

Small Modular Reactors: Nuclear 101 - A Dive Into Nuclear Technology

Steve Livingstone, PhD, P.Eng
Senior SMR Specialist, SMR Unit
Climate Change Branch, Ministry of Environment

saskatchewan.ca



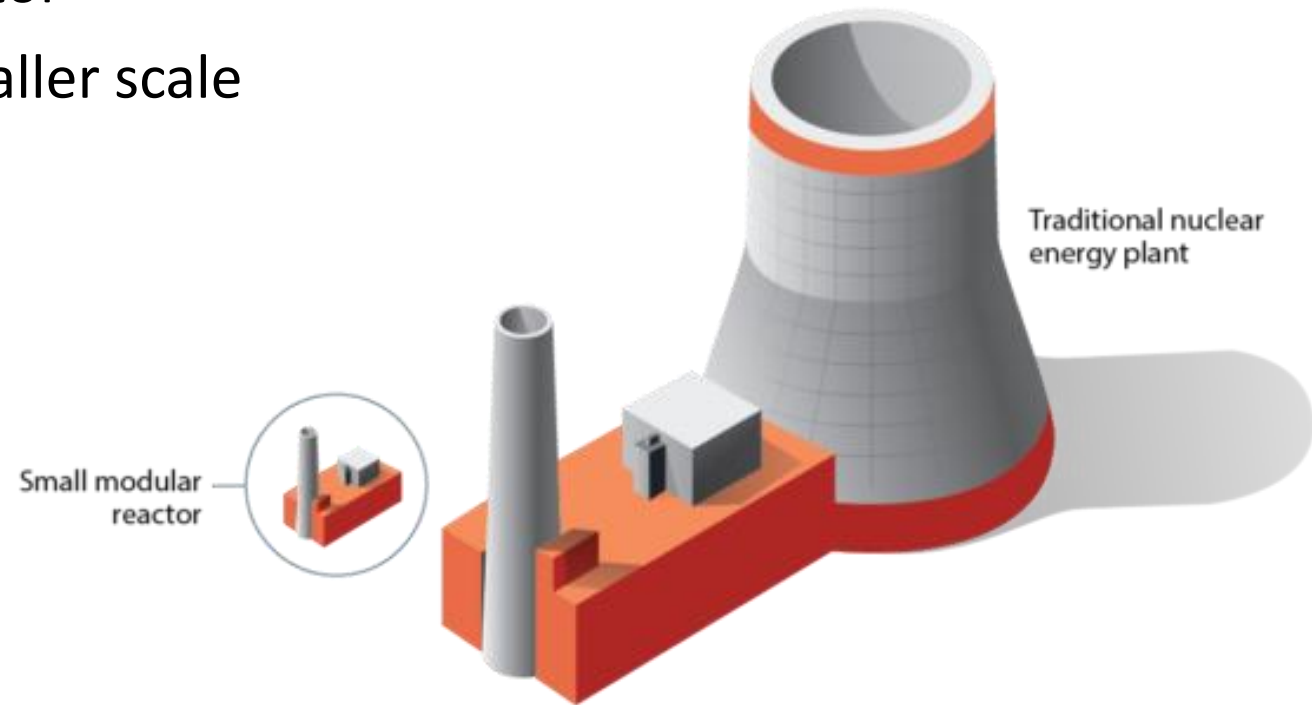
Agenda

- Brief discussion:
 - What is an SMR
 - SMR Context in SK
- Nuclear 101
- Audience Questions



What is a Small Modular Reactor?

- New generation of nuclear power reactor
- Generate clean ~~electricity~~ heat at a smaller scale
- Advantages:
 - Add new units to meet capacity needs
 - Lower upfront capital investment
 - Remote sites or by industry for heat
 - Low emissions
 - Stable baseload power



What is a Small Modular Reactor?



Eight CANDU Reactors
6,400 MWe max output

Russia's floating SMR
64 MWe and simultaneously **60 MWth**



SaskPower total capacity **3,542 MWe** from 17 generating facilities,
so **~ 300 MWe** SMR units are appropriate scale for Saskatchewan

Research Reactor – SMR – Large Nuclear

	Research Reactor	SMRs	Nuclear Reactor
SIZE	20 kWth - 5 MWth	5 - 300 MWe	300 - 1600 MWe
OUTPUTS	<ul style="list-style-type: none">• Research• Neutrons• Radiation• Isotopes	Heat for <ul style="list-style-type: none">• Electricity• Industrial processes• District heating• Hydrogen production	<ul style="list-style-type: none">• Heat for Electricity• Isotopes
CONSTRUCTION	Lab scale	Modular	Significant

SLOWPOKE-2 reactor in Saskatoon 1981-2019

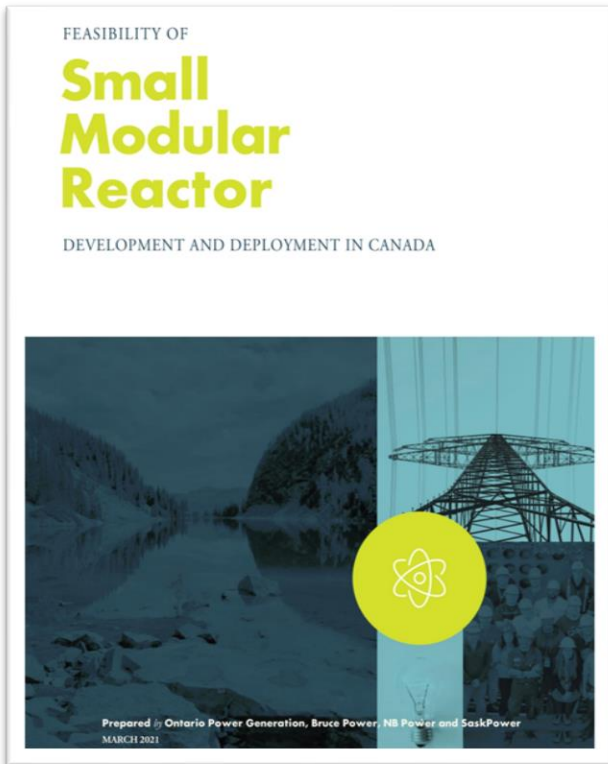
SMR Context in Saskatchewan

Provincial Actions to Date

- March 2018 - SaskPower signed MOU with Ontario Power Generation
- Dec 2019 - MOU with SK, ON, NB to collaborate on the development of SMRs. Alberta signs MOU in August 2020.
- Dec 2020 - Canada's SMR Action Plan – GOS, FNPA, Creative Fire, SaskPower, Fedoruk Centre, U of R, SMA
- April 2021 - MOU Feasibility Report released
- May-June 2021 - Targeted SMR engagement on SK's strategic priorities with government, industry, academia, training and Indigenous organizations
- May-September 2021 SaskPower and FNPA public and Indigenous engagement on future supply options
- MOU Strategic Plan (forthcoming)



Growth Opportunities – MOU Feasibility Report



SMRs can create new global markets for SK Uranium

- Global market for SMRs expected ~\$150B/year for 2030-2040
- Even a fraction of this market would significantly increase uranium demand

