A Methodology for Accurately Predicting the Estimated Critical Rod Positions for Hot Startups at the MURR

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Facility Overview

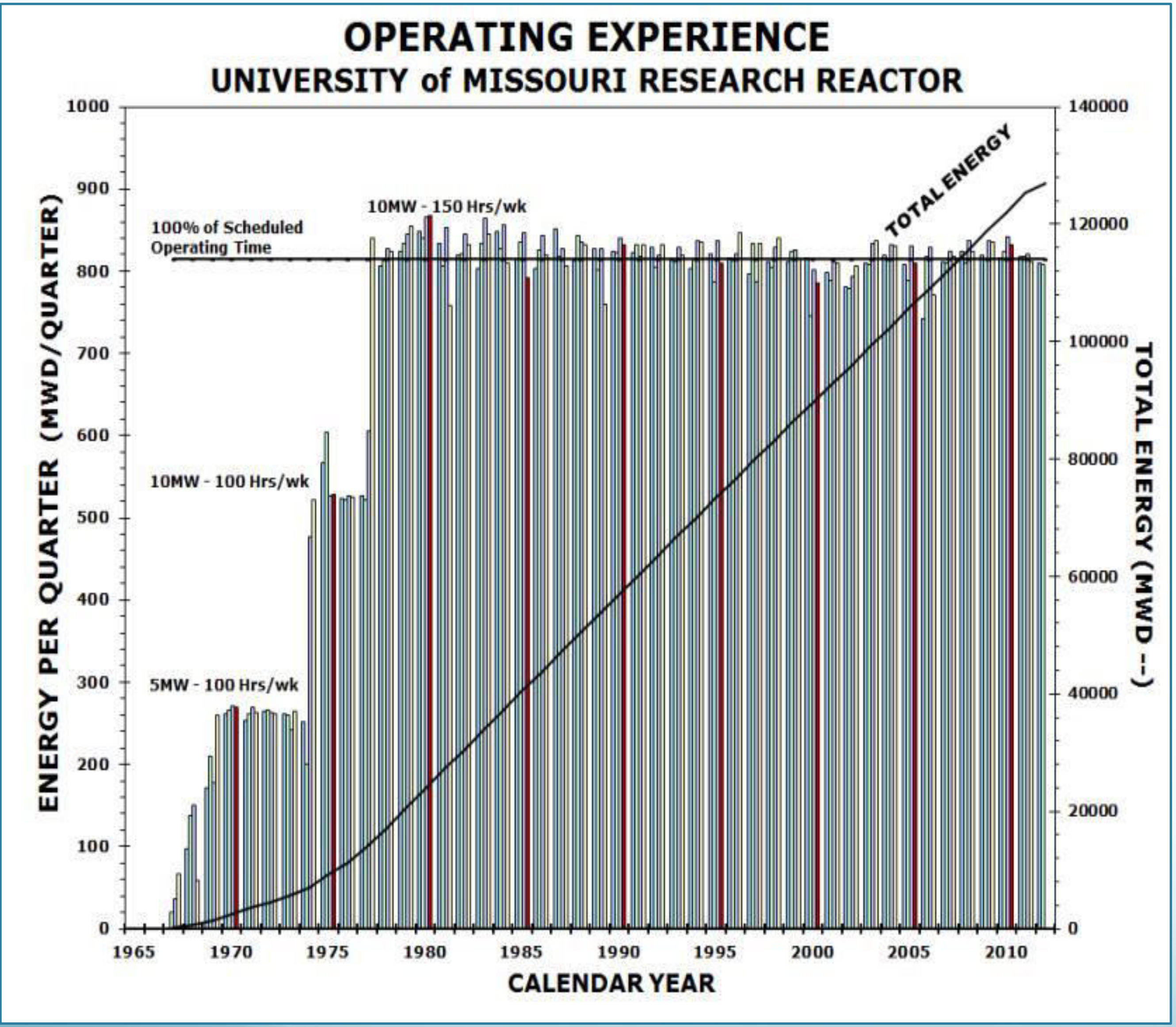
Location: University of Missouri main campus in Columbia, Missouri, USA [200 km West of St Louis].

Purpose: Multi-disciplinary research and education facility also providing a broad range of analytical and irradiation services to the research community and the commercial sector.

Type: MURR® is a pressurized, heterogeneous, reflected, open pool-type, which is light-water moderated and cooled.

History:

- First achieved criticality on October 13, 1966
- Initially licensed at 5 MW
- Uprated in power to 10 MW in 1974
- Started ≥150 hours/week operation in September 1977
- Submitted relicensing application in 2006 to the NRC



- **Weekly operating cycle**
- **Core fueled by eight fuel elements in various stages of burn up (0 – 150 MWDs)**
- **Most of the available excess reactivity at the beginning of cycle is used by xenon poison buildup**
- **Current core fuel configuration + Xenon buildup limits fuel cycle to approximately 7 days/week at full-power**

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Reactor Production & Loss of Xenon-135

