NUCLEAR REACTOR SAFETY SYSTEMS:

A Review of Four Critical Reactor Core Safety Systems

Joseph Cummings Advisors: Nicholas Cerruti, Hillary Bennett

Washington State University

INTRODUCTION

Reactor safety systems are designed to control reactivity, temperature, and radio-activity in order to complete the following goals:

- Prevent the occurrence of a dangerous scenario
- Deescalate the severity of an unprevented accident
- Mitigate the negative outcomes from a situation

SCRAM

- Most common reactor safety system
- Takes advantage of reliable control rods

Materials

- Boron-10
- Cadmium-113

Control Mechanisms

- Hydraulic piston
- Electric motor
- Pneumatic system

SCRAM Insertion Techniques

- Electromagnetic decoupling
- Gravity
- Hydraulic pressure

SCRAM Signal Examples

- Seismic trip
- Electrical supply failure
- High power level
- High temperature
- LOCA

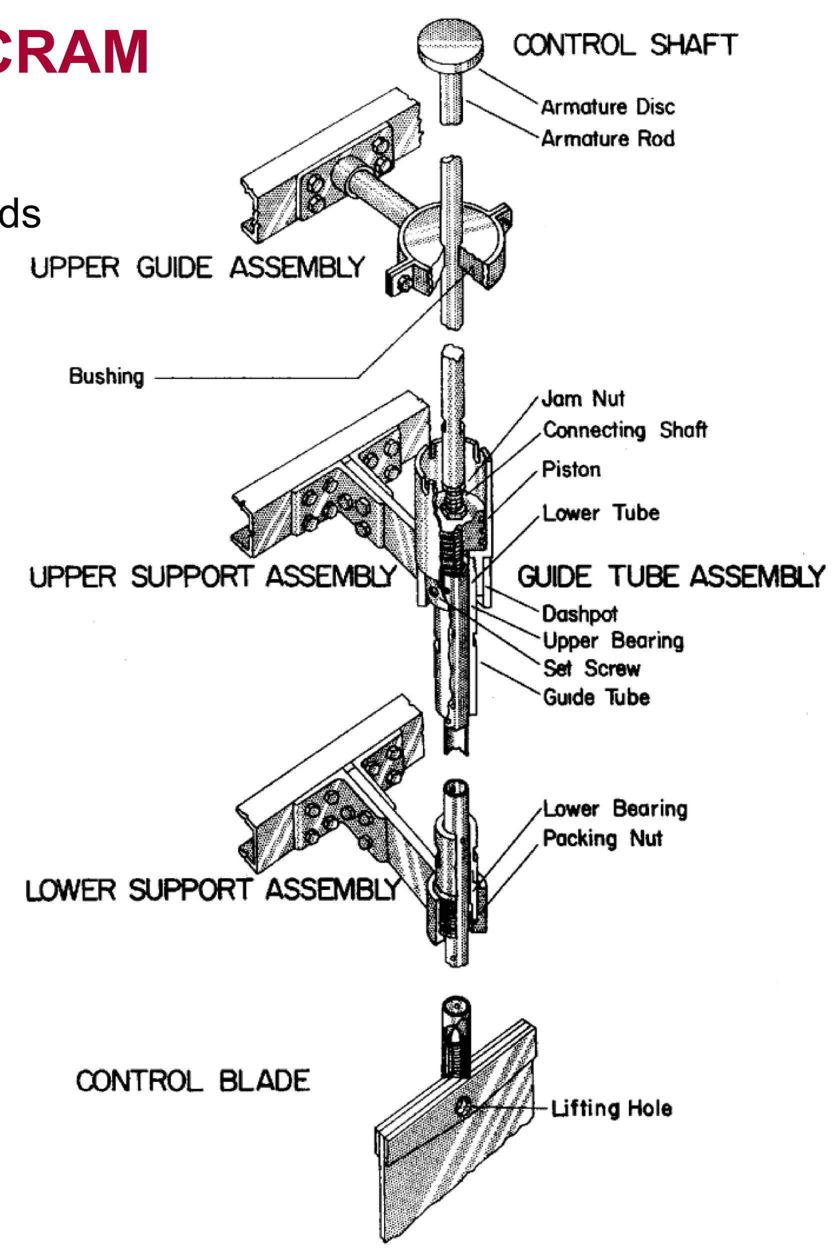

Figure 1- An example of a control rod from the WSU TRIGA Research Reactor

Source: Safety Analysis Report for the WSU Modified TRIGA Reactor, June 2002.

