Accelerator Driven Subcritical Reactors

Introducing GEM*STAR – A Particularly Advantageous Example

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Technology to revitalize the nuclear power industry through improved safety, waste management, efficiency, and proliferation resistance.
Outline

• “Nuclear Reactors 101” – how they work
• Subcritical operation – avoids many problems
• Why now? – answers to historical objections to ADSR
• GEM*STAR – specific example of ADSR
  – Passive safety
  – Burns all nuclear waste streams, including its own
  – Extracts most of the 94% energy left in spent nuclear fuel
  – Needs no isotope enrichment or reprocessing
• Summary
Each fission yields:
- 2-3 fragments
- 2-3 neutrons
- 1-3 gammas
- Energy released ~ 200 MeV

Some neutrons are lost, some are absorbed.

Many fragments are radioactive – that is important.

http://www.scienceclarified.com
Nuclear Reactors 101
Criticality Factor

• A key parameter of a nuclear reactor is the criticality factor:

\[ k = \frac{\text{(# neutrons that induce new fissions)}}{\text{( # fissions that created them)}} \]

• \( k \) depends on the fuel mixture, the geometry, and the probability of a neutron inducing fission vs. being absorbed.

• If \( k > 1 \) the reaction grows without bound until something stops it (typically the system exploding violently). **Bomb**.

• If \( k < 1 \) the reaction stops, typically in less than 1 second. **Subcritical reactor**.

• All current reactors operate with \( k = 1 \), maintained within about 1 part per million. **Critical reactor**.
Nuclear Reactors 101
Neutron Moderation

- The neutrons emitted from a fission are fast neutrons with kinetic energies of 1-10 MeV.
- In a typical reactor fuel mixture, fast neutrons are more likely to be absorbed than to induce fission.
- That makes $k=1$ difficult to achieve with fast neutrons.
- A moderator is used to slow the neutrons down to become thermal neutrons ($< 1$ eV), via elastic collisions.
- Thermal neutrons are much more likely to induce fission.
- Moderators have low A and low neutron absorption.
- Typical moderators: water, heavy water, and graphite.
- The geometry is important.
Nuclear Reactors 101
Delayed Neutrons – Needed for Control

- Neutron-induced fission occurs within femtoseconds; neutron moderation and transport takes microseconds.
- That is too fast to be able to control the reaction.
- Fortunately many fission products are radioactive, and some of them emit neutrons with a delay from milliseconds to minutes—typically 0.6–0.8% of the neutron flux.
- The reactor operating point is set to be subcritical for the fission neutrons alone, but critical when the delayed neutrons are included.
- This is slow enough that control can be maintained.
Nuclear Reactors 101
Cooling and Control

- The reactor must be maintained at $k=1$ to operate.
- *Control rods* are used, which are made of powerful neutron absorbers. With them fully inserted, $k<<1$.
- In operation, the control rods are partially withdrawn to set the operating point (where $k=1$).
- At the operating point, higher temperature will reduce $k$, while cooling down will increase it (combination of thermal expansion and moderation efficiency).
- Thus the reactor will automatically generate enough power to maintain its temperature – if you increase the cooling capacity it will increase power, etc.
- The control rods can be inserted at any time to shut down the reactor.
Nuclear Reactors 101
Fuel Handling

• As a reactor operates, some of the fissionable portion of its fuel is burned, and fission fragments build up in the fuel rods.
• Some fission fragments are powerful neutron absorbers.
• So the control rods must be gradually withdrawn to maintain the operating point.
• Typically every 12-18 months, \(\frac{1}{4}-\frac{1}{3}\) of the fuel rods are replaced. They still contain \(\sim 94\%\) of their initial energy.
• The spent fuel rods are stored on-site, usually with water cooling to remove the decay heat from their residual radioactivity.
• That radioactivity remains dangerous for \(> 100,000\) years.
Nuclear Reactors 101

Summary

• Nuclear reactors depend on many details of nuclear physics. Fortunately that is now very well known.

• They must operate at k=1.000000 ± 0.000001. Fortunately this is possible.

• They depend on $^{235}\text{U}$, which is difficult to obtain and of limited supply on earth. Isotopic enrichment is required, which makes it intimately connected with concerns about nuclear weapons proliferation.

• There are significant concerns about safety.

• But the big problem is that the U.S. has no viable plan for the handling of nuclear waste.
Subcritical Operation

- Subcritical operation cannot sustain itself, so an external source of neutrons is required.
- The most appropriate source is a proton accelerator generating spallation neutrons:
  - 600-1000 MeV
  - 1-10 MW
- Appropriate k values: 0.97<k<0.99.
- k closer to 1 gives more output power for a given beam power. That power ratio can range up to 200 or so.
- As fission stops when the accelerator is turned off, this can provide significantly improved safety.
- The neutron source permits operation even with large amounts of fission fragments – can burn waste.
Why now?

