Are Small Nuclear Reactors the Answer to Sustainable Energy for Canada?

Paul Doherty

James Smith

Paul Doherty's Nuclear Industry Background

- Developed early interest in nuclear at U. Manchester, UK
- Hired by OH's Central Nuclear Services and worked on several high profile projects including: PNGS A Calandria Vault corrosion; Ion Chamber support SCC, Moderator HX corrosion (operated two 40x10 R&D trailers at PNGS and DNGS), DNGS new build issues, Zebra mussel control, chemical cleaning monitoring, electrochemical monitoring, FAC ...
- Worked for two years in the energy management division
- Joined B&W in 1993; supervised major R&D projects and supported sales
- R&D Projects in welding, new SG alloys, chemical cleaning, chemistry…
- Contributed to several EPRI committees including: Yucca Mountain, Secondary side chemistry, chemical cleaning
- Environmental Degradations Conf. and Fontevraud Conf. Organizing/Technical committees

Global Nuclear Energy Timeline

- 1932 - Discovery of the neutron
- 1951 - First commercial production of electricity using nuclear energy
- 1954 - First US Nuclear Powered Submarine launched
- 1957 – Shippingport reactor starts up, reactor originally for aircraft carrier
- 1962 – Canada's NPD reactor starts up, "**proof of concept**" for **CANDU**
- 1970s - 25 countries had initiated nuclear-based electricity generation projects to satisfy their growing need of power.
- Interest in nuclear power was fueled by a growing concern for energy security owing to continuous depletion of fossil-based fuels, increasing oil prices and more recently by mounting concerns for the potential effects of environmental degradation by fossil-based energy sources.

Why the Nuclear Industry Stalled

- A drop in oil prices and two major accidents; one at Three Mile Island in the US (1979), and another at Chernobyl in the former Soviet Union (1986), stalled the nuclear industry growth during the 1980s.
- Three Mile Island and Chernobyl raised major safety and reliability concerns and the industry was never able to replicate its initial growth performance.
- Several countries (most notably France) continued to build their civil nuclear plans.
- This contributed to a relatively smaller global industry growth in the period 1980 – 2000.

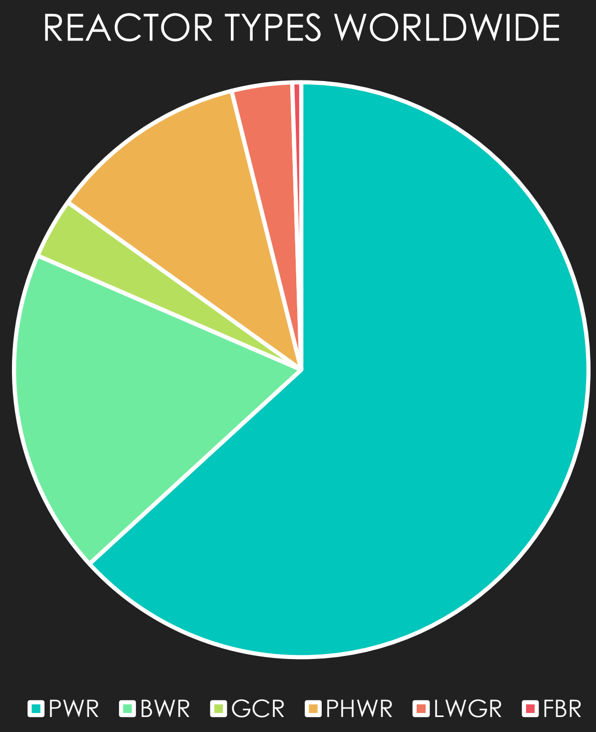
Nuclear Industry Overview

- **2018** – thirty-one countries produced electricity from nuclear plants.
- This is approximately **18,000** reactor-years of operating experience.
- **451** commercially operating nuclear reactors representing an installed generating capacity of **394** Gigawatts.
- Approximately **315** reactors were in commercial operation in **19 OECD** member countries representing an installed generating capacity of **298** Gigawatts.
- **Russia, India and China**, together have **96** reactors in operation and **32** more under construction.

