History of Nuclear Power Development

Key Points to Operational Safety, Quality and Reliability,

Navy Captain Hyman G. Rickover received nuclear power training at Oak Ridge in 1947
Director Naval Reactors Branch in the Bureau of Ships, joint activity with AEC in 1949
Submarine Nautilus commissioned 1954; 1st commercial reactor (Shippingport,PA) 1957
https://en.wikipedia.org/wiki/Naval_Reactors#History

Management and Personal Principles:

Attention to detail and adherence to rigidly-defined standards and specifications
Attitude change to large American commercial manufacturer's and CEOs
DoD and NASA compliance requirements. {Recall large variable spacing between U. S. car doors to main frame (1/8-5/8 inch) during the 50s & 60s.}

Brief History of Quality Assurance and Reliability

William Edwards Deming; https://en.wikipedia.org/wiki/W._Edwards_Demin
"Statistical Product Quality Administration" Recall the Japanese recovery after WWII 1950s

Joseph Moses Juran; https://en.wikipedia.org/wiki/Joseph_M._Juran
Known for adding the human dimension to quality management

William Edwards Deming (October 14, 1900 – December 20, 1993)
Walter Andrew Shewhart (March 18, 1891 – March 11, 1967)

Deming is best known for his work in Japan after WWII, particularly his work with the leaders of Japanese industry. That work began in July and August 1950, in Tokyo and at the Hakone Convention Center[4], when Deming delivered speeches on what he called **"Statistical Product Quality Administration".** Many in Japan credit Deming as one of the inspirations for what has become known as the Japanese post-war economic miracle of 1950 to 1960, when Japan rose from the ashes of war on the road to becoming the second-largest economy in the world through processes partially influenced by the ideas Deming taught.

Dr. Walter A. Shewhart pronounced like "shoe-heart", was an American physicist, engineer and statistician, sometimes known as the father of Statistical Quality Control and also related to the Shewhart cycle.

Invented the control chart working for Bell Labs in the 1920s while seeking to improve the reliability of their telephony transmission systems. Because some equipment had to be buried underground, there was a strong business need to reduce the frequency of failures and repairs.

Shewhart's work pointed out: the importance of reducing variation in a manufacturing process; understanding continual process-adjustment; bringing production processes into a state of statistical control to improve Reliability.

Significant Points of Interest/Discussion of Nuclear Power Plant Construction

Available Resources of the 1970s

Limited availability of trained professionals in the many technical areas and management fields

<u>Pioneering explorers</u>. Just as challenging and dangerous as space exploration in early 60s.

Innovative thinking and New Capabilities Design Required
(i.e. Why not design & build it RIGHT the first time)

Design & Development, Quality, Reliability, Safety; Life Sciences, Environmental Impact, Operational Maintenance; Security, Fuel Storage, and Decommissioning; Cost effectiveness.

However, in my opinion, Federal Government NUCLEAR SAFETY Requirements was Priority #1 at the very beginning.
Rickover's management philosophy was applied to Commercial Nuclear Power Generation.
Convincing power corporation CEOs was another matter. However, the Design & Development
Engineers used redundant safety systems which really paid off.

What are the forms of energy?

Mechanical energy is the energy that moves objects by applying a force.

Chemical energy is the energy released when the chemical bonds of a material change.

Electrical energy is the flow of tiny charged particles called electrons. Electrons move through a conductor, like copper wire.

Radiant energy is energy traveling in waves.

More forms of energy

Nuclear energy is energy stored in the center (nucleus) of an atom. That energy binds the center together and is released when atoms split apart.

Thermal energy is heat energy.

Energy from gravity is the energy of position or place.

How does a nuclear power plant work?

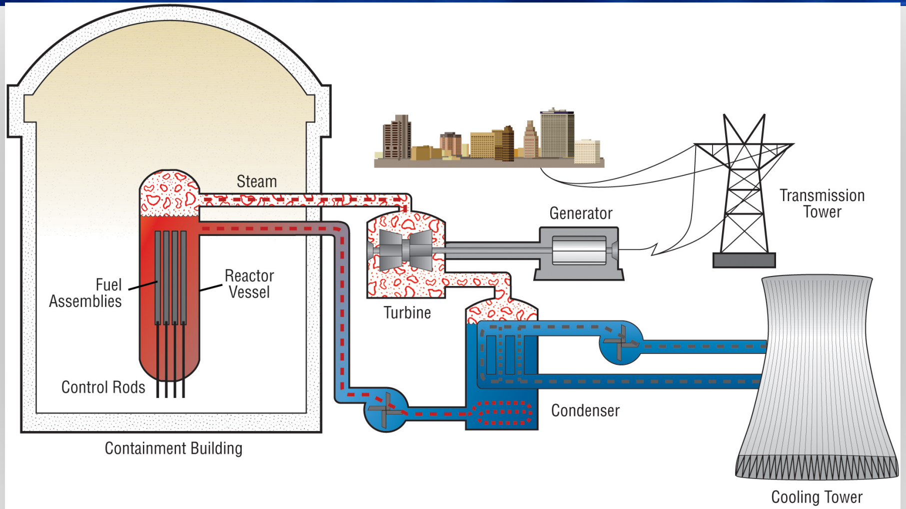
1. Atoms are split to heat water to produce steam.
2. Steam turns the blades of a turbine.
3. The turbine spins a coil of wire on the shaft of a generator that turns inside a magnetic field.
4. Electrons flow in the coil…..That is electricity!

Animated diagram: Nuclear power station - how it works
http://www.nrc.gov/reading-rm/basic-ref/students/animated-pwr.html

For discussion: Two main types of nuclear power plants

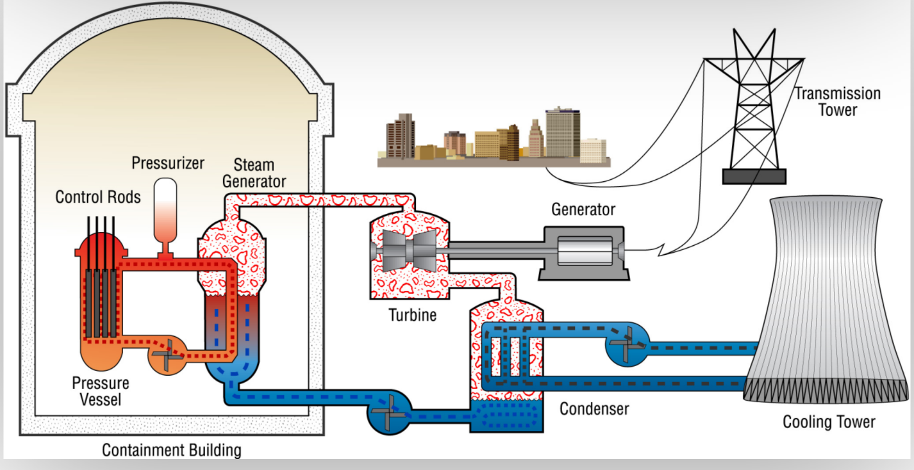
Boiling Water Reactor (BWR)

- The reactor water boils to produce steam. Two loops, control rods enter from bottom.



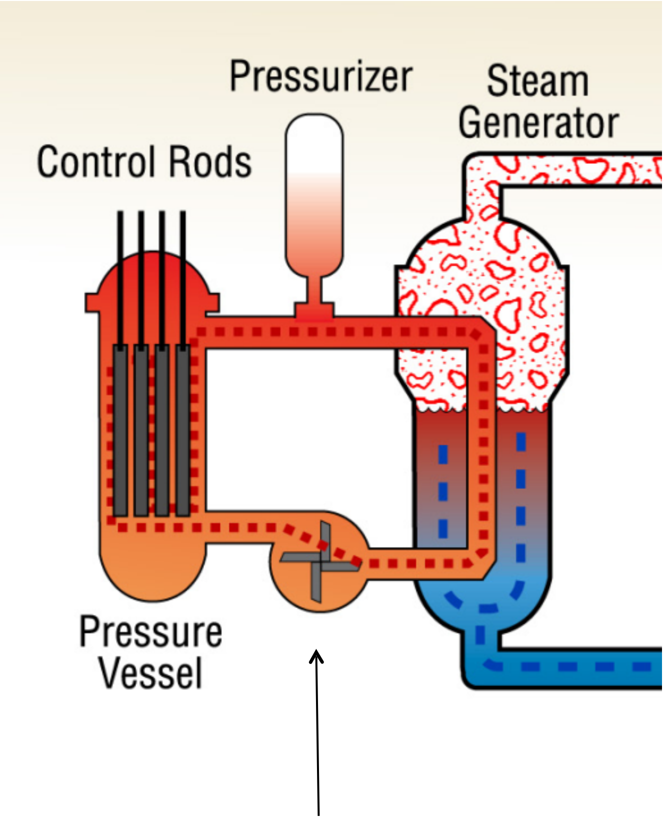
Pressurized Water Reactor (PWR)

- The reactor water is under pressure and does not boil.
- Water from the reactor heats pipes in a steam generator. Water that is turned into steam never mixes with the water in the first loop.



