a place of mind

FACULTY OF EDUCATION

Department of
Curriculum and Pedagogy

Physics
Nuclear Physics:
Nuclear Reactors

Science and Mathematics
Education Research Group

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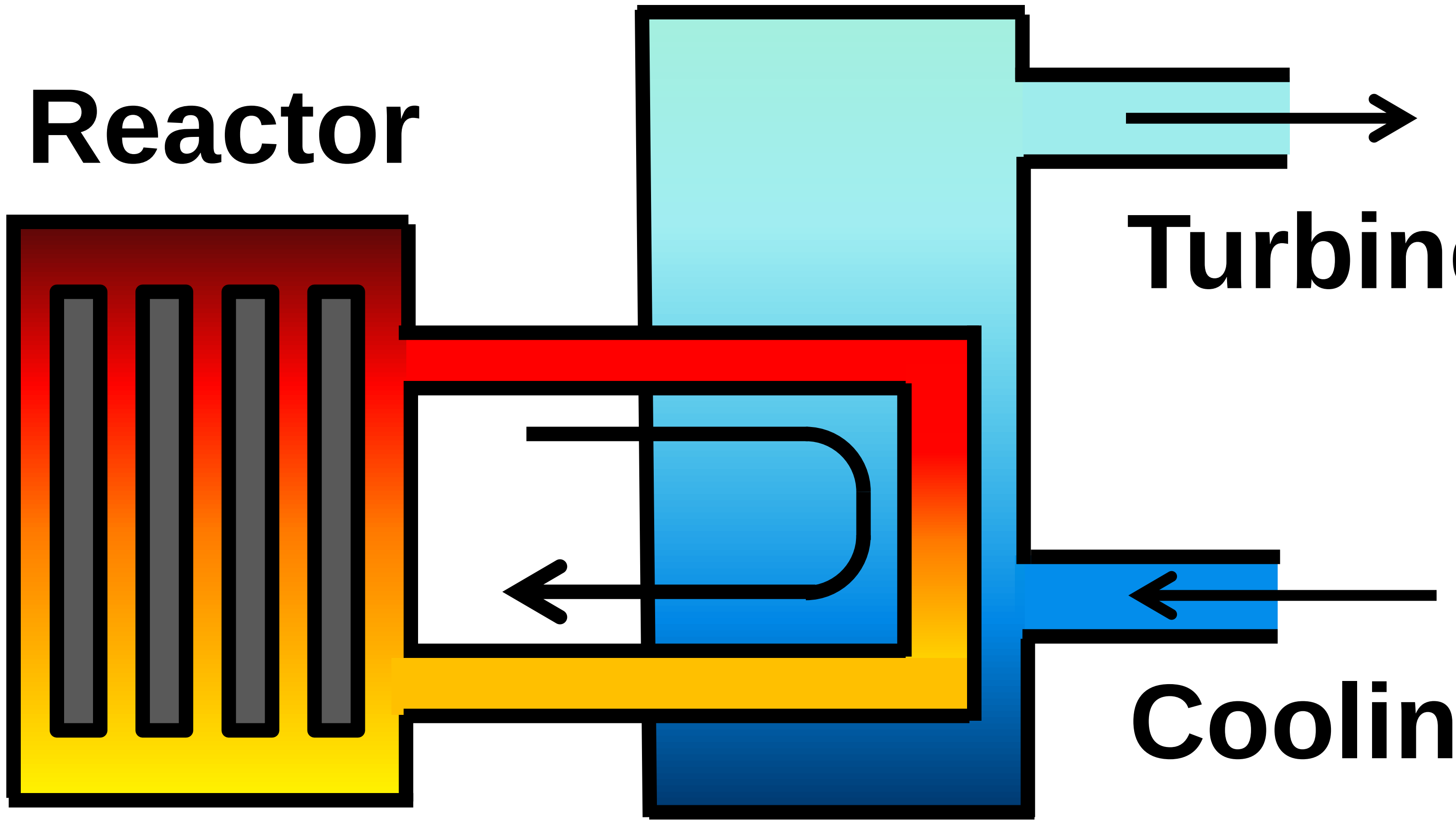
Nuclear Reactors



Nuclear Reactors I

The following nuclear fission reaction releases $2.8 \cdot 10^{-11}$ J of energy.

$$^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{144}_{56}\mathrm{Ba} + {}^{89}_{36}\mathrm{Kr} + 3\,{}^{1}_{0}\mathrm{n}$$

Suppose we are able to react 1 kg of pure ^{235}U. About how much energy would we produce?

