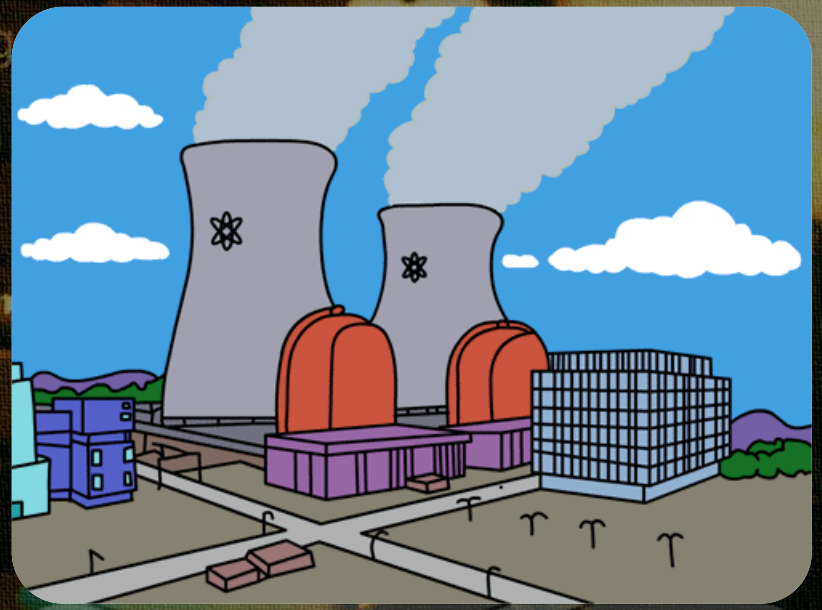
Nuclear Power Plants

Present and future



Thomas A. Adams II
McMaster University
Department of Chemical Engineering
McMaster Advanced Control Consortium
McMaster Institute for Energy Studies

Lecture 3.3 – 2018 Edition

Preamble

- This is not meant to be an exhaustive, or even introductory primer on nuclear energy.

- There is a separate major for that.

- The goal of this discussion is to provide enough background knowledge of nuclear energy systems such that chemical engineers can see where they can make substantial future contributions.

1. Background

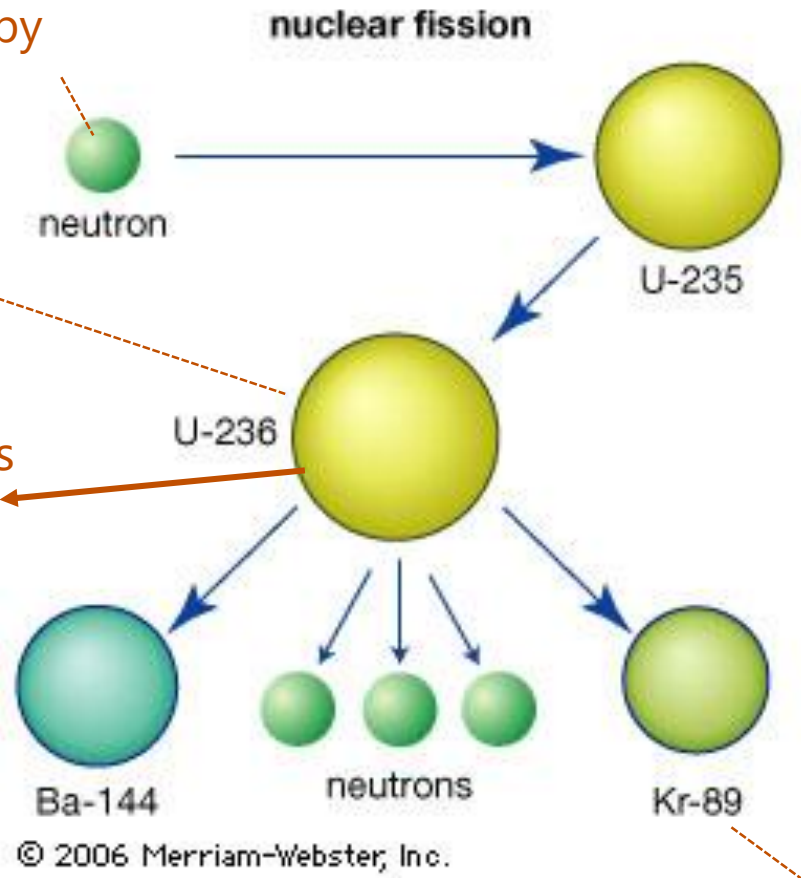
Prevalence, Geography etc

Fission Basics

You can induce fission by firing neutrons into it.

The U-236 is unstable and breaks apart quickly

The atom also increases in kinetic energy (temperature)



More neutrons are released than initially bombarded. This causes a chain reaction since more U235 can be bombarded, so it multiplies quickly.

99.9% of uranium in uranium ore is U-238, which is non-fissile, meaning it most neutrons are too weak to split it, so it doesn't cause a chain reaction.

Uranium must be "enriched" to 3% U-235 to have enough to sustain a chain reaction.
(1) react uranium into UF_6 gas
(2) use centrefuge to separate it by gravity via tiny mass differences.

Weaponized form is >90% U-265

The atom can split into many different combinations of products. Each can then be split again with more neutrons.
Most continue to decay on their own, for up to years (emitting gamma radiation)

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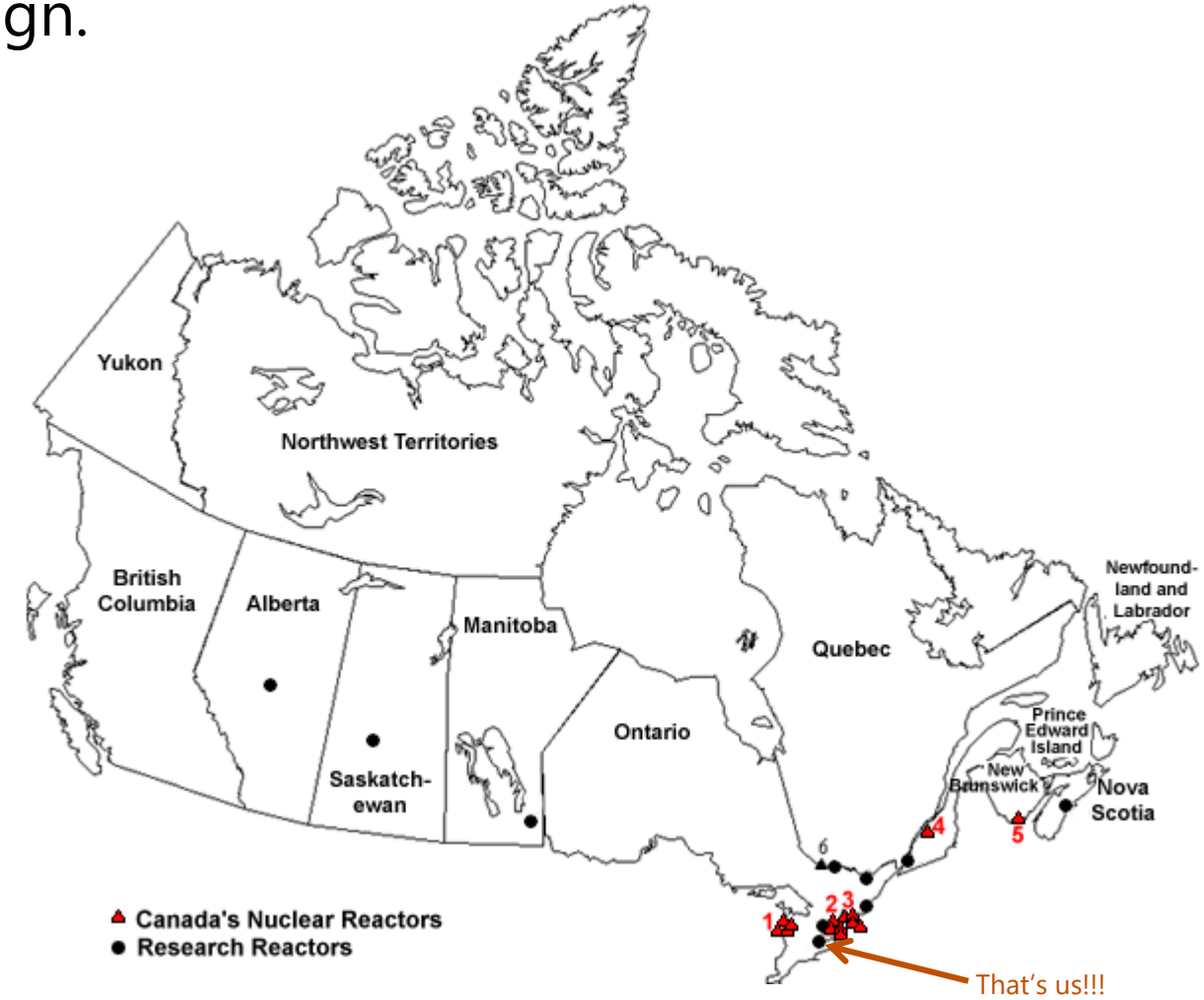
Source: World Nuclear Association. Physics of uranium and nuclear energy. Sept (2014). Encyclopedia Britannica. Nuclear Weapons (2013)

