The Smallest SMRs

Ken Kozier & David Sears

AECL-Chalk River Laboratories

Western Focus Seminar/33rd Annual CNS Conference

Saskatoon, SK, 2012 June 10-13

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Outline

- What is a ***very Small Modular Reactor* (SMR)**?
- Why they may be of interest to **Canada**; what is the market?
- What's been done ***before*** elsewhere & in Canada?
  - Slowpoke Energy System
  - Nuclear Battery
- What are others doing ***now***?
  - Emphasis placed on ***transportable*** reactor core modules & ***autonomous/unattended*** operation
- What is the ***future*** potential for very small reactors in Canada?

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What do we mean by a '*very* SMR' (or 'Micro Reactor')?

- ***Small*** **Reactor**: defined by power output
  - **IAEA**: <**300 MWe/~1000 MWt** [**SMR** = **S**mall & **M**edium **R**eactors]
  - **CNSC**: <**200 MWt/~70 MWe** [RD-367 Design of Small Reactor Facilities]
    - A risk-informed "***flexible/graded***" approach to licensing, but the same process irrespective of size
- ***For this talk***: very SMR is **<<10-30 MWe/<<30-100 MWt** (still a ***BIG*** subject)
- May be small in ***physical size*** at low power output
  - Examples: **200 kWe/1.1 MWt EBR-I** NaK fast reactor 1951-63; 52 kg HEU
  - **0.65 kWe/45 kWt SNAP-10A** space reactor 1965

Canadian remote SMR market

- ***Electricity & heat*** in remote off-grid locations currently served by diesel generators
  - >300 isolated communities that rely on diesel generators for electricity; 50% in the North + ***mines*** + military installations
  - Energy use/capita & cost increases with latitude
  - ***Diesel fuel cost***: **$5 /litre** in **CFS Alert 82° N** [2007 Jan.]
  - Most Canadian Arctic community needs are **<<10 MWe**, somewhat more (~2 to 38 MWe) for mines
- Sustainable economic & social development of Canada's North requires stable, secure, low-cost & environmentally responsible energy

> ***Value proposition***: Reliable low-cost energy → ***mining development*** → jobs → social advancement → stable communities → enhanced sovereignty

- Current reliance on fossil fuels is ***vulnerable***: fuel costs, supply logistics, security of supply of 'Arctic' fuels, environmental concerns


May 29, 2011

Global warming jeopardizing ice highways, study says

By Nathan VanderKlippe

From Monday's Globe and Mail

Canada will lose winter-road access to nearly 400,000 square kilometres of land by mid-century, UCLA researchers predict

Arctic Canada Diesel Fuel Users

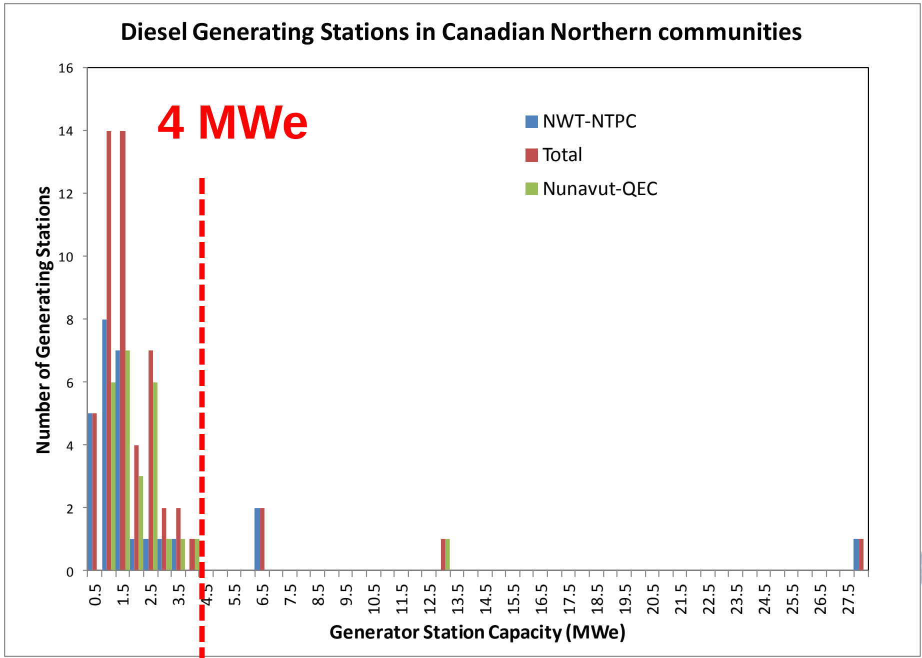
- Resource Extraction

- National Defence: CFS Alert 82° N

- Remote Communities
  - *Example*: Grise Fiord: 76° N, pop.141
  - Average annual T=-16.5° C

Diesel electricity generating stations in Canadian Northern communities [Wikipedia]

- 53 communities in **NWT** & **Nunavut**: total ~100 MWe
- 49 generating stations **<4 MWe** [**~160** 0.5-MWe units]
- Need small units for redundancy, transportability, baseload operation (no information on daily & seasonal load factors)
- **Energy costs: Qulliq Energy Corporation, *Nunavut***
  - Electricity: Lowest (Iqaluit) **$0.5239 /kWh** Highest (Kugaaruk) **$1.0271 /kWh** (National Energy Board; after Govt. subsidy)
  - Fuel ***subsidies*** consume **~$200 million** per year; **~20%** of the entire **Govt. of Nunavut** budget. (pop. **31,906** [2011]; **$6270 per person**)
  - **Total energy cost: ~$11,000/5,440 litres per person; 26% for electricity**
- Diesel fuel supplied by ship from Montreal
- Only alternative is by ***air*** if early freeze-up
- Only 3 suitable airstrips
- A single air shipment cannot satisfy ***daily*** fuel requirements in most communities
- **92%** of Nunavut **$1.4B** budget comes from Federal Govt.



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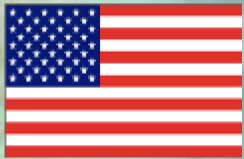


The past: Early US Army Corps of Engineers 'Packaged' Reactor Program: 1954-77

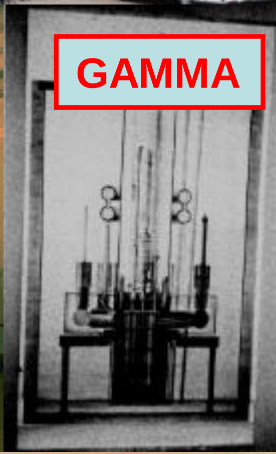
- 8 reactors built mainly by American Locomotive Co.: mostly High Enriched Uranium (HEU) PWRs
- **SM-1**: **2-MWe** **Ft. Belvoir**,VA,**1957-4-4** to 1973
- **SL-1**: **300-kWe BWR** NRTS, Idaho, 1958-61
- **PM-2A**: **2-MWe** Camp Century, Greenland, 1960-64
- **ML-1**: **253-kWe** gas turbine, 15 tons, NRTS, 1962-63
- **PM-1**: **1.25-MWe**, Sundance, WY, 1962-68
- **PM-3A**: **1.75-MWe**, McMurdo Sound, Antarctica, 1962-72
- **SM-1A**: **2-MWe**, Ft. Greely, Alaska, 1962-72
- **MH-1A**: **10-MWe** + H_2O, on Sturgis, Panama Canal, 1968-77

Some Russian small reactors

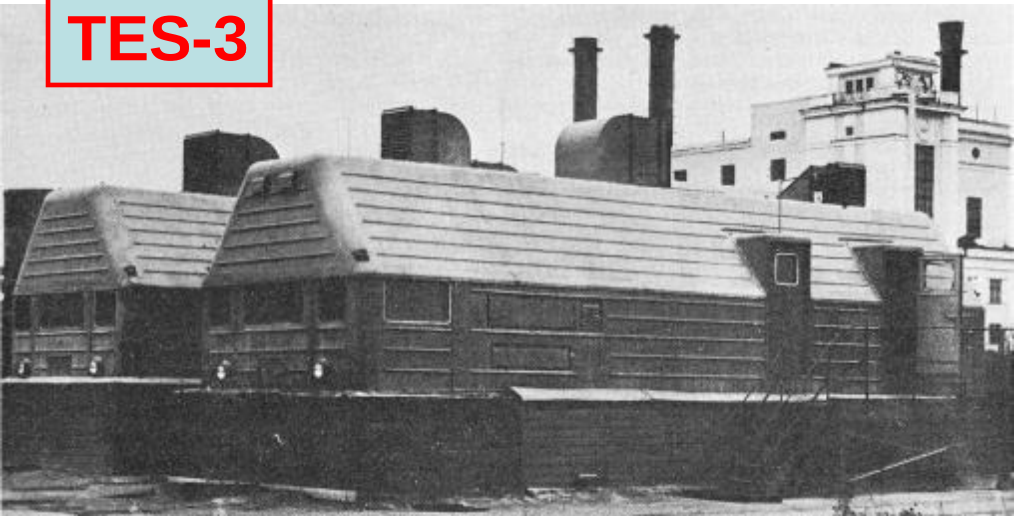
- **AM-1: 5 MWe**/30 MWt IPPE, Obninsk <u>**1954**</u>-2002: RBMK precursor
- **GAMMA**: **6 kWe**/220 kWt Bi-Te-Se **TE**'s; Ti vessel [6 km ocean depth],1981-92, Kurchatov Institute, Moscow
- Russian space reactors: 37 launched 1967-88
  - **ROMASHKA [0.8 kWe/40 kWt], BOUK**: <0.5 kWe **TE**
  - **TOPAZ**: <10 kWe **thermionic**; COSMOS-1867 in 1987 <u>***~11 months unattended operation record***</u>
- Portable: **TES-3 2 MWe** 1961-65; **PAMIR 0.6-MWe** 1985-86

