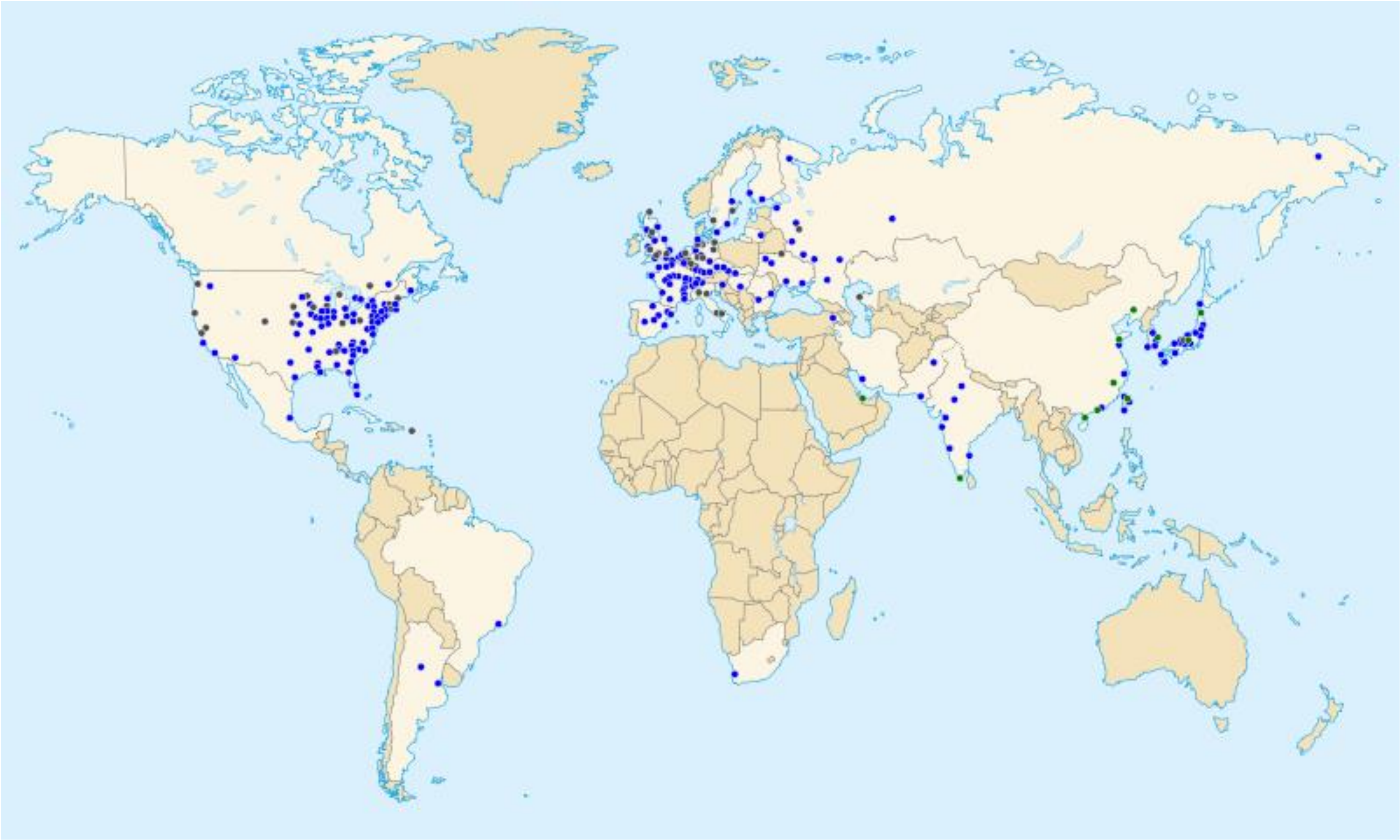
Status of Advanced Nuclear Systems

David Blessing

Reactors Around the World



Why Nuclear?

- Building nuclear reactors generates very little CO_2. Operating them generates essentially none.
- There are ample supplies of coal, oil, and natural gas to meet our energy needs for years to come.
- If it weren’t for climate change, we could let the market determine where and how much nuclear power to deploy. But climate change requires we stop burning fossil fuels.
- About 40 million kilowatt-hours of electricity are produced from one ton of natural uranium. Producing this much electrical power from fossil fuels would require burning over 20,000 tons of coal or 290 million cubic feet of gas.

