Small Modular Nuclear Reactors
~ The Canadian Context ~

A Slide Show

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The Point Lepreau CANDU Nuclear Reactor

The Point Lepreau Reactor – a CANDU-6 model (about 600 MW electrical)
The fuel is natural (unenriched) uranium; the coolant and moderator are heavy water.
Inside a CANDU reactor

Uranium atoms are split in the CORE to heat water. Hot water is pumped to the BOILER (Steam Generator). Steam turns the blades of a TURBINE to generate electricity. Everything in the “primary cooling circuit” (on the left) becomes RADIOACTIVE.
### Small Modular Nuclear Reactors being “pre-evaluated” by Canadian Nuclear Safety Commission (CNSC)

<table>
<thead>
<tr>
<th>VENDOR</th>
<th>SITE</th>
<th>SITE OWNER</th>
<th>BACKER(S)</th>
<th>REACTOR TYPE</th>
<th>DESIGN ACRO</th>
<th>MW</th>
<th>Fuel</th>
<th>Waste &quot;Plan&quot;</th>
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</thead>
<tbody>
<tr>
<td>ARC Nuclear Canada Inc.</td>
<td>Point Lepreau</td>
<td>NB Power</td>
<td>NB government, NB Power</td>
<td>Sodium cooled fast reactor</td>
<td>ARC-100</td>
<td>100</td>
<td>13.1 % enriched uranium</td>
<td>“removed for recycling”</td>
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<tr>
<td>GE-Hitachi Nuclear Energy</td>
<td>Darlington</td>
<td>OPG</td>
<td>OPG</td>
<td>Boiling water reactor</td>
<td>BWRX-300e</td>
<td>300</td>
<td>3.4 to 4.95 % enriched uranium</td>
<td>‘segregated’ for “final disposal”</td>
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<td>Moltex Energy</td>
<td>Point Lepreau</td>
<td>NB Power</td>
<td>NB government, NB Power</td>
<td>Molten Salt Reactor</td>
<td>SSR-W</td>
<td>300</td>
<td>Reactor grade plutonium</td>
<td>off site “disposal” of fuel waste</td>
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<td>NuScale Power, LLC</td>
<td>-</td>
<td>-</td>
<td>Bruce Power, OPG</td>
<td>Pressurized water reactor</td>
<td>NuScale</td>
<td>60</td>
<td>&lt; 4.95 % enriched uranium</td>
<td>wet then dry storage, long term in “national” plan</td>
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<tr>
<td>StarCore Nuclear</td>
<td>Chalk River / Pinawa</td>
<td>AECL</td>
<td>CNL</td>
<td>High-temperature gas cooled reactor</td>
<td>StarCore</td>
<td>10</td>
<td>15 % enriched uranium</td>
<td>off-site waste, entombment on site of reactor</td>
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<tr>
<td>Terrestrial Energy Inc.</td>
<td>Darlington / Chalk River</td>
<td>OPG / AECL</td>
<td>OPG</td>
<td>Molten Salt Reactor</td>
<td>IMSR</td>
<td>200</td>
<td>&lt; 5 % enriched uranium</td>
<td>Liquid Fuel Waste</td>
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<tr>
<td>Ultra Safe Nuclear Corporation</td>
<td>Chalk River</td>
<td>OPG</td>
<td>Global First Power (Proponent), CNL</td>
<td>High-temperature gas cooled reactor</td>
<td>MMR-5 and 10</td>
<td>5-10</td>
<td>19.75 % enriched uranium</td>
<td>Spent fuel in “national” plan</td>
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<tr>
<td>X Energy, LLC</td>
<td>Darlington</td>
<td>OPG</td>
<td>OPG</td>
<td>High-temperature gas cooled reactor</td>
<td>Xe-100</td>
<td>80</td>
<td>15.5 % enriched uranium</td>
<td>Wet then dry storage, long term in “national” plan</td>
</tr>
</tbody>
</table>

Some SMNRs are “fast” reactors, meaning the neutrons are not slowed down by a “moderator”. Without a moderator, the fissile material in the nuclear fuel must be much more concentrated.  

Source: [www.stop-smrs.ca](http://www.stop-smrs.ca)
Most Small Modular Nuclear Reactors plan to use unorthodox fuels and unusual coolants. Fuel: Enriched Uranium (HALEU) or plutonium. Coolant: molten salt, liquid metal, or gas.
TRISO coated fuel particles are supposed to contain all fission products including gases.

WHAT IS TRISO FUEL?

Intended for any high temperature gas-cooled reactor that is “moderated” (i.e. uses “slow” neutrons)

Coated particle

Outer pyrolytic carbon
Silicon carbide
Inner pyrolytic carbon
Porous carbon buffer

Fuel kernel (UCO, UO₂)

[uranium - dioxide or oxycarbide]

diameter of kernel < 1/2 mm
In natural uranium, only 7 atoms out of 1000 are “fissile” (yielding energy). The other 993 atoms are non-fissile, but some “become” plutonium atoms. The earliest reactors, and all CANDU reactors, use natural uranium as fuel.

Plutonium is fissile and usable as a nuclear fuel, but it can only be extracted from used uranium fuel that has been MELTED or DISSOLVED into a LIQUID form.

Because all reactor-produced plutonium is usable in nuclear weapons, the “reprocessing” of used uranium fuel to extract plutonium is very controversial.