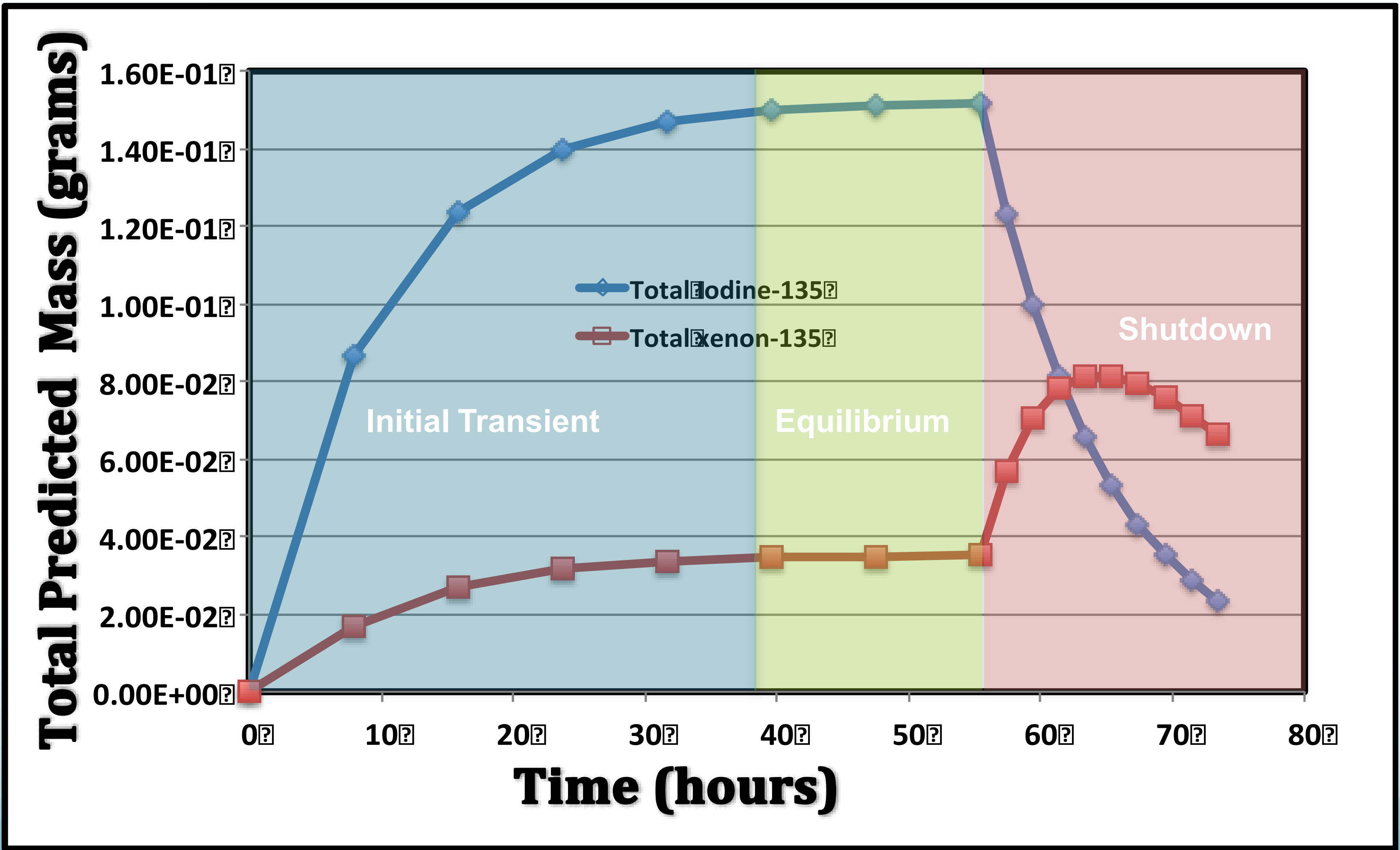
- The most significant neutron poison, xenon-135 ($t_{1/2}$=9.10hr), is produced from two nuclear pathways:
  - a 5% branch directly from uranium-235 fission yield
  - and a 95% branch from the iodine-135 ($t_{1/2}$=6.57hr) decay

- Xenon-135 neutron capture cross-section = 2.6 million barns
  - Significant source of negative reactivity

- Xenon concentration build up stages:
  - Initial transient:
  - $d[\text{Xe-135}]/dt = (\text{Xe-135})_{\text{fission}} + (\text{Xe-135})_{\text{I-135 decay}} - (\text{Xe-135})_{\text{capture}} - (\text{Xe-135})_{\text{decay}}$
  - Equilibrium:
  - $(\text{Xe-135})_{\text{fission}} + (\text{Xe-135})_{\text{I-135 decay}} = (\text{Xe-135})_{\text{capture}} + (\text{Xe-135})_{\text{decay}}$
  - Shutdown:
  - $d[\text{Xe-135}]/dt = (\text{Xe-135})_{\text{I-135 decay}} - (\text{Xe-135})_{\text{decay}}$

Iodine-135 and Xenon-135 Behavior During Reactor Transients at MURR

The predicted I-135 and Xe-135 buildup to equilibrium for 55.4 hours of operation from a starting core MWDs = 600 followed by shutdown.



After shutdown during equilibrium conditions, Xe-135 builds up and peaks due to I-135 decay in ~10 hours resulting in xenon deadtime.

Interruptions in MURR Operational Schedule: Unscheduled/Unplanned Shutdowns

Unscheduled/Unplanned shutdowns can severely impact the production of critical medical isotopes that are generated during the MURR weekly operating cycle.

If an unscheduled/unplanned shutdown occurs reactor restart is done as quickly as possible in order to minimize downtime.

Unscheduled/Unplanned Shutdowns from Equilibrium Xe-135 conditions options:

- **Refuel core**
- **Wait out xenon deadtime**

Unscheduled/Unplanned Shutdowns from Initial Xe-135 Transient conditions options:

- **Hot Startup**
- **Refuel core**
- **Wait out xenon deadtime**

Purpose of Study

A "Hot Startup" is one where there is a question regarding the availability of enough remaining core excess reactivity to override the Xe-135 buildup following the unplanned shutdown.

