Research and Educational Opportunities in Nuclear Nonproliferation at North Carolina State University

Presented to ORNL Workshop on Nuclear Nonproliferation
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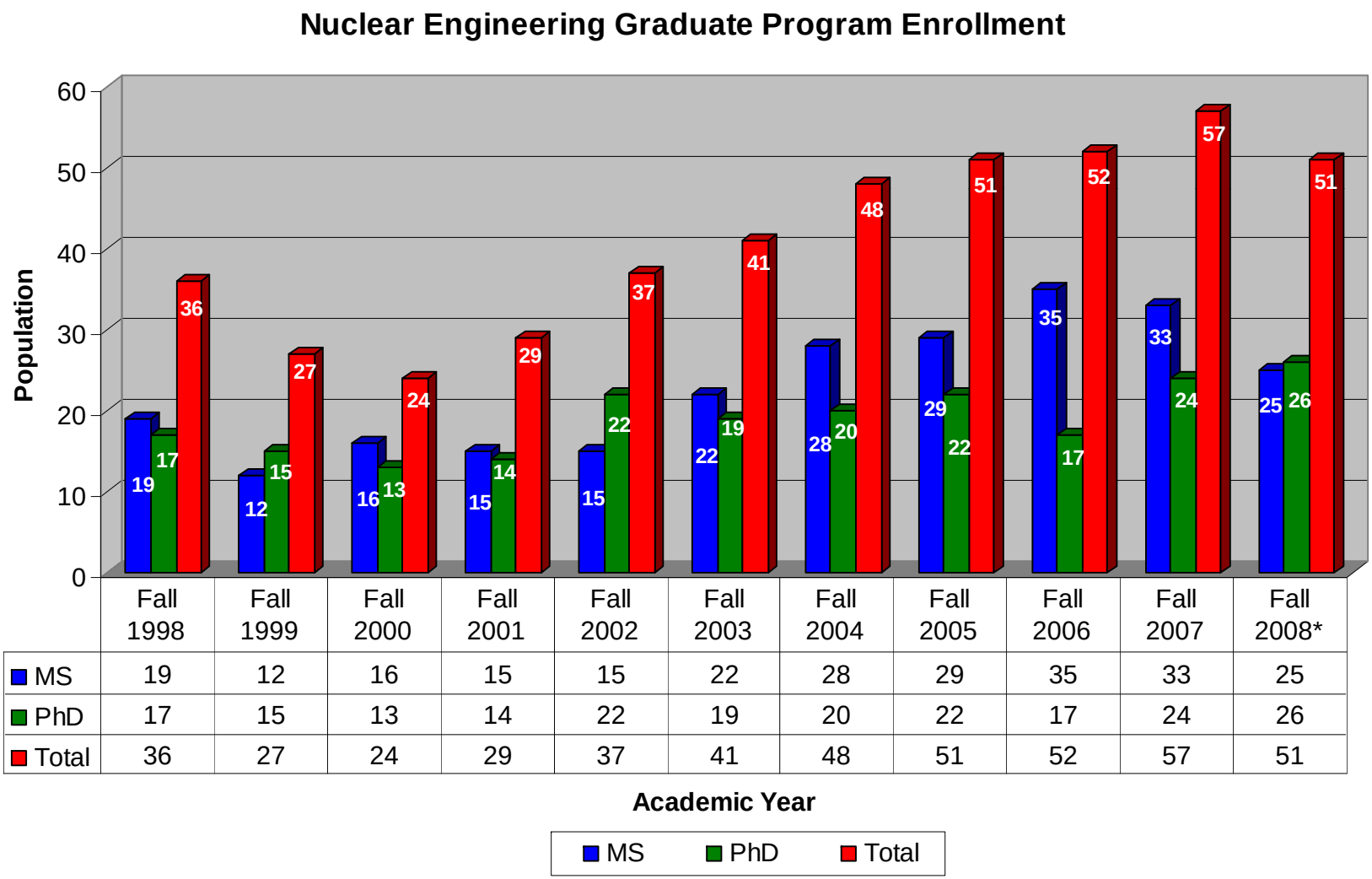
NCSU Nuclear Engineering

- One of the first NE Departments in the U.S.
- Ranked 7th in the Nation according to the U.S. News and World Report
- Lead on INIE/MUSIC Consortium
- Member of Idaho National Laboratory/Nuclear University Collaborators
- Participant in Homeland Security Fellowship Program
- Full-time NE Faculty: 13
- Enrollments
  - Undergraduates: BSNE 153
  - Graduates: MS/MNE/PhD 53
- Annual Research Expenditure: ~$3.8M (2006)/2.8M (2007)

Graduate Program Enrollment
for last decade



	Fall 1998	Fall 1999	Fall 2000	Fall 2001	Fall 2002	Fall 2003	Fall 2004	Fall 2005	Fall 2006	Fall 2007	Fall 2008*
MS	19	12	16	15	15	22	28	29	35	33	25
PhD	17	15	13	14	22	19	20	22	17	24	26
Total	36	27	24	29	37	41	48	51	52	57	51

Undergraduate Enrollment

Year	2004		2005		2006		2007		2008	
Semester	F	S	F	S	F	S	F	S	F	S
Students	102	106	121	125	133	124	136	129	153	

Future Plans

- Full-time Faculty: 17 (Add 4) in 4 years
- Graduate Enrollment Target: 80
- Undergrad Enrollment Target: 160

Existing Courses related to Nonproliferation*

- Nuclear Fuel Cycle (NE 512)
- Radiation and Reactor Fundamentals (NE 520)
- Nuclear Waste Management (NE 531)
- Nuclear Nonproliferation Policy (NE 591)
- Nuclear Laboratory Fundamentals (NE 721)
- Nuclear Reactor Analysis (NE 723)
- Radioisotope Measurement Applications (NE 726)
- Nuclear Engineering Analysis (NE 727)
- Radiation Detection (NE 761)
- Radioisotope Applications (NE 762)

* Adding a course on Nuclear Nonproliferation and Safeguards under consideration

Full Time NE Faculty

- **Yousry Azmy,** Computational reactor physics, transport analysis
- **Hany Abdel-Khalik,** Computational reactor physics, Inverse problems.
- **Dimitry Anistratov,** Computational physics, numerical transport theory, numerical analysis.
- **Mohamed A. Bourham**, Plasma-wall interaction, pulsed power, plasma diagnostics, plasma instabilities, low-temperature plasmas, plasma coatings.
- **J. Michael Doster**, Heat transfer and thermal hydraulics in reactors and plasma and medical devices, computational stability of thermal-hydraulic models, radiation transport calculations.
- **Jacob Eapen,** Molecular and multiscale modeling of materials and transport, Thermal hydraulics
- **Robin P. Gardner**, Radioisotope measurement applications, Monte Carlo simulation of radiation gauges and analyzers, radiation detection.
- **John G. Gilligan,** Plasma-materials interaction, plasma physics, fusion technology.
- **Ayman I. Hawari**, Radiation measurements, gamma-ray spectrometry, nuclear reactor dosimetry, application of neutrons in nondestructive analysis.
- **K. Linga Murty**, Nuclear materials, deformation and cracking mechanisms, dynamic properties of defects in materials, in-situ mechanical testing using indentation microprobes.
- **Steve Shannon,** Plasma-assisted processing of materials, Electronic properties of materials ,
- **Paul J. Turinsky**, Fuel management optimization, computational neutronic analysis, Advanced fuel cycle analysis.
- **M-S. Yim**, Nuclear waste management, fuel cycle studies, radiological science, policy studies.

Faculty Experience related to Nonproliferation

- Dr. Hany Abdel-Khalik:
  - Research in inverse problem solving
- Dr. Robin Gardner:
  - Research in radiation detection and radioisotope analysis
- Dr. Ayman Hawari:
  - Research in radiation detection and nuclear material monitoring
- Dr. David McNelis:
  - Research in nuclear fuel cycle, environmental studies, and policy
- Dr. Man-Sung Yim:
  - Research in nuclear fuel cycle, nuclear waste management, nonproliferation, radiological science, and policy
  - Sam Nunn International Security Fellow, Sam Nunn School of International Affairs, Georgia Tech (2003-2004)

Related Research Work: Robin Gardner

- "Developing an Inverse Approach to Monitoring for Special Nuclear Materials"
- "Development of Accurate and Fast Monte Carlo Spectral Simulation Algorithms for Proliferation Detection"
- "Investigation of Methods for Practical Implementation of Coincidence Prompt Gamma-Ray Neutron Activation Analysis"

Related Research Work: Ayman Hawari

- Innovative Scintillators for Nonproliferation Applications
- Active/passive interrogation techniques
- SNM monitoring
- Nuclear fuel monitoring

Related Research Work: Man-Sung Yim

- "A Study of Spent Fuel Reprocessing through Continuous Pyroprocessing"
- "A Fuzzy Logic Barrier Method for Nonproliferation Applications"
- "Development of Predictive Models for a Country's Nuclear Proliferation Decisions"
- "Development of Predictive Capability for Early Detection of Nuclear Material Diversion Attempts at Nuclear Facilities"

Fuzzy Logic Barrier Method (FLBM) for Non-Proliferation Applications

Steve Skutnik

Jun Li

Man-Sung Yim

Why FLBM?

- Less resource-intensive than PRA
- No requirement for sensitive info
- Useful for “roughing out” novel fuel cycle PR performance
- Can be viewed as a **complementary** method to PRA, rather than as a replacement
  - Useful for those who lack access to PRA resources
    - See: academia, commercial utilities, policy makers, etc.

