Virginia Tech Activities on the Design and Analysis of Advanced Subcritical Reactor Systems

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For presentation 4th Workshop on ADS and thorium, University of Huddersfield, Huddersfield, England, Aug. 31-Sept. 2, 2016.

NSEL Nuclear Science and Engineering Laboratory Virginia Tech Research Center, Arlington, VA

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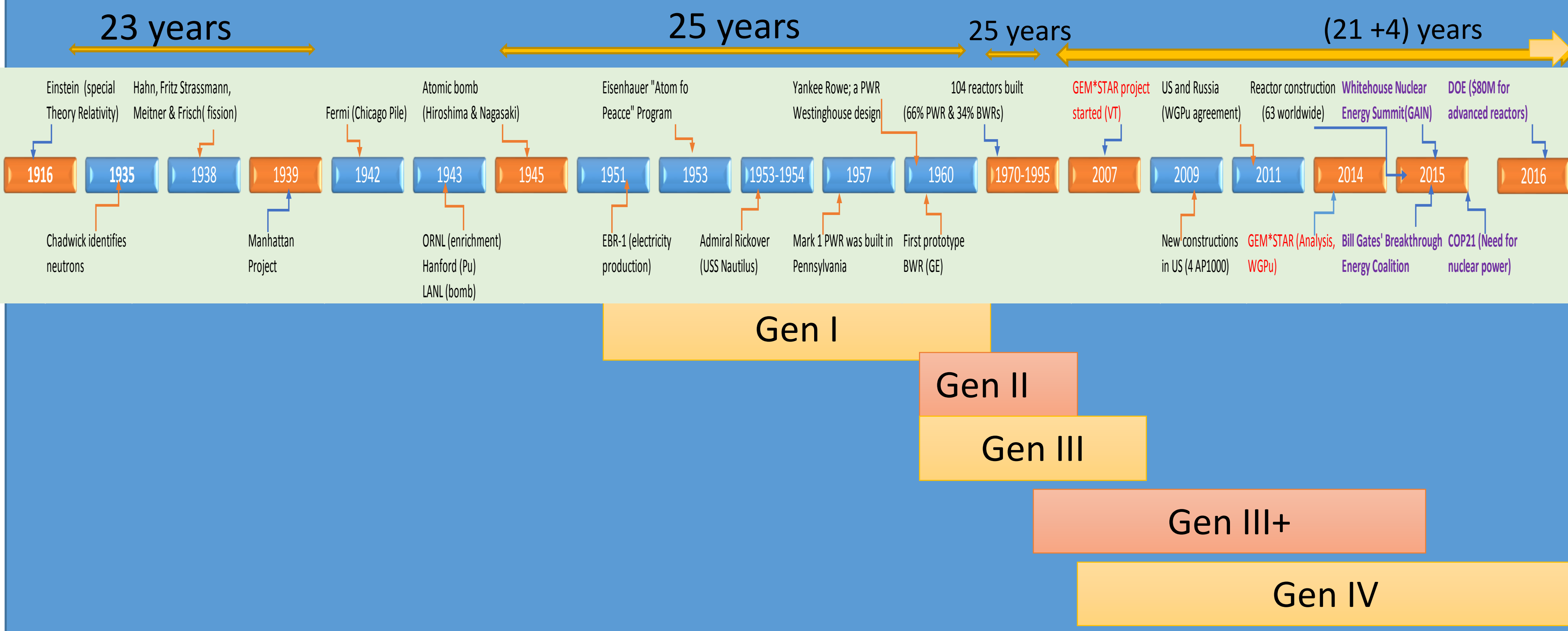
- Why ADSR?
- Analysis of GEM*STAR design*
- @Virginia Tech, ***S^3NPower***

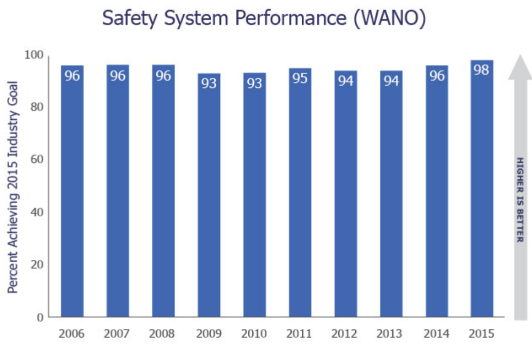
*W. Walters, A. Haghighat, B. Vogelaar, and K. Royston, Analysis and Burnup Modeling of the GEM*STAR Accelerator-Driven System, *Proceedings of PHYSOR 2016*, May 1-5, 2016, Sun Valley, Idaho, USA

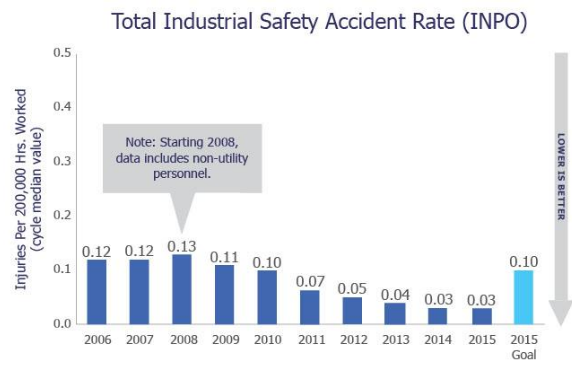
A Journey – Nuclear Technology

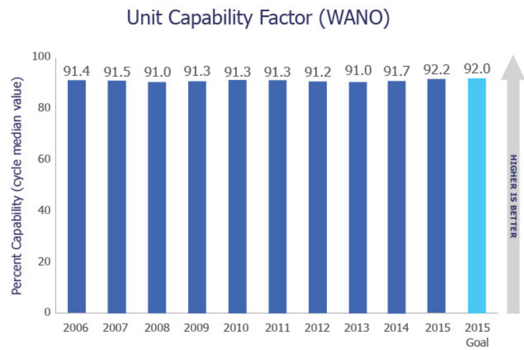


Status of United State Nuclear Power – LWR's

- **Nuclear Power Plants Set Records for Safety, Operational Performance in 2015** **(NEI, SmartBrief, March 18, 2016)**



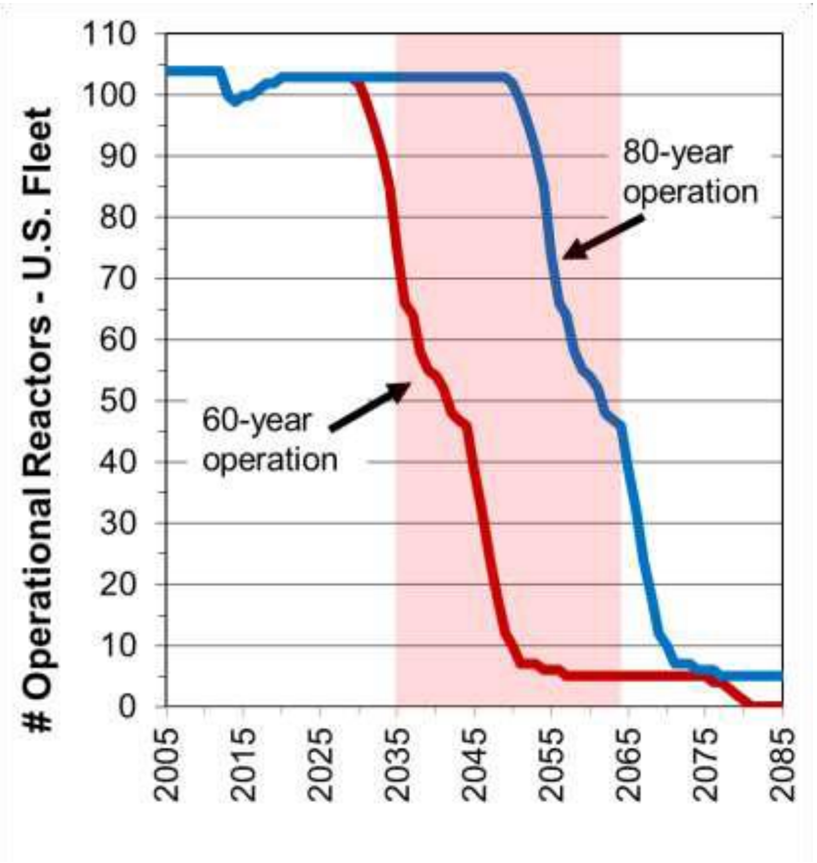




US Nuclear Reactors – Operating Life

US Reactors are approaching their 40-year life; majority have permission for 20 years of plant life extension (PLE).