Top 12 Leading Nuclear Power Users

- In 2018, the top 12 leading nuclear power producers were:
  - USA 99 Reactors 806 TWh 20% of total (coal represents 60%)
  - France 58 Reactors 382 TWh 72% of total
  - China 39 Reactors 233 TWh 4% of total
  - Russia 35 Reactors 190 TWh 18% of total
  - Korea 25 Reactors 141 TWh 27% of total
  - Canada 19 Reactors 95 TWh 15% of total (60% of Ontario total)
  - Ukraine 15 Reactors 80 TWh 55% of total
  - Germany 8 Reactors 72 TWh 12% of total (being phased out 2022)
  - UK 15 Reactors 64 TWh 19% of total
  - Sweden 9 Reactors 63 TWh 40% of total (were to have all closed 2011)
  - Belgium 7 Reactors 40 TWh 50% of total
  - Japan 42 Reactors 29 TWh 4% of total (most remain closed)

Reactors Operating Worldwide (451 Total)



Note: 60 New Reactors under Construction, 50 are PWR

Areas Where Nuclear Power is #1 Energy Source

- In 2018, several areas: France (72%), Ontario (60%), Ukraine (55%), Belgium, Hungary and Slovakia (all at about 50%) stand out because of their reliance on nuclear power generation.
- France has spearheaded the use of nuclear-based power generation in the world, current Government trying to reduce nuclear to 50%
- Nearly three-quarters of all France's power comes from nuclear plants
- Lithuania was close to 75%, but now zero due to closure of one plant
- Ontario (presently 60%, will reduce to 50% by 2024 with Pickering closure)

Canada

- Canada has ~ 75 years of nuclear energy generation experience.
- Atomic Energy of Canada Ltd (**AECL**) in 1952
- Government has funded its R&D programmes since inception.
- **AECL** also receives commercial revenues from its ventures.
- Canada has unique situation where nuclear development is under Federal Government, whereas power generation under Provinces. Developing and building reactors has little opportunity for ROI for Federal Government.
- Attempts at Build/Own/Operate/Transfer (e.g. Gentilly 1) have failed.
- Big Ontario build programme in 1960s and 1970s partly result of Federal Government concern about Ontario's heavy coal fired buildup, based on imported US coal, balance of trade deficit, etc. Gov'ts co-operated and gambled on CANDU and programme largely paid off.

Canada - Timeline

- 1930 – Uranium discovered in Great Bear Lake, NWT
- 1950's – France, UK and Canada develop nuclear power programmes based on "**natural**" uranium reactors in absence of enriched uranium
- 1957 – Development of NPD-2 the first **CANDU** reactor on-line in 1962)
- 1971 – PNGS 1 and 2 and Gentilly 1
- 1972-3 – PNGS 2 and 4
- 1976-8 – BNGS 1, 2, 3 and 4
- 1979 – Three Mile Island Accident
- 1990-3 – DNGS 1,2,3 and 4
- 1999 – Atomic Energy Control Board granted operating licenses for Maple 1, reactors started in 2000 and 2003, major commissioning issues, shut in 2008, probably cost taxpayers $1B ($650M on reactors alone, plus Nordion lawsuit)

Chalk River - Timeline

- Government set up Chalk River Laboratories in the 1940s; have been the locus of all **AECL** R&D. Post war mandate, to develop a power reactor which used no enriched fuel because of GoC concerns re stigma that **enriched fuel = weapons**.
- 1947 - 42-MW National Research Experimental (**NRX**) reactor built
- 1957 - 135-MW National Research Universal (**NRU**) reactor
- Other research reactors followed, two 10-MW MAPLE units latest design developed.
- Six research reactors were built on university campuses.
- **AECL** has done all the developmental work on the **CANDU** reactor types; NOTE: commercial developments now done by SNC-Lavalin subsidiary CANDU Energy
- Recently proposed the development of the next-generation **AFCR CANDU** Reactor and also had the lead role internationally in developing the Generation IV super-critical water-cooled **CANDU-X** reactor. Project shelved.