First loop

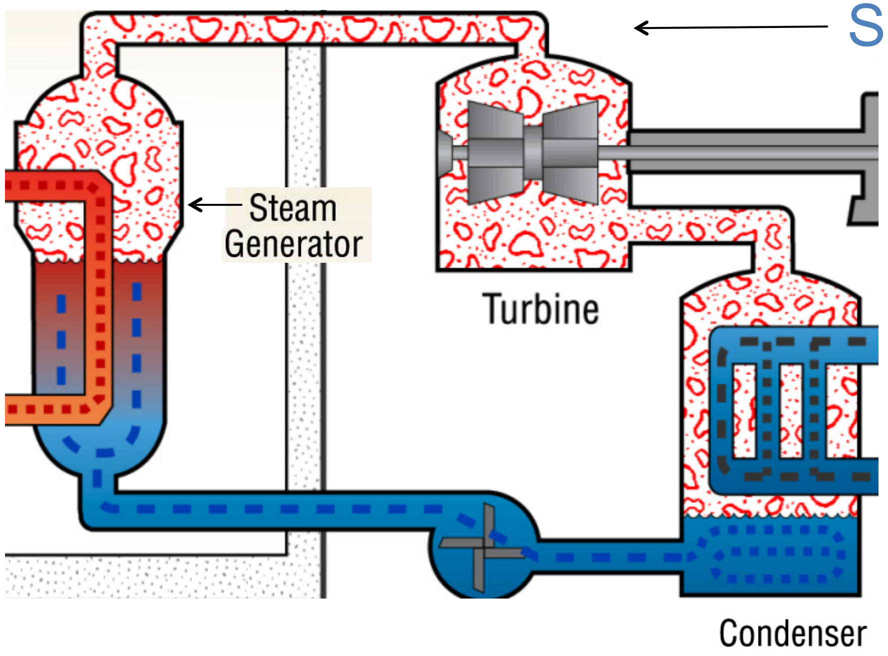
The first loop carries water heated to a very high temperature in the reactor to the steam-generator.



First loop

Second loop

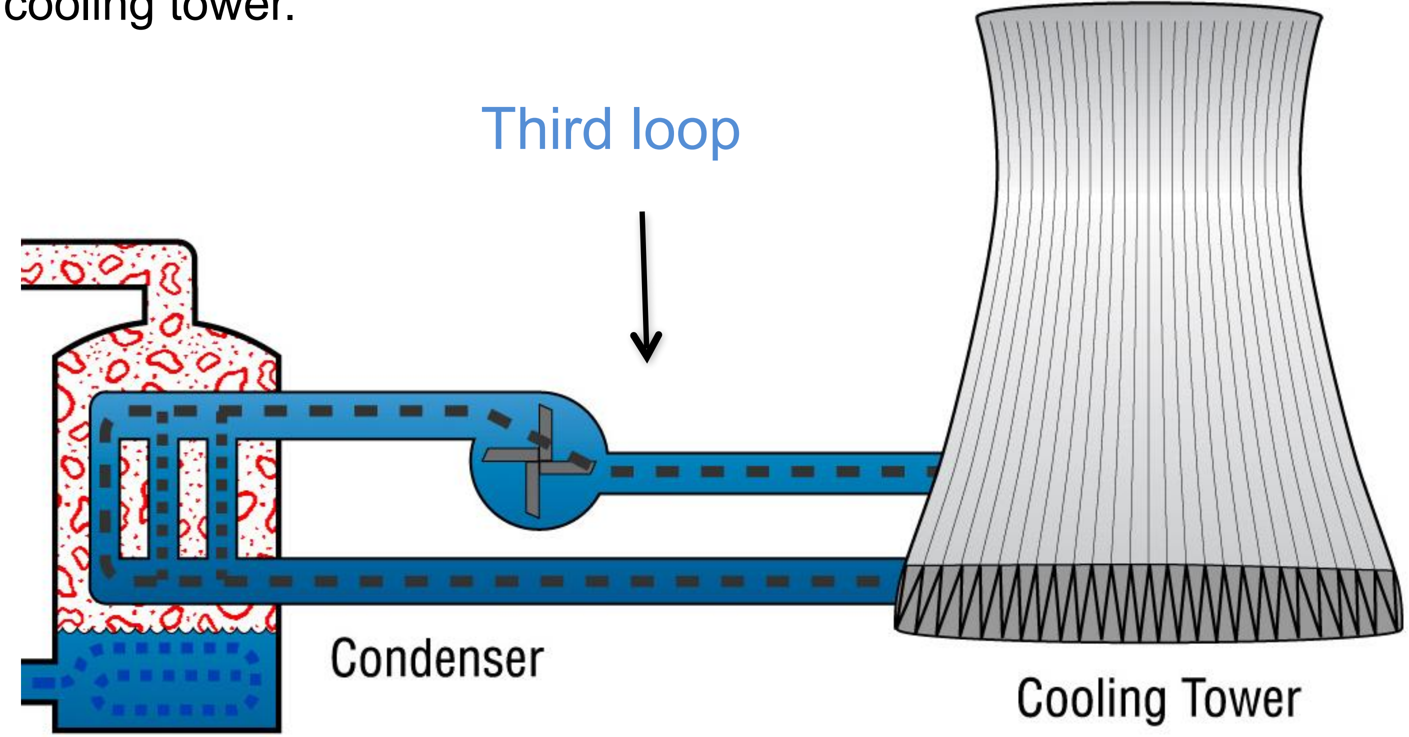
- The second loop carries the heat energy as steam to the turbines and spins the blades of the turbines.
- The turbines are attached to the generators, which change the mechanical energy of the spinning turbine into electricity.



Second loop

Third loop

The steam is cooled by the condenser, turning it back into a liquid. The third loop contains cooling water drawn from the river. The purpose of the third loop is to cool down the steam in the second loop. The water cools as it drops from high in the cooling tower.

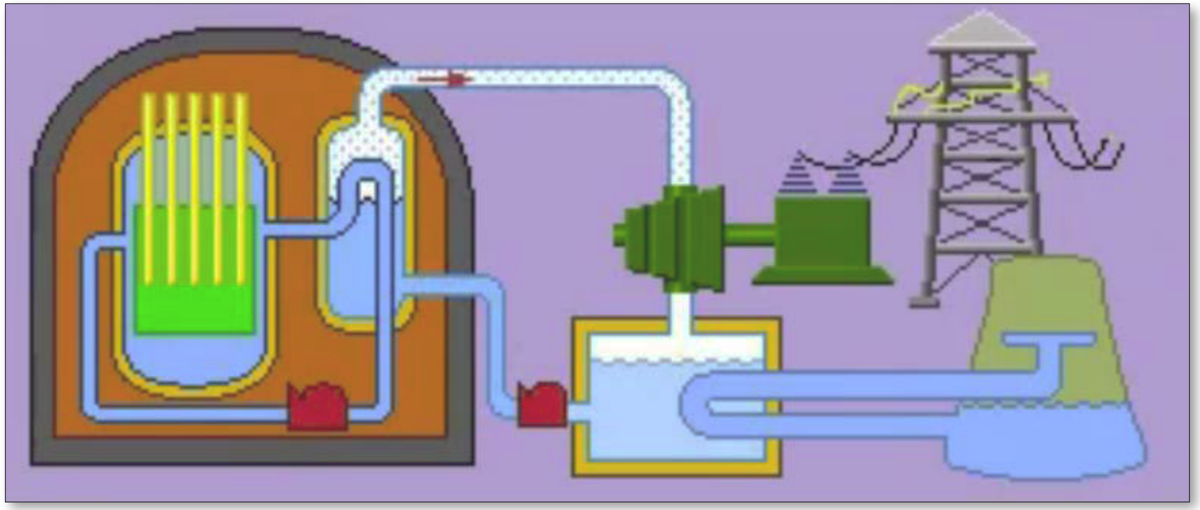


3 Loops with 3 purposes

The three loops in a pressurized water reactor have three purposes.