PROMPT NEGATIVE TEMPERATURE COEFFICIENT (PNTC)

- Reduces reactivity as temperature increases
- Uses physical properties to prevent runaway chain reaction

Cell Effect

- Increasing moderator temperature decreases moderation efficiency
- Large magnitude in TRIGA research reactors

Void Coefficient

- Steam pockets (voids) lower moderator density
- Most prevalent in water moderated BWRs

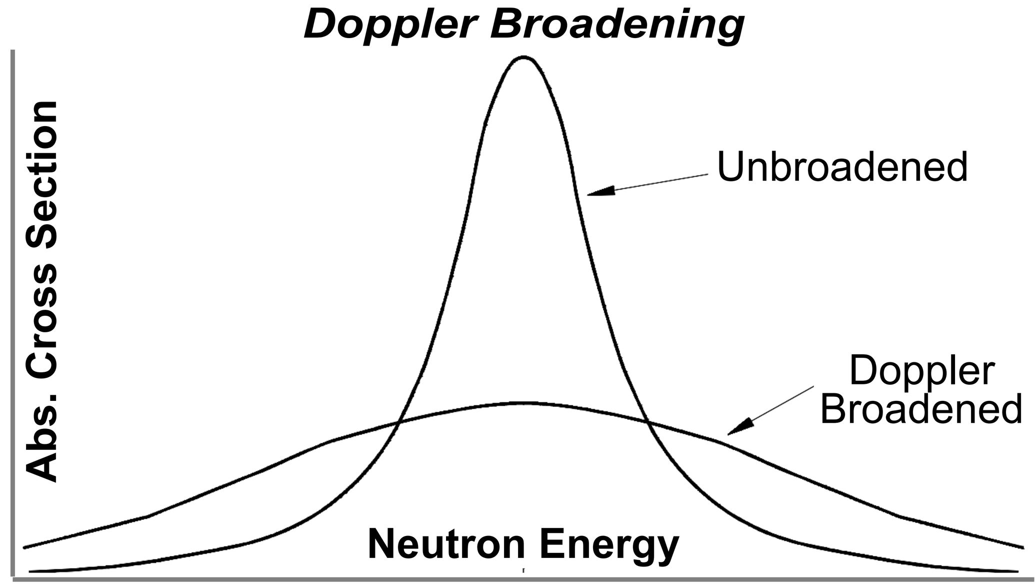

Figure 2- A generic plot of absorption cross section vs. energy at two different temperatures demonstrating doppler broadening

Source: DOE Fundamentals Handbook: Nuclear Physics and Reactor Theory. Vol 2. Jan 1993.

Doppler Broadening

- Thermal oscillations broaden uranium-238 neutron absorption cross section spectrum due to higher variance of relative velocities

Thermal Expansion

- Reduction of fuel and moderator density makes fission less probable

EMERGENCY COOLANT CONTROL SYSTEM (ECCS)

- Response to a loss of coolant accident (LOCA)
- Critical to maintain core cooling
- Prevent loss of coolable geometry
- Water input able to compensate for double-ended break of largest pipe
- Coolant can contain neutron poison additives (boric acid)

