Use of Quantitative Methods to Support Nuclear Nonproliferation

Presented to Oak Ridge National Laboratory
January 26, 2009

Man-Sung Yim
Department of Nuclear Engineering
North Carolina State University

Nuclear power in the world

- Many countries don’t have appropriate energy infrastructure for rapid industrial development.
- They want to diversify their energy mix especially to reduce greenhouse gas emission.
- To many countries, nuclear energy appears a guarantee of energy independence.
- Nuclear power improves self-esteem: nuclear scientific and technological development.
- Many third world countries are interested in nuclear option.
- Are they ready for nuclear technology?

Nuclear weapon development

- Nuclear technical capability – fissile materials
- Detonation capability
- Delivery capability
- These require a significant amount of investment for an extended period of time.
- State with a gross national product (GNP) of about ~$100 billion

Civilian nuclear power vs. proliferation

- Developing civilian nuclear capability does not bear direct relationship with nuclear weapon development.
- There are over 35 countries in the world who possess the civilian nuclear capability. Other than the first nuclear club countries (i.e., U.S., Russia, U.K., France, and China), only 4 countries (Israel, India, Pakistan, and North Korea) appear to possess nuclear weapons.
- Although the vast majority of States have committed to forgo the manufacture and acquisition of nuclear weapons, the recent incidents in Iran, North Korea and Iraq have renewed a concern over proliferation.

A dedicated route to acquire fissile?

- The dedicated route would be cheaper, less time consuming and possibly yield higher quality weapons material.
- History indicates that using a dedicated route has not been practiced among potential proliferators.
- Except for the early nuclear weapons states where weapons programs predated civil applications, most of the states with nuclear ambition have used civilian nuclear power program as cover for any on-going weapons work.

Country	Interaction between civilian and military program [Matt Bunn, 2001]
South Africa	Nuclear energy program began initially as civilian. Foreign assistance was used to build up an indigenous technical base for its weapons program.
Taiwan	Under the cover of civilian nuclear energy program, covert nuclear weapons program was pursued.
South Korea	A secret nuclear weapons program was begun simultaneously with the construction of its first civilian nuclear power plant but was stopped under U.S. pressure.
Argen-tina	Civilian nuclear program served as a cloak for a nuclear weapons effort. The weapons program was abandoned in the 1980s.
Brazil	The military ran an unsafeguarded "parallel program" which was cancelled later under a civilian government.
Sweden	Sweden originally had an integrated program for both nuclear energy and nuclear weapons.
Yugo-slavia	The country pursued a secret nuclear weapons program terminated in 1987, still retains a base of expertise and nearly 50 kilograms of fresh 80% enriched HEU fuel.

Country	Interaction between civilian and military program [Matt Bunn, 2001]
France	Nuclear weapon development was closely interconnected with the civilian program.
Israel	France provided plutonium production reactor and reprocessing plant for civilian purpose under the cover of substantial secrecy. No safeguards requirements were in place.
India	From the inception, military and civilian nuclear energy programs were closely interconnected.
Pakistan	Military and civilian nuclear energy programs were substantially integrated; enrichment technology was commercially obtained from Urenco.
Iraq	Civilian nuclear technologies acquired from abroad were used as basis for nuclear weapons program.
Iran	Nuclear program was initially civilian. Technologies relevant to a nuclear weapons program were obtained through China, Russia, and Pakistan.
North Korea	Secret extensive nuclear weapons program has been underway under the cover of civilian applications.

Civilian nuclear power vs. Dynamics proliferation

- Presence of trained nuclear scientists and engineers make a difference in the cost of nuclear weapon program.
- An established nuclear program creates a bureaucracy that can affect the politics and decision making regarding nuclear weapons.
- Owners could want to take advantage of their expensive nuclear establishment for prominence, pride, and security.
- A state’s bureaucracy and politics surrounding nuclear establishment plays a larger role in defining the relationship.

Civilian nuclear power vs. proliferation

- Proliferation takes place when the fissile materials from the civilian nuclear power program are diverted and know-how from civilian nuclear programs is used for military purposes.
- Training and education of people to support nuclear power program is linked to nuclear proliferation as the skills and capabilities of nuclear scientists and engineers are common between civilian and military program.

International Developments with Nuclear Power

- US
  - A total of 16 new reactor license applications (as of October 2008)
- Germany
  - Reconsidering its nuclear phase-out policy
- Italy
  - Italy will begin new nuclear power station construction by 2013, reversing the phasing out.
- India
  - Entered a new agreement with US on civilian power development
- Brazil
  - Brazil's company has submitted a six-reactor plan to government, while ministers talk of building more than one per year until 2050.
- Netherlands
  - Phase-out plans for the country's one reactor have been relaxed
- Switzerland
  - Swiss energy company Atel has submitted an application to build a new nuclear power plant

International Developments with Nuclear Power

- New Planned Reactors:
  - Iran
  - Turkey
  - Indonesia
  - Vietnam
  - Egypt
  - Israel
- New Nuclear Energy Program:
  - UAE
  - Jordan
  - Libya
  - Poland

Preventing the diversion of civilian nuclear technology

- Enhance proliferation resistance of nuclear fuel cycle technologies.
- Internationalize sensitive parts of the nuclear fuel cycle.
- Develop economy around proliferation resistance.
- Strengthen IAEA policing capability.
- Detect any diversion attempts early.
- Establish a global nuclear material accounting system.
- Strengthen the physical boundary between civilian and military nuclear program.
- Establish effective export control monitoring system.
- Effectively address motivational factors for weapon development.
- Develop and nurture nonproliferation culture.

Developing Economy around Proliferation Resistance

- Currently there is no incentive for improving or enhancing proliferation resistance from a selling company's perspectives.
- The company will normally be competing against companies from other nations that may not have an equal standard of proliferation resistance.
- The incentive to promote improved proliferation resistance must be generated by the governments of the exporting nations because they have the most concern about the issue.
- Proliferation resistance of nuclear fuel cycle facilities needs to be quantified.

Assessment of nonproliferation characteristics of a system

- Proliferation resistance
  - The degree of difficulty that a system poses to the acquisition of nuclear weapon(s).
  - Attribute-based analysis
- Proliferation risk
  - The likelihood of a potential proliferator obtaining nuclear weapons within a given time period
  - Scenario-based analysis

PR evaluation models

- Two general categories of models
  - Scenario Analysis (i.e., Probabilistic Risk Assessment)
  - Attribute Analysis (AA) (i.e., Multi-Attribute Utility (MAU) analysis)
- **Proposal:** Apply fuzzy logic to attribute analysis methods
  - i.e., "Fuzzy Logic Barrier" method

Probabilistic Risk Assessment (PRA)

- **Scenario-based**
  - Proliferation events characterized by specific event sequences
  - Specific scenarios leading to proliferation are identified and modeled and proliferation risk is quantified.
  - The approach can apply to actions or activities not necessarily part of a physical nuclear complex.
  - Resource-intensive
  - Requires detailed (often sensitive) knowledge of actors/facilities for accuracy
- **Dominant means of evaluating PR in facilities** (e.g., DOE PRPP Working Group)

Attribute Analysis / MAU

- **Attribute-Based**
  - Analyze system behavior through a series of complimentary system “attributes”
  - A problem is decomposed to examine various attributes. At the completion of the analysis, the results are aggregated to interpret the results.
  - Draw conclusions regarding system performance by weighting these attributes
  - **PR Application example:** TOPS barrier framework
    - Proliferation events characterized by specific “barriers” to proliferation attempts, (e.g. attributes)

Barriers Table

Barriers Framework Applied to the once-through LWR Cycle (LWR-OT)														
Stage of the fuel cycle	**Material Barriers**					**Technical Barriers**						**Institutional Barriers**		
	Isotopic	Radiological	Chemical	Mass & Bulk	Detectability	Facility Unattractiveness	Facility Access	Available Mass	Facility Detectability	Skills, Expertise, & Knowledge	Time	Safeguards	Access Control and Security	Location
Front-end of the cycle														
Transport of fresh fuel	VH	I	M	H	M	VH	I	L-M	M	VH	VH	I	M	H
Reactor operations														
Fresh fuel storage	VH	I	M	VH	M	VH	I	I	VH	VH	VH	I	M	VH
Fuel handling	VH	I	M	VH	M	VH	L	I	VH	VH	VH	I	M	VH
…														

Why use fuzzy logic?

- Attribute analysis represents an assessment of linguistic quantities
  - i.e., how "well" a barrier performs in deterring a proliferation attempt
- Fuzzy logic is well-suited for applications involving operations upon linguistic quantities
  - Provides a means of formally assessing linguistic barriers – a problem identified by the original TOPS committee

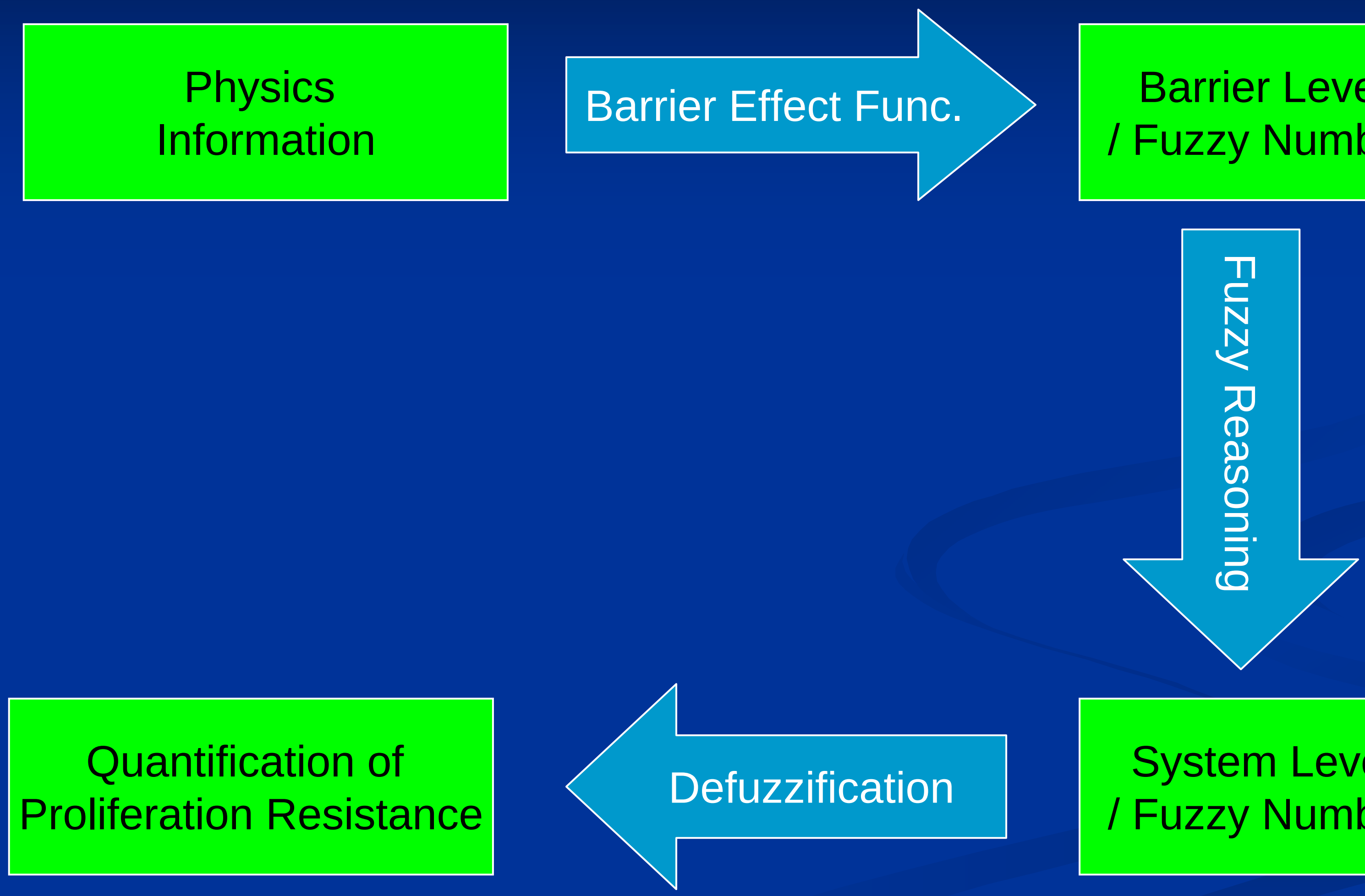
Why FLBM?

- 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.
- Allow qualitative and quantitative assessment of a system's proliferation resistance by using measurable or quantifiable variables.
- Allow the user an option to adjust the data.
- Allow direct ranking of a fuel cycle systems.
- Use this model to evaluate critical security areas in different fuel cycle scenarios.
- Evaluate the effectiveness of existing and proposed proliferation barriers.

Information Process of the Model



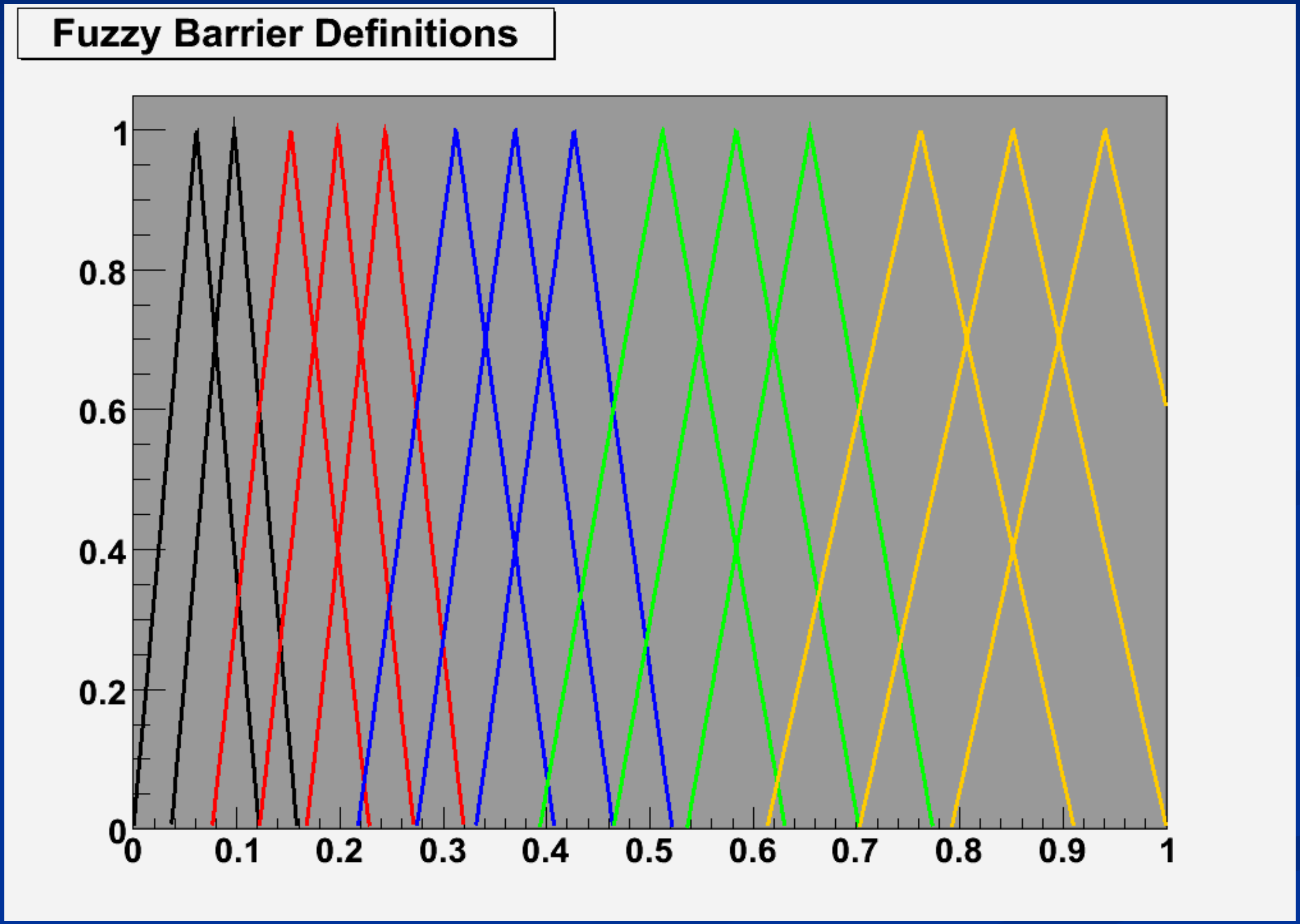
Required Inputs for Proliferation Resistance Evaluation

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

Example: Barrier Effectiveness for Equivalent Enrichment

Name	Equivalent Enrichment	
Unit:	%	
Level	xmin	xmax
Ineffective minus	80	1.10E+31
Ineffective plus	50	80
Low Minus	45	50
Low	40	45
Low plus	30	40
Moderate minus	20	30
Moderate	10	20
High minus	5	10
High	1	5
Very High	0	1.00E+00

Barrier definitions



Barrier Classifications

- VH: Theft attempts by multiple insiders, or larger groups of armed outsiders, even if working together, can be blocked with high confidence.
- H: Theft attempts by single insiders or small groups of outsiders, or both working together, can be blocked with good confidence
- M: At most times, theft attempts by a single insider would be detected, but the system still has exploitable vulnerabilities in extraordinary circumstances.
- L: With some prior planning, material could be removed with a small probability of detection by a knowledgeable insider, or could be stolen by a small group of lightly armed outsiders.
- I: Material could be easily removed without detection by one knowledgeable insider, or could easily be stolen covertly by one person or small group of outsiders.