SMRs can create economic growth

- Thousands of new jobs during planning, construction, operations and decommissioning phases
- GDP Growth of more than \$8B over the life of the project

SMRs are an opportunity for Indigenous participation

- SMR equity partnerships could provide stable, long term financial returns, and create high quality jobs
- Indigenous Peoples make up 10 per cent of SIMSA members' employees

Next Steps

Business Case

- Government of Saskatchewan-led study
- Economic benefits: growth, jobs, investments, import/export, supply chain
- Expanded emission reduction opportunities

Supply Chain Study

- Joint study with PrairiesCan and Alberta
- Identify opportunities for Saskatchewan and Alberta's industries to participate in Canadian SMR supply chain

MOU Strategic Plan

- Factors that influence success of SMR development and deployment
- Actions that provincial power utilities will take to finalize assessment
- Project risks and benefits provinces will consider in decision making

Canadian SMR Streams – Feasibility Report

- *Stream 1*: SMR on grid (SaskPower)
- *Stream 2*: Advanced SMR (waste burners and fast reactors)
- *Stream 3*: SMR off grid



Federal Actions to Date

- Published *A Call to Action, A Canadian Roadmap (2018)*
- Published the *SMR Action Plan (2020)*
- Engaged with citizens across Canada, including Indigenous people
- Funding support for SMR vendor technology development (Terrestrial Energy, ARC, Moltex)

We took a national approach to engagement...

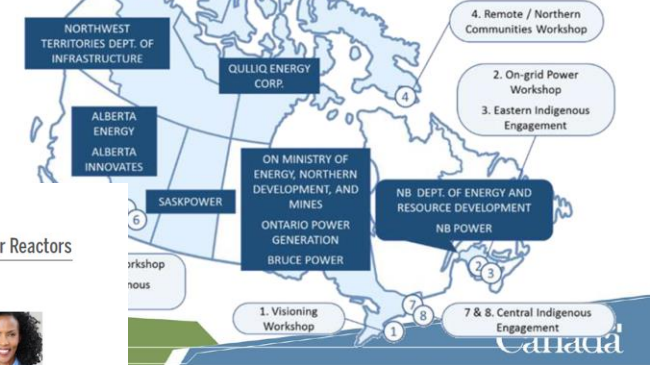
**NRCan-convened,
stakeholder-driven:**

- Nov 2017 – Sept 2018
 - Extensive engagement
 - Analysis by experts
- Collaborative, innovative leadership
 - Provinces, Territories
 - Power Utilities
- 8 workshops across Canada
 - 55 organizations
 - 10 sectors/subsectors

A Call to Action:

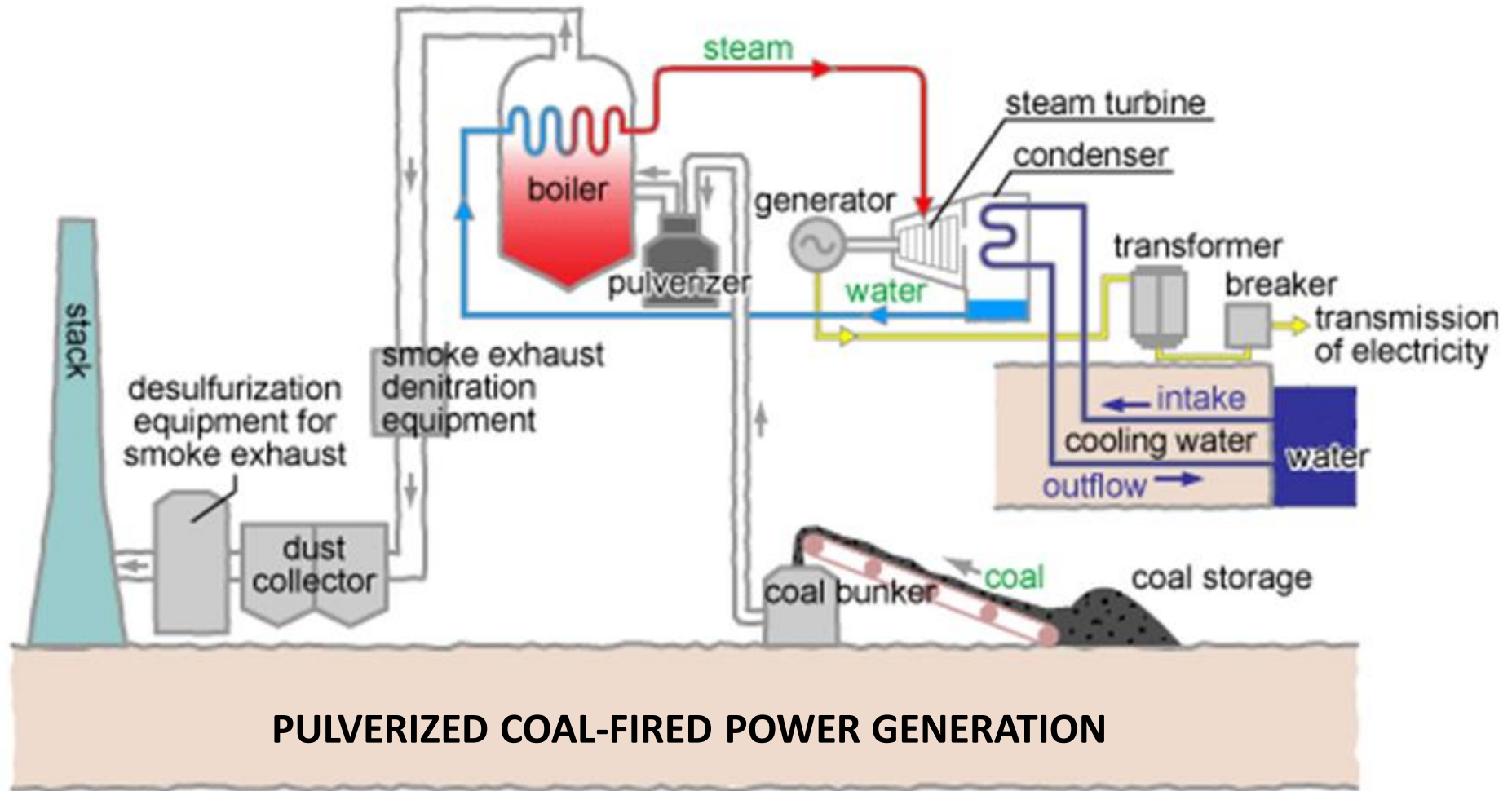
A Canadian Roadmap for Small Modular Reactors