Even with 20-year PLE, we have to START building NOW!



Why ADSR?

- To address key issues facing LWR technology:

> - **Used Nuclear Fuel**
> - **Proliferation (Enrichment, Reprocessing)**
> - **Safety (Fuel melting, beyond design accidents)**
> - **Timeline**
> - **Cost**

GEM*STAR concept

- The concept was developed by Charlie Bowman (ADNA) and Bruce Vogelaar (VT Physics)

Key design features of GEM*STAR	GEM*STAR addressing all issues of LWR's
Accelerator Driven Subcritical Reactor (ADSR)	• Flexible fuel cycle, burning of UNF, less waste • No enrichment, no reprocessing, conversion of WGPu • simplified safety system
Fuel & Coolant: Molten salt fuel [$(LiF)_2UF_4$]	• No fuel melting, • High boiling point, low pressure & lower construction cost • High temperature & higher efficiency • Generation of syngas for liquid transport fuel
Moderator: Graphite	Thermal spectrum

Waste

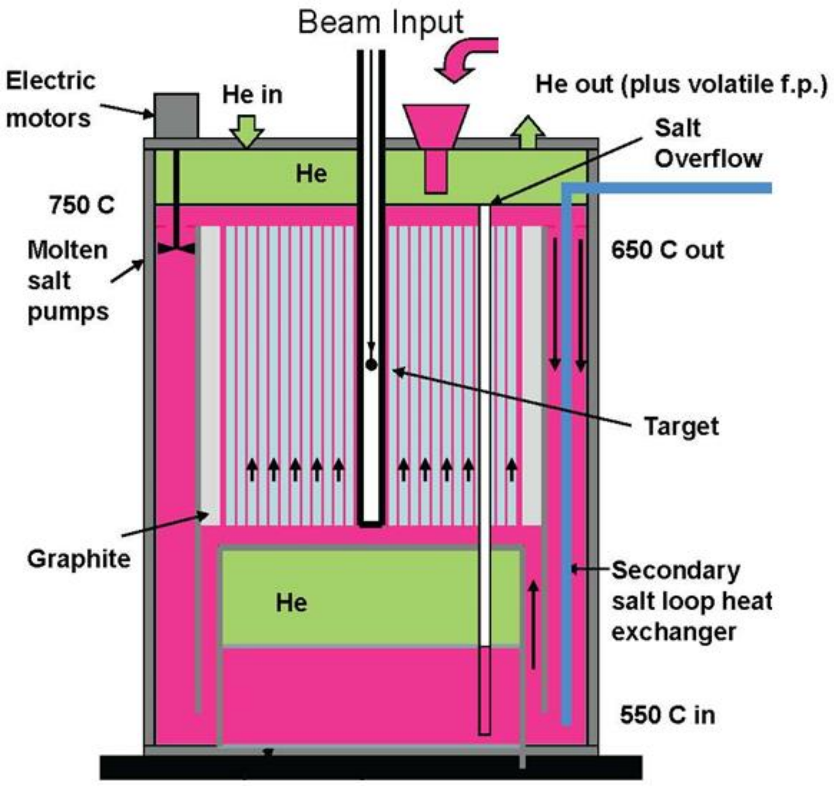
Proliferation

Safety

Timeline

Cost

GEM*STAR - Schematic



Parameters considered for this GEM*STAR analysis

Parameter	Value
# Fuel channels (x-direction)	46
# Fuel channels (y-direction)	47
# Fuel channels in blanket region	6
Total fuel channels (small)	1190
Total fuel channels (large)	972
Small fuel channel diameter	4.60 cm
Large fuel channel diameter	10.46cm
Fuel channel pitch	16.0 cm
Total height (z)	720 cm
Total depth (y)	736 cm
Total width (x)	720 cm
Fuel salt composition	$(LiF)_2UF_4$
Operating temperature	1000 K
Fuel density	3.61 g/cc
Total fuel salt volume (V)	1.97×10^7 cc
Fuel salt replacement rate (v)	13.5 ℓ/day
Mean fuel residence time (V/v)*	4.0 years
Proton Accelerator Energy	600 MeV
Proton Current*	10 mA
Target	Uranium

*Note: Proton current can be effectively increased or decreased by lowering or raising the fuel replacement rate

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Previous GEM*STAR modeling

Assumptions:

- The reactor is assumed to be in steady state (i.e., $\frac{dN}{dt} = 0$ for all isotopes)
- All fission products are modeled as B-10 (in quantities such that the total cross-section remains constant)
- No decay modes or (*n, xn*) reactions were modeled, only fission and absorption resulted in isotopic changes.
- The neutron absorption chain was only modeled as U238-Pu239-Pu240-Pu241-Pu242.

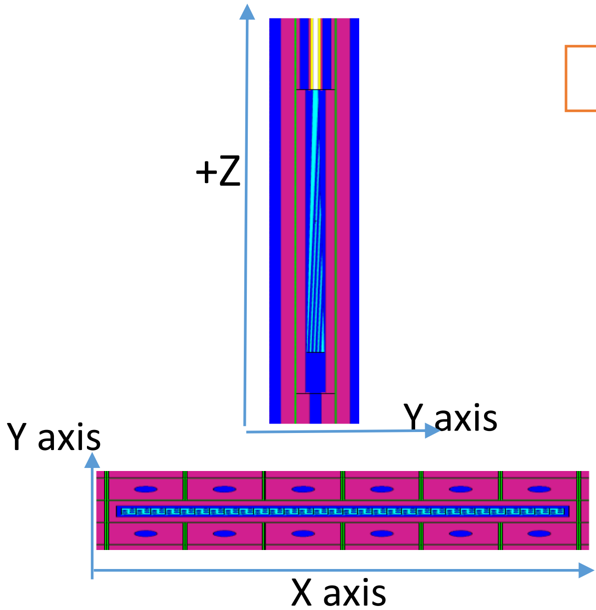
GEM*STAR Analysis

- Investigated the target and neutron generation
  - Target (beam energy, spallation neutrons, spectrum, spatial distribution)

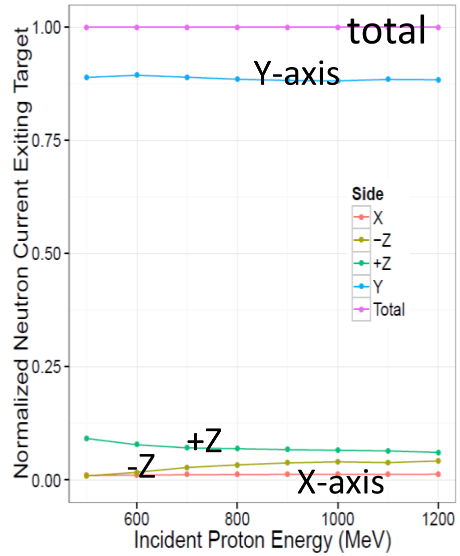
- Performed detailed reactor physics analysis for natural uranium fuel and different feeds
  - Fixed source subcritical calculations by performing proton + neutron simulations
    - Examined number of proton histories and statistical uncertainty
    - Examined temperature effects and Doppler broadening
    - Examined statistical uncertainty

