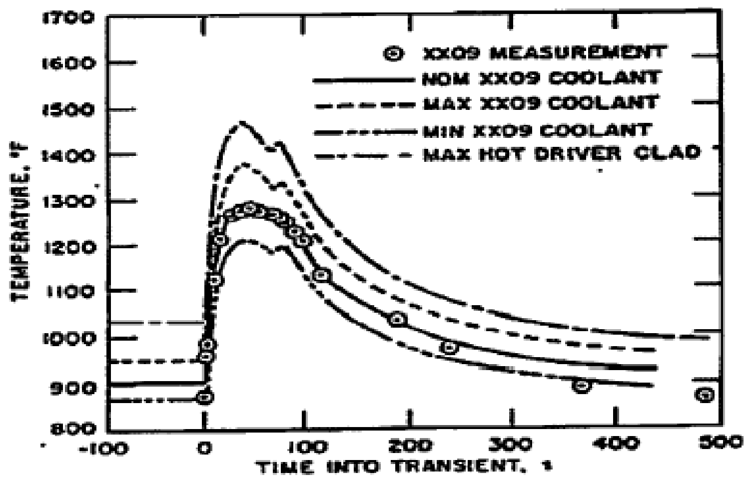

Fig. 3. Loss of flow without scram from 100% power with 100 s pump coastdown time. Test 45. Pretest predictions and measurements of in-core temperatures

Loss of Heat Sink Without Scram

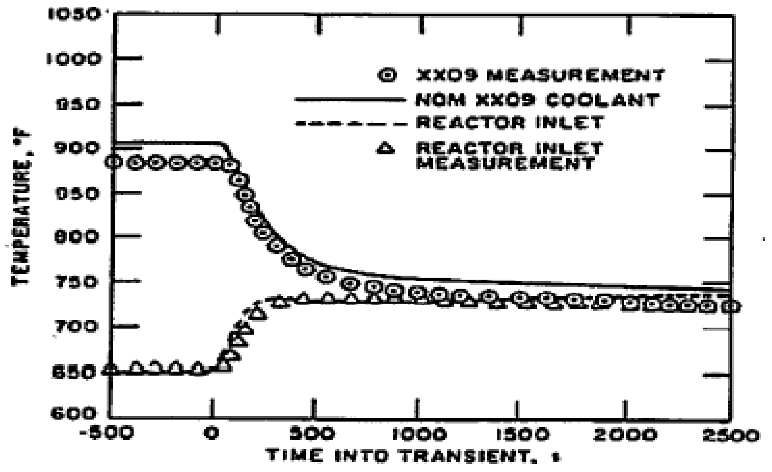

Fig. 4. Loss of heat sink without scram from 100% power. Test B302. Pretest predictions and measurements of reactor temperatures

Analysis Shows Similar Response for the ARC-100

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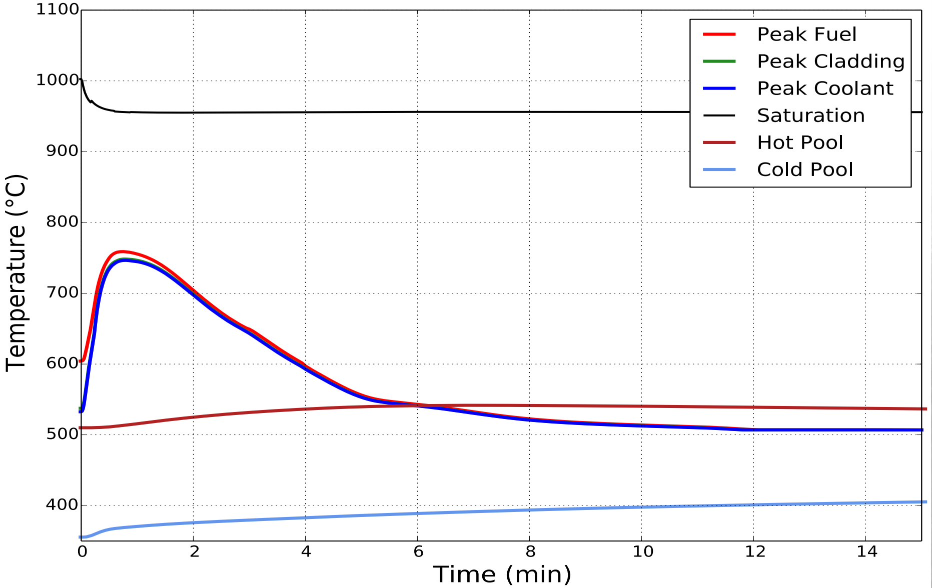
The Unprotected Station Blackout Does Not Damage the Plant

- In-core temperatures peak within first minute
- Decrease below pre-transient temperatures as power decreases
- Large fuel melting and sodium boiling margins maintained
- Clad temperatures rise barely above slow eutectic threshold
  - For only 80 seconds
- Hot pool temperature peaks at 542°C below Service Level D limit of 704°C

Margin	Nominal	UTOP
Peak Fuel Temp	605°C	759°C
Fuel Melting Margin	596°C	442°C
Peak Cladding Temp	543°C	748°C
Max. Clad Penetration	-	2%
Peak Sodium Temp	539°C	750°C
Sodium Boiling Margin	463°C	190°C



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Severe Accidents

- Severe accidents, those that would lead to fuel damage, are precluded in the ARC-100 by virtue of the self-protecting response of the reactor.

- Anticipated Transients Without Scram (ATWS) do not lead to fuel damage as demonstrated by actual tests in the EBR-II. They are not severe accidents.

- Sodium voiding does not occur in these transients so that there is no mechanism for rapid insertion of reactivity.