AM-1

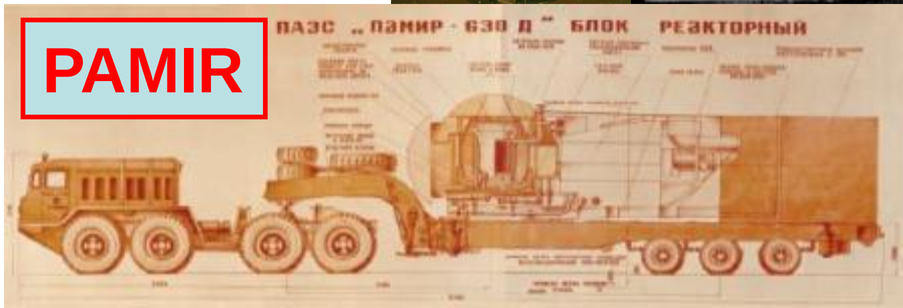
GAMMA



TES-3

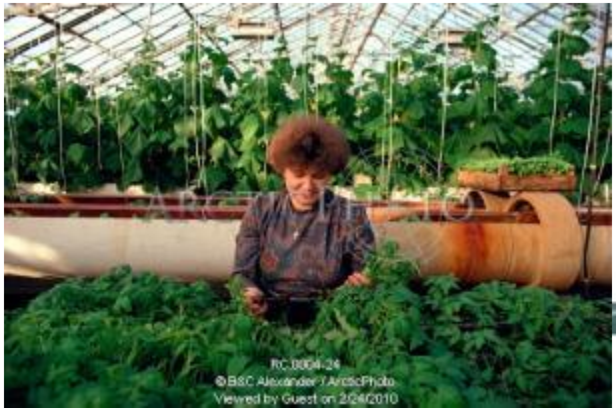


PAMIR



Russia's existing Bilibino Nuclear Power Plants

- 4x12 MWe **EGP-6** reactors
- Most northern Nuclear Power Plants 68° N
- H_2O-cooled graphite-moderated channel reactors based on AM-1
- **1973 - …**; electricity & heat for ***gold mine***, greenhouse & town of 4,500
  - Provides ~70% of energy needs
  - Average load 15-25MWe
  - **670** plant staff!!!; 40% of electricity cost



Early Canadian 'CANDU-ish' Very Small Power Reactor experience

- **Nuclear Power Demonstration (NPD)** **Rolphton, Ontario**
  - **22 MWe** [19.5 MWe net]; 1st PHWR
  - CGE/AECL/OH partnership
  - 1st critical **1962** Apr. 11; S/D **1987**
- **Whiteshell Reactor (WR-1)**, **Pinawa, Manitoba**

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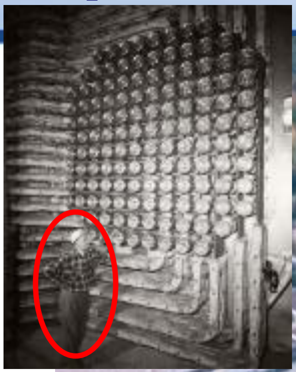
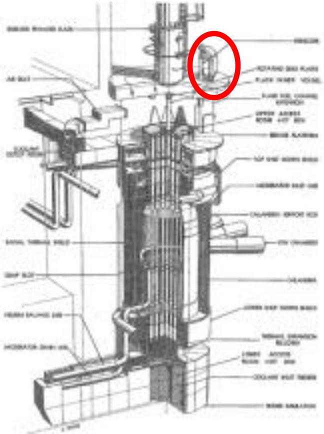
  - **60 MWt** [13-15 MWt to **heat Whiteshell Laboratories** **(WL)**]
  - prototype **Organic Cooled Reactor** built by Canadian General Electric
  - 1st critical **1965** Nov. 1; S/D **1985** May



WR-1



Scaling up from existing small reactors

- Compact **20-kWt SLOWPOKE-2** (Safe LOW POwer ***k***-ritical Experiment) tank-in-pool research reactor; 8 units built **1971-85** including **SRC** & **U of A**
  - **Licensed for *unattended* operation for up to 24 h**
  - Inherent/passive safety features
  - 0.88 kg ^{235}U HEU; 1.12 kg ^{235}U LEU

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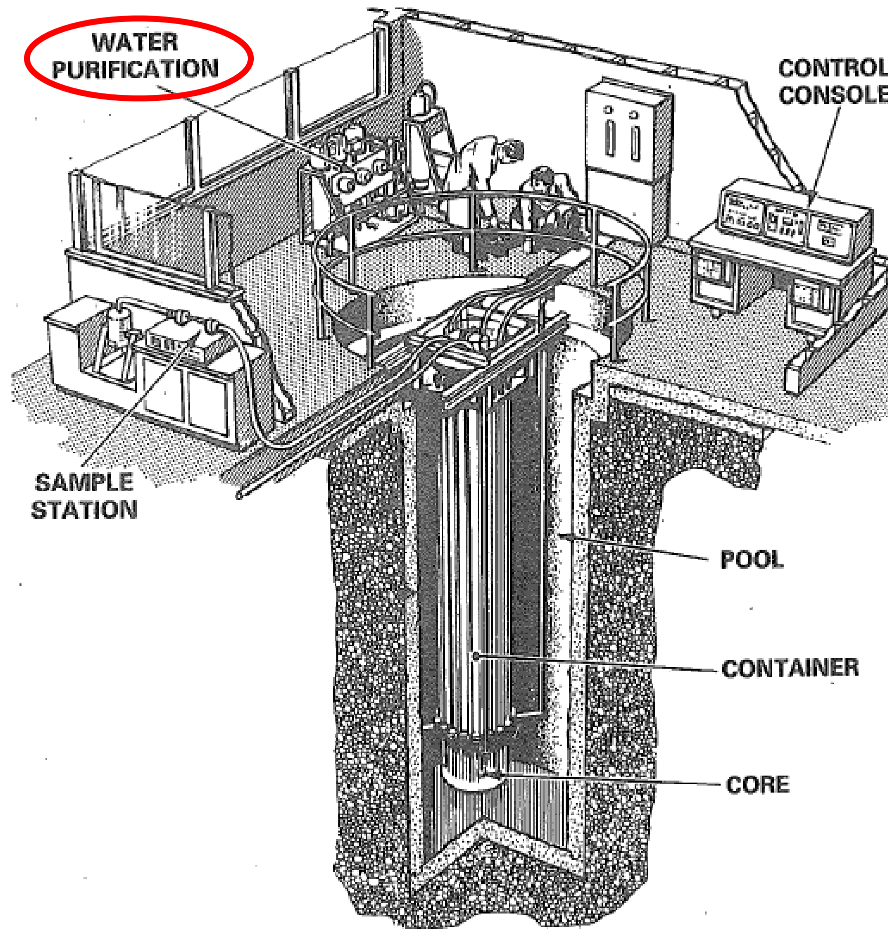

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2-MWt SLOWPOKE Demonstration Reactor (SDR) at WL

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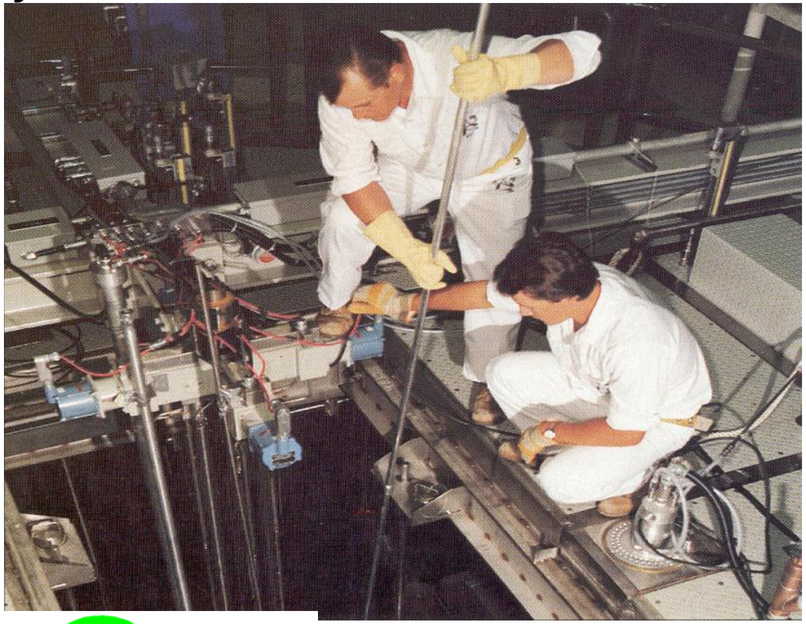
- Interest in heating reactors ~1984 [CFS Alert 2-MWt]; **Local Energy Systems** business unit formed under W.T. Hancox
- Construction started 1985 spring; 1st criticality **1987 July 15**
- 4.3-m diameter x 10-m deep steel-lined pool; 100 kg U
- Operated briefly for physics & thermalhydraulics tests