- Over 750 calculations performed for this study

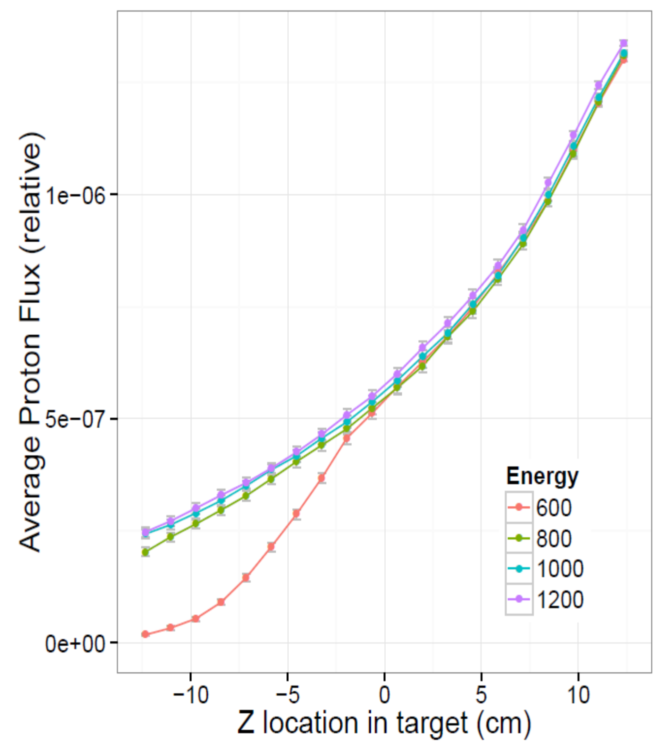
Target Analysis - using MCNP6



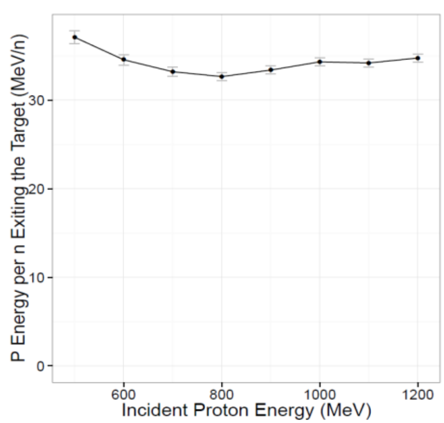
Neutron current on different surfaces



Axial proton flux within the target

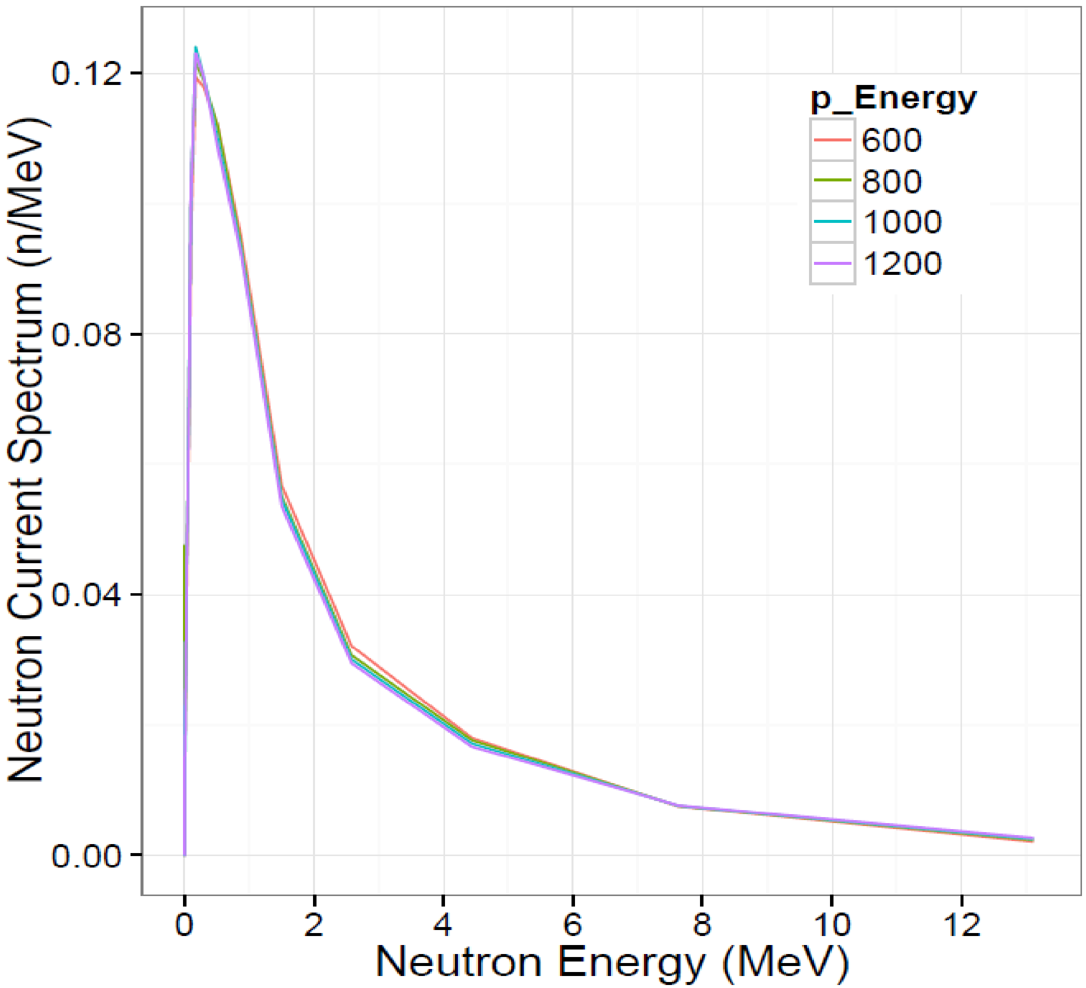


How much proton energy is used for the existing neutrons from the target?



Neutron spectrum leaving the target

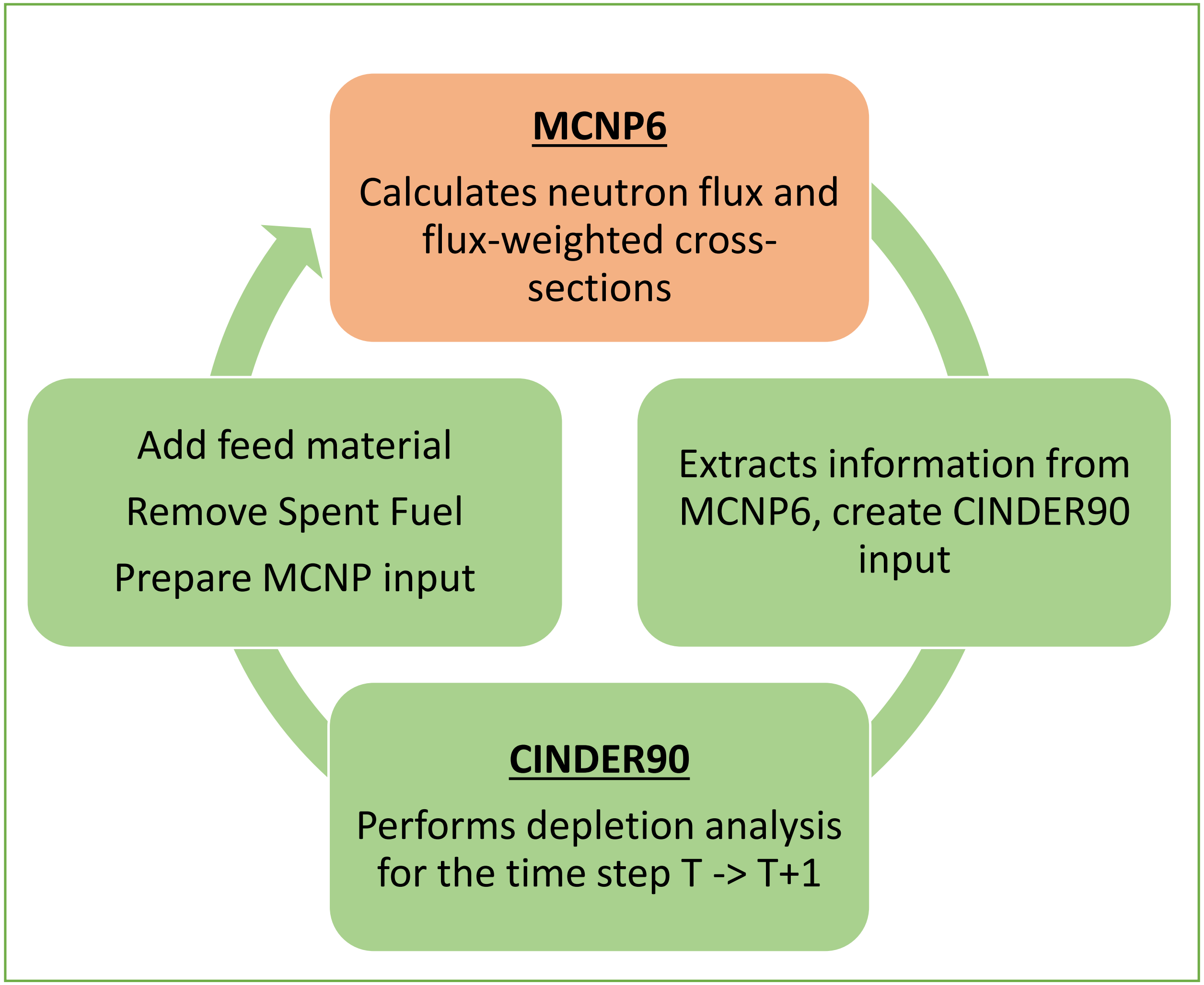
(1-σ statistical uncertainty < 5%)