A. $1 \cdot 10^{-10}$ J

B. $7 \cdot 10^{10}$ J

C. $2 \cdot 10^{13}$ J

D. $7 \cdot 10^{13}$ J

E. $3 \cdot 10^{24}$ J

Atomic mass of ^{235}U: 235.04 u

1 mol = $6.022 \cdot 10^{23}$

Press for hint

Solution

Answer: D

Justification: For every uranium nuclei that is reacted, $2.8 \cdot 10^{-11}$ J is produced. We must first find out how many uranium nuclei are in 1 kg. The atomic mass of ^{235}U is approximately 235 u, so the are 0.235 kg of uranium per mole.

$$1\,\text{kg U} \times \frac{1\,\text{mol U}}{0.235\,\text{kg U}} \times \frac{6 \cdot 10^{23}\ \text{U nuclei}}{1\,\text{mol U}} = 2.5 \cdot 10^{24}\ \text{U nuclei}$$

We assume that all of these nuclei react (the actual percent yield of 1 kg of uranium is much less than 100%), and the total amount of energy produced is:

$$2.5 \cdot 10^{24}\ \text{U nuclei} \times \frac{1\,\text{fission reaction}}{1\,\text{U nucleus}} \times \frac{2.8 \cdot 10^{-11}\ \text{J}}{1\,\text{fission reaction}} = 7 \cdot 10^{13}\ \text{J}$$

Nuclear Reactors II

In the previous question, we determined that 1 kg of pure uranium-235 will produce about $7 \cdot 10^{13}$ J of energy. However, enriched uranium fuel used in nuclear reactors only contains about 5% of uranium-235.

What is the energy density of uranium fuel? Note that 1 GJ is equivalent to 10^9 J.

A. 3.5 GJ/kg
B. 3500 GJ/kg
C. 70000 GJ/kg
D. $1.4 \cdot 10^6$ GJ/kg
E. $3.5 \cdot 10^9$ GJ/kg

Solution

Answer: B

Justification: The energy density of uranium fuel is the amount of energy produced by 1 kg of fuel. Since there is only about 5% of uranium in uranium fuel, we multiply the energy output of 1 kg of pure uranium by 5%:

$$\frac{7\cdot 10^{13}\ \text{J}}{1\,\text{kg uranium}}\times\frac{0.05\,\text{kg uranium}}{1\,\text{kg uranium fuel}}=3.5\cdot 10^{12}\ \text{J/kg}$$

This is equivalent to

$$3.5\cdot 10^{12}\ \text{J/kg}\times\frac{1\,\text{GJ/kg}}{10^{9}\ \text{J/kg}}=3500\,\text{GJ/kg}$$

Be sure to check your units and conversions.

Nuclear Reactors III

The energy density of coal is approximately 30 MJ/kg. The energy density of uranium fuel is approximately 3500 GJ/kg (see previous question).

How much coal is required to produce the same amount of energy as 1 kg of uranium fuel?

A. $8.6 \cdot 10^{-6}$ kg
B. 0.12 kg
C. 8.6 kg
D. 120 kg
E. $1.2 \cdot 10^{5}$ kg

Solution

Answer: E

Justification: We want to find how many kilograms of coal are required to produce 3500 GJ, the amount of energy produced by 1 kg of uranium fuel. This can be found using the following conversions:

$$3500\,\text{GJ} \times \frac{10^9\ \text{J}}{1\,\text{GJ}} \times \frac{1\,\text{kg coal}}{30\,\text{MJ}} \times \frac{1\,\text{MJ}}{10^6\ \text{J}} \approx 120000\,\text{kg coal}$$

Notice how all units cancel, leaving only kilograms of coal. This shows how much larger the energy density of uranium fuel is over coal.

Alternative Solution

Answer: E

Justification: We can set up an equation relating the amount of fuel and the fuel densities of uranium and coal.

$$1\,\text{kg U} \times \frac{3500\,\text{GJ}}{1\,\text{kg U}} = x\,\text{kg coal} \times \frac{30\,\text{MJ}}{1\,\text{kg coal}}$$

Solving this equation tells us the amount of coal required to produce the same amount of energy as 1 kg of U. Solving for x gives:

$$x = \frac{3500 \cdot 10^9}{30 \cdot 10^6}\,\text{kg coal} \approx 120000\,\text{kg coal}$$

Nuclear Reactors IV

The following fission reaction is *self-sustaining*. This means that another fission reaction may be started after the completion of the first reaction.

$$^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{144}_{56}\text{Ba} + {}^{89}_{36}\text{Kr} + 3\,{}^{1}_{0}\text{n}$$

The main reason this reaction is self-sustain is because...