Power Generation in Canada

- Canada’s nuclear energy production peaked in 1994 at 102.4 TWh.
- Subsequently nuclear energy production declined to 67 TWh by 1998 because reactors were shut down, and increased to 85.6 TWh in 2005, due to improved reactor performance and refurbishment.
- There has been renewed interest in nuclear energy. This has been spurred by increasing demand (particularly within Ontario), and to a lesser degree, a desire to comply with Canada’s Kyoto Agreement obligations.
- In 2004 the Provincial Government of Ontario proposed plans to build several new nuclear reactors in the province. All plans were deferred.

CANDU Size History

NPD	22 MWe	1950's	
Douglas Point	220 MWe	1960's	
Pickering	540 MWe	1960's	
Bruce 480 fuel channel	800 MWe	1960's	
CANDU 6 380 fuel channel	700 MWe	1970's	(GII, Pt. Lepreau, Cordoba, Wolsong 1)
Darlington 480 fuel channel	880 MWe	1970's	
CANDU 3 (not sold)	360 MWe	1980's	
CANDU 6 Improved	700 MWe	1990's	(Romania, Wolsong 2-4, Quinshan Ph III)
EC6, including AFR (not sold)	700 Mwe	2000's	
ACR (not sold)	1000 MWe	2000's	
CANDU 9 (not sold)	900 MWe	1990's	
CANDU AFCR (not sold)	750 Mwe	2000's	
CANDU-X (not sold, shelved)		2000's	

Ontario Outlook

- The province of Ontario dominates the Canadian nuclear industry.
- Ontario contains all of the country’s nuclear power generating capacity. Ontario has 18 operating reactors providing ~60% of the province’s electricity.
- The province has refurbished 4 reactors. (one at Darlington underway)
- Ontario consumed approximately 157 TWh of electricity in 2018
- Ontario exports a small portion of generated power, may increase imports in the future (e.g. from Hydro Quebec)
- The portion of Ontario's electricity production from hydroelectric generators is approximately 22% of total consumption, or 34.8 TWh.

Ontario "Integrated Power Supply Plan"

- In September 2007, the Ontario Power Authority filed it's first-ever 20-year "Integrated Power Supply Plan" (IPSP) with the Ontario Energy Board.
- The IPSP was similar to, and was built on the Ontario Energy Ministry's "Supply-mix" directive issued in June 2006, which directed the province to:

  1) Double the amount of hydroelectric, wind and other renewable capacity on its grid by 2027;

  2) Slash peak demand by 6,300 MW by implementing aggressive conservation programmes, also by 2027; and

  3) Retire Ontario Power Generation's 6,434 MW of remaining coal-fired plant by 2014.

What is a “SMR”?

- Small Modular Reactor
- Up to about 300 MWe capacity
- Can be as small as 3 MWe capacity
- Advanced, Inherent Safety features
- Can serve multiple purposes, including power generation, industrial heat, building heat, desalination, hydrogen production, etc.
- “Smaller, Simpler, Cheaper” (reference: AECL “Roadmap” document)
- Costs predictable, competitive, due in part to modular construction
- Can be on-grid, off-grid, end-of-grid

James Smith Experience with Small Reactors

- Extensive engineering and Business experience, CANDU and PWR
- Participated in CANDU 3 development (components) while at BWXT
- Participated in PTAC (Petroleum Technology Association of Canada) Study in 2010. Concluded large, commercially available reactors could not meet PTAC requirements. However, small gas-cooled reactors could meet requirements (particularly high steam pressure)
- Authors of PTAC report formed Northern Nuclear Industries Inc., 2014
- Business started as a post-retirement activity for James Smith and Ralph Hart (formerly of AECL, General Dynamics, IAEA, Westinghouse and SNC-Lavalin).

James Smith Experience with Small Reactors

- N2I2 Examined many alternatives for "best fit" SMR for Canada with thought of developing it. Looked at small PWR, GCR, Fast Reactors, Molten Salt reactors etc., with careful attention to timeframe to develop. Concluded use Triso/Pebble fuel, lead cooled thermal reactor.
- All work was self funded. Found zero interest in Governments to fund it, and found zero interest in private funding, and near zero market interest. Issues were length of time to produce product, complex project risks, technology risks, licensing risks etc.
- 2016, R. Hart passed away, effectively shutting down N2I2 (some consulting work continued, but reactor development stopped).
- Through the above, James Smith developed deep understanding of the technological and financial challenges of this business.