Boiling Water Reactor (BWR) Reactor Pressure Vessel (RPV) Diagram

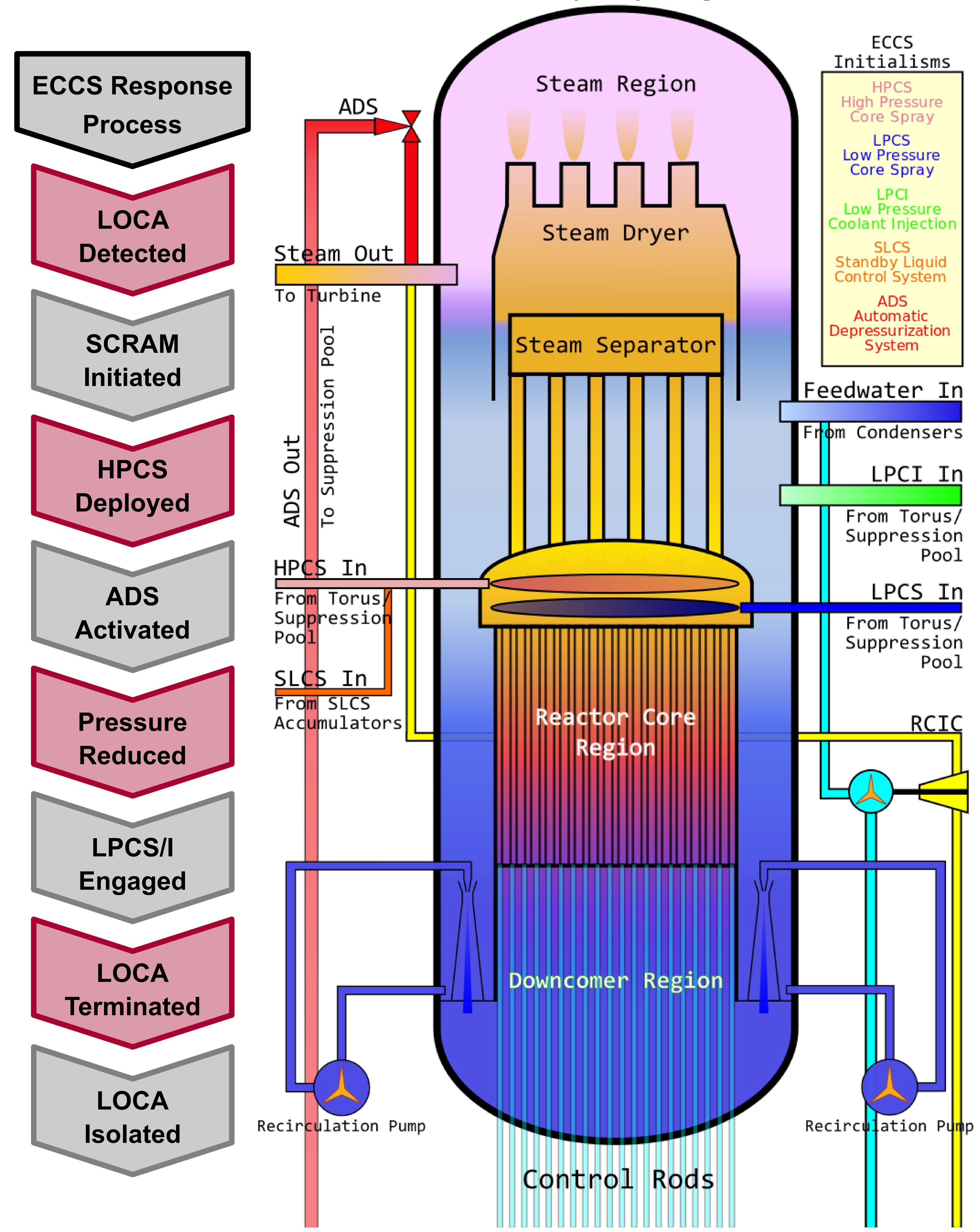

Figure 3- Diagram of the in core coolant systems of a boiling water reactor with acronym definitions

Source: Katana0182 at English Wikipedia, CC BY 3.0 <https://creativecommons.org/licenses/by/3.0>, via Wikimedia Commons

REFERENCES

Hargraves, Robert and Ralph Moir. "Liquid Fluoride Thorium Reactors: An old idea in nuclear power gets reexamined." American Scientist, July-August 2010.

"Safety Analysis Report for the WSU Modified TRIGA Reactor." June 2002.

"Training Manual: Reed Research Reactor." September 2014.

"DOE Fundamentals Handbook: Nuclear Physics and Reactor Theory." Vol. 1 and 2. Jan 1993

Hench, J. E. and D. J. Liffengren. "The Effect of Fuel Rod Failure on Emergency Core Cooling System Design for Boiling Water Reactors." Nuclear Technology, 1971.

L. Wang, B. Chen, and D. Yao, "Reactivity temperature coefficient evaluation of uranium zirconium hydride fuel element in power reactor." Nuclear Engineering and Design, vol. 257. 2013.

LIQUID FLUORIDE THORIUM REACTOR (LFTR)

- Utilizes fertile material thorium-232 to make uranium-233
- Chemical separation refines uranium-233 from outer chamber
- Fissile material moved to central chamber

Salt Plug

- Salt plug kept solidified at bottom of core by electric fan
- Fueled material flows out of core in case of power outage or overheating

Radioisotope Removal

- Chemical separation removes fission products from core
- Core reprocessing maintains stable uranium content, removing the need for refueling

Stable Coolant

- Fluoride salt coolant remains liquid at high temperatures
- Does not require boiling water in contact with fuel
- Reduced containment pressure requirements due to lower pressures