General Fission Reactor Characteristics

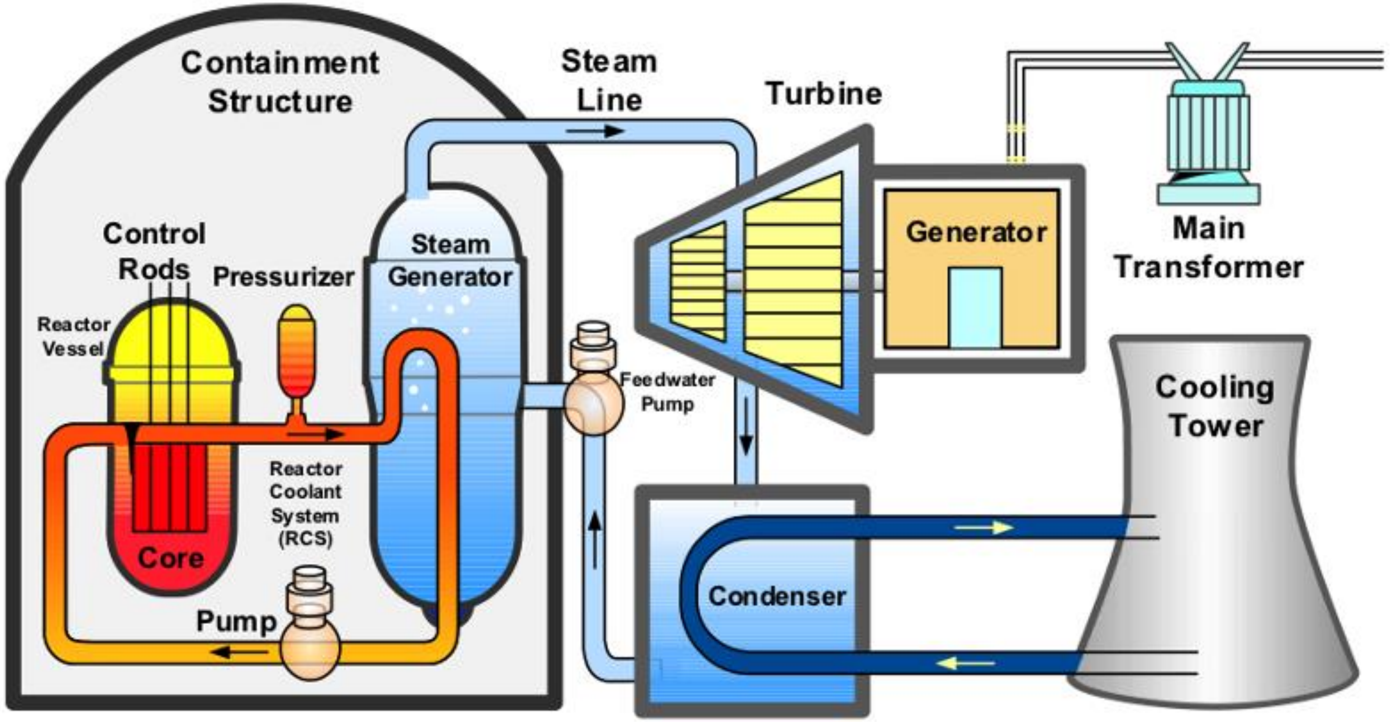
- Fissionable material either in solid fuel elements or dissolved in the coolant
- Devices to control fissioning rate
- Reactor control system
- Circulating primary coolant to carry fuel heat out of the reactor; either liquid or gas
- Some means to carry away after-shutdown heat
- Energy conversion cycle typically a steam plant with turbines, condensers, heat rejection system
- Containment vessel to prevent spread of fission products from reactor accident
- Support systems to maintain pressures, coolant chemistry, and support refueling and maintenance/repair

Existing Reactor Technology

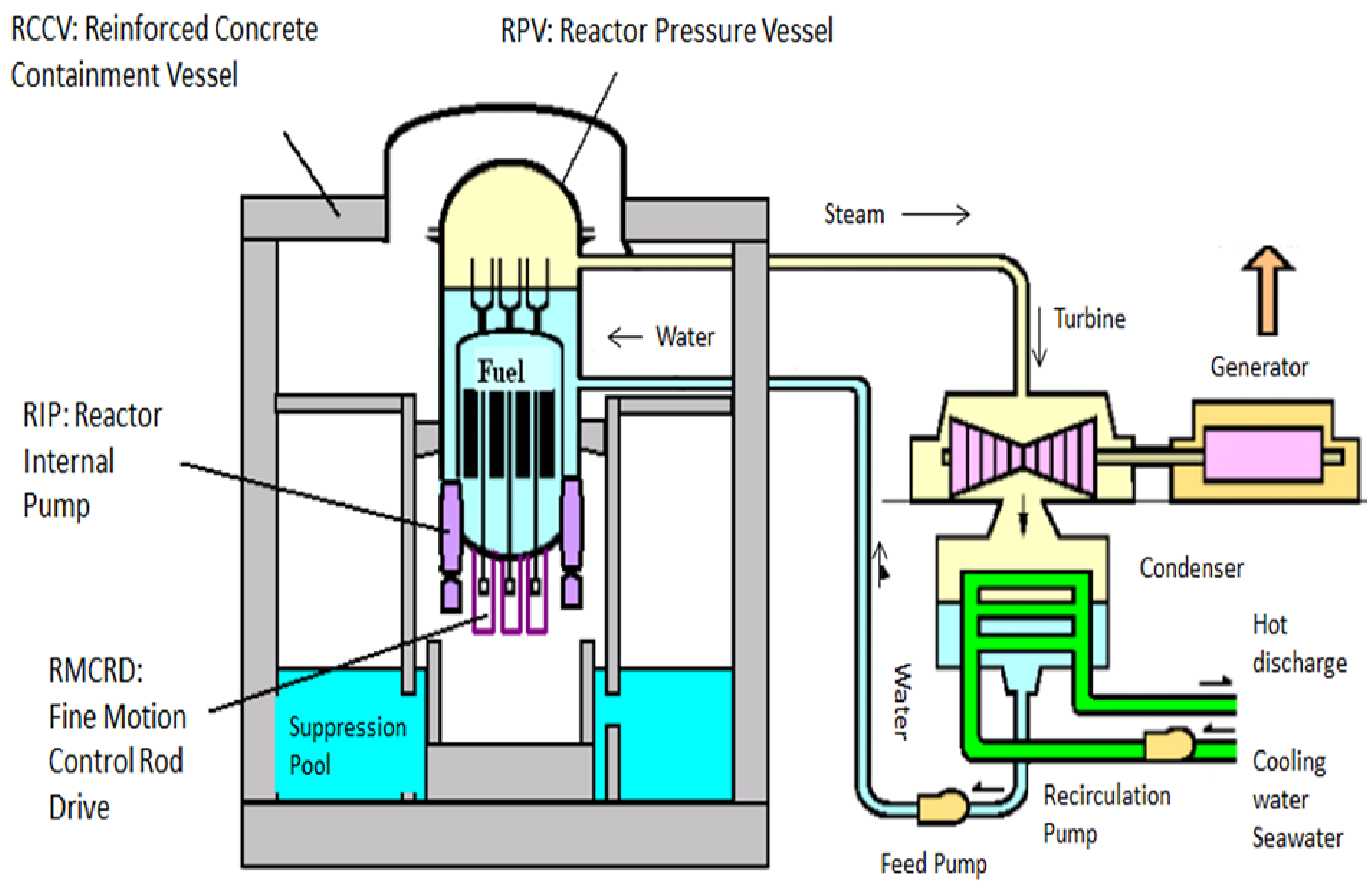
- Nearly all water cooled and moderated
- Either
  - pressurized water (PWR) with a steam generator to transfer heat from primary coolant to secondary steam
  - or direct to steam turbine (BWR)
- Fuel lightly enriched uranium in oxide pellets encased in zirconium alloy tubes bundled together.
- Fission products contained within fuel tubes. Primary coolant pressure boundary and containment provide two more barriers to release of fission products.
- Reactor refueled every second year or so
- Used fuel stored on site in U.S. Some reprocessing in other countries.
- PWRs in U.S. based on U.S. Naval experience
- PWR is right reactor type for submarines; not necessarily for commercial applications.
- Nuclear requires infrastructure support to build, operate, and maintain