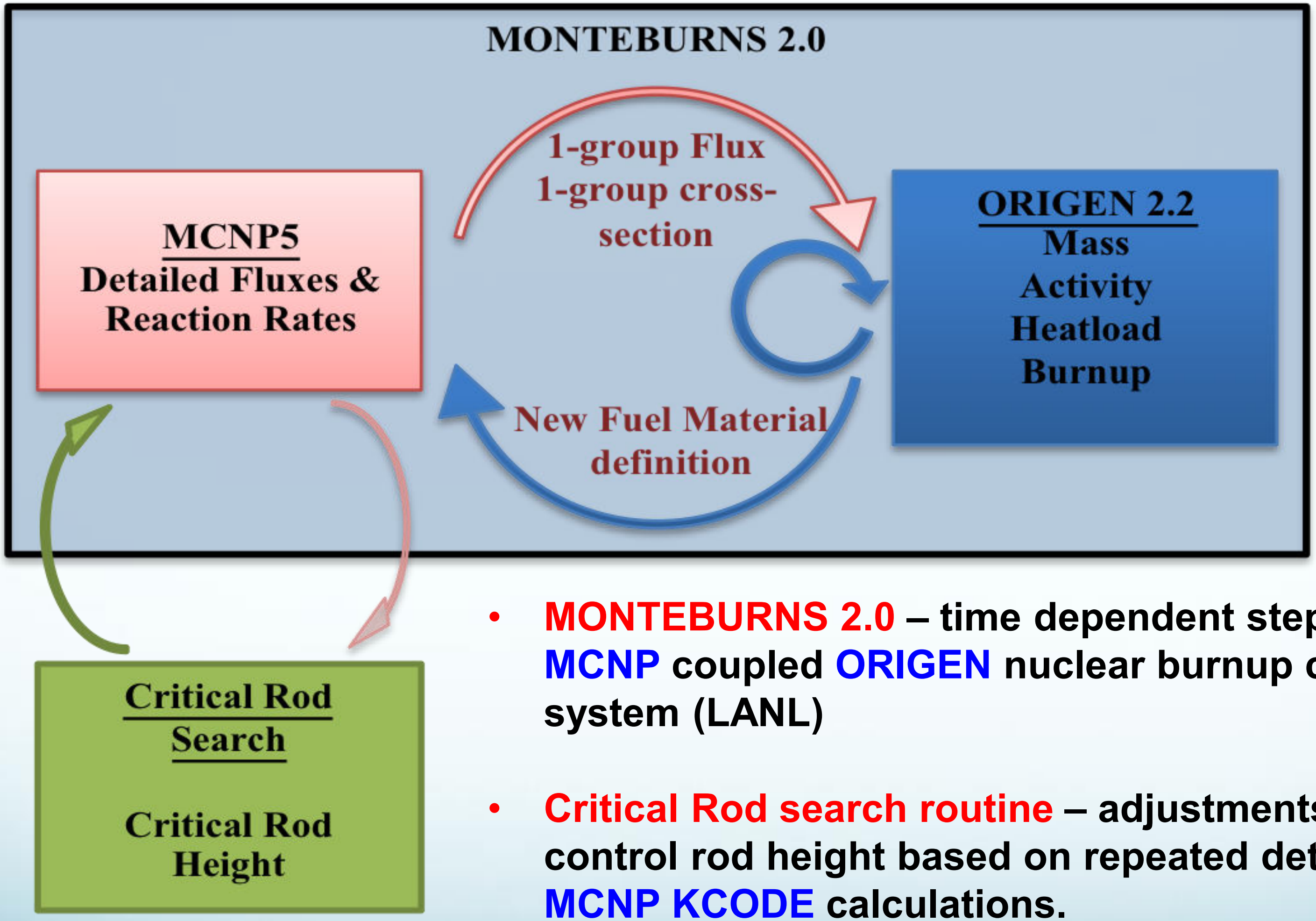
It would be advantageous to predict whether a Hot Startup is possible and, if a restart is possible, then predict an Estimate Critical Position (ECP) based on;

- the maximum control rod travel and height prior to the unplanned shutdown
- the reactor downtime following the unplanned shutdown
- the total rod worth and effects from operating history of the core, beryllium reflector burnout, flux-trap sample loadings, etc.

Based on the above factors, the goal in this work is to develop a novel methodology, using an "in-house" modified version of MONTEBURNS 2.0 with a critical rod search routine, to predict the ECP for Hot Startups thus, determining the Hot Startup possibility.