The three loops are separate. The water in one loop never mixes with the water in another loop. Only the heat energy moves from loop to loop.

Watch this video clip and write down what the three purposes are:
http://www.youtube.com/watch?v=NW9qB2dN_o8&NR=1



What makes up a fuel assembly?

The fuel is assembled like this:

Fuel pellets

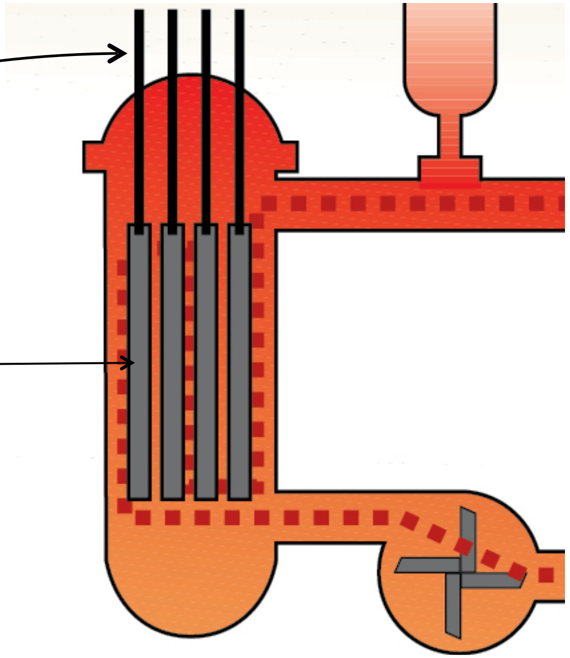
Fuel rods

Fuel assemblies

This is where fission happens!

Inside the reactor core, fission takes place within each fuel assembly.

The control rods control the rate of fission.

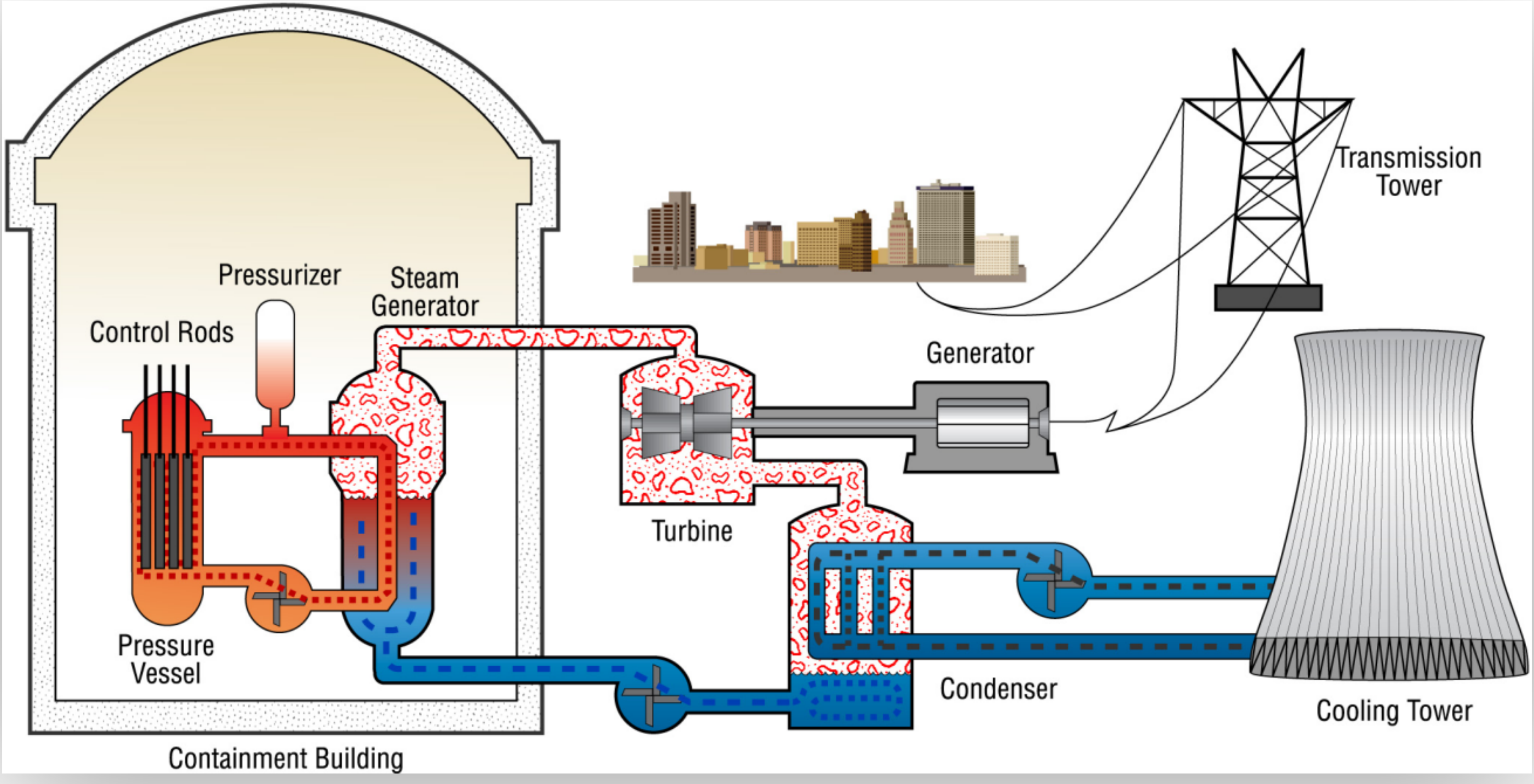


Control rods

Fuel assemblies

Pressurized water reactor

The steam to run the turbine is produced in a steam generator.

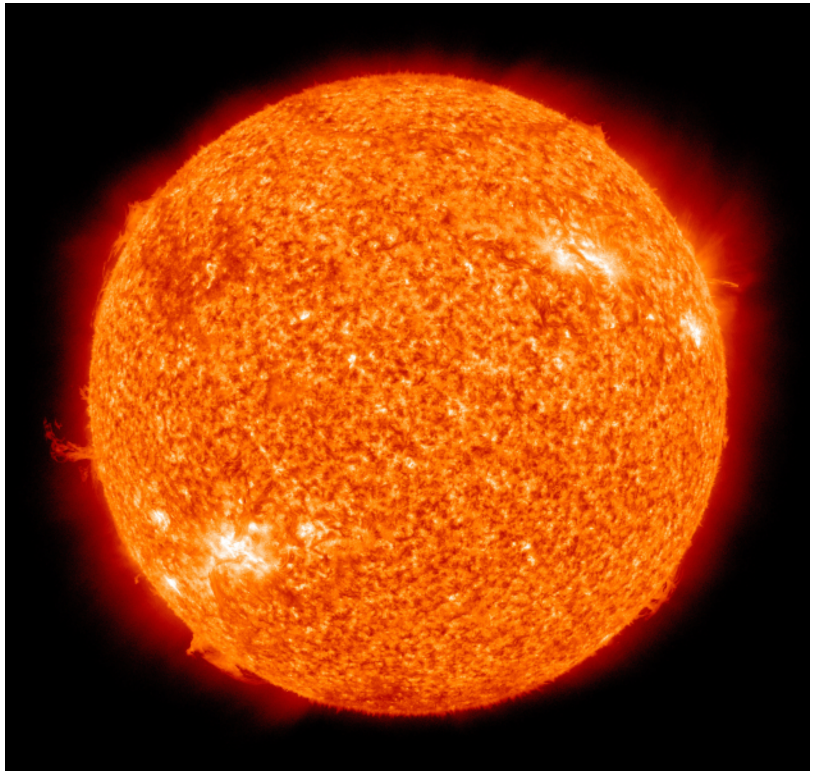


Fusion

Fusion is the opposite of fission. Fusion is a nuclear reaction in which light isotopes of hydrogen ***fuse*** together.