A. Uranium-235 is highly unstable
B. ^{144}Ba and ^{89}Kr are highly unstable
C. Neutrons are generated as a product
D. The reaction generates enough energy to start another reaction
E. Mass and energy are conserved in the reaction

Solution

Answer: C

Justification: A neutron is required to start the nuclear reaction. The neutron is absorbed by uranium-235 to produce highly unstable uranium-236:

$$^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{236}_{92}\text{U}$$

$$^{236}_{92}\text{U} \rightarrow {}^{144}_{56}\text{Ba} + {}^{89}_{36}\text{Kr} + 3\,{}^{1}_{0}\text{n}$$

The 3 neutrons that are produced by the reaction can then react with 3 other uranium-235 nuclei, starting 3 additional fission reactions. As long as enough uranium-235 remains and the released neutrons have the right amount of energy, fission reactions will continue to be triggered, thus sustaining the reaction.

This process is known as a <u>chain reaction</u>.

Solution Continued

Answer: C

Justification: It is important to understand why the other options do not result in a self-sustaining reaction.

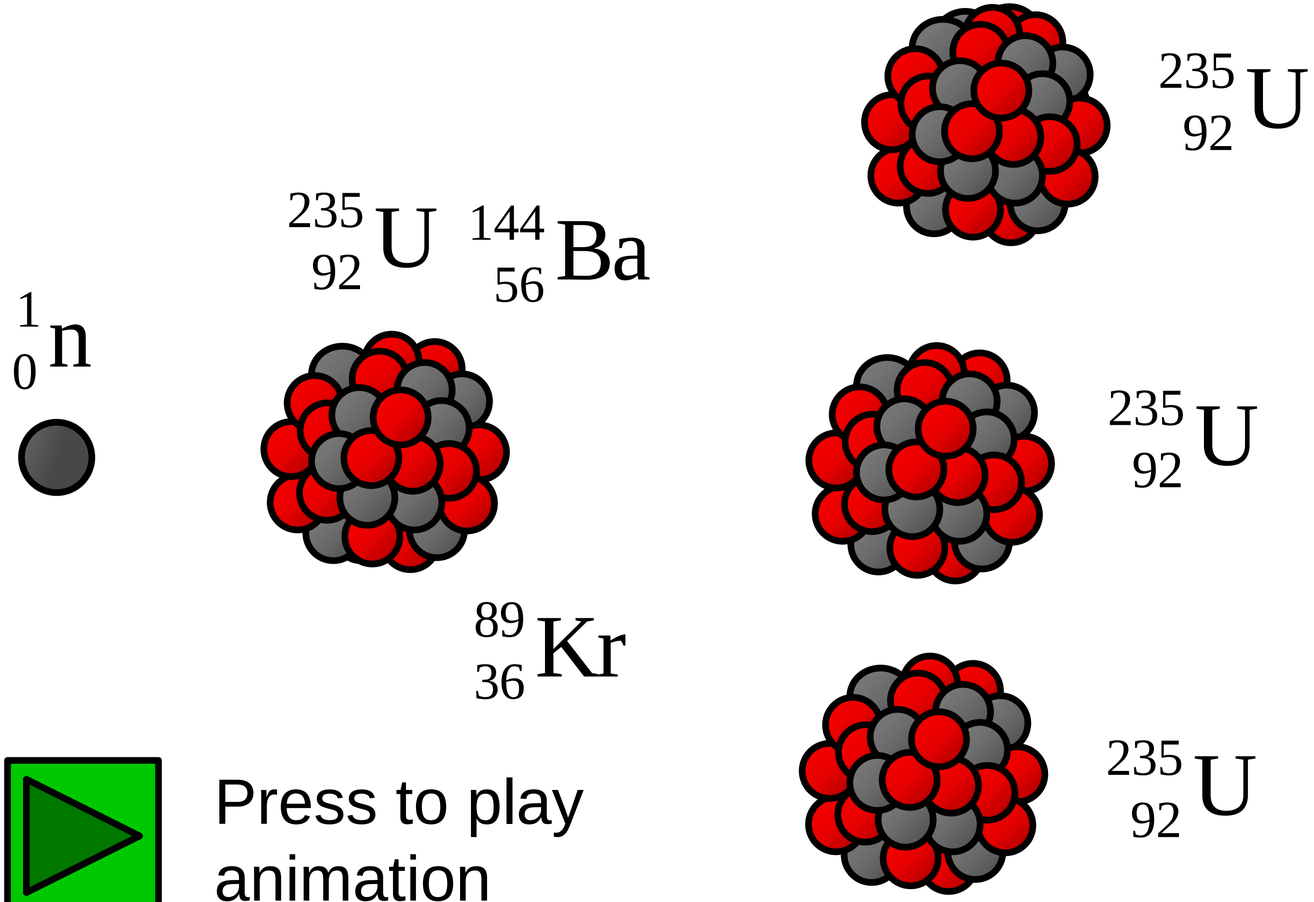
A / B: While unstable elements are more likely to react than stable elements, unstable elements do not cause reactions to occur.