Barrier weight selection

- 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
  - Use a reproducible metric
  - Model calibration
  - Consistent weight selection process

Barrier weights as relative importance of each barrier (A covert proliferation attempt by a "developing" country)

Barrier	Proposed Weight	TOPS relative importance (Unsophisticated State, Covert)
Isotopic barrier	130	High
Chemical Barrier	55	High
Radiological Barrier	5	Moderate
Mass and Bulk Barrier	0.15	Low
Detectability Barrier	0.14	Moderate
Facility Unattractiveness	13.3	Moderate
Facility Accessibility	1	Low
Available Mass	55	High
Diversion Detectability	1	Moderate
Skills/Expertise /Knowledge	3.2	Moderate
Time	1	Moderate

Barrier Levels Comparison

SystemID: 1 SystemName: PWR-OT Total Stage #: 7

Stag	StageName	Barri	Barri	Barri	Barri	Barri	Barri	Barri	Barri	Barri	Barri	Barrier1
1	Mining/Milling	VH	L	M	VH	M	VH+	H	M	VH+	H	H
2	Conversion	VH	L-	M	VH	M	VH	I	M	VH+	VH	M
3	Enrichment	VH	L	M	VH	M	L	M	L	VH+	I	H
4	LEU Fuel Fabrica	VH	L	M	VH	M	VH+	L	L	VH+	H	H
5	PWR	L-	VH	VH	L	VH	L	VH	I	VH+	H	M
6	AFR Storage	I+	VH	VH	L	VH	VH	H	I	VH+	VH	I
7	Permanent Dispos	I+	VH-	VH	I	VH	VH+	H	I	VH+	VH	I

(Proliferation Resistance Model)

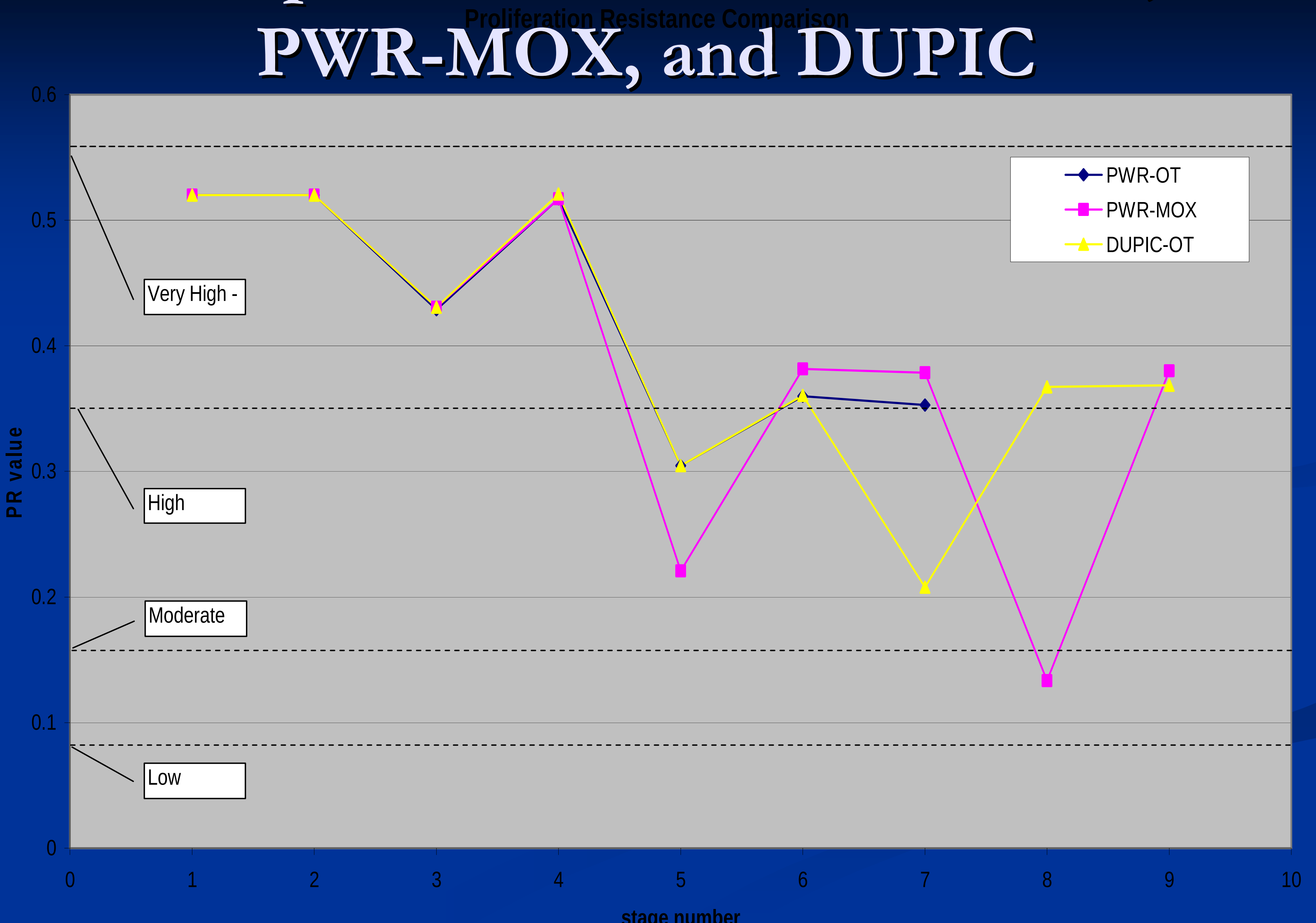
	1	2	3	4	5	6	7	8	9	10	11
1 Milling	VH	I	M	H	M	VH	I	I	I	VH	M
2 Conversion	VH	I	L	H	M	VH	I	I	M	M	M
3 Uranium enrichment	VH	I	L	M	M	I-M	M-VH	I	VH	I	H
4 Fuel fabrication	VH	I	L	M	M	VH	I	I	M	M	H
5 Reactor irradiation	L	VH	VH	VH	VH	L-H	VH	I	VH	M	H
6 Storage (of spent fuel)	L	H-VH	VH	VH	VH	VH	H	I	VH	VH	H
7 Repository emplacement	L	H-VH	VH	VH	VH	VH	VH	I	<VH-VH	VH	I

(LLNL report)

“Calibrating” a PR model

- Model can be “calibrated” by evaluating the stage-level PR values for a well-characterized system (i.e., LWR, once-through)
  - Vector should conform to intuitive expectations

Comparisons of PR of PWR-OT, PWR-MOX, and DUPIC



Quantitative results and Qualitative Interpretations

System Name	System Mean PR	System Level indicated by System Mean PR	Min Stage Mean PR	System Level indicated by Min Stage Mean PR
PWR-OT	0.3285	H	0.2232	M+
PWR-MOX	0.2938	H-	0.1129	L+
DUPIC-OT	0.3033	H-	0.1533	M-

Comparison of Proliferation Resistance of Fuel Cycles (Method 1: Fuzzy Barrier Method; Method 2: Multi Attribute Multi Utility Method; Method 3: TOPS Framework)

Stage Name	Method 1			Method 2			Method 3	
	OT	MOX	DUPIC	OT	MOX	DUPIC	OT	MOX
Reprocessing		0.11 (L+)			0.25	0.44		(L)
Fuel fabrication	0.50(VH-)	0.16(M-)	0.21(M+)	0.58	0.34	0.52	(VH-)	(L)
Reactor Operation	0.18(M)	0.24(M+)	0.14(M-)	0.9	0.9	0.78	(M)	(L+)
Dry Storage	0.21(M+)	0.25(M+)	0.22(M+)	0.64	0.78	0.58	(M)	(M)
Disposal	0.20(M+)	0.25(M+)	0.22(M+)	0.6	0.58	0.54	(M)	(M)

Calibration, cont'd

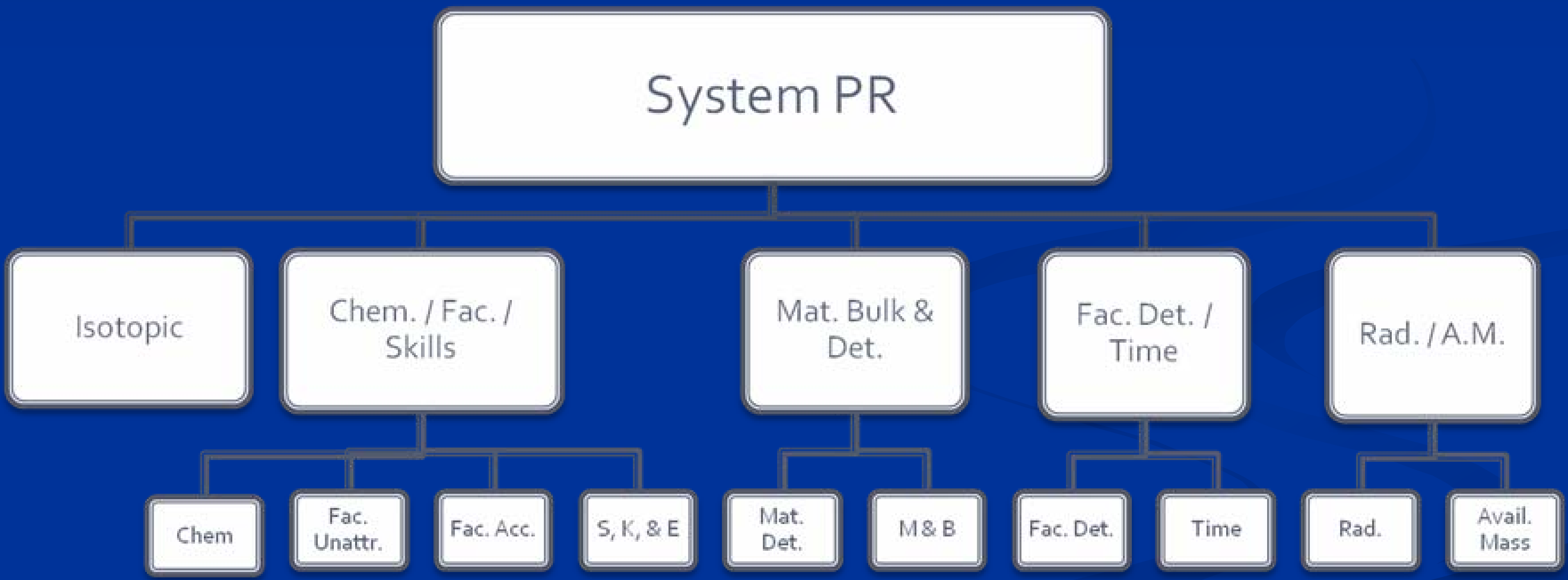
- Weights / pair-wise comparisons adjusted for unexpected / unwanted effects
  - Counter-intuitive outcomes
  - Extreme variance

Consistency in weighting

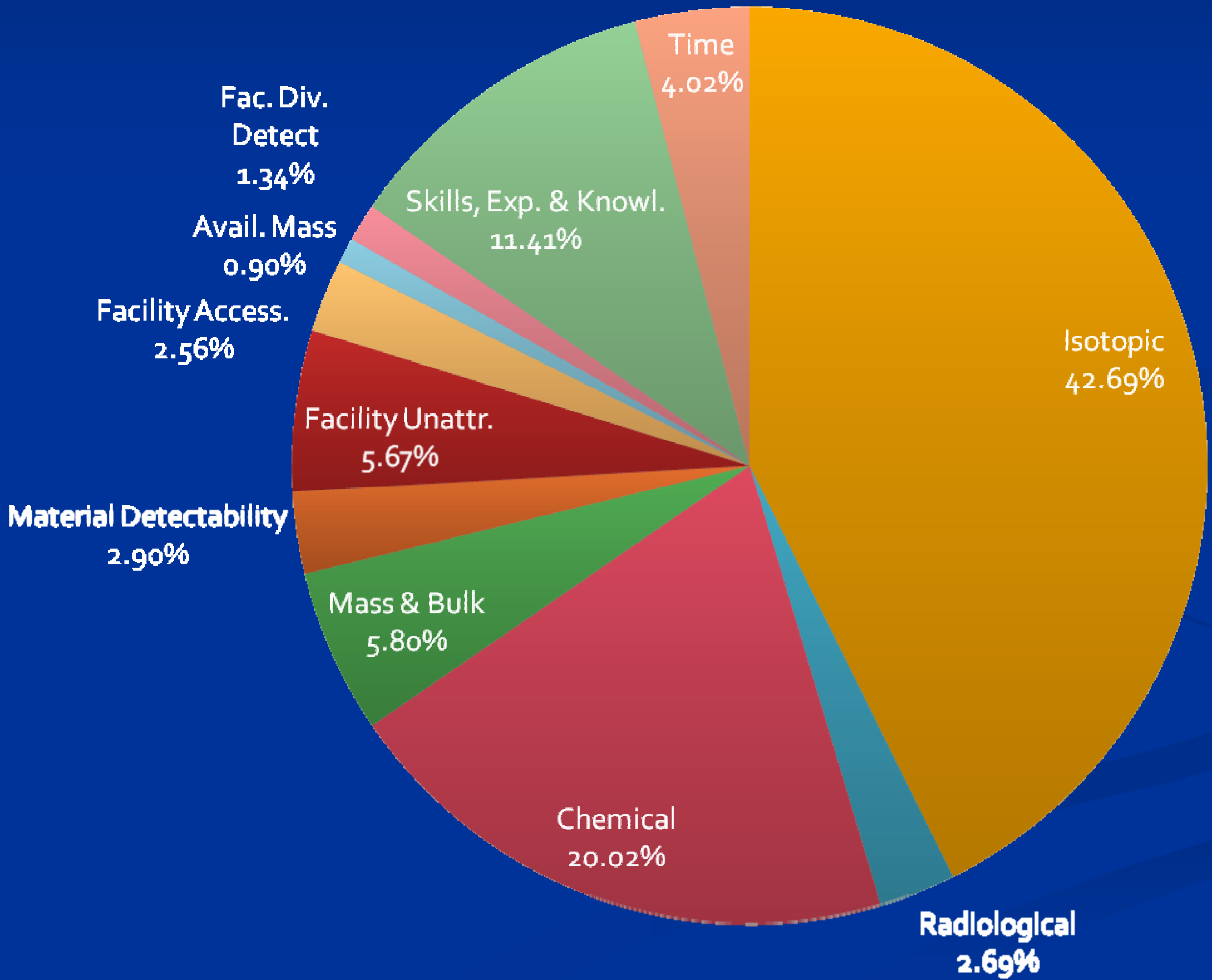
- In addition to providing "calibrated" weights, we want a system to provide for a consistent means of evaluating weights between experts
- This is pursued through an Analytical Hierarchical Process (AHP) method (Saaty)
  - Construct a reciprocal matrix of the pair-wise comparisons
  - Weights can be found as the solution to the eigenvector, i.e.:

$$Aw = \lambda w$$

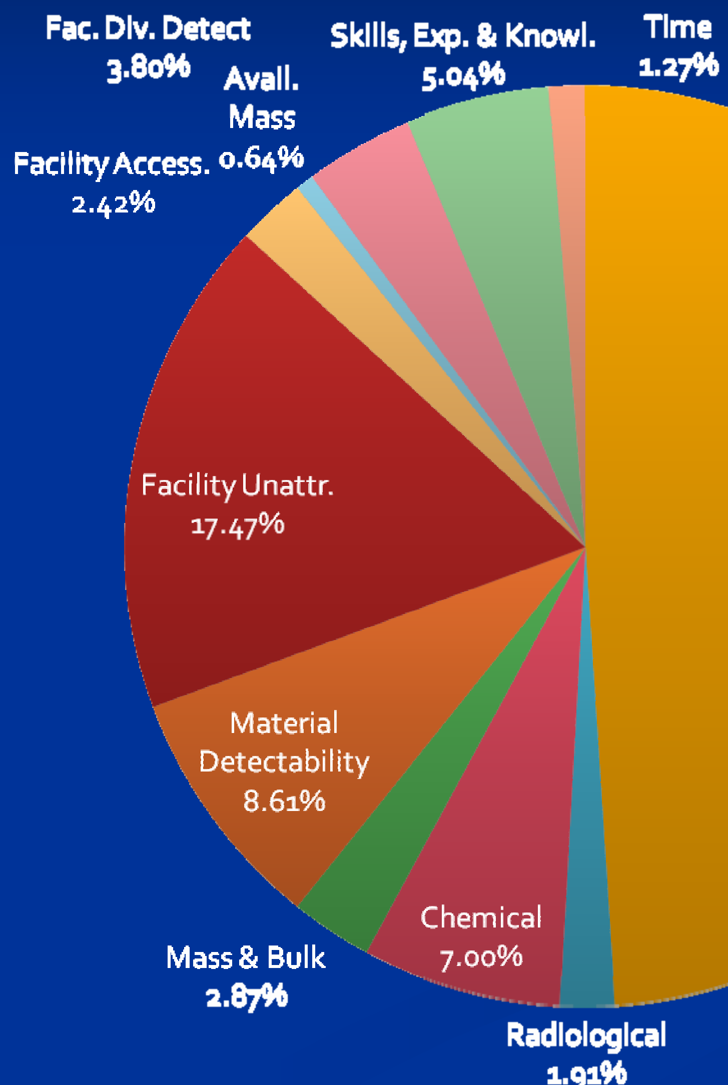
FLBM Hierarchy



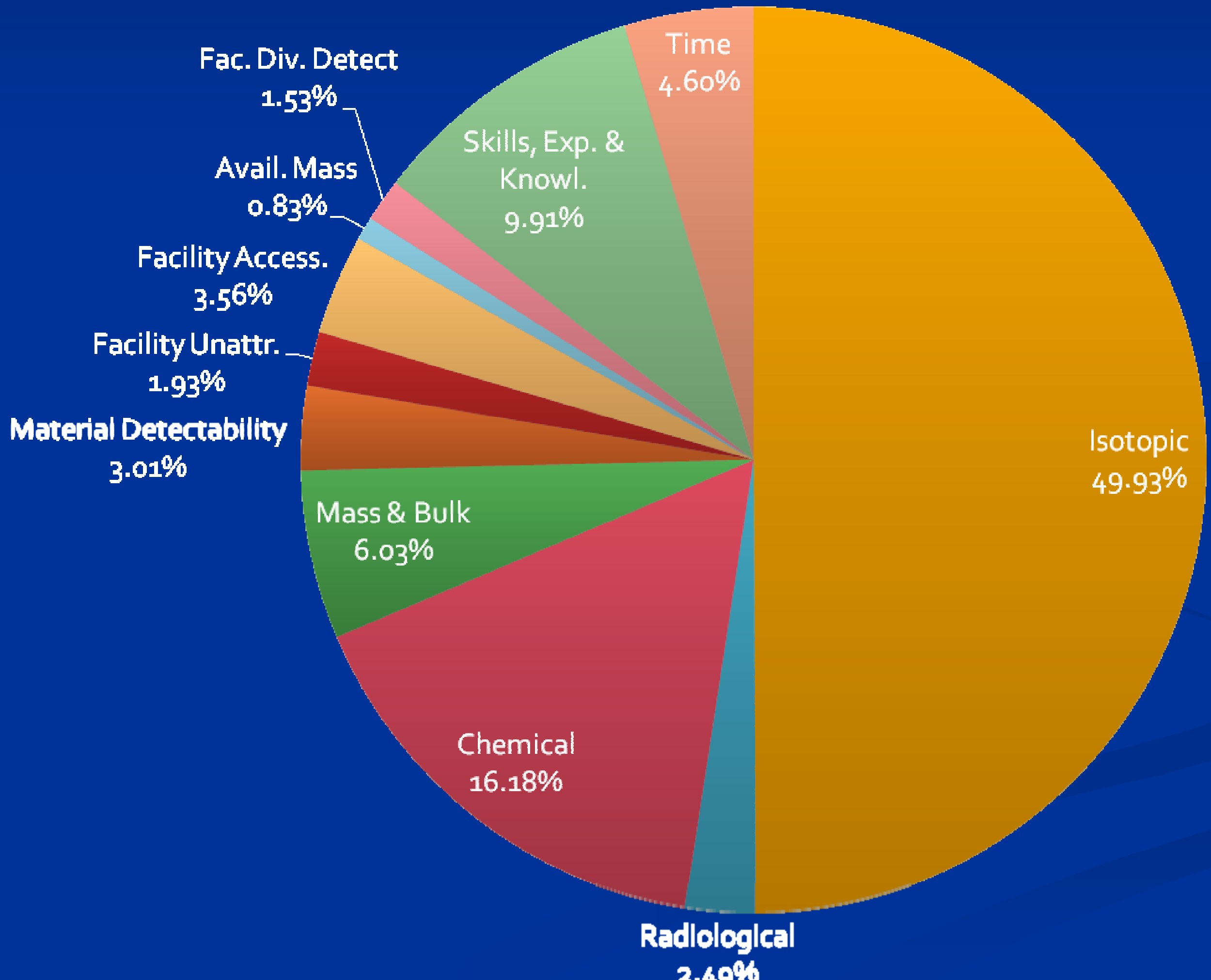
Expert weight: Ex. #1



Expert weight: Ex. #2



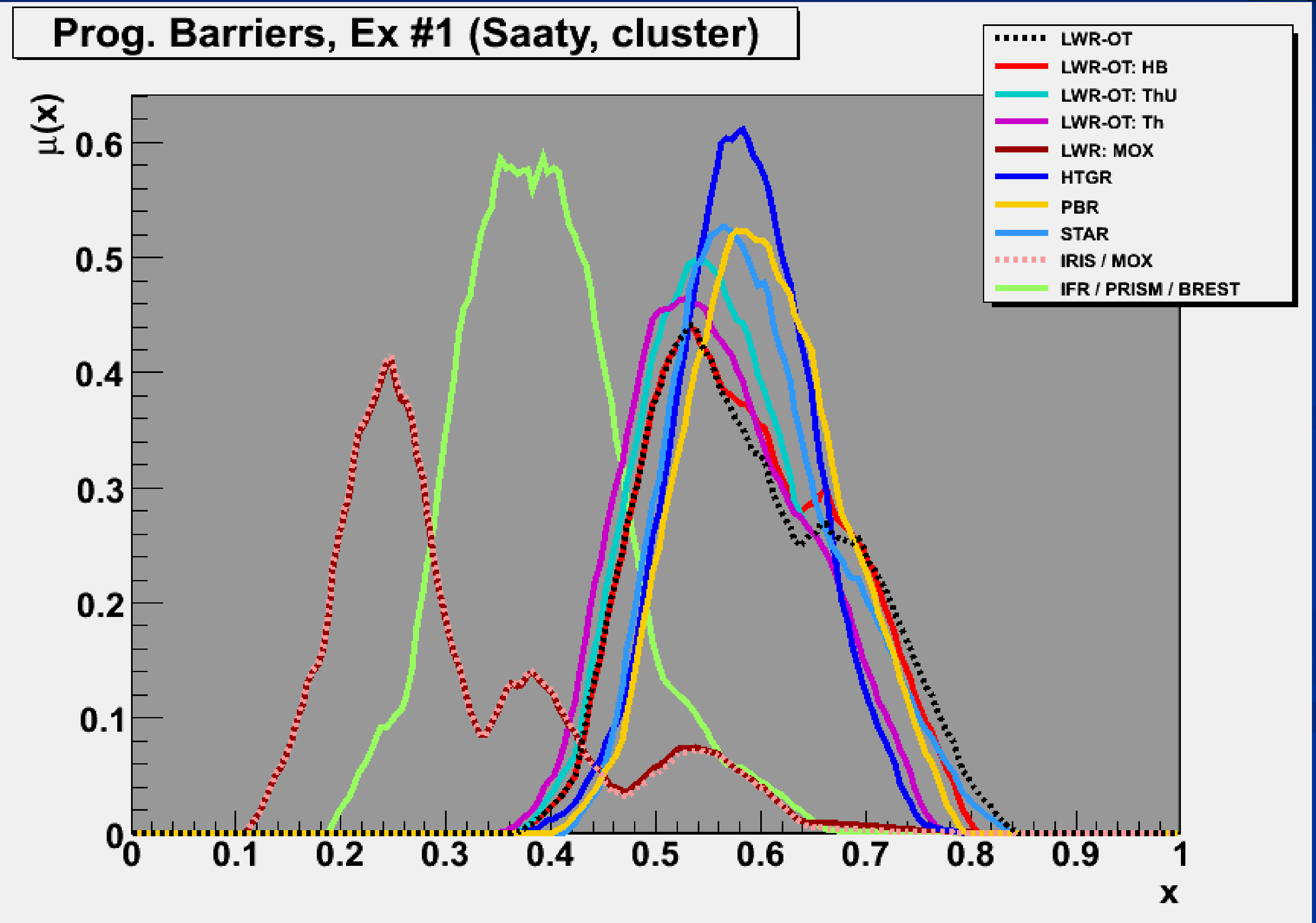
Expert weight: Ex. Conf.



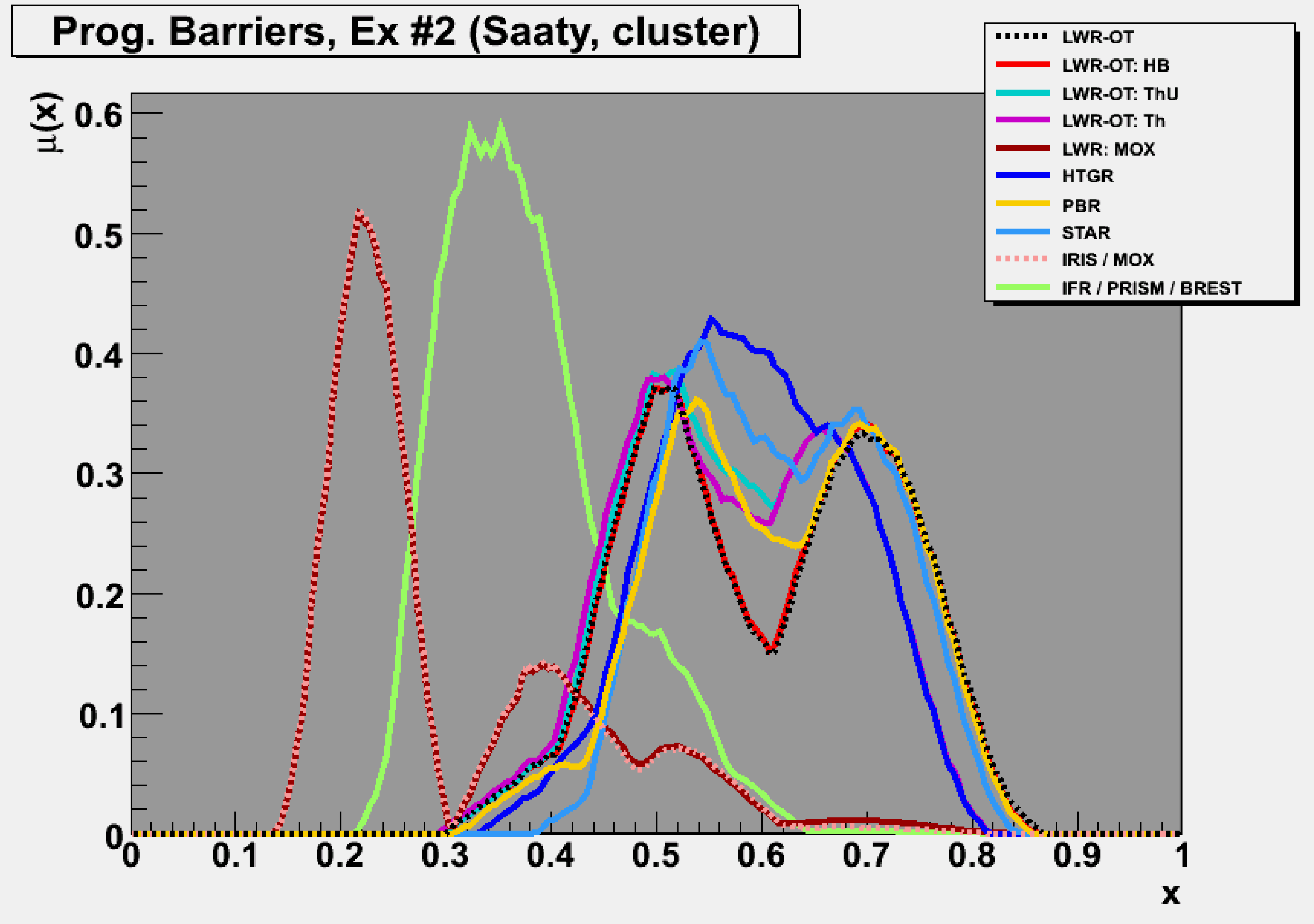
Using the FLB model

- 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

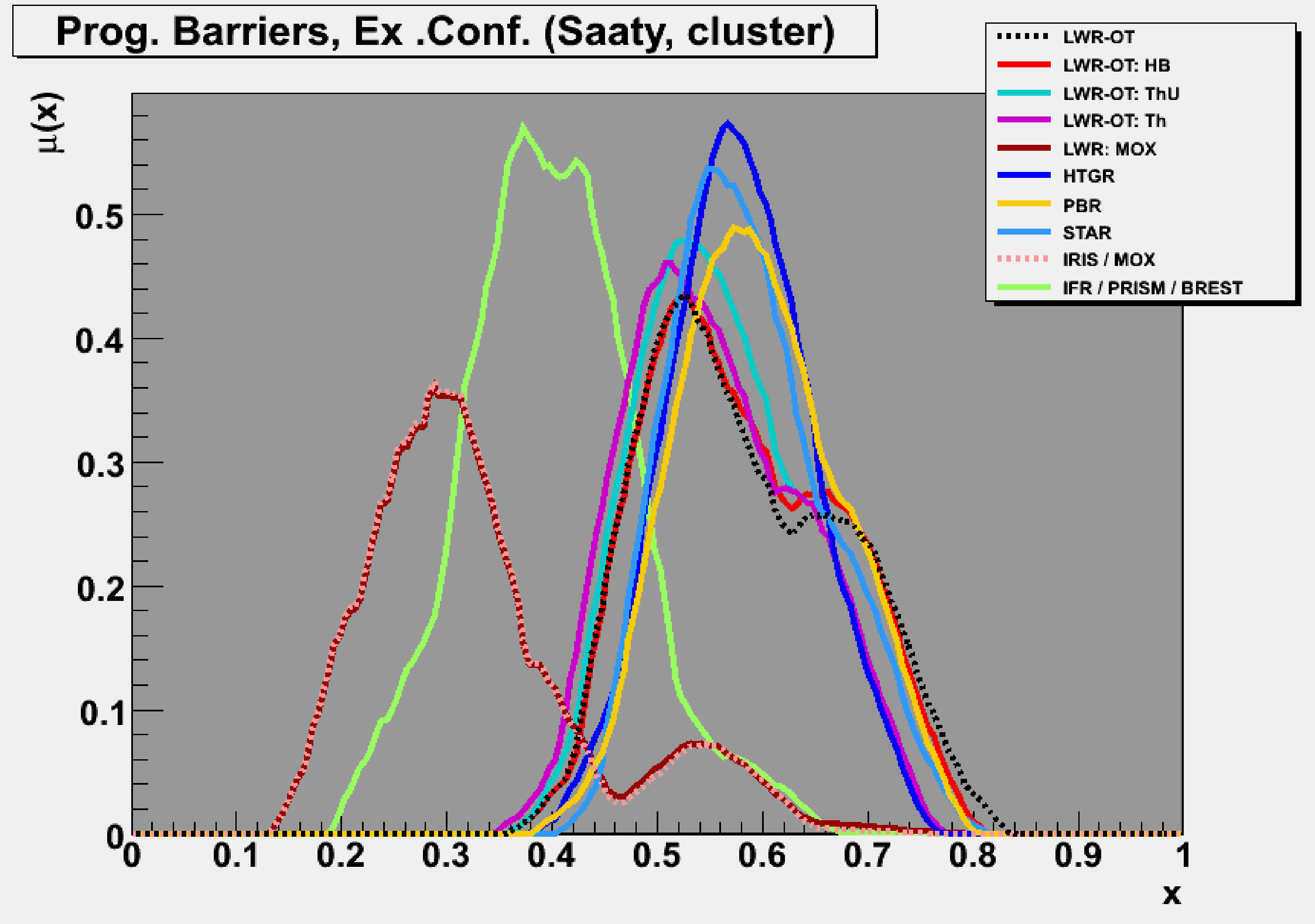
Example: System comparison (Ex. #1)



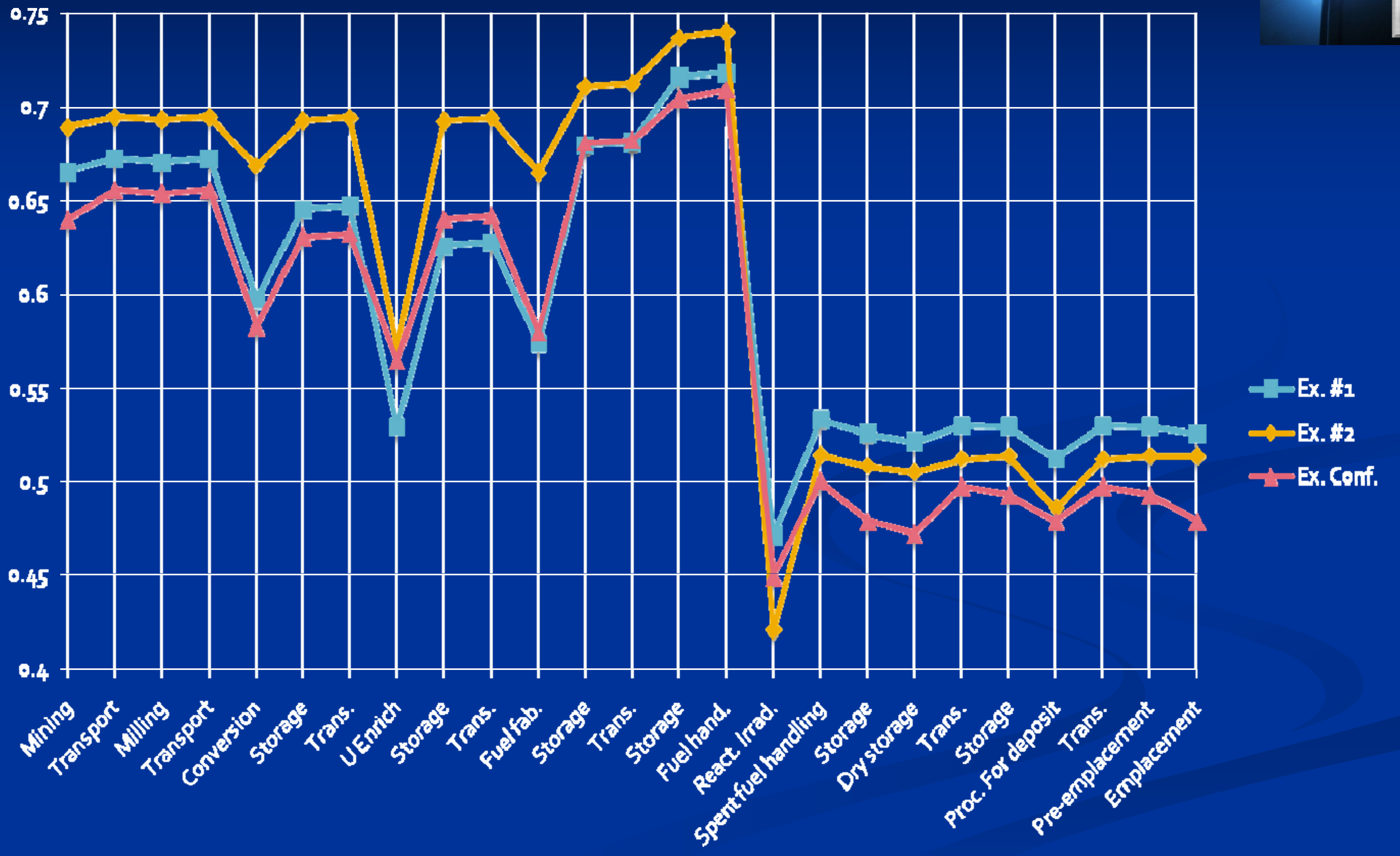
Example: System comparison (Ex. #2)



Example: System comparison (Ex. Conf.)