SUMMARY OF KEY FINDINGS

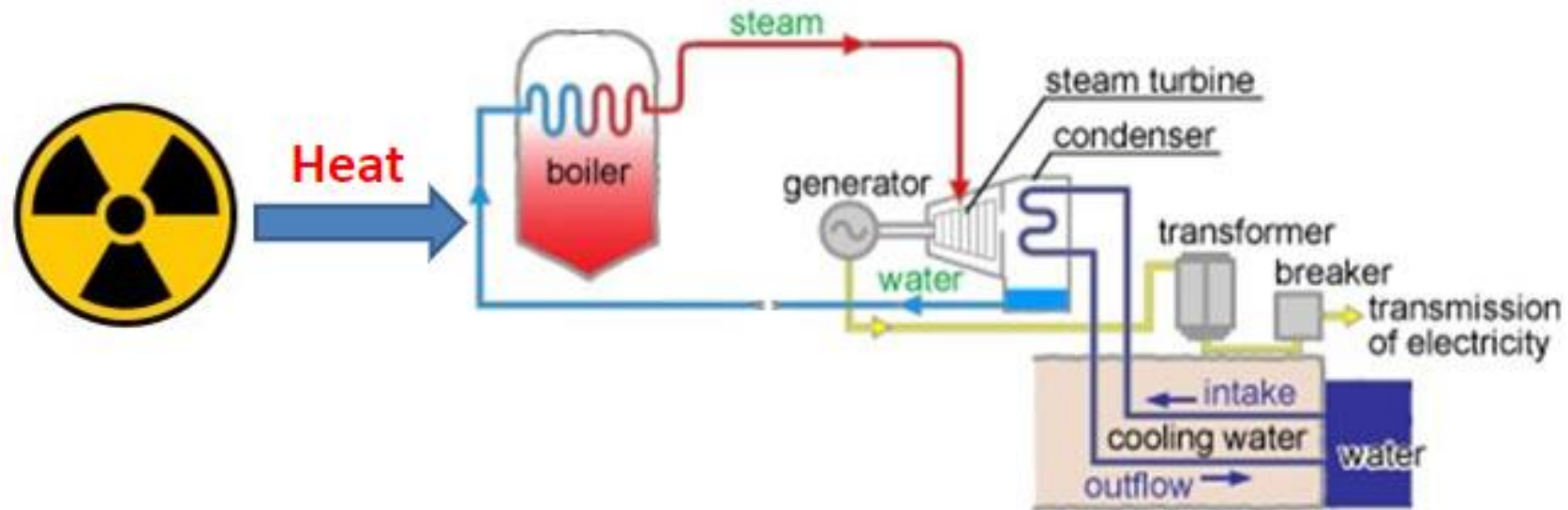


Nuclear 101

Power Generation

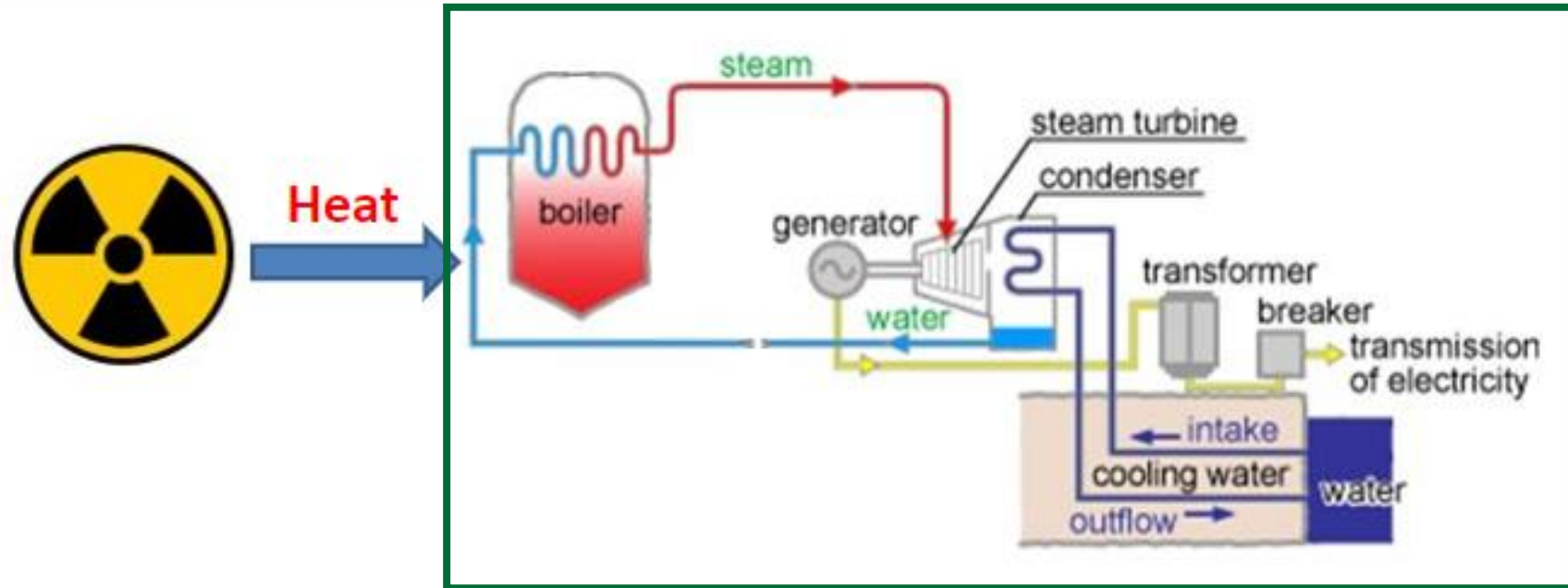


Nuclear Reactor



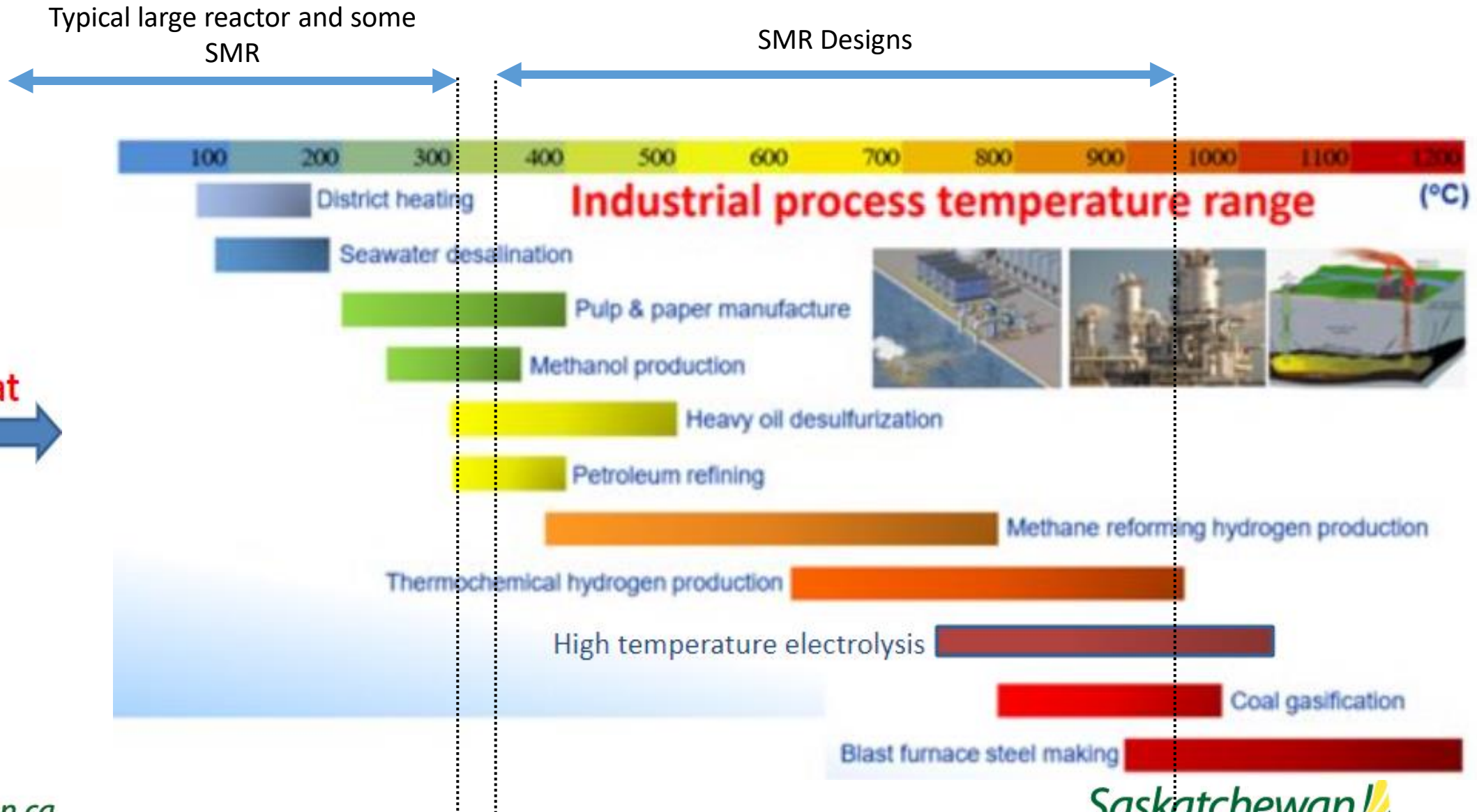
- Production requires a **HEAT SOURCE** (Fuel)
- Reactors use Uranium instead of coal/gas/biomass