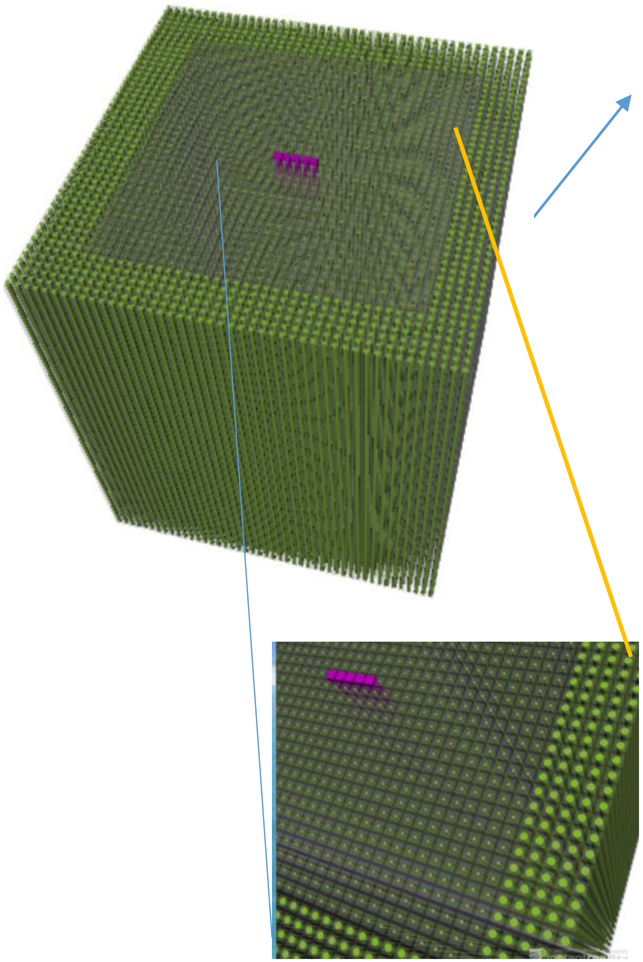
E_{MP} = 200 keV
E_{ave} = 8.5 - 10.9 MeV
E_{median} = 2 MeV

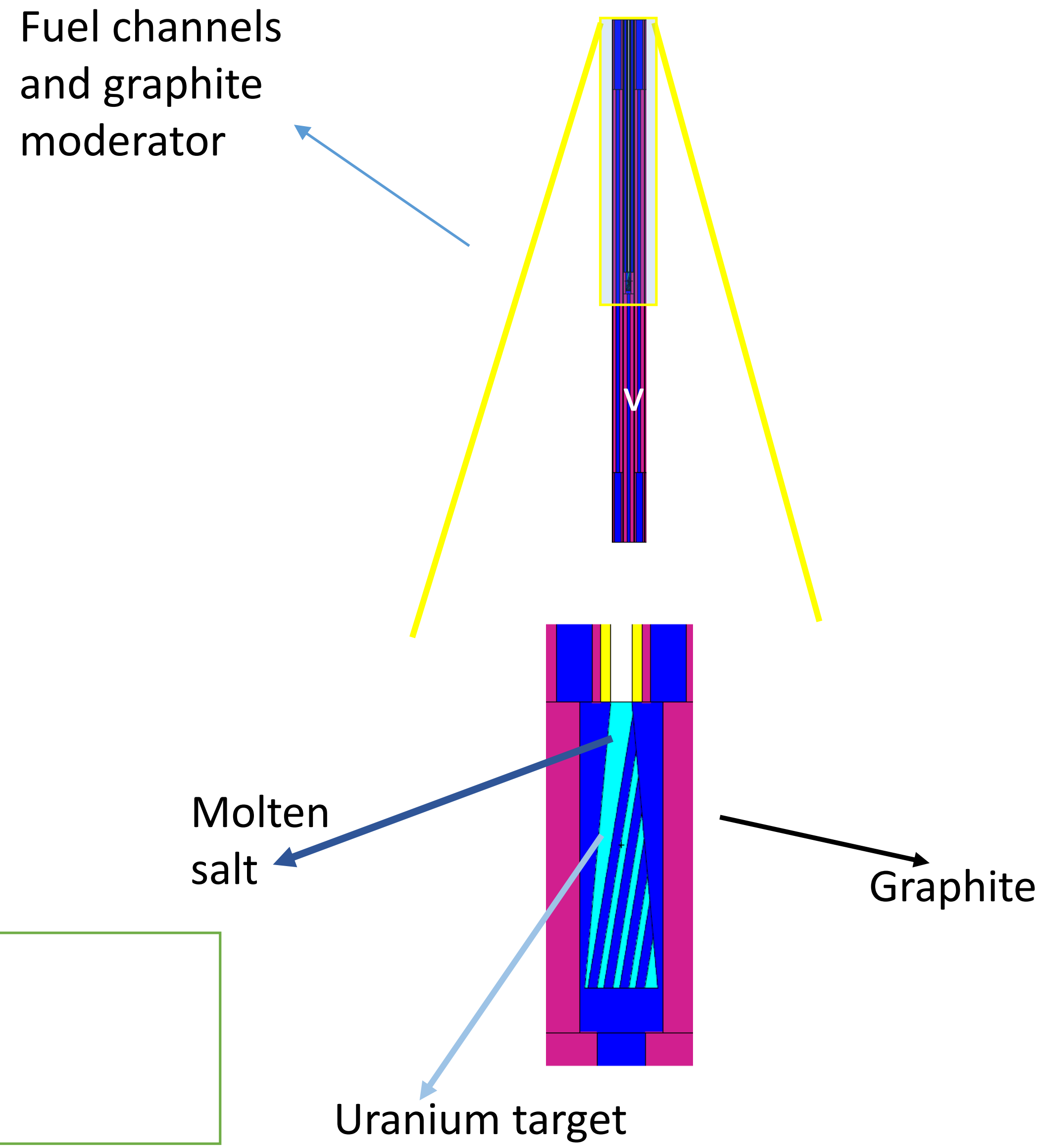
Reactor Physics Analysis

- ***Monteburns*** is used for fuel burnup analysis:
  - It couples MCNP to a depletion code such as ORIGEN2.1 or CINDER90



GEM*STAR MCNP Core model





Core Size: 720x736x720 cm3
Fuel channel radius (small): 2.3 cm
Fuel channel radius (large): 5.23 cm
Fuel channel pitch: 16 cm