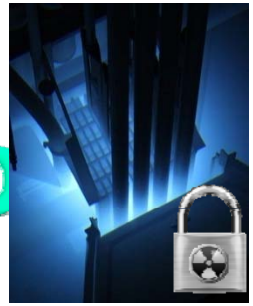
FLBM: General Goals

- Create a **transparent** and **reproducible** model for proliferation resistance in the nuclear fuel cycle
- Use this model to evaluate critical security areas in different fuel cycle scenarios
- Evaluate the effectiveness of existing and proposed proliferation barriers

Required Inputs for Proliferation Resistance Evaluation

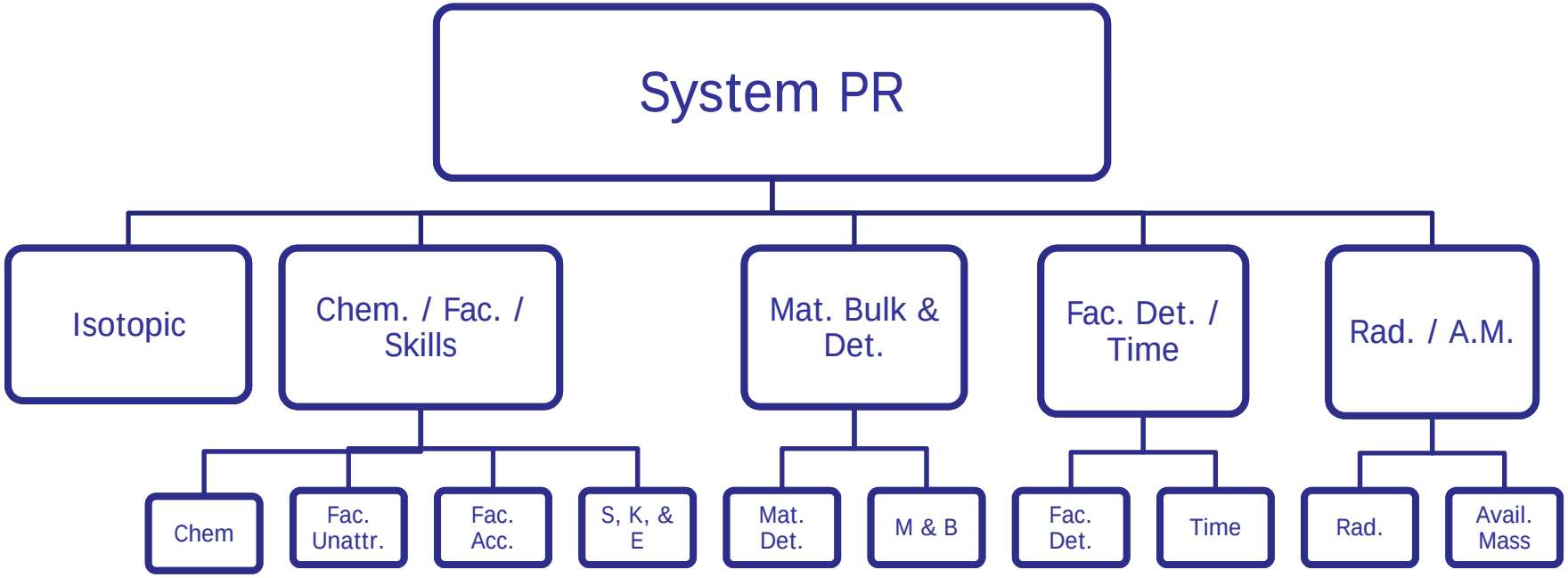
Item	Name	Unit	Comments
1	StageWeight		Concentration of sensitive materials
2	CriticalMass	Kg	Bare sphere Critical Mass (CM)
3	Enrichment	%	Equivalent Enrichment (233U, 235U, 239Pu)
4	SFN	n/Sec/Kg	Spontaneous neutron generation rate
5	HeatRate	W/Kg	Heat generation rate
6	Radiation	MeV/Sec/Kg	Gamma Radiation
7	SeparationCost	$/Kg	Cost to extract the fissile materials
8	DoseRate	mrem/Hr/Kg	Dose rate at 1-meter distance
9	Concentration	# of CM/Kg	Concentration of fissile material
10	Detectability		Detectability levels (Five levels)
11	FacilityModificationTime	Weeks	Modification time needed to produce 1 CM in a year
12	FrequencyofAccess	Days/Yr	Frequency of possible access to facility
13	AvailableMass	# of CM	Available fissile materials
14	UncertaintyofMeasurement	# of CM/Yr	Uncertainty of measurement
15	Knowledge	Yr	Time needed to modify skills and apply them to weapons programs
16	Time	Yr	Time of residence of the materials of interest

Barrier weight selectio

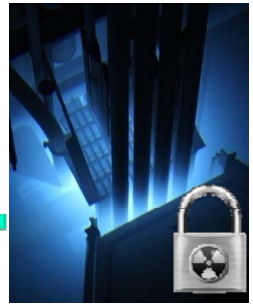


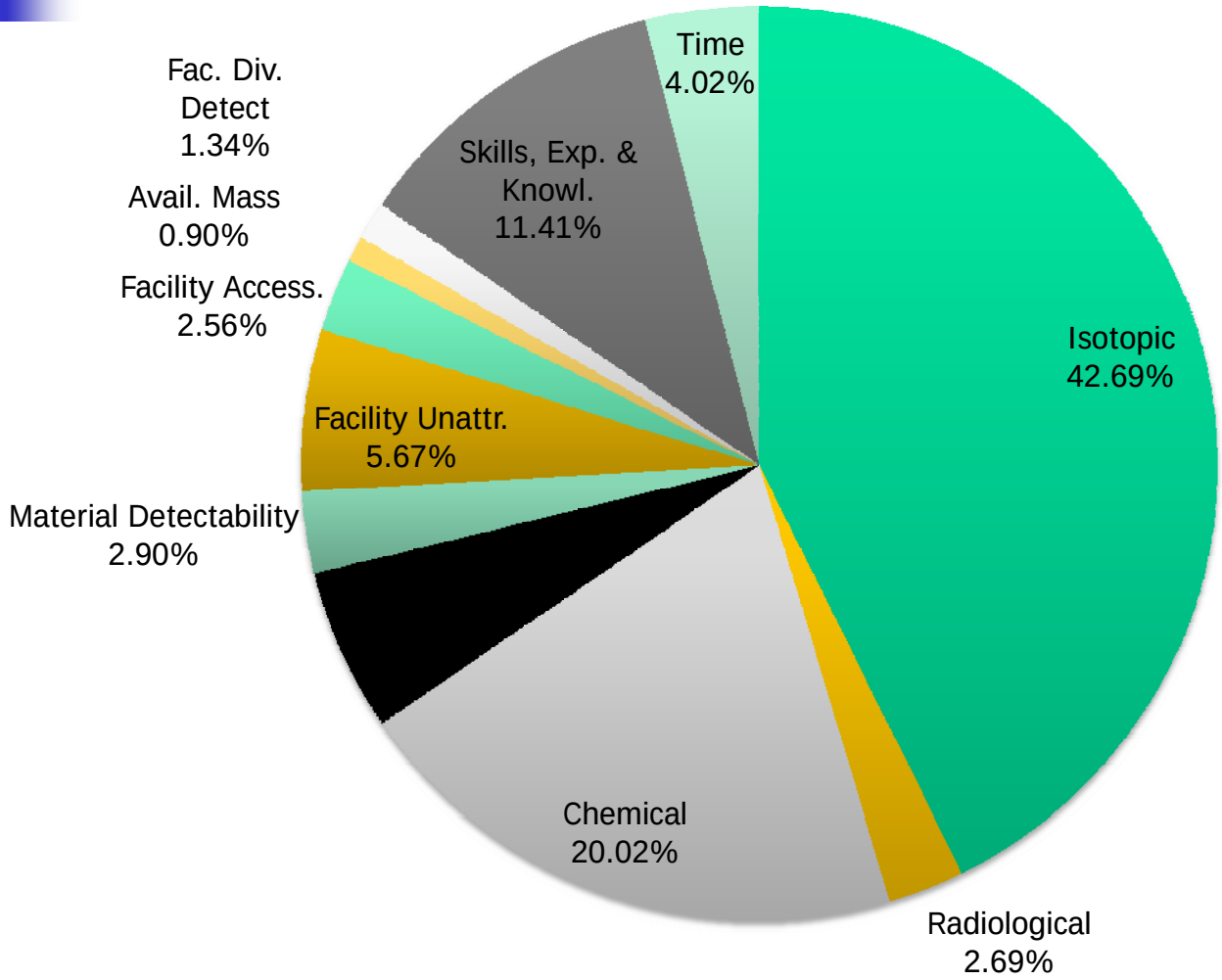
- The problem: AA/MAU models are often criticized for the “subjectivity” inherent in such models
- **Solution:** limit the space of barrier weight possibilities to minimize subjective variance
  - Model calibration
  - Consistent weight selection process

