Nuclear Fuel

A nuclear fuel pellet contains about 4 grams of fuel

It produces the same amount of energy as a ton of coal or 150 gallons of gasoline

It's fairly cheap - $3 per pellet (compare to 150 gallons of gasoline!)

It produces no greenhouse gases, nor VOCs, nor NO, nor SO_2

It does not rely on petroleum

So why isn't it the primary fuel used in the U.S.?

Nuclear Power

What **is** nuclear power?

Nuclear power plants run on the principle of **nuclear fission**:

The process of splitting a large **nucleus** into smaller ones, usually by bombarding the target nucleus with neutrons

Why does this produce energy?

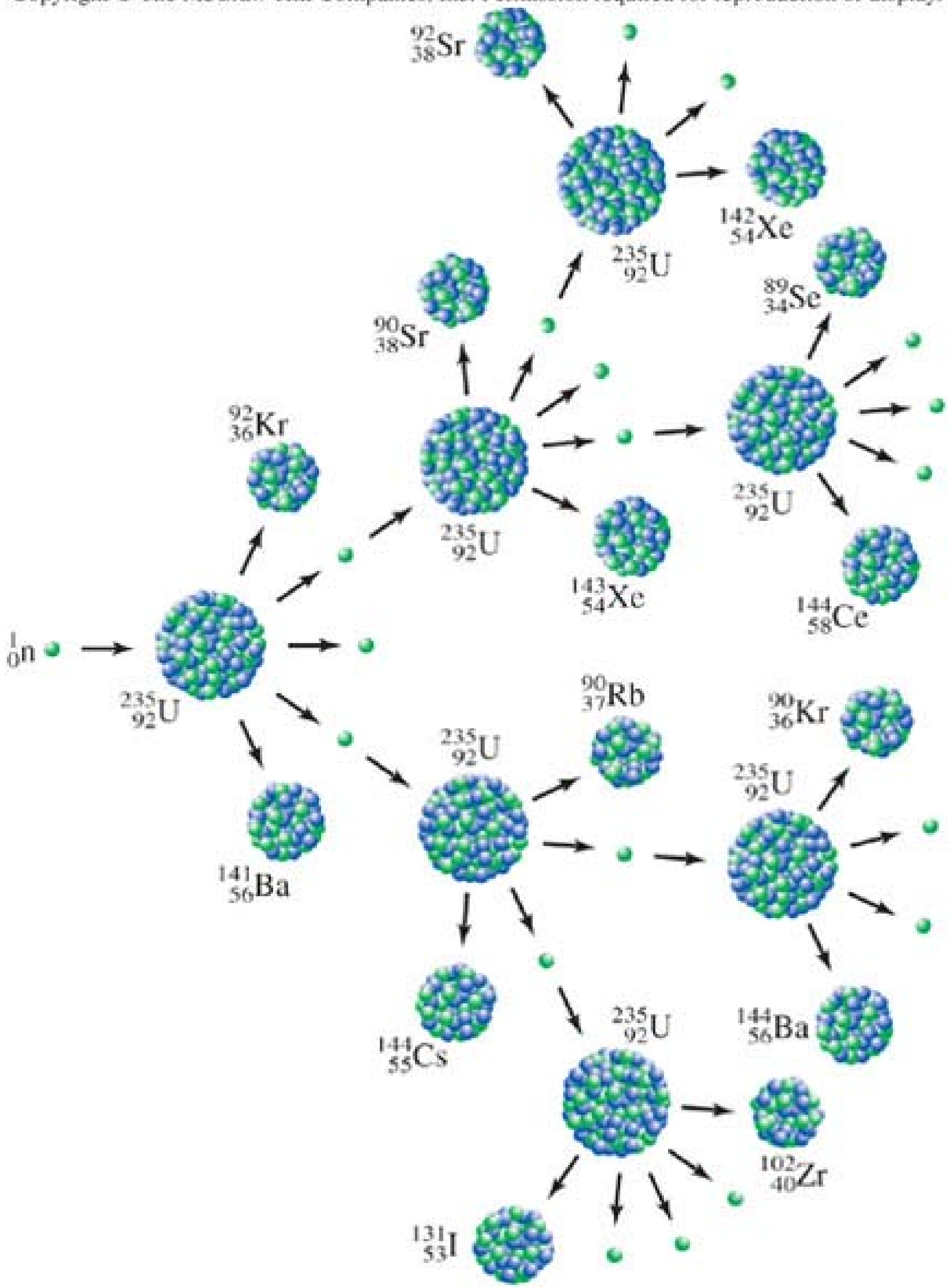
The products of this reaction actually possess **slightly** less **mass** than the reactants

Nuclear Fission

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3^{1}_{0}n$$

But two things should worry you about this analysis:

- Why do neutrons appear on both sides? Shouldn’t they cancel?
- If the mass numbers on both sides are equal, where is the energy coming from?