Local Energy Systems

A BUSINESS UNIT OF ATOMIC ENERGY OF CANADA LIMITED

Slowpoke

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10-MWt SLOWPOKE Energy System (SES-10)

- Commercial follow-up to SDR for **urban** low-temperature hot-water heating systems (**85° C**); up to 150,000 m^2 of floor area, 1500 apartments
  - Canadian interest: Université de Sherbrooke initially & ***University of Saskatchewan*** later
- ~1100 kg of fuel every 4 to 6 years (removed after 10-12 years)
- 6-m diameter x 13.5-m deep steel-lined pool
- Unpressurized; natural circulation; ***unattended operation* for weeks**

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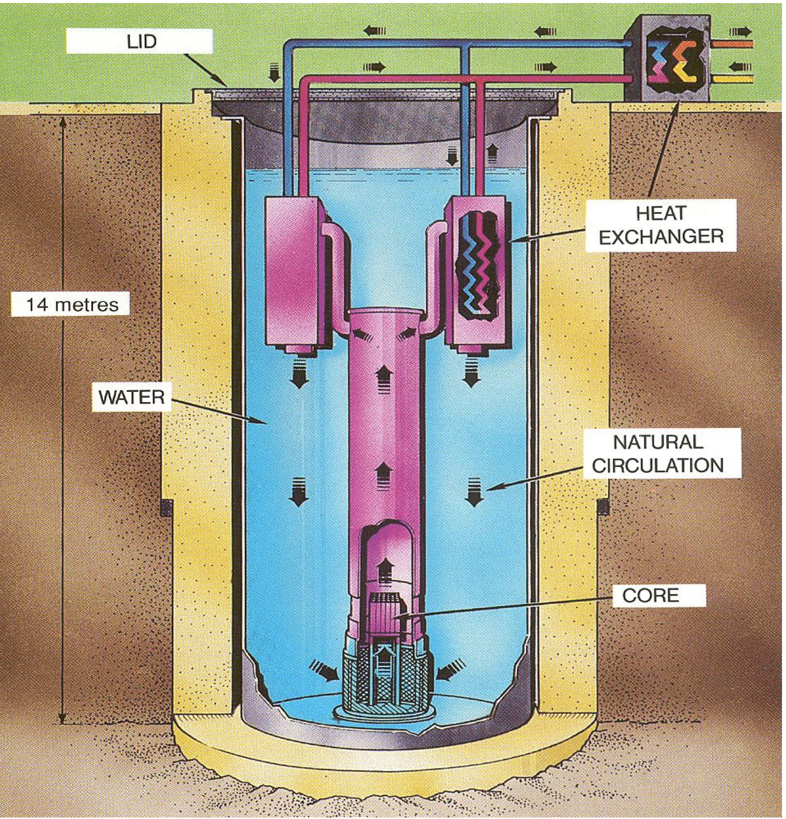
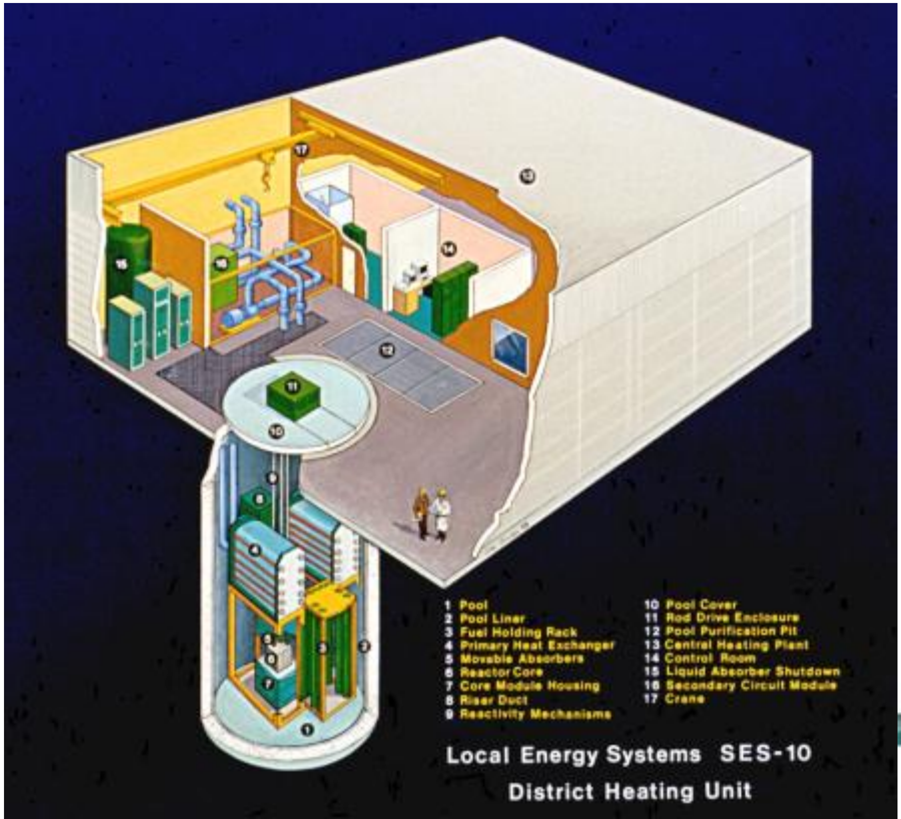
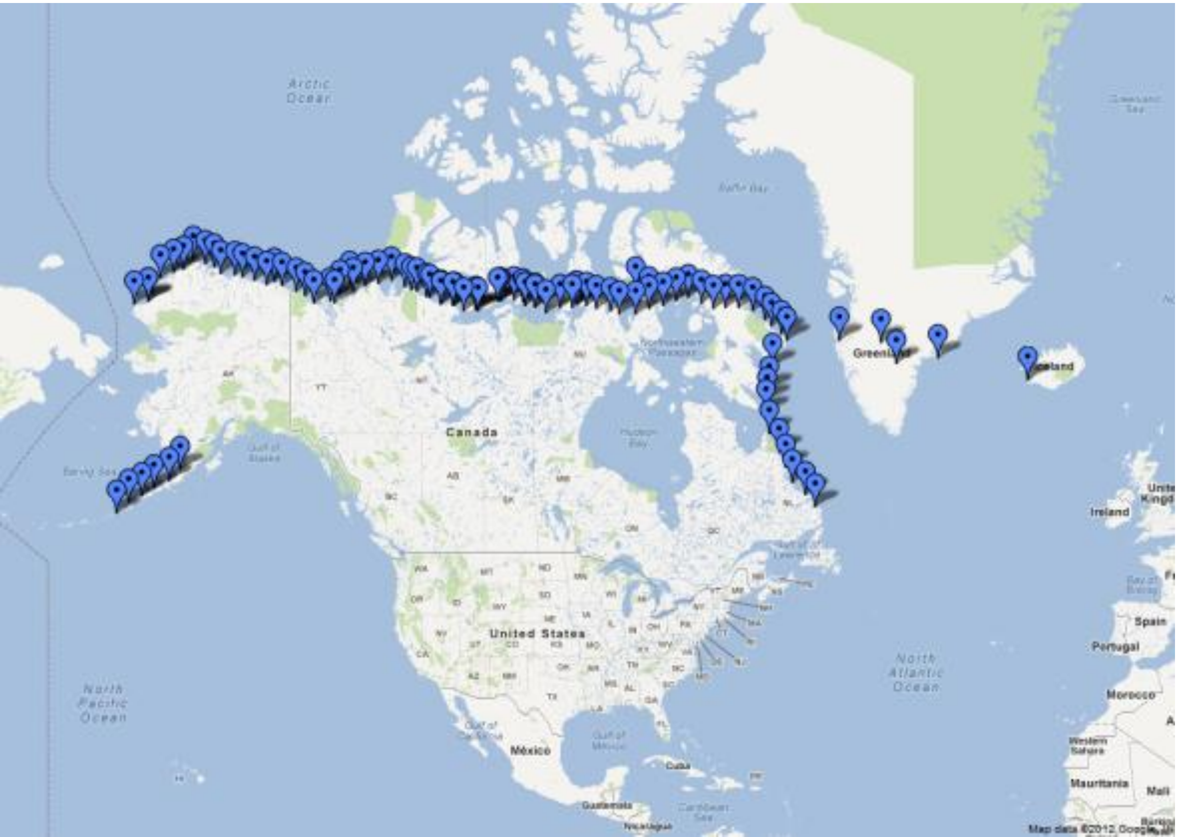




North Warning System (NWS) application

(US/Canada agreement signed at 1985 'Shamrock Summit')

- Replacement for aging NORAD DEW line to detect cruise missiles
- 13 minimally attended Long Range Radar & **39 unattended Short Range Radar** (**15 kWe**) sites across 7000 km at ~70° N latitude
- Extraordinary **reliability** requirement >99.99% (<1 hr/a) for 20 years
- Helicopter transport (**<12 Mg**); hazardous 'whiteout' conditions