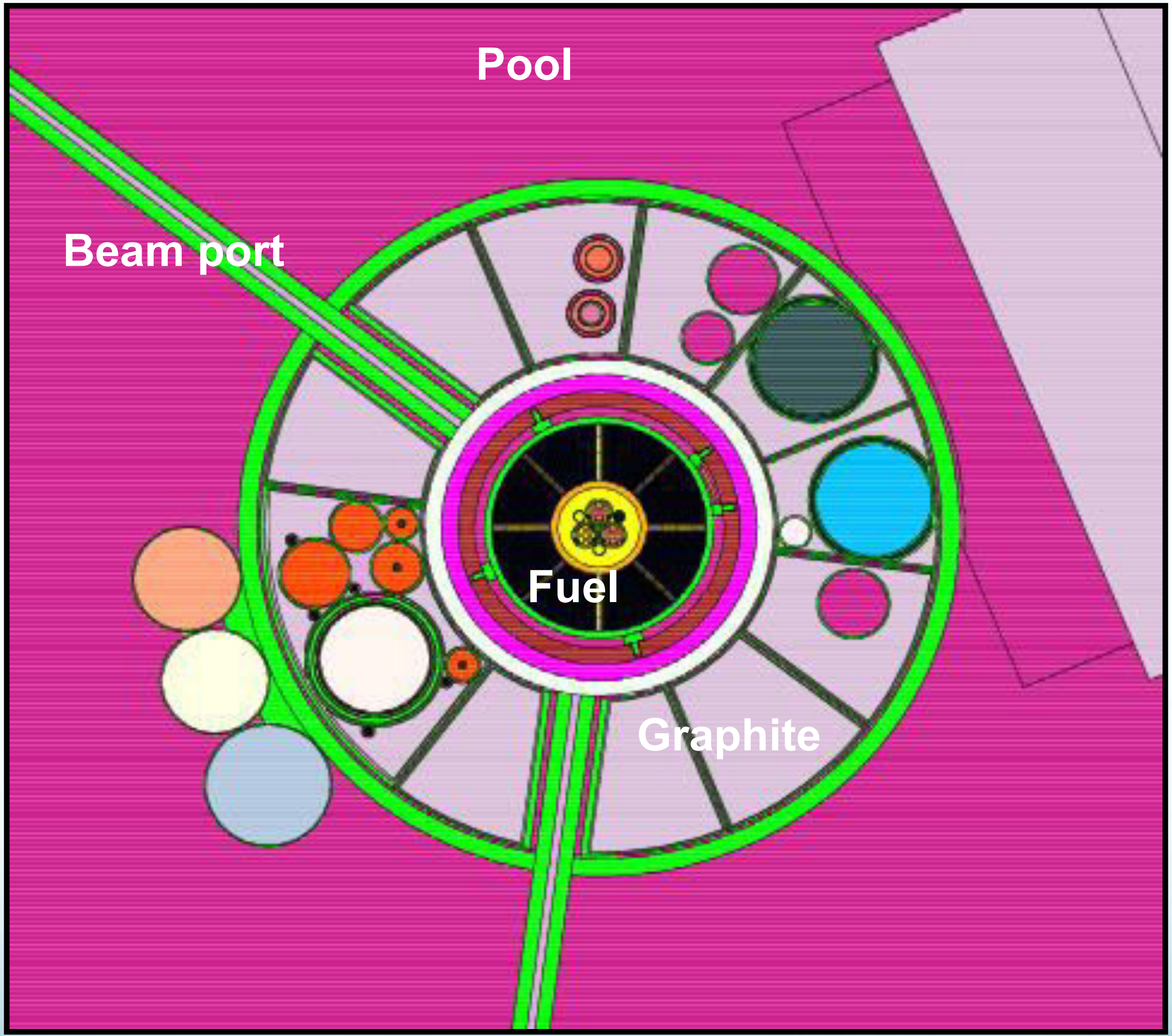
Computational Methodology

MONTEBURNS 2.0 Modified with Critical Rod search routine



- **MONTEBURNS 2.0 – time dependent stepwise MCNP coupled ORIGEN nuclear burnup code system (LANL)**
- **Critical Rod search routine – adjustments to control rod height based on repeated detailed MCNP KCODE calculations.**
    - **Returns a critical rod height if the KCODE k_{eff} is 1.0000±0.03% and control rod is less than maximum travel**

MCNP5 MURR Core Model Geometry



Changeable Details in the MURR MCNP Model to Capture Weekly Core Configuration

- **Selectable megawatt-days for individual xenon-free fuel element** – any weekly mixed-fuel core configuration can be modeled using a material data bank from a MURR fuel depletion/shuffling cycle simulation.

- **Selectable megawatt-days for individual control rod** – any present mixed (depleted) rod configuration can be modeled using a material data bank from a control rod depletion/shuffling cycle simulation.

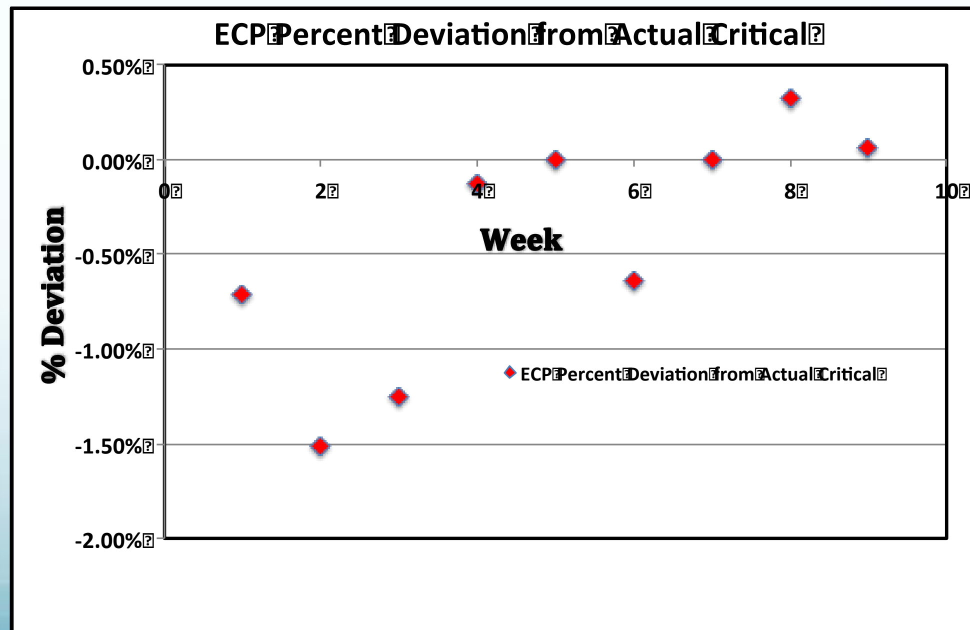
- **Selectable flux trap sample loading** – weekly flux trap sample configuration can be modeled.