- Regardless, tests have been undertaken in the TREAT facility to determine the behavior of metallic fuel under a major power excursion leading to fuel failure.
    - Cladding breach at 4 times nominal power and after cladding breach, fuel softened and moved vertically within the fuel pin, providing strong negative reactivity
    - After cladding breach, fuel moved vertically, solidifying as a porous mass above

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Technical & Licensing Issues, Costs

Technical Issues

- The availability of HALEU for fuel

- Verification of 20-year refueling interval
- Fuel qualification necessary for ARC-100 UZr metal fuel having different dimensions compared to EBR-II fuel
- The baseline ARC-100 design is based on EBR-II design, 30 year operational experience

Overall system TRL : High

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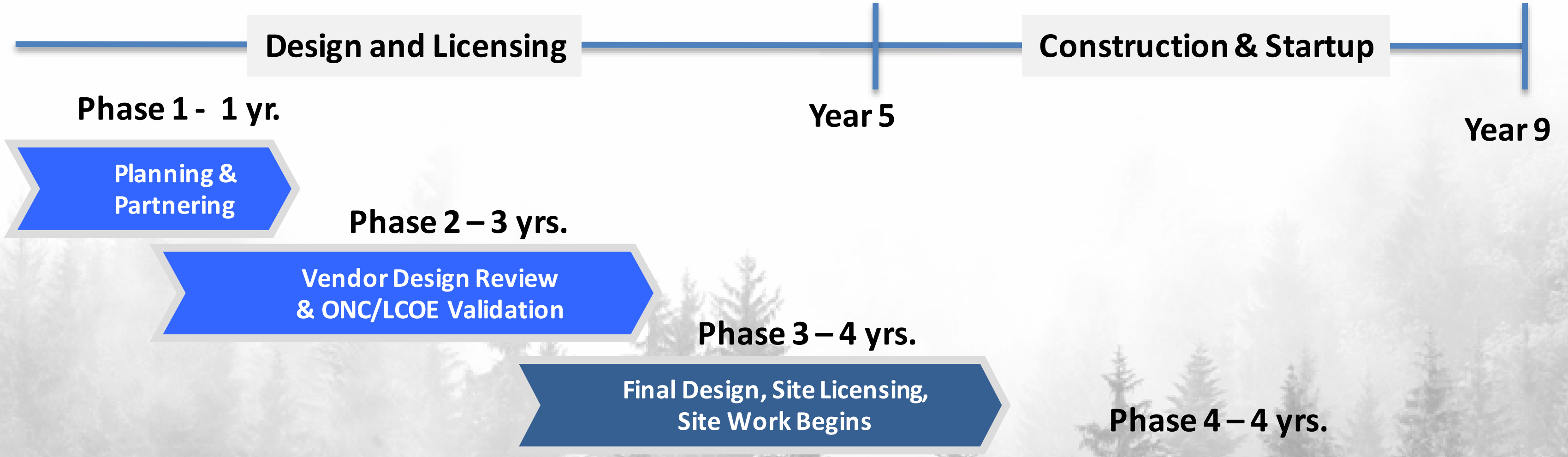
Licensing

- ARC's licensing efforts have focused on the Canadian regulatory system (REGDOC-3.5.4, *Pre-Licensing Review of a Vendor 's Reactor Design) since a design for the New Brunswick Power's Point LePreau site is being pursued. Vendor Design Review 1 (VDR1) successfully completed (2019) and VDR2 is now being pursued.*

- The ARC-100 built at the Point LePreau would be a heavily instrumented FOAK



Waste Management

- Extensive quantitative data base exists from EBR-II, FFTF, BN350, Sizewell for both operation and decommissioning

- The design of major ARC-100 components, as they progress, will emphasize choices that reduce waste

- Anticipated 60 year accumulation of selected rad waste from day to day operation
  - sodium analytic samples ~ 1 to 2 m^3
  - solid waste (maintenance/repair) ~ 1 m^3
  - solid waste (fuel washing) ~ 1 m^3
  - cold traps ~ 1 m^3

- First of a Kind, year to year operation associated with fuel removal for surveillance
  - Years 7, 14, 20 : total HT9 ~ 5 tons, B_4C ~2 tons
  - Year 20, 40, 60 (open cycle) fuel assemblies; ~65 tons hardware, ~ 11 tons HLW, ~ 32 tons, ILW, LLW

- D&D – Reflector (40 tons) , Shield (17 tons HT9 and 10 tons B4C), control assemblies (4 ton HT9, 0.6 ton B4C) in addition to fuel (once through);
  - inventory of sodium cleaned and reacted to produce sodium hydroxide at concentrations that are solid for land- fill disposal, (EBR-I&II,FERMI and BN350 sodium disposed of in this manner) ,
  - EBR-II tank with primary components filled with concrete and entombed in place below grade

Preliminary Costing Activities

- Capital, operating costs and resulting LCOE are being modeled continuously using the Gen IV International Forum cost framework
- Those results are proprietary at present
- Target for LCOE at NOAK (NOAK = FOAK + 10) is less than $55/MWh.

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Summary: ARC-100 Safety, Fuel Cycle and Waste Management

- Inherent physics of design and use of metal fuel lead to superior levels of ARC-100 operational safety

- The reactor and the associated fuel cycle have been designed to reduce proliferation risk and enhance nuclear security
  - No access to the fuel
  - Fuel that is unattractive for weapons use
  - 20-year assurance of initial fuel load
    -reduced incentive to develop indigenous enrichment capability

- Pyroprocessing of used fuel can reduce volume and radiotoxicity of waste
  - Reactor operation produces very small volume of waste
  - EBR-II spent fuel treatment demonstrated at the Idaho National Laboratory
    - ➢ Significant reduction in volume and radiotoxicity if recycle is employed
    - ➢ Decommissioning technology developed and employed successfully at EBR-II

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