FLBM Hierarchy

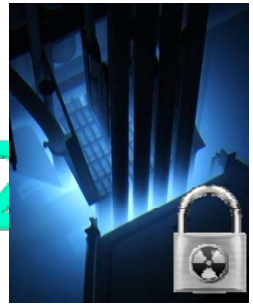


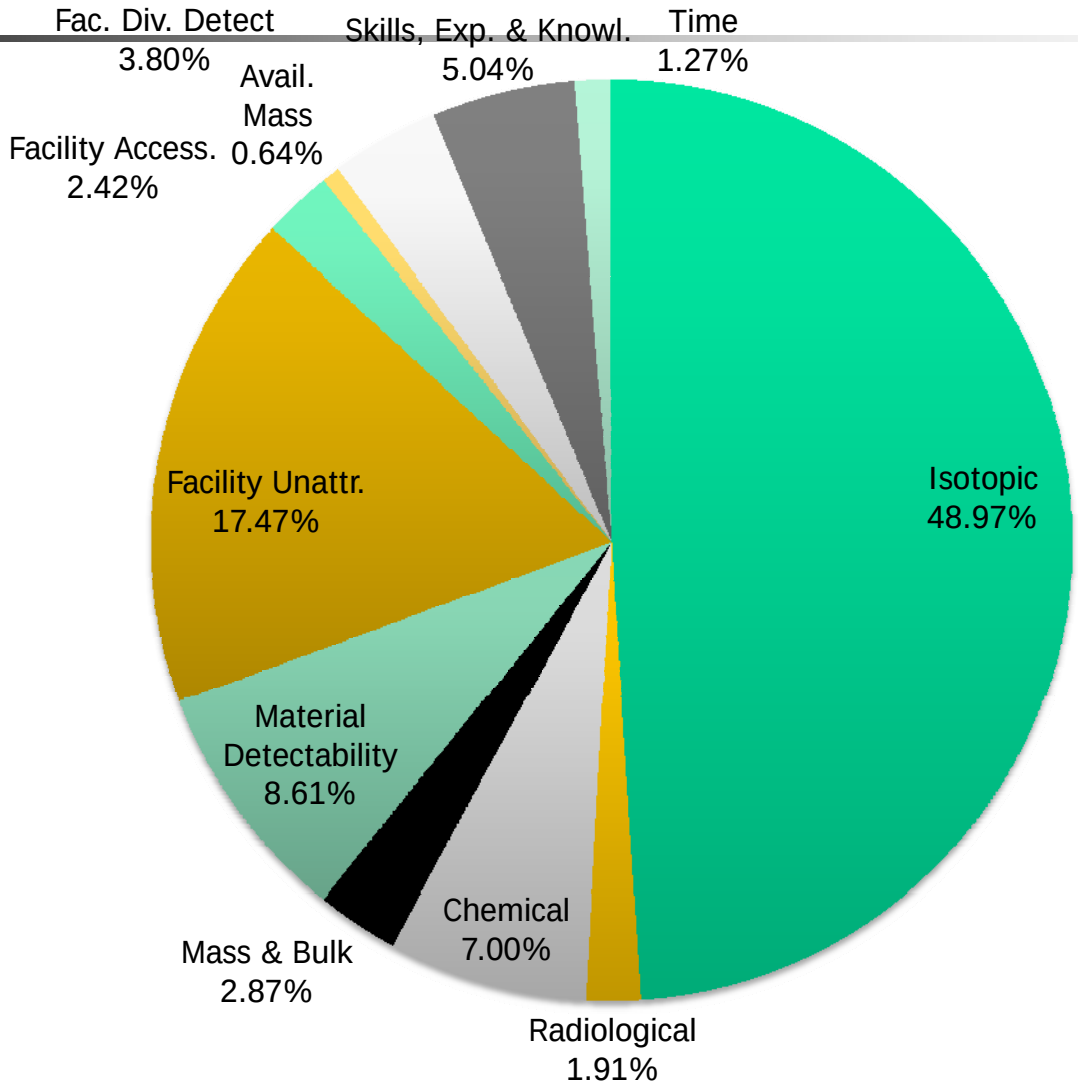
Expert weight: Ex. #1



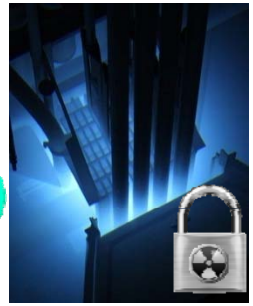


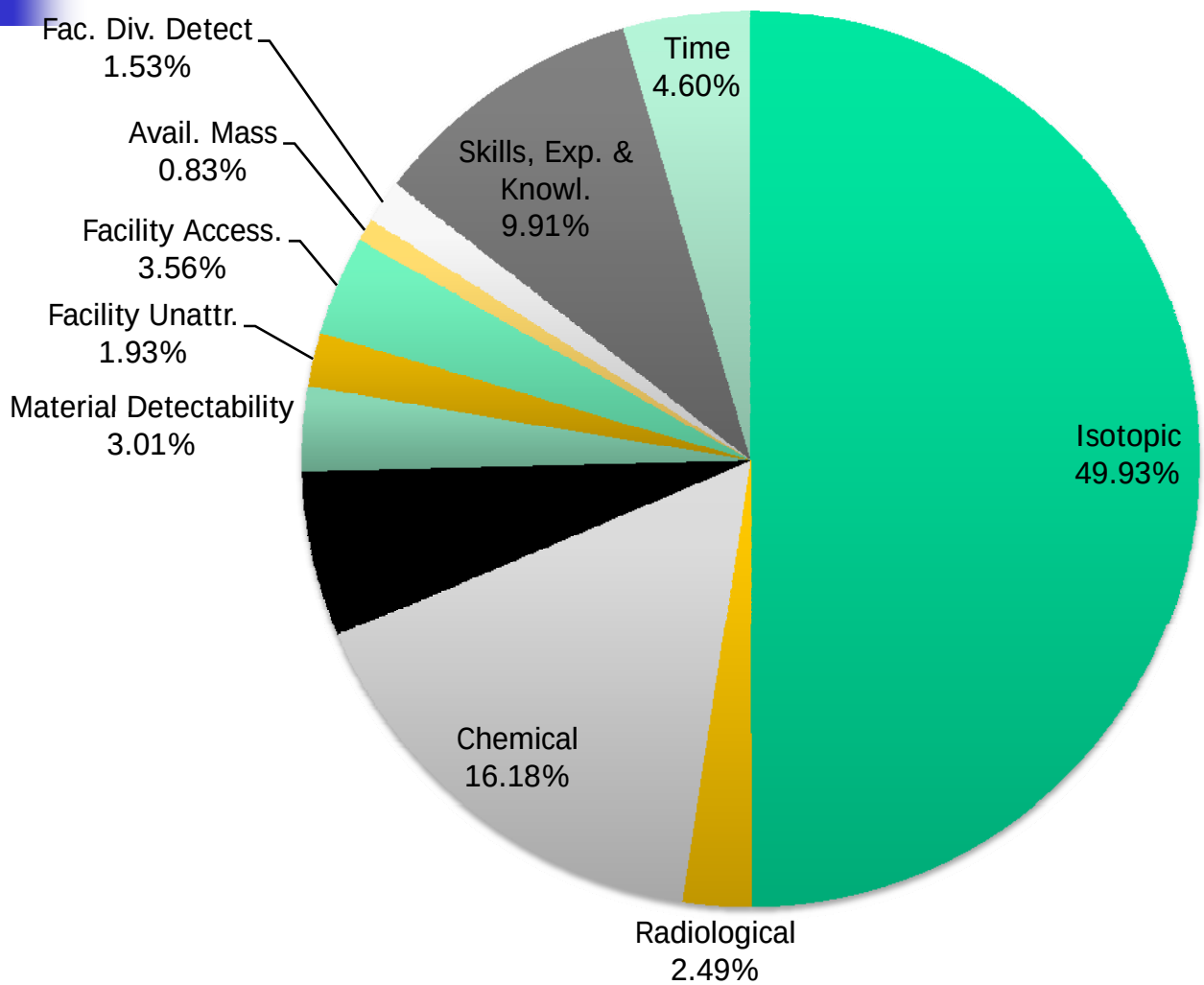
Expert weight: Ex. #2





Expert weight: Ex. Co

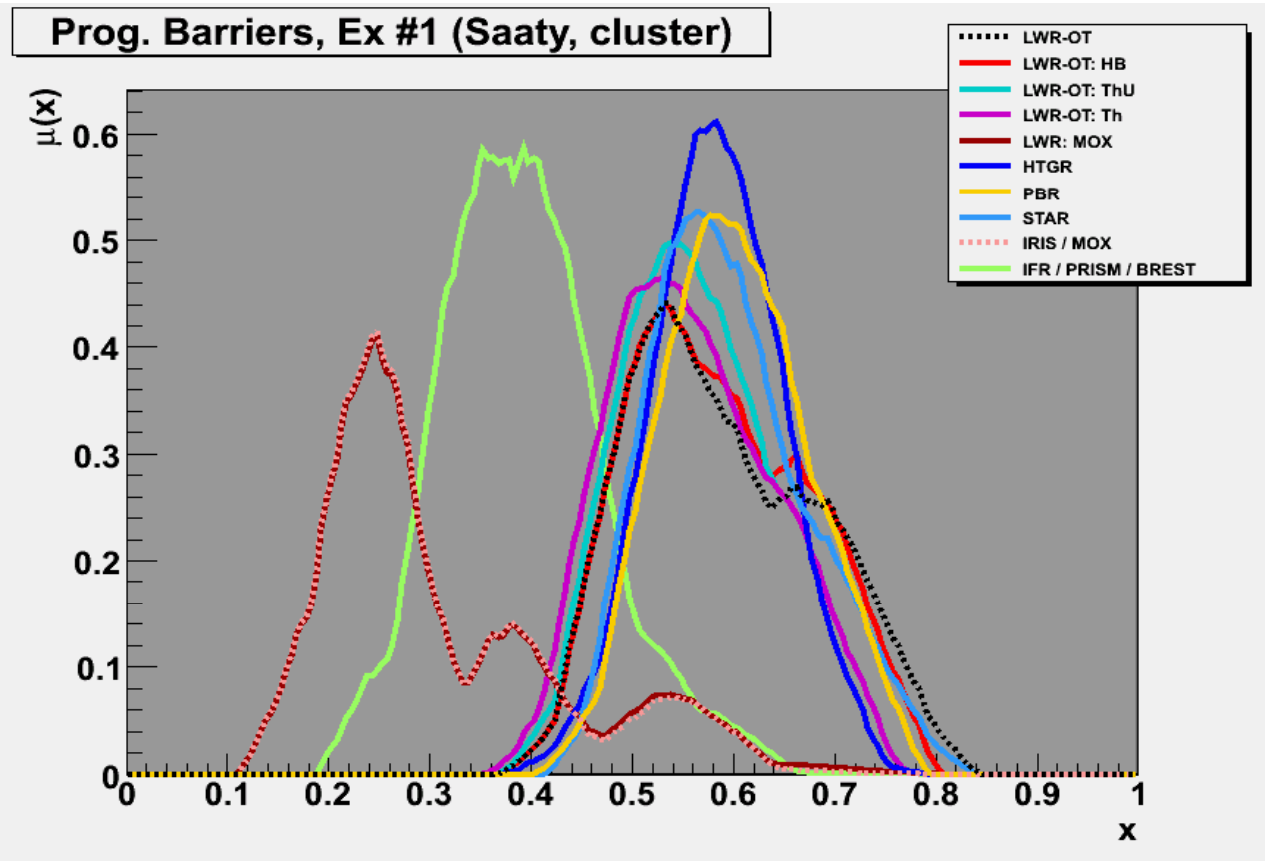




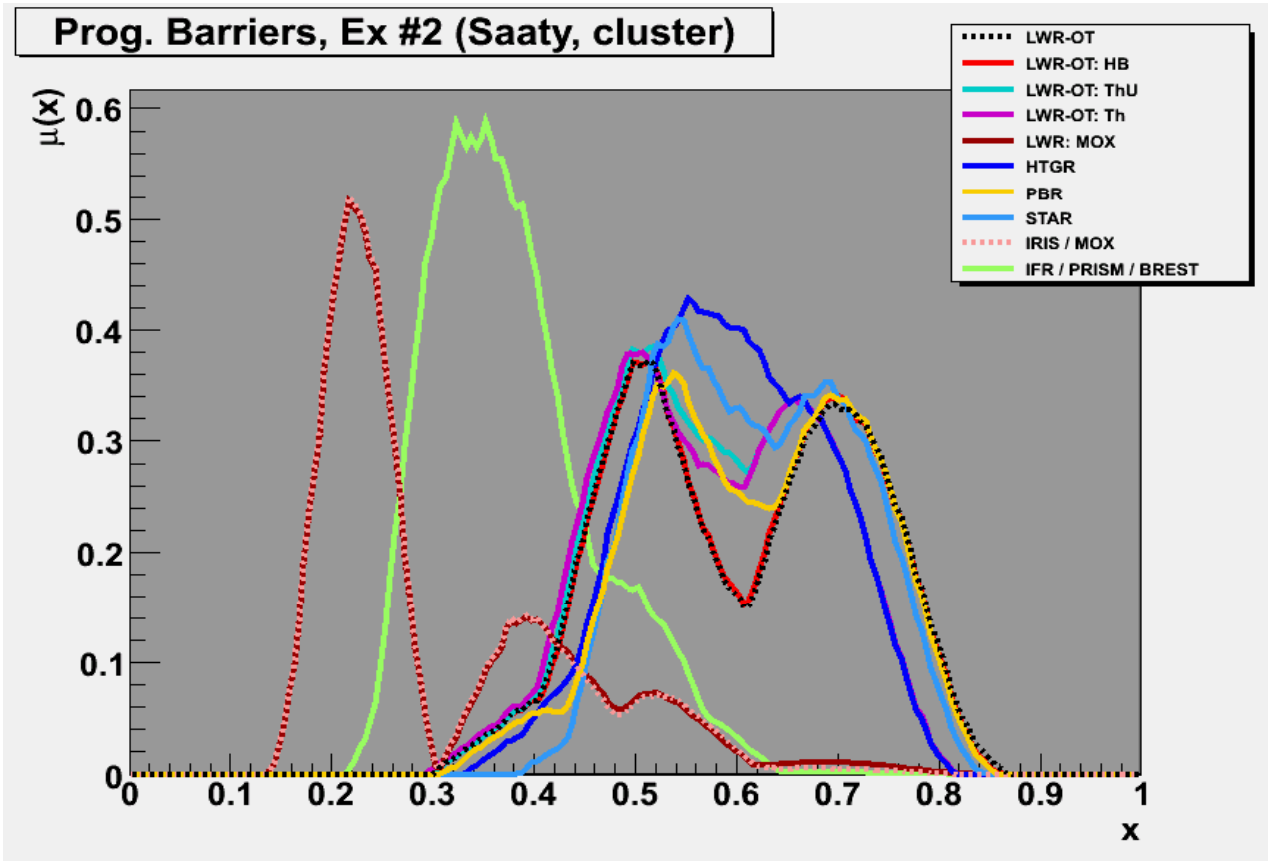
Using the FLB model