Nuclear Reactor



- Production requires a **HEAT SOURCE** (Fuel)
- Reactors use Uranium instead of coal/gas/biomass
- Balance-of-Plant (BOP) needs same supply chain and jobs as coal/gas

Nuclear Reactor as a Heat Source



Nuclear Fuel 101

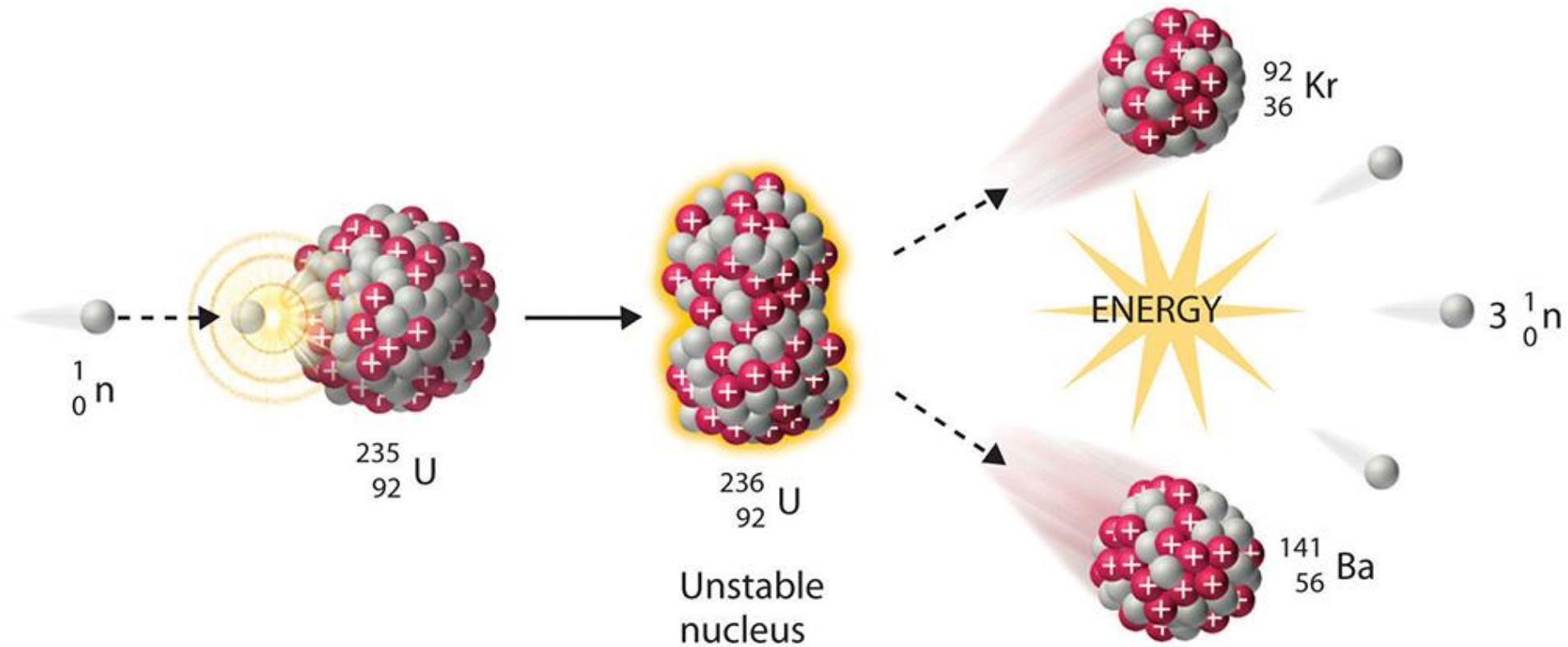


Mined Uranium:

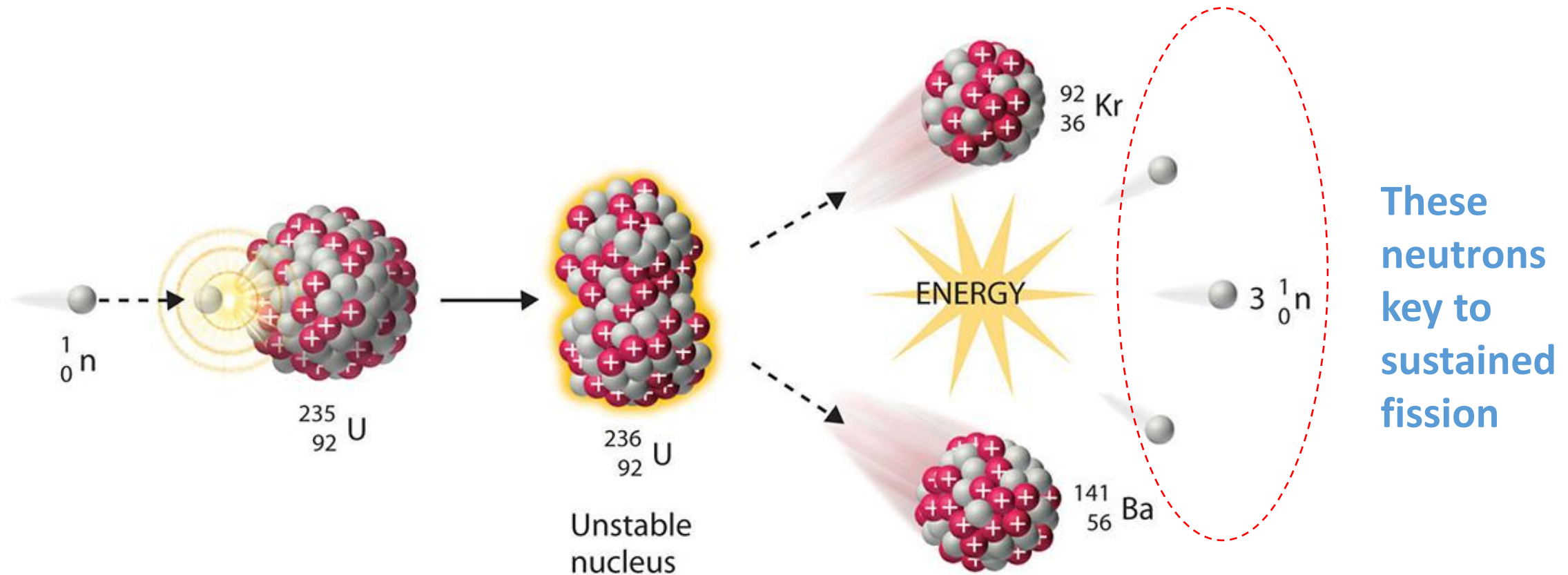
- 99.27% is Uranium-238
- 0.72% is Uranium-235
- Fuel for SMR*

*Except advanced fast SMRs that use Uranium-238

Fission ($E = mc^2$)



Fission ($E = mc^2$)



How to sustain fission:

CANDU

1) Try and save as many of those neutrons as possible. This is the **Canadian approach with CANDU**, and UK approach with Gas Cooled reactors. Hence, no enrichment capacity in Canada.

SMR

2) **Enrich the fuel** to increase the amount of U-235 to 1-20 % (recall natural is 0.7%). Now you have higher density of U-235, so more U-235 atoms per volume for fission. Therefore, you can allow neutrons to be captured so more design flexibility.

Advanced SMR

3) Build a **fast** reactor to operate on U-238 instead (well, partly, it also converts U-238 to Pu-239). First nuclear power plant in USA in 1957. Produce ~60 times more energy from uranium but historically more expensive to build.

Nuclear Security

CBC | MENU

NEWS Top Stories Local COVID-19 Opinion World Canada Politics

World

Iran plans 20% uranium enrichment 'as soon as possible'



Decision comes after approval of bill aimed at hiking enrichment to pressure Europe on sanctions relief

The Associated Press - Posted: Jan 02, 2021 10:36 AM ET | Last Updated: January 2



Iran's Atomic Energy Organization president Ali Akbar Salehi, seen here at the UN atomic agency headquarters in Vienna on Sept. 16, 2013, said Iran would need to switch out natural uranium in centrifuges at the Fordo nuclear facility for material already enriched to four per cent to begin the process of going to 20 per cent uranium enrichment. (Alexander Klein/AFP via Getty Images)

Iran and watchdog reach deal over nuclear site monitoring

12 September



Iran nuclear deal



GETTY IMAGES

Rafael Grossi (centre), head of the IAEA, met Iran's nuclear energy chief Mohammad Eslami (left) this week

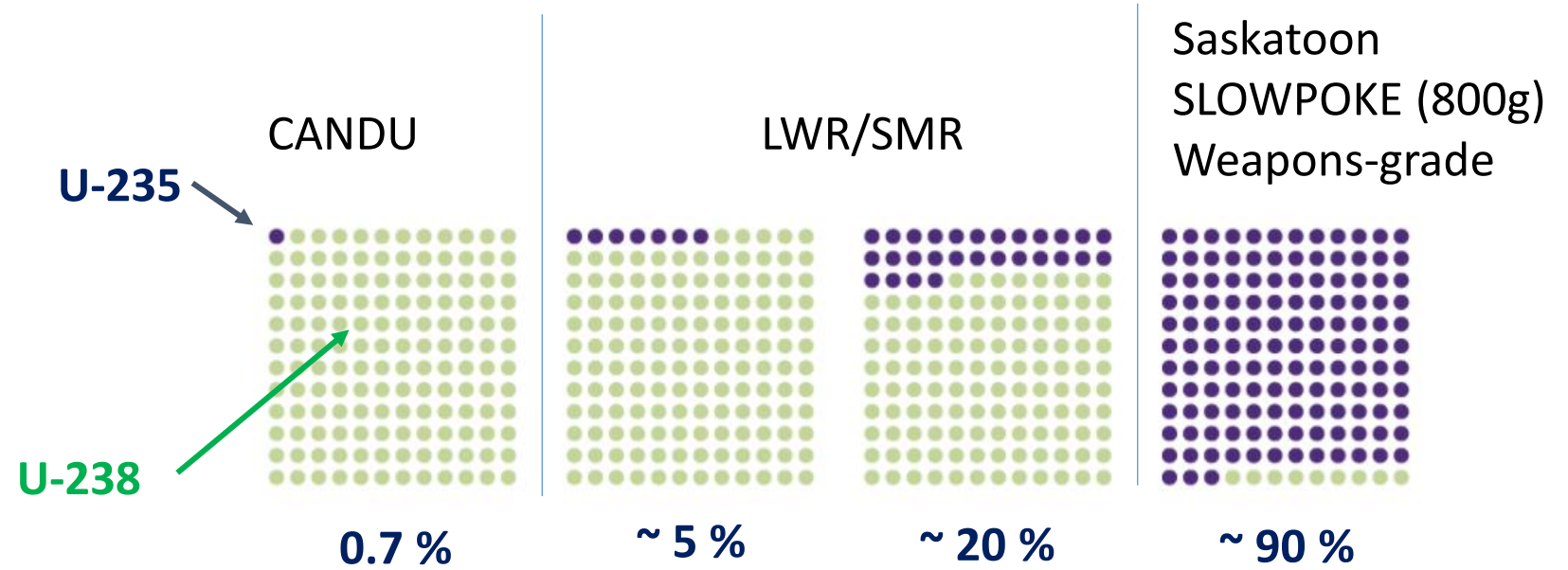
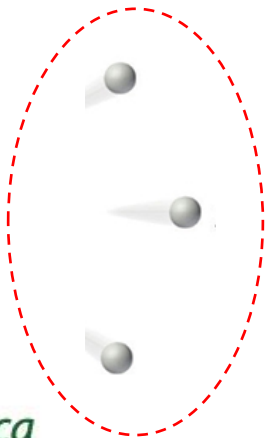
Iran has agreed to allow the global nuclear watchdog to service cameras used to monitor Iranian nuclear sites.