Temperature effect

Temperature (°K)	Fission rate density ($s^{-1}cm^{-3}$)	Fission Heating (MeV/s)
293.6	6.16E+01 (1.99%)*	1.14E+04 (1.99%)
600	7.24E+01 (2.10%)	1.34E+04 (2.01%)
1000	1.21E+02 (2.32%)	2.25E+04 (2.32%)
1200	1.21E+02 (2.26%)	2.26E+04 (2.26%)

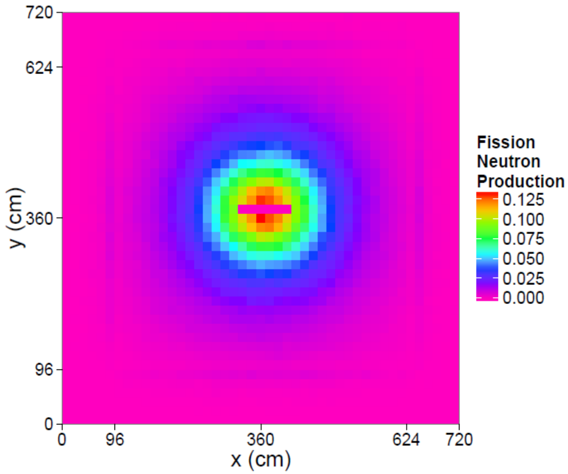
*1-σ statistical uncertainty

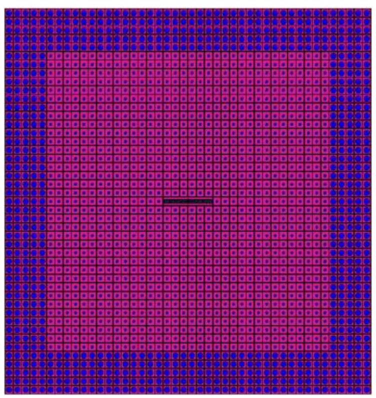
Temperature	Multiplication (M)
293.6 K	10.08
600 K	11.79
1000 K	19.41
1200 K	19.40

$$M = \frac{Electric\ Power}{Beam\ Power}$$

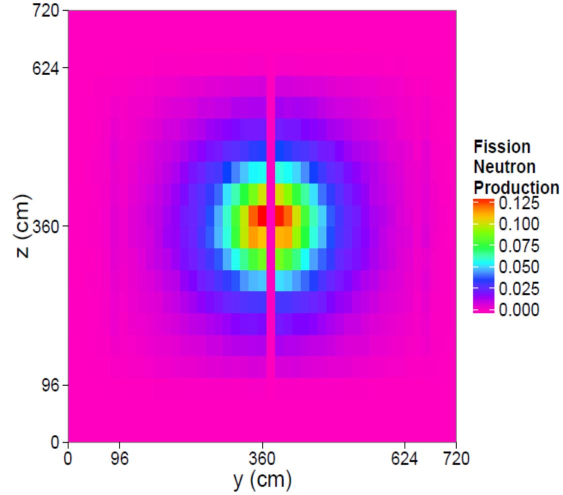
Fission density distribution

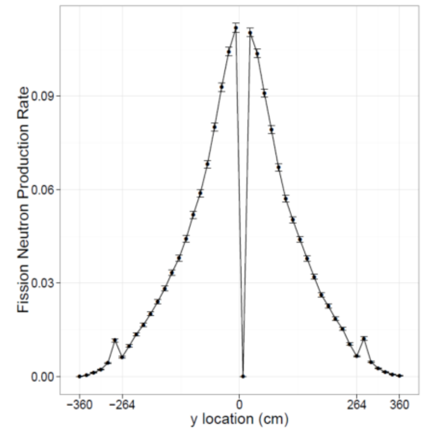
X-Y

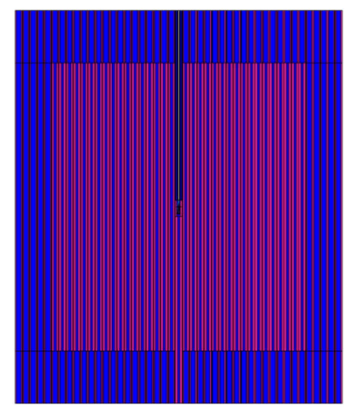




Y-Z







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Time to equilibrium?

- The *Monteburns* code system enables repeated transport and depletion calculations until an equilibrium cycle has been achieved.
- Different combinations of time steps, leading to an equilibrium, are examined
- For each time step
  - at the beginning, fresh fuel is added
  - at the end a fraction of all materials plus 100% of Xe, Kr, and noble metals are removed

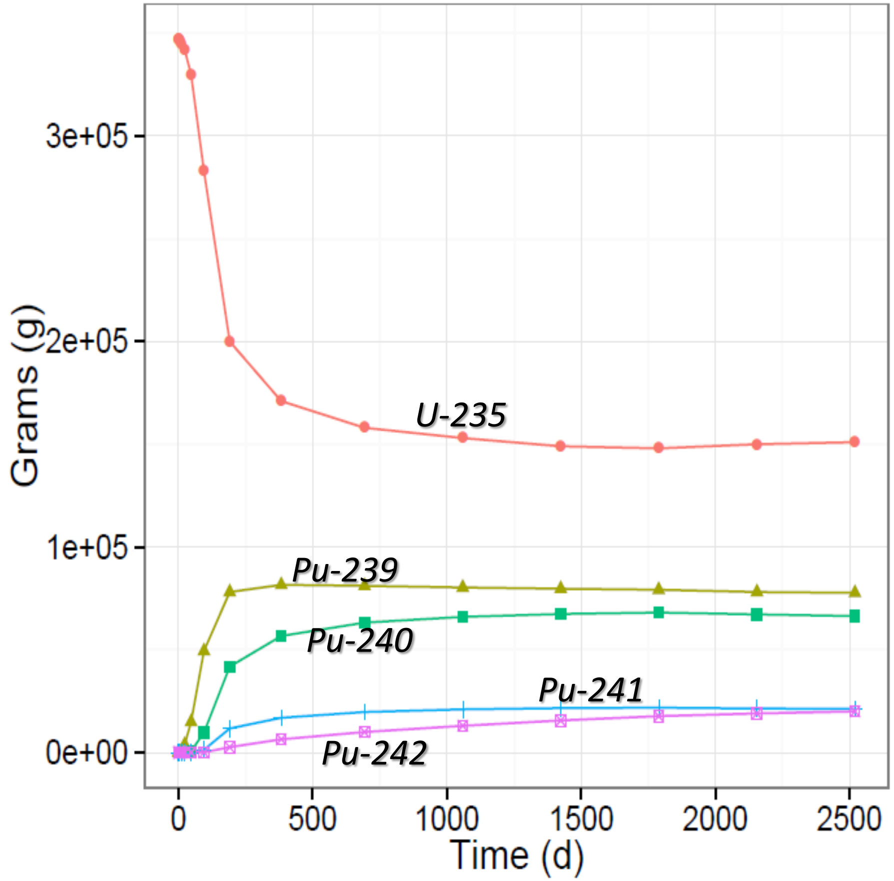
Example – time-step sequence and residence time

Step number	Time Step (days)	Total time (yrs)
1	1	0.003
2	2	0.008
3	4	0.019
4	8	0.041
5	16	0.085
6	32	0.173
7	64	0.348
8	128	0.699
9	256	1.400
10	365	2.400
11	365	3.400
12	365	4.400
13	365	5.400
14	365	6.400
15	365	7.400
16	365	8.400

Effect of time step on materials concentrations (gram) at equilibrium

Isotope	Maximum Time step			
	2d	3m	6m	1y
U 235	1.37E+05	1.36E+05	1.34E+05	1.35E+05
U 238	4.79E+07	4.78E+07	4.78E+07	4.79E+07
Pu 239	8.44E+04	8.40E+04	8.45E+04	8.45E+04
Pu 240	7.10E+04	7.09E+04	7.21E+04	7.20E+04
Pu 241	2.27E+04	2.27E+04	2.31E+04	2.31E+04
Pu 242	2.18E+04	2.16E+04	2.17E+04	2.15E+04
Total	4.82E+07	4.81E+07	4.81E+07	4.82E+07