D: It is true that a lot of energy is produced by a single fission reaction. However, neutrons are required to start a fission reaction, not energy. In fact, the neutrons from the fission reaction often contain too much energy to absorbed by uranium and must be slowed down.

E: Mass and energy are conserved in all reactions, not just self-sustaining reactions.

Animation: Chain Reaction

$$^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{144}_{56}\mathrm{Ba} + {}^{89}_{36}\mathrm{Kr} + 3\,{}^{1}_{0}\mathrm{n}$$



Press to play animation

Nuclear Reactors V

In order for a fission reaction to be self-sustaining, a critical mass of uranium-235 is required.

$$^{235}_{92}\mathrm{U} + ^{1}_{0}\mathrm{n} \rightarrow ^{144}_{56}\mathrm{Ba} + ^{89}_{36}\mathrm{Kr} + 3^{1}_{0}\mathrm{n}$$

Why is it necessary for a reaction to have critical mass?

A. It is more likely for neutrons to trigger a new reaction when lots of uranium is present

B. Many uranium nuclei are required in a single fission reaction

C. It is the amount of radioactive material safe for a reaction

D. It is the maximum mass of uranium allowed before the reaction can no longer be controlled

E. It maximizes the energy produced in a single reaction

Solution

Answer: A

Justification: Critical mass is the minimum mass of uranium-235 required to be present in order for a reaction to be self-sustaining.

In order for a chain reaction to occur, the three produced neutrons must hit an additional uranium-235 nuclei with the correct amount of kinetic energy. If there is not enough uranium-235, it is unlikely that the three neutrons will hit an uranium-235 nucleus. Therefore, a critical mass of uranium-235 increases the probability that a chain reaction will occur and sustain the reaction.

Note that only 1 uranium nuclei is required to trigger a single fission reaction, but many uranium nuclei are required to sustain the reaction.

Nuclear Reactors VI

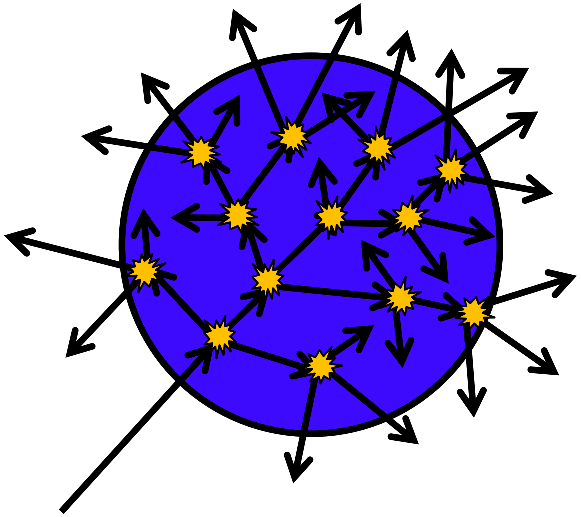
What is the ideal shape for the uranium-235 sample used in a nuclear reactor?