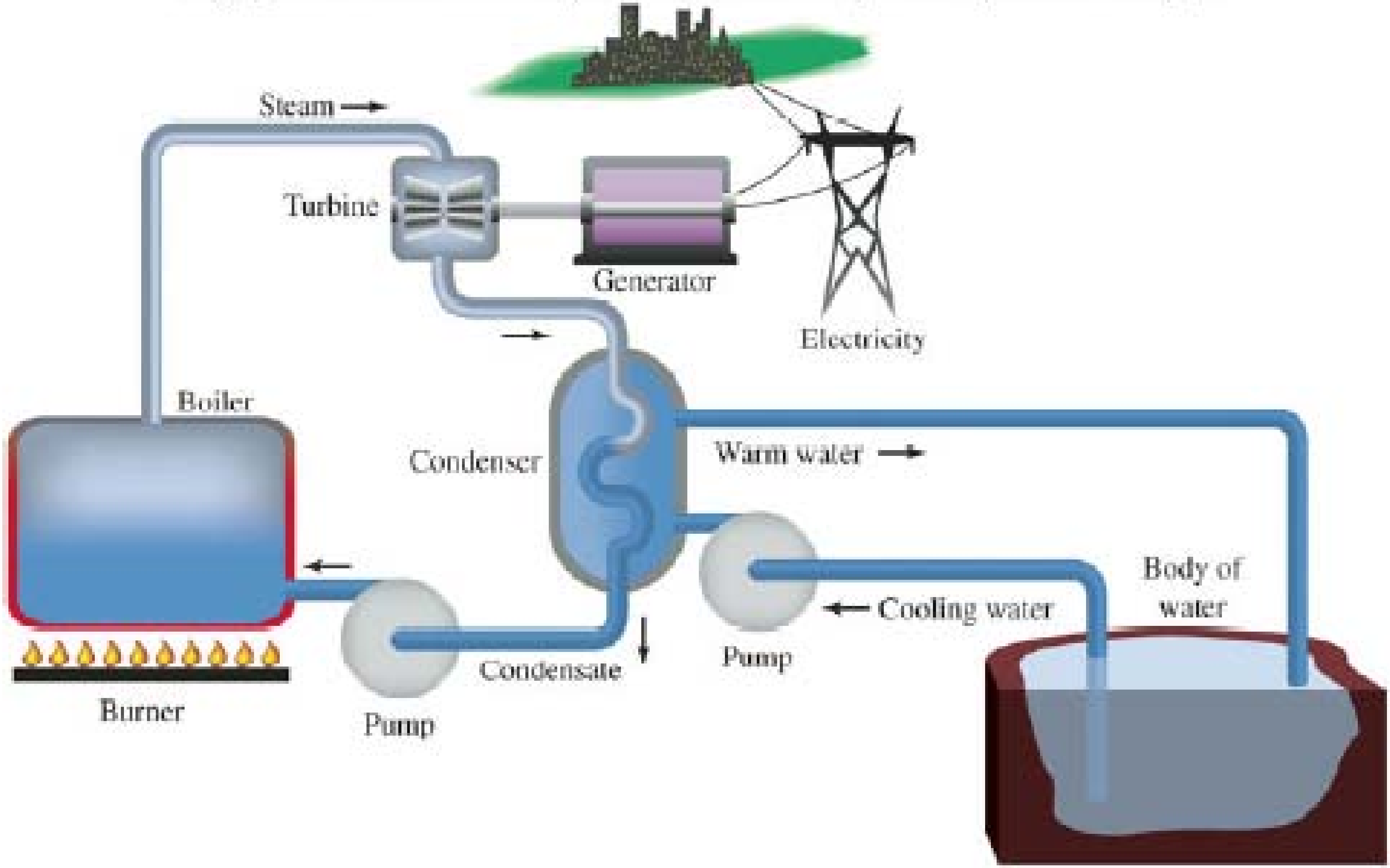


A **chain reaction** is one in which the products of an initial step undergo further reaction

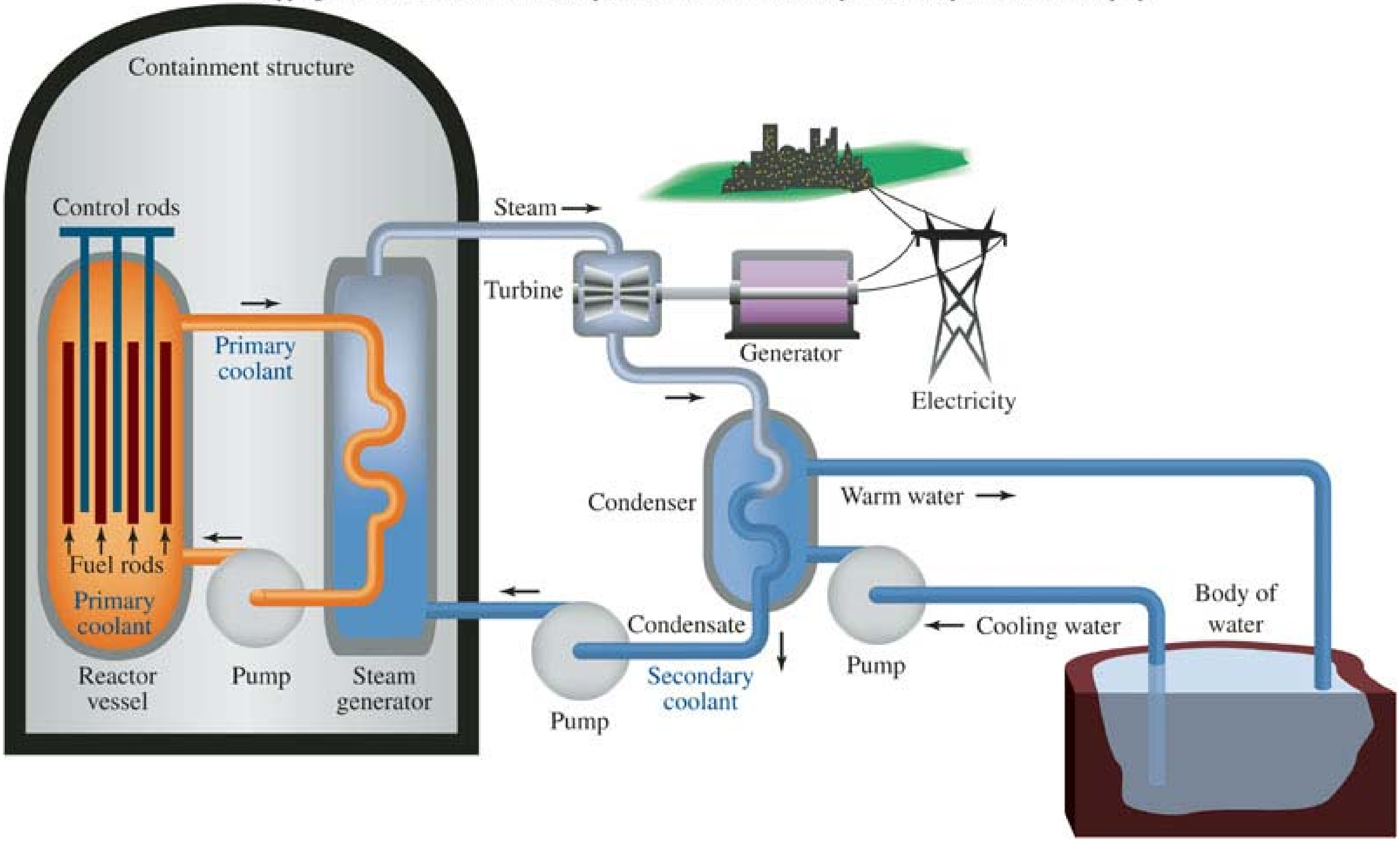
An important concept with regard to chain reactions is that of **critical mass**:

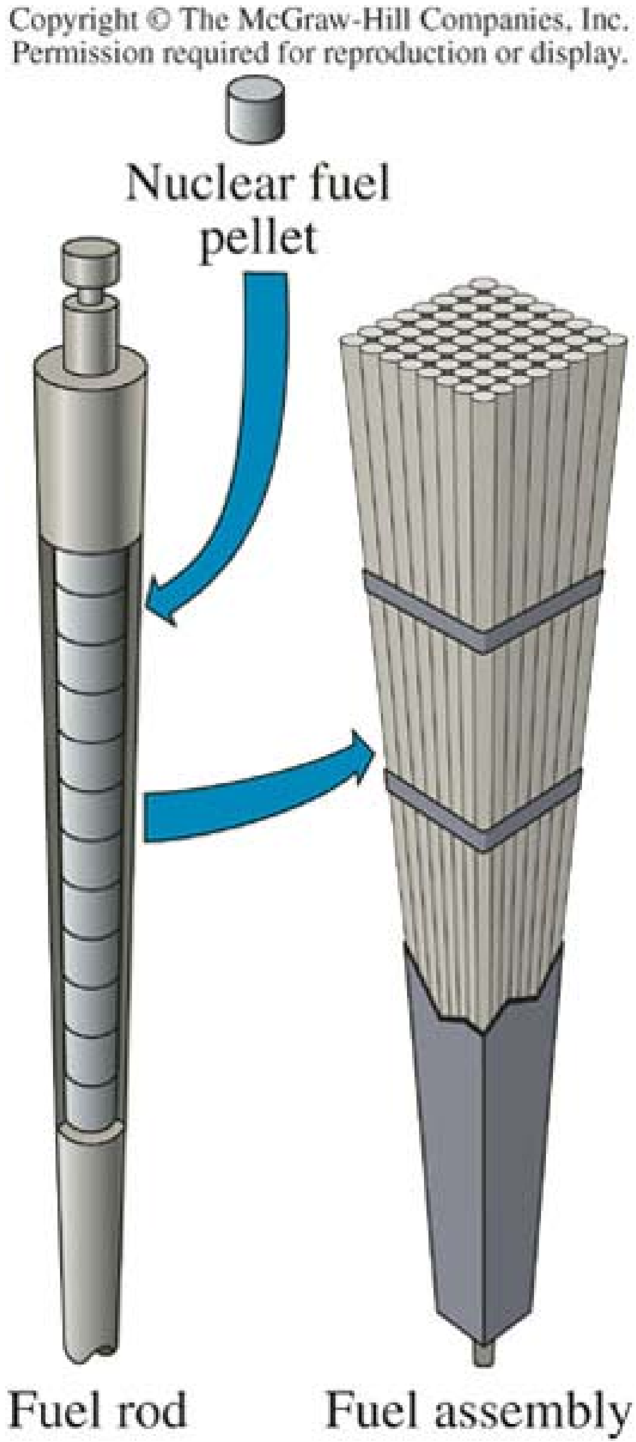
The amount of fissionable material which is necessary to sustain the chain reaction

A Coal-Burning Power Plant



A Nuclear Power Plant





U-235 fuel is present in eraser-sized pellets of UO_2

Stored end-to-end in metal fuel rods

Fuel rods are gathered together in fuel assemblies

Fission is initiated by neutrons – in most cases, these neutrons come from another nuclear reaction, the decay of plutonium in the presence of beryllium