PWR

4. Nuclear reactor power plant



BWR


RCCV: Reinforced Concrete Containment Vessel
RPV: Reactor Pressure Vessel
Steam
Turbine
Generator
Water
Fuel
RIP: Reactor Internal Pump
Condenser
Hot discharge
Water
RMCRD: Fine Motion Control Rod Drive
Suppression Pool
Cooling water Seawater
Recirculation Pump
Feed Pump

Nuclear Anxiety

ISSUE	REALITY
Fear of radiation	Small harm from small amounts of radiation. Large doses can be lethal.
Worry about tie to nuclear weapons	The technologies are distinct and one does not lead to the other.
Worry about safety and reactor accidents	• Chernobyl worst case; we don't have any of those reactors and never did • Three Mile Island; poor design and even worse operator actions; containment held • Fukushima; started with major tsunami and sustained loss of electric power. Japanese government reaction excessive and harmful. No radiation-related deaths or acute effects have been observed among nearly 25,000 workers • New nuclear designs feature **passive safety;** huge step forward; no electric power or operator action needed for long-term cooling

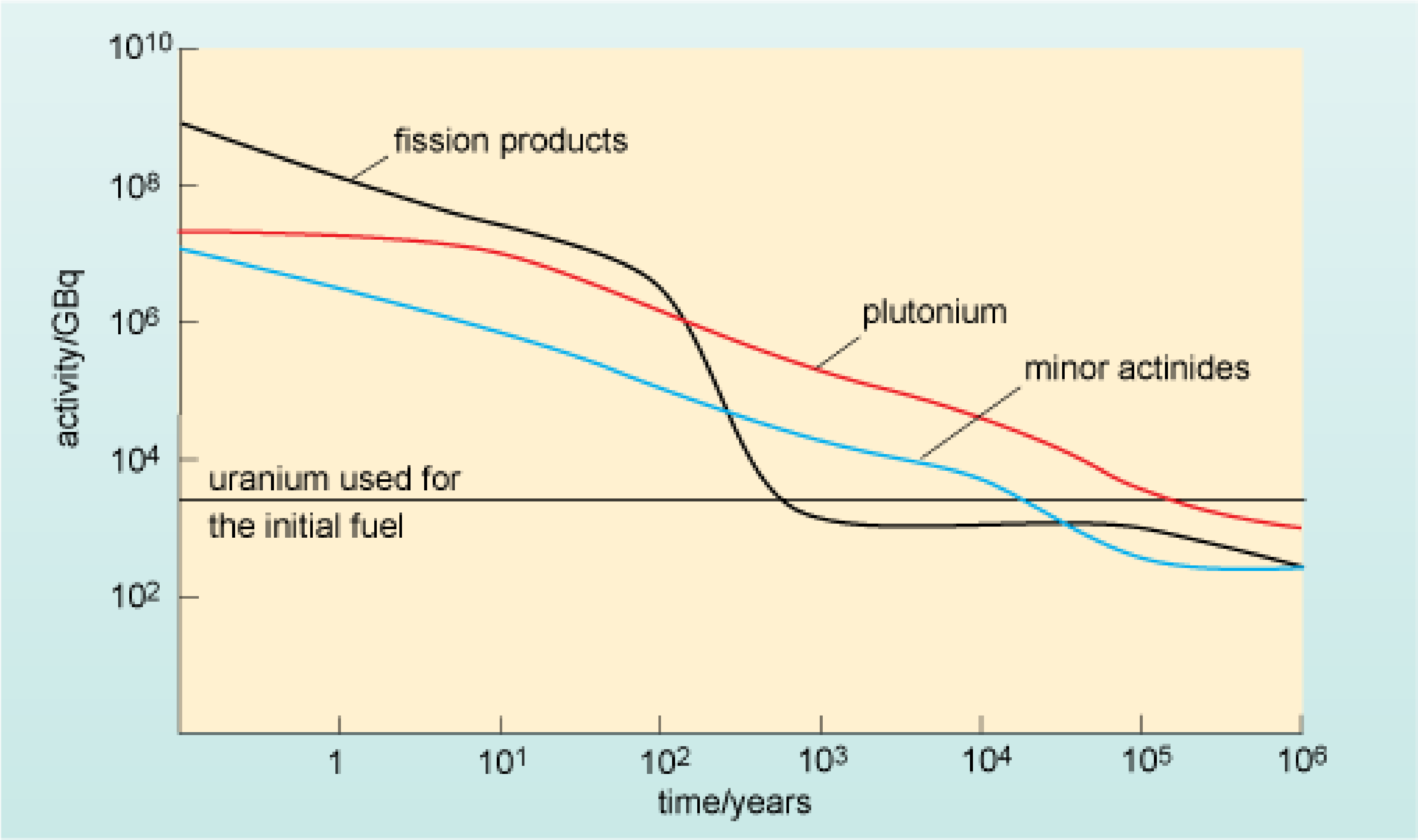
Other Forces

- Anti-nuclear people have an agenda
  - Push for features to add cost with excuse of “safety”; prevent new reactors
  - Disagree with abundant electric power in principle (e.g. RMI)
  - Exaggerate risks and denigrate nuclear advocates
- Renewable businesses want to grow: new reactors seen to compete with them
- Concern that building new nuclear takes too long and will be too costly. However, new designs can be built more quickly and more cheaply than older designs. Especially true of Small Modular Reactors

Issues with Used Nuclear Fuel

- Fission produces wide range of elements with wide range of chemical properties. A few are gases.
- Some fission product isotopes are radioactive.
- Those with short half lives produce intense radioactivity but die away quickly. Storing used fuel for a few years reduces these dramatically.
- Transuranics (heavier than U) come from neutron capture in U. Some of these, especially Pu isotopes, have very long half lives and are radiotoxic.
- Design of Yucca Mountain repository dominated by longest-lived radioisotopes.
- All of the used fuel from all US reactors to date, if piled on a football field, would reach less than 25 feet tall. And all of it is contained and monitored now
- Reprocessing used fuel and burning transuranics in a fast reactor reduces high level wastes by a factor of 20. Shorter-lived fission products can be stored outside a long-term repository.
- **The issue is political not technical**

Used Fuel Radiation Lifetime



Paper Reactors

An **academic reactor or reactor plant** almost always has the following basic characteristics: (1) It is simple. (2) It is small. (3) It is cheap. (4) It is light. (5) It can be built very quickly. (6) It is very flexible in purpose ("omnibus reactor"). (7) Very little development is required. It will use mostly "off-the-shelf" components. (8) The reactor is in the study phases. It is not being built now.