Answers to Historical Objections to ADSR

• Doubt that a multi-MW accelerator could be built.
• Belief that such an accelerator would be too expensive and inefficient to operate.

   **Superconducting accelerators answer both.**

• Expectation that frequent accelerator trips would cause mechanical fatigue in the reactor fuel rods.

   **Eliminated by using molten salt fuel, and by designing the accelerator for high availability.**

• Doubt that the neutron economy would be viable.

   **Addressed with modern materials and simulations.**
GEM*STAR

- Our long-range goal is to sell intrinsically safe and versatile nuclear reactors to address world energy needs.
- GEM*STAR is an Accelerator-Driven Subcritical Reactor designed to burn nuclear waste, natural uranium, depleted uranium, thorium, and excess weapons-grade plutonium.
- It uses a superconducting accelerator and molten salt fuel to achieve greatly improved safety, address the issues of nuclear waste, and be both economically and politically feasible.
- Note these technologies have already been demonstrated.
- We believe that even in an era of cheap natural gas that GEM*STAR will be economically attractive.
The Molten Salt Reactor Experiment operated at ORNL, 1964-1969. It demonstrated the key aspects of using molten salt fuel. It was a critical reactor tested with several different fuels. They routinely powered it down for weekends, something no conventional reactor could do.
GEM*STAR

Nuclear fuel plus carrier salt
He out (plus volatile f.p.)

2.5 MWb yields:
500 MWt
220 MWe
GEM*STAR
Advantages

• Proven technology put together in a new way.
• The reactor operates at atmospheric pressure.
  – No pressure vessel.
  – Major design simplification, and eliminates many accident scenarios.
• Volatile fission products are continuously removed.
  – Avoids possibility of release (total ~ a million times lower).
• No fuel rods.
  – No Zircaloy that can instigate a hydrogen explosion (Fukishima).
  – No mechanical fatigue from accelerator trips.
• No critical mass is ever present, and cannot form.
• No reprocessing or isotopic enrichment is needed.
  – More proliferation resistant than other technologies.
• Passive response to most accident scenarios: turn off the accelerator – passive air cooling is then sufficient.
GEM*STAR

- One thing it does particularly well is to dispose of excess weapons-grade Plutonium.
  
  34 metric tons of excess weapons-grade plutonium is slated to be destroyed by the 2000 U.S.-Russian Plutonium Management and Disposition Agreement.

- GEM*STAR destroys it more completely than other approaches.

- The Pu is fed continuously into the reactor, and is immediately rendered not weapons-grade (even before burning is complete).
green=neutron, cyan=gamma, brown=graphite, purple=molten-salt fuel. This single 1 GeV proton generated 402,138 tracks (not counting e⁻).
GEM*STAR
Energy Multiplier vs. Beam Energy

ADSR-4

Energy Multiplier (1 sec) vs. KEbeam (MeV)

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ADSR
Summary

• Accelerator Driven Subcritical Reactors offer the promise to address the major problems associated with nuclear power – both technical and political.

• ADSR can be very flexible in fuel: spent nuclear fuel, natural uranium, depleted uranium, surplus weapons material, and thorium.

• Burning the waste from current reactors can potentially extend their lifetime and turn a huge liability into highly profitable use.

• Burning the spent nuclear fuel from the current fleet of nuclear reactors is vastly superior to throwing away its enormous internal energy and just piling it in a hole in the ground for 100,000 years.

• With a fleet of systems like GEM*STAR there is enough uranium out of the ground today to supply the current U.S. electrical power usage for more than 1,000 years.
Summary – GEM*STAR

• Safety:
  – Fission stops when the accelerator is turned off.
  – Without fission, passive air cooling is sufficient.
  – Passive response to most accident scenarios.
  – Design avoids all historical reactor accident scenarios involving radioactive release.

• Waste Management:
  – Burns all nuclear waste streams, including its own.
  – Ultimate waste stream is > two orders of magnitude smaller.

• Efficiency:
  – Extracts most of the 94% energy left in spent nuclear fuel.

• Proliferation Resistance:
  – Needs neither isotopic enrichment nor reprocessing.
  – Waste stream is never useful to build weapons.
At the recent **White House Summit on Nuclear Energy** it was clear that nuclear energy is an important part of U.S. energy policy for the future.

That cannot happen without a sensible approach to the handling of nuclear waste#, which we don’t have today.

**ADSR is among the best approaches known.**

# E.g. Illinois has a moratorium on new nuclear facilities tied to a national policy on waste management.