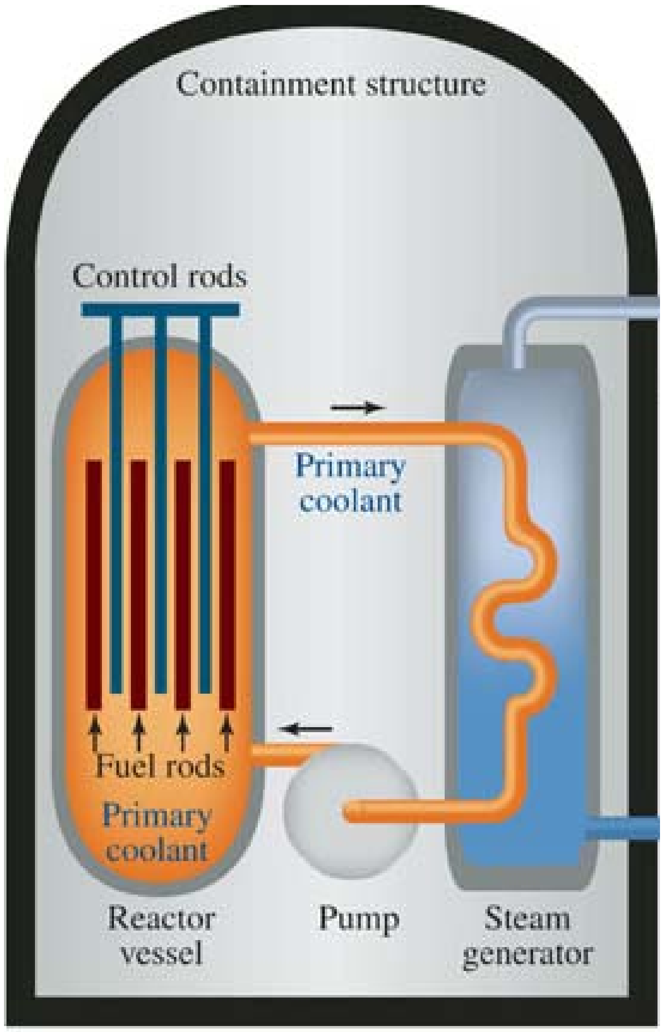
$$^{238}_{94}Pu \rightarrow ^{234}_{92}U + ^{4}_{2}He$$

$$^{9}_{4}Be + ^{4}_{2}He \rightarrow ^{12}_{6}C + ^{1}_{0}n + ^{0}_{0}\gamma$$

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3^{1}_{0}n$$

Remember – this is a chain reaction! It can easily run out of control

A Nuclear Power Plant



If a neutron from the fission of U-235 strikes another U-235, the chain reaction continues

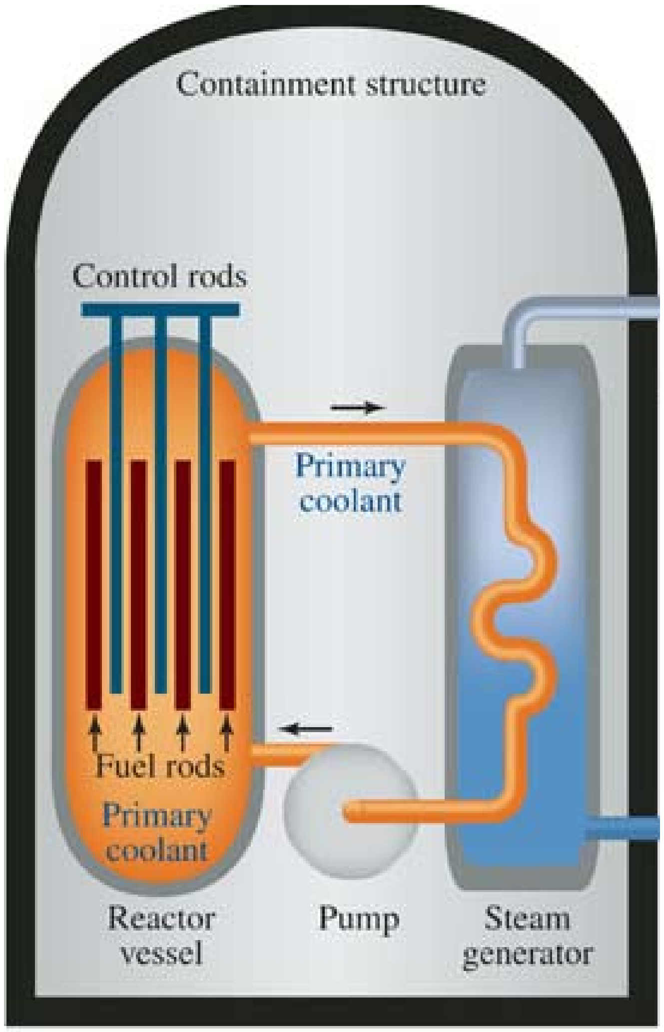
So the reaction is slowed by the insertion of *something else* for the neutrons to strike: **Control rods** are composed of cadmium, silver and indium, and are inserted between the fuel rods

By changing the number of control rods and the depth to which the rods are lowered, the rate of the fission reaction can be adjusted

If the control rods are removed, the reaction “goes critical” – meaning that the fission becomes self-sustaining

The reaction can still be shut down by the rapid re-insertion of the control rods, and this is standard emergency procedure

A Nuclear Power Plant



The fuel rods and control rods together are immersed in the **primary coolant** – usually an aqueous solution of boric acid