Canada's Reactors

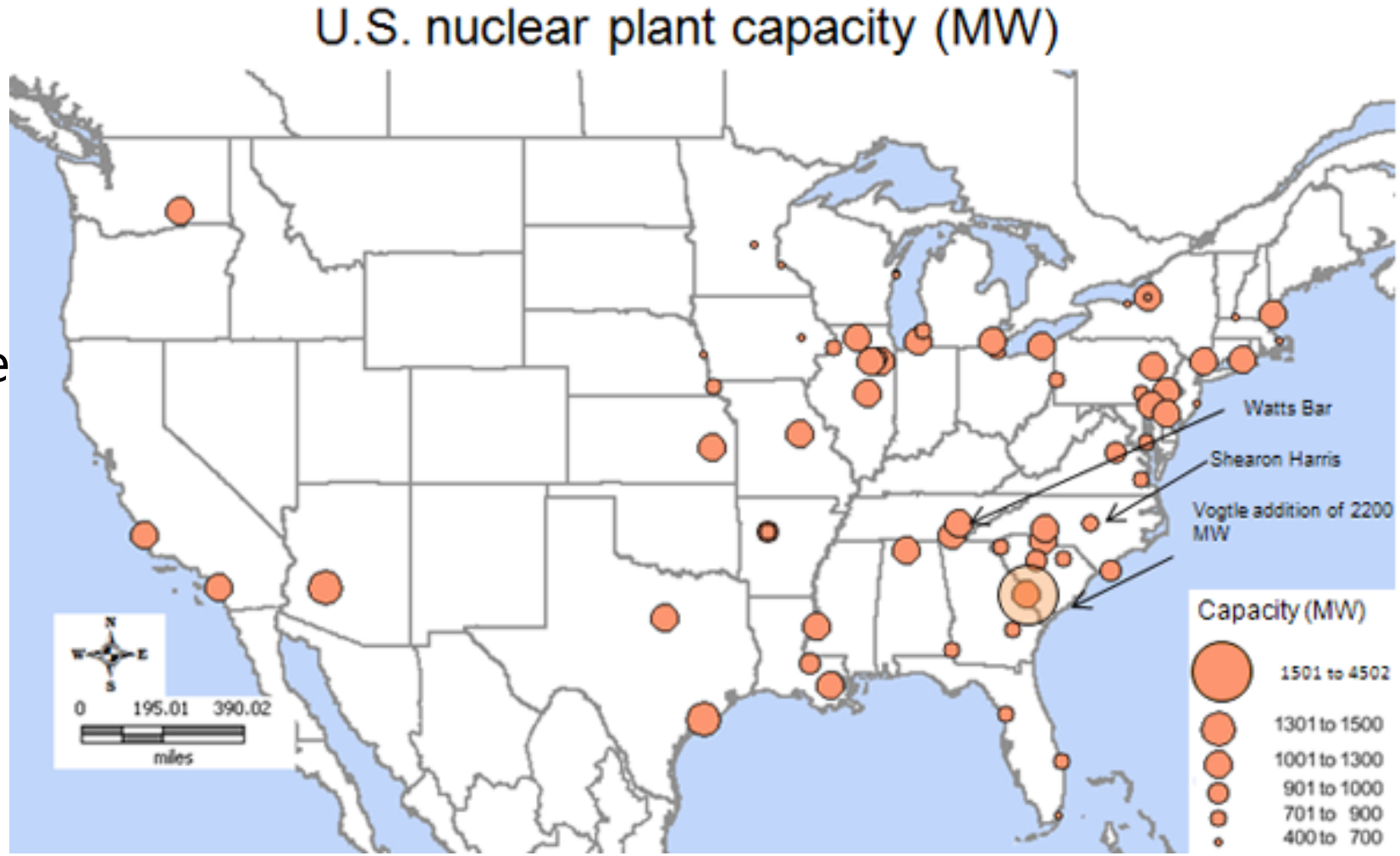
- The "CANDU" reactor is Canada's design.
  - CANDU="Canadian Deuterium Uranium"
  - 5 Locations, 22 reactors, 12.6 GW
  - 15% of total Canada electricity
  - 35% of Ontario mix capacity
    - (Close to 50% of actual production)
  - This design is used in
    - Romania (x2)
    - Pakistan (x1)
    - India (x2)
    - China (x2)
    - Argentina (x1)
    - Korea (x4)



Source: Canada Nuclear Safety Commission. Also, Canadian Nuclear Association "Candu Worldwide". *Independent Energy System Operator*, "Supply Overview", http://www.ieso.ca/imoweb/media/md_supply.asp

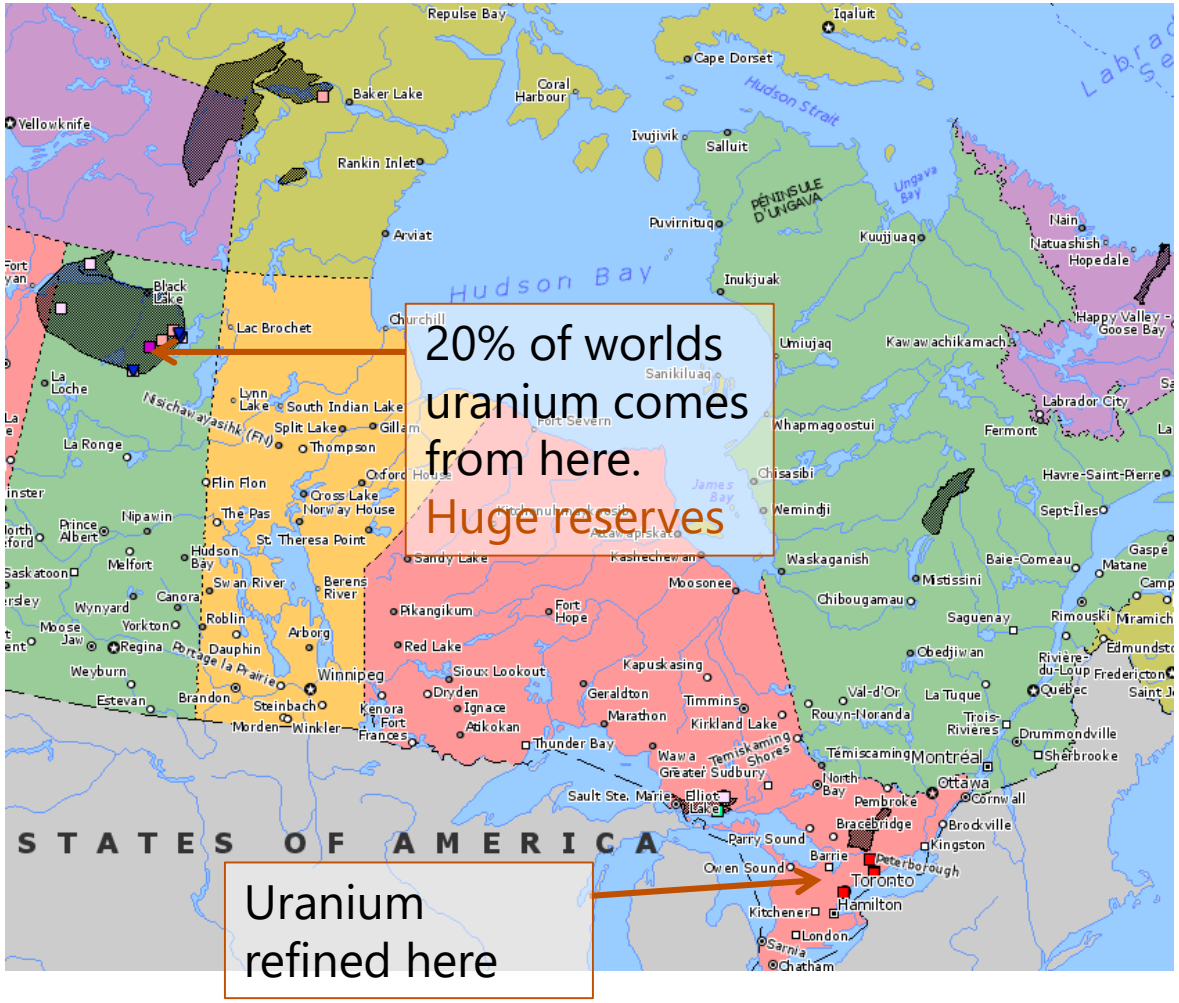
USA

- 104 Reactors. 20% of US mix.
  - Median start date: 1978
  - Most Recent: 1996
- Reactor at Vogtle has been approved for first time in 30 years (last was 1988). Will be Gen III+ (discussed later).
  - $27.7 billion to build!!!
  - 2.2 GW total.
  - Approval to expand given Sep 27, 2018
  - PS they have job openings



Sources: US Energy Information Administration. http://www.eia.gov/todayinenergy/detail.cfm?id=5250
Also, US EIA Form EIA-860, "Annual Electric Generator Report."
Geuss M, Vote results: Construction will continue on Vogtle nuclear power plant, Ars Technica, Sep 27 2018

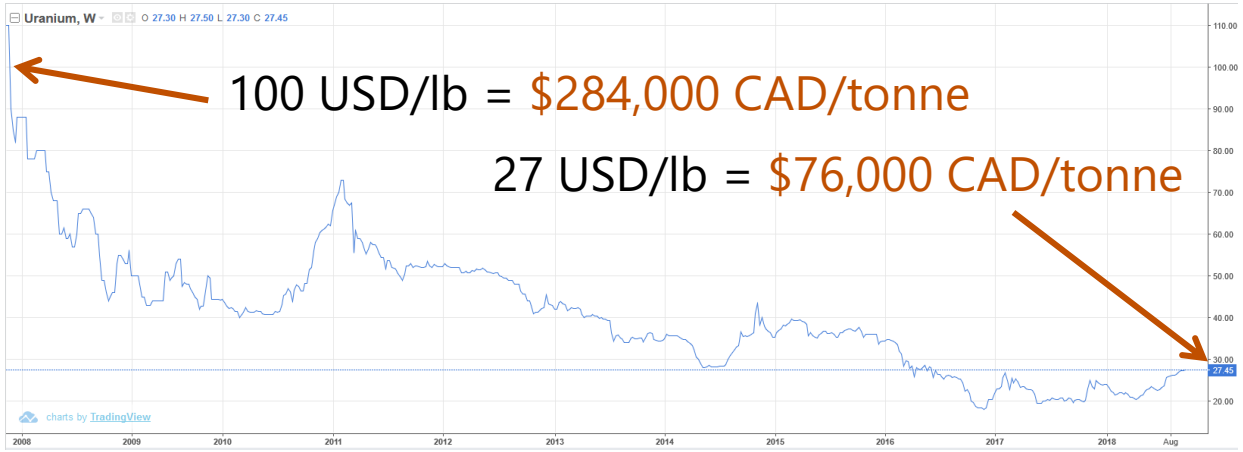
Uranium in Canada



- Canada exports $330 million/yr (more than any other metal). Is also the largest producer in the world.

