Nuclear Energy / The Hydrogen Economy
AOSC 433/633 & CHEM 433

Ross Salawitch

Class Web Site: **http://www.atmos.umd.edu/~rjs/class/spr2015**

Topics for today:

- **Nuclear Energy Production**
  - **History**
  - **Reactor Technology**
  - **Waste**
- **Hydrogen Economy**
  - **Overview**
  - **Source?**
  - **An Interesting Unintended Consequence**

Lecture 22

5 May 2015

Nuclear Power History

- Use of nuclear power developed by military; currently around 150 ships, globally
  - allowed submarines to stay underwater for extended periods of time
  - 1954: *U.S.S. Nautilus*, first nuclear powered submarine
- 1956: first commercial nuclear power plant, U.K.
- 1957: first U.S. commercial nuclear power plant, Shippingport, Pa

It took more than 8 hours to lower the 58 reactor core into the pressure vessel in October 1957. There was a clearance of only six-hundredths of an inch between the core and the steel wall of the pressure vessel.

http://www.portal.state.pa.us/portal/server.pt/community/history/4569/it_happened_here/471309

Pros and Cons of Nuclear Energy

Discussions about nuclear energy evoke strong emotions. Climate change concerns have led some to reassess their views regarding this power source.

To those influencing environmental policy but opposed to nuclear power:

As climate and energy scientists concerned with global climate change, we are writing to urge you to advocate the development and deployment of safer nuclear energy systems. We appreciate your organization's concern about global warming, and your advocacy of renewable energy. But continued opposition to nuclear power threatens humanity's ability to avoid dangerous climate change.

We call on your organization to support the development and deployment of safer nuclear power systems as a practical means of addressing the climate change problem. Global demand for energy is growing rapidly and must continue to grow to provide the needs of developing economies. At the same time, the need to sharply reduce greenhouse gas emissions is becoming ever clearer. We can only increase energy supply while simultaneously reducing greenhouse gas emissions if new power plants turn away from using the atmosphere as a waste dump.

Renewables like wind and solar and biomass will certainly play roles in a future energy economy, but those energy sources cannot scale up fast enough to deliver cheap and reliable power at the scale the global economy requires. While it may be theoretically possible to stabilize the climate without nuclear power, **in the real world there is no credible path to climate stabilization that does not include a substantial role for nuclear power.**

We understand that today's nuclear plants are far from perfect. Fortunately, passive safety systems and other advances can make new plants much safer. And modern nuclear technology can reduce proliferation risks and solve the waste disposal problem by burning current waste and using fuel more efficiently. Innovation and economies of scale can make new power plants even cheaper than existing plants. Regardless of these advantages, nuclear needs to be encouraged based on its societal benefits.

http://dotearth.blogs.nytimes.com/2013/11/03/to-those-influencing-environmental-policy-but-opposed-to-nuclear-power

Pros and Cons of Nuclear Energy

Discussions about nuclear energy evoke strong emotions. Climate change concerns have led some to reassess their views regarding this power source.

Quantitative analyses show that the risks associated with the expanded use of nuclear energy are orders of magnitude smaller than the risks associated with fossil fuels. No energy system is without downsides. We ask only that energy system decisions be based on facts, and not on emotions and biases that do not apply to 21st century nuclear technology.

While there will be no single technological silver bullet, the time has come for those who take the threat of global warming seriously to embrace the development and deployment of safer nuclear power systems as one among several technologies that will be essential to any credible effort to develop an energy system that does not rely on using the atmosphere as a waste dump.

With the planet warming and carbon dioxide emissions rising faster than ever, we cannot afford to turn away from any technology that has the potential to displace a large fraction of our carbon emissions. Much has changed since the 1970s. The time has come for a fresh approach to nuclear power in the 21st century.

We ask you and your organization to demonstrate its real concern about risks from climate damage by calling for the development and deployment of advanced nuclear energy.

Sincerely,

Dr. Ken Caldeira, Senior Scientist, Department of Global Ecology, Carnegie Institution
Dr. Kerry Emanuel, Atmospheric Scientist, Massachusetts Institute of Technology
Dr. James Hansen, Climate Scientist, Columbia University Earth Institute
Dr. Tom Wigley, Climate Scientist, University of East Anglia and the National Center for Atmospheric Research

http://dotearth.blogs.nytimes.com/2013/11/03/to-those-influencing-environmental-policy-but-opposed-to-nuclear-power

Pros and Cons of Nuclear Energy

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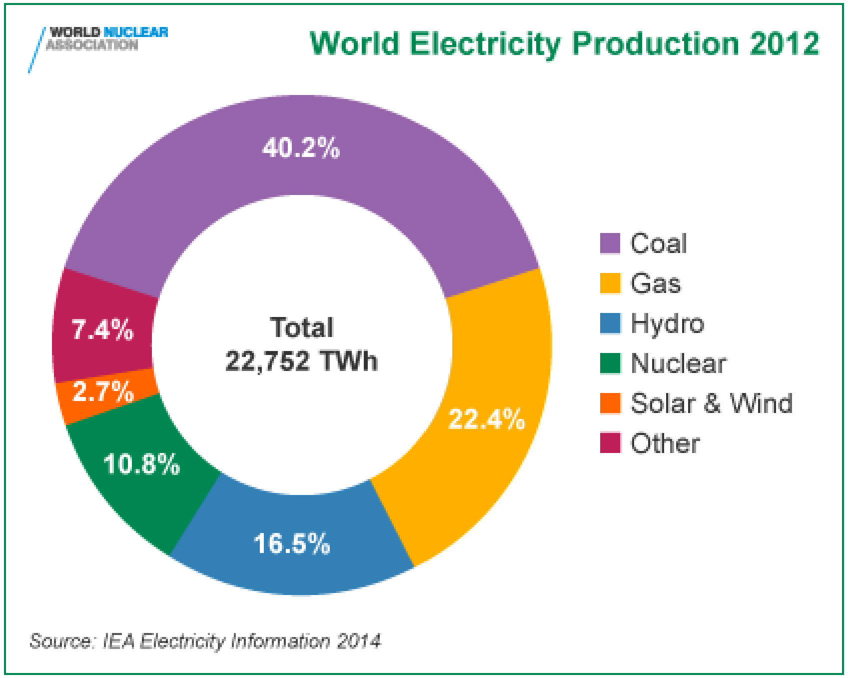
Fukushima Daiichi nuclear disaster

http://www.whoi.edu/oceanus/feature/communicating-science

World Production: Nuclear

Electricity Generation Production via nuclear = 10.8 %



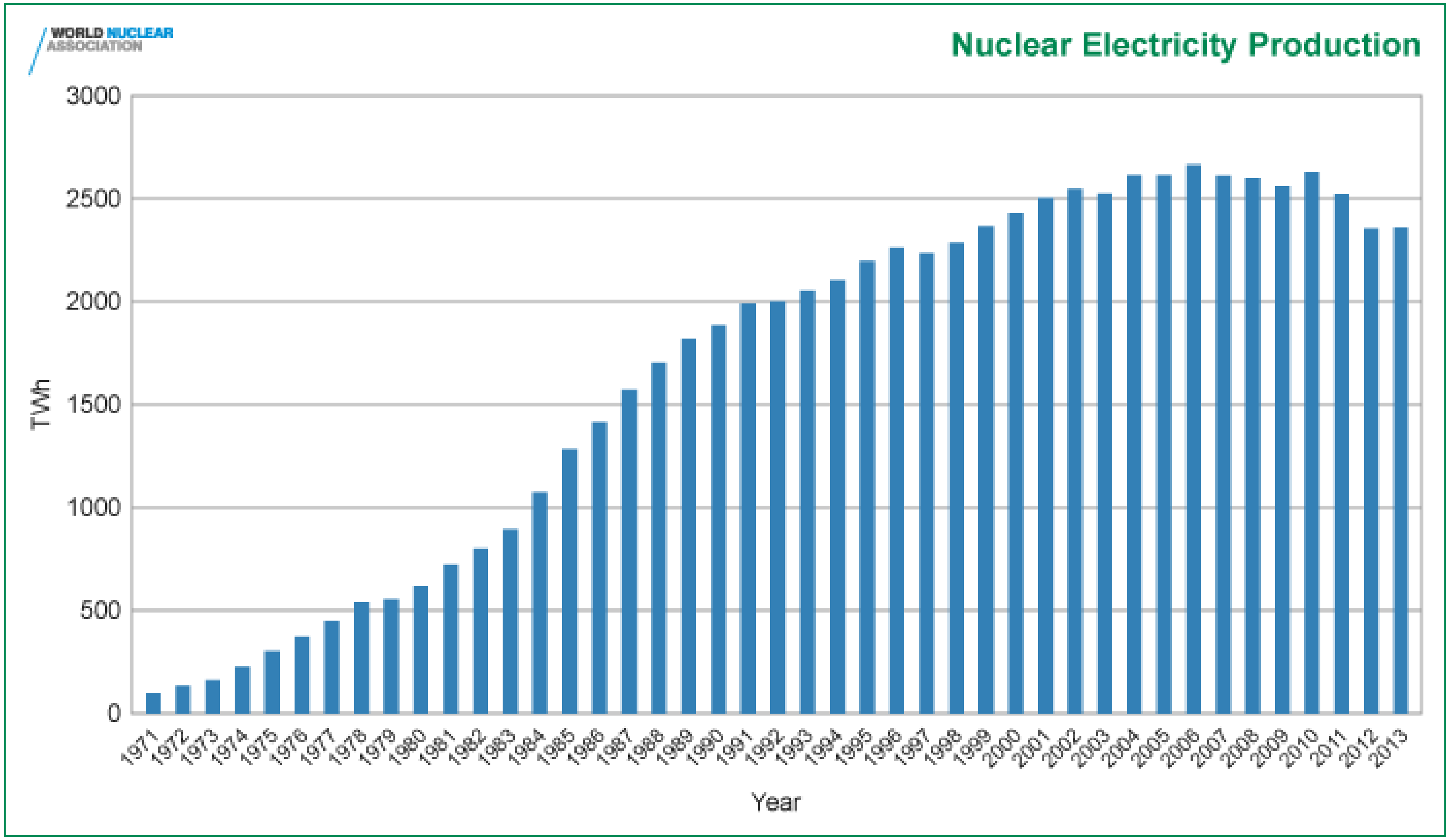
Total Source	GW (year 2012)
Coal	1,810
Natural Gas	1,391
Hydro-electric	979
Liquid Fossil Fuel	388
Nuclear	**373**
Wind	268
Solar, Tidal	94
Biomass	87
Geothermal	10
Total	5400

http://www.eia.gov/forecasts/ieo/ieo_tables.cfm

http://www.world-nuclear.org/info/Current-and-Future-Generation/Nuclear-Power-in-the-World-Today

World Production: Nuclear

Electricity Generation Production via nuclear peaked 2006 to 2010 and has declined since



http://www.world-nuclear.org/info/Current-and-Future-Generation/Nuclear-Power-in-the-World-Today

World Production: Nuclear

CC states roughly 440 nuclear power plants
World Nuclear Assoc states 435 as of Feb 2015