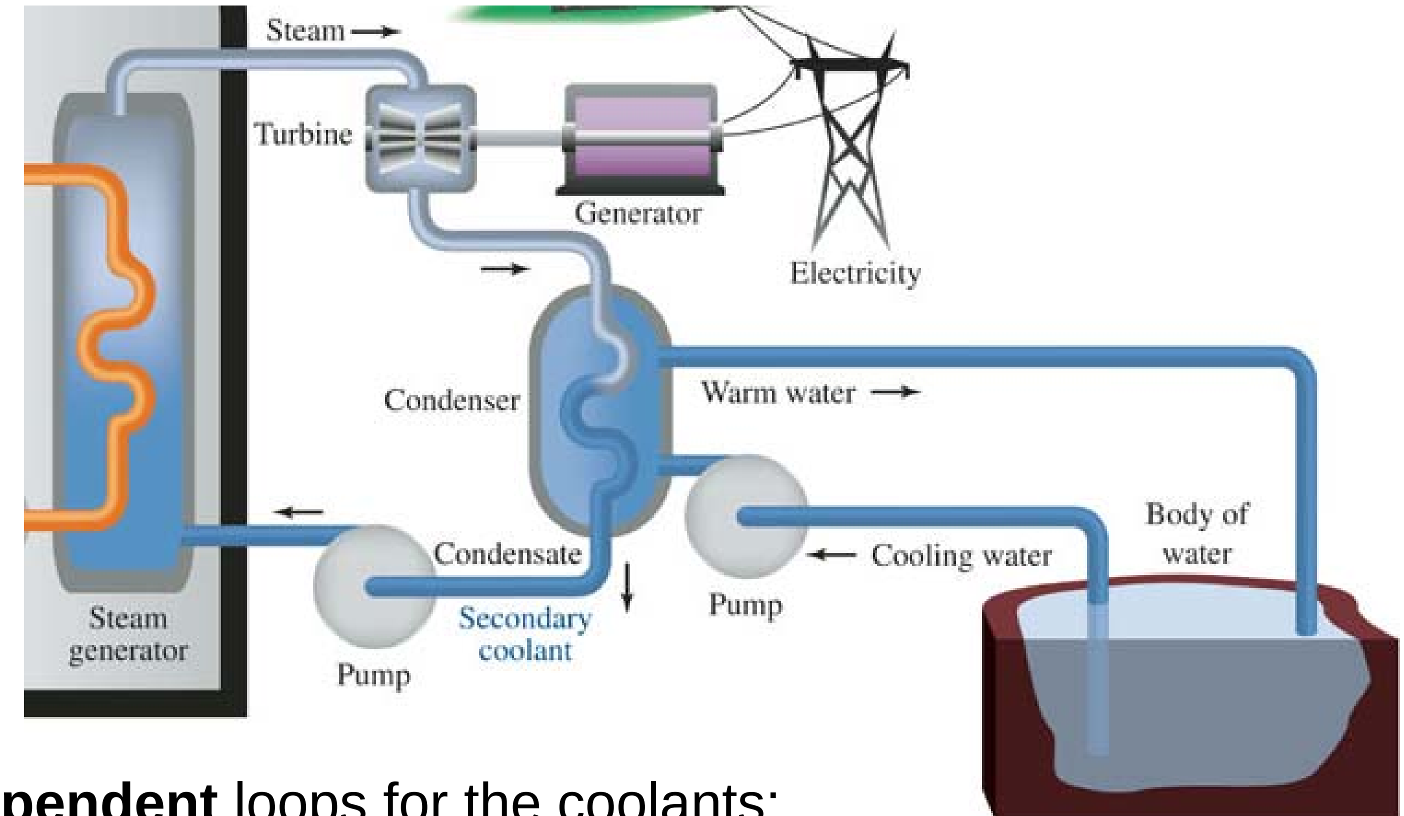
The boron atoms absorb any stray neutrons, and the liquid itself is heated to very high temperatures by the energy of the fission reaction

Because the system is sealed, the liquid doesn't boil

Instead the extremely hot primary coolant is passed through the **secondary coolant** – the water in the steam generator, which boils to drive the turbine