- Can use the FLB model to evaluate system performance on several levels
  - **Comparative:** Evaluating the total system performance of several fuel cycles
  - **Cross-section:** Evaluate the PR performance of each stage of an individual fuel cycle
  - **Decomposition:** Break systems down into stages and barriers for analysis

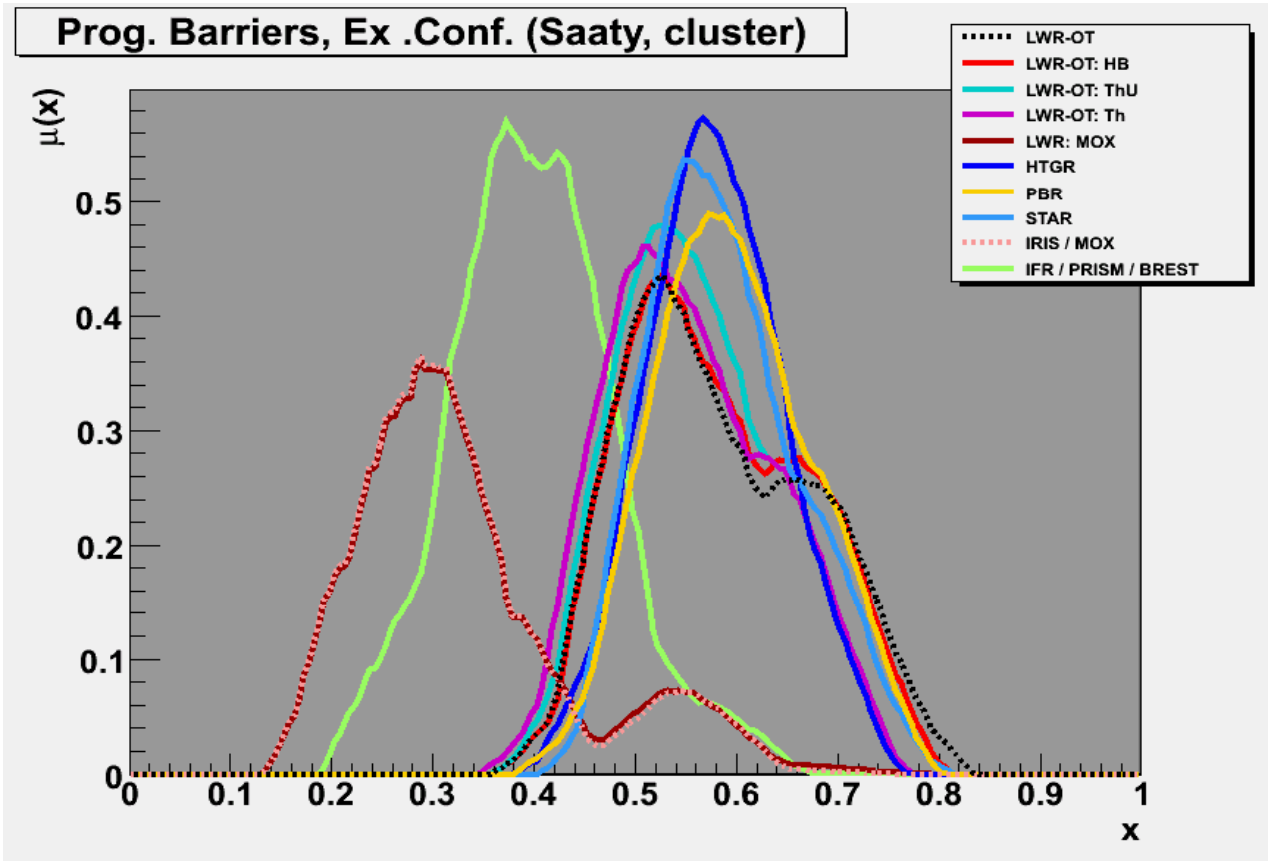
Example: System compari (Ex. #1)