Nuclear Security

Recall mined Uranium:

- 0.72% is Uranium-235
- 99.27% is Uranium-238

Enrichment increases relative amount of U-235 to “catch” those neutrons

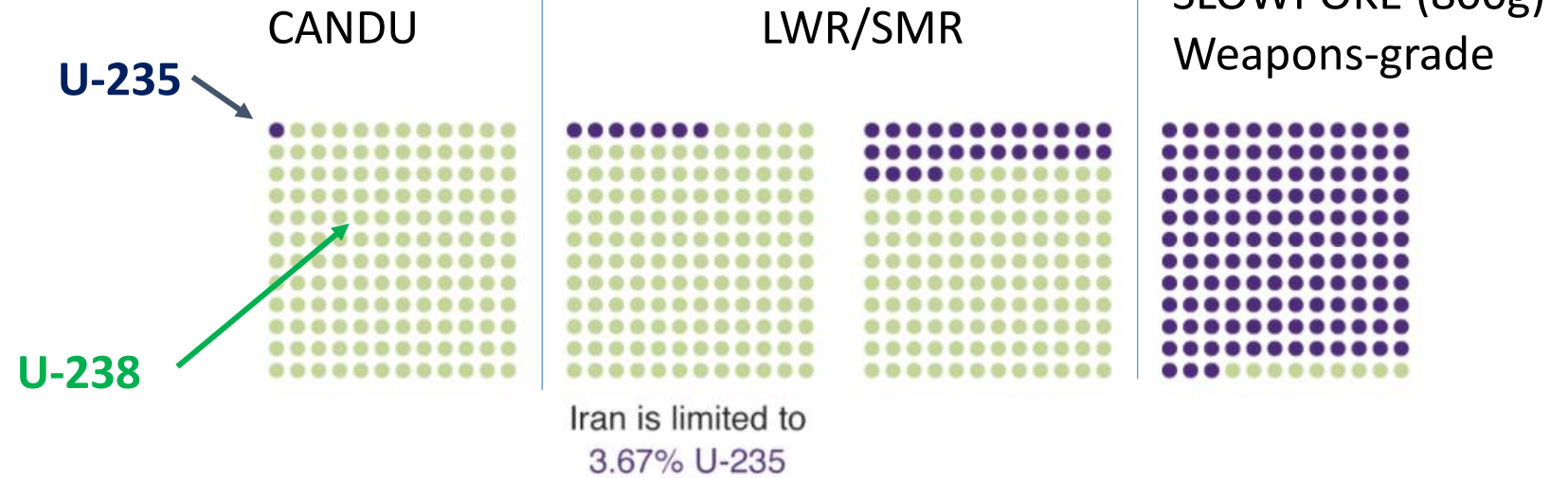
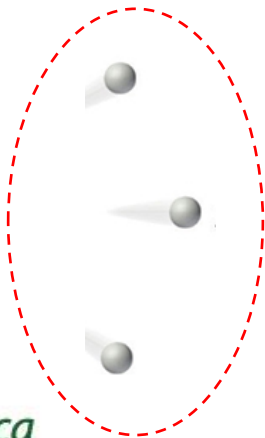


Nuclear Security

Recall mined Uranium:

- 0.72% is Uranium-235
- 99.27% is Uranium-238

Enrichment increases relative amount of U-235 to “catch” those neutrons



How much effort is required to get to weapons-grade uranium?

Very little extra effort is needed to get from 20% enriched uranium to bomb material

83.5% effort needed to reach 4% U-235 > **+8.5% effort** needed to reach 20% U-235 > **+8% more effort** to reach 90% U-235

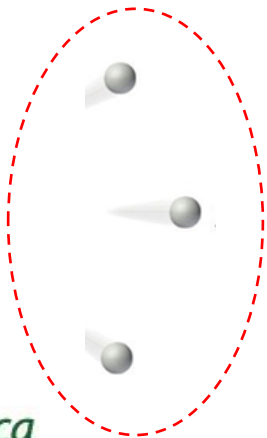


Nuclear Security

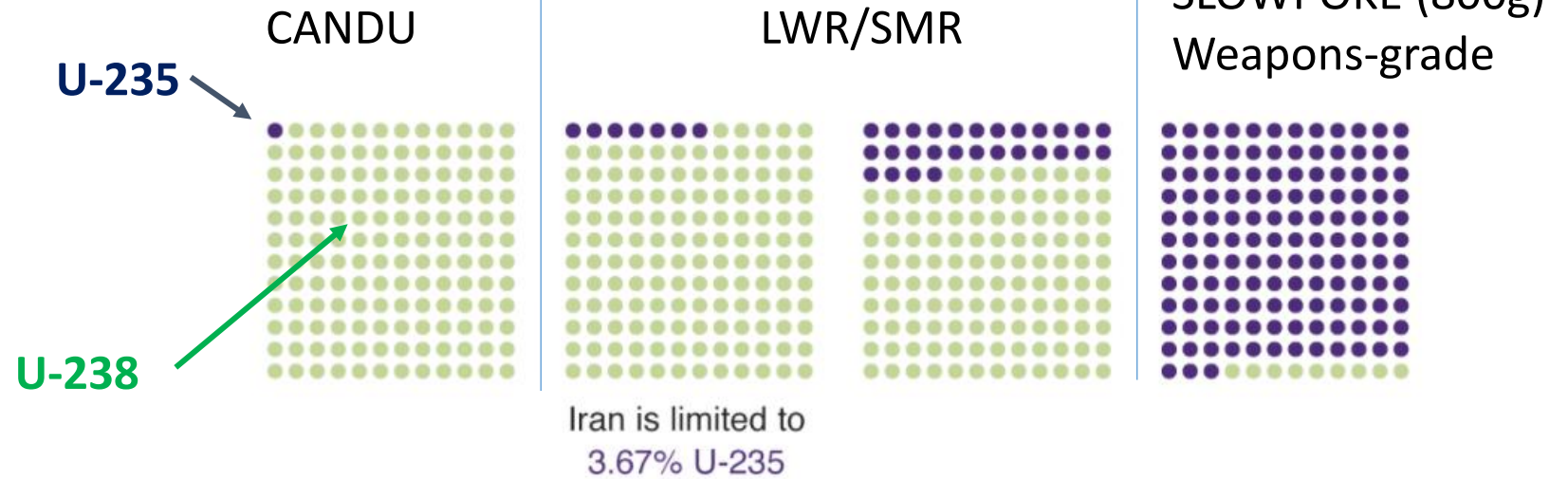
20% is not practical for weapons purposes, and therefore regulated limit for civilian nuclear use.

Canada has been at forefront of IAEA safeguards practices.

Safeguards implemented by CNSC



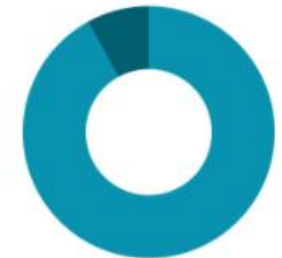
saskatchewan.ca



How much effort is required to get to weapons-grade uranium?

Very little extra effort is needed to get from 20% enriched uranium to bomb material

83.5% effort needed to reach 4% U-235 > +8.5% effort needed to reach 20% U-235 > +8% more effort to reach 90% U-235



Where Does Enriched Fuel Come From?