On the other hand, a **practical reactor plant** can be distinguished by the following characteristics: (1) It is being built now. (2) It is behind schedule. (3) It is requiring an immense amount of development on apparently trivial items. Corrosion, in particular, is a problem. (4) It is very expensive. (5) It takes a long time to build because of the engineering development problems. (6) It is large. (7) It is heavy. (8) It is complicated.

H. G. Rickover

Small Modular Reactors

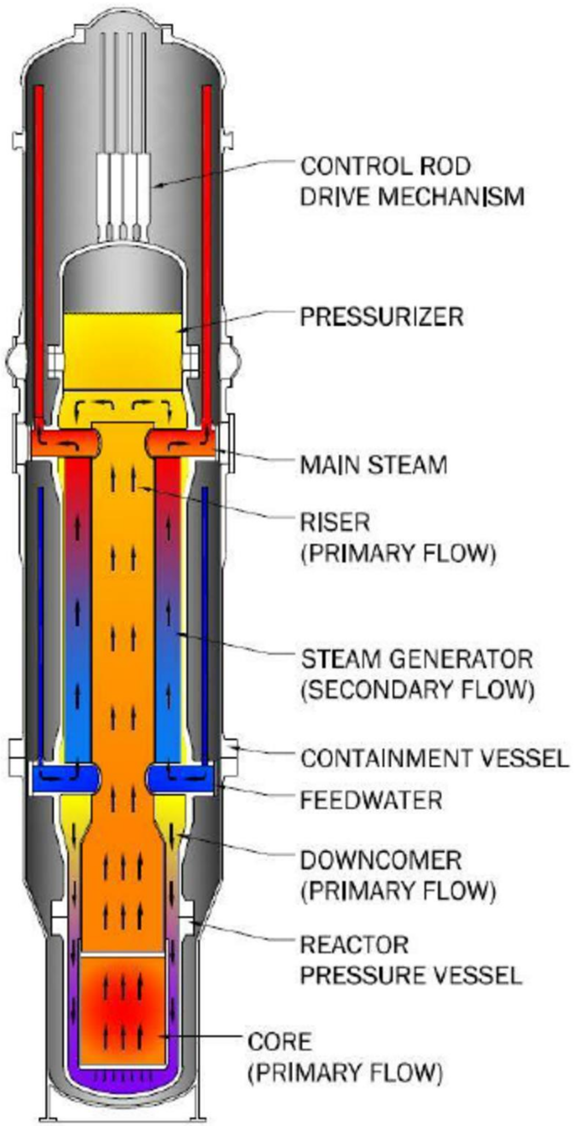
- Much less than 1000 MWe
- Focus on reducing capital costs and time to deploy by simplification, factory production and deploying as power needs increase.
- Passive safety; after-shutdown decay heat removal uses natural forces; no dependence on operator action or electric power
- Biggest challenge is economic; no economy of scale
- Reduces dependence on major power grid
- NUSCALE and GE BWR designs based on light water technology and are readily licensed
- Advanced reactors use different coolants and core materials. Licensing them will be more challenging

Advanced Reactors

- Most reactors being built now are large PWRs or BWRs
- Advanced reactors use other coolants; liquid metal, molten salt or helium.
- Strong focus on:
  - Passive safety—no operator action or electric power required for long term cooling
  - Minimum capital cost—Simplification, factory fabrication, faster build
  - Some also aim to close fuel cycle; burn waste or even breed new fuel
- DOE funding some development
- Dozens of reactor design startups. Most are conceptual designs; billions of dollars of engineering work required to reach start of construction. About 28 have gotten substantial design done
- Various fuel forms; some aid reprocessing, others focus on robustness
- Strong interest and development work in China, Russia, Japan
- First SMR in Russia; floating on barge; supplies electric power and heat for desalination