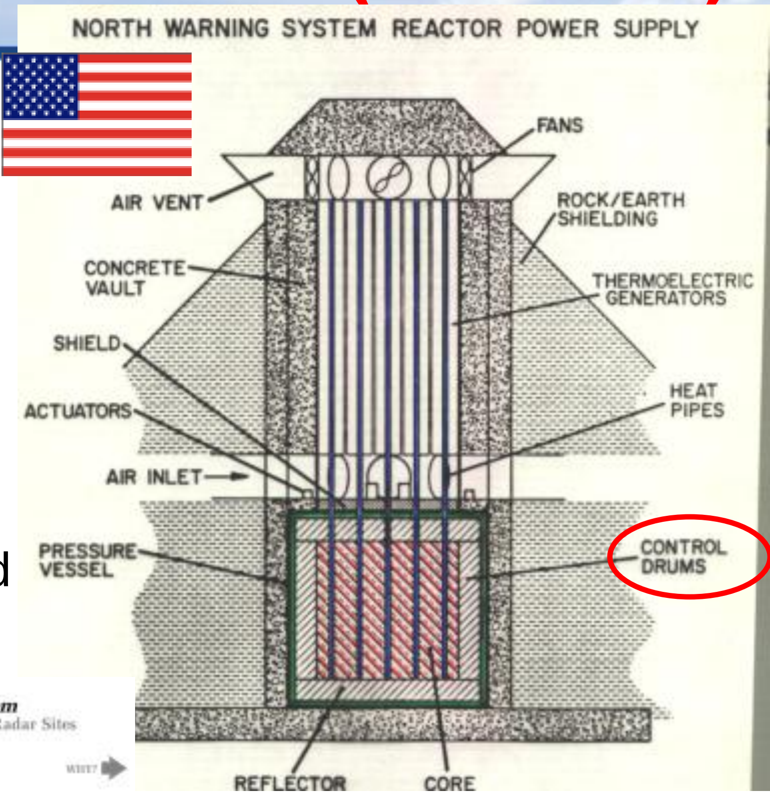
Diesel vs. Reactor

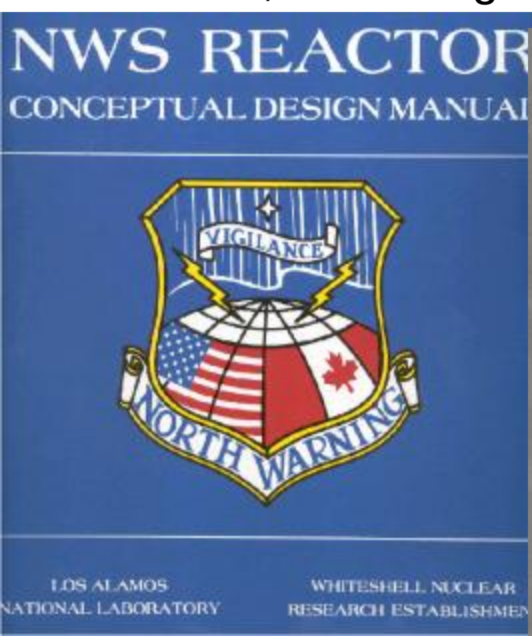
	Diesel	Reactor
Number of Units	4	1
Power/Unit	15/40 kWe*	15/40 kWe
System Weight	130 Tons	22 Tons
Maintenance Interval (Mos)	3	12
Overhaul Interval (Years)	1	20
Annual Fuel Consumption	18,000Gals.	0
Refuel Trips/Year	26	0
Life Cycle Cost	$3,109K	$2,238K

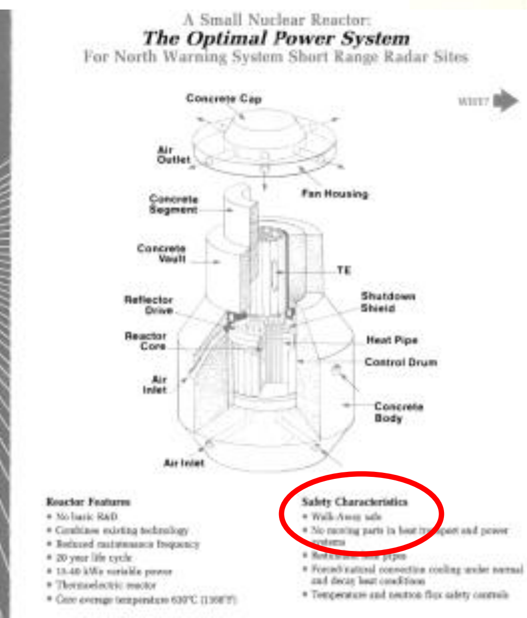
* Three units required for maintenance period.

NWS reactor concept 15 kWe net (200 kWt)

- 1984 joint USAF/DOE/LANL & DND/AECL/WL investigation
- Innovative hybrid of space & high-temperature reactor concepts
- **Heat pipe** cooled reactor (**19 SS/K**); air-cooled **TE** conversion system, TRISO coated particle fuel [no containment building]
- Ambitious **schedule**: demonstration by end **US FY86** [~$24 million]; deploy 2 prototypes by end FY87; remaining SRRs FY88-91







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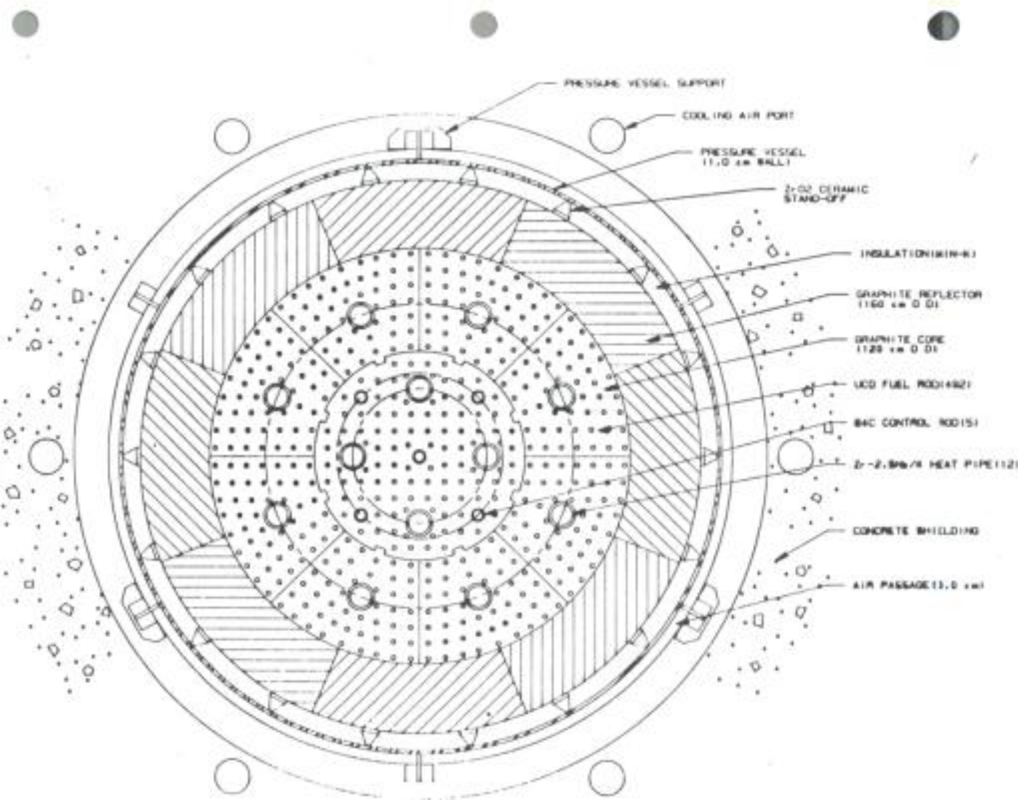
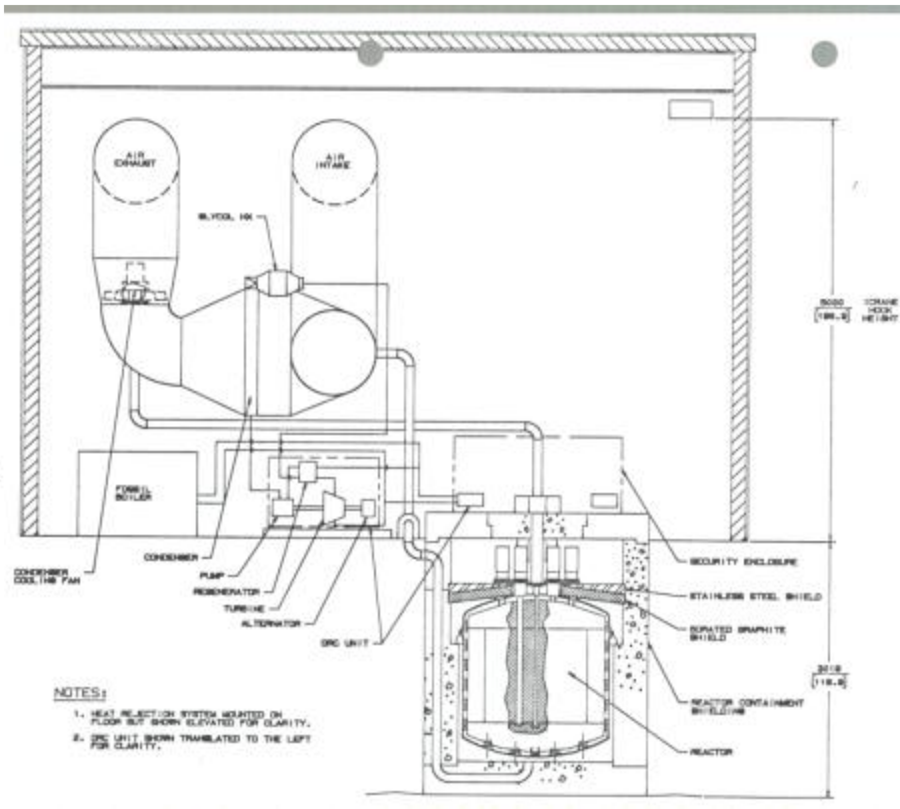
Compact Nuclear Power Source (CNPS)