For natural uranium fuel and feed



Remark: For the most part, an equilibrium is achieved after only 2 years

Use of GEM*STAR for:

- Burning of LWR UNF
- Electricity Generation
- Conversion of WGPu

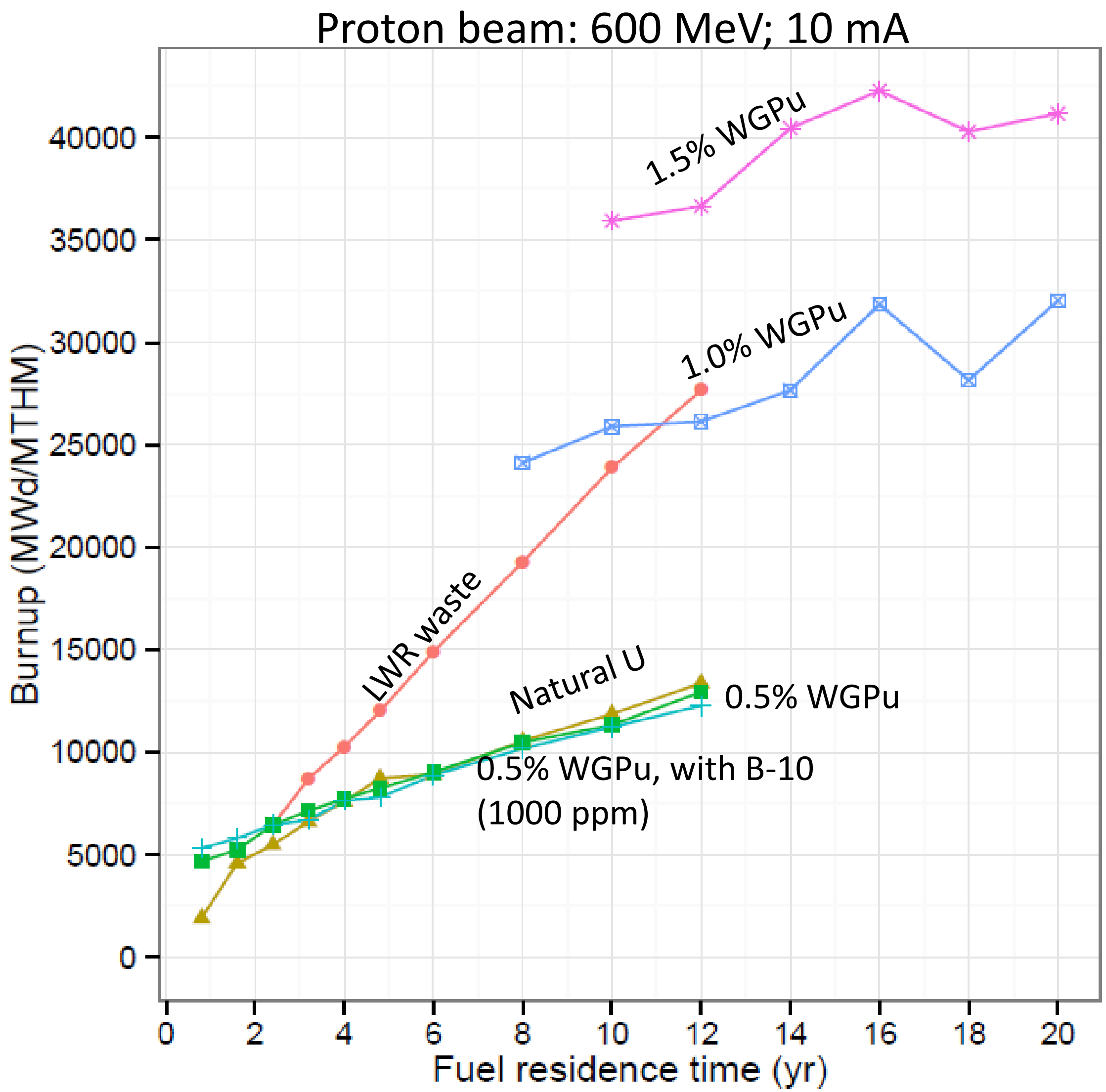
Examined feeds

Fuel Material	Description
Natural Uranium	0.711 w% U-235
LWR Waste	5.0 w% original enrichment 40 GWd/MT, 10 years cooling
0.5% WGPu	Balance is depleted uranium
1.0% WGPu	Balance is depleted uranium
1.5% WGPu	Balance is depleted uranium

Reminder

Isotope	Half-life (yr)	WGPu Weight (%)	LWR Weight (%)
Pu-239	24k	93%	53%
Pu-240	6.6k	6%	24%
Pu-241	14	1%	15%
Pu-242	373K	0.1%	6%

Comparison of burnups vs. residence time for different feeds

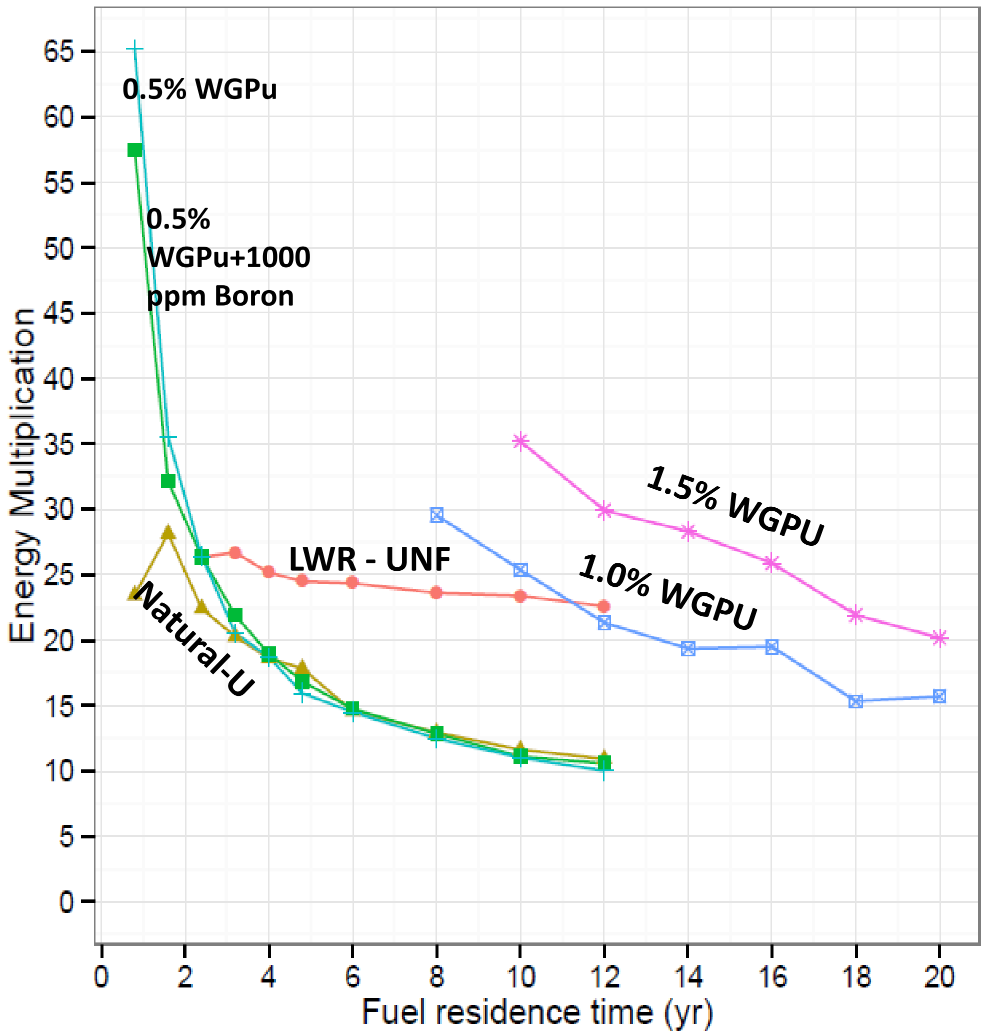


NOTE: Data is not presented for low-residence times for LWR-waste and WGPu, because the reactor becomes supercritical.