- **Selectable stage of beryllium reflector burnout** – beryllium burnout profile at one-year increment up to the life expectancy (26000 MWD with HEU core) can be modeled using a material data bank from a beryllium depletion simulation.

Benchmarking for Critical Rod Height Search Routine Predictions: Initial Startup ECP

Core Configuration Date	Actual Initial Critical Height (inches)	Predicted Initial Critical Height (inches)	% Deviation	Flux Trap Configuration
Week of 1/28/2013	16.79	16.67	-0.71%	Strainer
Week of 2/04/2013	16.52	16.27	-1.51%	FT Samples
Week of 4/29/2013	15.98	15.78	-1.25%	FT Samples
Week of 6/10/2013	15.44	15.42	-0.13%	FT Samples
Week of 8/05/2013	16.74	16.74	0.00%	Strainer
Week of 8/12/2013	15.71	15.61	-0.64%	FT samples
Week of 8/19/2013	15.84	15.84	0.00%	FT samples
Week of 8/26/2013	15.64	15.69	0.32%	FT samples
Week of 9/02/2013	15.67	15.68	0.06%	FT samples

- **Highly accurate xenon-free weekly models - %deviation shows an improvement from -1.2% to ±0.25% after week 3.**
- **Beryllium burn-out effects + Updated thermal neutron scattering data for primary coolant/moderator water.**



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Benchmarking the Predicted Xenon Behavior During Unscheduled Shutdown/Hot Startup Events

Event:

- **Initial xenon-free core = 600 MWDs startup on 06/10/2013**
- **Unscheduled reactor shutdown occurred after 11.5 hours of normal operation.**
- **Successful Hot Startup was initiated after 1.5 hours of reactor downtime.**

Time into normal operation from critical (Hours)	Actual Control Rod height inches	Predicted Control Rod Height inches	% Deviation
0	15.44	15.41	0.194%
5.75	17.16	17.19	-0.175%
11.5	19.25	19.15	0.519%
Time into Hot Startup operation from critical (Hours)			
0	22.95	22.73	0.959%
1.00	21.04	21.00	0.190%

Data shows highly accurate predictions in tracking Xe-135 buildup during reactor operations.

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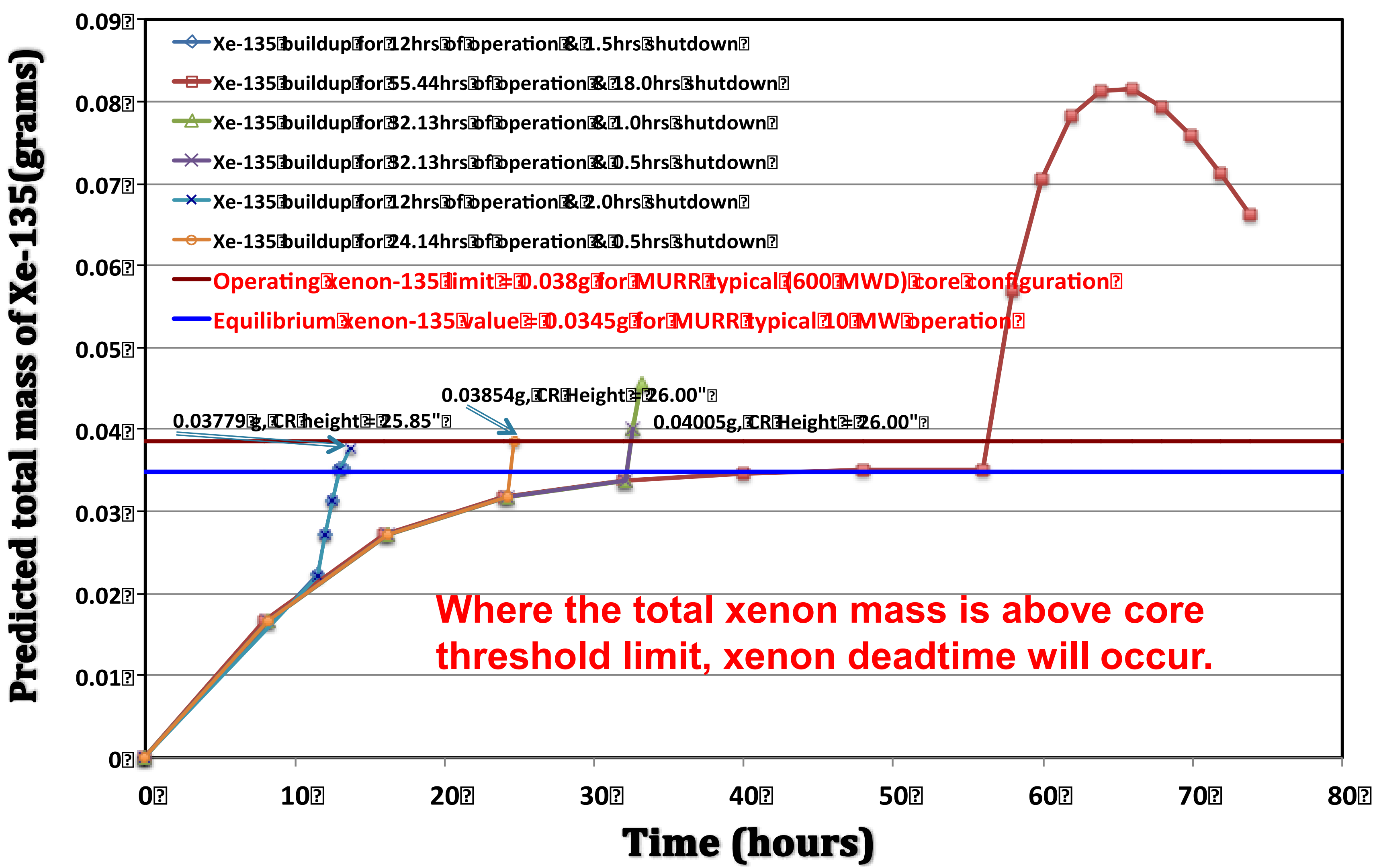
Predicted ECP for Simulated Unscheduled Shutdown/Hot Startup Cases