There's more energy in Saskatchewan uranium reserves than all Canadian conventional oil. (does not include tar sands)

Prices are up almost fivefold since the last US plant was built.
Good for selling… Disincentivizes new plants



'08 '09 '10 '11 '12 '13 '14 '15 '16 '17 2018

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Sources: US Energy Information Administration. See image tag. Also, World Nuclear Orgaization. http://www.world-nuclear.org/info/inf49.html
Natural Resources Canada – The Atlas of Canada – Uranium Resources and Nuclear Energy.
Majescor Resources – Uranium in Canada. http://www.majescor.com/en/commodity-info/ucanada.aspx
US EIA – 2014 Uranium Marketing Annual Report

2. Generations I-IV

Past, present, and future. A brief selection.

Generation I

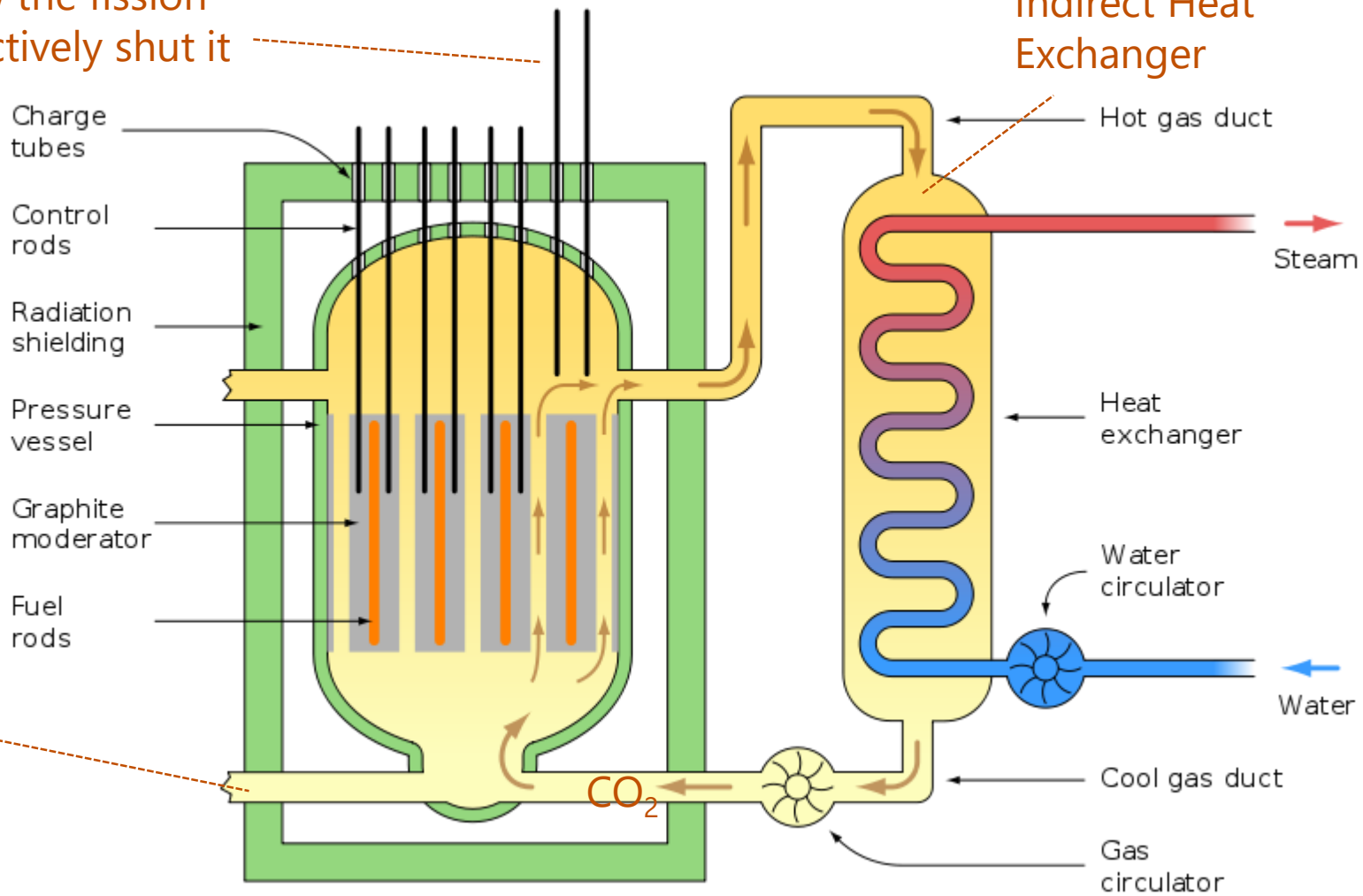
- Post WWII (1950-1960s) development.
- All shutdown (last license ended Dec 31 2015).
- Nuclear power processes themselves are simple.
  - Most design issues are safety related.
- Active cooling systems. Expensive.
  - After control rods are injected, there is still "Decay heat".
  - Must pump coolant through to continually remove this heat.
- A few examples:
  - Magnox (UK)
  - Dresden
  - Fermi 1

Sources: Wood, J. Nuclear Power. (2009) Ch 2. Also, World Nuclear Association
BBC: Wylfa nuclear plant given extension. Sept 30 (2014)
Golderb GM, Rosner R. Nuclear Reactors: Generation to Generation. American Aca Arts Sci (2011)

Gen I: Magnox (UK design)

Control rods slow the fission chain reaction (actively shut it down)…

Indirect Heat Exchanger



This is an indirect power generation scheme.

CO_2 was used because there was thought to be a danger from using water directly.

Sources: Wood, J. Nuclear Power. (2009) Ch 2. Also, World Nuclear Association. Image from Wikipedia (sorry!)

All now retired.

Generation II

- Typical US and French fleets in use today.
- (Also Fukushima Daiichi.)
- Pressurized-Water Reactors (PWR) – 65 in US
  - Use pressurized water as coolant, does not boil
- Boiling Water Reactors: (BWR) – 34 in US
  - Use regular water as coolant, boils to make steam directly.
- Heavy Water Reactors (CANDU, etc) – 21 in Canada
  - Use atmospheric heavy water (D_2O) as coolant.

  (Deuterium is an isotope hydrogen with a neutron and a proton).

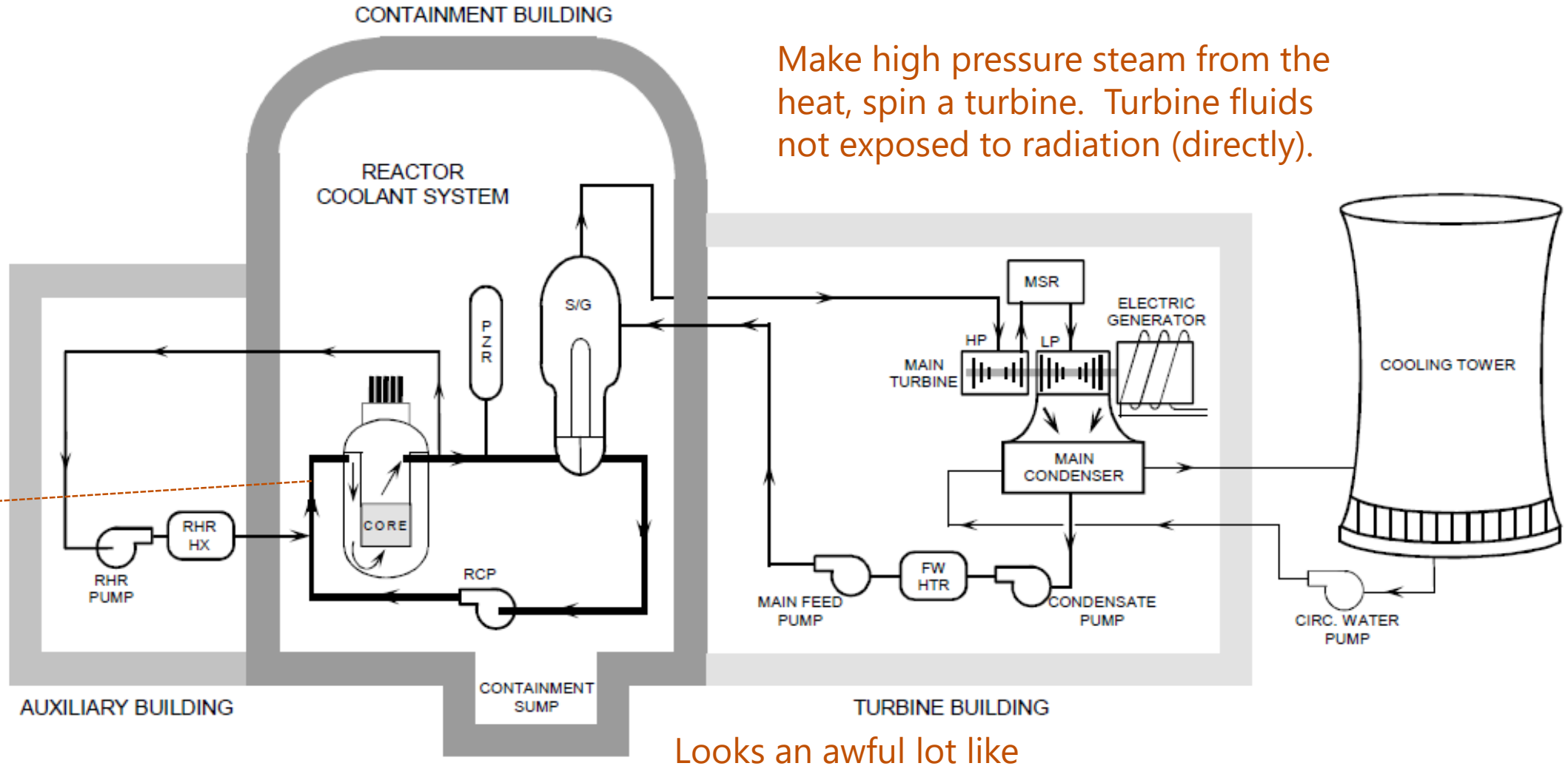
  Stable isotope. Found in human body naturally in tiny amounts.