Fusion

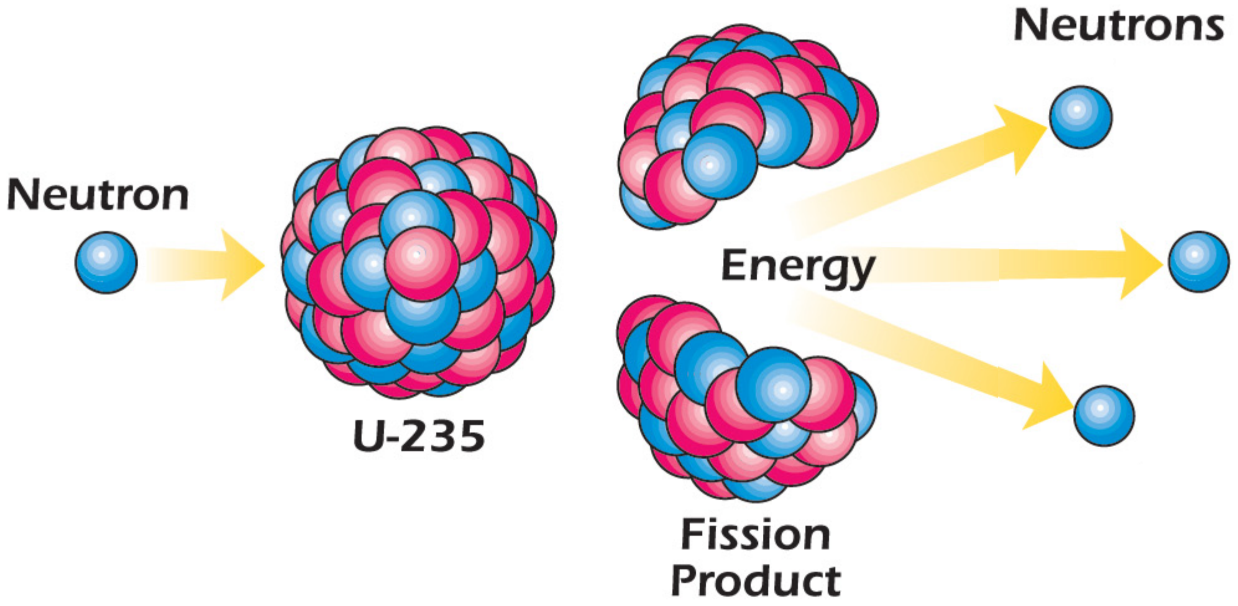
- Creates new atoms
- Releases a large amount of energy
- May someday offer clean, abundant energy



How does fission happen?

- Step 1: A neutron strikes the nucleus of a heavy and unstable isotope, like U-235.
- Step 2: The nucleus becomes unstable.
- Step 3: The nucleus vibrates and splits.

This split is fission!



What is radiation protection?

Radiation dose is determined by the amount of

- **Time** that a person is exposed to ionizing radiation
- **Shielding** used protect a person
- **Distance** between a person and a radioactive substance.

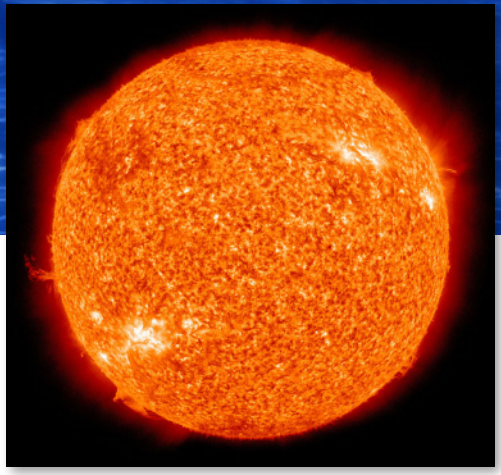
UV rays in sunlight are non-ionizing radiation, but the same principles apply.

Two types of radiation

Non-ionizing radiation is low energy. We use it to carry signals to our radios, TVs, and cell phones.

Ionizing radiation is high energy. We use it for medical x-rays. Its high energy can cause disease or it can treat disease.

You are surrounded.



You are always surrounded by radiation. Radiation is everywhere.

- The bricks in your school have natural minerals that are radioactive.
- Cosmic radiation from the stars showers us constantly.
- Radioactive minerals were in the banana you ate this morning.

Think of radiation as a natural energy that surrounds us all the time.

Who discovered the energy of atoms?

Scientists from around the world ran experiments and realized the atom contains large amounts of energy.

- Wilhelm **Roentgen** discovered an invisible energy he called an x ray. (1895)
- Henri **Becquerel** observed that uranium gave off similar energy. (1896)
- Marie **Curie** studied uranium rays and discovered radioactivity as energy from within the atom. (1898)
- Ernest **Rutherford** understood the “enormous energy” of such matter. (1904)

Many other scientists have contributed to our knowledge of elements and atoms.

What is the strongest force known in nature?

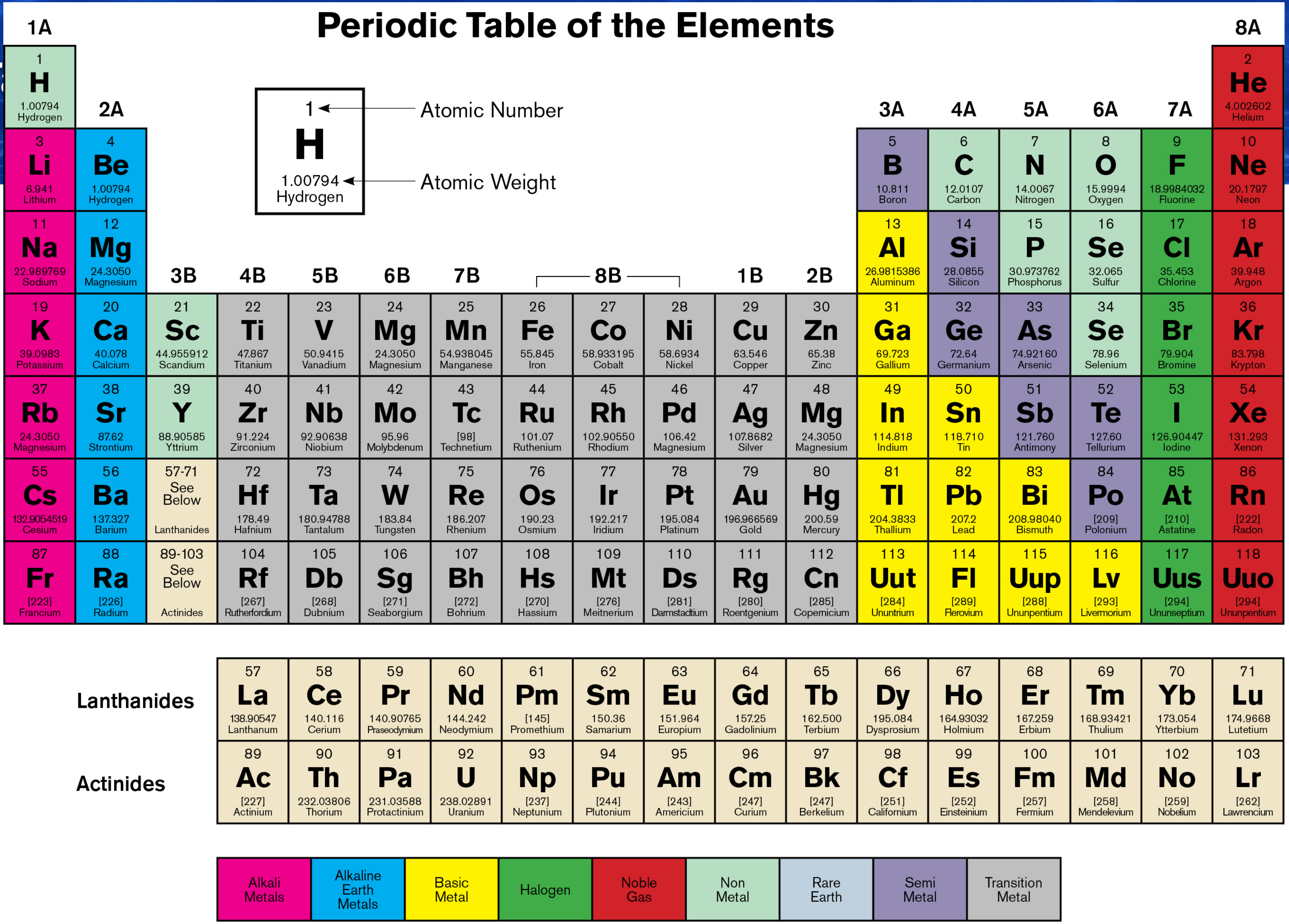
Some proton-neutron combinations are more stable than others.