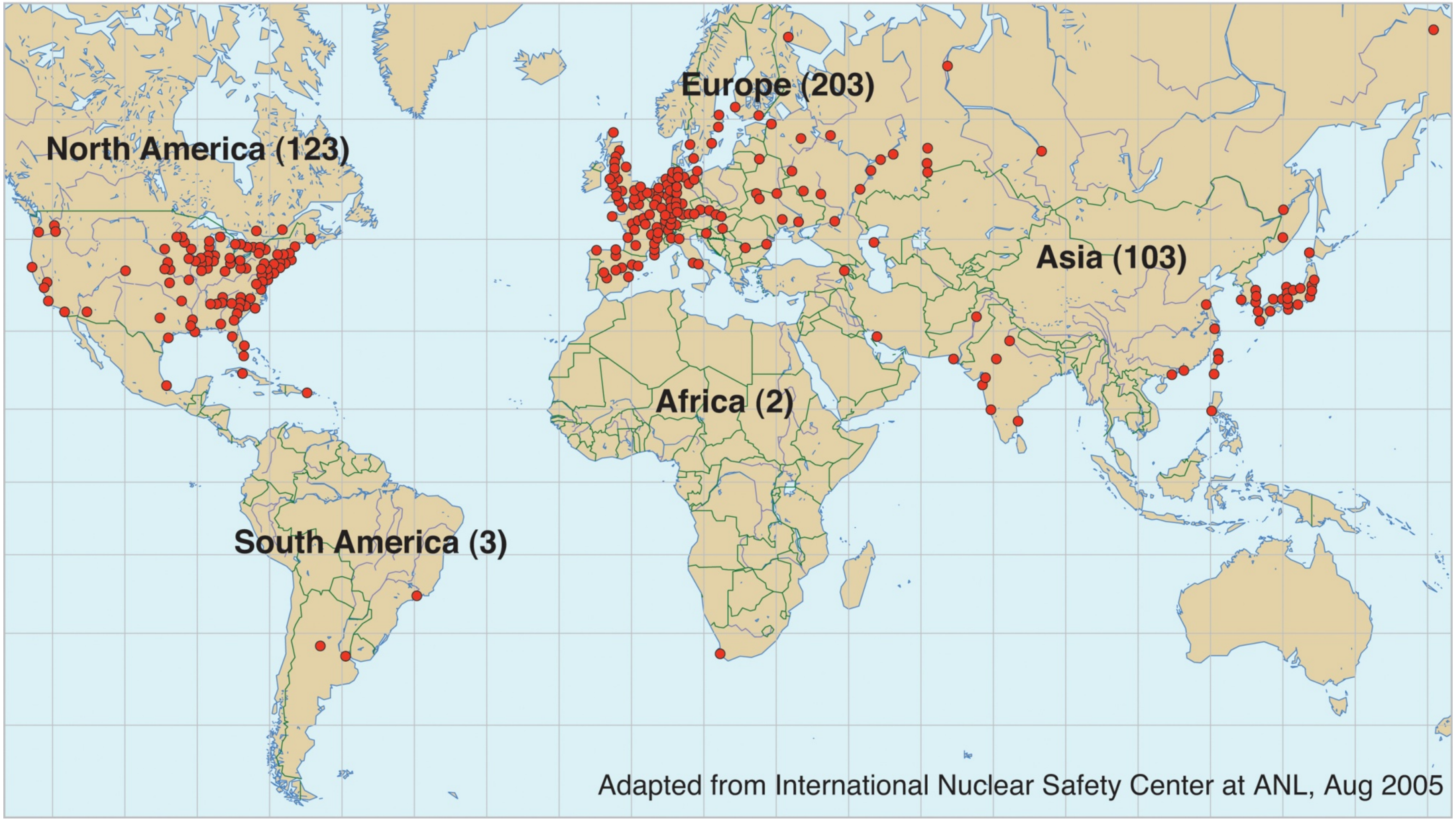


Figure 7.2, Chemistry in Context

World Production: Nuclear

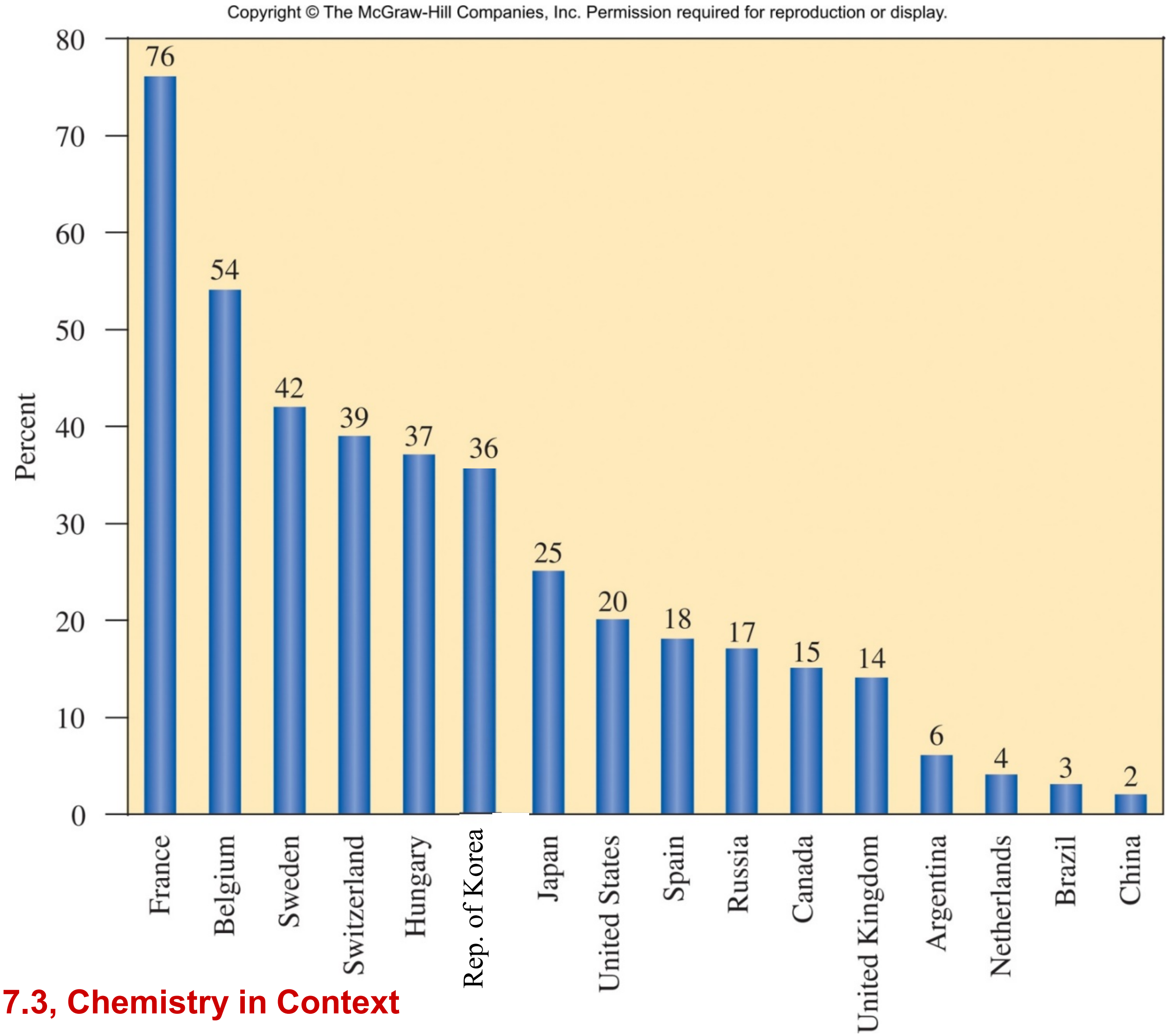
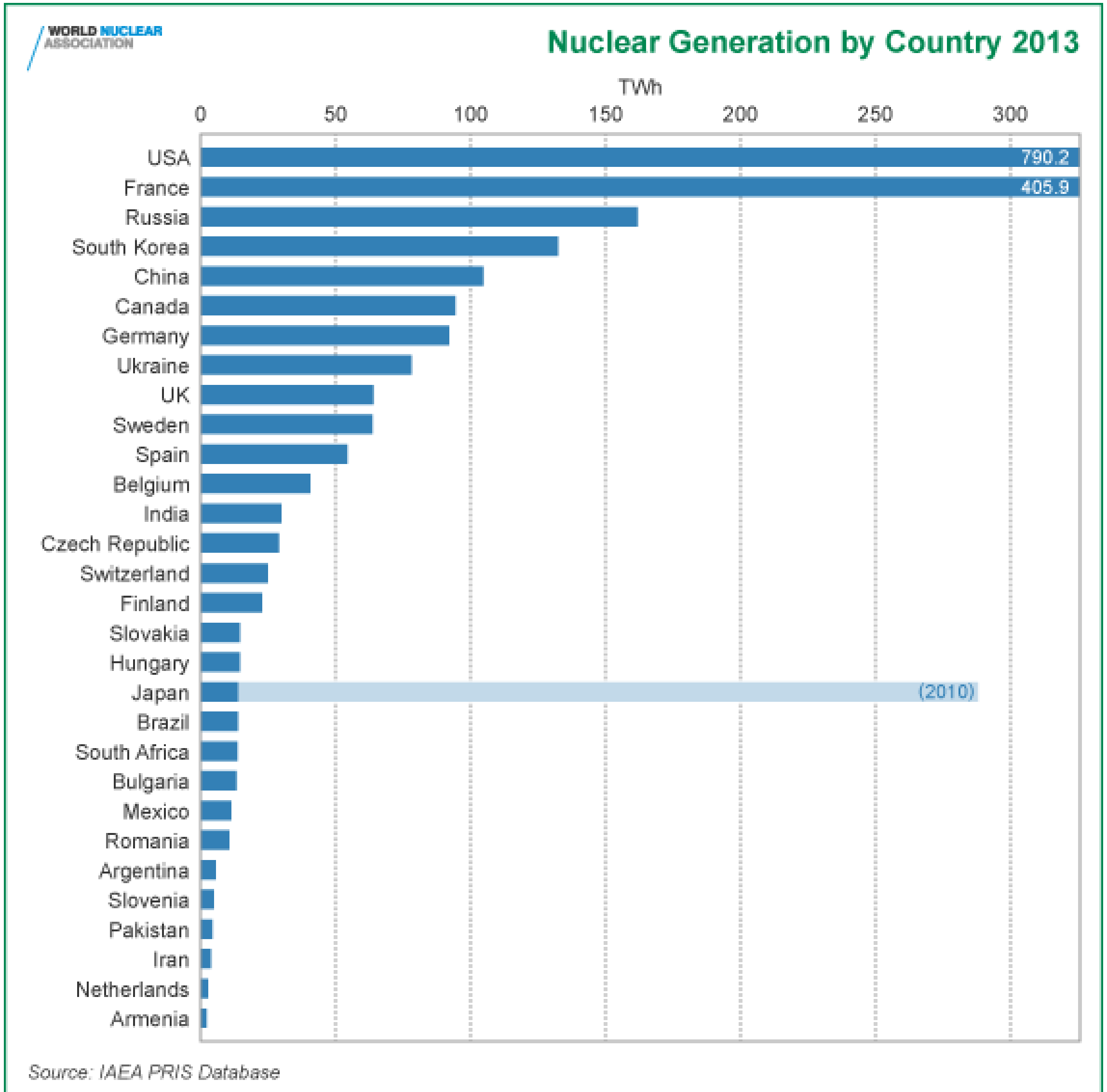