- Predicted Initial, Shutdown and Hot Startup ECPs for the 600 MWD (typical) core.
- Benchmark
- Limiting case to where the xenon-135 concentration can be overridden – control rods near maximum withdrawn limit of 26 inches where the rod worth is very small.
- Hot Startup cannot occur; k_{eff} is less than 1.0000±0.03% and control rods is at or exceed maximum withdrawn limit of 26”.

Initial Critical ECP inches	Days of Full-power Operation	Shut down ECP inches	Shut down period hours	Hot Start up ECP inches
15.42	0.50	19.15	0.5	20.04
15.42	0.50	19.15	1.0	21.18
15.42	0.50*	19.15	1.5*	22.73
15.42	0.50	19.15	2.0	23.85
15.42	0.50	19.15	2.5	25.83
15.42	0.62	19.71	0.5	21.16
15.42	0.62	19.71	1.5	24.88
15.42	0.75	20.29	0.5	22.01
15.42	0.75	20.29	1.0	24.32
15.42	0.75	20.29	1.5	26.00
16.30	1.00	22.90	0.5	26.00
16.30	1.33	23.38	0.5	26.00

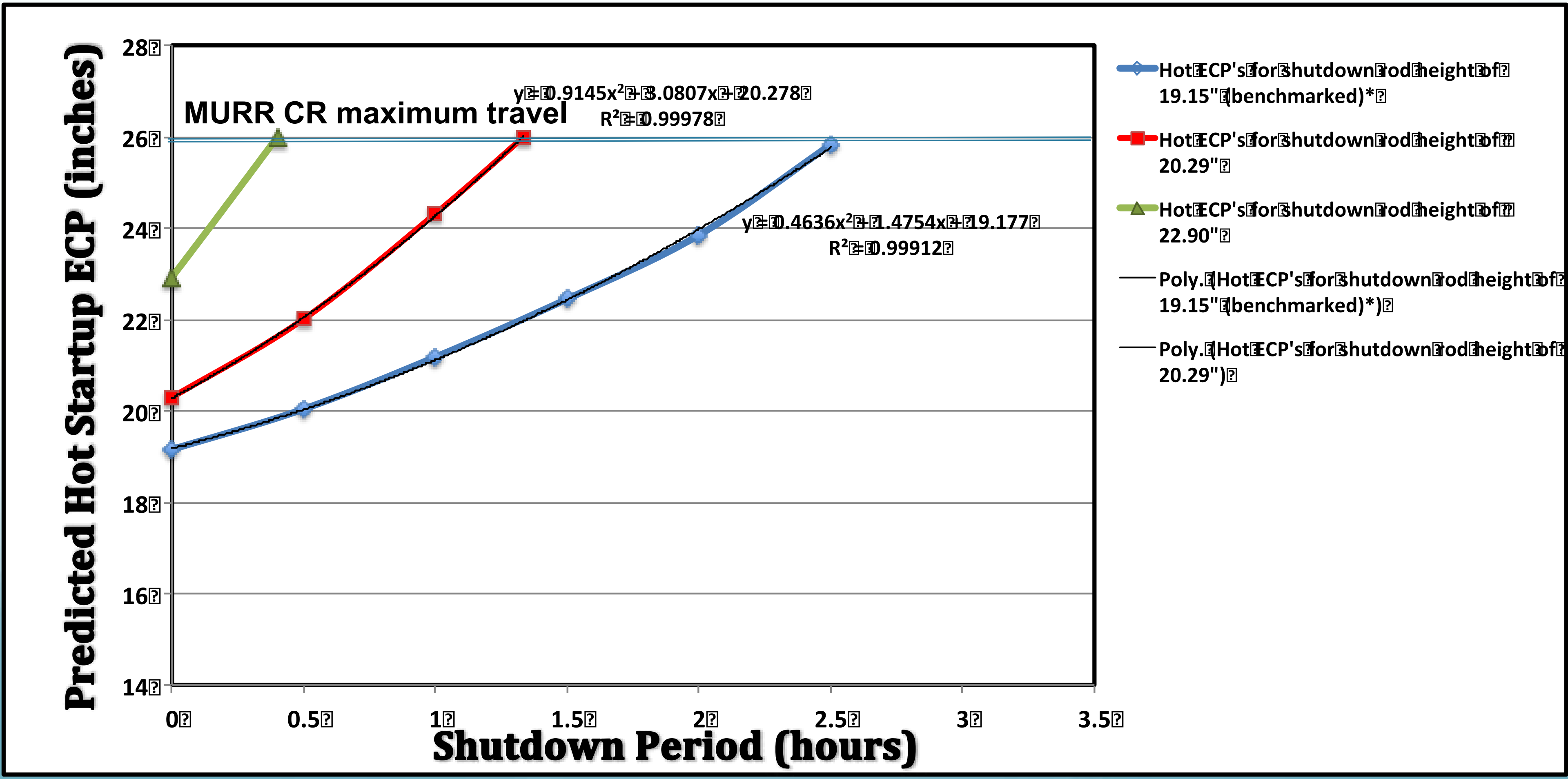
Xenon-135 Transients for Various Simulated Unscheduled Shutdown Cases



Hot Startup ECP Prediction from Computational Model

Predicted Hot Startup ECP curves for three different shutdown control rod heights for MURR 600 MWD core configuration.