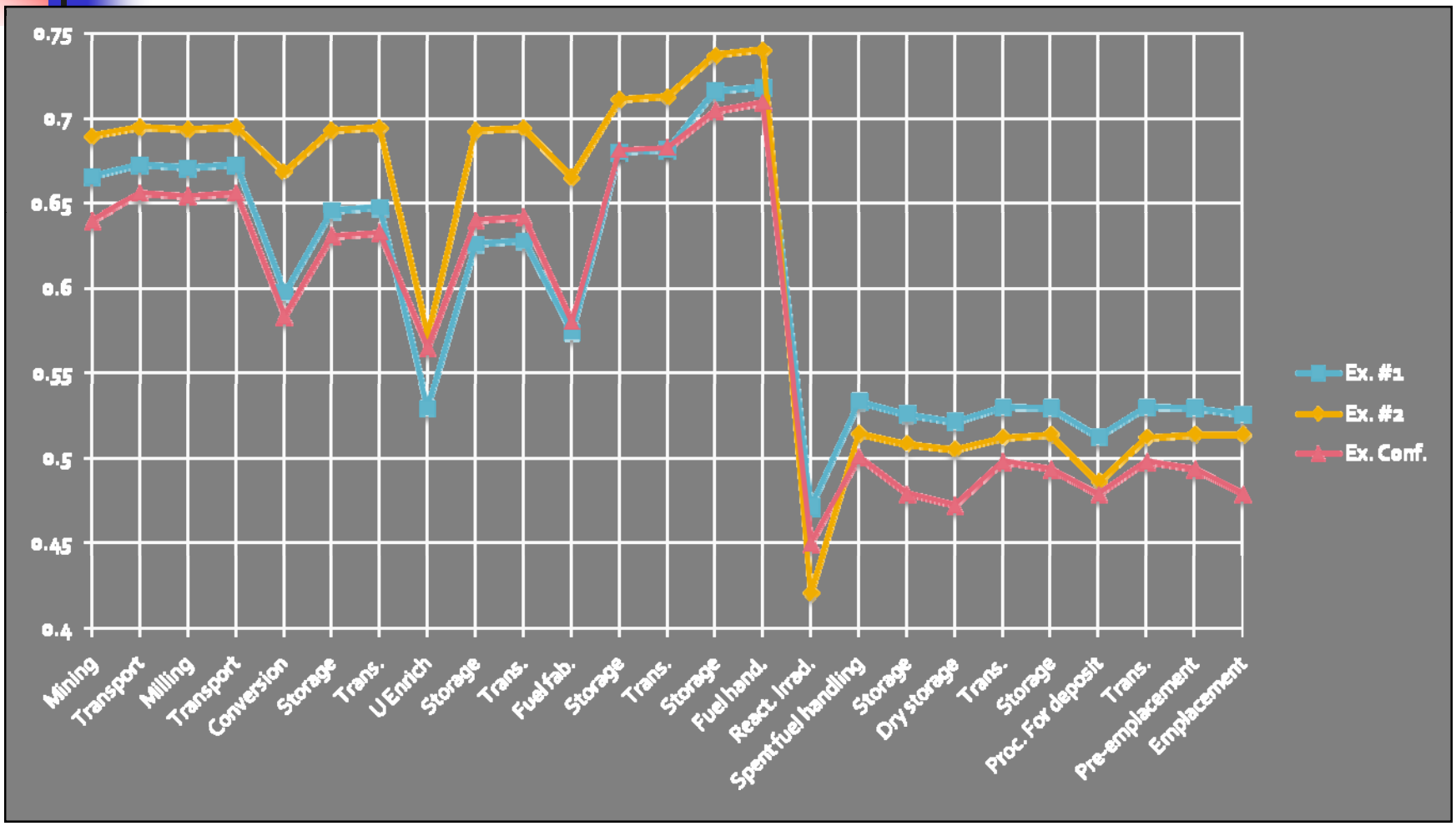
Example: System compari
(Ex. #2)



Example: System compari
(Ex. Conf.)