Figure 7.3, Chemistry in Context

World Production: Nuclear



http://www.world-nuclear.org/info/Current-and-Future-Generation/Nuclear-Power-in-the-World-Today

U.S. Production: Nuclear

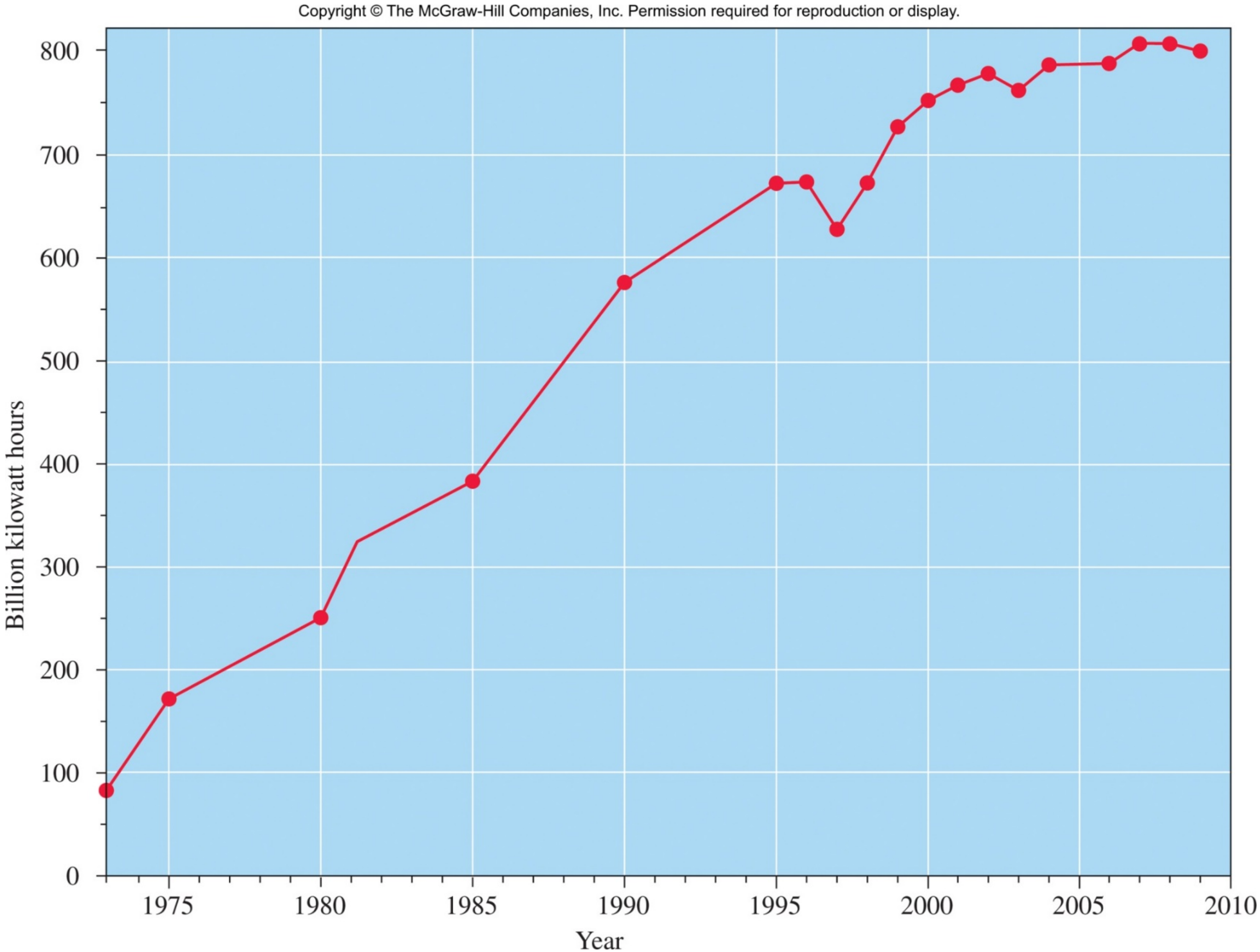
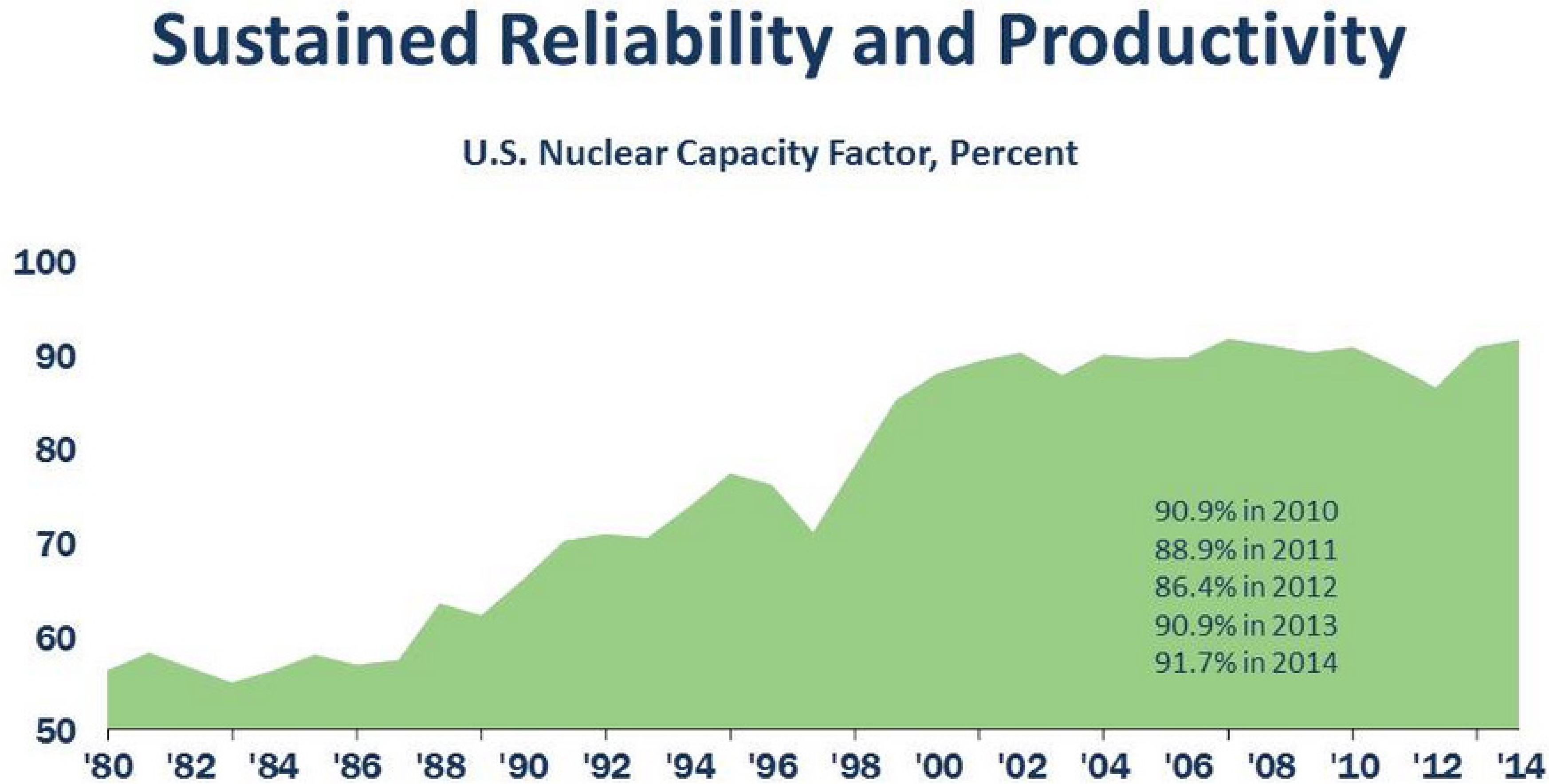


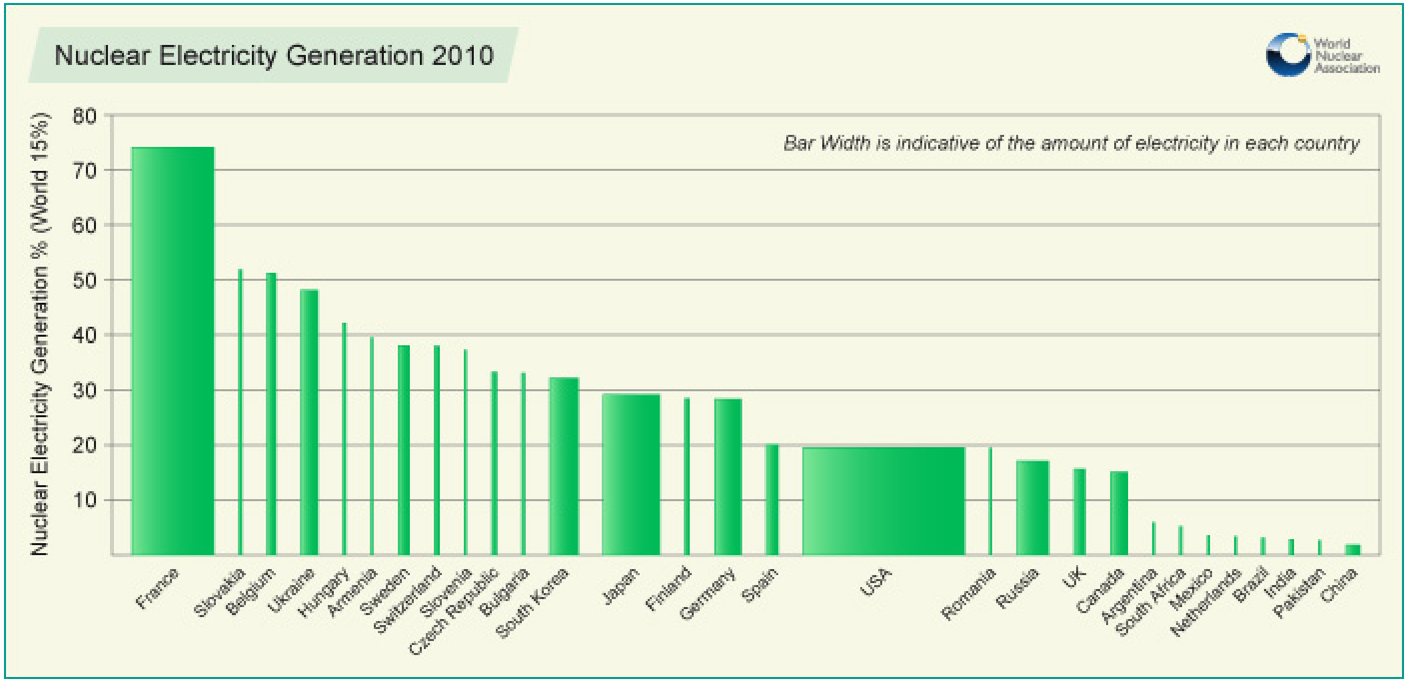
Figure 7.1, Chemistry in Context

U.S. Production: Nuclear



http://www.nei.org/Knowledge-Center/Nuclear-Statistics/US-Nuclear-Power-Plants/US-Nuclear-Capacity-Factors