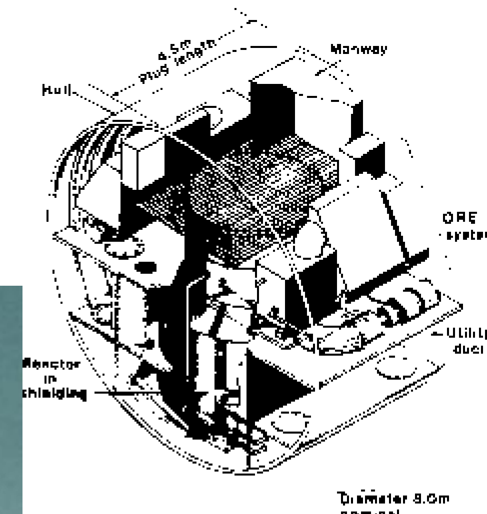
- NWS power requirement increased to **20 kWe** [40 kWe maintenance]
- More efficient power conversion system – toluene **Organic Rankine-cycle Engine (ORE)** [**135 kWt**; 64 kg U; **12 Zr-2.5%Nb/K** heat pipes]
- Much shorter heat pipe condenser region due to ORE vaporizers
- **5 B_4C control rods** instead of 18 rotating reflector drums



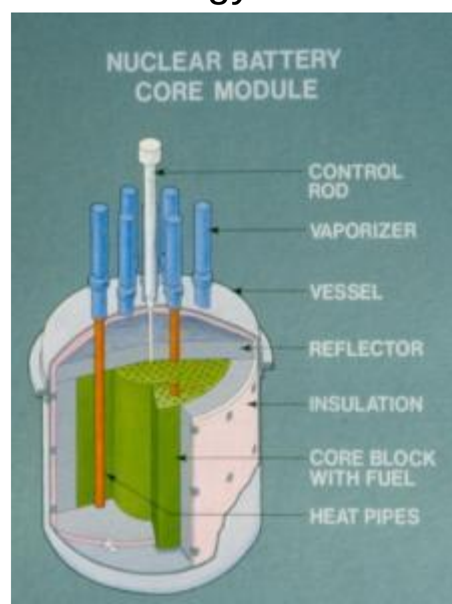


“Nuclear Battery” (W.T. Hancox) Concept Evolution

- Joint CNPS project ceased ~1986-87
- **LANL**: 1987-88 CNPS critical expts.
- **WL**: **500-kWe** **Air Independent Propulsion (AIP)** System for Canadian Submarine Acquisition Project (**CASAP**) version for **Canadian Navy**
  - **ORE**-based design much more compact (seawater condensers)



- **Remote Village Electricity: 600 kWe/2.4 MWt**
  - **Solid-state graphite** core block [2.5-m x 2-m] functions as a **thermal energy storage cell** from which useful energy is passively extracted using 159 **Nb-1%Zr**/K heat pipes
  - Complementary follow-up to SES-10, but at earlier stage of design
  - **No refuelling** for core lifetime: **15 years**
  - LEU TRISO fuel (0.5-mm UO_2 kernels); burnable poisons; ~**550° C** core
- **High-Grade Steam Heat Source**
- R&D work ceased in 1989



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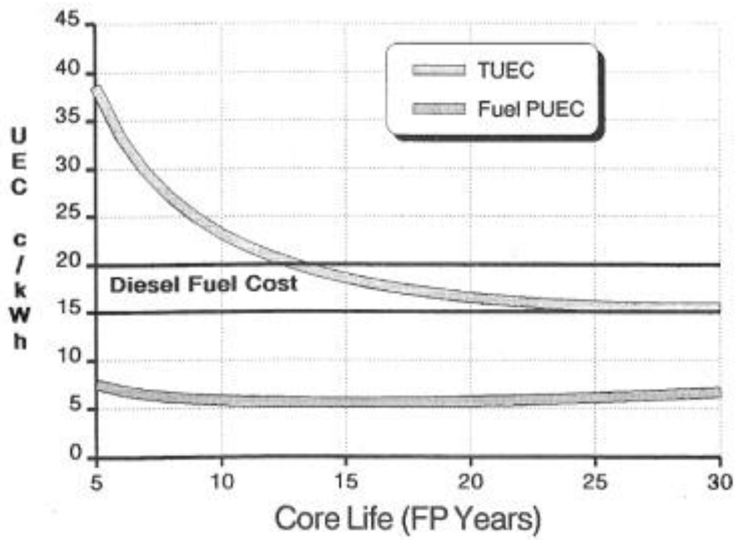
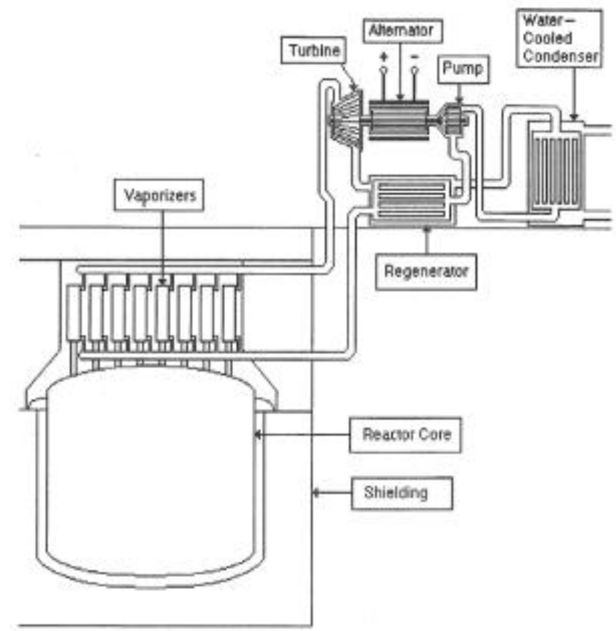
Canadian Nuclear Battery market potential

- **Village electricity:**
  - Competitive with diesel fuel at **~$0.2 /kW$_e$h** (1988)
  - **~150** units





- **Alberta Oil Sands:** ~22% of global recoverable petroleum (1988) [2.3x10^{10} m^3 & 6.8 GJ/m^3 "huff-&-puff" process]
  - High-temperature steam conditions similar to an **OCR** [secondary coolant loop **≥370° C**]
  - **140,000** units!!! [**1 NB** = 13,149 MWd]

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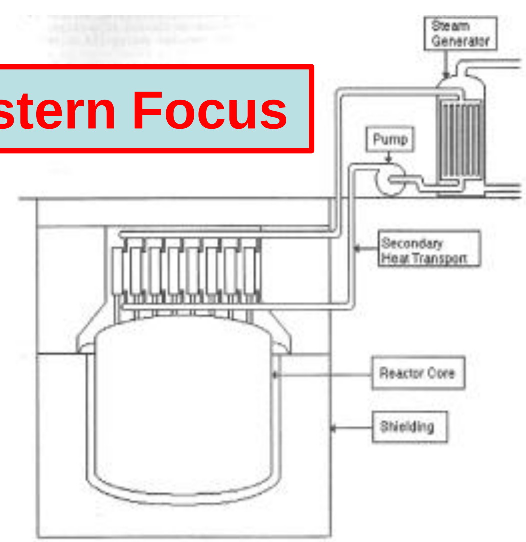
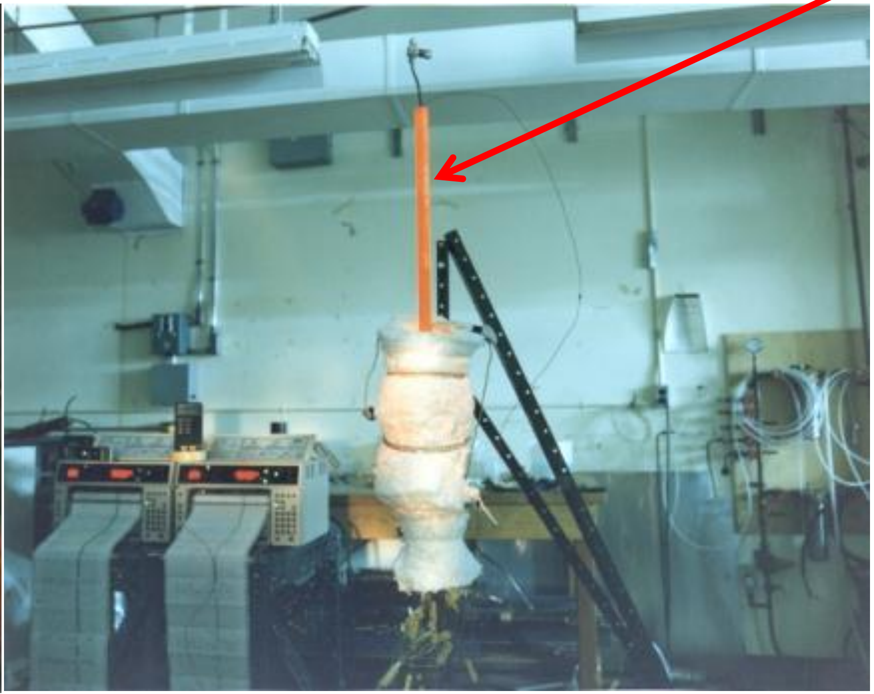
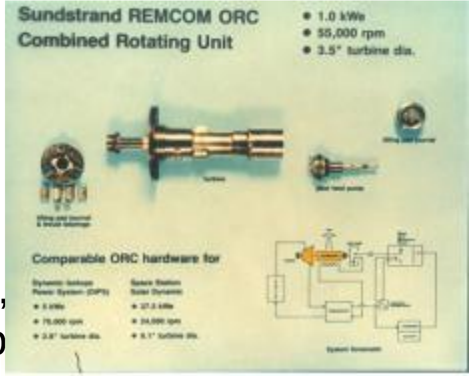