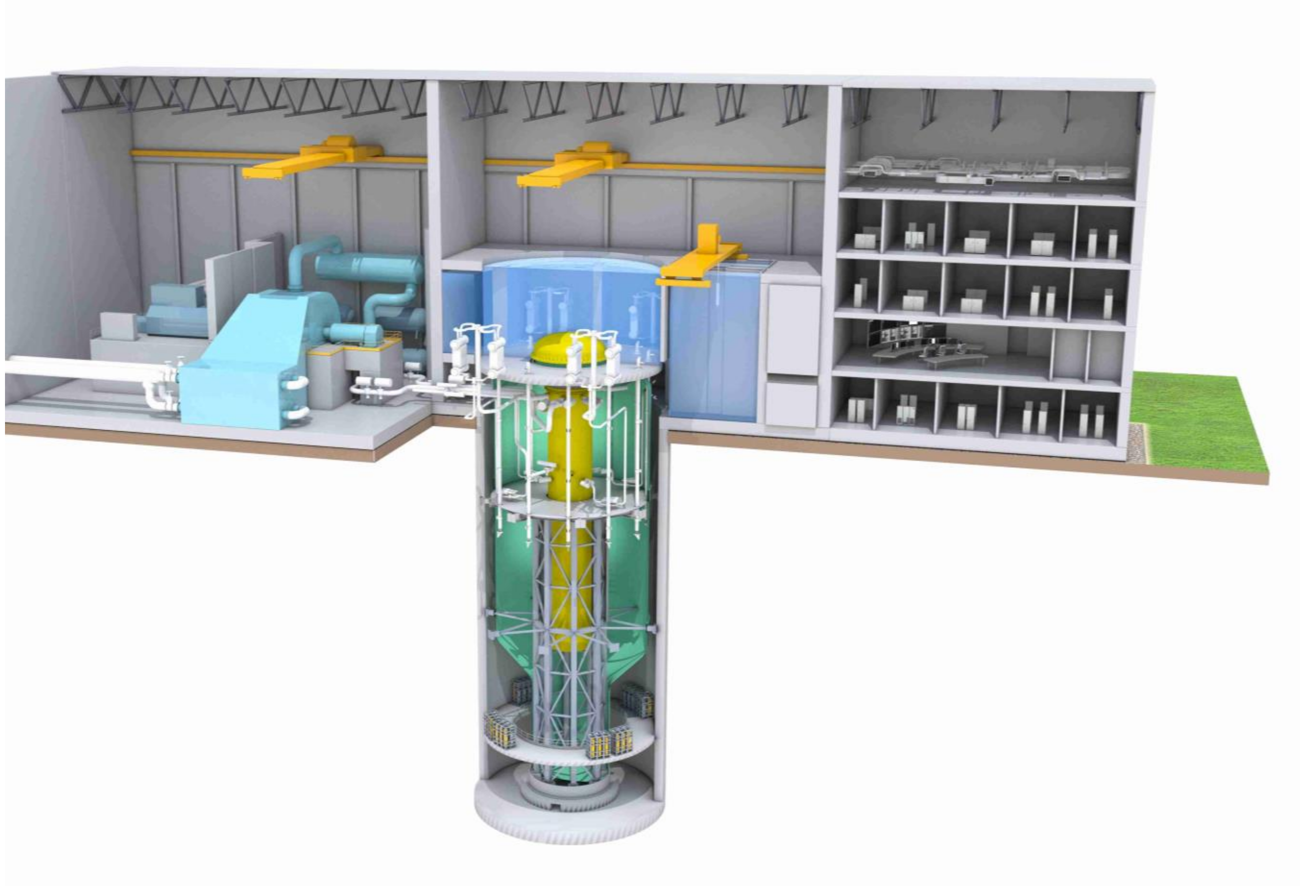
NUSCALE

- 200 MWth (60 MWe) PWR Modules
- Conventional UO_2 fuel
- Each module has core, two steam generators and a pressurizer.
- Modules fabricated in a factory
- Up to 12 modules in a below-grade water pool
- Decay heat removal by heat transfer to water pool
- Module removed from pool and disassembled to refuel
- NRC approved design (9/2020)
- License application in 2023
- First installation at Idaho National Laboratory; first module startup planned for 2030
- Collaborating with utilities in Canada, Europe, Middle East, Asia
- Capital cost about $3,500 per KWe; 36 months construction time



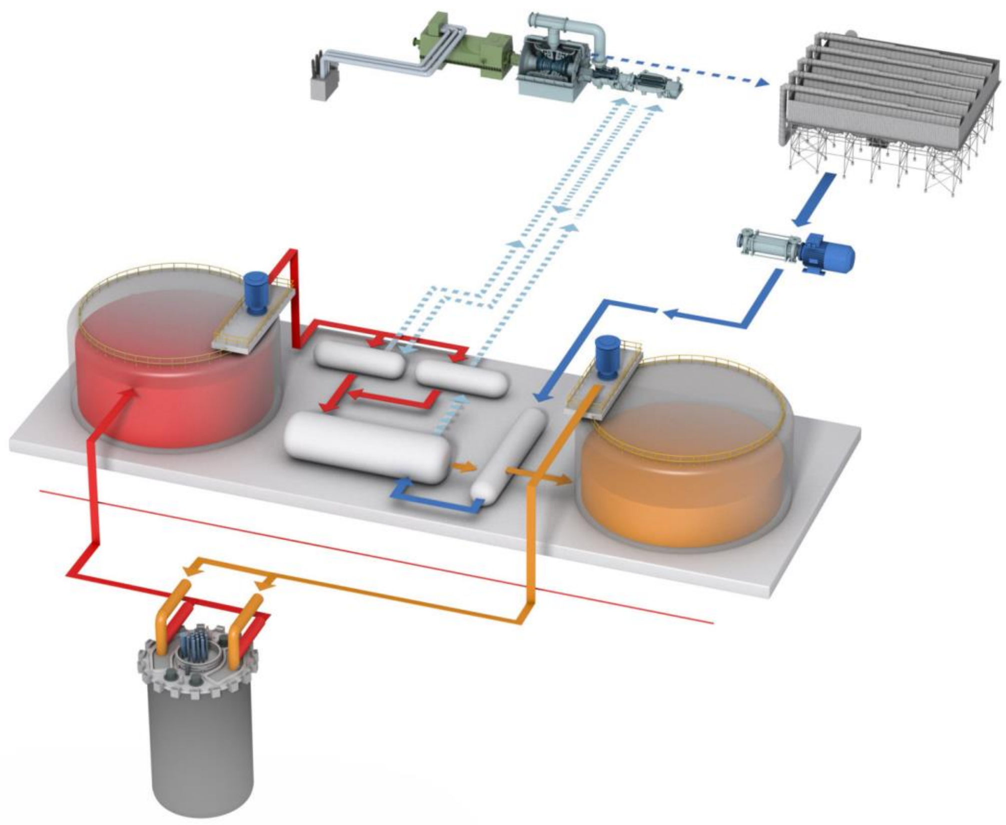
GE-H BWRX-300

- 300 MWe BWR
- Focus is on passive safety and reduced capital cost
- Reactor below grade
- Decay heat removal to pool of water on top with natural circulation of water coolant
- Conventional $U0_2$ fuel
- Based on NRC-certified ESWBR
- NRC approved first licensing report 12/2020
- Capital cost about $2,250 per KWe for nth of a kind
- GE collaborating with utilities in Europe and Canada



NATRIUM

- Terrapower/GE-H/Bechtel partnership
- Sodium cooled fast reactor located below grade
- Passively safe
- 345 MWe
- Metallic fuel; uranium zirconium alloy
- Design to cost
- Molten salt and steam systems not reactor grade
- $80M grant from DOE to develop
- Intermediate loop is molten salt for energy storage.
- Steam generator coupled to molten salt to provide steam to steam turbines
- Stored heat in molten salt couples to concentrating solar or wind turbines