Sources: Wood, J. Nuclear Power. (2009) Ch 2. Also, World Nuclear Association
US Nuclear Regulatory Commission, "Power Reactors"
Candu.com – "Candu 6"

Gen II: Pressurized Water Reactors

Make high pressure steam from the heat, spin a turbine. Turbine fluids not exposed to radiation (directly).

High pressure water contacted with fuel, but not boiled.

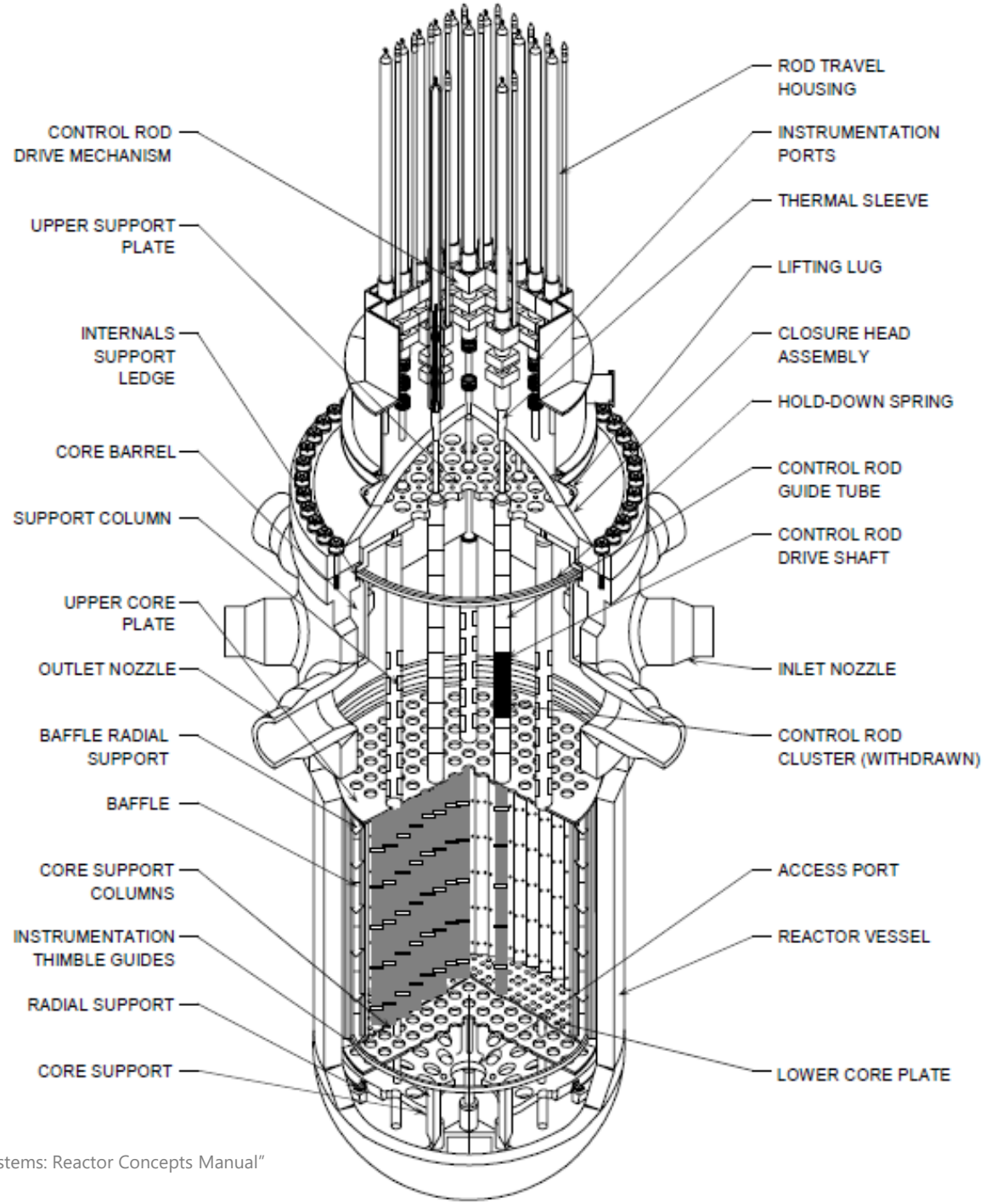


Looks an awful lot like the previous model…

Sources: Wood, J. Nuclear Power. (2009) Ch 2. Also, US Nuclear Regulatory Commission, "Pressurized Water Reactor Systems: Reactor Concepts Manual"

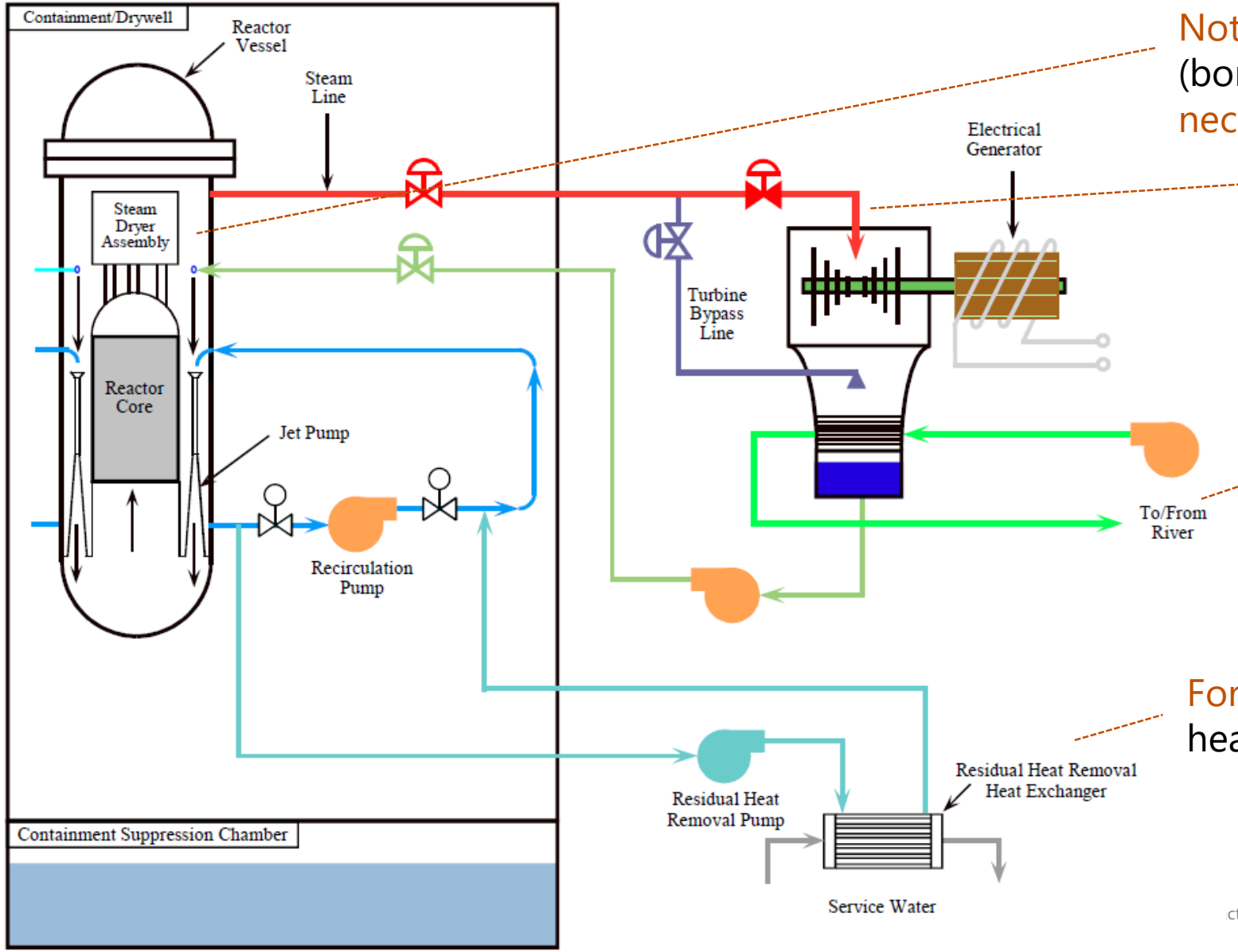
Reactor Core Detail

- The differences in the details of the design that enables paradigm shifts in technology (Gen I-IV)…
  - Enables direct boiling of water, etc.
  - Many layers of safety, etc.