Depending on the shutdown height during the initial Xe-135 transient, the shape of Hot-Startup ECP curves varies.



Limitations in Hot Startup ECP Predictions using Computational Model

- Hot Startup ECP curves must be redone for any significant change in the MURR core configuration:
  - Control rod megawatt-days
    - Rod (blade) replacement every 6 months
  - Total core (fuel) megawatt-days
    - Typically consistent (580 – 610 megawatt-days) per week
  - Beryllium reflector megawatt-days
    - Constant burnout; replacement every 8 years
  - Flux-trap load
    - Weekly variation; small
- Computationally expensive; takes weeks to generate series of Hot Startup ECP curves

Investigation of an Analytical Model for Hot Startup ECP

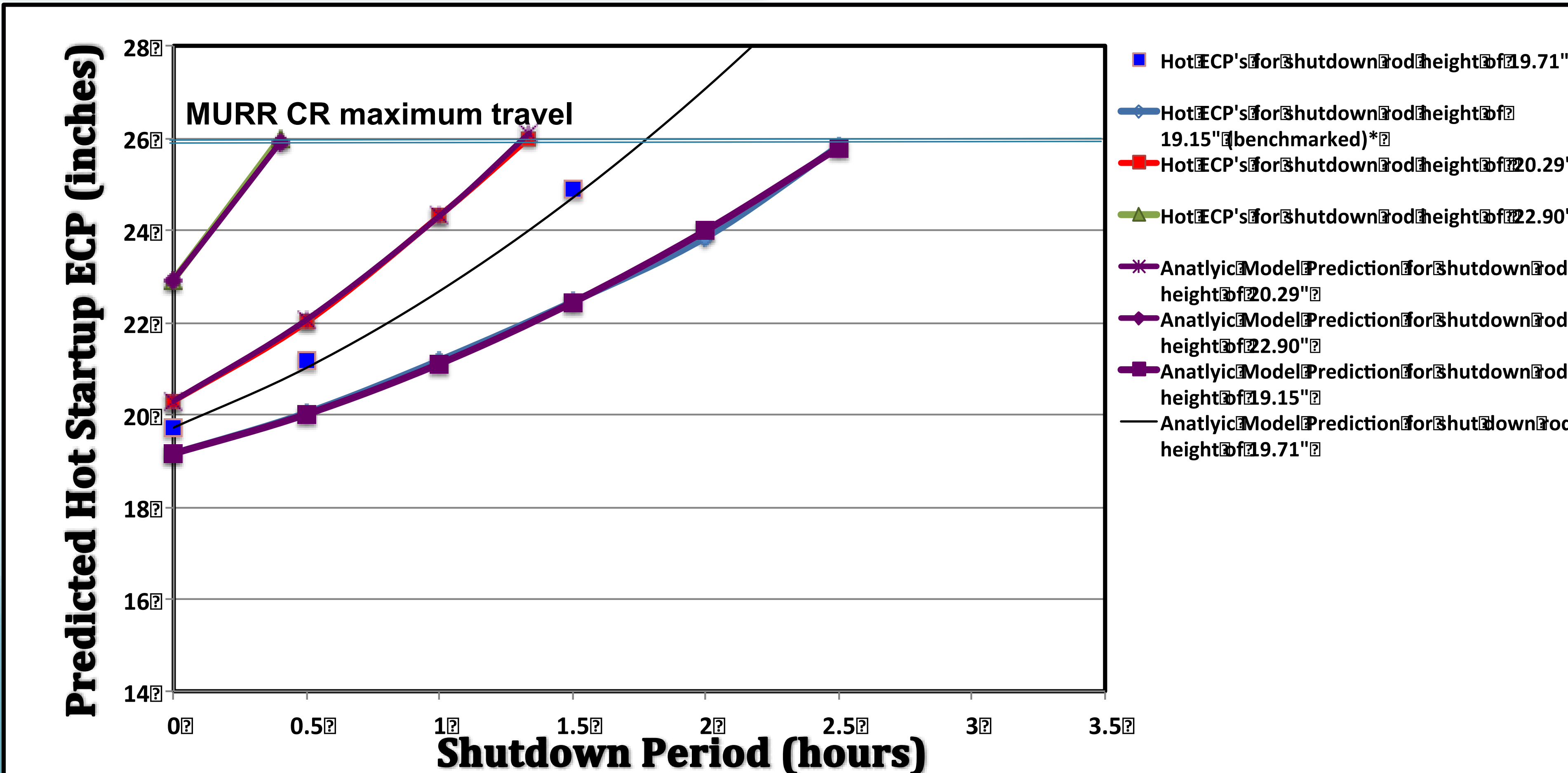
$$h_{ECP*} = azt^2 + bzt + zc + h_{ref}$$

where, h_{ECP*} = Hot Startup ECP, $h_{ref} = 18.065$,

$$z \text{ is } f([\text{Xe-135}]) = \frac{(h_{shutdown} \quad h_{ref})}{c}$$

$a = 0.24$, $b = 0.762$, $c = 0.551$, t = shutdown period

h_{ref} is the shutdown rod height below which the occurrence of xenon deadtime is no concern.