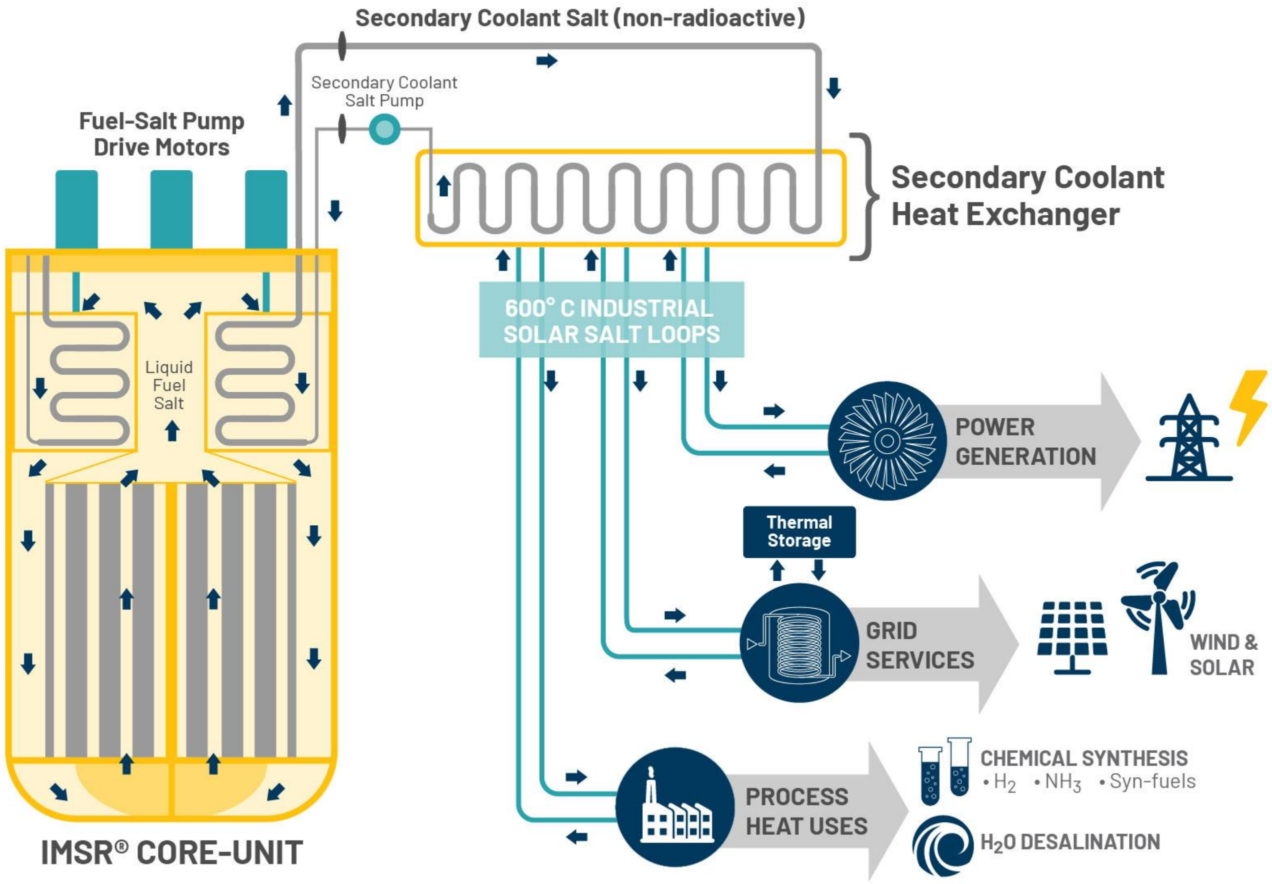


Molten Salt Reactors

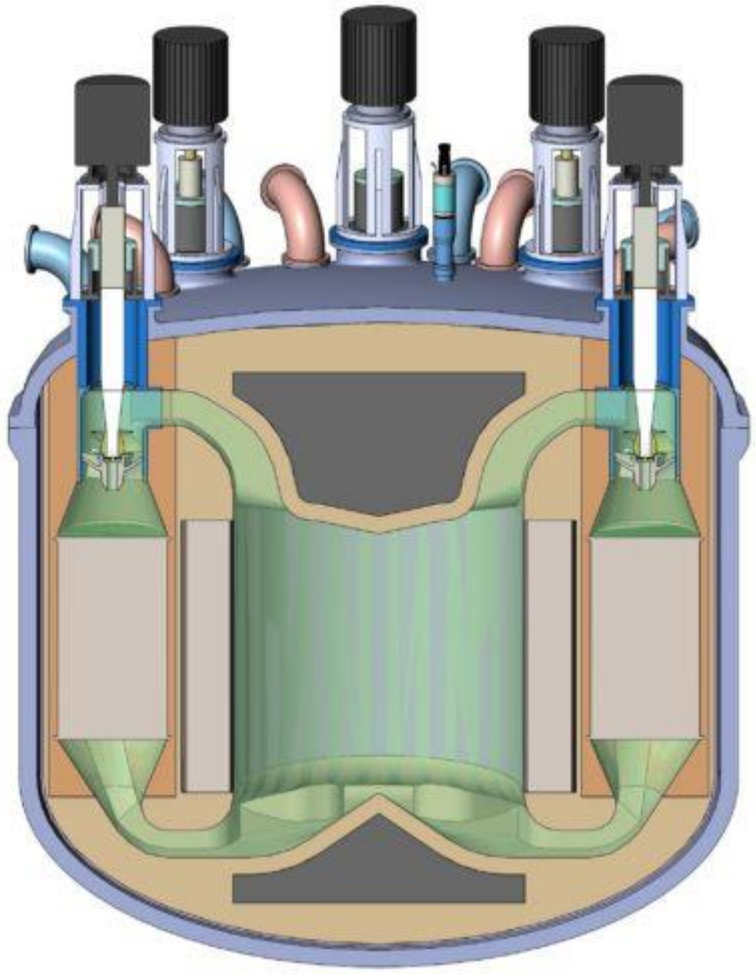
- First developed at ORNL (Molten Salt Reactor Experiment; 1957-1976)
- Molten fluoride or chloride salt is coolant
- U or Th fuel
- Salt has high melting point (reactor has to be really hot)-aids power generation and/or process heat
- Near zero operating pressure
- Can either have fuel elements cooled by salt or have fuel dissolved in salt.
- Kairos Power uses pebble bed fuel continuously added and removed from core.
- Terrestrial Energy and Terrapower have fuel dissolved in salt. Requires complex auxiliary systems to manage fission products and add fuel
- Can be a breeder or burner