Sources: US Nuclear Regulatory Commission, "Pressurized Water Reactor Systems: Reactor Concepts Manual"

Gen II: Boiling Water Reactor



Not shown: a tank of nuclear poison (boron) stands ready to inject if necessary

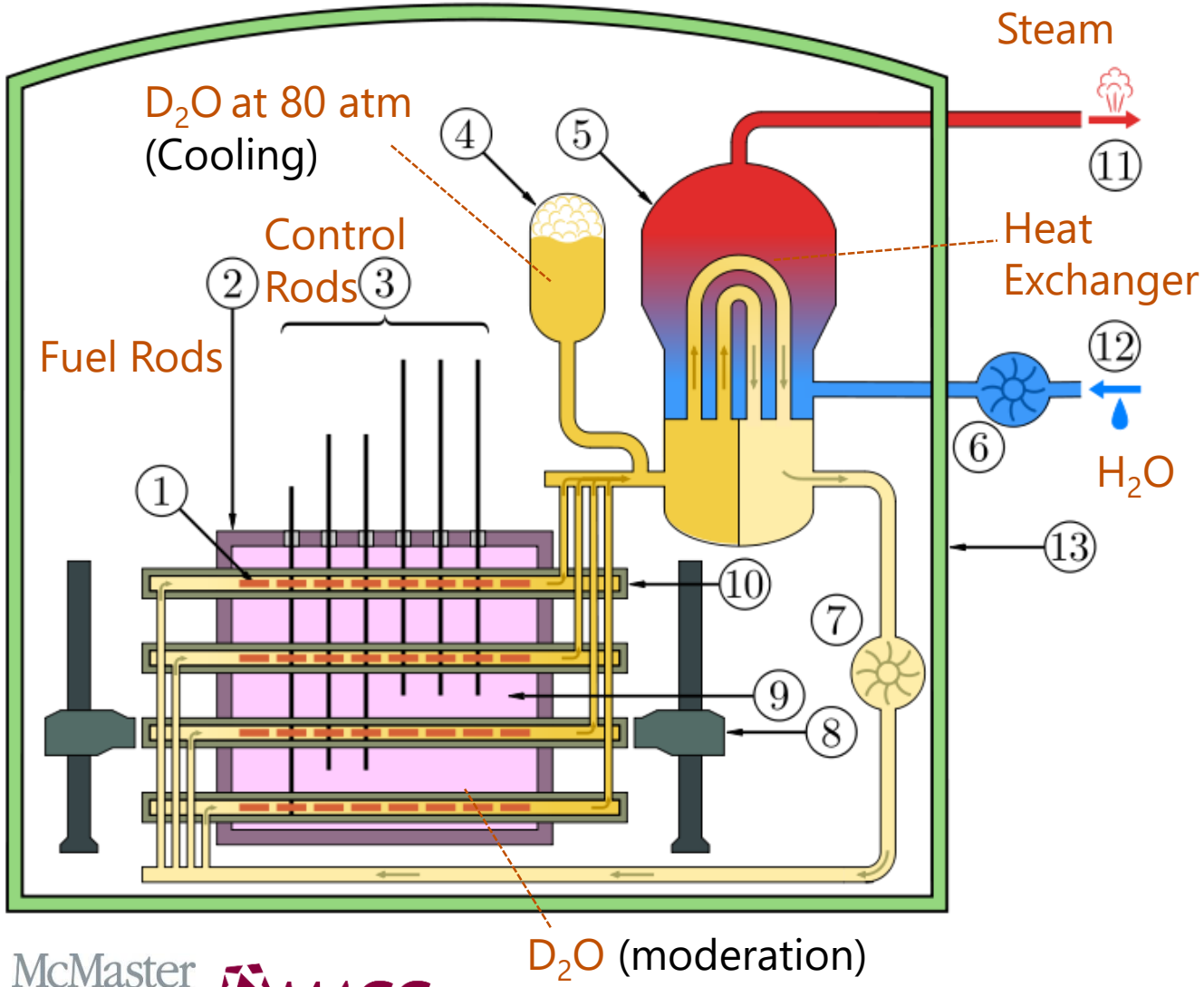
Water cools the reactor to make steam which is injected into turbines. No intermediate heat exchanger.

Not Shown: A radioactive material cleanup system cleans the main coolant.

For emergencies, can remove extra heat with a second heat exchanger

ctor Systems: Reactor Concepts Manual"

Gen II: CANDU



- Heavy water allows better moderation of fission
- Balance between critical minimum and runaway.
- Allows use of partially or even unenriched uranium and less fuel consumption.
- Has to do with how the neutrons hit heavy water in just the right way.
- Can do some load following.

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Sources: Wood, J. Nuclear Power. (2009) Ch 2. Image from Wikipedia (sorry!). Verified by other sources (nuclearfaq.ca, etc)

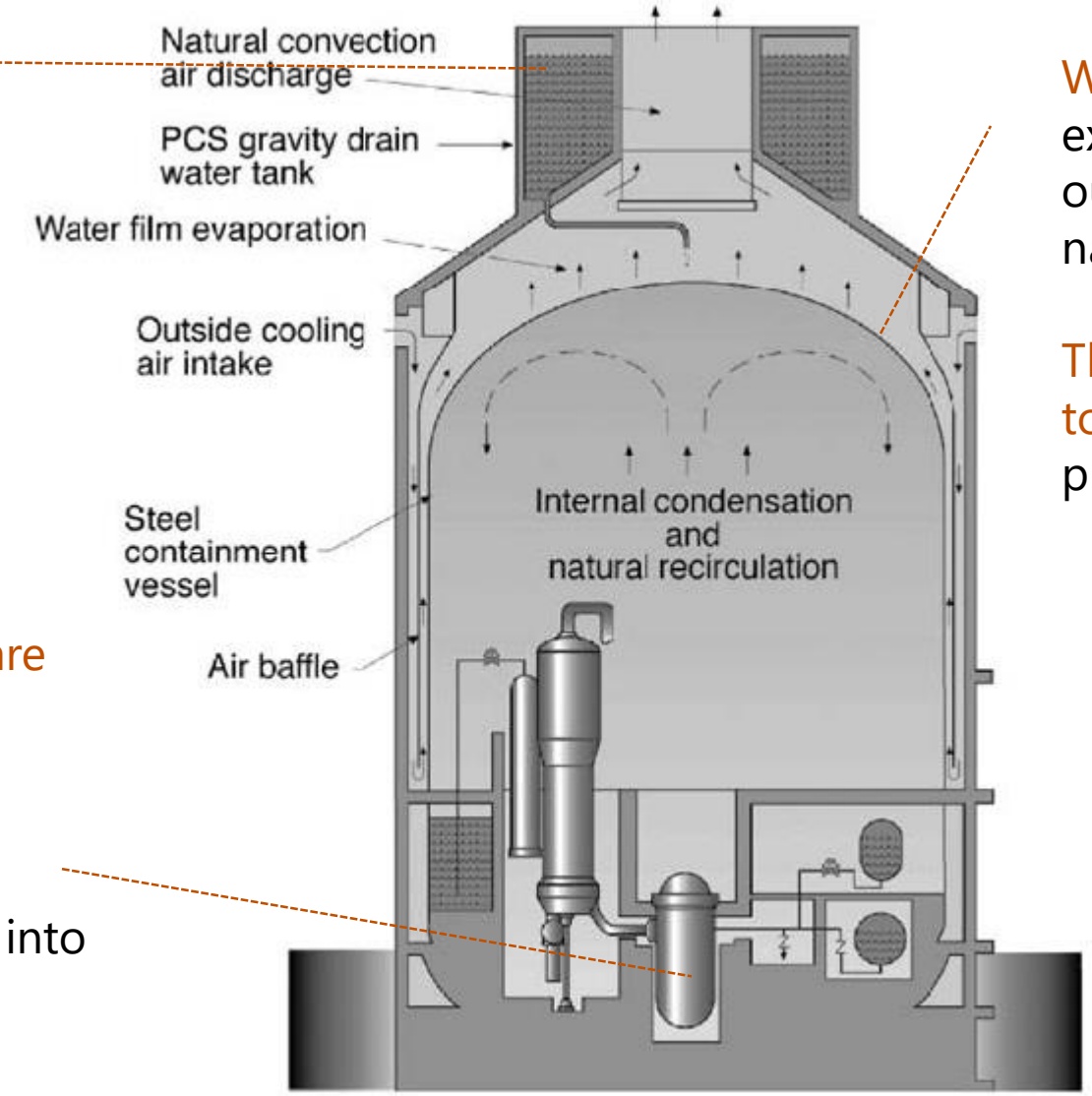
Generation III (exists) and III+ (future)

- Latest deployable tech, since 1996
  - All major new plants built in next decade are likely to be Gen III
  - Built upon proven designs but with better safety & efficiency
  - Each group has an improved version of their Gen II reactor, for the most part.
    - ABWR – Advanced BWR (General Electric). 4 operating in Japan.
    - AP1000 – A PWR with new passive cooling (Westinghouse…who are now bankrupt…). Several under construction in China and US
    - ACR-700 – Advanced CANDU Reactor. Uses H_2O as coolant, D_2O as moderator only (much cheaper). Sort of light-heavy water hybrid. (Gen III+)
    - Many others…
  - Generally lower capital investment … I guess not for the AP1000 (Vogle)

Sources: Wood, J. Nuclear Power. (2009) Ch 8.

Gen III: AT1000 – Passive Cooling

Tanks of stored water are released to fall onto the containment vessel.



When all else fails, heat exchange occurs through wall of outer containment vessel by natural convection of air.

Think natural convection cooling towers, operating on the same principle.

Other systems: control rods are held above the fuel by electromagnets

As soon as power is lost, the control rods immediately fall into place by gravity.

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Sources: Wood, J. Nuclear Power. (2009) Ch 8.