A Nuclear Power Plant

A Nuclear Power Plant

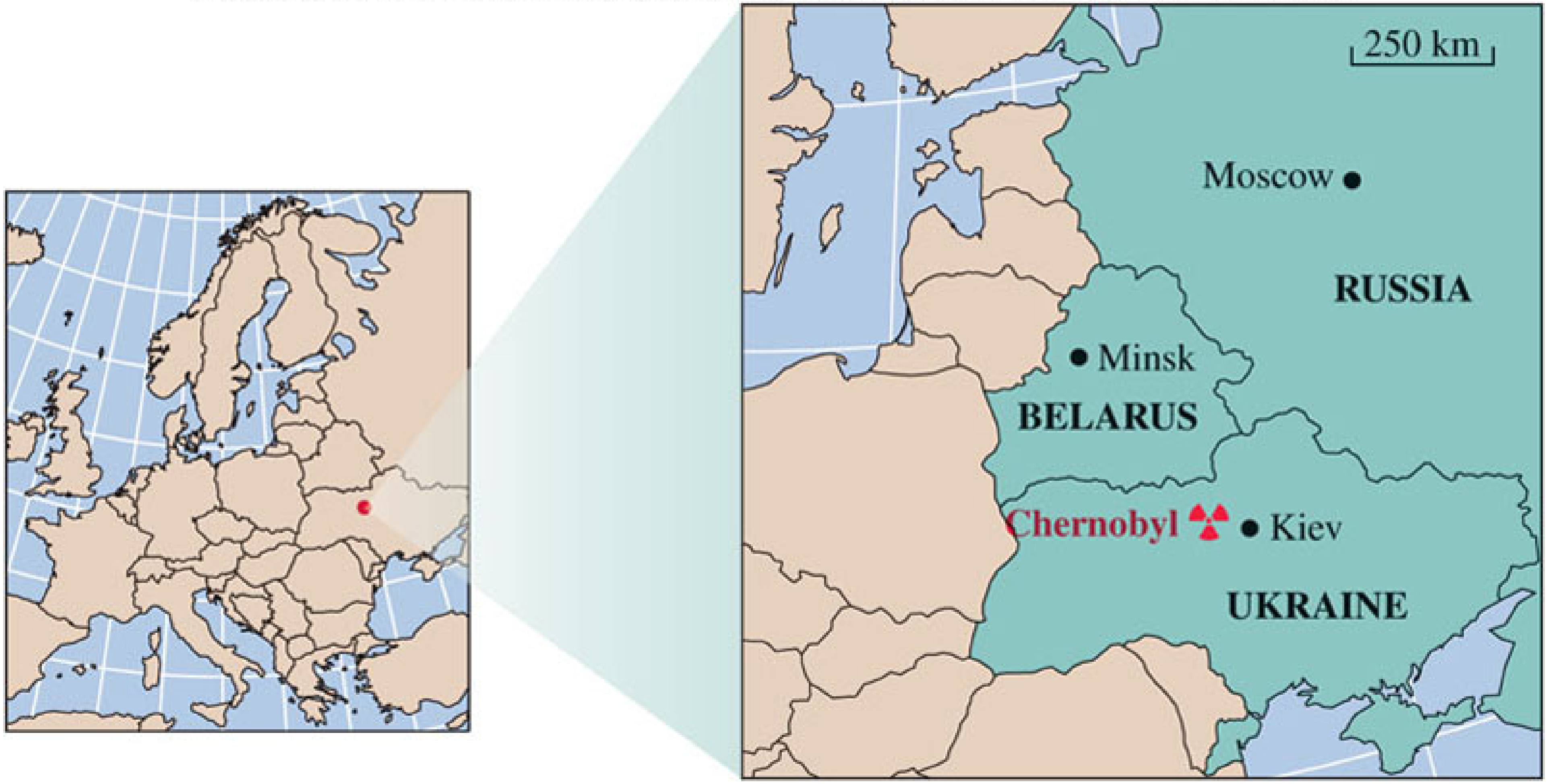


Three **independent** loops for the coolants:
Primary coolant, inside the containment structure
The secondary coolant, contained within the steam generator
The water for the condenser comes from rivers or oceans, and is well isolated from the nuclear components
Water leaving the condenser is distributed so as to minimize the temperature change of the source

Nuclear Power

So… what goes wrong?

Let’s analyze the worst nuclear disaster to date, the meltdown of the reactor at Chernobyl

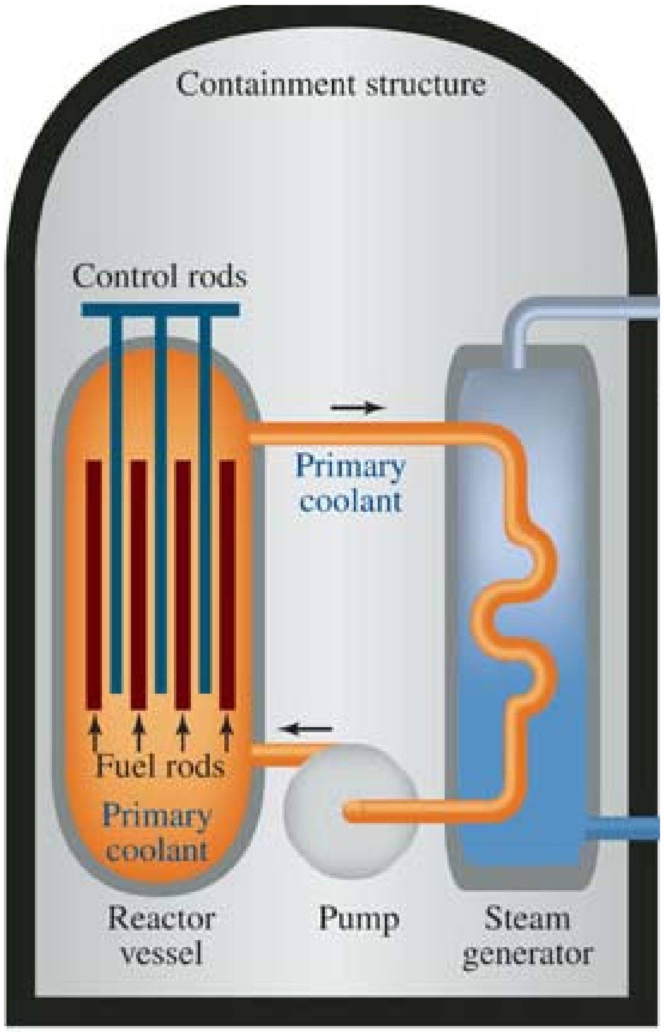


The “breadbasket” of Russia –

Rural, agricultural

120,000 people lived within a 30km radius

Anatomy of a Meltdown



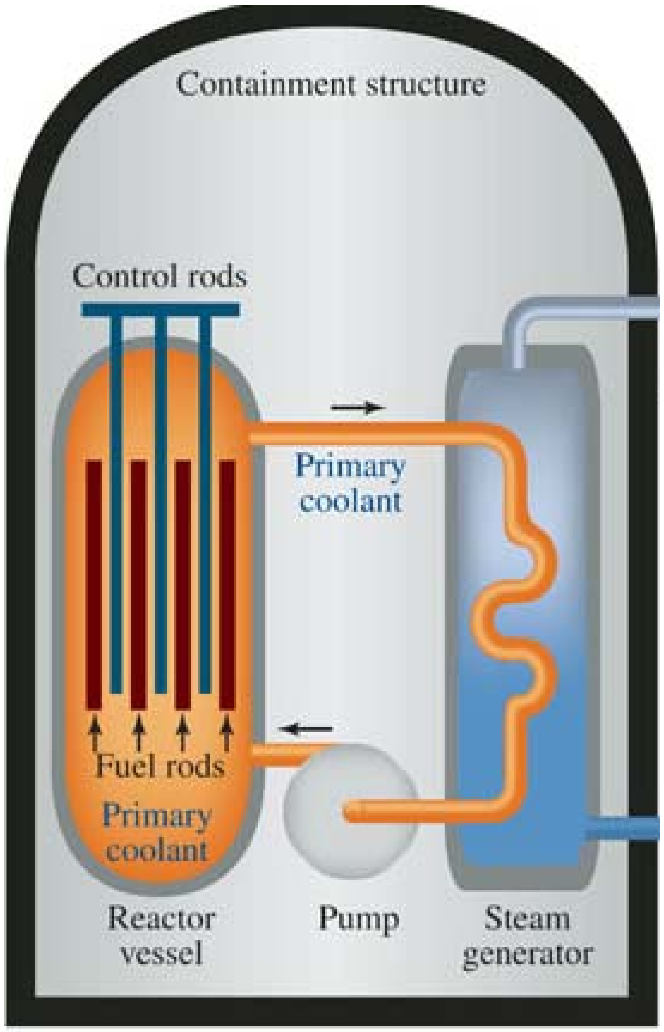
At Chernobyl, a routine safety check of Reactor 4 was underway on April 26, 1986