Terrestrial Energy MSR

- Graphite provides neutron moderation
- Core unit with graphite replaceable.
- Passively safe
- 195 Mwe
- Low enriched U fuel



TerraPower Molten Chloride Salt Fast Reactor

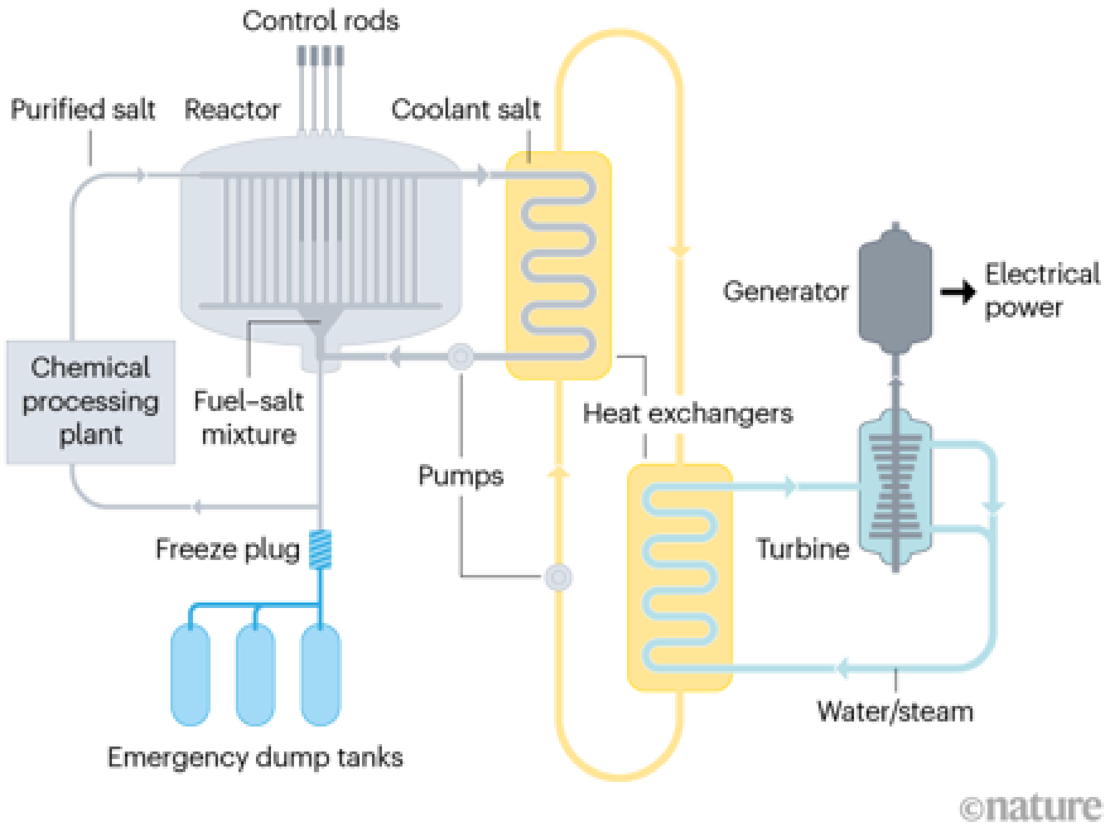


- Conceptual Design
- Design development jointly funded by DOE, Southern Company and TerraPower
- Uranium fuel dissolved in chloride salt
- Continuous fueling
- Test of a non-nuclear molten salt loop this year.

Nuclear Development in China

- #3 in number of reactors now behind US and France
- Variety of PWRs from France, U.S. and Russia as well as indigenous designs
- 18 new large PWRs under construction.
- Building a very high temperature gas cooled reactor
- 125 MWe small modular PWR design being built; expected completion of two units in 2026
- 200 Mwe small gas cooled reactor with pebble bed fuel now operating and second unit being tested.
- 600 MWe sodium cooled fast reactor prototype under construction
- Prototype molten salt reactor with dissolved thorium fuel being tested now.

Chinese Molten Salt Thorium Reactor



- The uranium/thorium fuel is dissolved in a fluoride salt.
- The mixture goes critical in the reactor vessel and not in the rest of the system.
- There is much mischief in the box labeled “Chemical processing plant”!
- Prototype in test phase now.

- BWXT **concept** for very small portable reactor
  - Gas cooled
  - 50 MWth
  - Uranium nitride fuel in TRISO balls. INL and ORNL developing fuel
  - DOE funding $85 M over 7 years
- Westinghouse **concept** for transportable reactor
  - Solid core; heat pipe cooled
  - Multiple year life
  - Up to 50 Mwe
  - Setup on site in 30 days
- Oklo Aurora
  - 1.5 MWe
  - Metallic fuel; uranium zirconium alloy surrounding heat pipes
  - Heat pipes carry heat to supercritical CO_2 gas turbine system
  - NRC denied application for combined build and operating license due to insufficient analysis, especially accidents

Conclusions on Fission Reactors

- All new reactor designs focus on minimizing cost and maximizing passive safety
- SMRs in near term likely based on existing light water reactor technology
- Lots of activity in US and rest of world, especially China
- Lots of new developments, especially China, Russia
- DOE funding R&D
- Regulatory path for light water reactors straightforward
- NRC has new licensing rules for advanced reactors
- Used fuel from light water reactors can be stored for now
- Advanced reactors capable of burning used fuel—dramatic reduction in long-term storage
- For all reactors, high capital costs and long time to construct require government support beyond what investors or utilities can manage.

What About Fusion?

- Nuclear fission derives energy from splitting heavy nuclei.
- Nuclear fusion derives energy from fusing light nuclei.
- Fusion occurs in stars at very high pressures and temperatures.
- Achieving those conditions on earth stably and for long periods is very hard.
- There are more than 40 private fusion companies globally, which have raised over $2.5 billion in investments to date, according to a report from the U.K. government.