World Production: Nuclear



http://breakingenergy.com/2013/11/19/nuclears-prospects-glass-half-full-or-half-empty

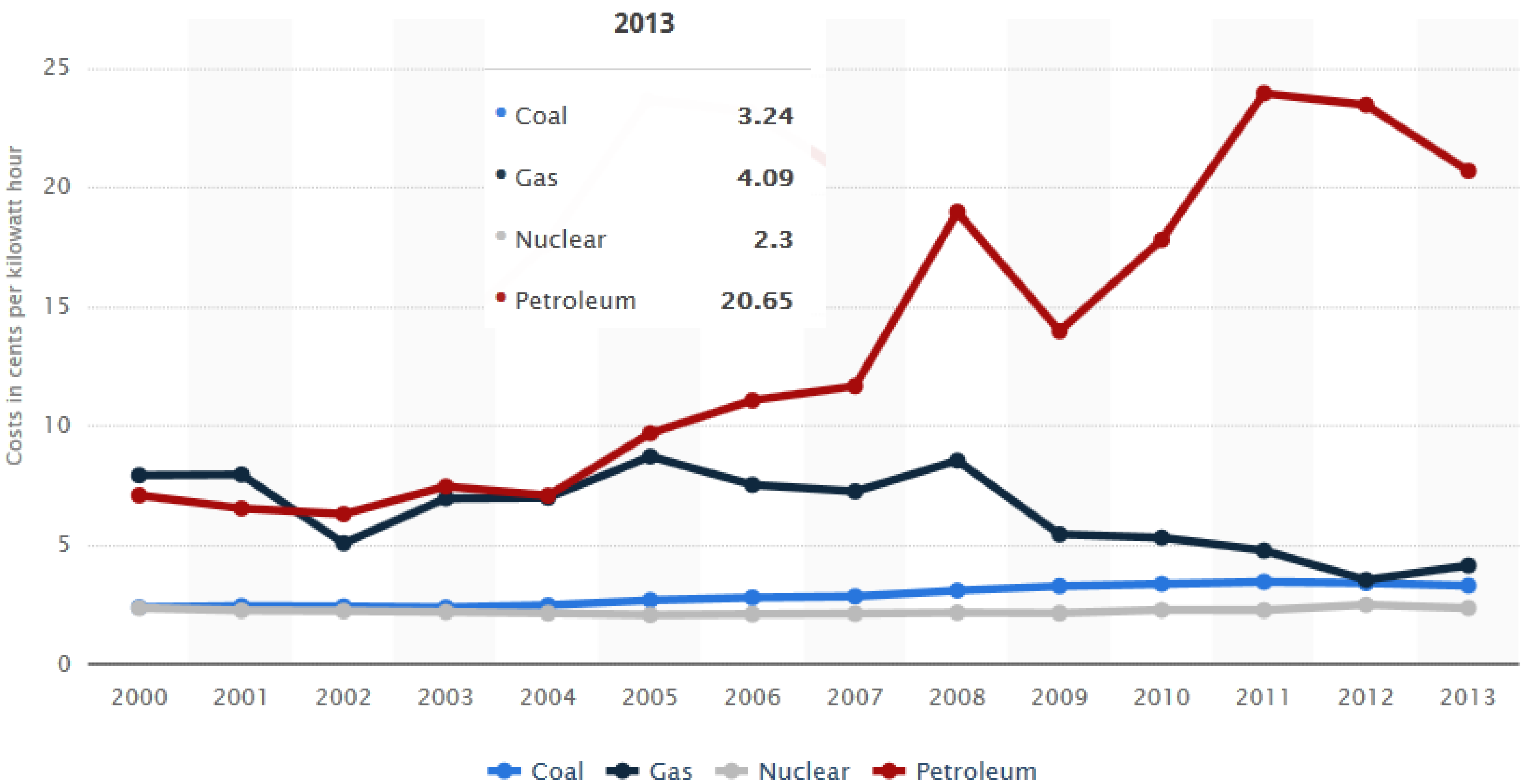
Nuclear Power:

- Generates ~11% of world's electricity
- 435 commercial reactors in 31 countries; 70 presently under construction
- 56 countries operate a total of about 240 research reactors and a further 180 nuclear reactors power some 140 ships and submarines

Electricity Costs: Nuclear

- Producing electricity at U.S. nuclear power plants, including fuel, operation and maintenance, declined from 3 ¢ kWh^{-1} in 1990 to 2.3 ¢ kWh^{-1} in 2013
- US nuclear plant capacity factor: 58% in 1980, 70% in 1990, 92% in 2014

increased plant capacity equivalent to 20 new nuclear reactors



http://www.statista.com/statistics/184712/us-electricity-production-costs-by-source-from-2000/

Figure 7.8, Chemistry in Context

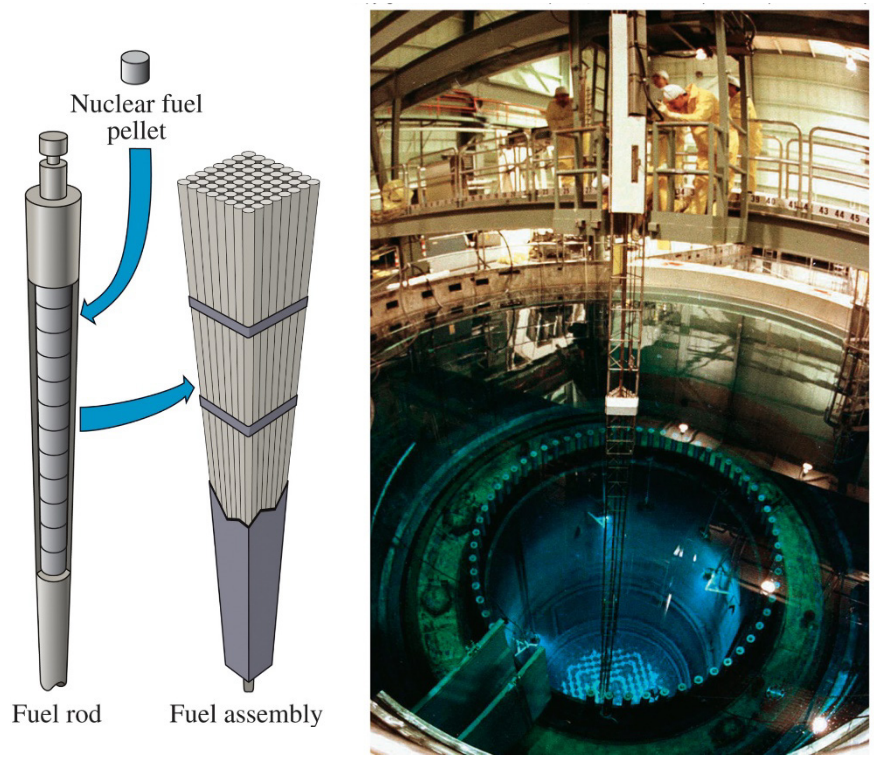
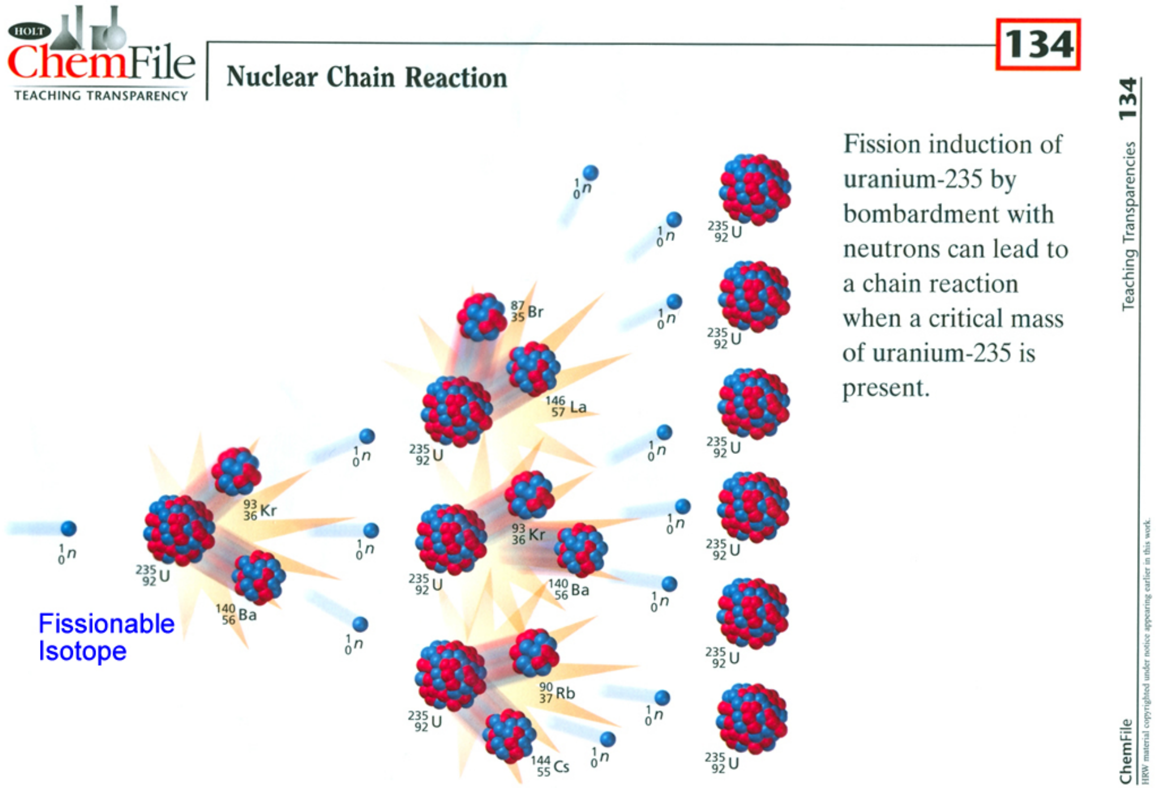


Figure 7.9, Chemistry in Context

Nuclear Power:

- ^{235}U (about 0.7% of natural uranium) is fissile; ^{238}U (dominant form) not fissile
- For reactor, uranium enriched to 3 to 5% using either gas diffusion (1 plant in U.S.) or gas centrifuge (two new plants being developed)
- Bomb grade uranium enriched to 90% ^{235}U
  - critical mass for uncontrolled explosion not present in conventional nuclear reactor
- Enriched UF_6 (gas at 56°C) converted to solid UO_2 pellets "size of a dime"
- Pellets stacked to form "fuel rods"



http://www.doccasagrande.net

Nuclear Fission:

- ^{235}U hit by "slow neutron" → splits into two smaller atoms, generating heat, more neutrons
  - slow neutrons: cause ^{235}U to split
  - fast neutrons: can be absorbed by ^{238}U, transmuting this element to ^{239}Pu
  - ^{239}Pu: int'l security concern ; half life of 24,110 yr
- Released neutrons lead to chain reaction (positive feedback) that releases lots of energy
- Today's reactors (Generation II)
  - Moderators, either deuterium, helium, or carbon (graphite), quench fast neutrons and maintain "delicate balance" of sustained chain reaction (which ceases with too few neutrons) and regulation of temperature (which gets too high with too many electrons)

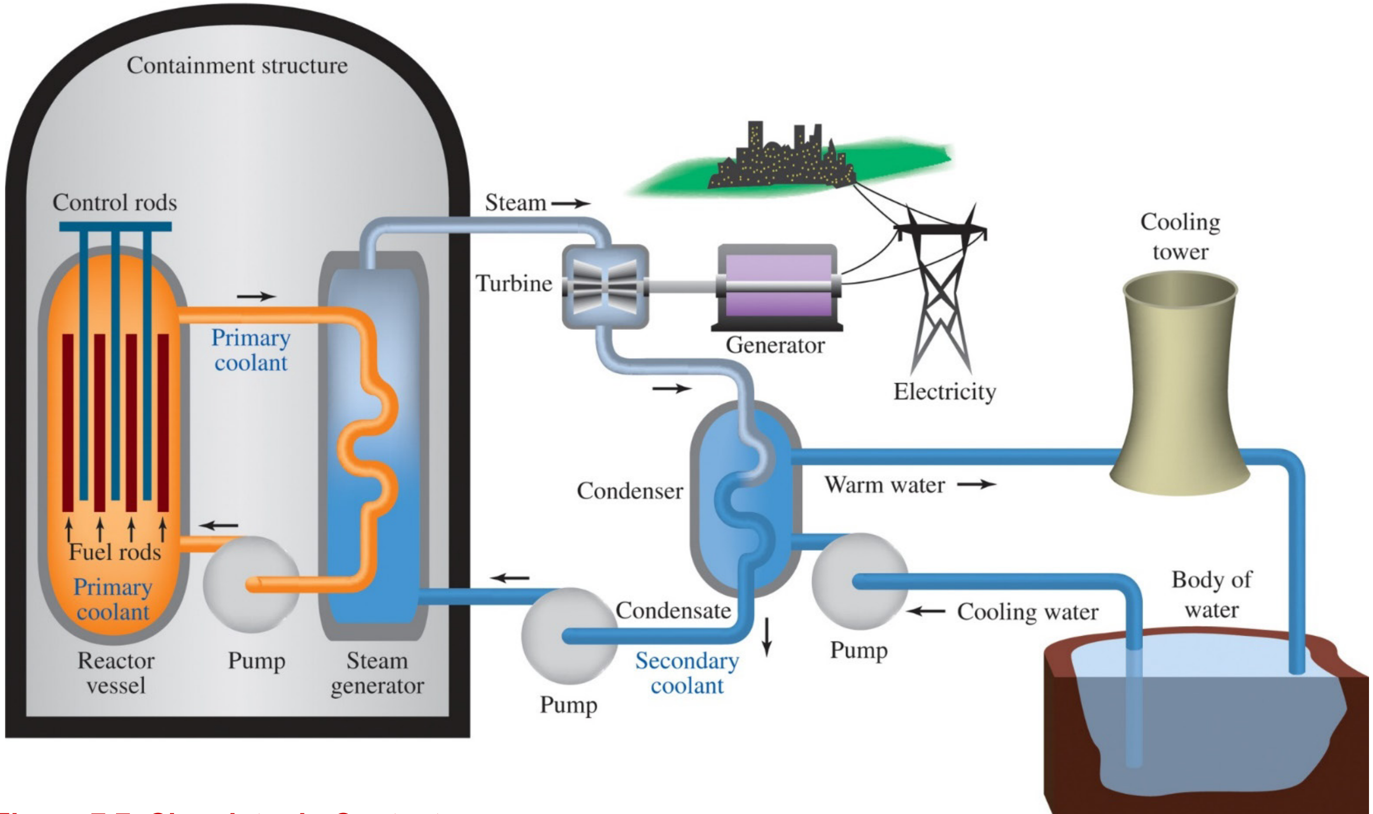


Figure 7.7, Chemistry in Context

Today's reactors (Generation II):

- Regular H_2O used as coolant, transfers heat to another system of H_2O
  - – generates steam which turns turbines
- Operates at ~300°C (not too hot) but at very high pressure (~150 times atmospheric)
- Water used for turbines drawn from nearby water source (river, lake, ocean, etc), returned to environment once cooled:
  - intake system not pleasant for local fish
  - concern over output raising temperature of nearby body of water

Figure 7.10, Chemistry in Context

Today’s reactors (Generation II):

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  - intake system not pleasant for local fish
  - concern over output raising temperature of nearby body of water

Nuclear Power: Waste

- HLW: High Level Waste (i.e., spent fuel)
  - 20 tons per plant per year → 2000 tons per year in the U.S.
  - contains ^{235}Uranium, ^{238}Uranium, ^{239}Plutonium, ^{131}Iodine, ^{137}Cesium, ^{90}Strontium
  - About 70,000 tons of spent fuel generated in U.S. (as of 2010)

Table 7.4 Half-life of Selected Radioisotopes

Radioisotope	Half-life ($t_{1/2}$)	Found in the spent fuel rods of nuclear reactors?
uranium-238	4.5×10^9 years	Yes. Present originally in fuel pellet.
potassium-40	1.3×10^9 years	No.
uranium-235	7.0×10^8 years	Yes. Present originally in fuel pellet.
plutonium-239	24,110 years	Yes. See equation 7.13.
carbon-14	5715 years	No.
cesium-137	30.2 years	Yes. Fission product.
strontium-90	29.1 years	Yes. Fission product.
thorium-234	24.1 days	Yes. Small amount generated in natural decay series of U-238.
iodine-131	8.04 days	Yes. Fission product.
radon-222	3.82 days	Yes. Small amount generated in natural decay series of U-238.
plutonium-231	8.5 minutes	No. Half-life is too short.
polonium-214	0.00016 seconds	No. Half-life is too short.

- Spent fuel from plants encased in ceramic or glass (vitrification)
  - radioactivity remains, but glass isolates waste from water supply
  - In U.S., presently stored "on site" at reactors with design capacity for ~25 yrs of waste

Nuclear Power: Waste

- U.S.
  - 1997: Federal Government Designated Yucca Mountain, Nevada (not far from Las Vegas) as sole site for long-term, high level nuclear waste storage
  - Nevada opposed
  - 2002: Senate gave final approval for Yucca Mountain Site based on EPA 10,000 year radiation compliance assessment
  - 2004: U.S. Appellate Court ruled compliance must address N.A.S. study that peak radiation could be experienced 300,000 yrs after site had been filled and sealed
  - 2009: EPA published in Federal Register a final rule, increasing compliance period to **1,000,000** years
  - 2011: Obama administration stopped financial support for Yucca, after $54 billion has been invested for capacity of 70,000 tons of spent fuel plus 8000 tons of military waste
- Rest of World
  - many countries recycle waste, considerably reducing mass of waste
  - Japan considering storing waste at Fukushima reactor site
    http://www.bloomberg.com/news/2011-05-26/fukushima-may-become-graveyard-for-radioactive-waste-from-crippled-plant.html
  - United Kingdom, Canada, and U.S. considering burial of waste in ~2 to 5 km boreholes:

Nuclear Power: Waste

• United Kingdom, Canada, and U.S. considering burial of waste in ~2 to 5 km boreholes:

Option	Examples
Near-surface disposal at ground level, or in caverns below ground level (at depths of tens of metres)	• Implemented for LLW in many countries, including Czech Republic, Finland, France, Japan, Netherlands, Spain, Sweden, UK and USA. • Implemented in Finland and Sweden for LLW and short-lived ILW.
Deep geological disposal (at depths between 250m and 1000m for mined repositories, or 2000m to 5000m for boreholes)	• Most countries with high-level and long-lived radioactive waste have investigated deep geological disposal and it is official policy in various countries (variations also include multinational facilities). • Implemented in USA for defence-related ILW. • Preferred sites for HLW/spent fuel selected in France, Sweden, Finland and USA[a]. • Geological repository site selection process commenced in UK and Canada.

http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Nuclear-Wastes/Appendices/Radioactive-Waste-Management-Appendix-2--Storage-and-Disposal-Options

Nuclear Power: Waste

• United Kingdom, Canada, and U.S. considering burial of waste in ~2 to 5 km boreholes:

Deep boreholes

As well as mined repositories which have been the focus of international efforts so far, deep borehole disposal of high-level radioactive waste has been considered as an option for geological isolation for many years, including original evaluations by the US National Academy of Sciences in 1957 and more recent conceptual evaluations. In contrast to recent thinking on mined repositories, the contents would not be retrievable.

The concept consists of drilling a boreholes into crystalline basement rock to a depth of about 5000 metres, emplacing waste canisters containing used nuclear fuel or vitrified radioactive waste from reprocessing in the lower 2000 metres of the borehole, and sealing the upper 3000 metres of the borehole with materials such as bentonite, asphalt or concrete. The disposal zone of a single borehole could thus contain 400 steel canisters each 5 metres long and one-third to half a metre diameter. These might be emplaced in strings of 40 canisters. The waste containers would be separated from each other by a layer of bentonite or cement.

Boreholes can be readily drilled offshore (as described in the section below on sub seabed disposal) as well as onshore in host rocks both crystalline and sedimentary. This capability significantly expands the range of locations that can be considered for the disposal of radioactive waste.