A. A plane / sheet
B. A cylinder
C. A cube
D. A sphere
E. A pyramid

Solution

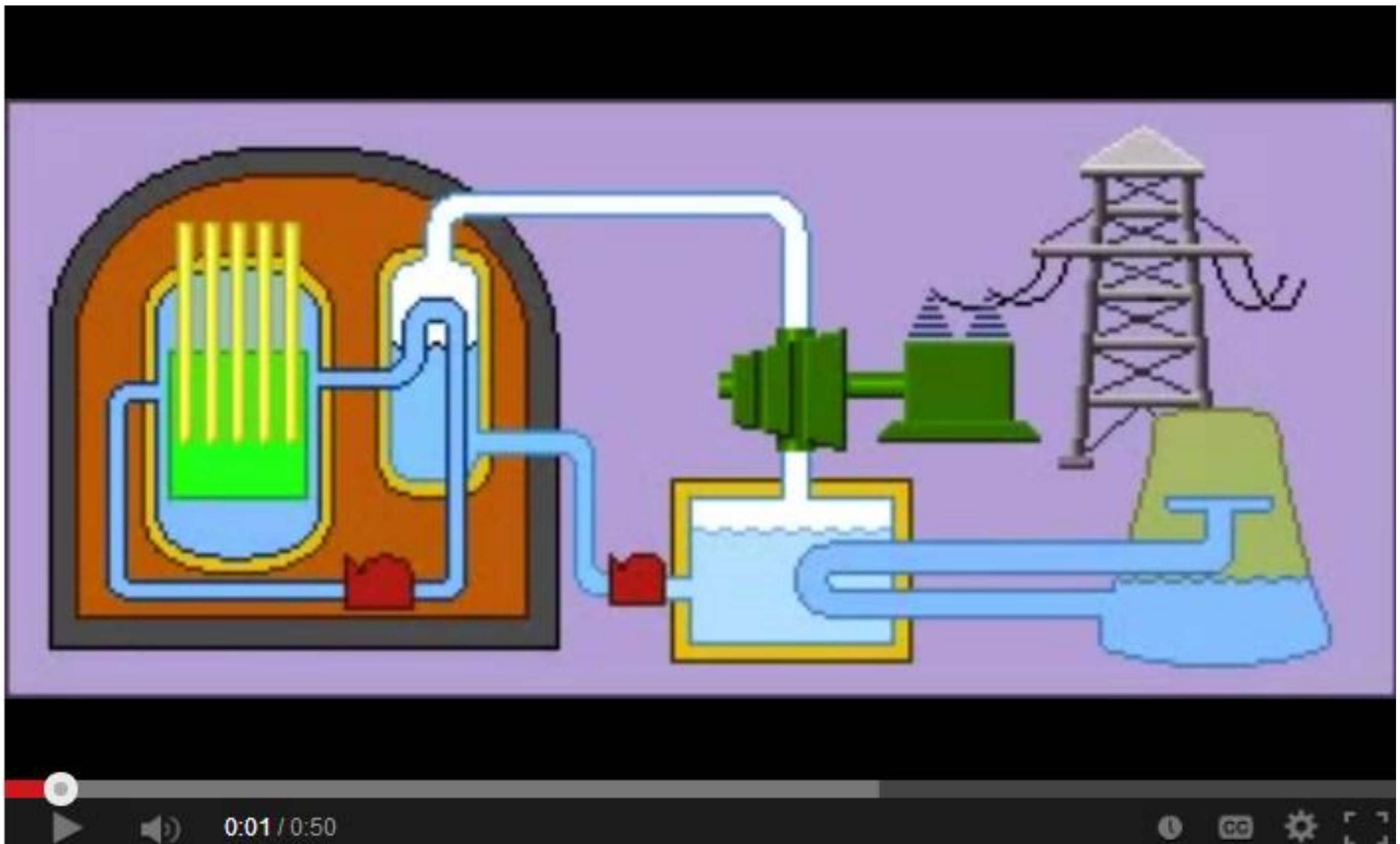
Answer: D

Justification: Pyramids, cubes and sheets have lots of surface area from which neutrons can fly off, hitting nothing. On the other hand, spheres minimize surface area while maximizing volume. When an uranium-235 sample is spherical, less uranium is required to achieve critical mass.



Extend Your Learning: Video

Title: How does a nuclear reactor work?



Nuclear Reactors VII

A moderator (often water) surrounds nuclear fuel in a nuclear reactor in order to slow down released neutrons.