- Stable combinations *are not likely* to change.
- Unstable combinations *are likely* to change at some time.

Elements with unstable isotopes can change suddenly, releasing energy.

And although all atoms are extremely small, the energy that holds their centers together is the **strongest** force known in nature.

Periodic Ta



Periodic Table of the Elements

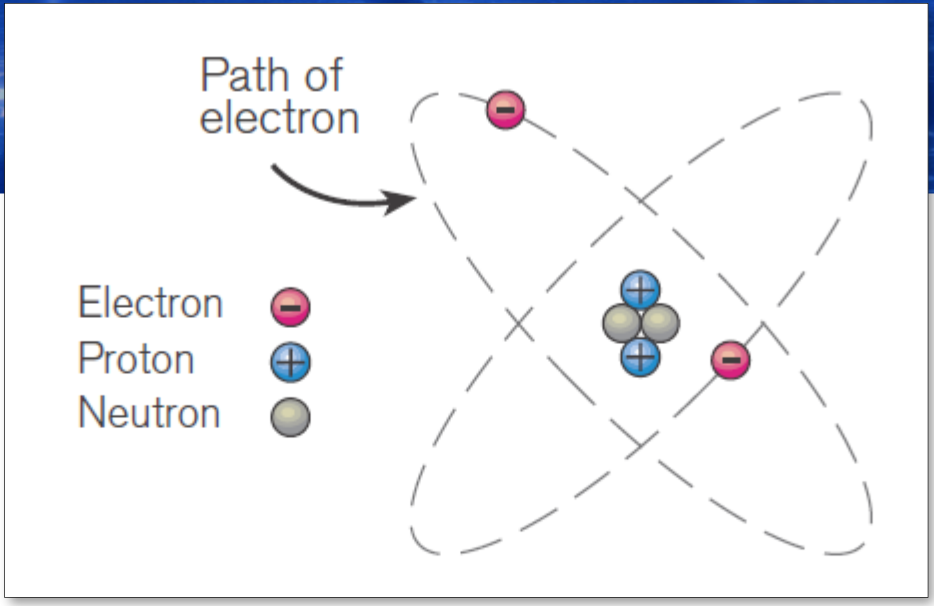
1 ← Atomic Number
H
1.00794 ← Atomic Weight
Hydrogen

1A	2A	3B	4B	5B	6B	7B	8B			1B	2B	3A	4A	5A	6A	7A	8A
1 **H** 1.00794 Hydrogen																	2 **He** 4.002602 Helium
3 **Li** 6.941 Lithium	4 **Be** 1.00794 Hydrogen											5 **B** 10.811 Boron	6 **C** 12.0107 Carbon	7 **N** 14.0067 Nitrogen	8 **O** 15.9994 Oxygen	9 **F** 18.9984032 Fluorine	10 **Ne** 20.1797 Neon
11 **Na** 22.989769 Sodium	12 **Mg** 24.3050 Magnesium											13 **Al** 26.9815386 Aluminum	14 **Si** 28.0855 Silicon	15 **P** 30.973762 Phosphorus	16 **Se** 32.065 Sulfur	17 **Cl** 35.453 Chlorine	18 **Ar** 39.948 Argon
19 **K** 39.0983 Potassium	20 **Ca** 40.078 Calcium	21 **Sc** 44.955912 Scandium	22 **Ti** 47.867 Titanium	23 **V** 50.9415 Vanadium	24 **Mg** 24.3050 Magnesium	25 **Mn** 54.938045 Manganese	26 **Fe** 55.845 Iron	27 **Co** 58.933195 Cobalt	28 **Ni** 58.6934 Nickel	29 **Cu** 63.546 Copper	30 **Zn** 65.38 Zinc	31 **Ga** 69.723 Gallium	32 **Ge** 72.64 Germanium	33 **As** 74.92160 Arsenic	34 **Se** 78.96 Selenium	35 **Br** 79.904 Bromine	36 **Kr** 83.798 Krypton
37 **Rb** 24.3050 Magnesium	38 **Sr** 87.62 Strontium	39 **Y** 88.90585 Yttrium	40 **Zr** 91.224 Zirconium	41 **Nb** 92.90638 Niobium	42 **Mo** 95.96 Molybdenum	43 **Tc** [98] Technetium	44 **Ru** 101.07 Ruthenium	45 **Rh** 102.90550 Rhodium	46 **Pd** 106.42 Magnesium	47 **Ag** 107.8682 Silver	48 **Mg** 24.3050 Magnesium	49 **In** 114.818 Indium	50 **Sn** 118.710 Tin	51 **Sb** 121.760 Antimony	52 **Te** 127.60 Tellurium	53 **I** 126.90447 Iodine	54 **Xe** 131.293 Xenon
55 **Cs** 132.9054519 Cesium	56 **Ba** 137.327 Barium	57-71 See Below Lanthanides	72 **Hf** 178.49 Hafnium	73 **Ta** 180.94788 Tantalum	74 **W** 183.84 Tungsten	75 **Re** 186.207 Rhenium	76 **Os** 190.23 Osmium	77 **Ir** 192.217 Iridium	78 **Pt** 195.084 Platinum	79 **Au** 196.966569 Gold	80 **Hg** 200.59 Mercury	81 **Tl** 204.3833 Thallium	82 **Pb** 207.2 Lead	83 **Bi** 208.98040 Bismuth	84 **Po** [209] Polonium	85 **At** [210] Astatine	86 **Rn** [222] Radon
87 **Fr** [223] Francium	88 **Ra** [226] Radium	89-103 See Below Actinides	104 **Rf** [267] Rutherfordium	105 **Db** [268] Dubnium	106 **Sg** [271] Seaborgium	107 **Bh** [272] Bohrium	108 **Hs** [270] Hassium	109 **Mt** [276] Meitnerium	110 **Ds** [281] Darmstadtium	111 **Rg** [280] Roentgenium	112 **Cn** [285] Copernicium	113 **Uut** [284] Ununtrium	114 **Fl** [289] Flerovium	115 **Uup** [288] Ununpentium	116 **Lv** [293] Livermorium	117 **Uus** [294] Ununseptium	118 **Uuo** [294] Ununpentium

Lanthanides	57 **La** 138.90547 Lanthanum	58 **Ce** 140.116 Cerium	59 **Pr** 140.90765 Praseodymium	60 **Nd** 144.242 Neodymium	61 **Pm** [145] Promethium	62 **Sm** 150.36 Samarium	63 **Eu** 151.964 Europium	64 **Gd** 157.25 Gadolinium	65 **Tb** 162.500 Terbium	66 **Dy** 195.084 Dysprosium	67 **Ho** 164.93032 Holmium	68 **Er** 167.259 Erbium	69 **Tm** 168.93421 Thulium	70 **Yb** 173.054 Ytterbium	71 **Lu** 174.9668 Lutetium
Actinides	89 **Ac** [227] Actinium	90 **Th** 232.03806 Thorium	91 **Pa** 231.03588 Protactinium	92 **U** 238.02891 Uranium	93 **Np** [237] Neptunium	94 **Pu** [244] Plutonium	95 **Am** [243] Americium	96 **Cm** [247] Curium	97 **Bk** [247] Berkelium	98 **Cf** [251] Californium	99 **Es** [252] Einsteinium	100 **Fm** [257] Fermium	101 **Md** [258] Mendelevium	102 **No** [259] Nobelium	103 **Lr** [262] Lawrencium

Alkali Metals	Alkaline Earth Metals	Basic Metal	Halogen	Noble Gas	Non Metal	Rare Earth	Semi Metal	Transition Metal

Are atoms the smallest?