Operators intentionally turned off the secondary coolant

But there were not enough control rods inserted to slow the reaction, and there was no failsafe mechanism to re-insert them rapidly

The heat produced by the now out-of-control chain reaction melted the containment structure

Anatomy of a Meltdown



The hot core components then came into contact with coolant water and with water supplied by emergency response teams

The reaction of extremely hot graphite with liquid water produced hydrogen gas, which reacted explosively with oxygen in the air

The 4000 ton steel plate that sealed the top of the reactor was blown off, and radioactive matter was blasted into the air

No actual **nuclear** explosion took place at Chernobyl

Anatomy of a Meltdown

The reactor burned for 10 days

The amount of radioactive particles emitted has been estimated as being 100 times that released in the two bombs dropped at the end of WW2

Wind carried the residue north, throughout Belarus and on to northern Europe

Over 250 million people were exposed to levels of radioactivity which may be sufficient to shorten their lives

The reactor itself was buried in tons of concrete, forming a “sarcophagus”

Anatomy of a Meltdown

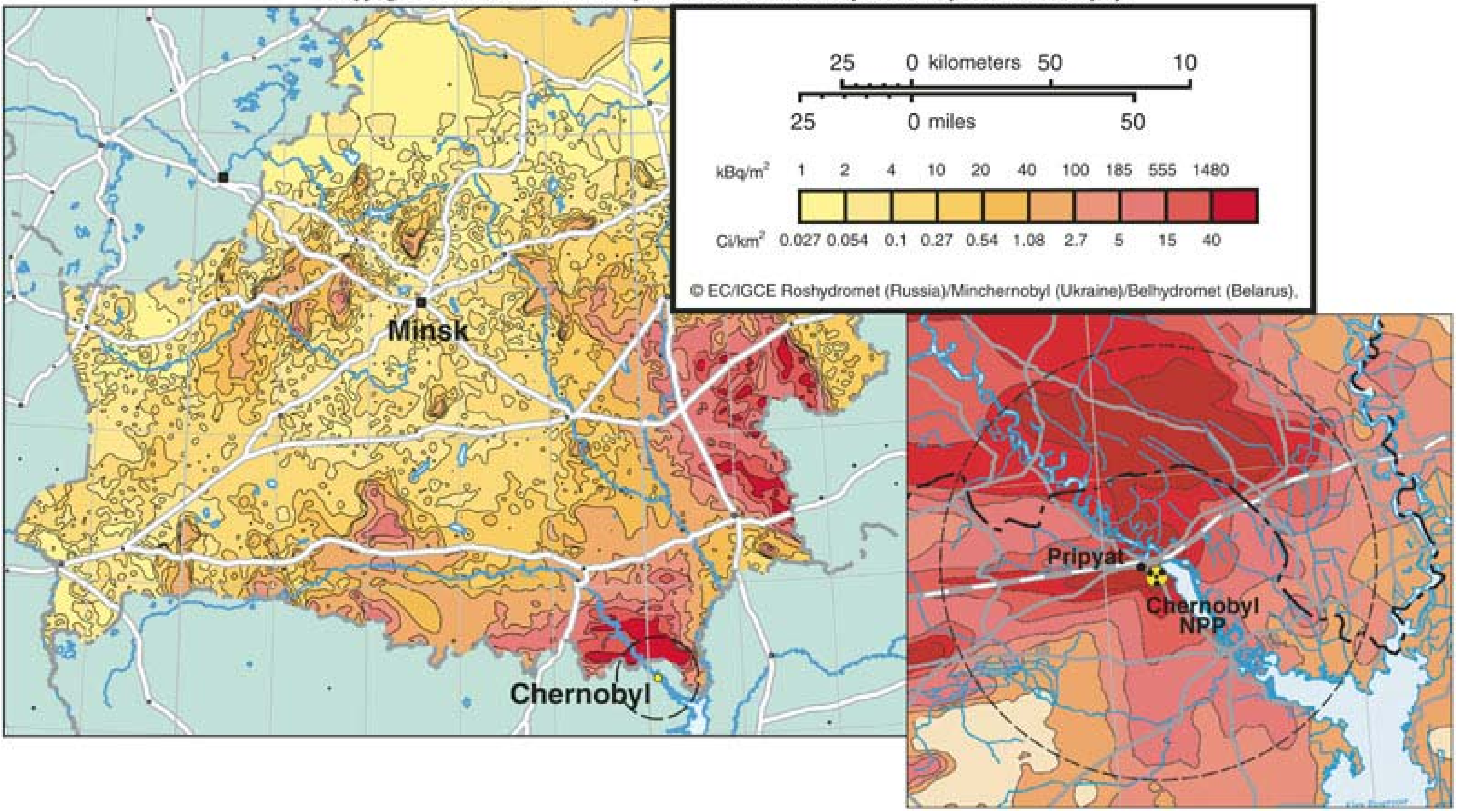
The last reactor (#3) at Chernobyl was shut down in 2000

The Ukrainian government is now seeking to replace the plant with a natural gas burning plant

The estimated expense of replacing the nuclear plant is $4 billion, $2.3 billion of which has been pledged by other nations

The total cost of cleaning up the disaster is estimated at $358 billion

Fallout from Chernobyl



The question that all countries asked in 1986, and continue to ask to this day:

Could it happen here?