Why is slowing down neutrons necessary in the reaction?

$$^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{144}_{56}\mathrm{Ba} + {}^{89}_{36}\mathrm{Kr} + 3\,{}^{1}_{0}\mathrm{n}$$

A. Moderators allow energy to be extracted from the reactions

B. Neutrons with too much kinetic energy will start too many reactions

C. Neutrons with too much kinetic energy cannot be captured by uranium-235

D. Both A and B

E. Both A and C

Solution

Answer: E

Justification: Neutrons must be slowed down by a moderator so that they can be absorbed by uranium nuclei. Recall that the fission reaction can be broken into the following two stages:

$$^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{236}_{92}\mathrm{U}$$

$$^{236}_{92}\mathrm{U} \rightarrow {}^{144}_{56}\mathrm{Ba} + {}^{89}_{36}\mathrm{Kr} + 3{}^{1}_{0}\mathrm{n}$$

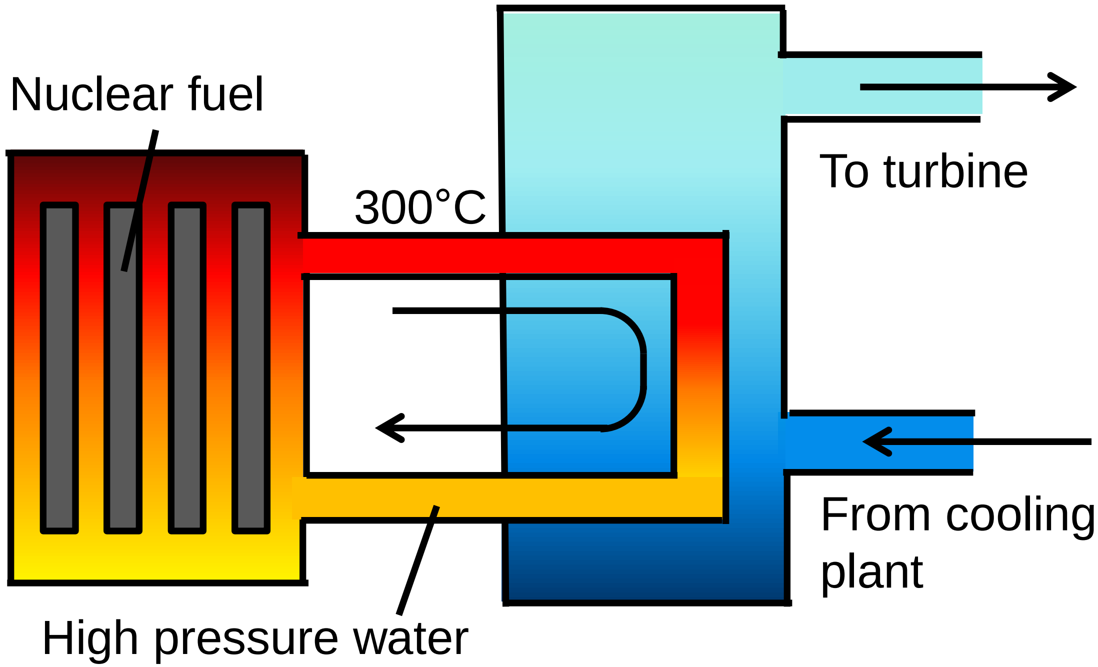
Neutrons that are too fast cannot be absorbed into the uranium-235 nuclei.

By slowing down the neutrons, the kinetic energy of the neutrons is transformed into thermal energy. This energy is then transferred to the moderator, and the water is heated. This is how energy is harnessed from the reaction.

Nuclear Reactors VIII

High pressure water circulates from the nuclear reactor to the steam generator.

What is the importance of the steam generator?



A. High pressure steam is needed in nuclear fission

B. Steam is necessary to turn heat into electricity

C. Allows cool water to return to the nuclear reactor

D. Both B and C

E. All of A, B, and C

Solution

Answer: D (Both B and C)

Justification:

A – Neither heat nor high pressure steam is required to trigger nuclear fission reactions. Only a neutron with the right amount of energy to be fused with a uranium is needed.