Natural Uranium	1-5 % Enriched	5 – 20 % Enriched	20+% Enriched
SK to ON to CANDU	SK to ON to UK/US/Europe enricher	SK to ON to ?	International treaties prevent Canadian U from being used for this purpose. Every U atom has a "flag"
~ 50,000 tons mined/year	~ 440 reactors in the world	Zero commercial reactors today	
SK usually 2nd largest	Small % use NU, most 1-5 %	Limited sources today	

Recall mined Uranium:

- **99.27% is Uranium-238**
- **0.72% is Uranium-235**

saskatchewan.ca

One option being explored by SaskPower and OPG uses 15%

Quick thoughts on radiation:

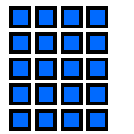
Quiz Time

Can you put these in increasing order of radiation dose?

- A) Eating one banana
- B) Living 80 km from a nuclear power plant
- C) Getting an arm X-Ray
- D) Living 80 km from a coal plant

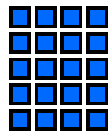
Quick thoughts on radiation:

- Sleeping next to someone (0.05 μSv)
- Living within 50 miles of a nuclear power plant for a year (0.09 μSv) **(B)**
- Eating one banana (0.1 μSv) **(A)**
- Living within 50 miles of a coal power plant for a year (0.3 μSv) **(D)**

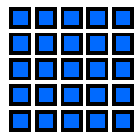


Arm x-ray
(1 μSv)

(C)

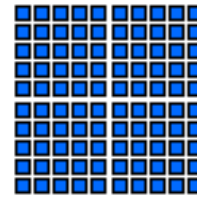


Using a CRT monitor
for a year (1 μSv)

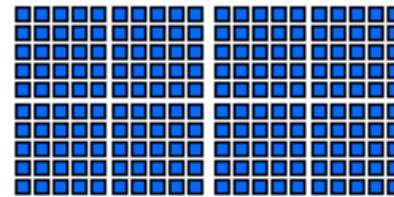


Extra dose from spending one day in
an area with higher-than-average
natural background radiation, such
as the Colorado plateau (1.2 μSv)

**Why do you think a coal plant
releases more radiation than a
nuclear plant?**

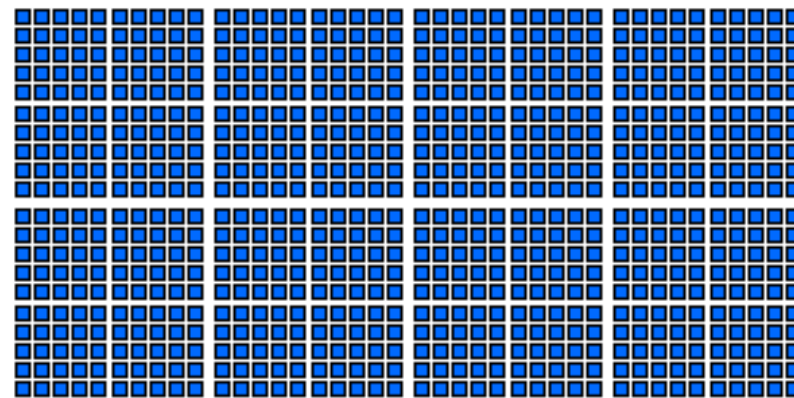


Dental x-ray (5 μSv)



Background dose received
by an average person over
one normal day (10 μSv)

Airplane flight from New York to LA (40 μSv)



***Great infographic from
xkcd.com/radiation**

Spent fuel: How much will there be?

- 1 kg of Low Enriched Uranium (LEU, 3.5 %) can generate 358 MWh of electrical energy
 - This is lower than enrichment SK will have, so even more energy/kg!
 - What is 358 MWh? My home is about 300 kWh/month.....

Spent fuel: How much will there be?

- 1 kg of Low Enriched Uranium (LEU, 3.5 %) can generate 358 MWh of electrical energy
 - This is lower than enrichment SK will have, so even more energy/kg!
- What is 358 MWh? My home is about 300 kWh/month, so
 - 1 kg of LEU can power my house for **99 years**.
 - 1 kg of coal can power my house for **5.5 hours**...

Spent fuel: How much will there be?

- 1 kg of Low Enriched Uranium (LEU, 3.5 %) can generate 358 MWh of electrical energy*
 - This is lower than enrichment SK will have, so even more energy/kg!
 - What is 358 MWh? My home is about 300 kWh/month, so
 - 1 kg of LEU can power my house for **99 years**.
 - 1 kg of coal can power my house for **5.5 hours**...
- **Consider 4 SMRs in SK**
 - At 300 MW each = 1200 MW total
- How much fuel would SK need for 1 year for 1200 MW?
 - $358 \text{ [MWh/kg]} / 24 \text{ [h/d]} / 365 \text{ [d/yr]} = 0.04 \text{ MW.y/kg}$
 - $(1/0.04) \text{ [kg/MW.y]} * 1200 \text{ MW.y} = \mathbf{30,000 \text{ kg}}$
 - LEU is dense (10000 kg/m^3), so that's **3 m^3**

*From <https://world-nuclear.org/information-library/facts-and-figures/heat-values-of-various-fuels.aspx> assuming 45,000MWd/t and 33% efficiency to convert heat to electricity.

Spent fuel: How much will there be?



- A two-car garage could store ~ 40 years of all the spent fuel from SK operating four 300MWe reactors
- BUT highly radioactive for 100,000 years, so can't be stored in a garage, and isn't a solid cube....
- FYI: All spent fuel in Canada, produced from 1962 - 2019 fits in one CFL field filled 1.6 m (5 ft 3") high
 - Or 100 two-car garages....

Spent Fuel (aka nuclear waste) Options

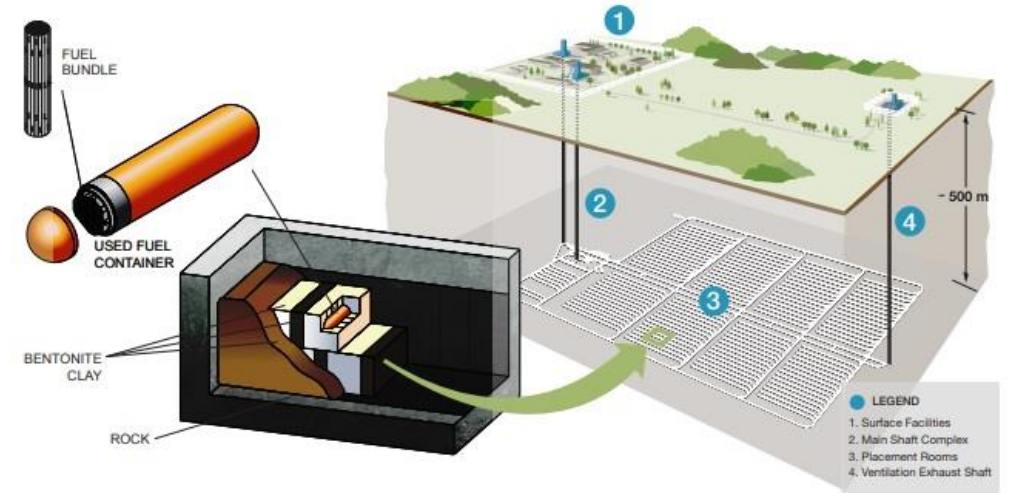


Current spent fuel stored on-site at the reactor (Note: you can stand next to it)