Nuclear Battery component technology R&D at WL

- **Gravity-Assist Zr-Potassium Heat Pipe**
  - Demonstrated heat transfer performance up to **1.1 kWt/cm^2 at 500° C**
  - Near-full-scale heat pipe transported **~19 kWt**



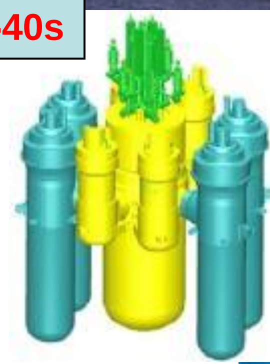


- **Toluene Organic Rankine-cycle Engine (ORE)**
  - Demonstration **1-kWe** toluene ORE unit operated at WL for **2400 h**, including **650 h** single continuous run with simulated remote startup

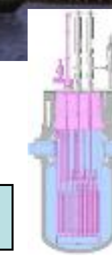
Now: Transportable (low political risk) SMRs derived from Marine/Naval Light Water Reactors (LWRs)

- Barge mounted **Russian KLT-40s** 2x35 MWe/150 MWt from **OKBM Afrikantov**; ***easy decommissioning***
  - ***Akademik Lomonosov*** (only SMR) under construction at Baltiysky Zavod shipyard; **~$340M [$4857 /kWe; *~5 cents/kWh*]**
  - Loop-type PWR derived from icebreaker reactor design: U-10%Zr alloy fuel; ***58 operators***
  - Expected S/U **2013** Vilyuchinsk, Kamchatka
  - **KLT-20** derivative: **20 MWe/70 MWt** 8 years

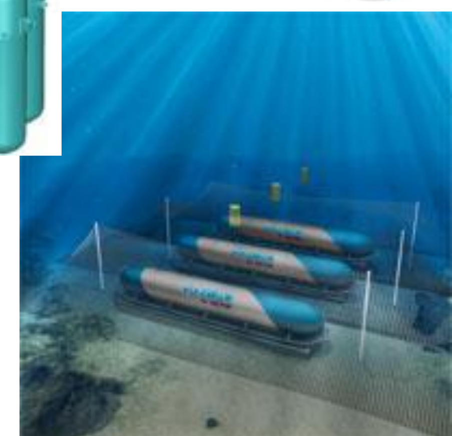
KLT-40s



KLT-20



- Subsea **French** 50-250 MWe **Flexblue** from **DCNS**
  - ***Remotely controlled*** from shore
  - Onboard control room for S/U, S/D & maintenance
  - Accessible by mini-submersible; ***concrete savings***
  - Service **<80 km** inland [no HVDC lines]; **~2/3 of global population**



Flexblue

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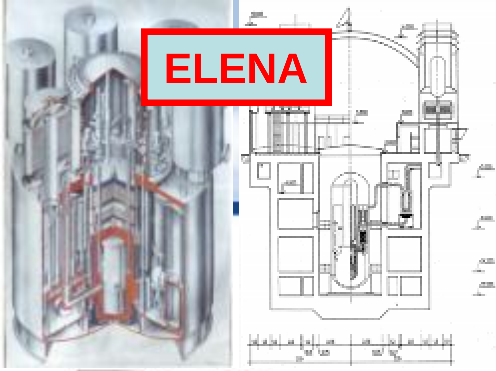
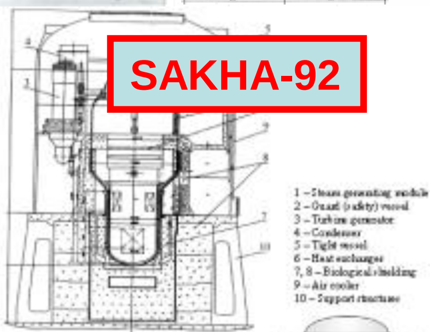
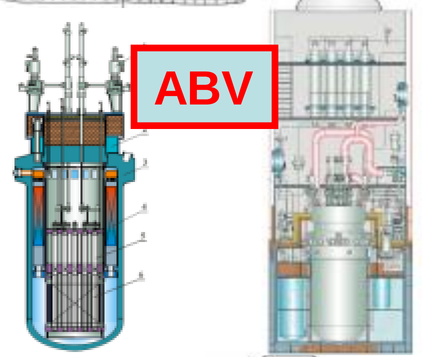
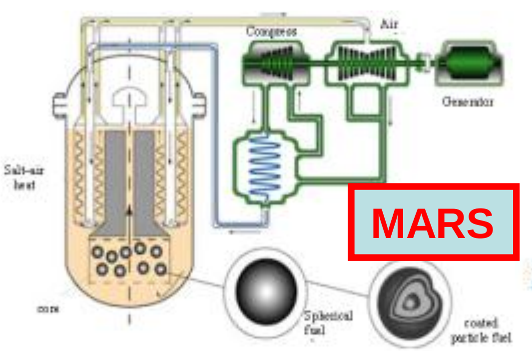
The *smallest* current Russian SMR designs & concepts

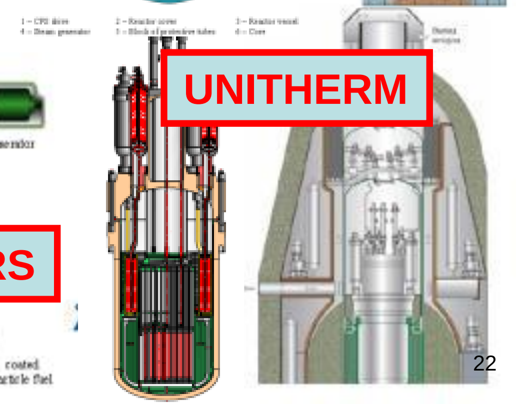
- **ELENA**: **68 kWe**[**TE**]/3.3 MWt **I(*Integral*)PWR for district heating**, **Kurchatov Institute** (**KI**), Moscow
  - Transportable, *autonomous/unattended*
  - 21.7 year core lifetime; scale-up from **GAMMA**
- **SAKHA-92**: **1 MWe**/7 MWt **IPWR**, 25 years, **OKBM, Nizhny Novgorod**, transportable by rail, sea or truck
- **ABV-3**: **2.5 MWe/16 MWt IPWR, OKBM Afrikantov**,10-12 years
- **UNITHERM**: **6 MWe/30 MWt** (or 2.5 MWe + 20 MWt district heating), **IPWR**, 20-year lifetime, **NIKIET/RDIPE**, Moscow
  - Transportable, *autonomous/unattended*
- **MARS: 6 MWe/16 MWt**, **KI**, ***Molten Salt Reactor*** concept,15 or ***60 years***, *autonomous*, air turbine
- **VKT-12**: **12 MWe *BWR*** 10 years, **RDIPE/RIAR**, Dimitrovgrad



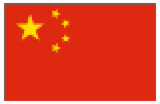






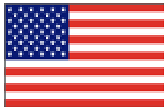


Some more very SMR designs & concepts

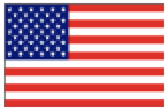


- **NHR-5:** 5-MWt integral heating reactor at INET, Tsinghua U., Beijing,1989 (with help from Germany)

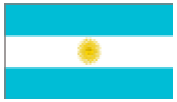
- **NBR (150 kWe) & SNB25:** **2.5 MWe**/25 MWt, RMC Kingston, unpressurized, 95° C outlet, refrigerant **ORE**



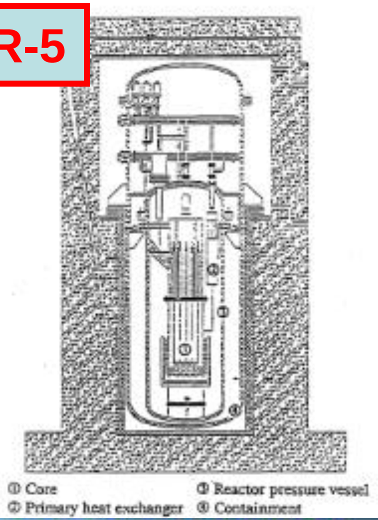
- **DEER:** 10 MWe/40 MWt Deployable Electric Energy Reactor, Radix Power & Energy