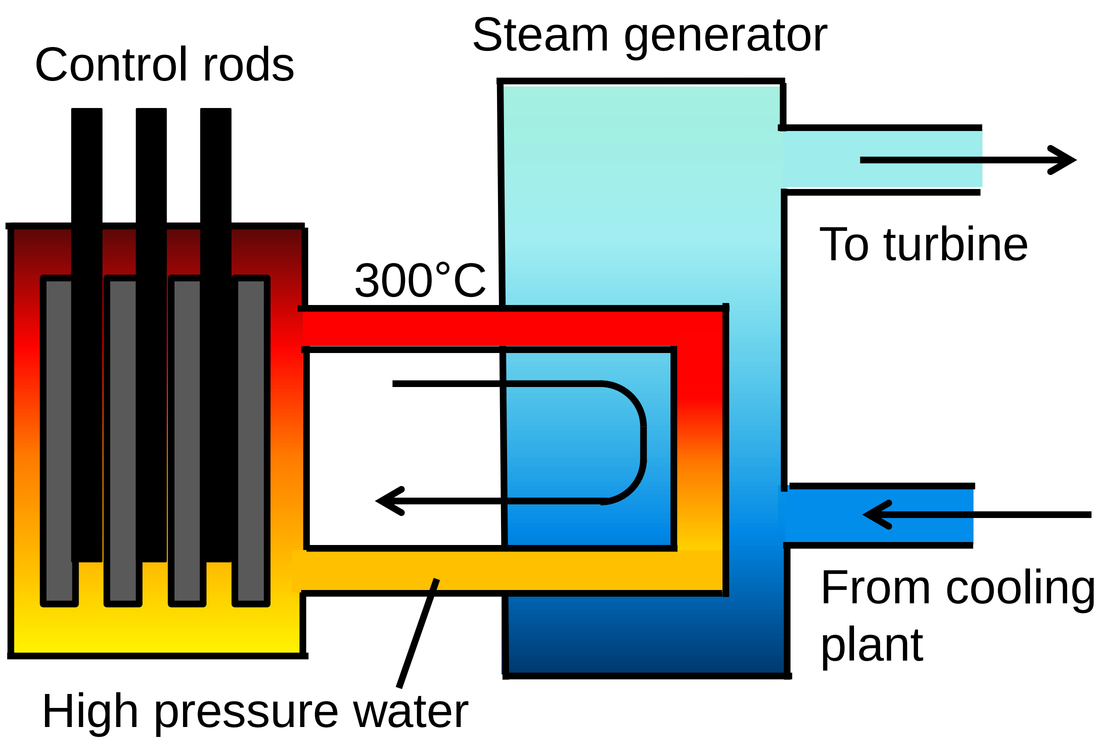
B – The steam generator requires heat to turn water into steam. High pressure steam is used to turn turbines that convert rotational kinetic energy into electricity.

C – After transferring heat to the steam generator, the cool water is then returned to the nuclear reactor. This is necessary to cool the nuclear reactor and allows more heat to be extracted.

Nuclear Reactors IX

When necessary, control rods are inserted into the nuclear reactor to reduce the number of fission reactions.

How are the fission reactions controlled?



A. Cooling down the nuclear reactor
B. Absorbing excess neutrons
C. Stopping the flow of high pressure water
D. Blocking the escape of radiation
E. Preventing heat from escaping the reactor

Solution

Answer: B

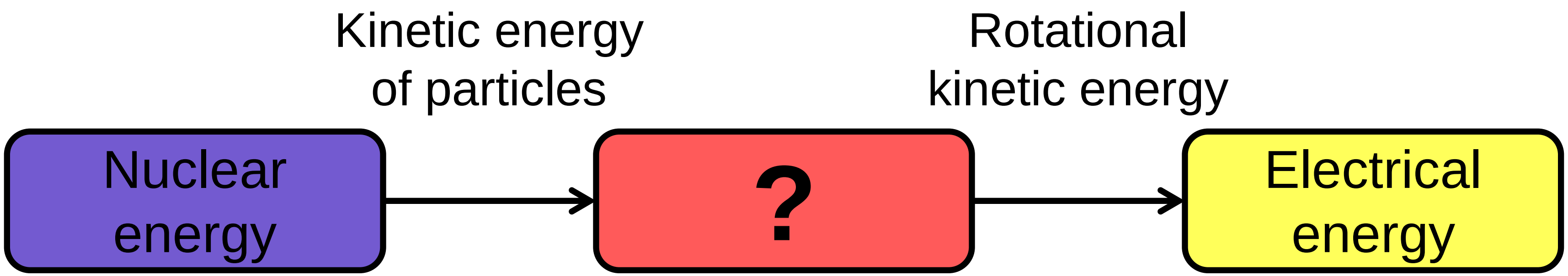
Justification: Neutrons are key to starting nuclear fission reactions and sustaining a chain reaction. By absorbing neutrons, the rate of reactions can be controlled.

$$^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{144}_{56}\text{Ba} + {}^{89}_{36}\text{Kr} + 3\,{}^{1}_{0}\text{n}$$

If a nuclear fission reaction is not controlled, too much heat can be produced, causing the reactor to meltdown. A famous example of a meltdown occurring was in 1986 in Chernobyl. Due to the health hazards of radioactive active material, several safety mechanisms are necessary in a nuclear reactor to prevent losing control over fission reactions.

Nuclear Reactors X

The diagram below shows the transformation of energy in a nuclear reactor. What is the missing type of energy?