• Admiral Rickover (US Navy) Quote (1953)

- “Important decisions about the future development of atomic power must frequently be made by people who do not necessarily have an intimate knowledge of the technical aspects of reactors. These people are, nonetheless, interested in what a reactor plant will do, how much it will cost, how long it will take to build, and how long and how well will it operate. When they attempt to learn these things, they become aware of confusion existing in the reactor business. There appears to be unresolved conflict on almost every issue that arises.
- I believe that this confusion stems from a failure to distinguish between the academic and the practical. These apparent conflicts can usually be explained only when the various aspects of the issue are resolved into their academic and practical components. To aid in this resolution, it is possible to define in a general way those characteristics which distinguish the one from the other.

Admiral Rickover comments: Summary

Academic Reactor

1. It is simple
2. It is small
3. It is cheap
4. It is light
5. It can be built very quickly
6. It is very flexible in purpose
7. Very little development required
8. Study Phase, NOT being built now

Practical Reactor

1. It is being built now
2. It is behind schedule
3. Immense development work
4. It is very expensive
5. Long time to build, development
6. It is large
7. It is heavy
8. It is complicated

Worldwide Status with SMRs

Country	Product	Description	Status
Russia	VBER	300 MWe PWR	Design complete, planned
	KLT 40S	35 MWe PWR	2 Barge Mounted, built, in operation
	SVBR	100 MWe Pb-Bi	"Fast", derived from subs/ready for deployment
	AVB	8 MWe PWR	Operating since 1980s
Argentina	Carem	25 MWe PWR	Under construction (2019)
China	HTR-PM	2 x 105 MWe HTGR	Under Const'n, Pebble fuel plant complete
	MSR	Molten Salt	2 prototype plants under construction, have all US documentation: Oak Ridge

Worldwide Status with SMRs

Country	Project	Description	Status
Korea	SMART	90 MWe PWR	Designed, Licensed
USA	NuScale	60 MWe PWR	Federal Co-Funding, designed, licensing at NRC, proposed site & operator
	BWXT mPower	360 MWe PWR	Co-funded, abandoned
	W IRIS	335 MWe PWR	Shelved
	W SMR	225 MWe PWR	Looking for site, operator, TVA?
	GE Prism	300 MWe Na fast	Fuel re-burner, on hold.

In the US, there are probably 20 additional "start-ups", including one funded by Bill Gates, mostly promoting "academic reactor" designs ranging from PWR to HTGR to Na-cooled fast reactors etc.

Is This an “Academic Reactor”?

SMR Claim:	**Academic Reactor:**
Simpler*	Simple
Smaller*	Small
Cheaper* (*Per AECL “Roadmap”)	Cheap
Lighter (low pressure coolant)	Light
Fast Modular Construction	Built very quickly
Power, Industrial heat, desal etc.	Flexible in Purpose
Can go to prototype quickly	Little Development Required
Not currently being built	Study Phase, Not being built

Practical Reactor Aspects of SMRs

- Every SMR uses enriched fuel, not currently allowed in Canada
- Canada has no fuel enrichment or enriched fuel fabrication capability
- US experience with SMRs:

  -about 10 years ago, Government co-funding offered to develop

  -B&W, spent $300M Federal + Virginia State funds, abandoned

  -NuScale, developed 50-60 MWe small PWR, 1 planned for Idaho

  -First Nuscale suggested to be $1.2B, subsequent $400 to $500M
- US estimates, licensing cost: $200M LWR, $1B Advanced Reactor*

* IF it can be licensed at all

Practical Reactor Aspects of SMRs

- In Canada, Power Generation is Provincial Responsibility
- Most Provinces/Territories do not want nuclear
- Indigenous Groups in particular do not want it
- Concerns about safety, reliability, requirements for outsiders as operators, spent fuel disposal, true costs, etc.
- Construction, including modular, is difficult and expensive in remote areas
- Enriched fuel, and licensing
- Very large engineering effort on all-new design, will be beyond **ASME** Code limits for most materials. Significant issues with material selection.