No. Most atoms are made up of even smaller particles called

- **protons**
- **neutrons**
- **electrons.**

Protons carry a positive electrical charge (+). **Neutrons** have no electrical charge.

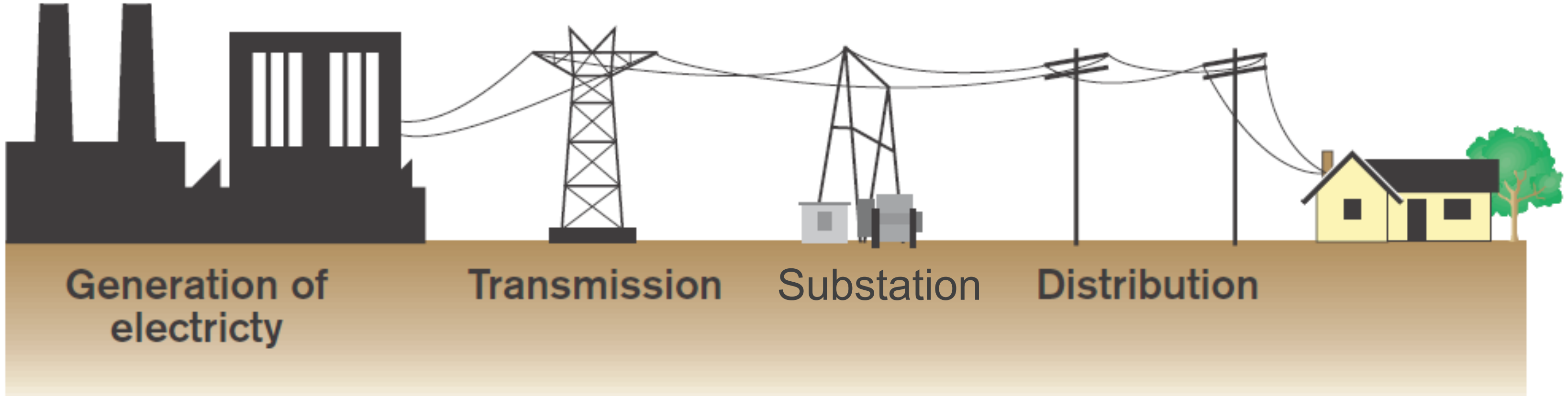
Protons and neutrons together make a dense bundle at the center of an atom. This bundle is called the **nucleus**.

Electrons have a negative electrical charge (-) and move around the nucleus. Electrons are the smallest of these particles.

Getting electricity to customers in 3 steps

Steps in getting electricity to customers:

1. **Generation** – converting a source of energy to produce electricity
2. **Transmission** – using high voltage lines from the power plant to send electricity across long distances
3. **Distribution**– using lower voltage wires to deliver electricity to local customers.



Memorandum of Understanding Between DOE and NRC on Nuclear Energy Innovation

NUCLEAR ENERGY in the FUTURE

The **U.S. Department of Energy** (DOE) and U.S. **Nuclear Regulatory Commission** (NRC) recently signed a Memorandum of Understanding (MOU) to share technical expertise and computing resources to speed up the deployment of advanced nuclear technologies. The MOU centers on DOE's new National Reactor Innovation Center initiative which was authorized by the Nuclear Energy Innovation Capabilities Act of 2017.

Authorized by the Nuclear Energy Innovation Capabilities Act of 2017.

DOE url: **https://www.energy.gov/ne/nuclear-reactor-technologies**

ADVANCED NUCLEAR

SIZES

SMALL

1 MW to 20 MW

Micro-reactors

Can fit on a flatbed truck. Mobile. Deployable.

MEDIUM

20 MW to 300 MW

Small Modular Reactors

Factory-built. Can be scaled up by adding more units.

LARGE

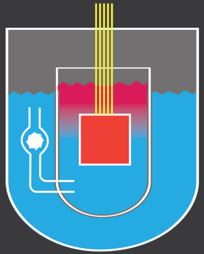
300 MW to 1,000 + MW

Full-size Reactors

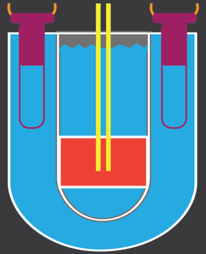
Can provide reliable, emissions-free baseload power

Advanced Reactors Supported by the U.S. Department of Energy

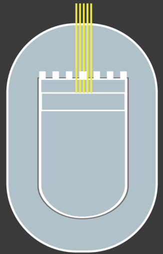
TYPES



MOLTEN SALT REACTORS –
Use molten fluoride or chloride salts as a coolant. Online fuel processing. Can re-use and consume spent fuel from other reactors.



LIQUID METAL FAST REACTORS -
Use liquid metal (sodium or lead) as a coolant. Operate at higher temperatures and lower pressures. Can re-use and consume spent fuel from other reactors.



GAS-COOLED REACTORS –
Use flowing gas as a coolant. Operate at high temperatures to efficiently produce heat for electric and non-electric applications.

BENEFITS

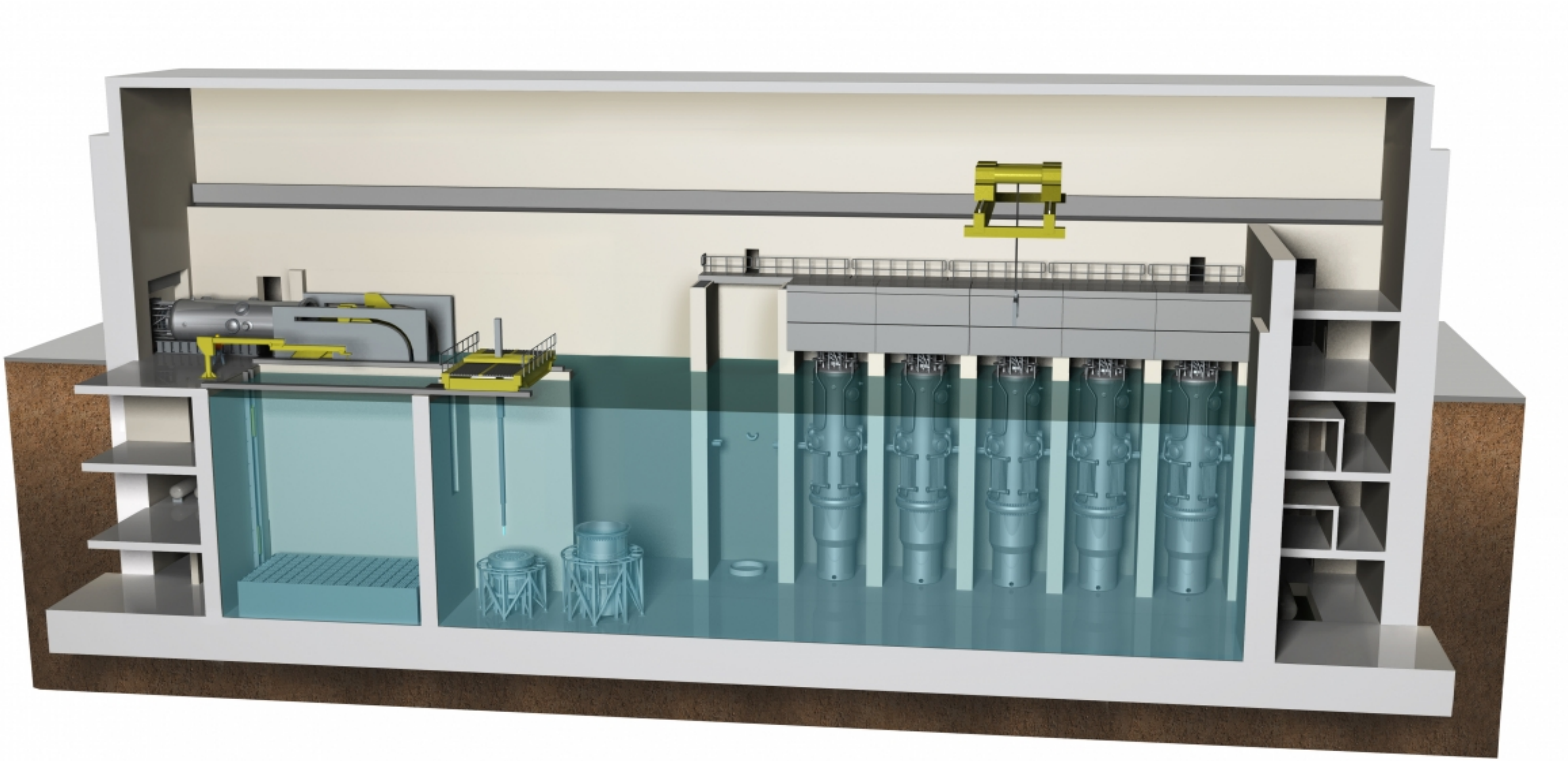
Enhanced Safety –
Rely on passive safety designs that don't require operator intervention in the event of an accident.