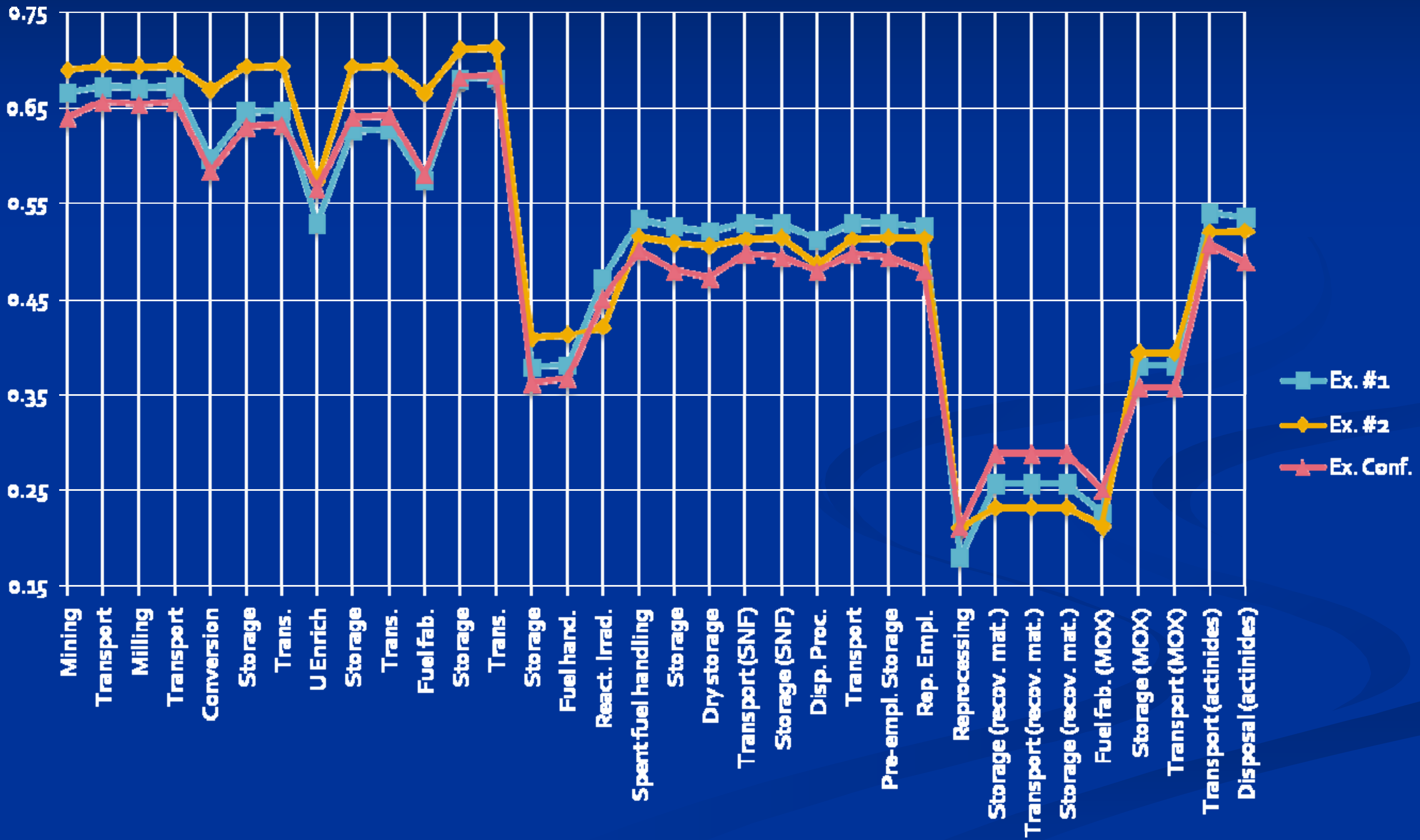


LWR OT: System Profile



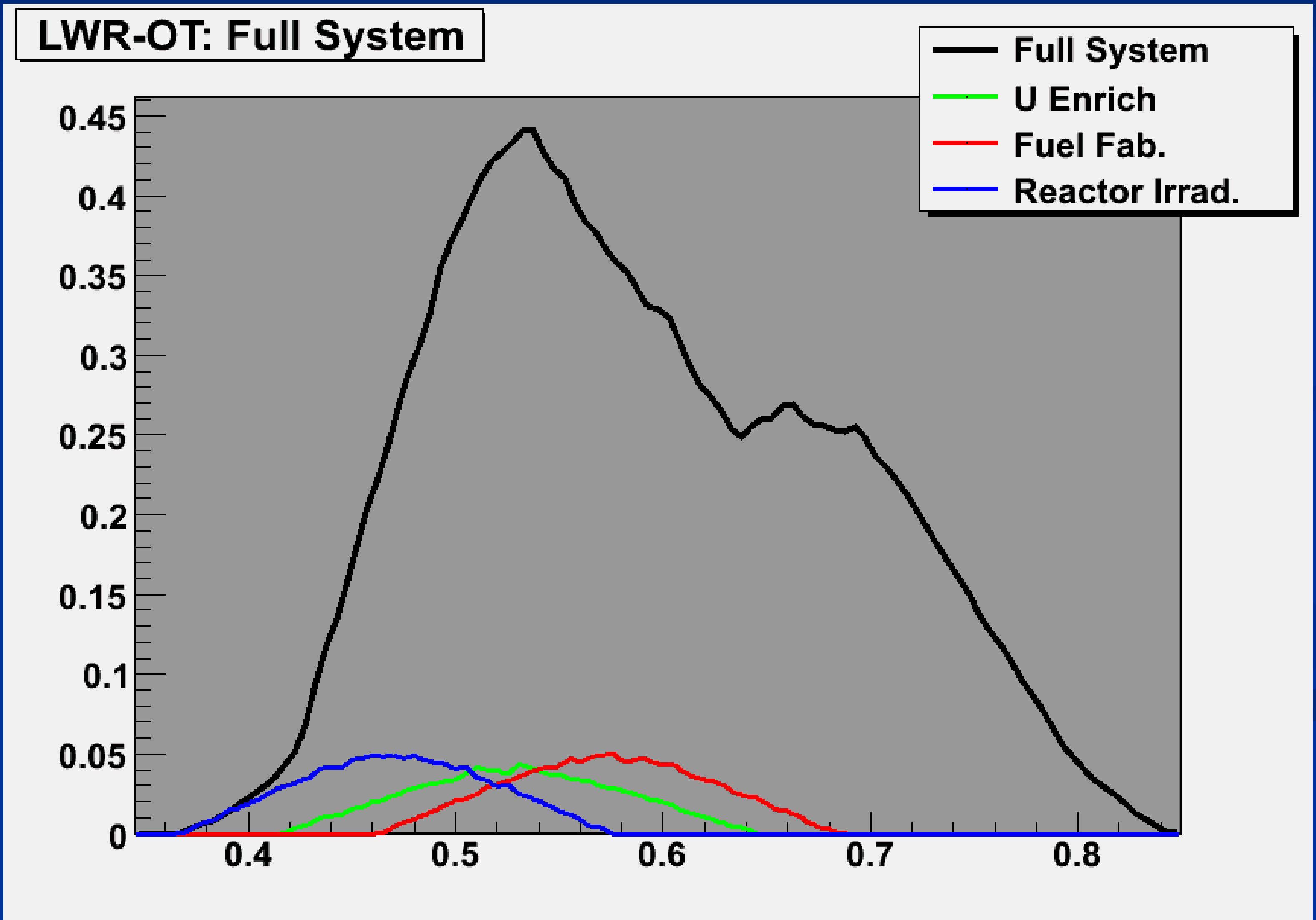
Higher values imply greater relative PR

LWR MOX: System Profile

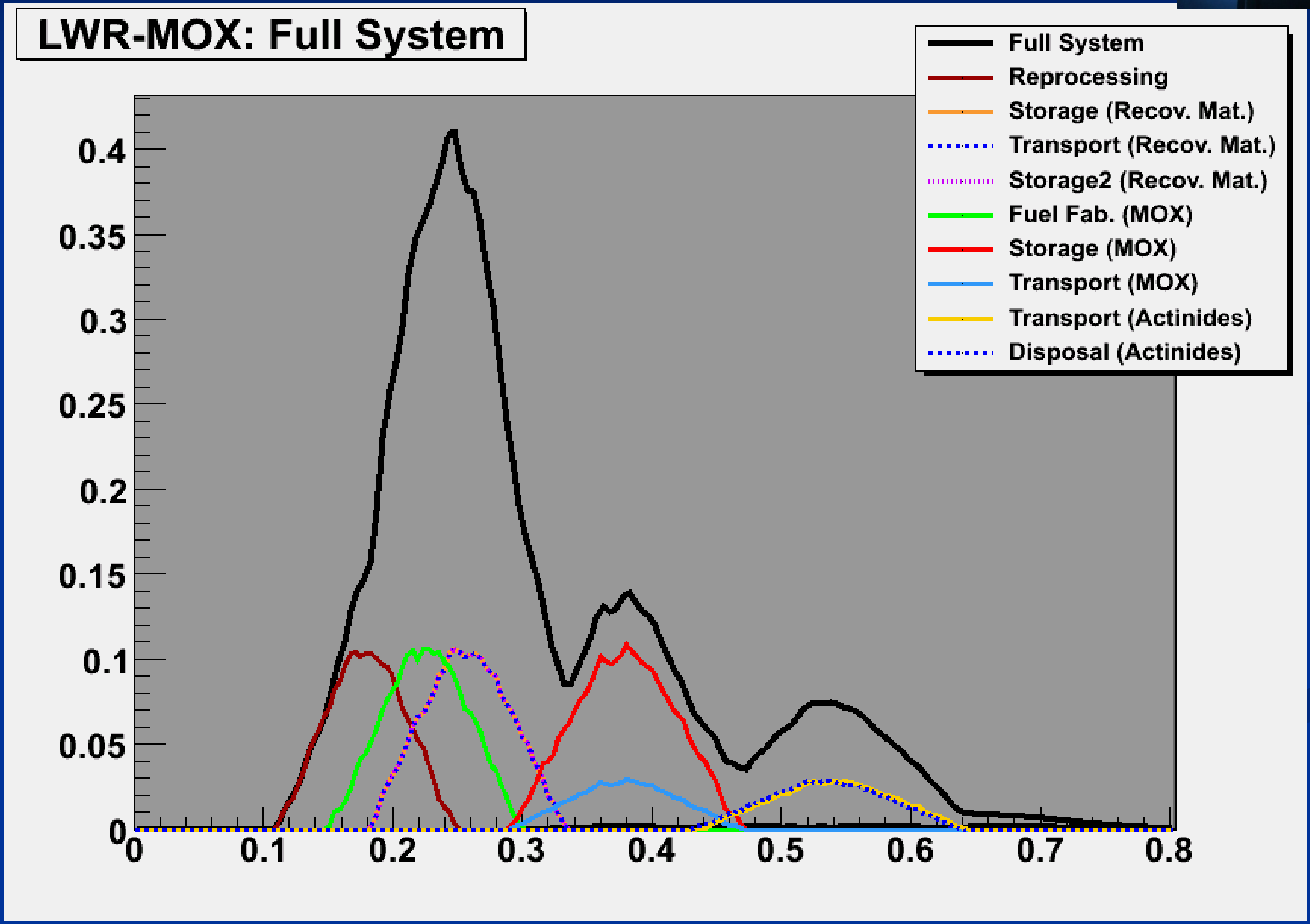


Higher values imply greater relative PR

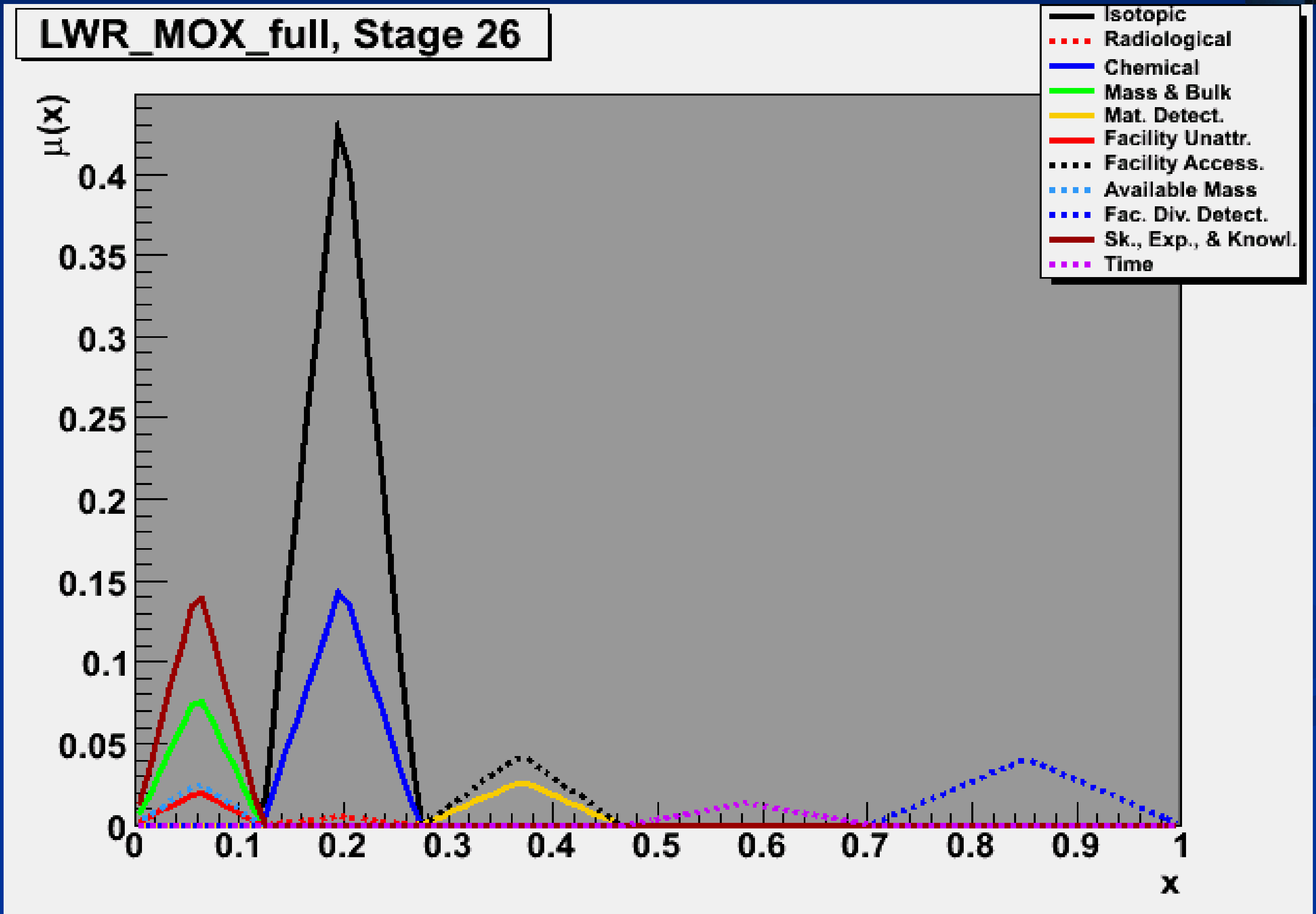
Stage decomposition: LWR OT (Ex. #1)



System decomposition: LWR MOX (Ex. #1)