**Current plan:
Disposal
(recall still full of
U-238)**



Re-use/Recycle/“Burn”



Emergency Planning Zones

Sunday, Jan 12 • 6:23 AM

A personal perspective from living near nuclear:

- If you live within 10 km of CANDU, you are encouraged to have Iodine pills
 - Limit from Chalk River research reactor is 8 km; my house was 8.4 km from reactor.
 - **Proposed SMR range is 0 km**
- I walked my dog past this often.
- I get emergency test messages on my phone
 - This one was an exercise sent in error



This is a Province of Ontario emergency bulletin which applies to people within ten (10) kilometres of the Pickering Nuclear Generating Station. An incident was reported at the Pickering Nuclear Generating Station. There has been NO abnormal release of radioactivity from the station and emergency staff are responding to the situation. People near the Pickering Nuclear Generating Station DO NOT need to take any protective actions at this time. Remain tuned to local media for further information and instructions.



Emergency Planning Zones

Recall earlier slide:

Research Reactor – SMR – Large Nuclear

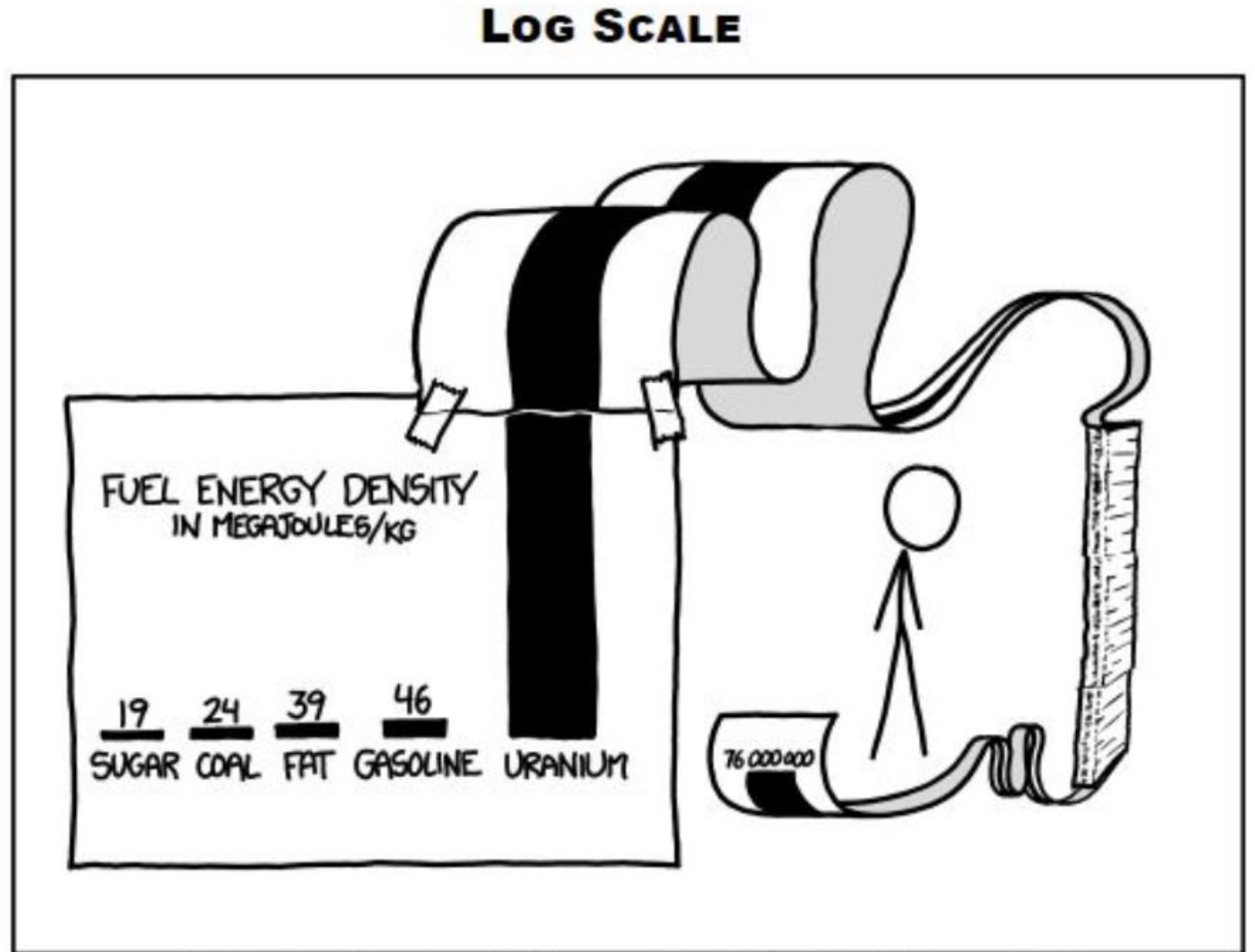
	Research Reactor	SMRs	Nuclear Reactor
SIZE	20 kWth - 5 MWth	5 - 300 MWe	300 - 1600 MWe
OUTPUTS	<ul style="list-style-type: none">• Research• Neutrons• Radiation• Isotopes	Heat for <ul style="list-style-type: none">• Electricity• Industrial processes• District heating• Hydrogen production	<ul style="list-style-type: none">• Heat for Electricity• Medical isotopes
CONSTRUCTION	Lab scale	Modular	Significant

- **Large reactor** = Evacuation zones, sirens, iodine pills, response teams...
 - **Control** the hazard. “**Safety by Engineering**”
- **SMRs** = In development (site boundary is emergency zone extent).
 - **Avoid the hazard** = “**Safety by Physics**”
 - E.g. BWRX-300 has **NO primary coolant pumps!**
Station blackout = cools itself
- **SLOWPOKE-2** was in Saskatoon = reactor room was zone extent
 - **Avoid the hazard.** First “**Inherently Safe**” reactor.

QUESTIONS



saskatchewan.ca



From xkcd.com

SCIENCE TIP: LOG SCALES ARE FOR QUITTERS WHO CAN'T FIND ENOUGH PAPER TO MAKE THEIR POINT PROPERLY.



Thank You!

saskatchewan.ca

Saskatchewan! 

Growth Opportunities

Saskatchewan Growth Plan (2019)



- **Advancing development of zero-emission SMR technology will:**
 - Support the growing economy;
 - Support 1.4 million people living in Saskatchewan.
- **Additional growth goals that SMRs could contribute to:**
 - Increase annual value of uranium sales to \$2B;
 - Create 100,000 more jobs;
 - Grow private capital investment in Saskatchewan to \$16B annually;
 - Grow Indigenous participation in Saskatchewan's natural resource industries; and,
 - Triple the growth of the technology sector.