Generation IV

- Future possibilities
  - Earliest demo plant around 2020 at best.
  - Take advantage of high-temperature, high efficiency techniques
  - "Passive" safety systems (like Gen III)
    - Example, plant will still cool even after all pumps, containment, generators, and even the control room have failed
    - Generally require research into materials and other issues since these cannot be realized yet.
  - Often "new" concepts (not direct improvements from previous generations)
- The following examples shown are not exhaustive…

Sources: Wood, J. Nuclear Power. (2009) Ch 9.

Gen IV: Molten Salt Reactor

Salt goes into core to get hot
Very low vapour pressure → great safety advantage

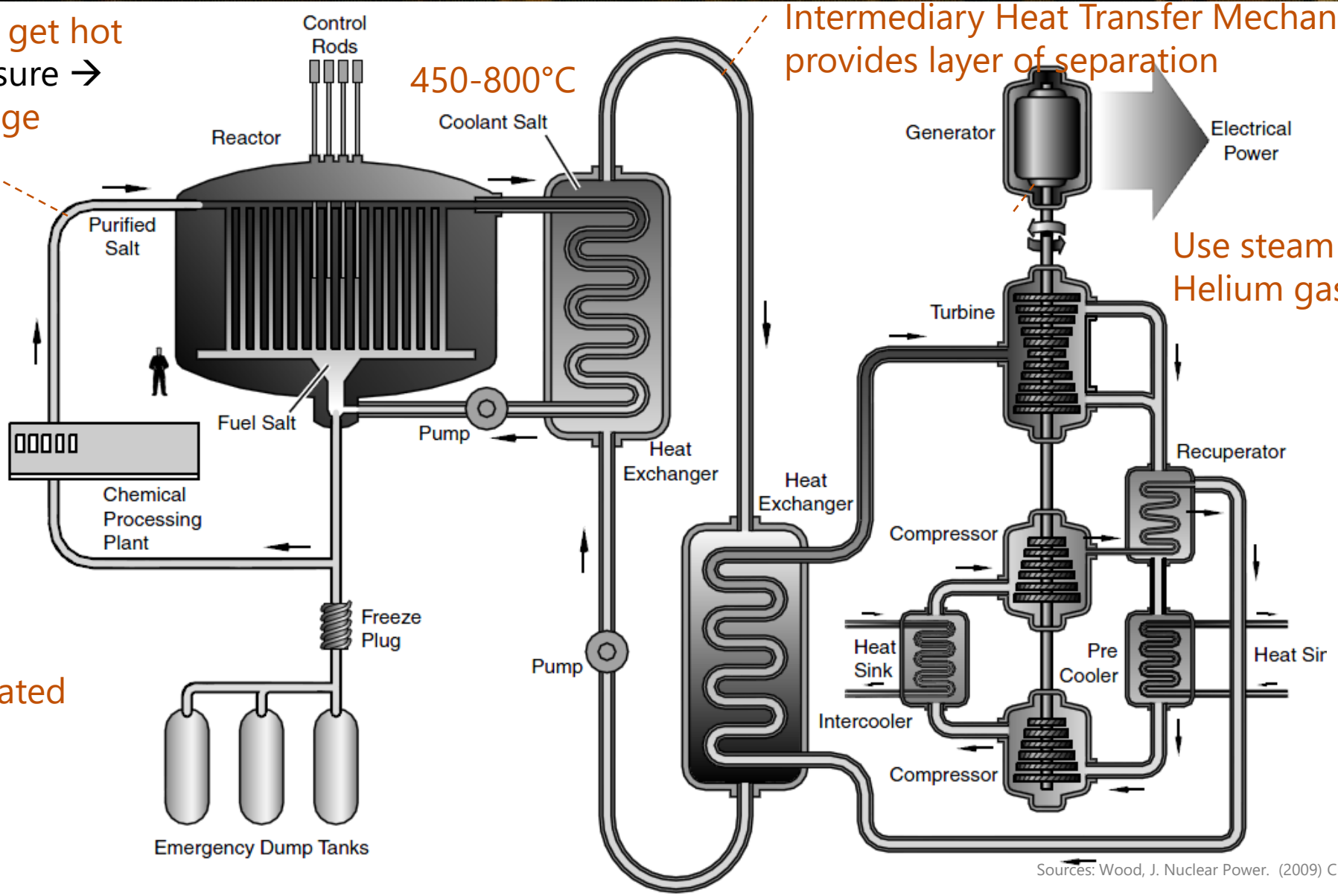
Lithium/Beryllium Fluoride Salts

Successfully demonstrated in 1954!!!

450-800°C

Intermediary Heat Transfer Mechanism provides layer of separation

Use steam cycle or Helium gas turbines



Sources: Wood, J. Nuclear Power. (2009) Ch 9.

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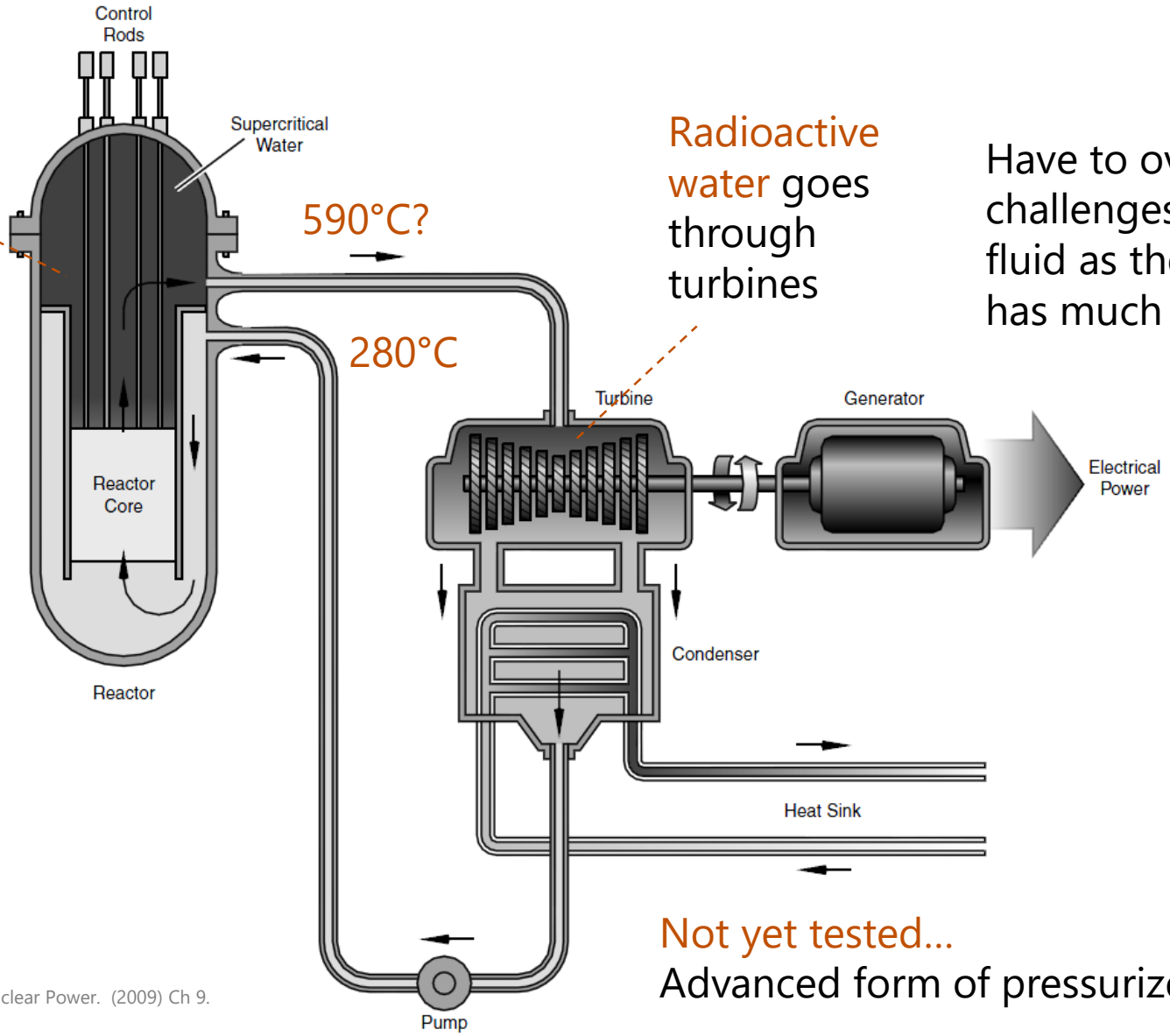
Gen IV: Supercritical Water Reactor

Supercritical water contacts reactor core directly



Radioactive water goes through turbines

Have to overcome material challenges (i.e., using a reactive fluid as the turbine fluid). But has much lower capital costs.

Dude get out of there!

Not yet tested…
Advanced form of pressurized water reactor.

Sources: Wood, J. Nuclear Power. (2009) Ch 9.

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Gen IV: Modular Helium Reactor

Has similar challenges to overcome in re: materials, turbines that work with irradiated fluids.