Practical Reactor Aspects of SMRs

- Actual construction, even as prototype, requires full **CNSC** licensing
- Licensing process involves comparison to existing standards .. Non-existent
- Main beneficiary of a prototype would be **SNC-Lavalin**, NOT **AECL**
- **AECL** is promoting program of prototyping 4 SMR types: China is prototyping Molten Salt Reactors, already committed to $3B (US) without even introducing the dissolved fuel. A 4-design program is a $10B program.
- Chalk River recently shut down last large research reactor (**NRU**), and has hired a Management Consortium to run and decommission the site. Building a prototype reactor would give Chalk River a new 60 year "lease on life". **CNL** would continue to absorb several billion dollars a year which could be spent elsewhere.

Practical Reactor Aspects of SMRs

- Large reactors are being sold internationally currently at about $3500/kw. First NuScale about $20,000/kw, and it is a PWR built on an existing licensed site. Northwest Energy is the designated operator. (Operator of Columbia Nuclear Plant)
- **AECL** experience with SMRs is very limited, Maple was a failure
- **SNC-Lavalin** was owners engineer for South African PBMR, project was a failure
- Will have to rely on foreign supply of enriched fuel, which will only be possible if Government radically changes 75 year old laws, and fuel design is identical to fuel already in production
- Even a prototype involves 10's of millions of engineering hours .. Resources? (Just to get to Proposal stage, **AECL** spent $250M on **ACR**)
- If Engineering is undermanned, project goes late, budget is blown, $$$

Are SMRs the Answer to Sustainable Energy in Canada?

- **CNL** is proceeding with its plans. 4 reactors have passed prequalification and have moved on to "due diligence" stage

  -Global First Power (with OPG) 5 MWe HTGR

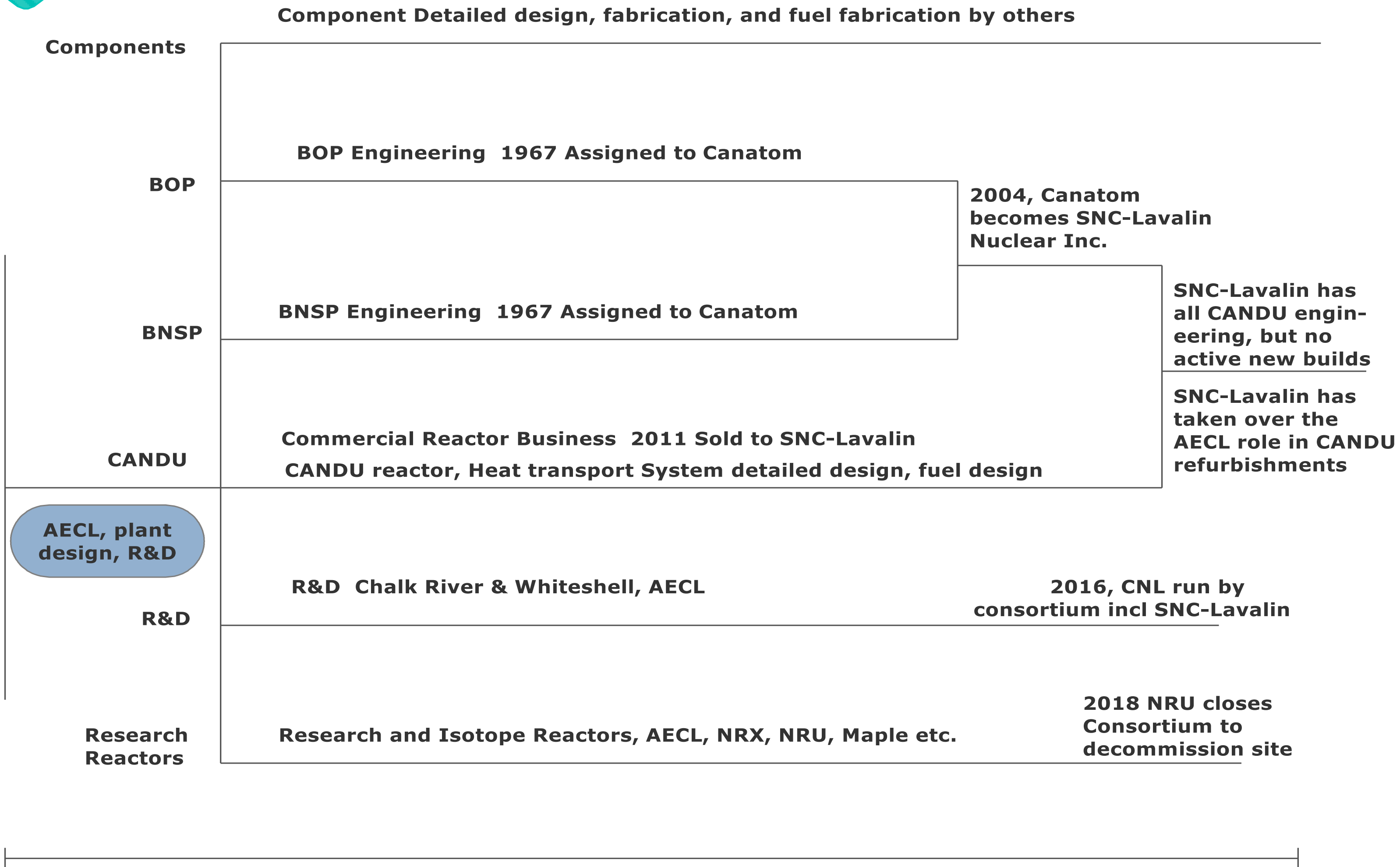
  -Ultra Safe Nuclear Corporation (Actually part of Global FP Offer)