Deep borehole concepts have been developed (but not implemented) in several countries, including Denmark, Sweden, Switzerland and USA for HLW and spent fuel. Compared with deep geological disposal in a mined underground repository, placement in deep boreholes is considered to be more expensive for large volumes of waste. This option was abandoned in countries such as Sweden, Finland and the USA. The borehole concept remains an attractive proposition for the disposal of smaller waste forms including sealed radioactive sources from medical and industrial applications.[o]

An October 2014 US Department of Energy report said: "Preliminary evaluations of deep borehole disposal indicate a high potential for robust isolation of the waste, and the concept could offer a pathway for earlier disposal of some wastes than might be possible in a mined repository."

http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Nuclear-Wastes/Appendices/Radioactive-Waste-Management-Appendix-2--Storage-and-Disposal-Options

Nuclear Power: Safety

- U.S.
  - 1979 : Three Mile Island near Harrisburg, Pennsylvania
  - Loss of coolant and partial meltdown
  - Release of radioactive gases: no fatalities, normal cancer rates in area

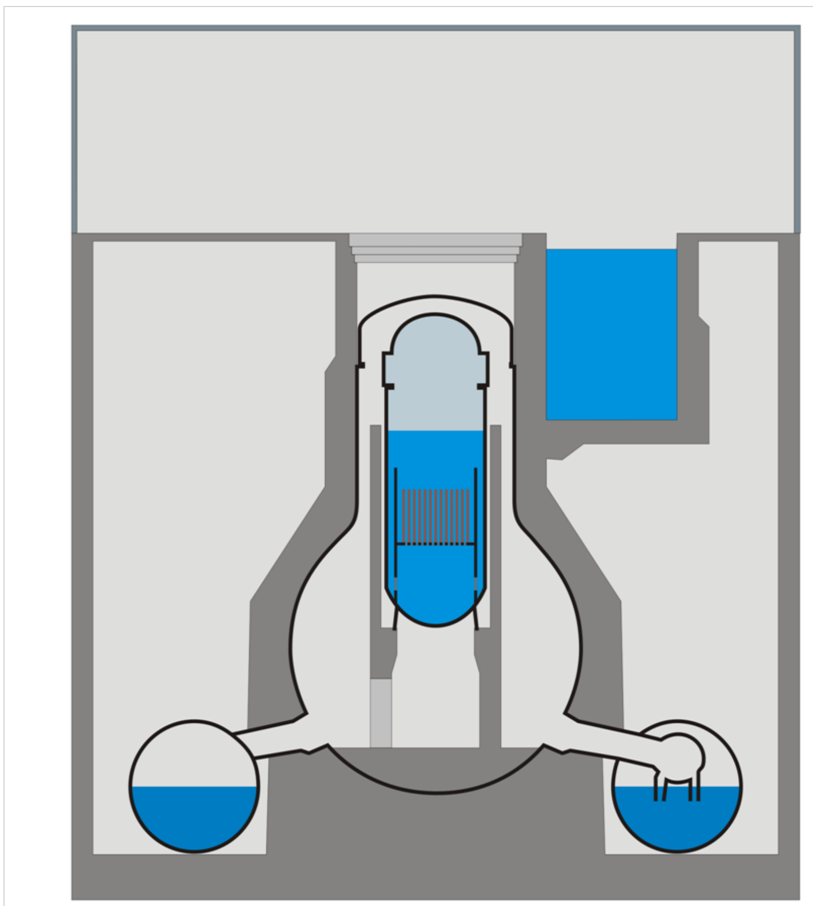
    The accident began about 4:00 a.m. on March 28, 1979, when the plant experienced a failure in the secondary, non-nuclear section of the plant. The main feedwater pumps stopped running, caused by either a mechanical or electrical failure, which prevented the steam generators from removing heat. First the turbine, then the reactor automatically shut down. Immediately, the pressure in the primary system (the nuclear portion of the plant) began to increase. In order to prevent that pressure from becoming excessive, the pilot-operated relief valve (a valve located at the top of the pressurizer) opened. The valve should have closed when the pressure decreased by a certain amount, but it did not. Signals available to the operator failed to show that the valve was still open. As a result, cooling water poured out of the stuck-open valve and caused the core of the reactor to overheat.

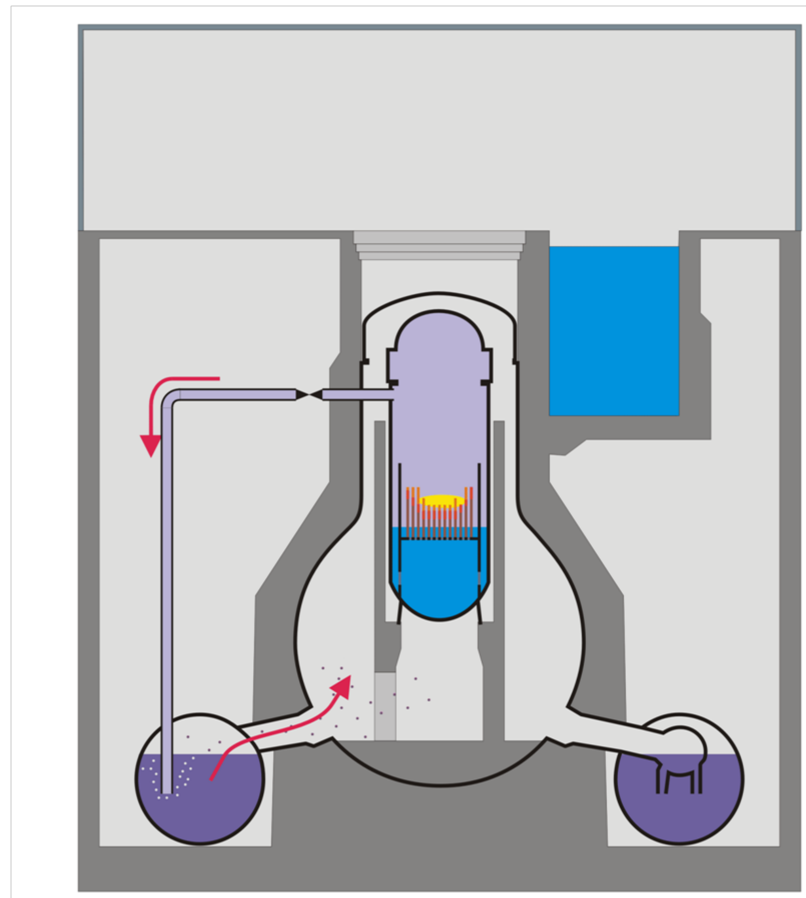
    For more info, see http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/3mile-isle.html
- Russia
  - 1986 : Chernobyl
  - During a test, operators interrupted flow of cooling water to core
  - Insufficient control rods were in reactor
  - Heat surge resulted, leading to ***chemical*** explosion
  - Water was sprayed; water reacted with graphite producing H_2 ($2H_2O + C \rightarrow 2H_2 + CO_2$), which caused additional ***chemical*** explosion
  - 31 firefighters and several people in plant died from acute radiation sickness; an estimated 250 million people were exposed to elevated radiation that may shorten their lives
  - Nuclear engineers state that no U.S. commercial reactors have Chernobyl design defects

Chemistry in Context, pages 299 to 302

Nuclear Power: Safety

- Japan (Reactors 1-3)
  - 11 March 2011, Earthquake off the coast. Reactors undamaged – go into containment isolation
  - Diesel generators power emergency cooling systems
  - Reactors designed to withstand 6.5m tsunami – reactor complex hit by 14m tsunami
  - Cooling system powered by batteries
  - Loss of battery power led to pressure build up, coolant turned to steam, fuel rods exposed - begin to burn





http://cisac.stanford.edu/events/the_nuclear_crisis_in_japan

Fukushima: Could this have been avoided?

- Diesel generators were located in basement
- Fuel located in above ground, external fuel tanks
- Tsunami flooded generators, wiped out fuel tanks

If generators had been on upper level of the building and fuel buried or kept at a higher elevation, we wouldn't be having this discussion!!!

The red box shows location of the destroyed back-up fuel tanks.

3/16/idiotic-placement-of-back-up-power-doomed-fukushima

Could another Fukushima happen?

National Geographic, 23 March 2011

For a world on the brink of a major expansion in nuclear power, a key question raised by the Fukushima disaster is would new reactors have fared better in the power outage that triggered dangerous overheating?

The answer seems to be: Not necessarily.

The nuclear industry has developed reactors that rely on so-called "passive safety" systems that could address the events that occurred in Japan: loss of power to pump water crucial to cooling radioactive fuel and spent fuel

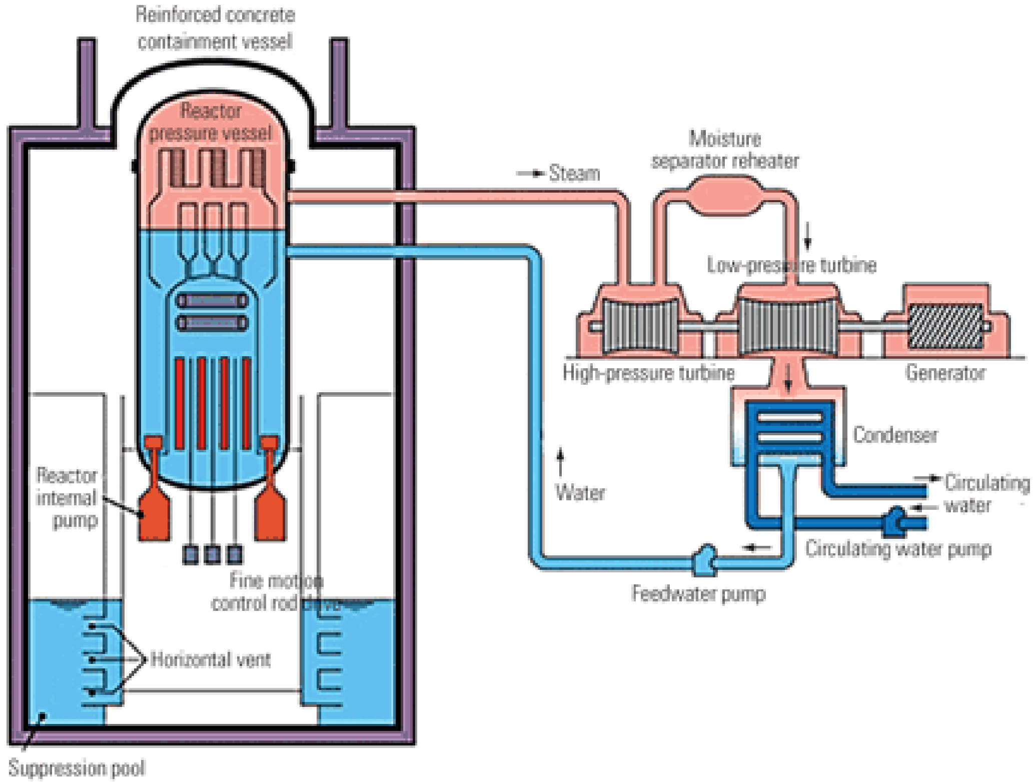
But these so-called Generation III designs are being deployed in only four of the 65 plants under construction worldwide. (Four reactors that are in the site-preparation phase and still awaiting regulatory approval in Georgia and South Carolina in the United States would make that eight of 69 plants.)

The vast majority of plants under construction around the world, 47 in all, are considered **Generation II** reactor designs—the same 1970s vintage as Fukushima Daiichi, and **without integrated passive safety systems**.

At the San Onofre Nuclear Station on the Southern California coast, modifications have been made that allow the operators to use a gravity-driven system to circulate the water to cool the plant for a period of time upon loss of power … But there are limits to such retrofits. "This is a huge volume of water," says Adrian Heymer, executive director of strategic programs for the NEI. "What happens to that tank in an earthquake?“

That's why there's been an effort to integrate a fully passive system from the get-go of the design process, he said. There is no ready reference list of which plants around the world have been modified with gravity-driven or other safety features. And as for new nuclear plants with integrated passive safety systems, deployment is slow.

http://news.nationalgeographic.com/news/energy/2011/03/110323-fukushima-japan-new-nuclear-plant-design/



Newer reactors (Generation III):

- Standard design – cheaper and quicker to build and license
- Simpler, rugged design easier to operate and less prone to accidents
- Longer operational lifetime
- Includes many **passive safety features** that decrease likelihood of meltdown

http://www.eoearth.org/article/Advanced_nuclear_power_reactors

Generation IV

- Initiated by DOE in 1999
- Focusing on "fast spectrum" reactors that cool using sodium
- Fast spectrum refers to use of "fast neutrons", which convert ^{238}U to ^{239}Pu
- Operate at atmospheric pressure but ~1000°C
- Lower pressure reduces risk of explosion
- ***But***: sodium + water would generate lots of energy (fire!!!) →
  safety concerns focused on prevention of this chemical reaction!
- Can recover more than 99% of energy from spent nuclear fuel
- Supported by members of both political parties, leading scientists
- Plutonium would be separated in process:

Good News: resulting waste would only have to be managed for ~500 years!
(for sufficient decay of 90-strontium to occur)

Bad News: presently, plutonium is mixed with nasty, shorter lived radionuclides.
If plutonium is isolated, it literally can be handled using gloves

For more info, see:

"Next Generation Nuclear Power", Lake, Bennett, and Kotek, *Scientific American*, Jan 2002.