Most power reactors use Low Enriched Uranium (LEU) in which 30 to 50 atoms out of 1000 are fissile: NON-CANDU reactors use this kind of fuel.

Many proposed SMNRs are planning to use fuel that is High Assay Low Enriched Uranium (HALEU) in which 50 to 200 atoms out of 1000 are fissile.

Highly Enriched Uranium (HEU, with 200-1000 fissile atoms per 1000, is disallowed for commercial use and is also being phased out for research reactors – because HEU is a powerful nuclear explosive material.

With higher enrichment, a smaller mass of uranium fuel is needed per unit of energy output. – and, for a given energy output, the used uranium fuel is more radioactive per kilogram.
This “slow” reactor (graphite moderated) uses fuel that is 22 times more energetic than CANDU fuel.

NUCLEAR FUEL
Fuel is 15.5 percent enriched uranium.

Each graphite “pebble” the size of a billiard ball is filled with thousands of tiny TRISO granules.

Pebbles enter from above and exit below, each pellet is re-used up to three times.

PRIMARY COOLANT
High temperature gas reaches temperature of close to 1000 deg C. – greater efficiency of electricity generation.
A “fuel pebble” is the size of a billiard ball (seen at your left).

It contains thousands of TRISO particles (see slide 6).
Each SOLID fuel rod is filled with a LIQUID solution of plutonium and transuranics in molten salt.
The PRIMARY COOLANT is molten salt that carries heat to the SECONDARY COOLANT (water).
The Moltex Stable Salt Reactor – Wasteburner (SSR-W)

- Heat exchangers passing heat to steam generators and turbine
- Support grid allowing fuel assemblies to be moved along the row
- Fuel assemblies containing the accident tolerant molten salt fuel
SSR Fuel = plutonium + other transuranics = 0.61 percent of the total mass of used CANDU fuel. This small fraction is used to fuel the SSR-W reactor. The other 99.39 percent is leftover waste.

Moltex WATSS = Waste to Stable Salt (pyroprocessing unit) to extract plutonium mix from used CANDU fuel.

PYROPROCESSING To provide fuel for the Moltex SSR-W reactor

Key: Process HLW ILW Re-use/Release to atmosphere

Radioactive metal cladding 19.8 %

contaminated non-fissile uranium 77.8 %

0.61 % ONLY!!

Zirconium from the cladding is reused in the coolant

Uranium stored for future use or disposed as Intermediate Level Waste

All long lived higher actinide waste reduced down to this stream which is reused as fuel

To atmosphere after decay & filtering

Potential energy source but contains Cs & I (HLW for 200-300 years)
NuScale – pressurized light water reactor, scaled down conventional PWR

NuScale’s combined containment vessel and reactor system

NUSCALE PWR
60 megawatts
= 1/10 of Point Lepreau

*Source: NRC

NuScale – pressurized light water reactor, scaled down conventional PWR
The most common moderators in use are water (light or heavy) and graphite.

Use of a moderator = “slow” reactor.

BWRs do not need boilers because the water used as coolant boils in the core.

Fuel is < 5 percent enriched. The coolant is light water which also serves as the moderator. Power is 300 MWe = 1/2 Lepreau

BWRX-300 = scaled down boiling water reactor – GE- Hitachi
Ultrasafe MMR = Micro Modular Reactor – 15 MWth – Helium-cooled – Molten Salt storage

Chalk River MMR
15 MW of HEAT
(5 MW Electricity POSSIBLE)

This design is now undergoing an EA by CNSC

MMR = Micro Modular Reactor (a “fission battery”)

Helium gas-cooled TRISO fueled – secondary coolant Is molten salt for heat storage as backup power.

Reactor Pressure Vessel

Ustrasafe MMR = Micro Modular Reactor – 15 MWth – Helium-cooled – Molten Salt storage
ARC-100
Liquid Metal Cooled
Fast Breeder Reactor

Liquid sodium reacts violently with air and on contact with water.

Enriched fuel
(10.1, 12.1, 17.2 %)
Is in METALLIC form
(more compact)

Larger reactors of this type were tried and abandoned in USA, UK, France, Germany
EBR-II – Precursor of the ARC-100 reactor at 1/5 the power

EBR-II
Fast reactor 1964-1994
Liquid Metal Cooled
Experimental Breeder Reactor

Pyroprocessing was developed to cope with the used EBR-II fuel.

So far, not successfully!!

ARC-100 (100 megawatts) is supposedly modelled on EBR-II (20 megawatts)
EBR-II fuel was 67 % enriched; ARC-100 fuel is 10.1, 12.1, 17.2 % enriched.
A breeder reactor requires continuous reprocessing of the used nuclear fuel.
The most obvious thing about the nuclear fuel cycle is that it is NOT a cycle!!

The Nuclear Fuel Cycle?

or

The Nuclear Fuel Chain?
... unless we decide to “recycle” the plutonium, opening Pandora’s box!!
There is a radioactive firewall between used reactor fuel and bombs

Il existe un pare-feu radioactif entre le combustible usé des réacteurs et les bombes
R = Recycling = Reprocessing = “Renaissance”

A reprocessing plant removes the firewall and makes plutonium more accessible

Une usine de retraitement supprime le pare-feu et rend le plutonium plus accessible
The End

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