  -StarCore Nuclear 14 MWe HTGR

  -Terrestrial Energy 195 Mwe IMSR

- The above are companies with average 15-20 employees, ideas only, with ideas to be evaluated by AECL. Most have made preliminary ("safety check") licensing submittals to CNSC, and are funded by small Government grants (not necessarily Canadian Government).

What Does AECL (CNL) Really Do?



What does AECL (CNL) Do?

ATOMIC ENERGY OF CANADA LTD.
FEDERAL CROWN CORPORATION
ADMINISTRATION OF CNL
40-50 PEOPLE

CNEA (CANADIAN NUCLEAR ENERGY ALLIANCE
CONTRACTOR HIRED TO OPERATE CNL
ONGOING OPERATIONS PLUS DECOMMISSIONING AND EVENTUAL SHUTDOWN
CONSORTIUM: SNC-LAVALIN, JACOBS, FLUOR

CANADIAN NUCLEAR LABORATORIES LTD.
GOVERNMENT "GOCO"
MAINLY CHALK RIVER, BUT ALSO AT PORT HOPE, WHITESHELL, ETC.
GOVERNMENT NUCLEAR SITES
APPROX 3300 EMPLOYEES

What does AECL (CNL) Do?

AECL 2018 Financial Statement:

Revenues: ($M)	2018	2017	2014 (Info)
Parliamentary Appropriations	826*	784	385
Commercial Revenue	88	111	130
Interest Income	4	5	
Total	918	900	
Expenses: ($M)			
Cost of Sales	65	84	
Operating Expenses	96	68	
Contractual Expenses	323	332	
Decommissioning, Waste Mgmt.	295	26	
Wrap-up Office Activities	5	5	
Total	784	515	
Surplus:	134	385	

*Capital Infrastructure $117M, Decommissioning & Waste Mgmt $450M, Nuclear Science & Technology $259M

NOTE: AECL ANNUAL REPORT IDENTIFIES $7.5B LIABILITY FOR DECOMMISSIONING, 75% OF WHICH IS AT CNL

What Does AECL (CNL) Do?

Areas of Nuclear Science & Technology Activities:

1. Health Focus on Alpha-emitting isotopes, cancer treatment
2. Environmental Interaction of Radioactive materials with ecosystems
3. Border Security Prevention of Smuggling of radioactive materials
4. Cybersecurity, as it relates to nuclear plants primarily
5. Clean Energy; “By 2026 CNL Will Demonstrate how effectively small modular reactors can provide safe and clean energy for Canadians including for remote communities and remote resource extraction industries.”

What Does AECL (CNL) Do?

AECL Annual Report Further Goes on to Say: (re SMRs)

AECL will work with **NRCan** and **CNL** to Understand:

- Existing Capabilities
- Technology Gaps
- Requirements
- **Overall Market Interest**
- Commercial Viability

What's Wrong with This Picture?