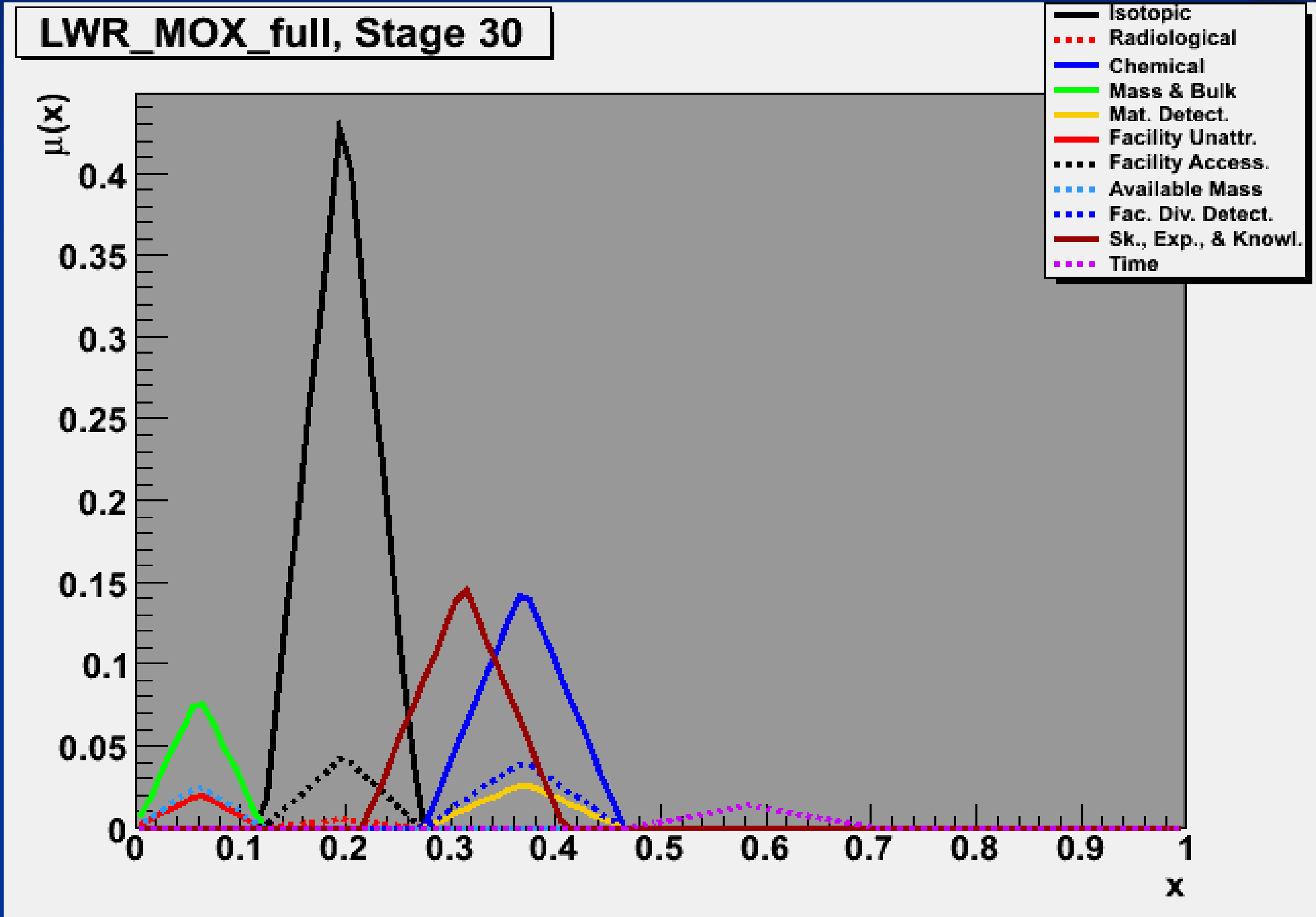
Stage decomposition: LWR MOX, Reprocessing



Indicators used for each intrinsic/technical barrier

Barrier	**Proposed Quantities**
Isotopic barrier	Bare sphere Critical Mass(CM) (kg)
	Equivalent Enrichment (%) (^{233}U, ^{235}U, ^{239}Pu)
	Spontaneous neutron generation rate (n/sec/kg)
	Heat generation rate (W/kg)
	Gamma Radiation (MeV/sec/kg)
Chemical Barrier	Cost to extract the fissile materials ($/Kg)
Radiological Barrier	Dose rate at 1-meter distance (mrem/hr/kg)
Mass and Bulk Barrier	Concentration of fissile material (# of CM/kg)
Detectability Barrier	Detectability levels
Facility Unattractiveness	Modification time needed to produce 1 CM in a year (weeks)
Facility Accessibility	Frequency of possible access to facility (days/yr)
Available Mass	Available fissile materials (# of CM)
Diversion Detectability	Uncertainty of measurement(# of CM/yr)
Skills, Expertise, and Knowledge	Time needed to modify the skills and apply it to weapons programs (yr)
Time	Time of residence of the materials of interest (yr)

Stage decomposition: LWR MOX, Fuel Fab. (MOX)



Safeguards Fee Model

$$SGF = \sum_i \Delta PR_i \bullet C_i + \sum_i \Delta PR_i \bullet C_i \bullet \phi \bullet \Delta T_i \; [\$]$$

where:

SGF = Safeguards Fee [$]

ΔPR_i = Relative proliferation resistance changes (difference to Very High Level at stage i)

C_i = unit charge at stage i [$ per unit pr value]

ϕ = carrying charge factor [yr^{-1}]

ΔT_i = delay between the investment for stage i and the midpoint of the irradiation of the fuel (yr)

Example: Fuel Cycle Comparisons

fuel cycle cost (cents/kWhe)			
	PWR-OT	PWRMOX	DUPIC
Adjusted FCC	0.460	0.819	0.498
Centroid Proliferation Resistance	0.374	0.323	0.331
NonProliferation Charge*	0.069	0.080	0.078
PR adjusted FCC	**0.529**	**0.899**	**0.576**

* Nonproliferation charge is assumed to be 15% of base FCC for LWR-OT (which is comparable to the SD of base FCC).

Observations

- FLBM can be a useful means of handling AA/MAU methods for the barrier framework
  - Can be a valuable alternative to PRA methods
- Subjectivity inherent to AA methods can be handled through consistent weight selection & calibration
- FLBM model can be a useful tool for analyzing cross-section of system PR performance

Observations

- FLBM framework can be used to target safeguards resources & priorities
- Open, transparent model allows for expert configurability
  - i.e., not a "black box" – can be adjusted and evaluated for impacts
  - FLB model should be viewed as an open framework for analysis; not an "absolute" model

Early Detection of Diversion

- For the world nuclear nonproliferation community to effectively cope with future proliferation attempts.
- Allows the international community to respond and take necessary actions - ideally using political and diplomatic influences without resorting to harsh measures such as sanctions or military actions.
- A capability to quantitatively predict the probability of a country's nuclear proliferation intent or activities is highly desirable.

Prediction of Proliferation

- Can we understand the determinants of nuclear proliferation and develop quantitative tools to predict nuclear proliferation events?

Nuclear Proliferation Decisions

- Nuclear proliferation decisions by a country is affected by three main factors: (1) technology; (2) finance; and (3) political motivation.
- Depends on a complex balance of both incentives and disincentives and bureaucracies within the country.
- Technological capability is important as nuclear weapons development needs special materials, detonation mechanism, delivery capability, and the supporting human resources and knowledge base.
- Financial capability is important as the development of the technological capabilities requires a serious financial commitment.

Nuclear Proliferation Decisions

- At the most fundamental level, the proliferation decision by a state is controlled by its political motivation:
  - International political power/prestige incentive
  - Military/security incentives
  - Domestic political incentives
- Their decision will also be affected by the degree to which the nuclear-weapon states are willing to apply security assurance or, conversely, diplomatic pressure.
- Their decision will also be strongly affected by the time and degree of illicit activity required to obtain nuclear weapons materials.
- Proliferation resistance of nuclear fuel cycle facilities makes a difference.

Records

- Out of 31 countries with currently operating commercial nuclear power plants, six countries own nuclear weapons (including the five nuclear weapons states – U.S., Russia, U.K., France, and China)
- Besides the five nuclear weapons states, out of 18 countries who explored nuclear weapons, four countries (Israel, India, Pakistan, N Korea) have acquired nuclear weapons.

Predicting Nuclear Proliferation

- There have been various efforts in the research community to understand the determinants of nuclear proliferation and develop quantitative tools to predict nuclear proliferation events.
- These efforts have shown that information about the political issues surrounding a country's security along with economic development data can be useful to explain the occurrences of proliferation decisions.
- However, predicting major historical proliferation events using model-based predictions has been unreliable.

Our approach

- Examine all three factor:
  - Technological capability
  - Financial capability
  - Political motivation
- Use open source information
- STATA, an integrated statistical package, was used for the model development.

Steps

- Develop database
  - The database covers a country’s nuclear technical capability profiles, economic development status, security environment factors and internal political and cultural factors.
- Analyze correlations among the input variables
  - To identify determinants of nuclear proliferation and to reveal the relationship between the proliferation decision of a nation and the basis or cause of the decision.
- Develop predictive model
  - The predictions were made using two different approaches: (1) using only the variables reflecting the country’s political and economic status; (2) using all of the variables reflecting the country’s technological, political, and economic status.
- Check the efficacy of the model
  - Eight countries with known histories of proliferation attempts and two countries with no proliferation attempts were selected for the comparison and testing false negatives and false positives.

The Database

- Country's political and economic status profiles explaining economic development status, security environment factors, and internal political and cultural factors;
- Country's nuclear proliferation events data;
- Country's nuclear fuel cycle capability profiles
- The database covers 189 countries spanning between 1945 and 2000.
- All of the information utilized in the study was from open source literature.

Country's political and economic status profiles

- Economic development status
  - Gross domestic product.
  - Gross domestic product per capita.
  - Squared 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 over time
- Security environment factors
  - Prevalence of democracies in the region.
  - Enduring rivalry.
  - Frequency of dispute involvement.
  - Security guarantee.
- Internal political and cultural factors
  - The scales of democracy and autocracy.
  - The change of democracy in the country.

Country's nuclear fuel cycle capability profiles

- Nuclear reactor operation experiences
  - Commercial and research reactors
- Presence of nuclear fuel cycle facilities
  - Uranium ore processing (t U/year)
  - U recovery from phosphates (t U/year)
  - Conversion (t HM/year)
  - Uranium enrichment (MTSWU/year)
  - Fuel fabrication – U or MOX (t HM/year)
  - AFR wet/dry spent fuel storage (t HM)
  - Spent fuel reprocessing (t HM/year)
  - Zirconium alloy /Zircaloy tubing (t/year)
  - Heavy water production (t/year)
- Existence and nature of safeguards

Proliferation events profiles

- 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.

Analyze correlations among the input variables

- Dependent variables were identified based on the strength of correlation with respect to a primary independent input variable.
- Any variable with correlation coefficient greater than the cutoff value against an apparent independent variable was removed.
- Depending on the cutoff value, the number of variables removed varies.
- From this, 10 different sets of independent input variables were generated.
- The selected 10 different sets of input variables were used to predict proliferation decisions against historical records.
- The resulting goodness of fit of the statistical models was compared to identify the better fit models.

Input Model	Variables Included
Model 1 – A model with no fuel cycle capability data	GDP; GDP per capita; Industrial capacity index; Number of enduring rivalry involved; Frequency of dispute involvement; Existence of strong allies; Polity democracy index; 5-yr change in polity democracy index; Prevalence of democracy in the region; Economic openness; 5 year change in economic openness
Model 2 – The best fit model	GDP; GDP per capita; Industrial capacity index; Number of enduring rivalry involved; Frequency of dispute involvement; Existence of strong allies; Polity democracy index; 5-yr change in polity democracy index; Prevalence of democracy in the region; Economic openness; 5 year change in economic openness; Population; Uranium ore production; Uranium conversion capability; LWR fuel fabrication facility;
Model 3 – The model with least number of inputs for fuel cycle data	GDP; GDP per capita; Industrial capacity index; Number of enduring rivalry involved; Frequency of dispute involvement; Existence of strong allies; Polity democracy index; 5-yr change in polity democracy index; Prevalence of democracy in the region; Economic openness; 5 year change in economic openness; Population; Uranium ore production; Dry storage facility for spent fuel; Spent fuel reprocessing; Heavy water production; Graphite reactors; IAEA membership; NPT membership; IAEA safeguards; IAEA Additional Protocol
Model 4 – A variation from Model 3	GDP; GDP per capita; Industrial capacity index; Number of enduring rivalry involved; Frequency of dispute involvement; Existence of strong allies; Polity democracy index; 5-yr change in polity democracy index; Prevalence of democracy in the region; Economic openness; 5 year change in economic openness; Population; Uranium ore production; Uranium enrichment capability; Dry storage facility for spent fuel; Spent fuel reprocessing; Heavy water production; IAEA membership; NPT membership; IAEA safeguards; IAEA Additional Protocol
Model 5 – A variation from Model 3, used for event history analysis	GDP; GDP per capita; Industrial capacity index; Number of enduring rivalry involved; Frequency of dispute involvement; Existence of strong allies; Polity democracy index; 5-yr change in polity democracy index; Prevalence of democracy in the region; Economic openness; 5 year change in economic openness; Population; Uranium ore production; Uranium enrichment capability; Dry storage facility for spent fuel; Heavy water production; IAEA membership; NPT membership; IAEA safeguards; IAEA Additional Protocol

Observations from the correlation analysis

- Several variables always worked as proliferation inhibitors:
  - Existence of strong allies
  - The level of democracy
  - Heavy water production capability
  - NPT membership
  - Acceptance of IAEA Additional Protocol.

Observations from the correlation analysis

- Several other variables always worked as proliferation promoters:
  - Industrial capacity index
  - Number of enduring rivalries (i.e., increasing security threats from neighboring countries)
  - Frequency of dispute involvement
  - Five-year change in the level of democracy (i.e., experiencing recent negative changes in the level of democracy)
  - Population size (i.e., having a large population)
  - Uranium ore production
  - Spent fuel reprocessing capability

Observations from the correlation analysis

- Several variables switched between being a promoter or an inhibitor depending on the level of proliferation or depending on the choice of input models:
  - GDP
  - GDP per capita
  - Prevalence of democracies in the region
  - Economic openness
  - Five-year change in economic openness
  - IAEA membership
  - IAEA safeguards
  - Uranium enrichment, dry storage facility for spent fuel, wet storage facility for spent fuel, the number of graphite reactors.

A multinomial logit model

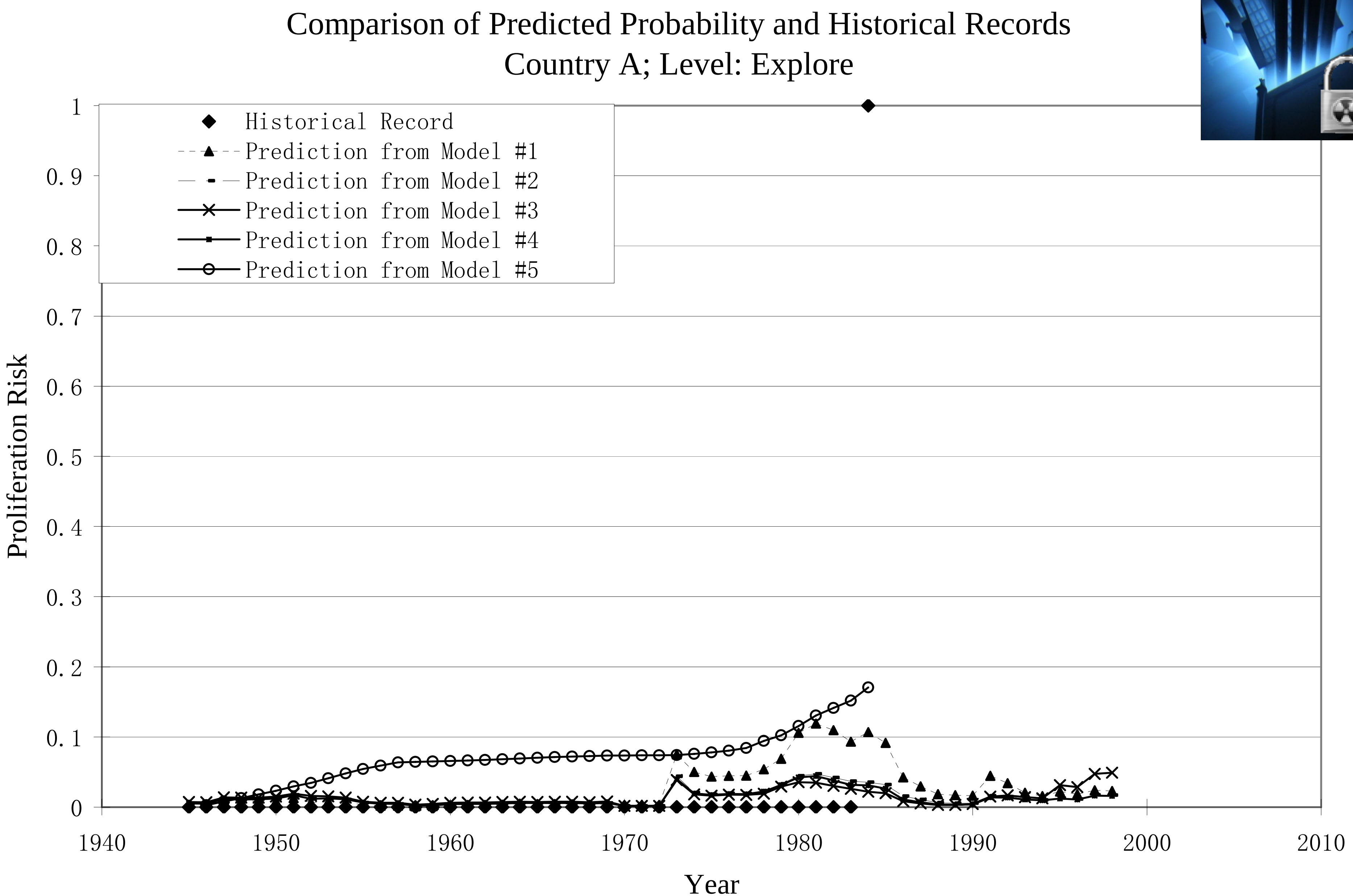
- The multinomial logit model is useful when the dependent variable is a nominal categorical variable and has multiple outcomes.
- The response is a set of choices whose probabilities depend on a vector $\mathbf{x}_i$ of covariates associated with the i-th group.
- The multinomial logit model can be represented as,