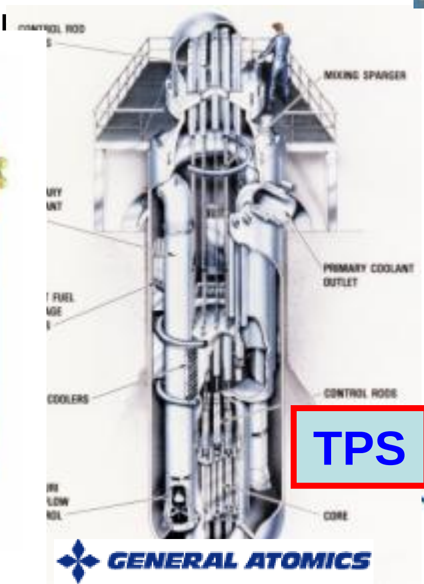


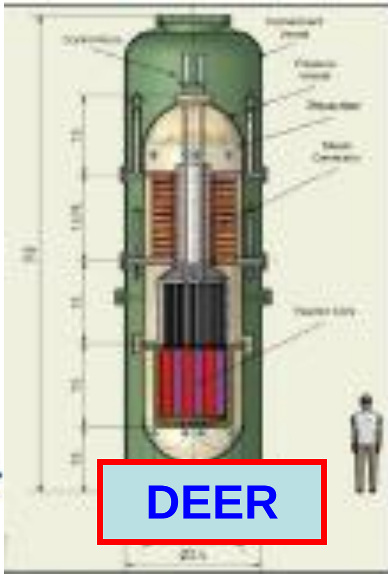
- **TPS:** 16.4 MWe/64 MWt TRIGA Power System General Atomics



- **CAREM-25:** 25 MWe/10

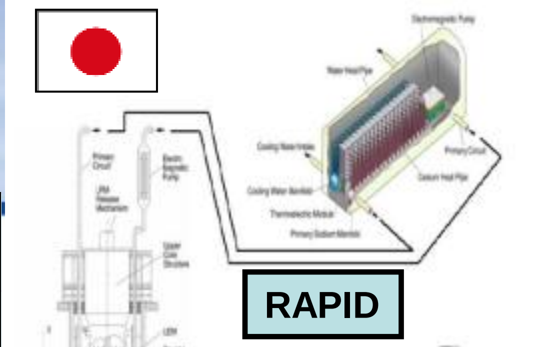


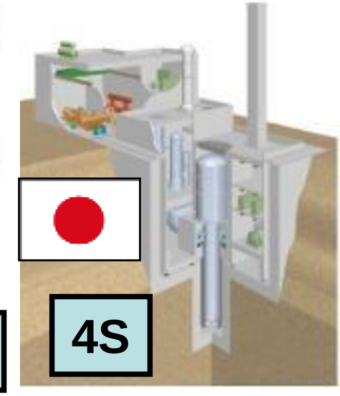


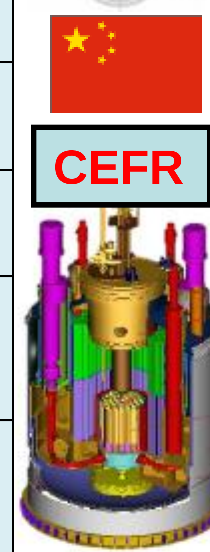


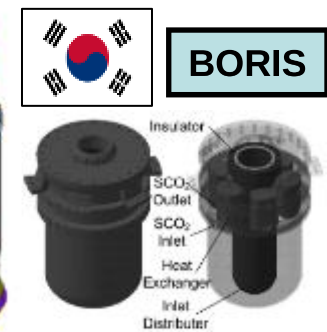
Some Liquid Metal Cooled SMRs

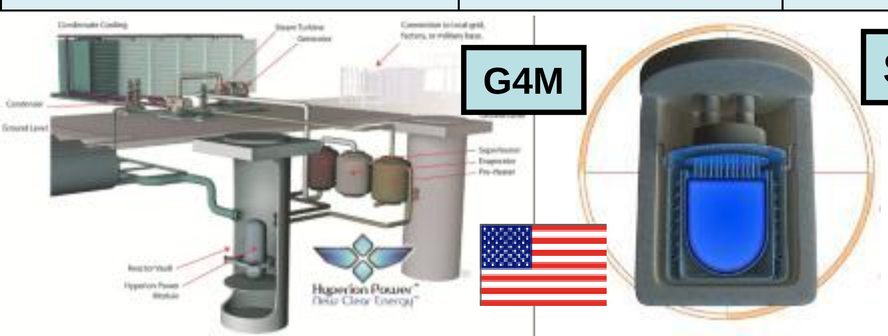
Concept	Developer	Power	Coolant	Lifetime (years)
RAPID Refuelling by All Pins Integral Design	CRIEPI, Japan	1 MWe/10 MWt	Na	10
4S Super-Safe Small & Simple	Toshiba, Japan	10 MWe/30 MWt	Na	30
BORIS Battery Omnibus Reactor Integral System	SNU, Republic of Korea	10 MWe/22.2 MWt	Pb	20
CEFR Chinese Experimental Fast Reactor	CIAE, China/OKBM	20 MWe/65 MWt	Na	-
SVBR-10 Lead-Bismuth Fast Reactor	AKME-Engineering, Russia	12 MWe/43.3 MWt	PbBi	15-20
SSTAR Small Sealed Transportable Autonomous Reactor	ANL	20 MWe/45 MWt	PbBi	30
G4M Gen4 Module (HPM Hyperion Power Module)	Gen4 Energy Inc. (Hyperion Power Generation Inc.)	25 MWe/70 MWt	PbBi	10

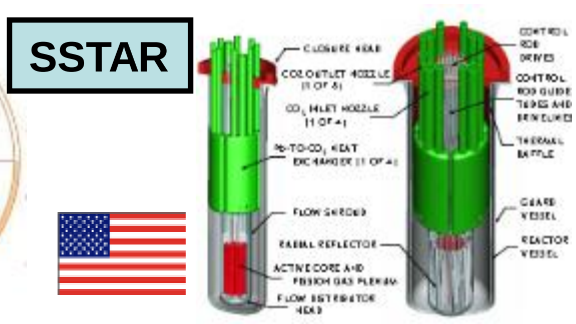






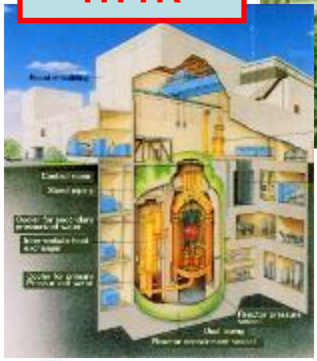


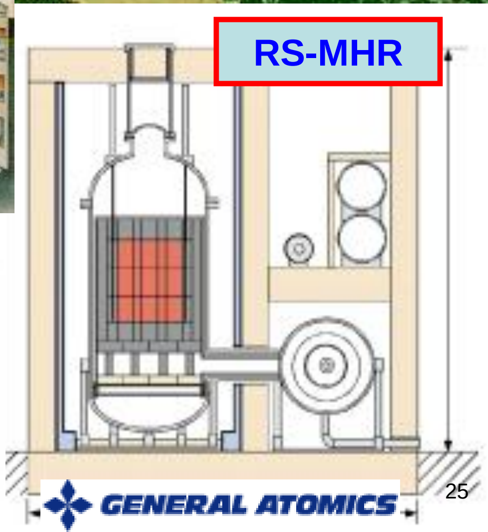


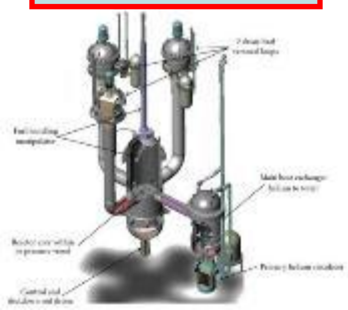


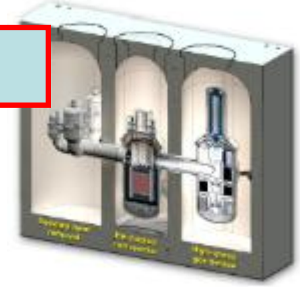
He gas-cooled SMRs

- **Pebble bed reactors**
  - **Germany AVR** 15 MWe/46 MWt, 1967-88
  - **China HTR-10** 10-MWt, Tsinghua U., 2000
- **Prismatic block reactors**
  - **Japan HTTR** 30 MWt test reactor, 1999
  - **General Atomics RS-MHR**: Remote Site MHR 10-25 MWe
- **Gas-cooled fast reactors**
  - **EM²: General Atomics** 40 MWe/200 MWt **30 years** without refuelling
  - **ALLEGRO:** 50-80 MWt GFR prototype **EURATOM/CEA**, Czech Republic, Slovakia, Hungary