Safety Precautions

America’s closest call took place in 1979 at the Three Mile Island power plant near Harrisburg PA

- The reactor lost coolant, and a partial meltdown occurred
- However, failsafe mechanisms DID work, and the radiation was completely contained

There have been others:

- 1975 at Brown’s Ferry, Alabama – a “normal” fire shorts out the electrical circuits, and the reactor has to be shut down by hand
- 1981 at Sequoyah, Tennessee – an untrained operator opens a valve which releases the primary coolant into the containment building
- 1983 at Salem, New Jersey – automatic safeguards failed repeatedly, and twice in three days the plant was within minutes of meltdown before manual shutdown

Safety Precautions

Newer designs include more safety features
U.S. engineers are confident that no catastrophes can occur in modern reactors
Modern reactors have incredibly thick, reinforced walls and domed containment vessels
Designed to withstand earthquakes, hurricanes, collisions with small planes
HOWEVER – no current reactors could withstand the direct impact of a passenger plane, and so the fear of terrorist attacks is a serious one.

Safety Precautions

American reactors are fairly safe – but what of the rest of the world?
The Czech Republic and Russia, in particular, have a history of inferior safety standards
Recall the area covered by the fallout from Chernobyl – knowing that your neighbors are safe is just as important as being safe yourself

Safety Precautions

Other than Chernobyl, the other enduring images of nuclear power are those of Hiroshima and Nagasaki

Many people fear that the nuclear reactor itself could undergo a similar explosion

Because the goal of a power plant is the slow, steady release of energy, it is constructed fundamentally differently than a bomb

- The fuel for a power plant is between 3 and 5% U-235
- The material for a bomb is upwards of 90% U-235

Both are **enriched Uranium** – that is, possessing a higher U-235 component than the naturally occurring 0.7%

Because of the relatively low U-235 concentration and the presence of primary coolants and control rods, the chain reaction is unable to run explosively

Enrichment of Uranium

The fuel for a power plant is between 3 and 5% U-235
The material for a bomb is upwards of 90% U-235
What’s the rest?
Uranium-238 – the most common isotope of Uranium
  also radioactive, but unable to undergo fission
How do we “enrich” Uranium?
The two isotopes are separated by passing them as gases through a membrane
  Uranium ore is converted into UF_6 (uranium hexafluoride, “hex”), which is a gas at relatively low T (135° F)
  Heavier gases move more slowly than lighter gases
  If you pass them through **enough** membranes, you can separate any two isotopes
  Which is good, because the masses of U-238 and U-235 differ by only 1%

Nuclear Fuel as Weapons?

A related fear is that nuclear fuel itself could be used to make nuclear weapons

The short answer is that this is unlikely – it is very expensive to enrich fuel uranium sufficiently

However, there are by-products of nuclear power which could be used

Recall that "the rest" of enriched uranium is U-238

Recall that U-238 isn't fissionable

But what **does** happen when a high energy neutron strikes U-238?

$$ {}^{238}_{92}U + {}^{1}_{0}n \rightarrow \left[{}^{239}_{92}U \right] \rightarrow {}^{239}_{93}Np + {}^{0}_{-1}e $$

"Beta decay" – the unstable nucleus emits an electron, converting a neutron into a proton

Nuclear Fuel as Weapons?

$$^{238}_{92}U + ^{1}_{0}n \rightarrow \left[^{239}_{92}U\right] \rightarrow ^{239}_{93}Np + ^{0}_{-1}e$$

But Np-239 is also a beta-emitter:

$$^{239}_{93}Np \rightarrow ^{239}_{94}Pu + ^{0}_{-1}e$$

And Pu-239 **is** able to undergo fission

Indeed, it is the plutonium from this process that was used in the nuclear bombs dropped in World War 2:

Spent fuel was gathered from “Breeder Reactors”, and the plutonium was chemically separated

Modern day “Breeder Reactors” instead use the plutonium formed as additional fuel, thus converting one fuel (U-235) into another (Pu-239) by burning it!

Nuclear Fuel as Weapons?

Thus it becomes imperative to safeguard the spent fuel from U-235 plants

For many years, the U.S. banned fuel recovery

That ban was lifted in 1981, but there is still no fuel recovery taking place in the U.S.:

> The price of U-235 is currently so low that extracting Pu from the spent fuel is not competitive

This is why the U.S. is so involved in the development of nuclear power in unstable regions of the world

Radioactivity

$$^{239}_{93}Np \rightarrow ^{239}_{94}Pu + ^{0}_{-1}e$$

“Beta decay” – the unstable nucleus emits an electron, converting a neutron into a proton

This is “radioactivity” – defined by Marie Curie as the spontaneous emission of radiation

There are two major processes of emission – alpha emission and beta decay

Alpha emission involves the emission of 2 protons and 2 neutrons – the nucleus of a Helium atom!

$$^{238}_{92}U \rightarrow ^{234}_{90}Th + ^{4}_{2}He$$

In addition, many processes emit radiation without emitting particles

On such form of high energy radiation is termed gamma rays

Types of Radioactivity

Table 7.2 Types of Nuclear Radiation

Type	Symbol	Consists of	Charge	Change to nucleus that emits it
Alpha	${}^{4}_{2}He$	2 protons 2 neutrons	2+	The mass number decreases by 4, and the atomic number decreases by 2.
Beta	${}^{0}_{-1}e$	an electron	1−	The mass number does not change, and the atomic number increases by 1.
Gamma	${}^{0}_{0}\gamma$	photon of energy	0	No change in either the mass number or in the atomic number.