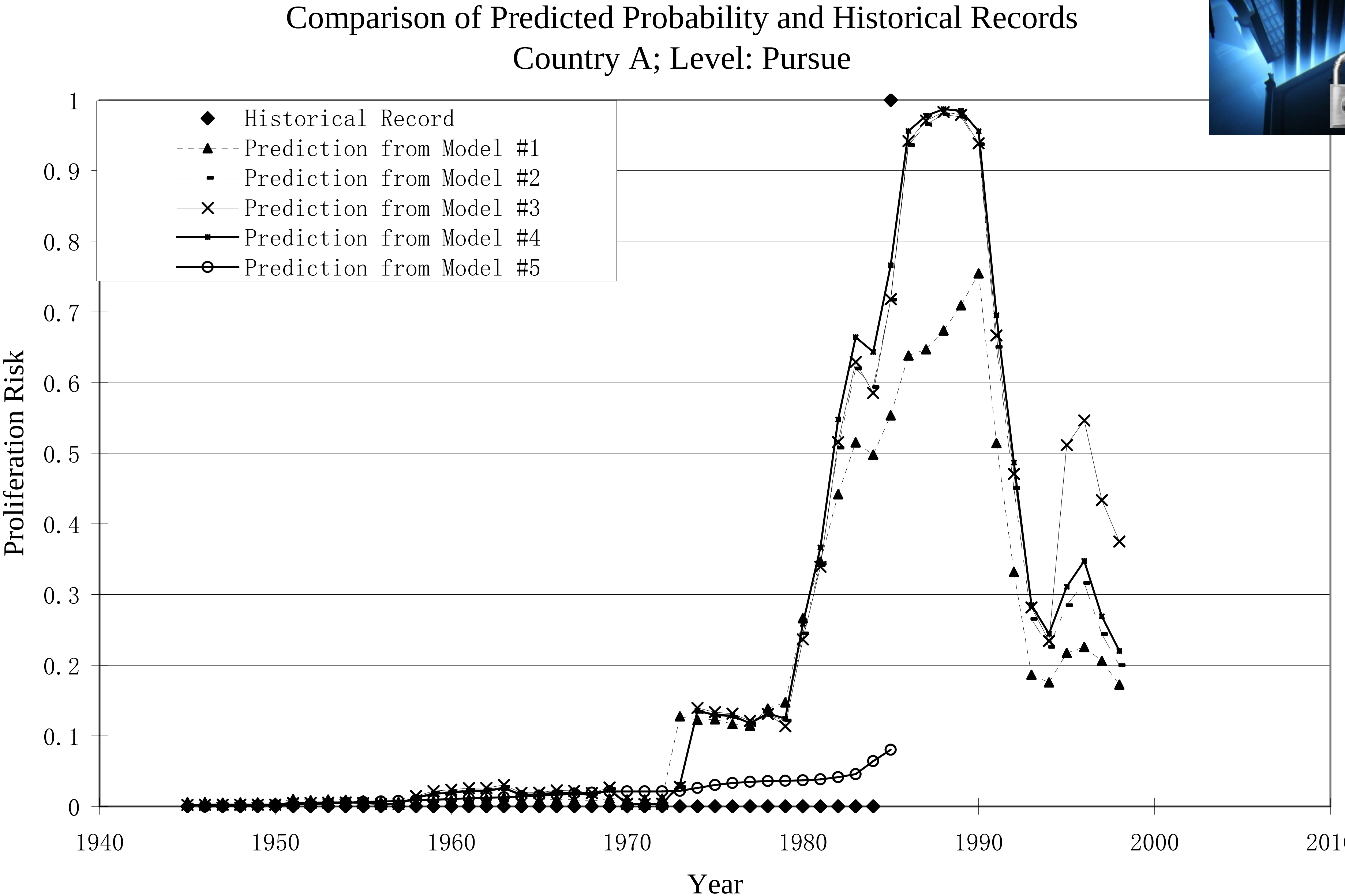
$$p_j = \frac{\exp(\beta_j x)}{\sum_j \exp(\beta_j x)} \quad for \;\; j = 0,1,2,3$$

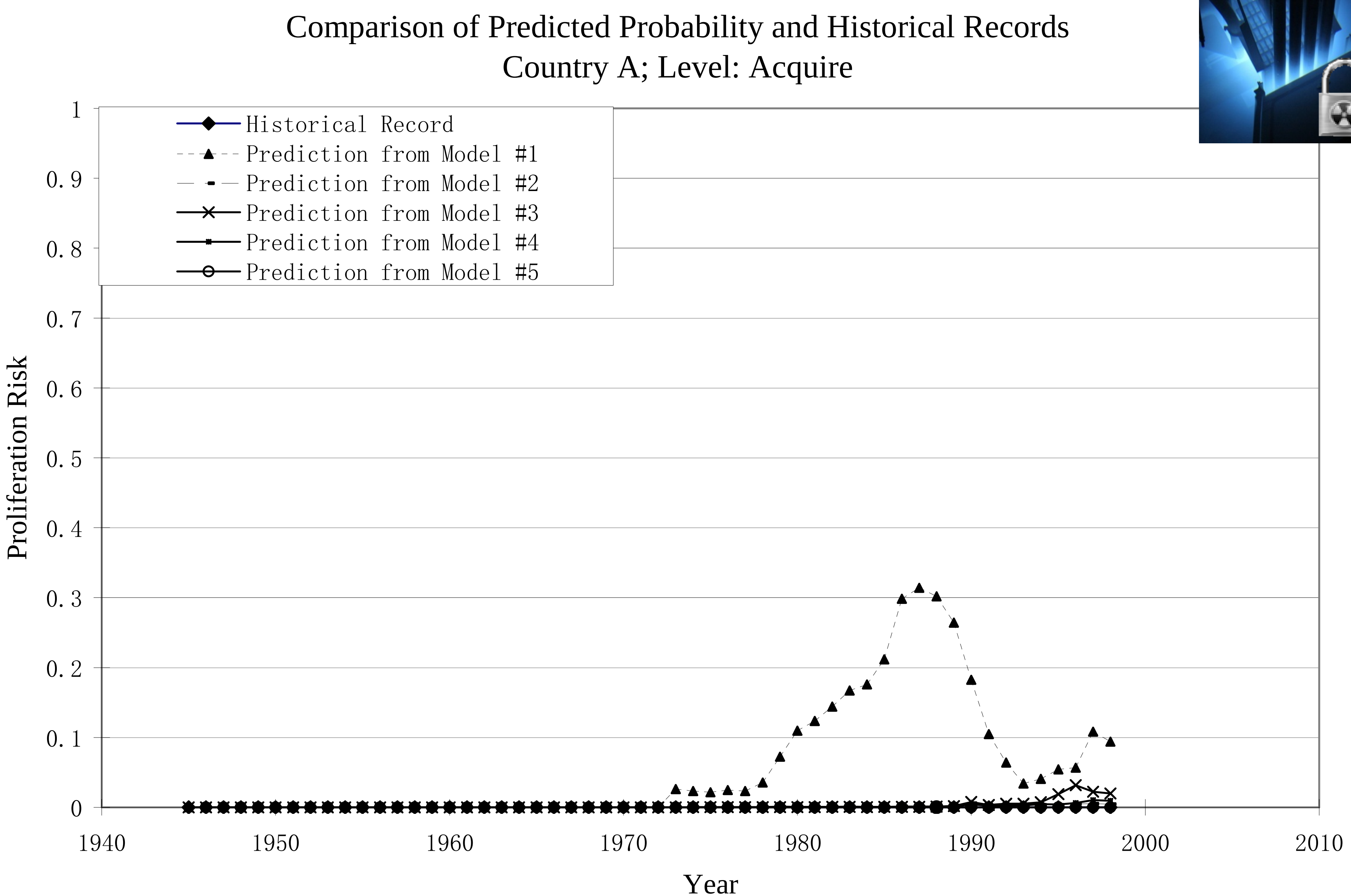
- where *Pj* is the probability of event j, βj is the correlation coefficient of x for event j, *x* is the vector of independent variables, and *j* represent proliferation levels.

Event history modeling

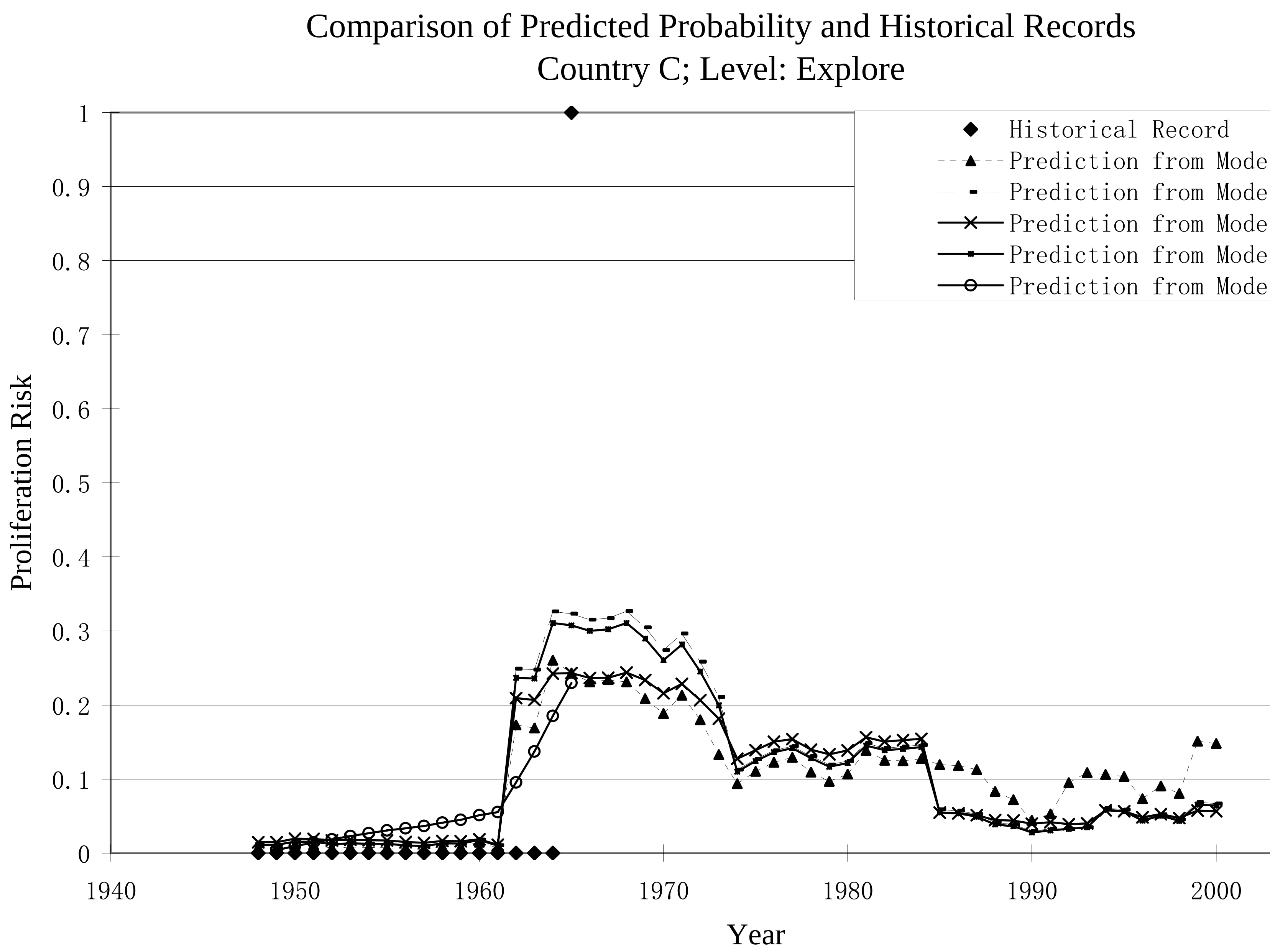
- Specifically examine the probability of an event based on an examination of the longitudinal data collected on a set of observations
- Event history analysis studies transition across a set of discrete states, including the length of time intervals between entry to and exit from specific states, i.e., changes from 'complying with nonproliferation' to 'making a positive proliferation decision'.
- The event history was captured by defining the rate at which units fail (or nonproliferation duration ends) by time *t* given that the unit had survived until *t*.
- Unlike a traditional time-series analysis, event history modeling can handle information on many observations over time.
- Unlike the traditional regression-based approach, event history modeling can handle time-varying covariates.
- The log-logistic model was used.


Comparison of Predicted Probability and Historical Records
Country A; 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

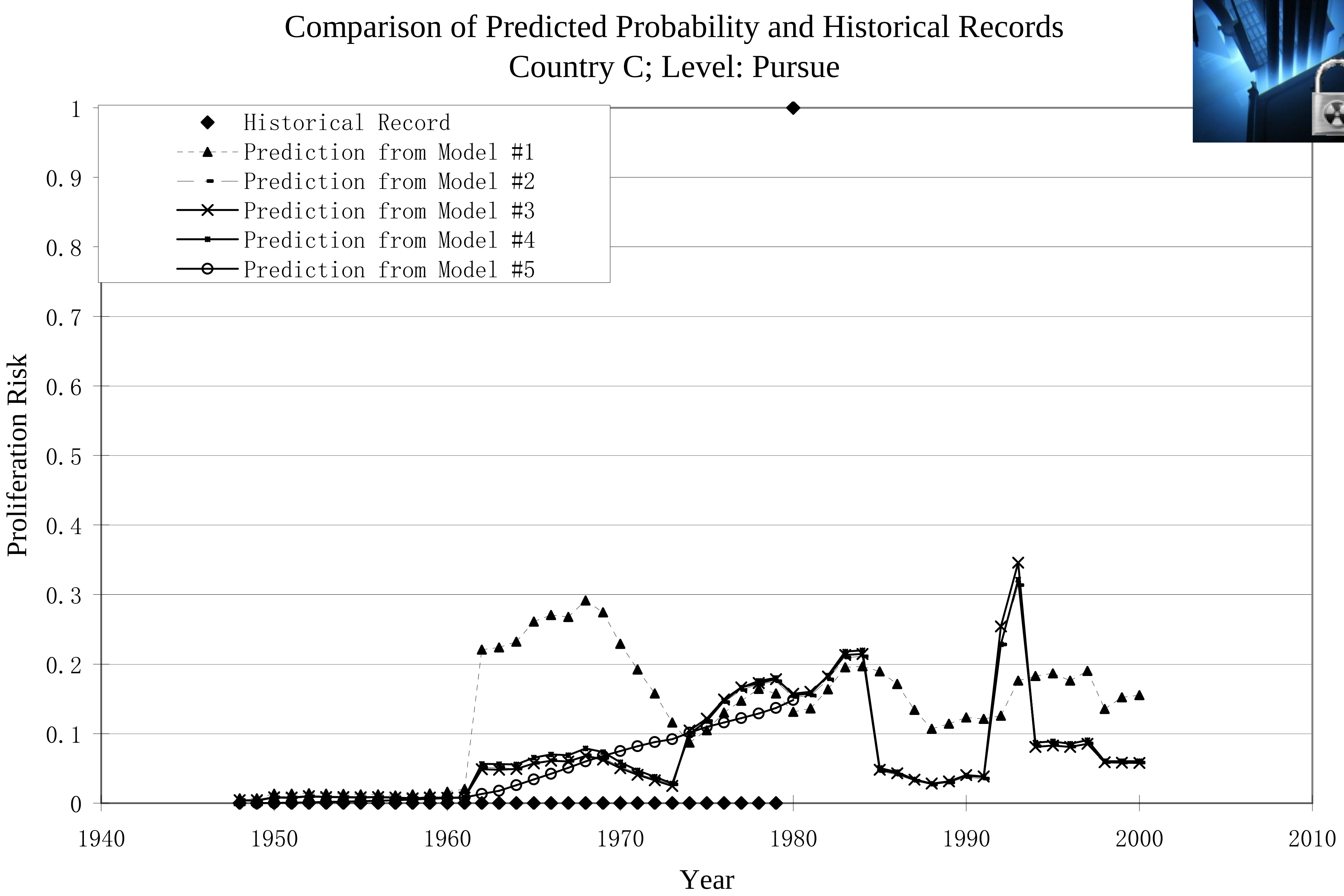

Comparison of Predicted Probability and Historical Records
Country A; Level: Pursue
Historical Record
Prediction from Model #1
Prediction from Model #2
Prediction from Model #3
Prediction from Model #4
Prediction from Model #5
Proliferation Risk
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1940
1950
1960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