A Universal Parameter for Predictions Using the Analytical Model

- **The shutdown rod height h_{ref} is expected to vary with core configuration**
  - **A change in the core configuration can be evaluated as a change in the value of h_{ref}**

- **The shutdown rod height h_{ref} for a particular reactor configuration yields a peak buildup quantity of xenon-135, below which is too small to cause a xenon deadtime regardless of reactor downtime.**
  - **For the typical 600 MWD core configuration the minimum shutdown rod height = 18.065" yield a peak Xe-135 mass = 0.038g**

- **Caveat: Due to a quadratic approximation to $h_{shutdown}$([Xe-135)]), below the minimum shutdown ECP (h_{ref}) the predicted Hot Startup ECP is not valid.**

SUMMARY

- A novel methodology was developed using an "in-house" modified version of MONTEBURNS 2.0 with a critical rod search routine to predict an Estimated Critical Position (ECP) for a particular MURR core configuration and state point.
- Benchmarks for the xenon-free Startup ECPs predicted by the critical rod search routine using a highly detailed MURR core MCNP5 model are shown to be highly accurate within ±0.25%.
- The computational simulations used to predict Hot Startup ECPs accurately tracks Xenon-135 production for any given core configuration hence, predicts the possibility of Hot Startup for a given reactor downtime quite well.
- Hot Startup simulations using the codes in this work are computationally expensive, however, their predictions serves as strong base for the development of an analytic model to predict the Hot Startup ECP.

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Thank you

Questions ?

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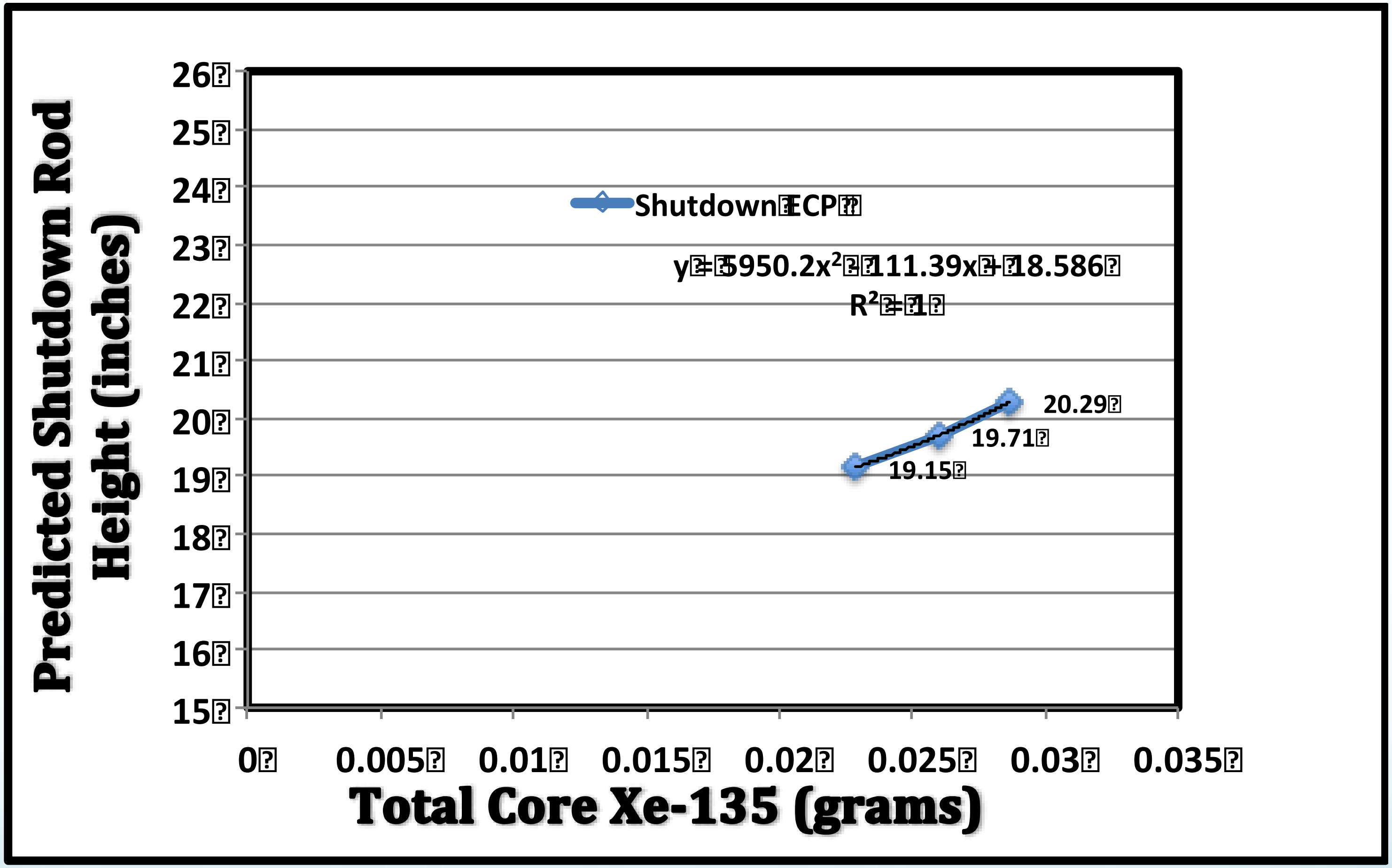
Extra Slide 1 shutdown rod height vs total Xe-135 mass



For $x_{(min)}$ => $dy/dx = 0$ => .0096g Xe-135

Minimum height (h_{ref}) =$y(x_{(min)})$ = 18.065”