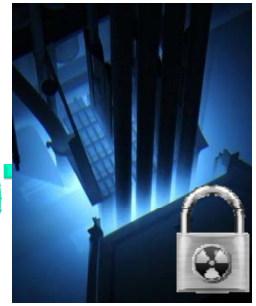


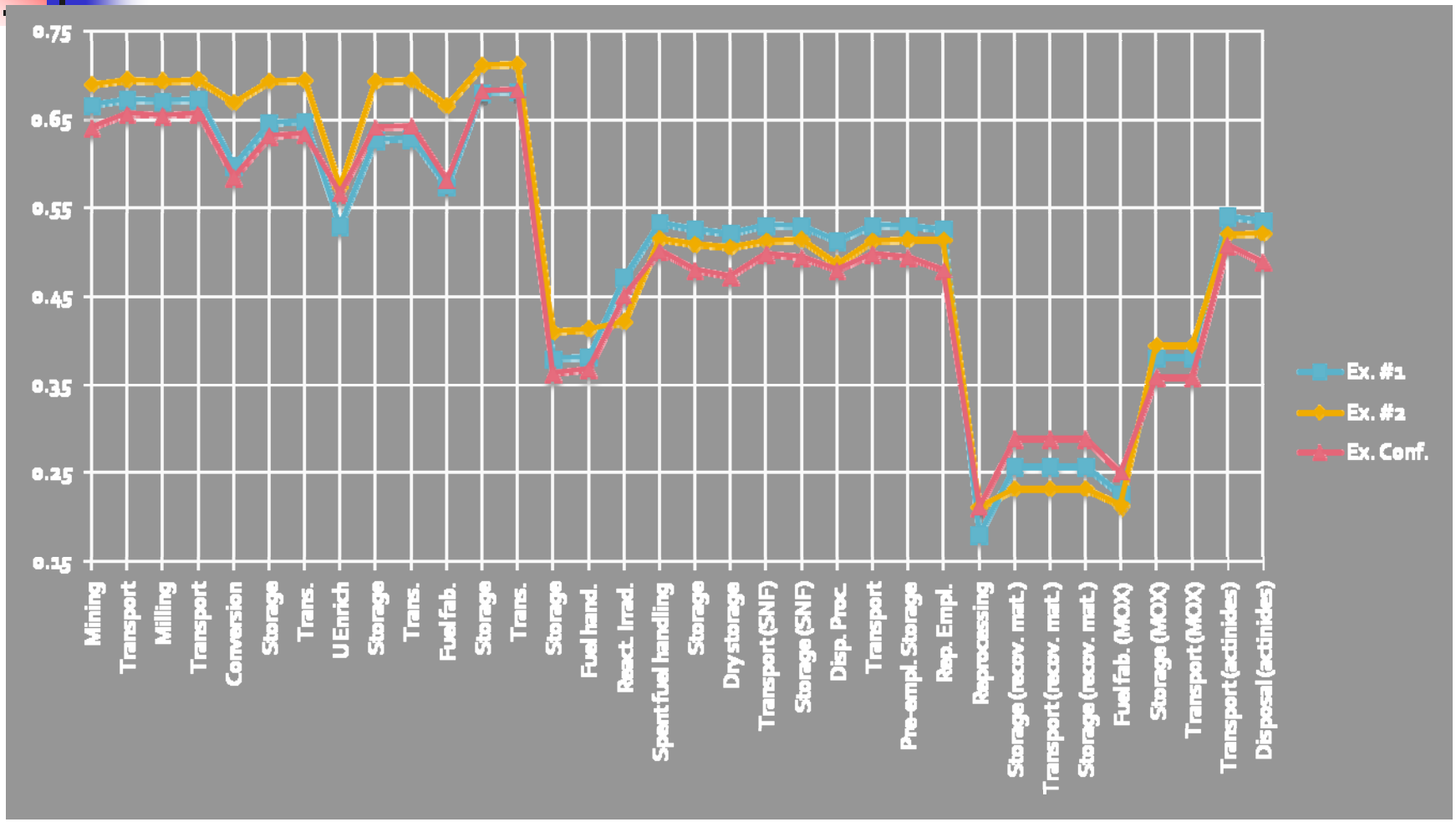
LWR OT: System Profil



Higher values imply greater relative PR

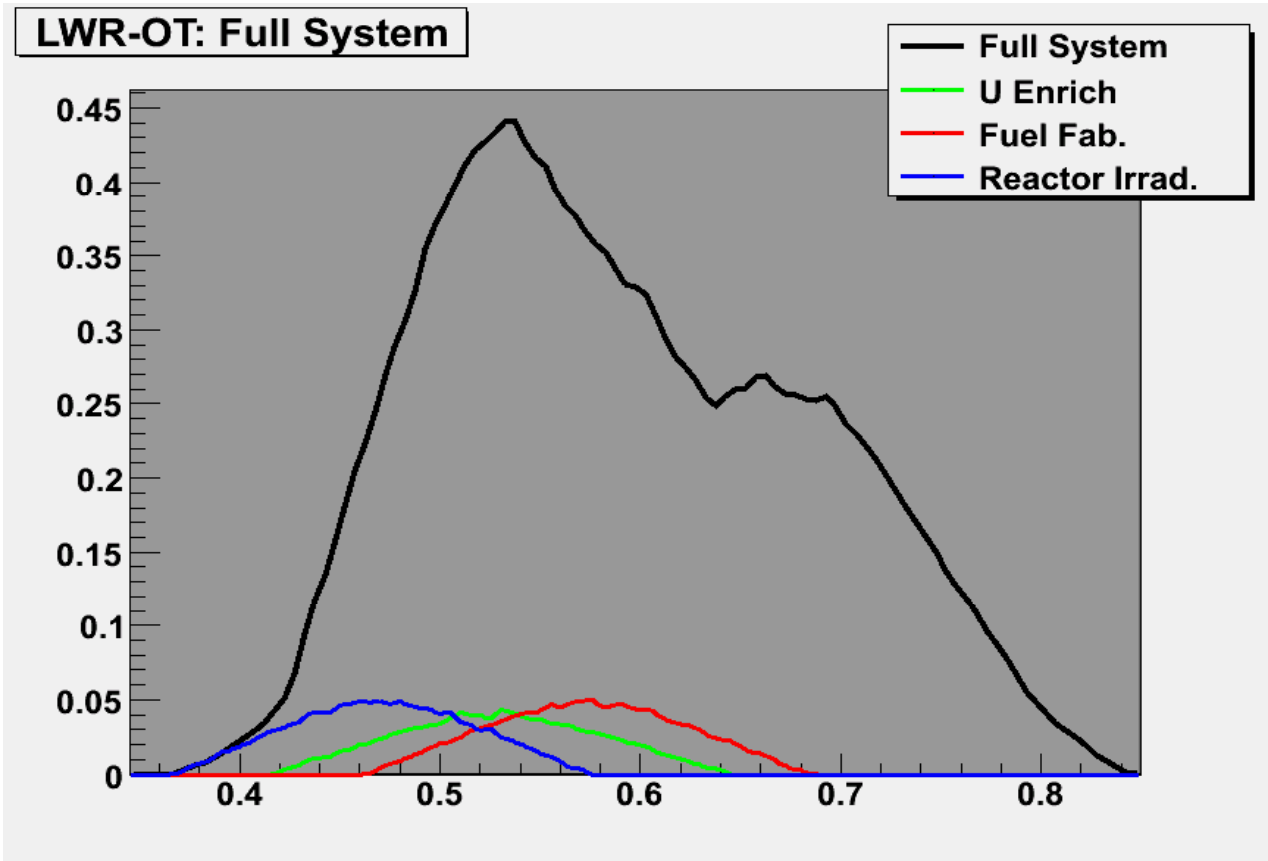
LWR MOX: System Pro



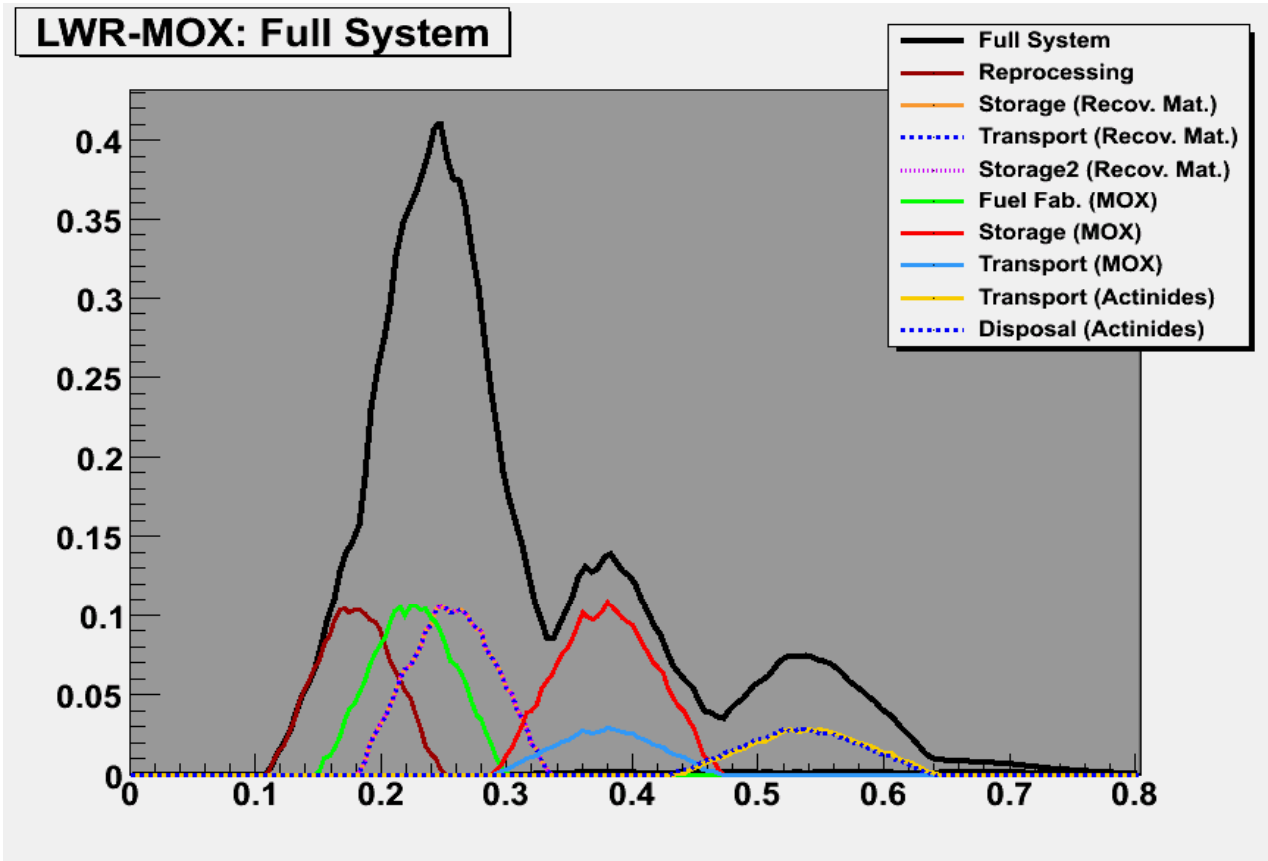


Higher values imply greater relative PR

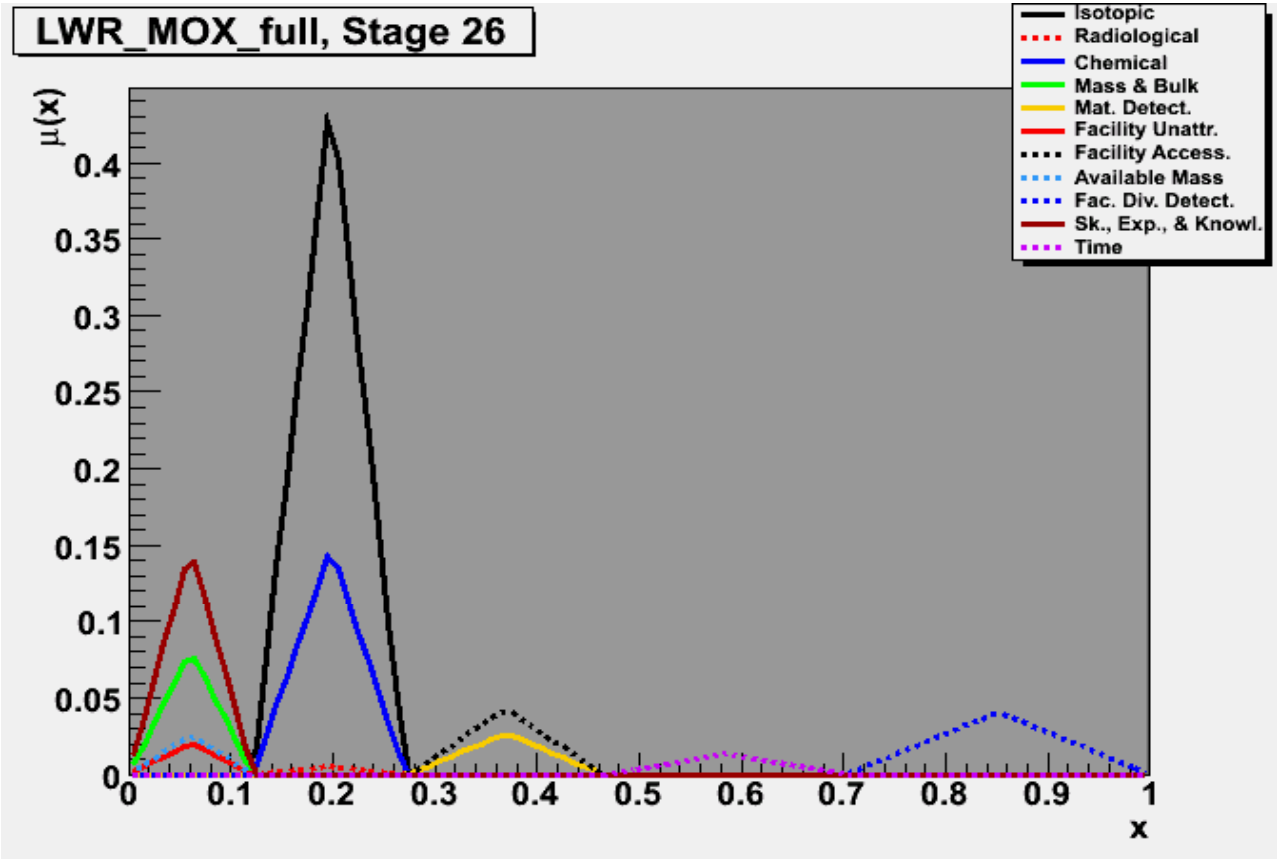
Stage decomposition: LWR OT (Ex. #1)



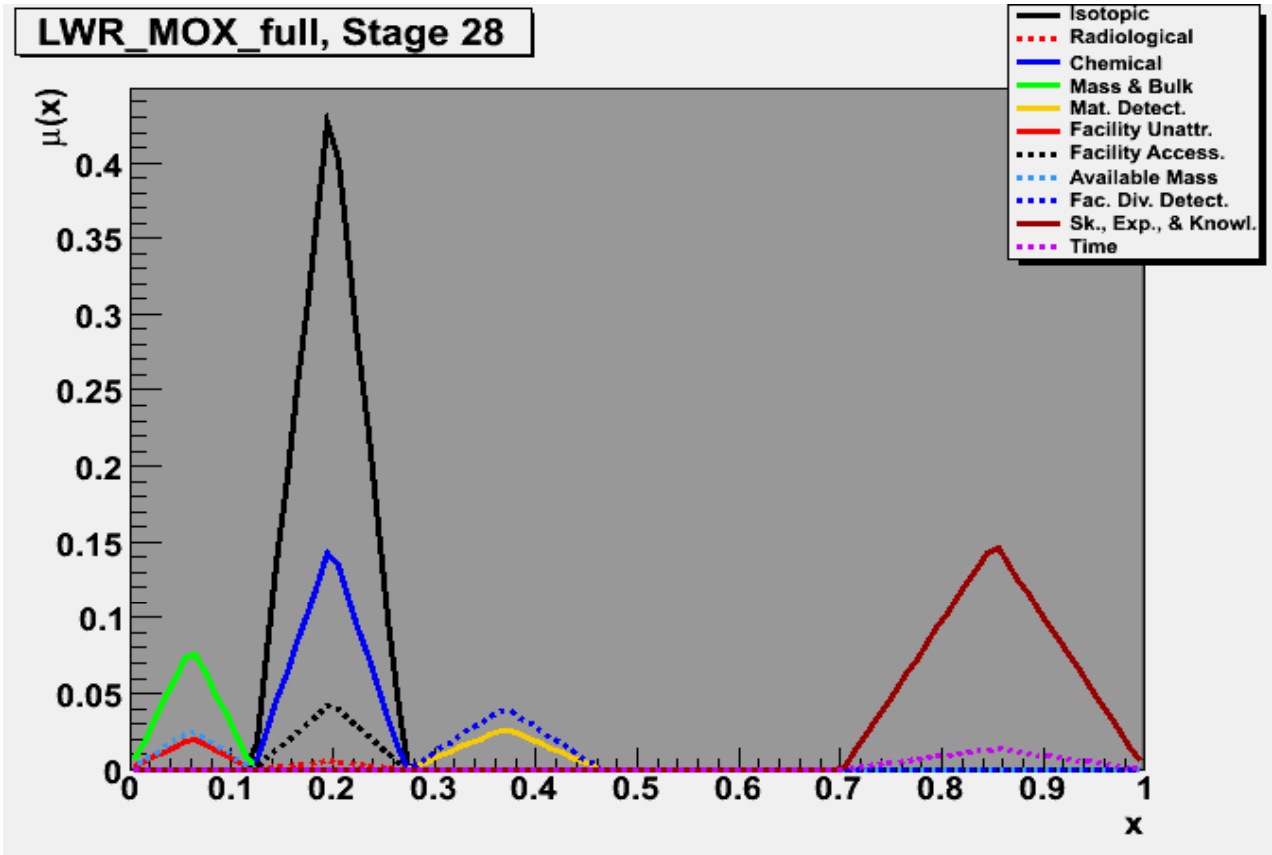
System decomposition: LWR MOX (Ex. #1)