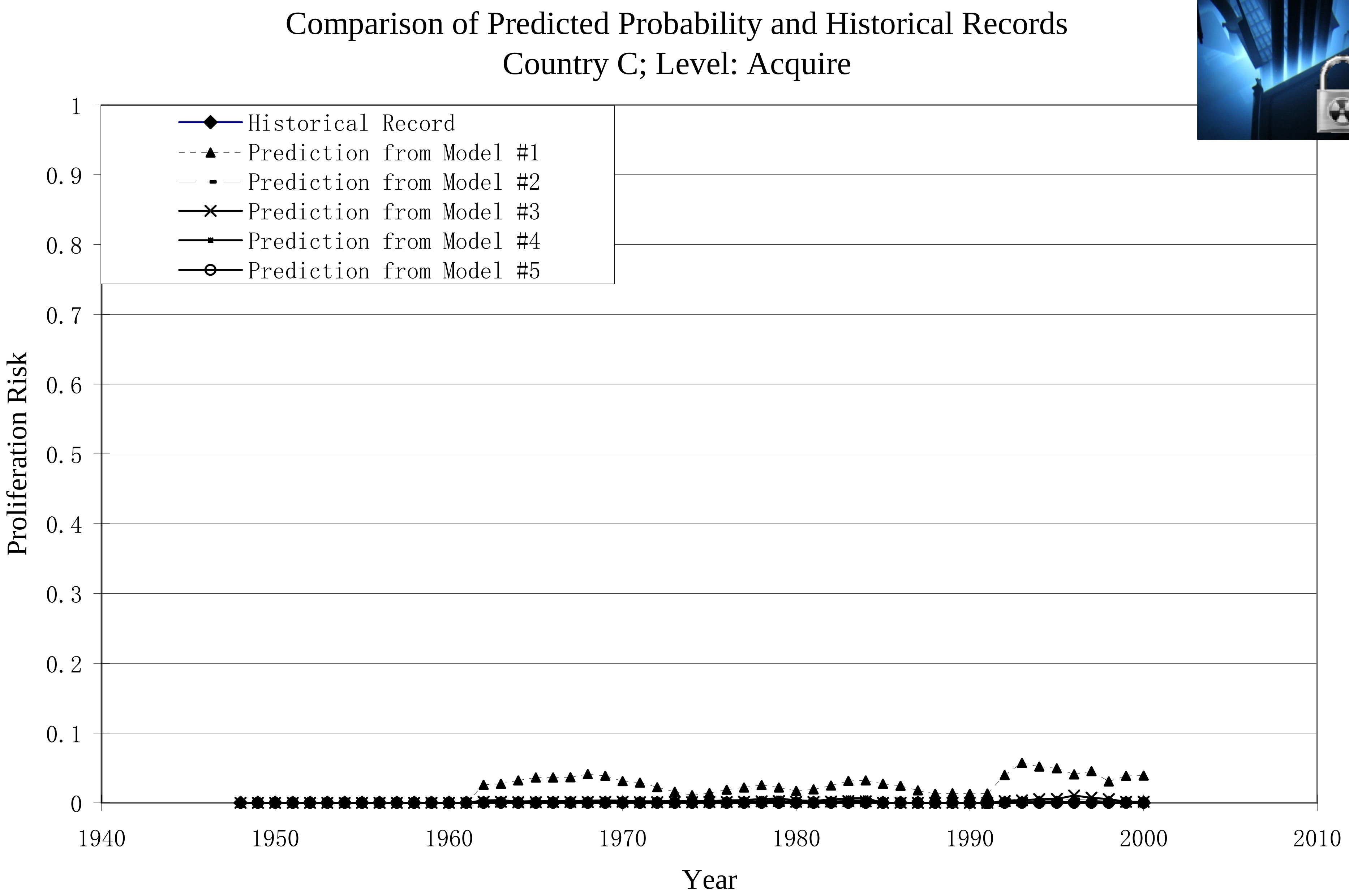
Comparison of Predicted Probability and Historical Records
Country A; Level: Acquire
Historical Record
Prediction from Model #1
Prediction from Model #2
Prediction from Model #3
Prediction from Model #4
Prediction from Model #5
Proliferation Risk
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1940
1950
1960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

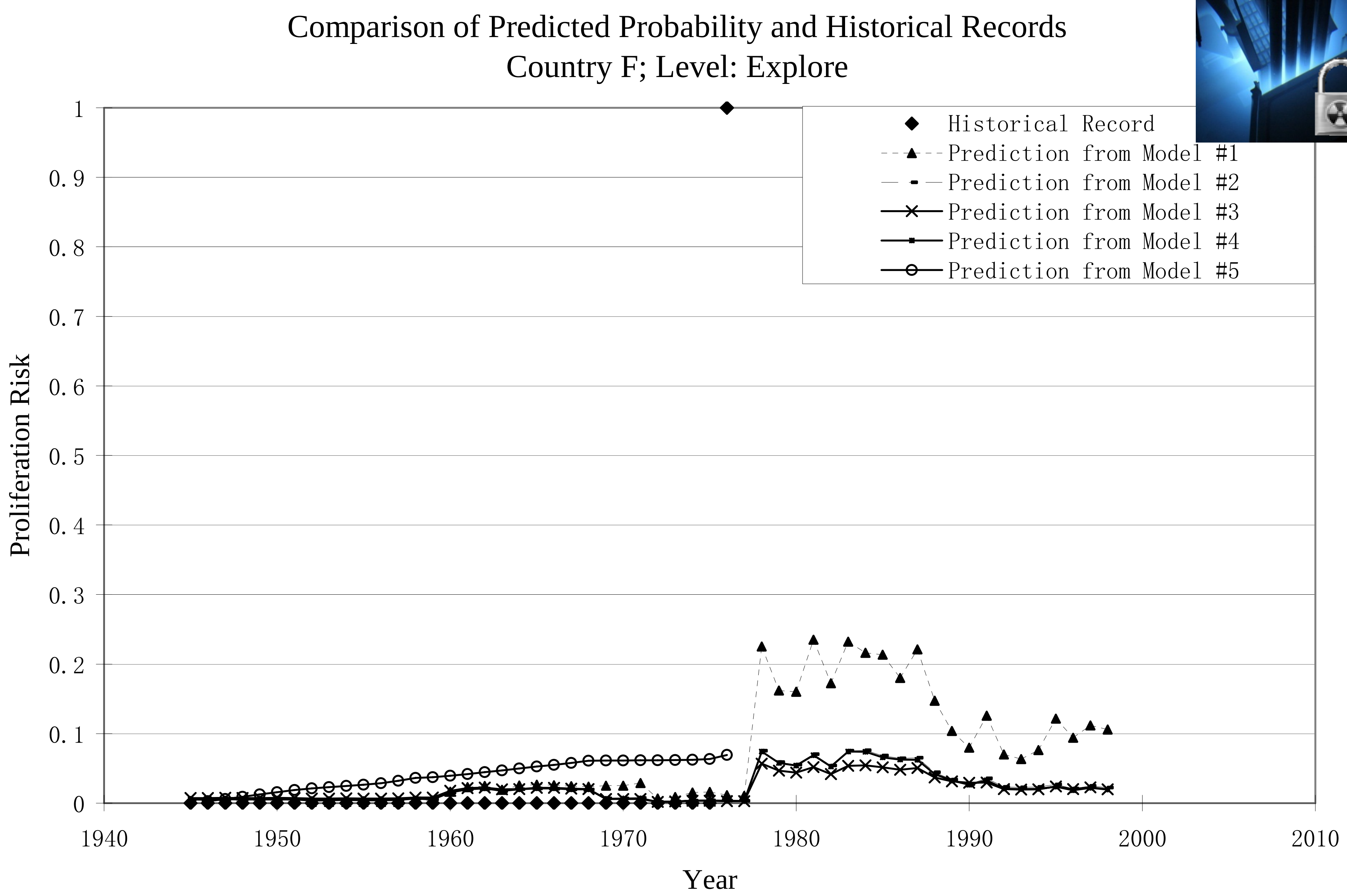


Comparison of Predicted Probability and Historical Records
Country C; Level: Explore
Proliferation Risk
Year
Historical Record
Prediction from Model #1
Prediction from Model #2
Prediction from Model #3
Prediction from Model #4
Prediction from Model #5
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1940
1950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

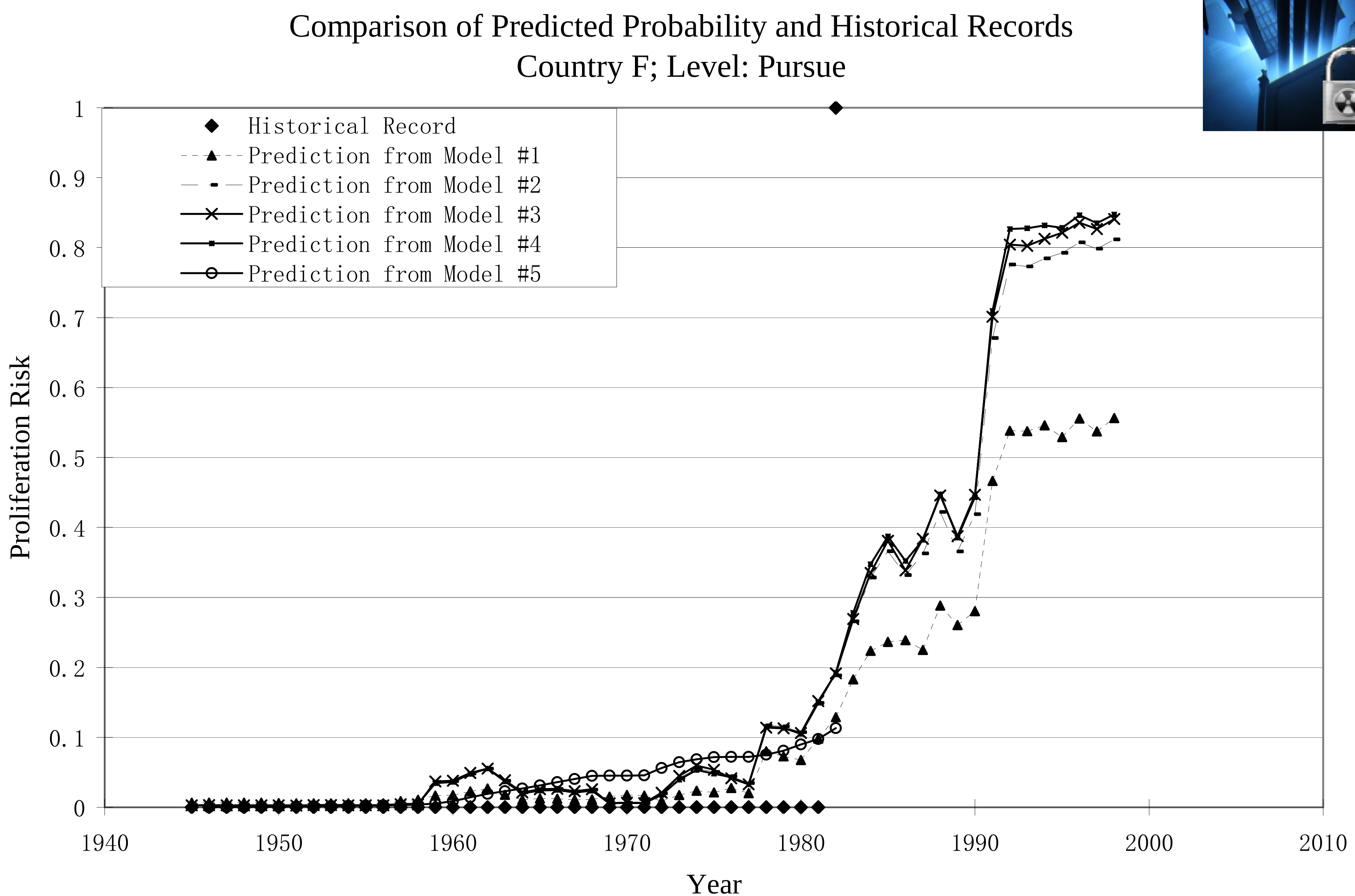


Comparison of Predicted Probability and Historical Records
Country C; Level: Pursue
Historical Record
Prediction from Model #1
Prediction from Model #2
Prediction from Model #3
Prediction from Model #4
Prediction from Model #5
Proliferation Risk
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1940
1950
1960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

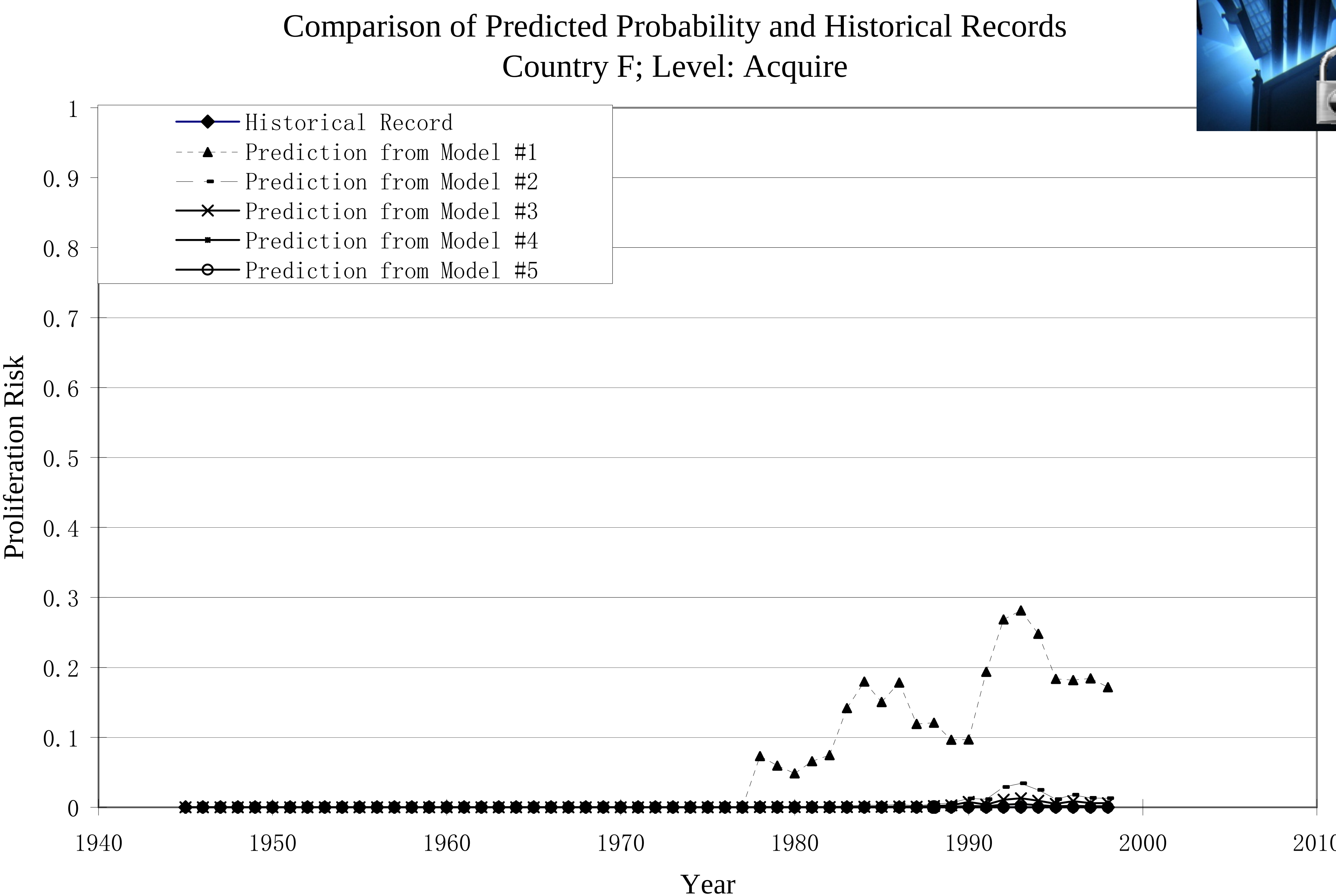

Comparison of Predicted Probability and Historical Records
Country C; Level: Acquire
Historical Record
Prediction from Model #1
Prediction from Model #2
Prediction from Model #3
Prediction from Model #4
Prediction from Model #5
Proliferation Risk
Year
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1940
1950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



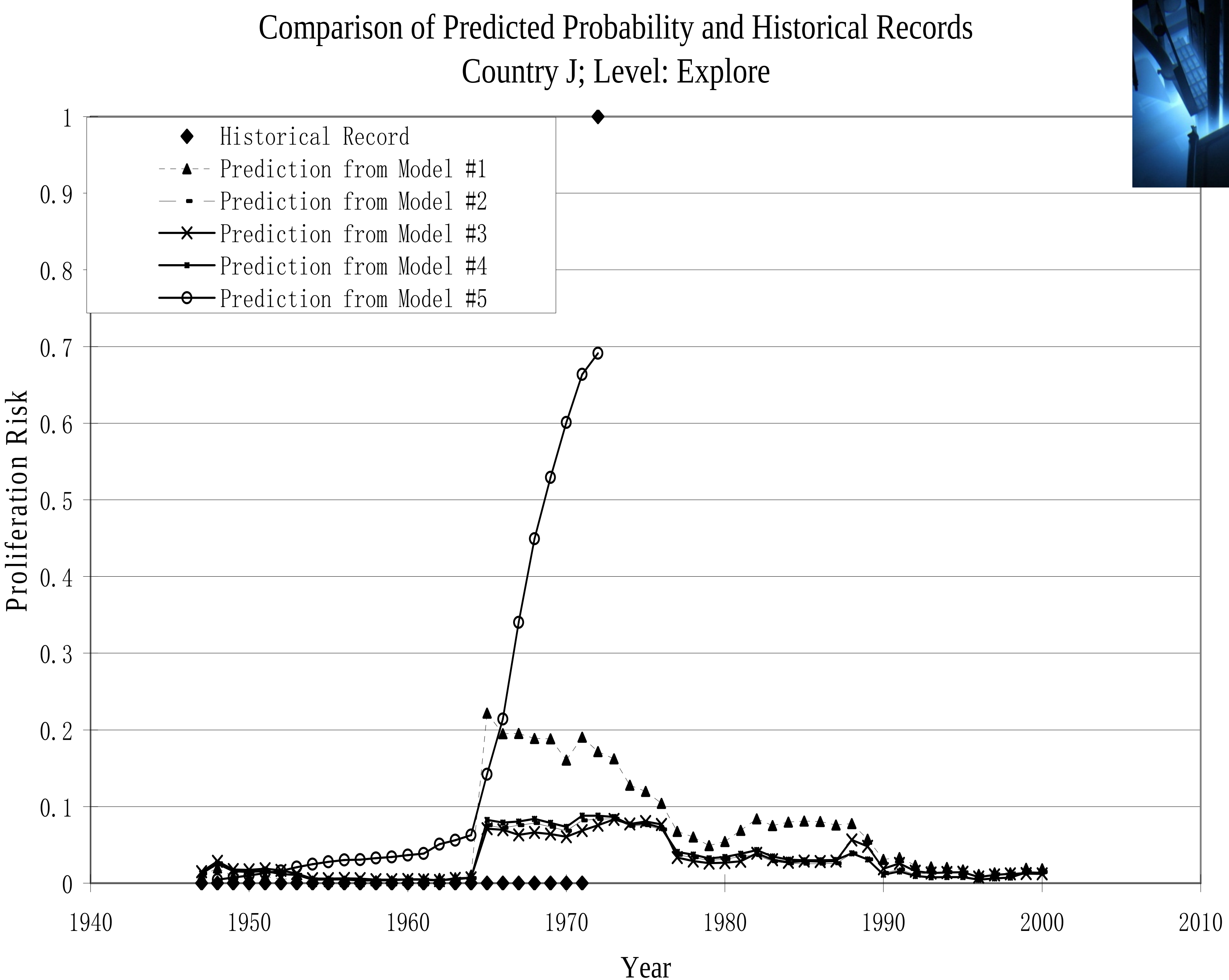
Comparison of Predicted Probability and Historical Records
Country F; Level: Explore
Proliferation Risk
Year
Historical Record
Prediction from Model #1
Prediction from Model #2
Prediction from Model #3
Prediction from Model #4
Prediction from Model #5
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1940
1950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