A. Pressure energy

B. Steam energy

C. Chemical energy

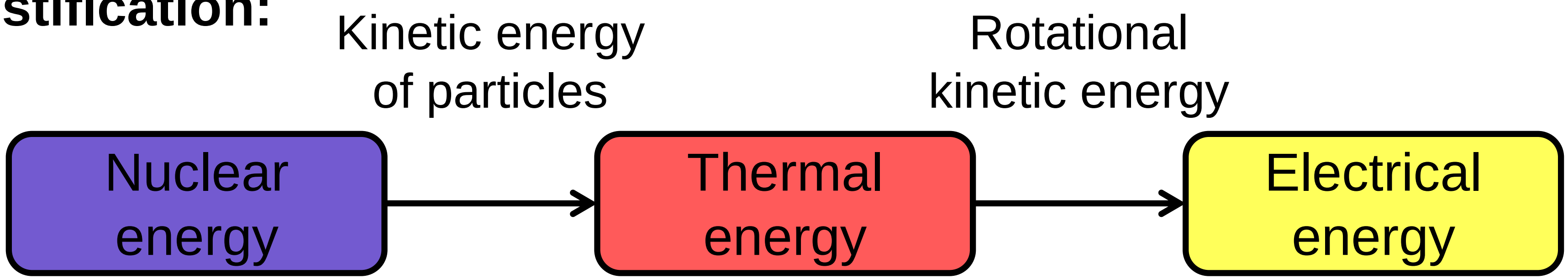
D. Thermal energy

E. Mechanical energy

Solution

Answer: D

Justification:



Only C, D, and E are types of energy. When fission products collide with nearby atoms, kinetic energy is transformed into <u>thermal energy</u>. As water begins to boil, high pressure steam turns large turbines, which change rotational kinetic energy into electrical energy.

Nuclear Reactors XI

Which one of the following is <u>not</u> an advantage of nuclear energy?

A. No smoke, low CO_2 emissions, low greenhouse gas impact
B. Uranium fuel has high energy density
C. Small impact on surrounding wildlife and environment
D. Possible to recycle nuclear waste for reuse
E. Radioactive nuclear waste is stored underground

Solution

Answer: E

Justification: Nuclear fission does not produce greenhouse gases or smoke from burning coal. Unlike wind turbines or hydroelectric plants, the impact on the physical environment from building a nuclear reactor is relatively small. However, radioactive waste from spent uranium fuel is produced instead.

There is currently no way to safely and cleanly remove the radioactive waste created by nuclear reactors. Moving the waste underground only hides the problem of nuclear waste. Ways to recycle radioactive waste are currently being investigated.

What are other disadvantages of nuclear energy?

Extend Your Learning: Pros / Cons of Nuclear Energy

There are several resources online with more information regarding the advantages and disadvantages of nuclear energy.

Try making a table of the pros and cons of nuclear energy and compare it to other methods of producing electricity.

Pros and Cons of Nuclear Power:
http://www.discovery.com/tv-shows/curiosity/topics/10-pros-cons-nuclear-power.htm

Health report after Chernobyl Accident:
http://www.unis.unvienna.org/unis/en/pressrels/2011/unisinf398.html

Nuclear Reactors XII

We have seen that nuclear fusion reactions release similar amounts of energy as nuclear fission reactions, without the need for radioactive fuels.

$$^{2}_{1}D + \,^{3}_{1}T \rightarrow \,^{4}_{2}He + \,^{1}_{0}n + 17.6\,\mathrm{MeV} \quad \text{(fusion reaction)}$$

Why is it currently not feasible to use nuclear fusion reactions to produce energy?

A. High temperatures are required for fusion to occur

B. Deuterium and tritium are extremely rare isotopes of hydrogen

C. Fusion reactions do not trigger chain reactions

D. Fusion reactions release just as much radioactive waste

E. Fusion reactions are very difficult to control once started

Solution

Answer: A

Justification: In order for nuclear fusion reactions to take place, two positively charged nuclei must be brought together. In order for this to occur, high temperatures (10^8 K) are required to overcome the electromagnetic forces pushing the nuclei apart (positive repels positive). Even though fusion reactions release a lot of energy, it takes much more energy to produce the conditions necessary for a fusion reaction to take place.

If effective nuclear fusion processes are discovered where more energy is produced than used, we will be able to see the advantages of nuclear power without the production of radioactive nuclear waste. The risks of uranium mining can also be avoided due to the abundance of hydrogen fuels.