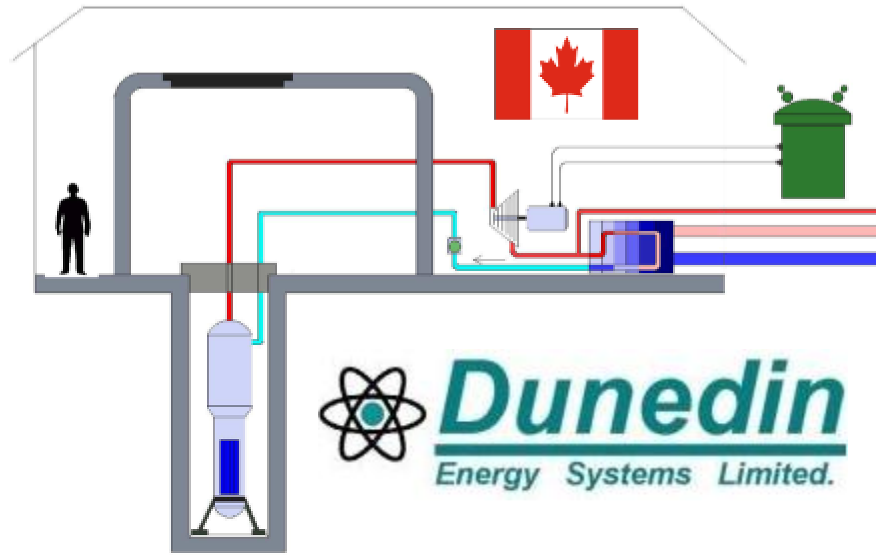




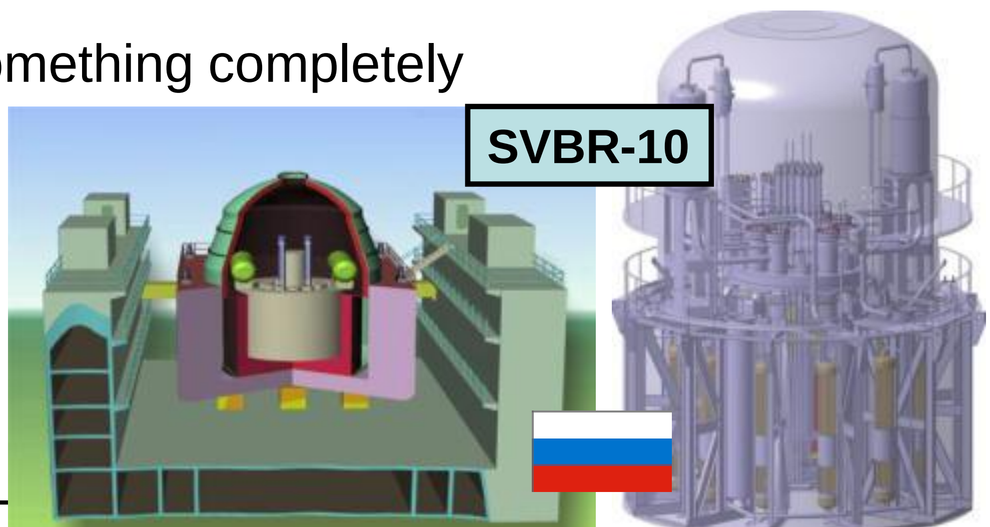


The future: What the Canadian very small reactor market might involve

- Compact **IPWRs** derived from Marine/Naval reactor technology
- Scaled down integral Pb-Bi **LMRs** also linked to Marine/Naval reactor technology [80 reactor-years of experience]
- Or maybe something completely different …..



5-MWe SMART (Small, Modular, Adaptable, Reactor Technology)



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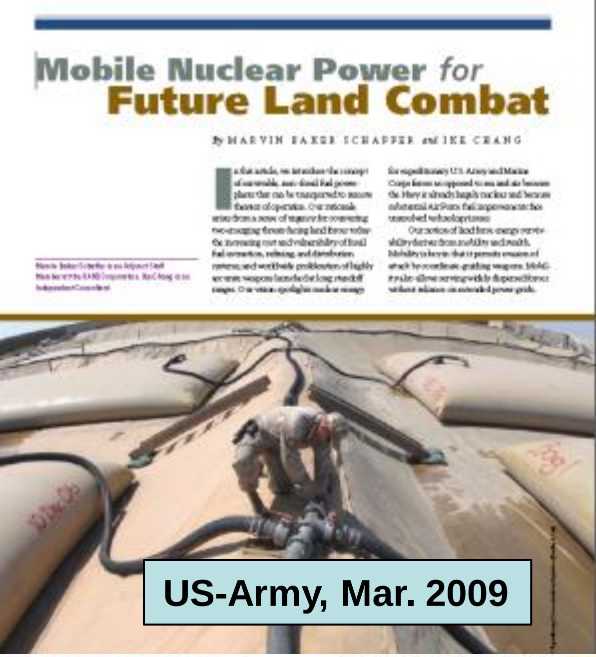
What we really need: The '*i*-Reactor' concept

(How do you like them Apples?)

- Must be compact, light & licensed to be ***transportable*** with containment & shielding
  - **Boeing Chinook 234**: Highest rated commercially certified lift capacity at **27,000 lbs/12.2 Mg**
- Must dissipate decay heat passively to ambient air at all times
- Must be licensable for ***autonomous reactor operation***
- This suggests a very low-power **(<1 MWe)**, compact **gas-cooled fast reactor**
  - Pressurized **He** primary coolant: ***inert***, light, ~550° C
  - **>50-year** core life without refuelling
  - <20 wt% ^{235}U LEU fuel; probably Be, BeO neutron reflector
  - Desirable to have essential loads powered by TEs
- ***Uncertain technical/economical feasibility***
- Requirements similar for a **Lunar Base** reactor

UNRESTRICTED / ILLIMITÉ

Recent interest in mobile reactors



Wrap-up

- A potential niche market exists for very small reactor units in remote **Canadian** locations, especially to support ***mine development***
- Very small reactors are technically doable, dozens of SMR concepts exist (especially from **Russia**), many are of **Marine/Naval** origin
  - Canada once was a leader in this field with AECL's **SES-10** & **Nuclear Battery** programs
- The very small reactor market might be addressed using existing technologies, but economic viability would likely require
  - **Post Fukushima**: guaranteed passive decay heat removal to ambient air & no hydrogen (or steam) explosion risk
  - Licensed for ***autonomous/unattended*** operation of the reactor core
  - ***Transportability*** of the nuclear portion as a sealed unit (new & used)
  - A large # of application units (>100) to be worthwhile; need a good technical fit with the Alberta **Oil Sands**
  - ***Social acceptance & a compelling business case/value proposition***

Western Focus

AECL EACL 1952 - 2012

Call for Abstracts

2nd International Technical Meeting on Small Reactors

2012 November 7-9
The Albert at Bay Hotel, Ottawa, Ontario CANADA

"Celebrating NPD's 50th Anniversary"

DRAFT

Objective
Atomic Energy of Canada Limited (AECL) is hosting the 2nd International Technical Meeting on Small Reactors. There is growing international interest and activity in the development of small nuclear reactor technology. This meeting will provide participants with an opportunity to share ideas and exchange information on new developments.

This Technical Meeting will cover topics of interest to designers, operators, researchers and analysts involved in the design, development and deployment of small reactors for power generation and research. A special session is planned to focus on small modular reactors (SMR) for generating electricity and process heat, particularly in small grids and remote locations. On the last day of the Technical Meeting (November 9th), AECL will host a tour of the Chalk River Laboratories for all interested attendees. The tour will include the ZED-2 and NRU reactors.

Following the success of the first Technical Meeting in November 2010, which captured numerous accomplishments of low-power critical facilities and small reactors, the second Technical Meeting is dedicated to the achievements, capabilities, and future prospects of small reactors. This meeting also celebrates the 50th Anniversary of the Nuclear Power Demonstration (NPD) reactor which was the first small reactor (20 MWe) to generate electricity in Canada.

Topics of Interest
Presentations related to the following topics are of interest to this Technical Meeting:

- Safety and Licensing
- Reactor Physics (physics code validation, bias and uncertainty, benchmarking, etc)
- Advanced Fuels (new compositions, inherently safe fuels, etc)
- Instrumentation and Control
- Thermalhydraulics (passive safety, heat pipes, etc)
- Research and Test Reactors
- Commercial SMRs for electricity generation
- Small reactors for remote locations
- Novel Concepts
- Autonomous Control and Operation

Abstract Submission
Authors should submit an extended abstract (two to three pages) with contact information, via electronic mail, to the Technical Program Chair, Shuwei Yue, (yues@aecl.ca). Extended abstracts will be published on CD in the Conference Proceedings.

Technical Meeting Organizers
Steering Committee……………………………Iain Harry, CIC
John Root, CCNI
Romney Duffey, DSM Associates
Marcel de Vos, CNSC
Paul Labbe, DRDC
Dan Meneley, UOIT
John McKenzie, SaskPower
General Chair…………………………………… David Sears
Technical Program Chair……………………………Shuwei Yue

Key Dates
Extended abstracts deadline………………………August 31, 2012
Early-Bird registration deadline ………… September 15, 2012

Further Information
Additional information may be obtained by visiting www.aecl.ca/SMR or by contacting Technical Program Chair, Shuwei Yue, AECL, Chalk River Laboratories, Chalk River, Ontario K0J 1J0 CANADA, Tel: (613) 584-3311 ext. 44635; Email: yues@aecl.ca.

NPD – Canada's First Power Reactor

- 2012 Nov. 7-9, Ottawa
- contact **yues@aecl.ca**

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