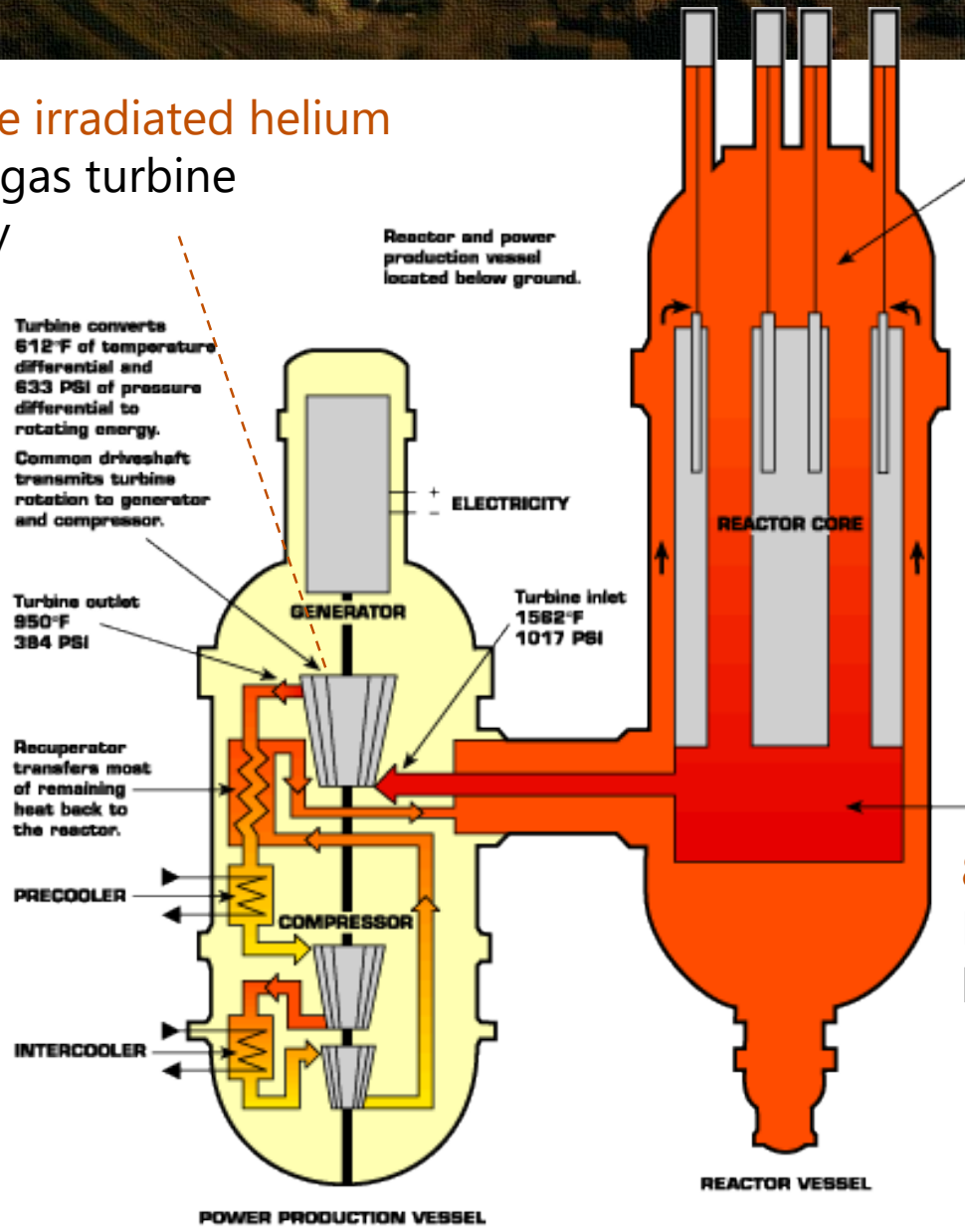
System is incredibly efficient (50%) and passively safe.

"No need for active systems in event of subsystem failure. Immune to major structural failure and operator error" – according to General Atomics

Basically, if the cooling system fails, the core will self-cool some. The design will allow for convection / radiative heat transfer out to ensure no meltdown.

Could use intermediary heat exchanger to avoid He passing directly through gas turbines.

Run the irradiated helium over a gas turbine directly



Pass He over reactor core directly

850-1000°C
Hottest kind

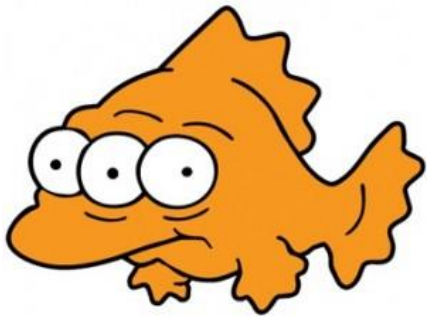
Sources: General Atomics. http://gt-mhr.ga.com/description.php

3. ACCEPTANCE AND RISK

Must be “socially” sustainable, is it, will it be?

"Green" status

- Except for that pesky nuclear waste, nuclear power is basically emissions free
  - Cleanest in essentially every category (sulfur, smog, etc.)
  - Zero direct CO_2 emissions as well. Nothing to sequester either.
- Increased interest in using nuclear for sustainability. But:
  - No one wants it in their backward
  - Perceived risk of disasters
  - Proliferation and security concerns
  - Really high capital cost



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Public Support for Nuclear (2013)

"The tragic events of March 11, 2011 in Fukushima, Japan appear to have instantly killed any momentum the nuclear industry had gained."

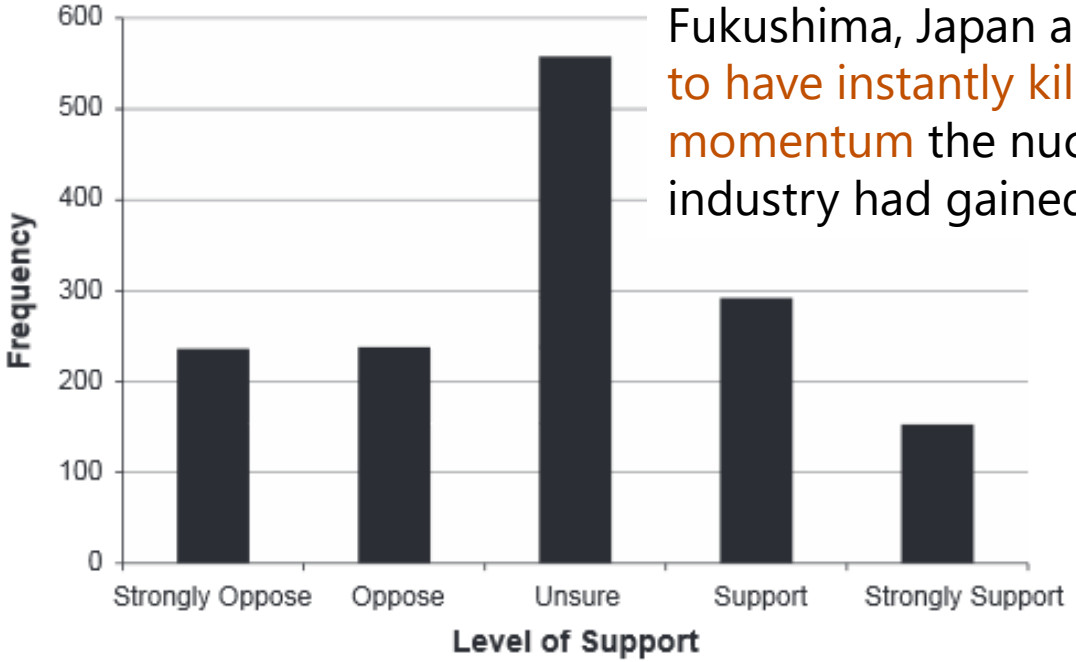
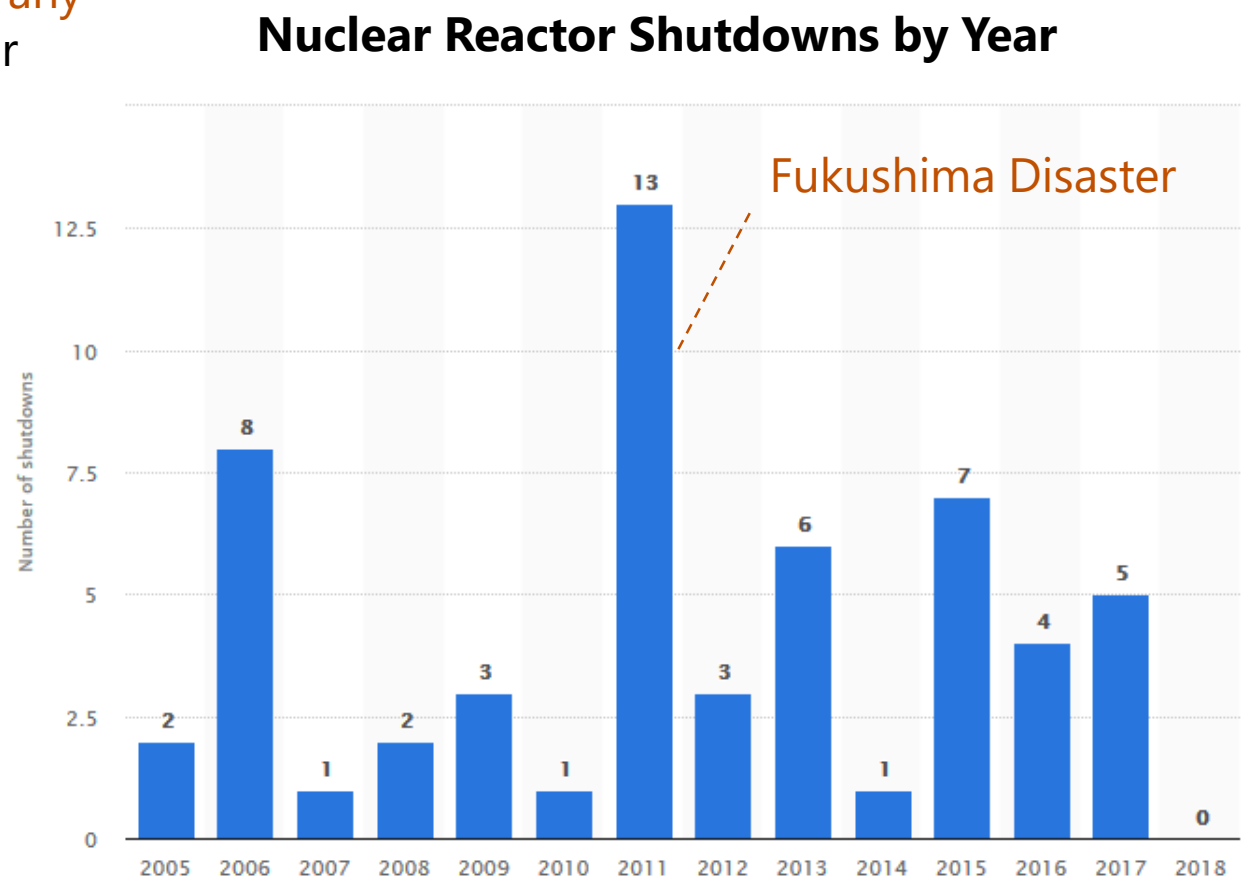


Fig. 1. Public support for policies that promote the increased use of nuclear power. *Source*: Compiled by authors.