"Smarter Use of Nuclear Waste", Hannum, Marsh, and Stanford, *Scientific American*, Dec 2005.

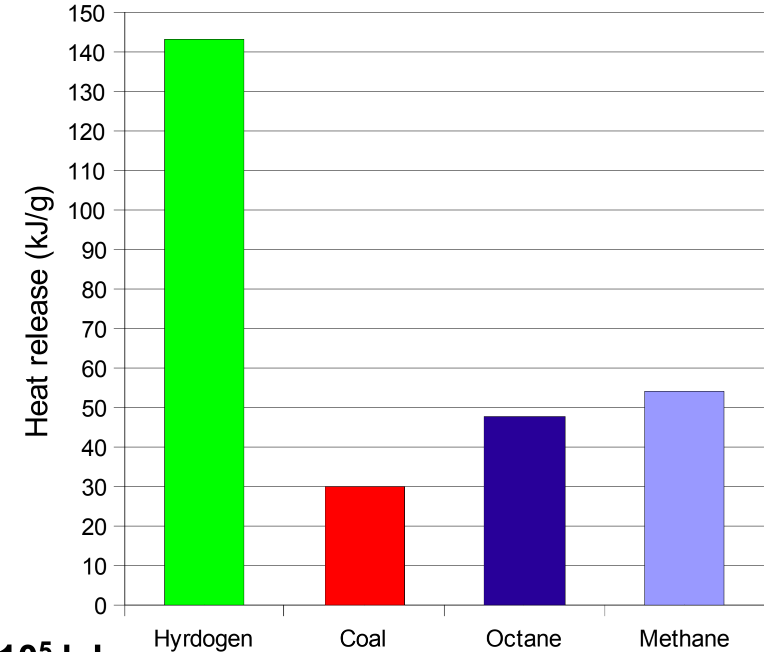
"Rethinking Nuclear Fuel Recycling", von Hippel, *Scientific American*, May 2008.

"Power to Save the World, the Truth about Nuclear Energy", Gwyneth Cravens, 2008.

Operating conditions of Generation IV reactors attractive for "high temperature hydrolysis of steam for hydrogen production"

(Olah et al., Section 9.3.5)

The Hydrogen Economy*



Hydrogen as a fuel source:

$$2H_2(g) + O_2(g) \rightarrow 2H_2O(l) + 286\ kJ$$

1 gram of hydrogen can yield 143 kJ

Much higher energy yield than fossil fuels and
<u>no harmful emissions</u> !!!!!

How does this compare to gasoline?

1 gallon of gasoline ≈ 2800 g ⇨ 2800g × 47.8 kJ/g =1.34×10^5 kJ

1 kg of hydrogen = 1000g ⇨ 1.43×10^5 kJ

In terms of energy available, 1 kg of hydrogen ≈ 1 gallon of gasoline

Fuel cell cars are more efficient than internal combustion engines

so, in theory, not as much hydrogen is needed

* Not a registered trademark

The Hydrogen Economy*

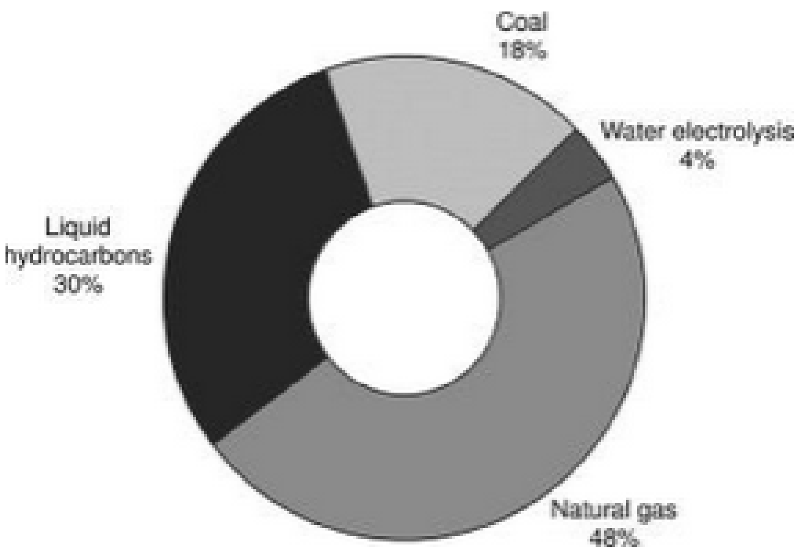


Figure 9.5. Sources for current worldwide hydrogen production

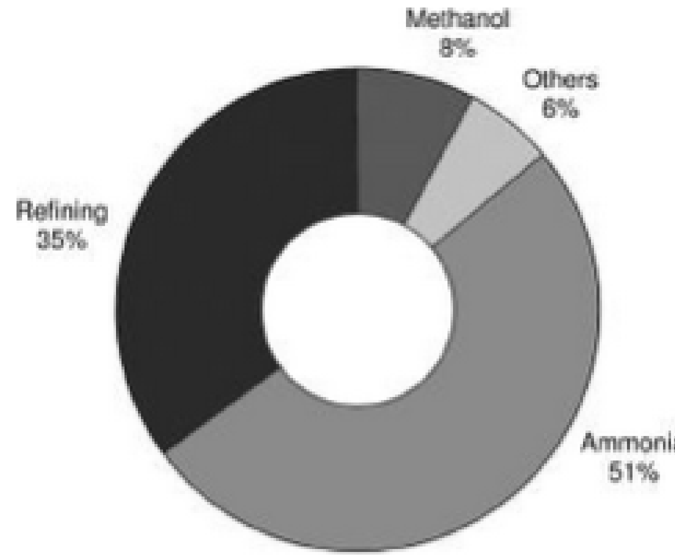


Figure 9.4 Main hydrogen consuming sectors in the world

Majority of world hydrogen produced using fossil fuels

used to create ammonia for fertilizer and to refine petroleum products

* Not a registered trademark

The Hydrogen Economy: Sources

Steam Reformation:

CH_4 is reacted with high temperature steam (700-1000º C) to create H_2

$$CH_4 + H_2O \rightarrow CO + 3H_2$$

CO can further react with water (*water-gas shift reaction*)

$$CO + H_2O \rightarrow CO_2 + H_2$$

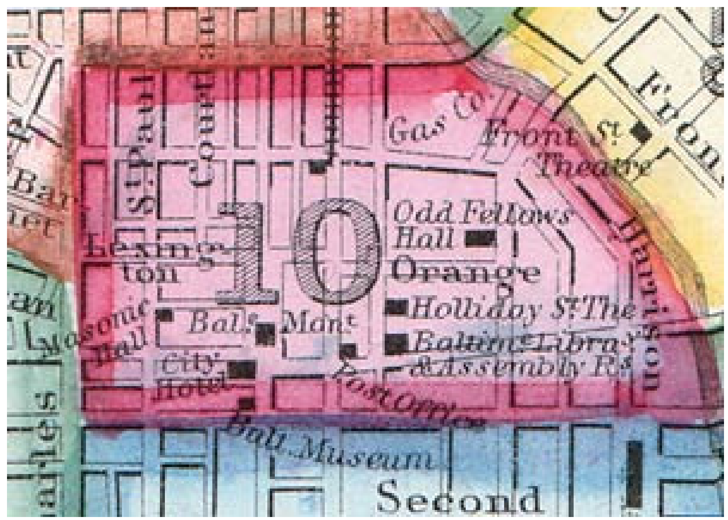
accounts for most of hydrogen produced in the US

The Hydrogen Economy: Sources

Coal Gasification “syngas”

Also known as “Town Gas” created by heating coal with steam to produce a gaseous mix of hydrogen and carbon monoxide

1816 – Gas Light Company of Baltimore became first US utility



Baltimore, 1863

Widely used up until early 1900's when electricity became more popular

With coal projected to be the fossil fuel of the future, syngas may play a more important role in addressing future energy needs

The Hydrogen Economy: Sources

Water electrolysis:

286 kJ are released when hydrogen reacts with oxygen to create water.
This reaction can be run in reverse to create hydrogen.

$$H_2O + 286\ \text{kJ} \rightarrow H_2 + \frac{1}{2} O_2$$

but 286 kJ are needed!

While this uses a lot of energy, it is potentially the cleanest way to make hydrogen.

No emission of GHGs if the electricity needed for electrolysis comes from either nuclear or renewable energy.

The Hydrogen Economy: Solar thermochemical

Thermochemical water splitting uses high temperatures—from concentrated solar power or from the waste heat of nuclear power reactions—and chemical reactions to produce hydrogen and oxygen from water. This is a long-term technology pathway, with potentially low or no greenhouse gas emissions.

HOW DOES IT WORK?

Thermochemical water splitting processes use high-temperature heat (500°–2,000°C) to drive a series of chemical reactions that produce hydrogen. The chemicals used in the process are reused within each cycle, creating a closed loop that consumes only water and produces hydrogen and oxygen. The necessary high temperatures can be generated in the following ways:

- Concentrating sunlight onto a reactor tower using a field of mirror "heliostats," as illustrated in Figure 1. For more information, see Chapter 5 of the SunShot Vision Study.
- Using waste heat from advanced nuclear reactors. For more information, see the U.S. Department of Energy's Nuclear Hydrogen R&D Plan.