Advantages of Fusion Systems

- No fission products.
- Fusion reactors become radioactive but there are relatively small amounts of material to dispose of and the half-lives are relatively short. Designers can choose materials that get activated.
- Fuel is plentiful (hydrogen, deuterium)
- There is no chance of a runaway power excursion that I can see.

Challenges with Fusion Systems

- Achieving fusion conditions takes a lot of power and there are all sorts of instabilities in the plasma that carry away energy. It is hard.
- The old saying goes that "fusion is 20 years off – and always will be."
- Most viable fusion systems fuse deuterium (which is a rare isotope of hydrogen that is naturally occurring) and tritium (a heavy isotope of hydrogen that must be produced).
  - D + T $\longrightarrow$ He + n; the energy is carried away by the hot helium and fast neutrons
  - Neutron damage to fusion reactor structures requires periodic replacement.
  - System must also generate tritium for fuel.

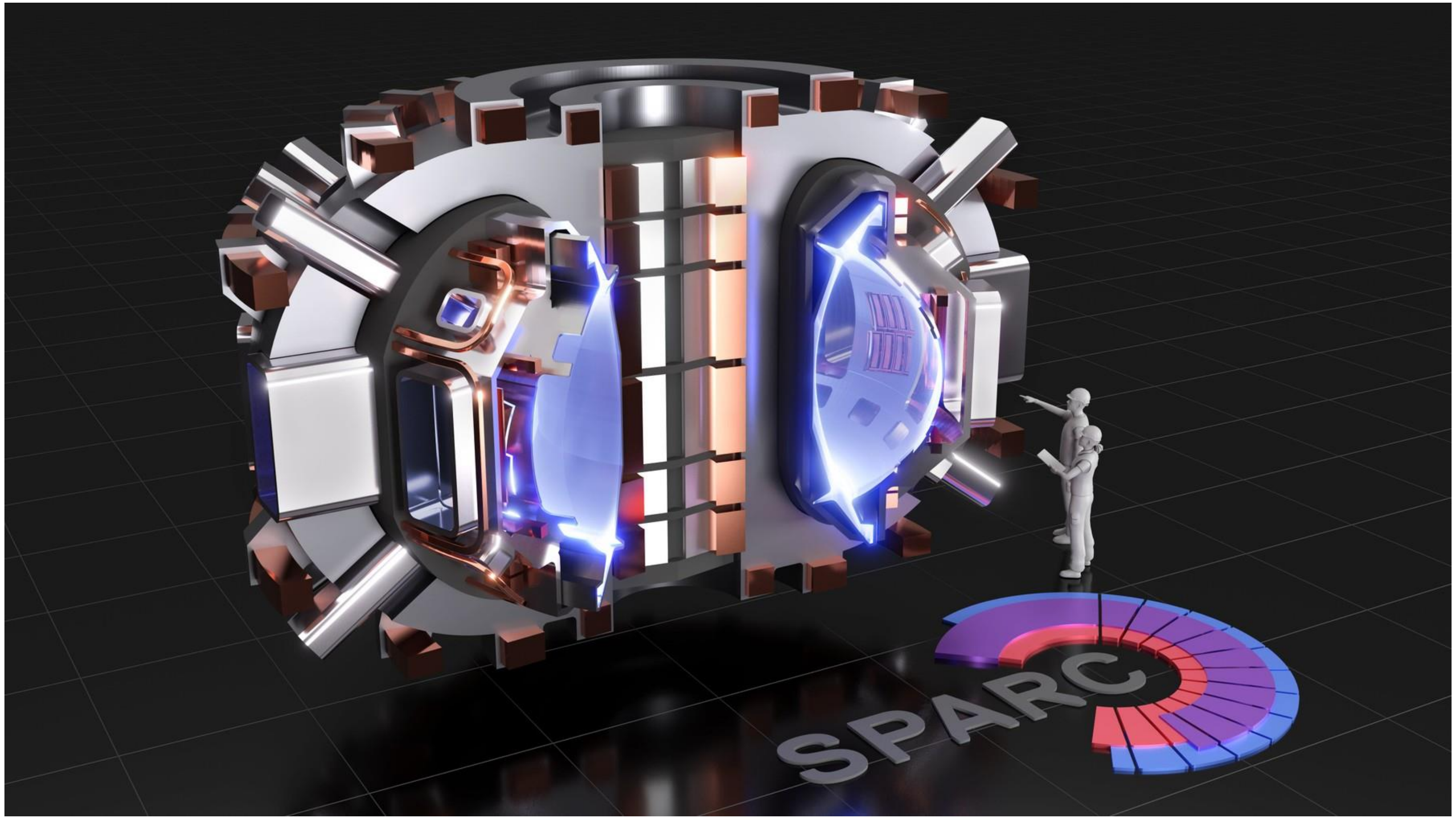
Types of Fusion Reactors

- Tokomaks; toroidal chamber containing hot plasma and surrounded by powerful magnets. Examples:
  - ITER (international collaboration in France)—under construction
  - SPARC (Commonwealth Energy in U.S.)—under construction
  - EAST (Experimental Advanced Superconducting Tokamak in China)--testing
- Inertial Confinement; lasers from multiple directions heat frozen D-T pellets encapsulated in diamond spheres
  - Lawrence Livermore National Lab

More on SPARC

- $1.8 billion in private investments
- SPARC is an R&D test reactor
  - Uses advanced superconducting magnets to achieve 20 T field strength—enables much smaller device. That is 400,000 times earth's magnetic field strength.
  - Designed to enable replacing inner wall
  - If it works, it will produce 10x's as much heat as the power it takes to run it for 10 seconds.
  - Will start up 2025
- Next version will be full scale and will have:
  - Molten salt (FLiBe) blanket just inside inner wall
    - Reduces neutron fluence to wall
    - Absorbs heat to go to power conversion system
    - Generates tritium to fuel the system
  - Power generation system (turbines and generators)

SPARC



Conclusions on Fusion

- Fusion power offers major advantages over fission reactors.
- Lots of R&D activity privately funded.
- Fusion reactions have been demonstrated but reactions not sustained and haven’t produced net useful energy. High temperatures in plasmas achieved for tens of seconds.
- By the end of this decade fusion test reactors will be operating.
- Much engineering still required to develop a complete system.
- Strong push to get actual prototypes operating.