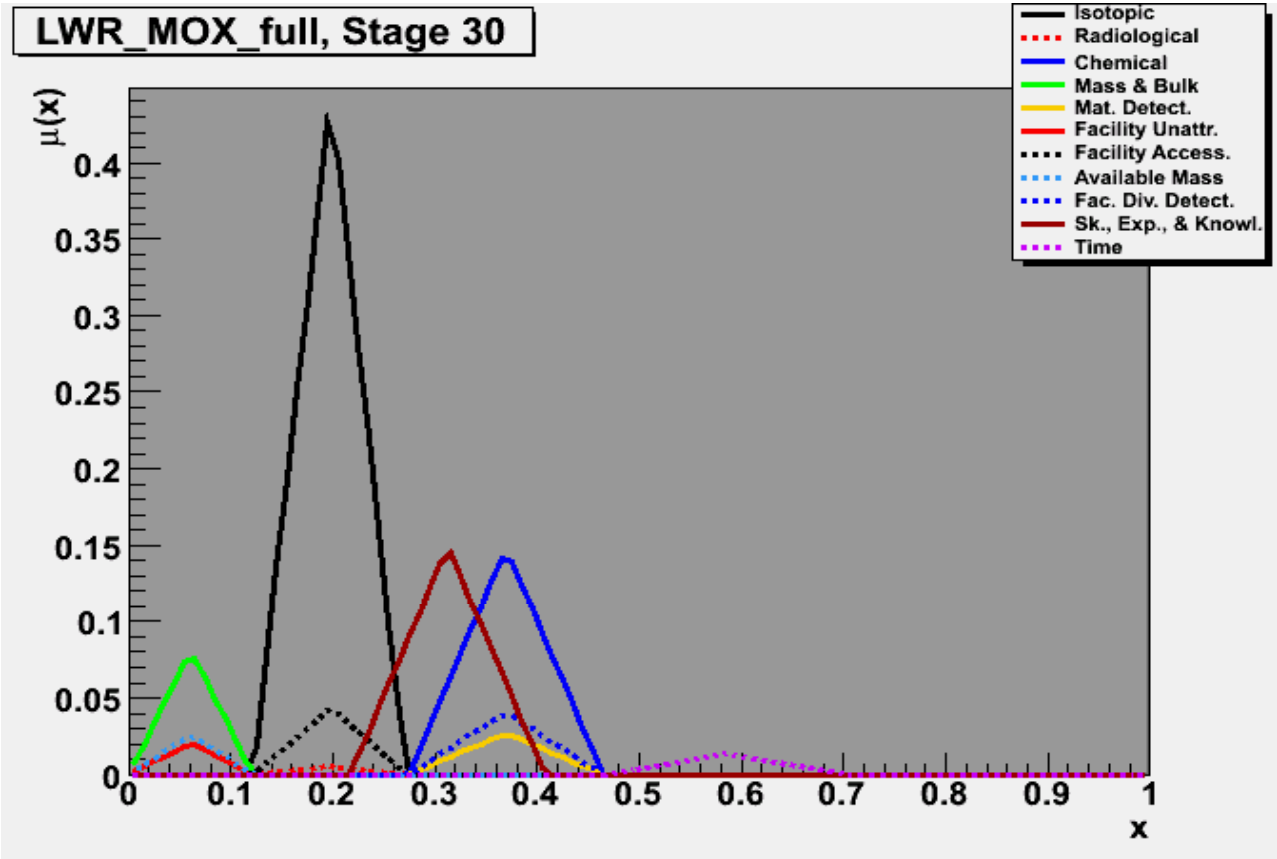
Stage decomposition: LWR MOX, Reprocessing



Stage decomposition: LWR MOX, Xport (Recov. M



Stage decomposition: LWR MOX, Fuel Fab. (MOX



Model-based prediction of a country′s nuclear proliferation decisions

Jun Li

Man-Sung Yim

David McNelis

Factors affecting nuclear proliferation decision by a country

- Technology
- Finance
- Political motivation

Country's general status profiles

[Singh and Way, 2004]

- Gross domestic product.
- Gross domestic product per capita.
- Industrial capacity index.
- Economic interdependence: trade ratio (exports plus imports over GDP) to measure the exposure to international economics.
- Economic liberalization: trade ratio change
- The scales of democracy and autocracy.
- The change of democracy in the country.
- Prevalence of democracies in the region.
- Enduring rivalry.
- Frequency of dispute involvement.
- Security guarantee.

Country Nuclear Fuel Cycle Profiles

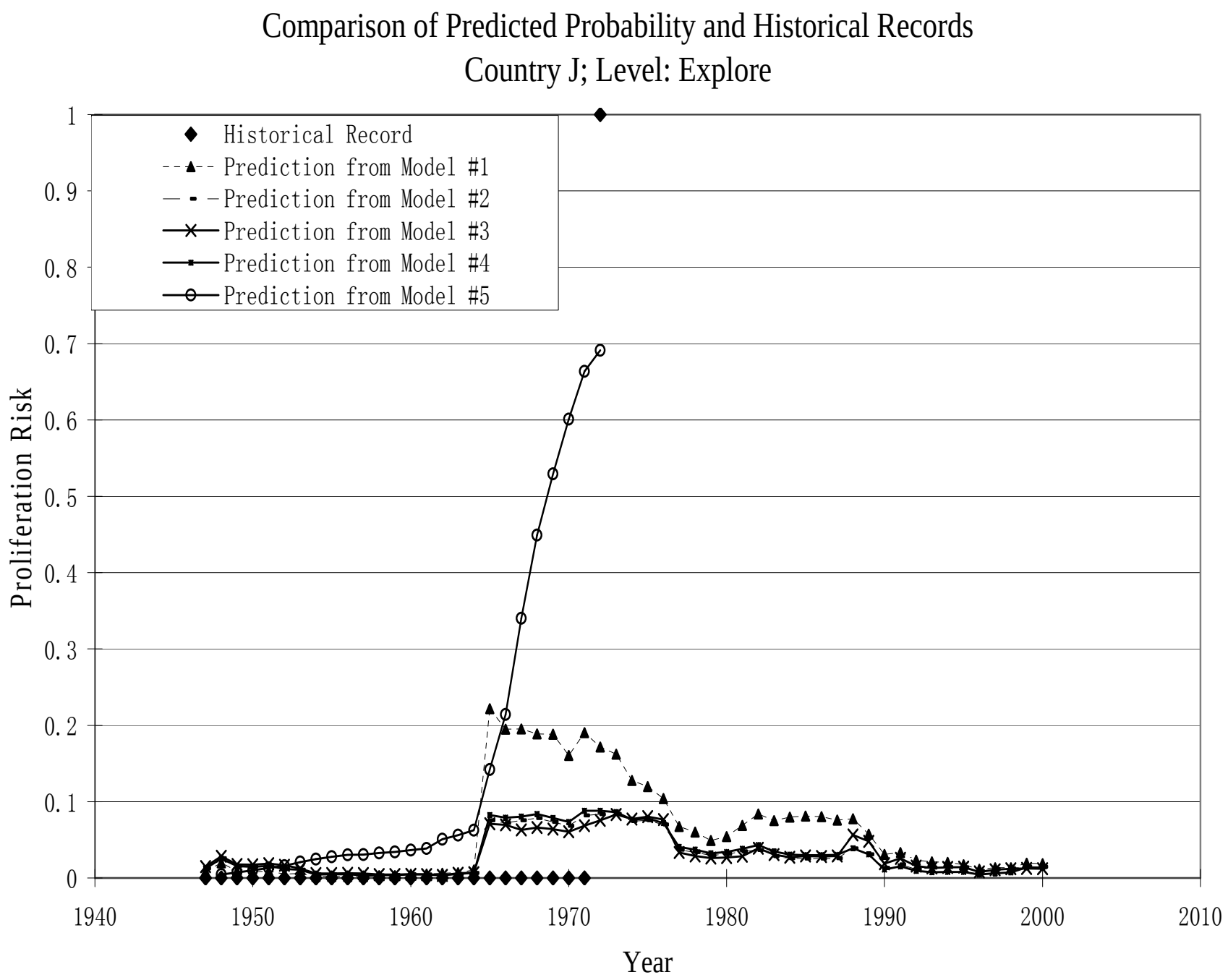
- Nuclear reactor operation experiences (both commercial and research reactors).
- Presence of nuclear fuel cycle facilities
- Existence and nature of safeguards