(a) Central receiver/reactor tower with heliostats (b) Modular dish-mounted receiver/reactor

http://energy.gov/eere/fuelcells/hydrogen-production-thermochemical-water-splitting

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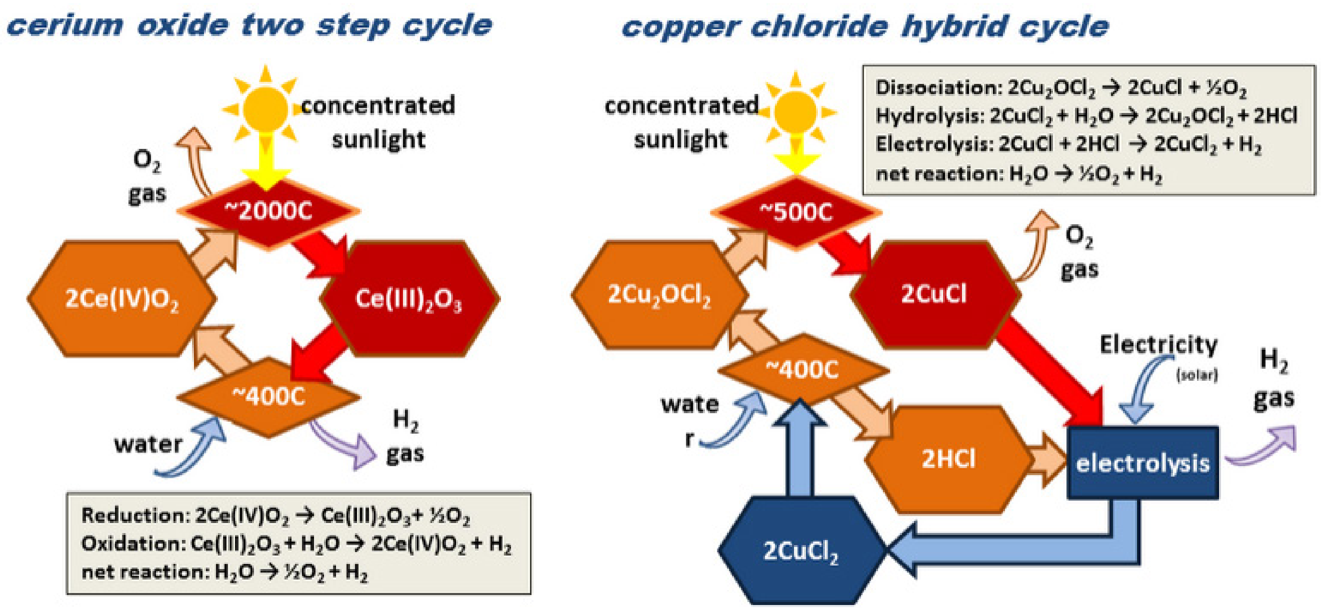


http://energy.gov/eere/fuelcells/hydrogen-production-thermochemical-water-splitting

The Hydrogen Economy: Storage

Compressed gas:

Need high pressure cylinders to hold enough hydrogen to power a vehicle

Assuming a normal car (10 gallon tank) is 25% efficient

$$10 \text{ gallon} \times 1.34 \text{x} 10^5 \text{ kJ/gal.} \times 0.25 = 3.35 \text{x} 10^5 \text{ kJ}$$

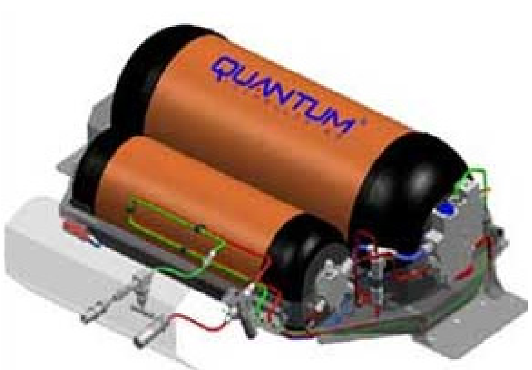
Newer hydrogen vehicles are supposedly ~60% efficient,

$$3.35 \text{x} 10^5 \text{ kJ} / (1.43 \text{x} 10^5 \text{ kJ/kg} \times 0.6) = \sim 4 \text{kg}$$

Hydrogen tanks for vehicle use are rated at 5500 PSI (~375 atm)

From the ideal gas law,

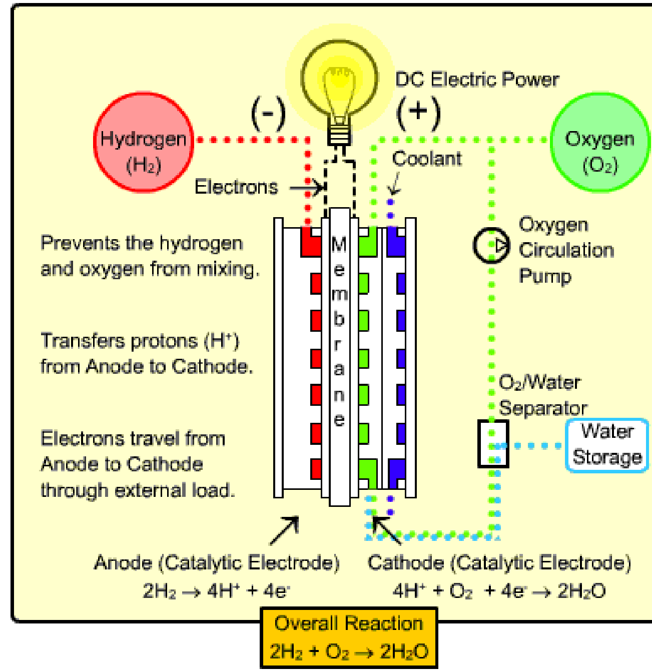
$$V = 2000 \text{ mol} \times 0.0821 \text{ L atm mol}^{-1} \text{ K}^{-1} \text{ 295K} / 375 \text{ atm}$$
$$= 129 \text{ L}$$
= 34 gallons … 3.4 times bigger than a standard liquid tank



- Gas tanks are heavy
- Hard to monitor how much fuel remaining

Hydrogen Fuel Cells

- Hydrogen comes in contact with platinum anode, converts $H_2 \rightarrow 2H^+$
- $2e^-$ pass through circuit to power car
- Protons pass through PEM and come in contact with oxygen and e^- to form H_2O
- Process generates < 1 volt so need stack of fuel cells to power vehicle



http://www.phy.mtu.edu/nue/images/HydrogenFuelCell.gif

Three large hurdles to widespread use of hydrogen fuel cell cars:
- **source of H_2 that does not involve release of GHGs**
- **"chicken & egg" dilemma of re-fueling infrastructure**
- **past prototype cars have been prohibitively expensice**

Hydrogen Fuel Cell Cars

AUTOMOBILES

International New York Times

Hydrogen Fuel Cell Cars Return for Another Run

APRIL 16, 2015

FOR decades, hydrogen has been the Dracula of automotive fuels: Just when you think a stake has been driven through its zero-emissions heart, the technology rises from the grave.

In 2015, even with gasoline cheaper than it has been in years, hydrogen is back to haunt those who insist that battery electric vehicles are the long-term solution for reducing fossil fuel consumption and carbon dioxide emissions.

This time — with hydrogen fuel cell costs falling significantly, and a tiny yet budding network of public fueling stations — automakers are placing their latest long-odds bet on hydrogen cars.

Hyundai has been first in the latest wave of fuel cell models, which are actually electric cars with one important difference: Instead of a plug-in battery that draws power from the electrical grid, a fuel cell generates power from an electrochemical reaction between onboard hydrogen and oxygen in the air. Clean water trickles out the tailpipe as the only byproduct.

A refilling station for hydrogen fuel cell vehicles near the University of California, Irvine.
Stuart Palley for The New York Times

http://www.nytimes.com/2015/04/17/automobiles/hydrogen-fuel-cell-cars-return-for-another-run.html

Hydrogen Fuel Cell Cars

International New York Times

In a technical riposte to most battery electric vehicles, which generally travel less than 100 miles on a charge, and take several hours to recharge, fuel cell cars operate as conveniently as gasoline models. They travel roughly 300 miles on a tank, and their ultrastrong carbon-fiber tanks can be pumped full of hydrogen in less than 10 minutes.

Count David Uselton and his wife, Suelyn, as true believers.

In June, the couple, from Dana Point, became the second California family to lease the hydrogen version of the Hyundai Tucson crossover sport utility vehicle. They are paying $499 a month with $2,999 down, decisively more than they would for the same Tucson with a gasoline engine. But perks include a $5,000 purchase rebate from the state and three years' worth of free hydrogen from Hyundai.

Mr. Uselton, a director of a global e-commerce company, remembers their teenage son's assembling a toy car model about eight years ago. The toy scooted across the floor, powered by a fuel cell that used sunlight to generate hydrogen from water.

"He thought it was really cool, and asked, 'Why can't every car work like this?' " Mr. Uselton said.

Like the nearly 70 other people who have leased hydrogen-fueled Tucsons, the Useltons were checked out by Hyundai to ensure the car would fit their lifestyle. The criteria included geographic proximity to the nine public hydrogen stations operating around Los Angeles and San Francisco.

Automakers have also talked up hydrogen cars, with skeptics seeing the technology as a pipe dream. Automakers' hands in some ways are being forced: California's powerful regulators have decreed that the six largest automakers build increasing numbers of zero-emissions models, toward a goal of having 87 percent of new cars produce zero tailpipe emissions by 2050.

Honda and Mercedes have leased small test fleets of hydrogen cars to California customers. How small? Since 2002, Honda has put 43 of its FCX and FCX Clarity models in consumers' hands. Among more than 28 million passenger cars on California's roads, barely 100 carry hydrogen onboard.

But still, automakers including Toyota — the unmatched king of hybrids — remain bullish on hydrogen. Toyota will offer its $58,325 Mirai fuel cell compact this year, exclusively in California for now. The car's name means future in Japanese. Honda will follow in 2016 with a car based on its streamlined FCV concept model.

To answer a vexing chicken-and-egg question, automakers are providing seed money to operate fueling stations, reassuring energy providers that if they build them, cars and customers will eventually come. California has committed up to $20 million a year to develop stations, with perhaps 40 expected to be in operation by the end of 2016.

Mr. Uselton hopes to see stations open north of Los Angeles, which would extend his Hyundai's range far enough for him to visit his daughter, a college student in Santa Barbara.

http://www.nytimes.com/2015/04/17/automobiles/hydrogen-fuel-cell-cars-return-for-another-run.html

Hydrogen Fuel Cell Cars

International New York Times

Today, most hydrogen is derived from natural gas production, diminishing its environmental edge. But backers see promise in producing hydrogen by splitting water using solar, wind or other renewable power. In Fountain Valley, Calif., Mr. Uselton fills his Tucson from a demonstration station, created via an Energy Department grant, that turns municipal waste into enough hydrogen to fuel up to 50 cars a day.

Mr. Lindsay at IHS said that with the internal combustion engine continuing to evolve and improve, it will be decades before the majority of Americans switch to alternative-fuel cars. But with enough cars and infrastructure, hydrogen could become a valuable part of the energy portfolio.

"We may end up having two different zero emissions technologies that will move us away from gasoline," he said.

Toyota is confident it could sell perhaps 3,000 Mirais here through 2017. Even that is a relatively small number, but the company envisions a hydrogen nucleus that will spread to the East Coast and eventually the whole nation.

http://www.nytimes.com/2015/04/17/automobiles/hydrogen-fuel-cell-cars-return-for-another-run.html

The Hydrogen Economy: Problems

Hydrogen Leaks:

- **Not a problem if occurring outside**
- **If inside (parking garage, house garage, etc.) hydrogen will quickly fill space**
  - **— easily ignited**
  - **— explosive in air at concentrations between 18 and 59%**
  - **— burns with a colorless flame**
- **Pressurized tank explosion**
- **Containment during car accident**

These problems assume that the hydrogen is pressurized or liquefied
If metal hydrides are used, these problems aren't as much of an issue.

Effects of Hydrogen Economy on Atmospheric Composition

If the world moved to a hydrogen economy, what would happen to atmospheric levels of H_2?

Presently, H_2 is about 0.5 ppm and is ***long lived in the troposphere***

H_2 is not a greenhouse gas.

If future levels of atmospheric H_2 happen to rise, this may have an important effect on atmospheric composition.

What effect could occur?

Hints: what happens to H_2 in an oxidizing atmosphere?

where will this transition occur?