Versatile –
Supports intermittent power sources and can provide heat energy for non-electric applications.

Waste Management –
Greatly reduce the amount of spent fuel requiring disposal. Some technologies can even re-use spent fuel.

Affordable –
Use advanced manufacturing to reduce capital cost.

Proposed Versatile Test Reactor (VTR)



Small Modular Reactor Technologies (SMRs)

The Department has long recognized the transformational value that advanced SMRs can provide to the Nation's economic, energy security, and environmental outlook.

Accordingly, the Department has provided substantial support to the development of light water-cooled SMRs, which are under licensing review by the Nuclear Regulatory Commission (NRC) and will likely be deployed in the next 10-15 years. The Department is also interested in the development of **SMRs that use non-traditional coolants such as liquid metals, salts, and helium because of the safety, operational, and economic benefits they offer.**

https://www.energy.gov/sites/prod/files/2018/01/f47/Small%20Modular%20Reactors%20-%20Adding%20to%20Resilience%20at%20Federal%20Facilities%20.pdf

Small Modular Reactor Technologies

Small modular reactors can also be made in factories and transported to sites where they would be ready to “plug and play” upon arrival, reducing both capital costs and construction times. The smaller size also makes these reactors ideal for small electric grids and for locations that cannot support large reactors, offering utilities the flexibility to scale production as demand changes.

Light Water Reactor Technologies

https://www.energy.gov/ne/listings/light-water-reactor-sustainability-technical-documents

Purpose for most DOE R&&D:

Extending the operating lifetimes of current plants beyond 60 years and, where possible, making further improvements in their productivity will generate early benefits from research, development, and demonstration investments in nuclear power. Note that the existing U.S. nuclear fleet has a remarkable safety and performance record.

Light Water Reactor Sustainability (LWRS)

Program Objectives

For the LWRS Program, sustainability is defined as the ability to maintain safe and economic\operation of the existing fleet of nuclear power plants for a longer-than-initially-licensed lifetime.

(1) Manage the aging of plant systems, structures, and components so that nuclear power plant lifetimes can be extended and the plants can continue to operate safely, efficiently, reliably and economically.

(2) Exceed the performance of the current labor-intensive business model

(3) Minimize risks of nuclear proliferation and terrorism.

(4) Develop sustainable nuclear fuel cycles

The Department of Energy's role in Objective (1) is to partner with industry and the NRC to provide support for timely component replacement strategies and to develop improvements in the affordability of new reactors

Advanced Reactor Technologies

Versatile Test Reactor (VTR)

In February 2019, the U.S. Department of Energy announced its plans to build a Versatile Test Reactor, or VTR. This new research reactor will be capable of performing irradiation testing at much higher neutron energy fluxes than what is currently available today.

Space Power Systems

For over 50 years the DOE and its predecessor agencies have been deeply involved in space research and exploration. Currently, the Office of Space and Defense Power Systems supplies Radioisotope Power Systems (RPS) to the National Aeronautics and Space Administration (NASA) and national security applications for missions that are beyond the capabilities of fuel cells, solar power and battery power supplies.

CHALLENGES AND INITIATIVES

1.0 Stockpiles of <u>used nuclear fuel</u> (UNF) and high-level waste (HLW)

2.O Enhancing accident tolerance of the existing reactor fleet (re; March 2011 events at the Fukushima Daiichi nuclear power plant

3.0 Establishment of the Fuel Cycle Technologies (FCT) program; Managing Research & Development

- **Five R&D campaigns**
  - **Fuel Cycle Options**
  - **Advanced Fuels**
  - **Separations and Waste Forms**
  - **Used Fuel Disposition**
  - **Material Protection, Control, and Accountability Technologies**
- **ESTABLISHING OBJECTIVES**
  - **Advanced Modeling & Simulation**
  - **Develop and apply M&S tools focused on Light Water Reactor (LWR) technologies for an improved understanding of important operational and safety issues in existing reactors. To enable industry to address reactor performance issues relative to safe operations and maintenance.**

Consortium for Advanced Simulation of Light Water Reactors

(CASL)

Demonstrate on new VERA Boiling Water Reactor (BWR) Neutronics Capability

(VERA) = Virtual Environment for Reactor Analysis

VERA nuclear reactor **simulation software** licensed--3/24/2020 to Electric Power Research Institute (EPRI)

- Objective of work is to implement and demonstrate modeling capability for BWR Control Cell
- Stretch goals of capability for 2-D, Full Core, BWR Core and 3-D single assembly modeling demonsreated

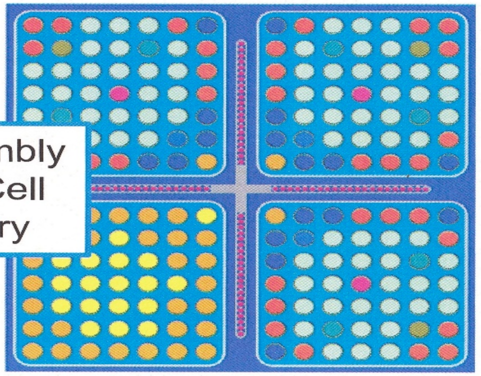
PDF for more DOE Tech Info:
https://www.casl.gov/sites/default/files/docs/CASL-U-2015-0278-000.pdf

Brief summary on CASL on next slide

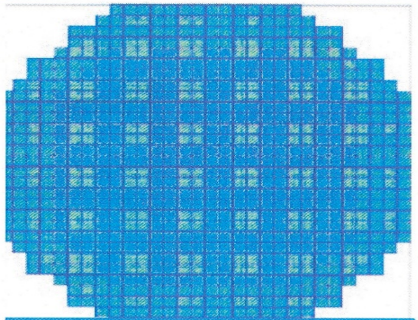
Demonstrate on new VERA Boiling Water Reactor (BWR) Neutronics Capability

- Objective of work is to implement and demonstrate modeling capability for BWR Control Cell
- Stretch goals of capability for 2-D, Full Core BWR core and 3-D single assembly modeling demonstrated