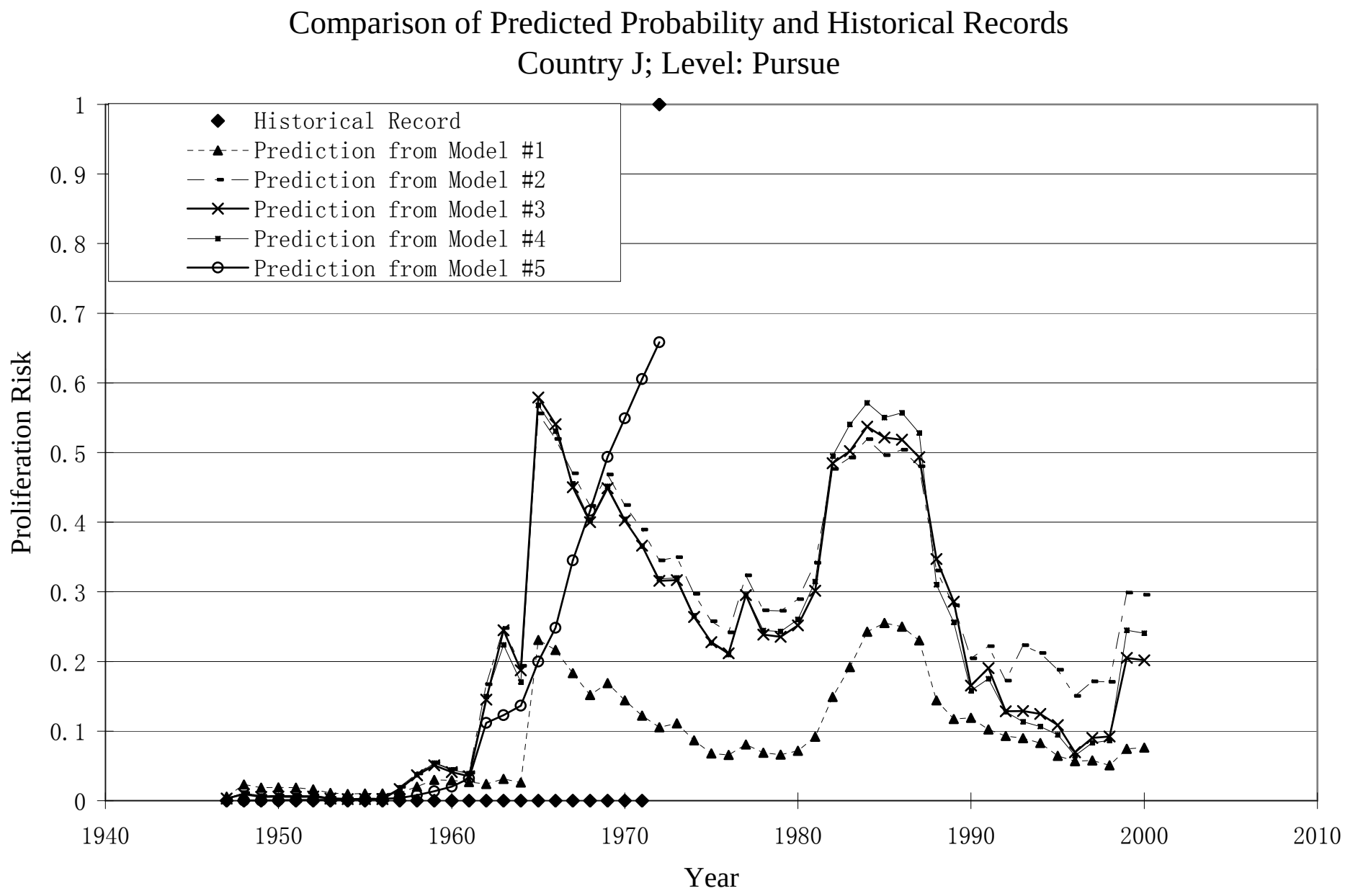
Predictive Tools

- A multinomial logit model
  - The response is a set of choices whose probabilities depend on a vector $\mathbf{x}_i$ of covariates associated with the i-th group.
- Event history modeling
  - The dependent variable measures the duration of time that units spend in a state before experiencing some event.
  - Consider time-varying covariates and use independent variables

Proliferation Events Data

- No interest (level =0): no proliferation attempt at all
- Exploration of weapons (level =1): countries have considered nuclear weapon and done some exploration work (*e.g., political authorization to explore, linking research to defense agencies*).
- Pursuit of weapons (level =2): countries have not only considered nuclear weapon but also started nuclear weapon program but did not acquire one yet (*e.g., political decision by cabinet-level officials, movement toward weaponization, development of single-use dedicated technology*).
- First explosion/assembly of weapons (level =3): countries have acquired at least one nuclear weapon.


Comparison of Predicted Probability and Historical Records
Country J; Level: Explore
Historical Record
Prediction from Model #1
Prediction from Model #2
Prediction from Model #3
Prediction from Model #4
Prediction from Model #5
Proliferation Risk
Year
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1940
1950
1960
1970
1980
1990
2000
2010


Comparison of Predicted Probability and Historical Records
Country J; Level: Pursue
Historical Record
Prediction from Model #1
Prediction from Model #2
Prediction from Model #3
Prediction from Model #4
Prediction from Model #5
Proliferation Risk
Year
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1940
1950
1960
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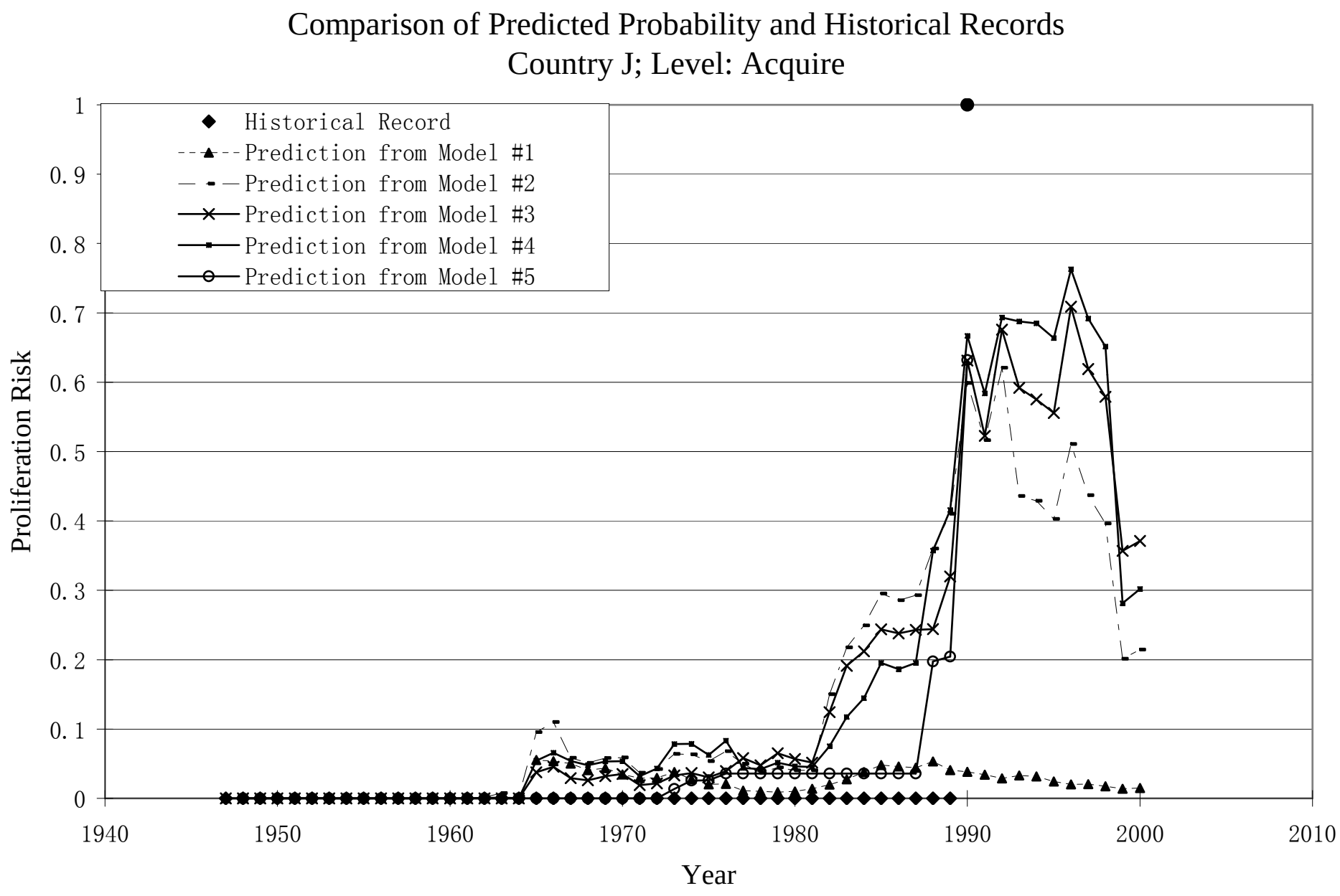
Comparison of Predicted Probability and Historical Records
Country J; Level: Acquire
Historical Record
Prediction from Model #1
Prediction from Model #2
Prediction from Model #3
Prediction from Model #4
Prediction from Model #5
Proliferation Risk
Year
0
0.1
0.2
0.3
0.4
0.5
0.6
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0.9
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1940
1950
1960
1970
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