Liquid Fluoride Thorium Reactor

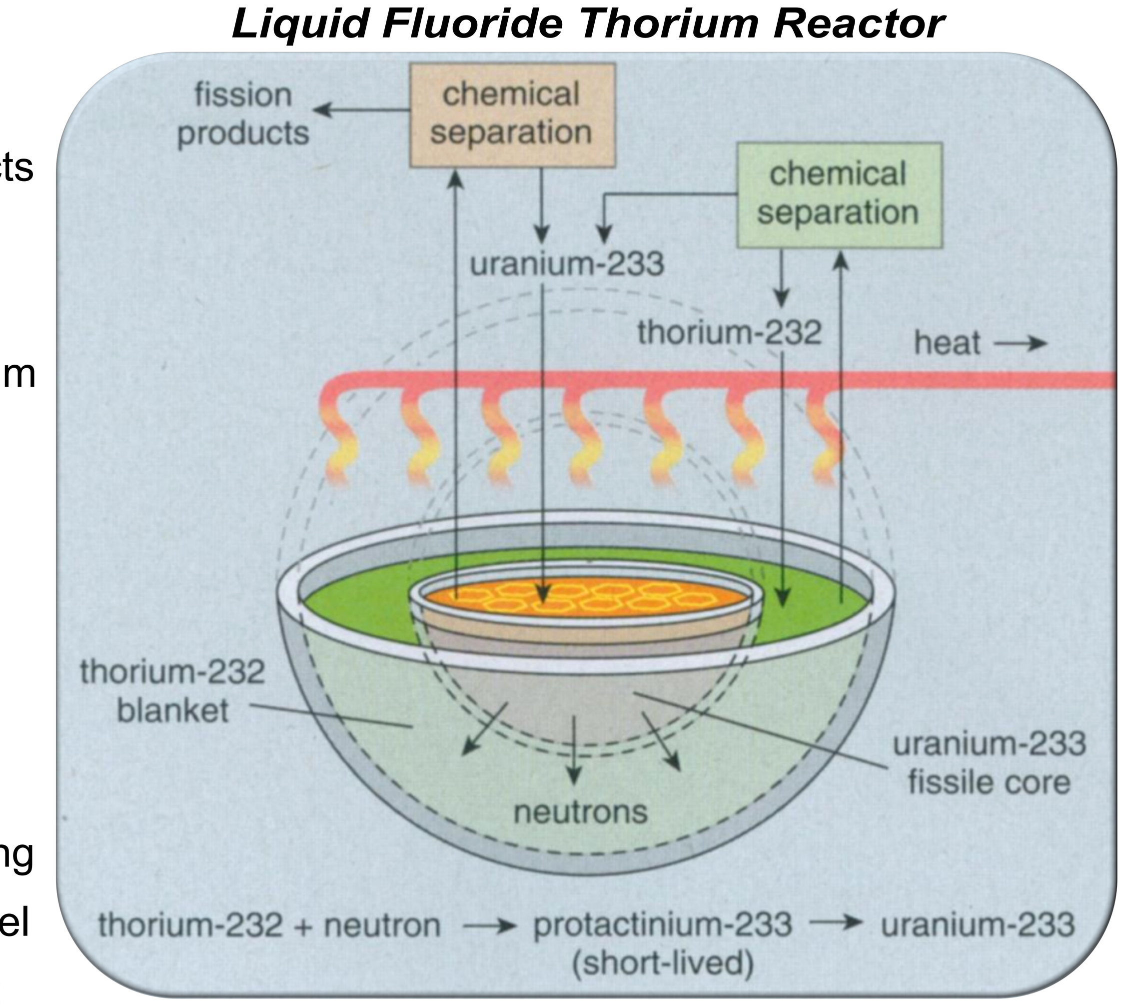

Figure 4- LFTRs have very different conceptual designs than standard nuclear reactors

Source: Hargraves, Robert and Ralph Moir. "Liquid Fluoride Thorium Reactors: An old idea in nuclear power gets reexamined." American Scientist, July-August 2010.

CONCLUSIONS

SCRAM

- Widely used for its reliability at inserting negative reactivity
- Successful at curbing reactor power quickly
- Incapable of addressing long term heat production in core
- Delayed neutron precursors continue to generate neutrons even after shutdown

Prompt Negative Temperature Coefficient

- Provides a 'frictional' force counteracting power transients, increasing stability
- All U.S. reactors are required to be under moderated
- Increasing cell effect magnitude in power reactor fuel promises elevated safety

Emergency Coolant Control System

- Necessary to counteract LOCAs in large reactors
- Introduction of additional systems provides opportunities for failure
- ECCS failures have disastrous results, requiring heavy operations surveillance

Liquid Fluoride Thorium Reactor

- Contains extremely promising safety potential using molten salt coolant
- Mobile liquid fuel slurry solves energy dissipation issues of solid fuel rods
- Regulatory issues associated with processing fuel
- Reduction in waste output relevant to current waste crisis facing nuclear field