Source: J.W. Stoutenborough et al. / Energy Policy 62 (2013) 176–184

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Perceived Risk

Perceived Risk Rankings by Group and Activity	College Students	League of Women Voters	Risk Experts
Nuclear power	1	1	20
Handguns	2	3	4
Smoking	3	4	2
Pesticides	4	9	8
Motor vehicles	5	2	1
Motorcycles	6	5	6
Alcoholic beverages	7	6	3
Police work	8	8	17
Contraceptives	9	20	11
Fire fighting	10	11	18
Surgery	11	10	5
Food preservatives	12	25	14
Spray Cans	13	14	26
Large Construction	14	12	13
Private aviation	15	7	12
Commercial aviation	16	17	16
X-rays	17	22	7
Hunting	18	13	23
Electric Power	19	18	9
Food coloring	20	26	21
Prescription Antibiotics	21	28	24

Activity	Directly Attributed Fatalities
Smoking	150,000
Alcoholic beverages	100,000
Motor vehicles	50,000
Handguns	17,000
Electric Power	14,000
Motorcycles	3,000
Swimming	3,000
Surgery	2,800
X-rays	2,300
Railroads	1,950
Private aviation	1,300
Large Construction	1,000
Bicycles	1,000
Hunting	800
Home Appliances	200
Fire fighting	195
Police work	160
Contraceptives	150
Commercial aviation	130
Nuclear power	100
Mountain climbing	30
Power mowers	24
HS & College football	23
Skiing	18

Notes

Data are from 1980, sorry couldn't find more recent study with these details.

1st Direct Death from Radiation at Fukushimi happened Sept 2018

>40 deaths were indirect from evacuation (taken from their hospital beds and didn't make it)

US & Canada nuclear industry has one of best safety records for any industry at all.

Source: Slovic, Fischoff, Lichtenstein. Facts and Fears: Understanding perceived Risk in Schwing and Albers, Societal Risk Assessment, How safe is safe enough (1980)
Meixler E. Japan Acknowledges the First Radiation-Linked Death From the Fukushima Nuclear Disaster. *Time Magazine*. Sep 8 2018

Fukushima Disaster

- March 11, 2011. Earthquake strikes Japan, and massive Tsunami follows.
- Boiler Feedwater Type. Active safety (need constant cooling to prevent reaction runaway).
- Three units were already down for repairs. The other three went dark. Control room is without power, cannot see meters, gauges to know what is going on.
- Backup batteries only lasted a few hours. Workers stole car batteries from parking lot to power critical control room systems.
- Multiple chains of failures in parallel occur over the coming weeks:
  - All three cores "melted down"
  - Many, many layers of failures from government, business, and engineers.

Source: Funabashi and Kitazawa. Bulletin of the Atomic Scientists (2012).
World Nuclear Agency. *http://www.world-nuclear.org/info/fukushima_accident_inf129.html*

- All of the many cooling and backup systems failed because generators were flooded by the Tsunami.
- Salt water later used which destroys the reactors permanently.
- Required 7 months of constant cooling to get below 80°C.

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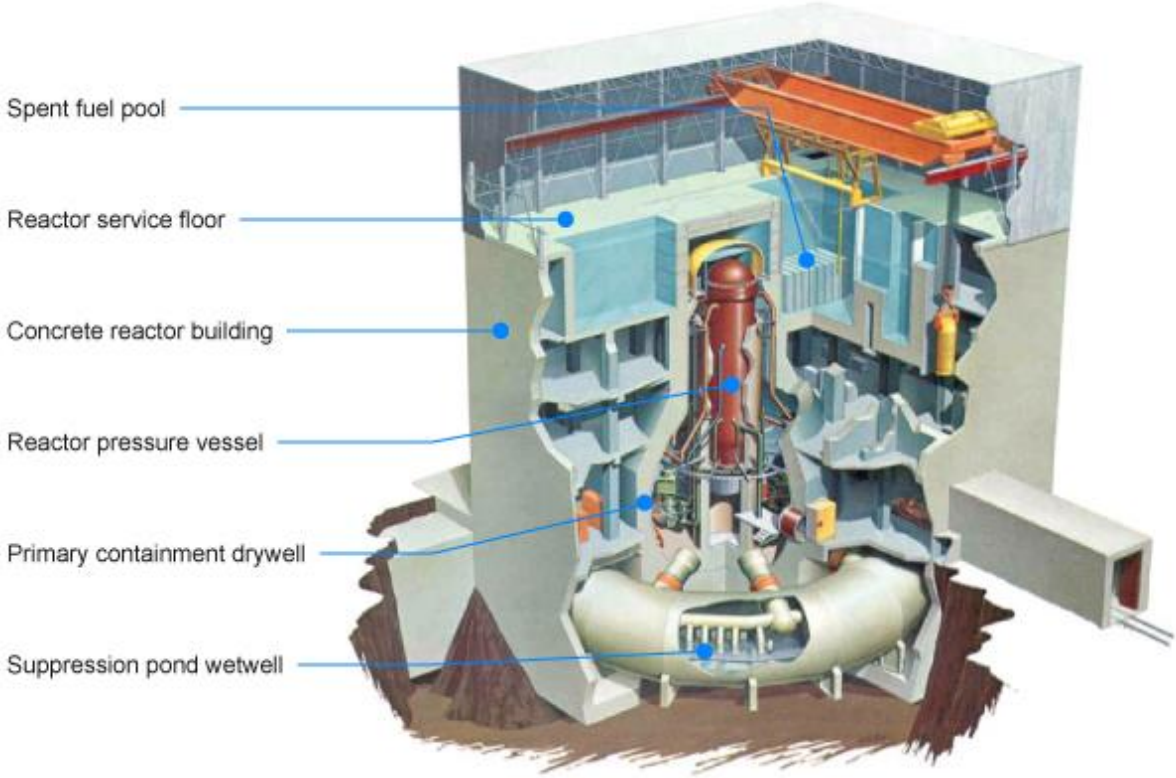
Disaster Continued

- H_2 gas leaks caused more explosions
- Earthquake damage prevented firetrucks etc. from getting to the site to supply cooling water.
- Reactors handled seismic blast ok
- Was designed to handle less of a Tsunami (did not expect one that big)
- Point: Reactor was actually designed against all known scenarios at the time, this was one they didn't think about.
- 120,000 evacuated, some permanently.
- The fuel rods are likely be active for another decade…
- Fascinating story of heroics, scandal, secrets, power plays, politics, & lies follows.



	Unit 1	Unit 2	Unit 3
Loss of AC power	+ 51 min	+ 54 min	+ 52 min
Loss of cooling	+ 1 hour	+ 70 hours	+ 36 hours
Water level down to top of fuel*	+ 3 hours	+ 74 hours	+ 42 hours
Core damage starts*	+ 4 hours	+ 77 hours	+ 44 hours
Reactor pressure vessel damage*	+11 hours	uncertain	uncertain
Fire pumps with fresh water	+ 15 hours		+ 43 hours
Hydrogen explosion (not confirmed for unit 2)	+ 25 hours service floor	+ 87 hours suppression chamber	+ 68 hours service floor
Fire pumps with seawater	+ 28 hours	+ 77 hours	+ 46 hours
Off-site electrical supply	+ 11-15 days		
Fresh water cooling	+ 14-15 days		

** according to 2012 MAAP analysis*

Source: Funabashi and Kitazawa. Bulletin of the Atomic Scientists (2012).
World Nuclear Agency. *http://www.world-nuclear.org/info/fukushima_accident_inf129.html*

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Fukushima "Fallout" (See what I did there?)

- Visschers et al. interviewed the same people a few months before and after the Fukushima incident (time travel? Lucky really) about their perceived risks:
  - Public perceptions decreased, but only a little considering the amount of attention given to the disaster
  - Perceptions of the benefits actually got stronger in many cases
    - Increased attention resulted in increased education and introspection
    - People with strong perceptions of benefits were swayed little in their overall opinions.
  - The disaster was not as bad as people thought it would be (100,000s of instant deaths, for example)
    - Some actual net decrease in fears about worst cases (only 2 direct deaths from explosion.)
  - Concluded that politicians in Germany and Switzerland, who immediately withdrew all nuclear support, acted rashly since their populations did not feel the same way.

Source: Visschers, Siegrist. *Risk Analysis* 2012. DOI: 10.1111/j.1539-6924.2012.01861.x

Today

- Workers received up to 250 mSv during crisis (~2,500,000 banana-equivalent doses)
  - Average person gets 6.2 mSv/yr from TV, airplanes, & space
- Leaks as much as 1.8 Sv/hr detected from the core
  - 4-5 Sv enough to kill about half of those exposed
  - About 1000 deaths from cancer predicted in this case
    - Child cancer among those living close to the plant increased 50x since 2011 (scientists are divided as to the definitiveness of the correlation)
- Major economic slowdown arose from power outages
  - Japanese gv't will restart other nuclear reactors
- 20km exclusion zone
- Complete meltdown (fuel rods cannot be found)

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The Times of London, Oct 8 (2015)
Noack R. Washington Post, Mar 12 (2015)