Example - Electricity production

$$\textit{Energy Multiplication } (M) = \frac{\textit{Electric power out (thermal fission energy*efficiency)}}{\textit{Beam power on target}}$$

Thermal efficiency = 44%



NOTE: Data is not presented for low-residence times for LWR-waste and WGPu, because the reactor becomes supercritical,

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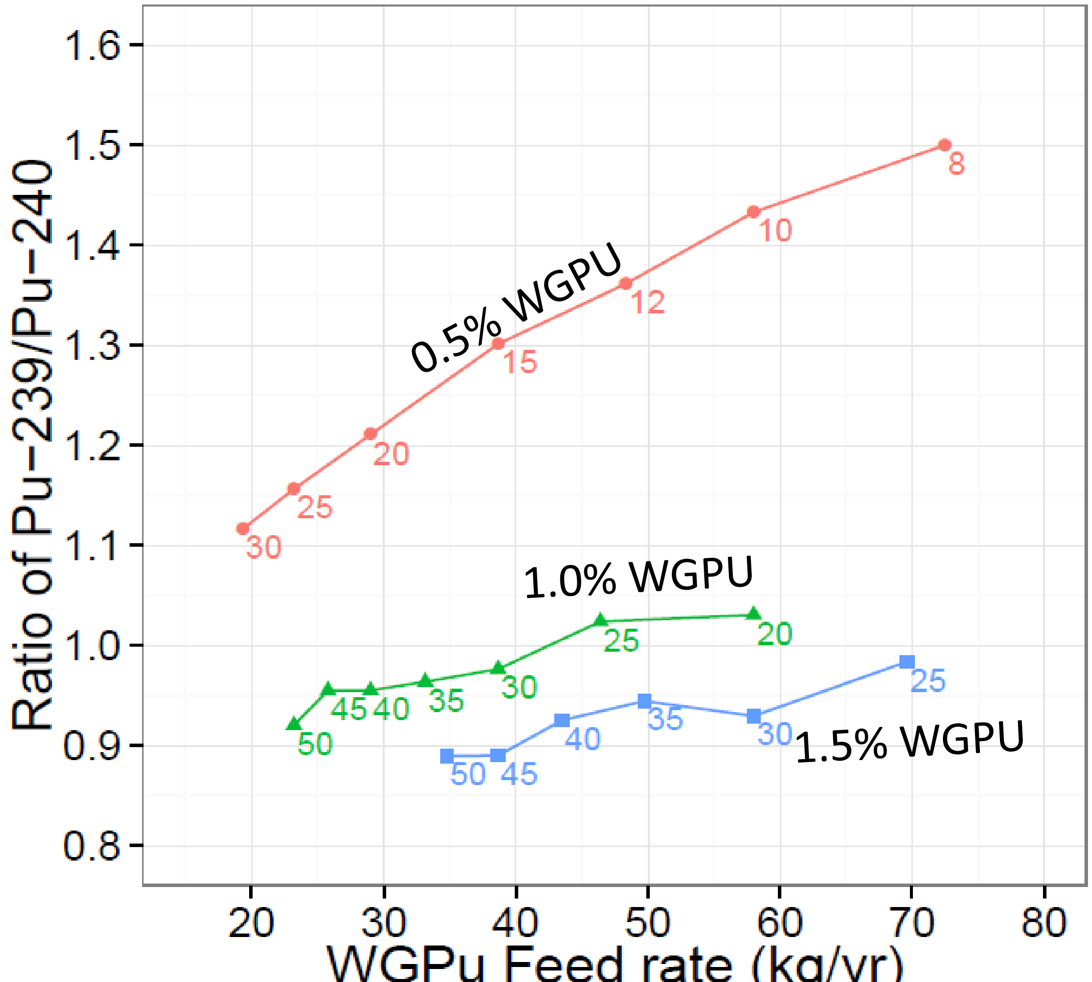
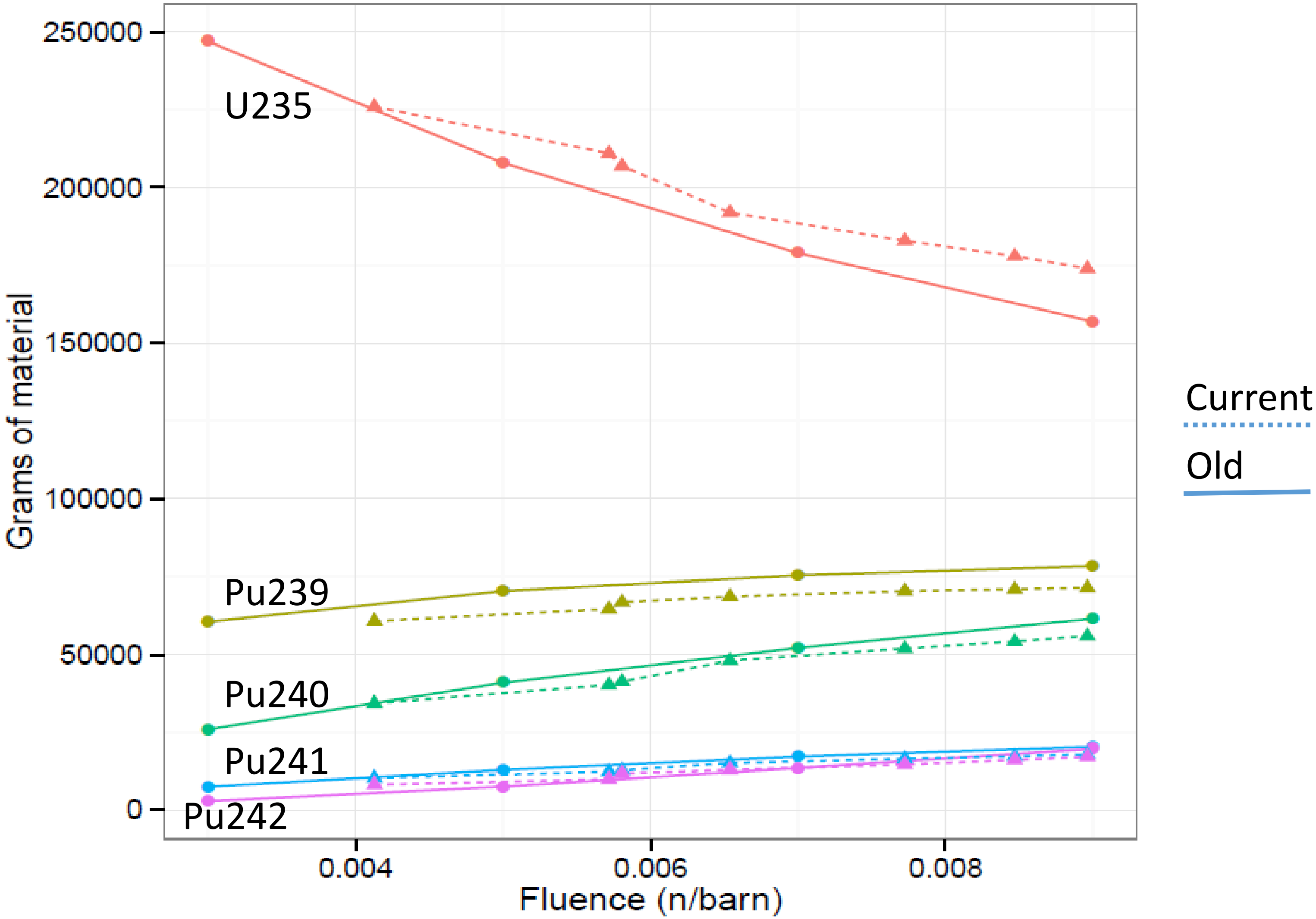
Variation of Pu239/pu240 for different feed rates and residence times