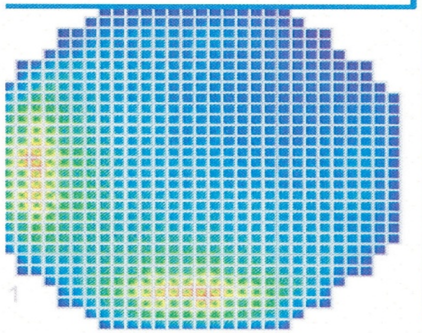
Science Highlight

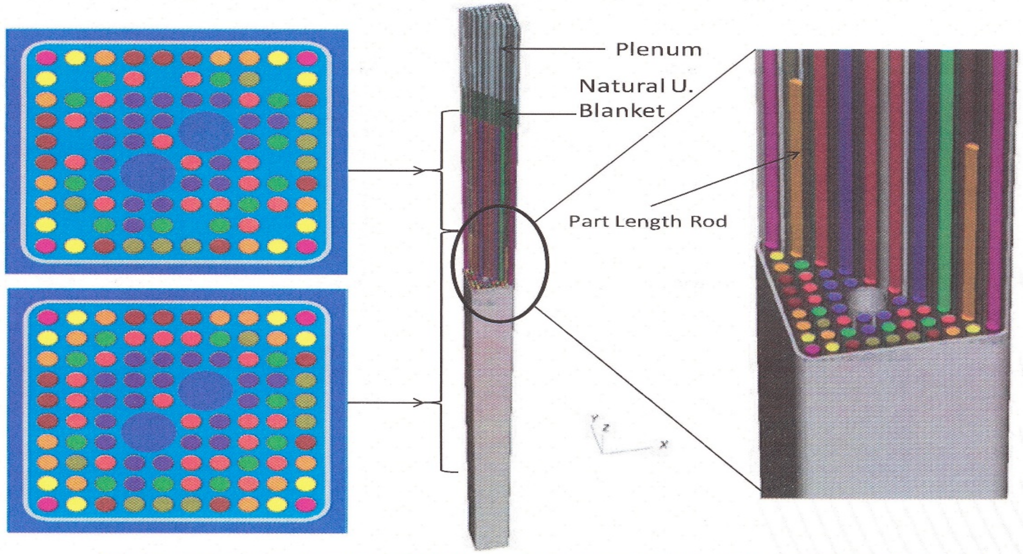


2x2 Assembly Control Cell Geometry

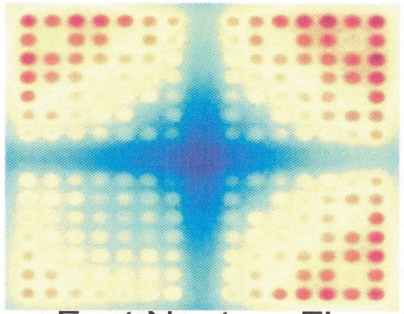


2-D Core Demonstration

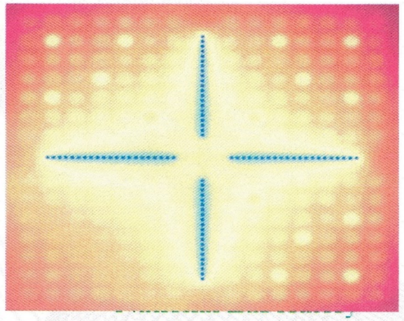




3-D Assembly Model Demonstration



Fast Neutron Flux



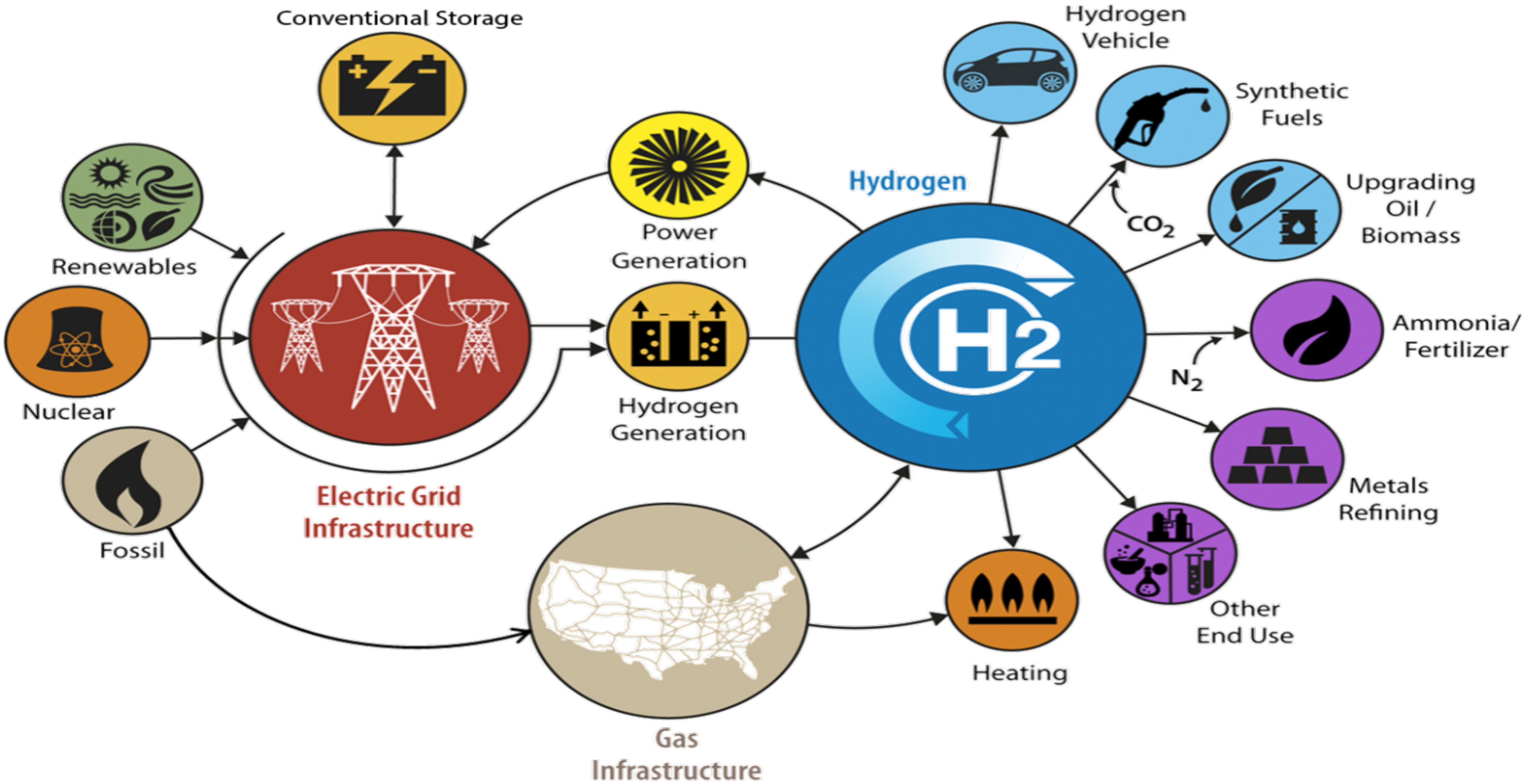
Thermal Neutron Flux

WHAT IS THE PROBLEM?

The U.S. lacks a scientific facility to provide fast neutron testing, required for rapid and accurate new material and nuclear fuel research and development.
Many U.S. companies are working on technologies to make the next generation of reactors and the existing reactors more economically competitive and reliable.
New reactors and support of existing reactors require continuing research and development of new materials and nuclear fuels.
The next few slides illustrate significant DOE progress.

HYDROGEN GENERATION

Utilize nuclear's thermal heat and electricity to produce hydrogen



First U.S. Small Modular Boiling Water Reactor Under Development

- New SMR design, GE Hitachi (GEH) is looking to reduce plant size by 90% compared to traditional large-scale boiling water reactors to significantly reduce construction costs.
- Compact SMR design is a 300-megawatt electric light water reactor based on Nuclear Power 2010 program
- Produces steam inside the reactor pressure vessel to greatly reduce the complexity and size of the plant.

  Key benefits include:

  Passive safety cooling
  Simplified design
  Reduced footprint
  Established supply chain
  Factory-built system
  Flexible baseload/load following.
- Allows the reactor to maintain optimal reactor pressure and temperatures for 7 days without power or operator intervention during off-normal events.

Modeling and Simulation

Advancements in engineering, computing power and visualization capabilities, new modeling and simulation tools are enabling scientists from all disciplines to gain insights into physical systems in ways not possible with traditional approaches alone.

Energy Innovation Hub for Modeling & Simulation (Hub); and the Nuclear Energy Advanced Modeling & Simulation (NEAMS) program.

5 Things You Should Know About Accident Tolerant Fuels

1. Accident tolerant fuels beat the heat and perform better

Withstand extreme heat and steam for longer than the current fuel system of uranium dioxide fuel and zircaloy cladding.

2. Accident tolerant fuels last longer

Could potentially use roughly 30% less fuel

3. Accident Tolerant fuels improve plant performance

Could possibly run with less downtime—leading to higher profit

4. Accident tolerant fuels are industry-led

Three US Companies, DOE, and the National Labs are currently testing

5. Accident tolerant fuels could debut by 2025