- **AECL** has a $7.5B acknowledged decommissioning liability at their sites.
- A "demonstration" nuclear project is a fully licensed nuclear power plant, MINIMUM $1-$2B. Small reactor start-up companies cannot afford this. Note AECL is talking about "projects" (plural) .. 4 projects have been mentioned, all "advanced" reactors .. Collectively $10B undertaking.
- **AECL/CNL** is a research organization, full engineering of plant, as required to license it, mainly benefits **SNC-Lavalin**.
- **CNSC** (and all other international licensing agencies) are ill-equipped to license "non-standard" plants. US Government estimated costs to license a non-LWR at $1B, "if it can be licensed at all".

What's Wrong With This Picture?

- Little or No Market interest.
- Indigenous groups do not want nuclear.
- Technology gaps are immense.
- CANDU was created due to unique requirement for non-enriched fuel. Federal and Provincial (Ontario) Gov'ts aligned and co-operated. There is no enriched fuel capability in Canada. ALL SMRs use enriched fuel. Therefore there is no fuel security using SMRs.

Are SMRs the answer to Sustainable Energy in Canada?

- In theory, a partial "yes", as reactors can be considered non-emission plants
- However, in the target markets they are noticeably not publicly acceptable, they are not expected to be economically acceptable, there will be questions about security of (fuel) supply, we have not yet answered the questions about waste disposal.
- In theory, SMRs could be used to "recycle" spent fuel from other reactors. However, this would involve investments in fuel reprocessing, further complication of the SMR designs, and for very little fuel reburning per reactor.
- To be considered "Renewable", typically a 1000 year fuel supply is required. This is theoretically possible with spent fuel recycling, use of Pu or Th fuels

Are SMRs the Answer to Sustainable Energy in Canada?

- Government has also increased funding to **CNL** ($800M over 5 years) simultaneous with announcing definite closing of **NRU**, presumably to pay for increased staff levels (now 4200 at **CNL** site, incl. Contractors). Hopefully the evaluation work on the SMRs is paid for by this funding and the reactor vendors.
- Government has also given funding ($500K) to **CNA** for a PR type document about the benefits of SMRs.
- These are all still "Academic Reactors". The big expenditures start when they move to detailed engineering, detailed licensing, and prototyping. The Government should <u>stop the programme long before this stage,</u> unless it is fully funded by others.

Are SMRs the Answer to Sustainable Energy in Canada?

- Possible alternatives for the Government of Canada:

  -There are ~100 SMR development projects going on around the world, with some being built now. Wait until they are designed, built, operated, tested, debugged, etc. and buy the nth of a kind. We don't have to develop a unique Canadian solution, especially considering that we will have to adapt to enriched fuel with any SMRs. Unwillingness to work with others led to Canada losing the ITER project ... $20B lost revenue.

  -Focus efforts on other sustainable projects for remote locations, such as Wind with Energy Storage, geothermal if available, below-permafrost gas etc.

  -If Government wants to pursue the SMR business, consider being owner/operator (eg at remote military bases) and look very closely at real cost of operation vs. alternatives

Recommendations

- Adopt a position that SMRs are likely not a good idea for Canada
- **AECL** can carry on present activities AS LONG AS **AECL** ensures that the activities of **CNL** (and **CNSC**) are limited to:
  - Preliminary reviews of technology, preliminary licensing reviews, **funded entirely by the designer/proponents,** and acknowledgement that the studies are on "academic reactors".
  - Market reviews are broadened to get Indigenous involvement and input not only to nuclear and SMRs but to sustainable alternatives, such as wind, natural gas under the permafrost, geothermal, hydro-electric, energy storage, etc. Necessary to review and understand the importance to the Indigenous People of safety, security, clean-ness of energy etc. Understand THEIR perspective. More suitable alternatives might exist.
  - **NO consideration of Demo Projects without an independent licensed operator with full financial backing, including cost/budget increases for delays (inevitable), and including risks such as licensing risk and eventual decommissioning liability coverage.**
  - There should be an independent 3rd Party Oversight of activities, in particular market interest reviews .. Too many opportunities for this to become a multi-billion dollar mis-adventure.