Note

Material	Ratio of Pu239/ Pu240
WGPu	15.2
LWR	2.2



Variation of Mass Actinides – *Natural U feed* (Current study vs. the Old approach)



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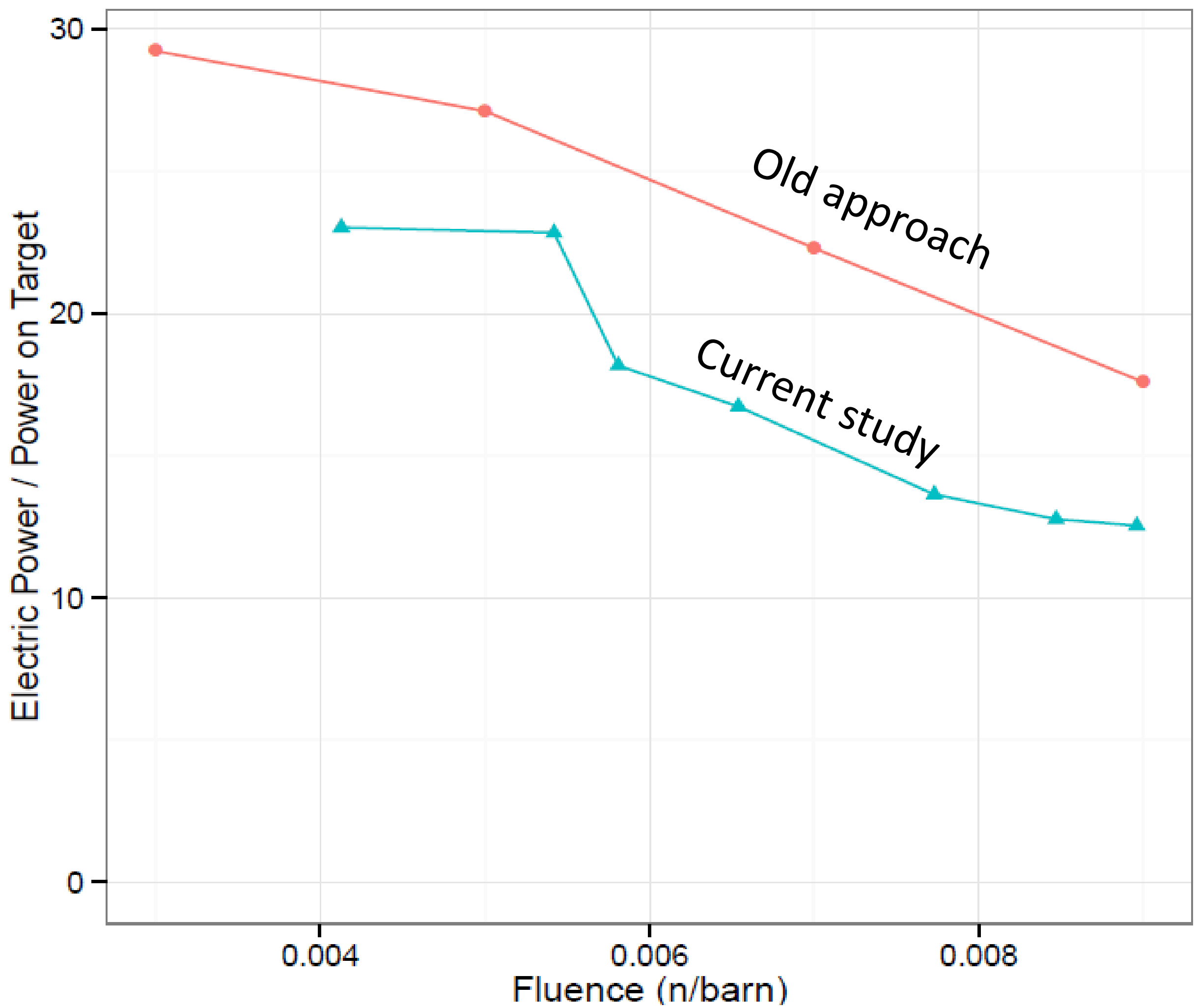
Variation of Electric Power Multiplication – *Natural U feed* (Current study vs. the Old approach)



Remarks

- Although the previous results by B. Vogelaar, et al is not accurate, but its general conclusion on the GEM*STAR concept is correct.

- Achieving an equilibrium cycle for U(nat.) in 2 years is highly promising; this has to be investigated for other fuels.

- This study further demonstrated the flexibility of GEM*STAR concept for burning of waste, WGPu conversion, & electricity generation.

What Next?

- Significant work is needed
  - Conduct experiments on an effective accelerator-target assembly
  - A new coupled reactor and target design
  - Multi-physics tools are needed for
    - Reactor kinetics of an ADSR system (delayed neutron precursors flow, bubble formation and collapse, and fuel thermal expansion)
    - Thermal hydraulics and heat transfer simulation of molten salt
    - Molten salt chemistry and fluid properties
  - Development of a novel robust fuel management strategy
  - Nuclear nonproliferation and safeguards monitoring

Over the past ten months

- Key meetings
  - Nov 2015, White Summit on Nuclear Energy
  - Dec 2015, COP-21 meeting on climate change challenges

- DOE's Public-private partnership initiatives
  - ➢ GAIN (Gateway for Accelerated Innovation in Nuclear)
  - ➢ Advanced Reactor Concept Development funding opportunity
    - Two contracts of $40 M with $10 M matching were awarded in Feb 2016
      - Southern Company Services partnership – molten chloride fast reactor
      - X-energy startup partnerships – Pebble bed HGTR

- Private capital investments
  - ➢ About $1.3 M private capital is received by over 40 startups working on various advanced reactor designs
  - ➢ Bill Gates formed the Breakthrough Energy Coalition

US Investment in advanced reactors

- Critical reactor designs
  - Molten Salt Reactors (MSRs)
  - Pebble bed High Temperature Gas Reactor
  - Liquid Metal Fast Reactors

- New research opportunities
  - Chemistry of molten salt
  - Corrosion effect of molten salt
  - Modeling tools for MSRs

- Why not ADSR?
  - It is believed that above critical reactors address all issues
  - Reliability of accelerators
  - Design of a reliable target
  - Behavior of molten salt fuel
  - Removal of fission products
  - Lack of experience

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- Received funding from the Virginia Tech's Energy and Materials Institute (EMI) to establish:
  A multi-disciplinary research cluster entitled ***S^{3}NPower*** (Safe, Secure and Sustainable Nuclear Power) to investigate reactor designs for power generation and/or burning of nuclear waste

- ***S^{3}NPower***
  - **Founding team includes:**
    Alireza Haghighat (NE, lead),
    Celine Hin (NE & MSE),
    Patrick Huber (Physics),
    Yang Liu (NE), and
    Bruce Vogelaar (Physics)

  - Working on the formation of ***S^{3}NPower*** **Inc.** with potential investment by VT

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- ***S^3NPower (continued)***

  - **Seeking private-public collaborators (**given talks and initiated discussions on collaborative work)

United States

US National labs (ANL, ORNL & INL), Universities (Georgia Tech, North Carolina State University, Penn State, University of South Carolina), industry (Southern Nuclear), nonprofit organizations (Virginia Nuclear Energy Consortium), and state & federal government agencies;

International

Politecnico di Torino

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- ***S^3NPower (continued)***
  - **Research activities**
    - Initiated studies on the *physics and kinetics of critical and subcritical reactor systems; initiated development of modeling tools*
    - Seeking funding for experimental and/or computational studies to address
      - Computational tools for ADSRs
      - Modular coupled reactor & target designs
      - Balance of Plant
      - Thermal hydraulics
      - Nuclear materials chemistry
      - Radiation effect
      - Nuclear nonproliferation detection and security

S^3NPower