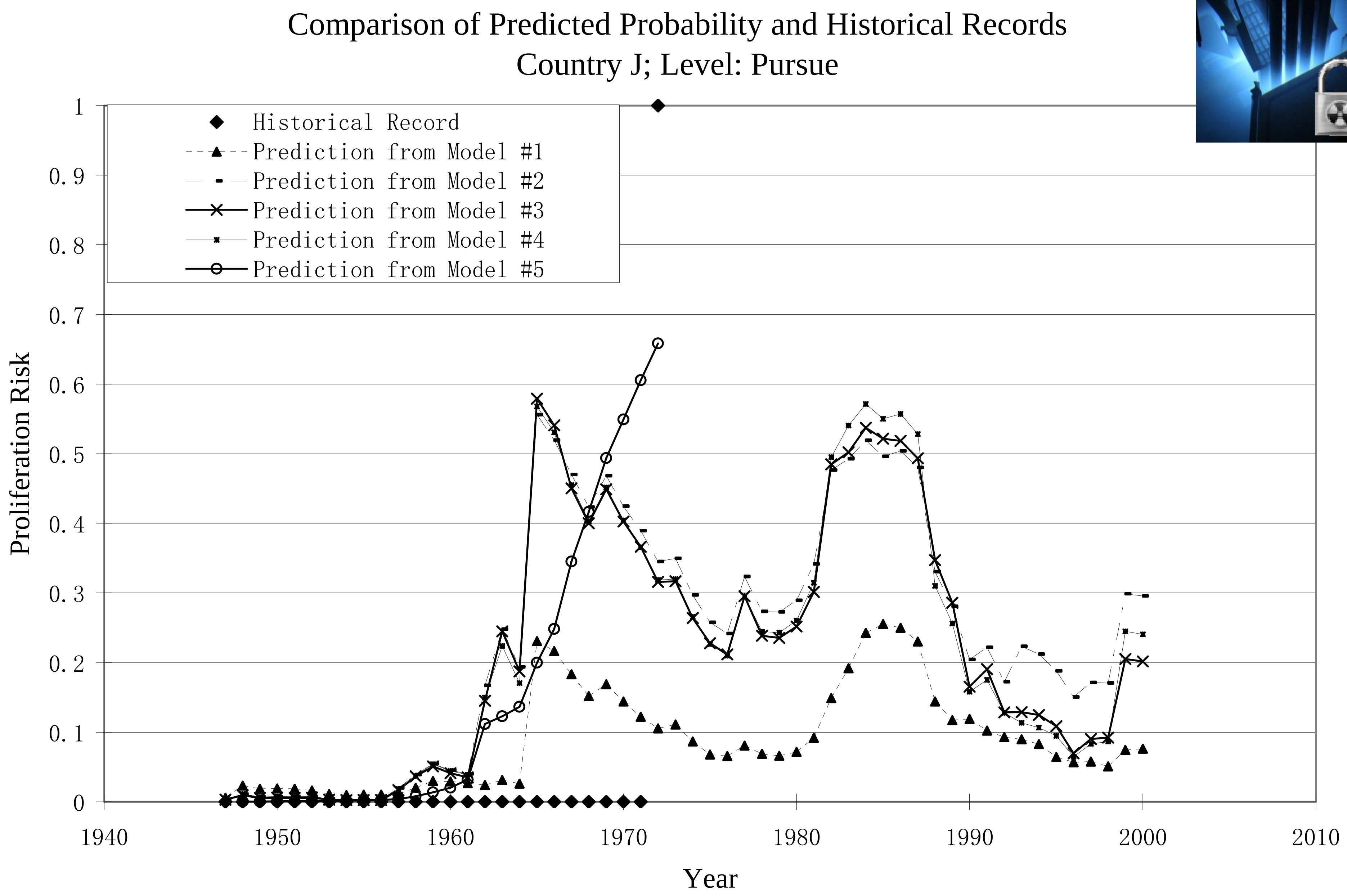


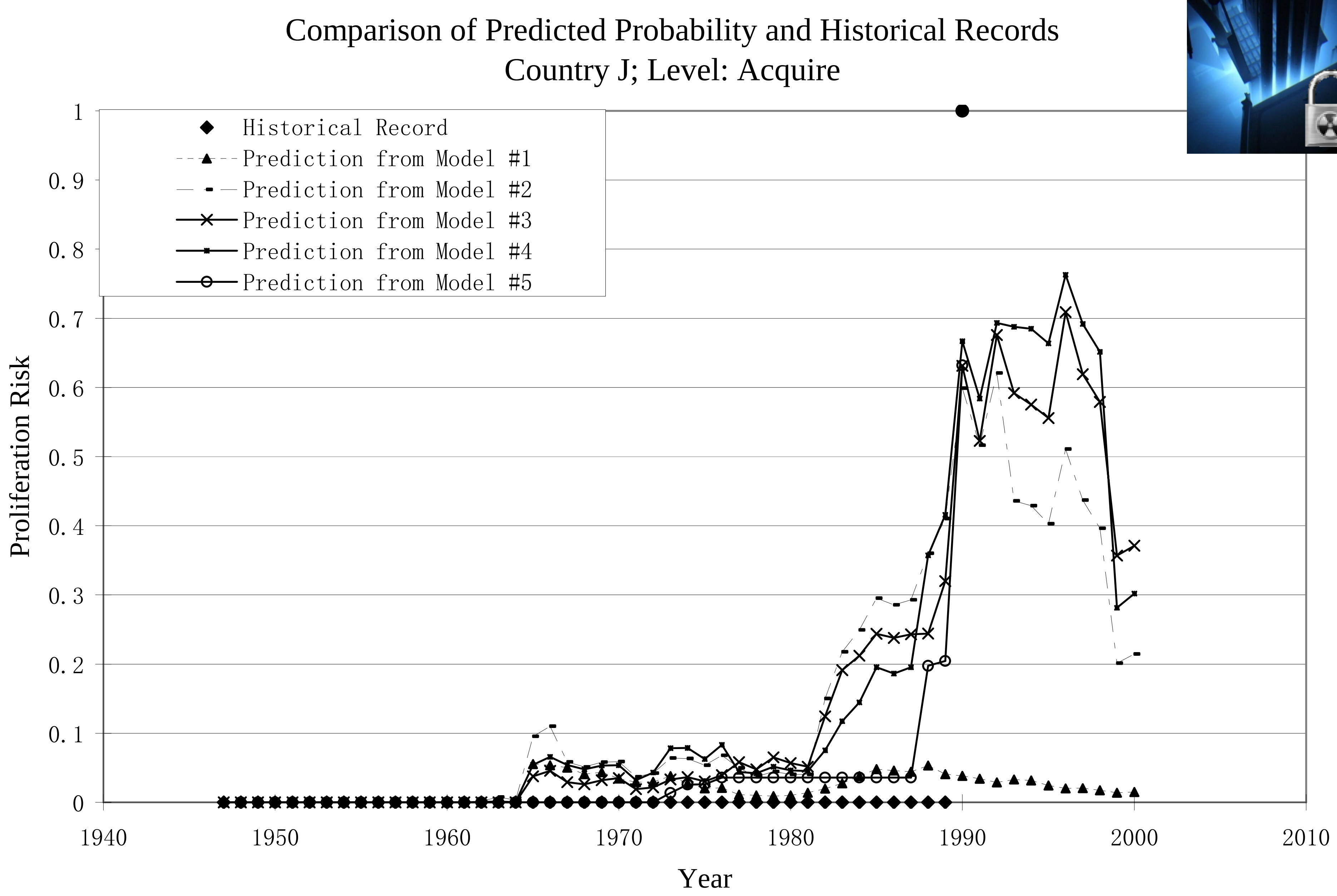
Comparison of Predicted Probability and Historical Records
Country F; Level: Pursue
Historical Record
Prediction from Model #1
Prediction from Model #2
Prediction from Model #3
Prediction from Model #4
Prediction from Model #5
Proliferation Risk
Year
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1940
1950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



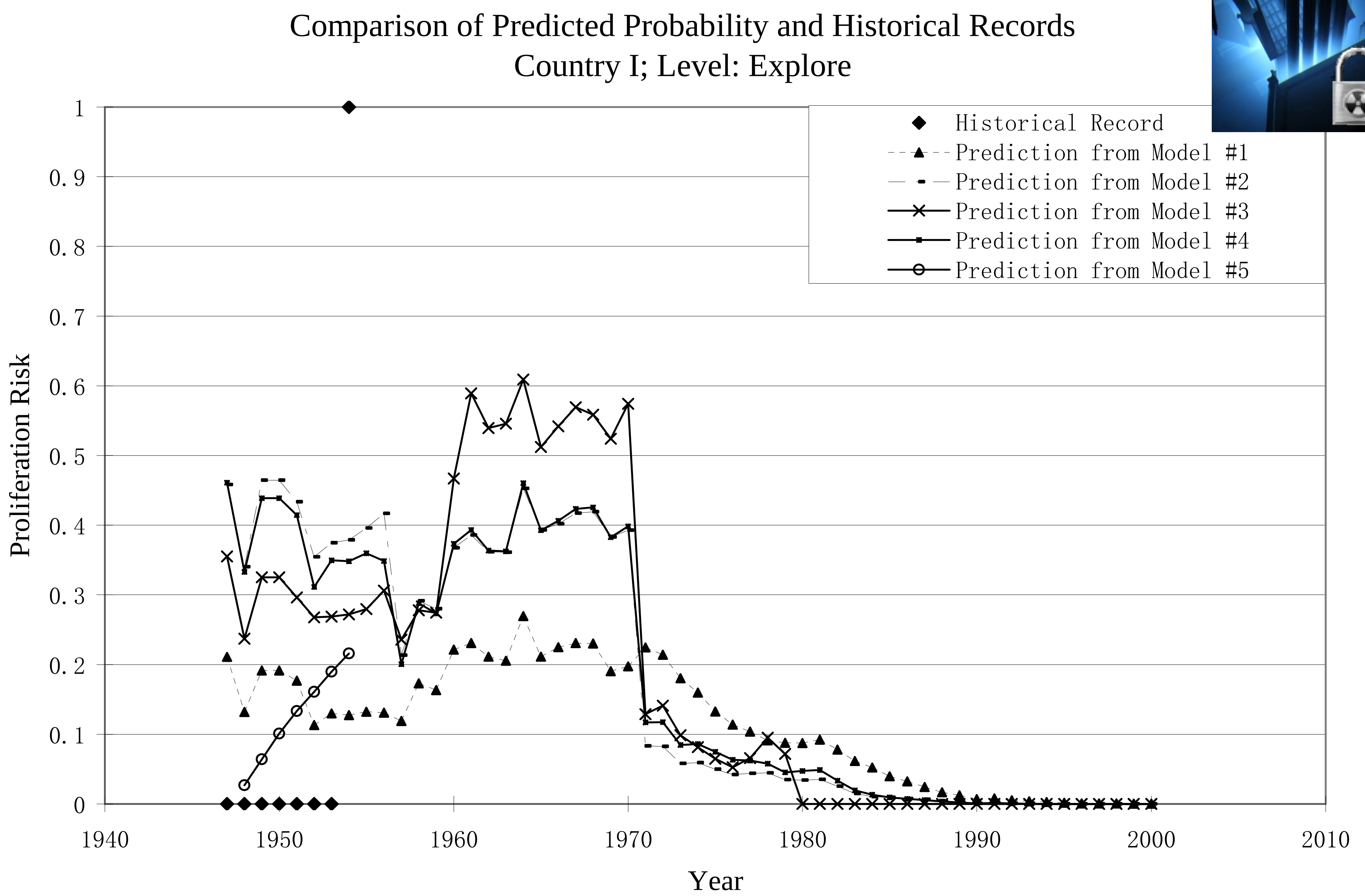
Comparison of Predicted Probability and Historical Records
Country F; Level: Acquire
Historical Record
Prediction from Model #1
Prediction from Model #2
Prediction from Model #3
Prediction from Model #4
Prediction from Model #5
Proliferation Risk
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1940
1950
1960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


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
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
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
1970
1980
1990
2000
2010

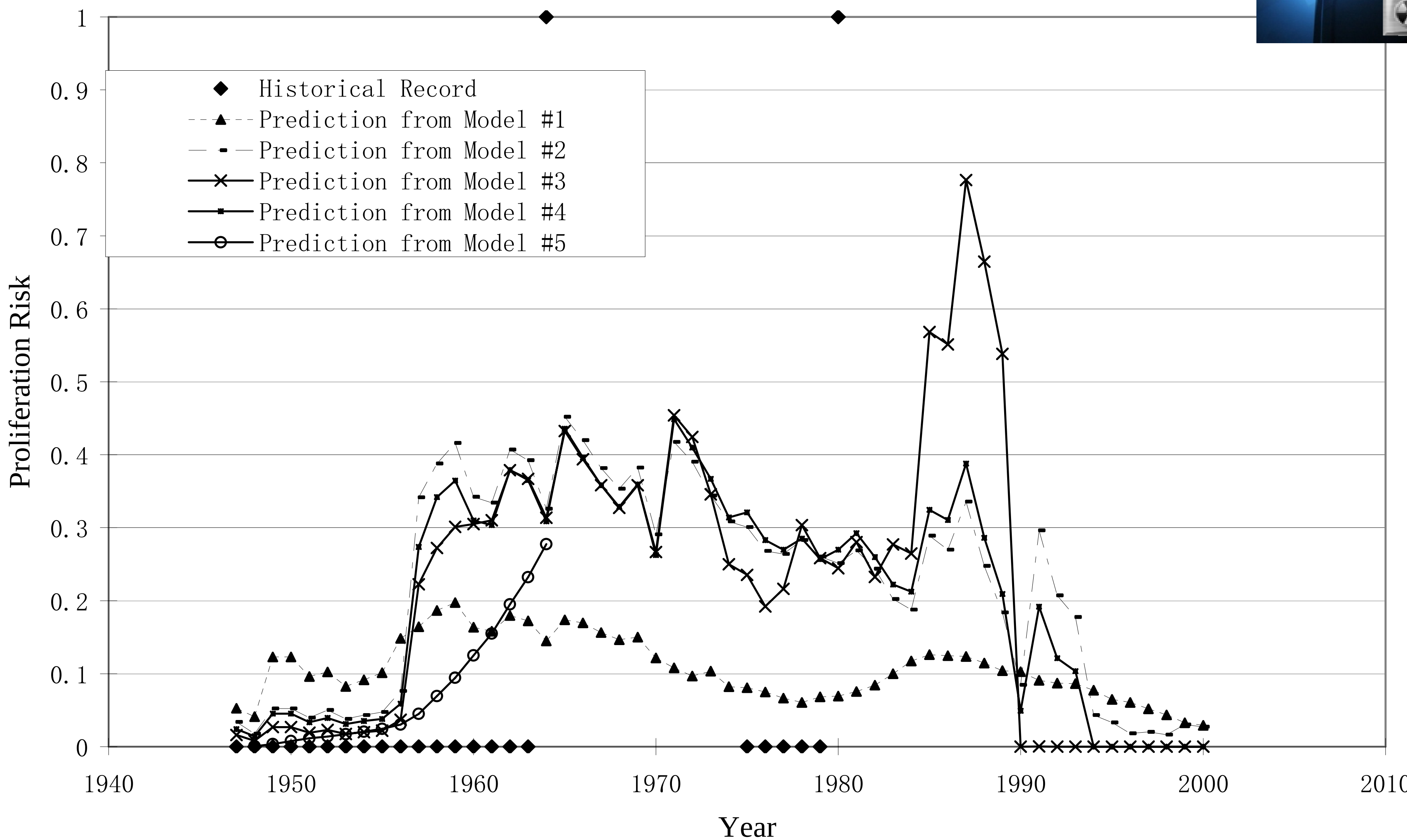


Comparison of Predicted Probability and Historical Records
Country J; Level: Acquire
Historical Record
Prediction from Model #1
Prediction from Model #2
Prediction from Model #3
Prediction from Model #4
Prediction from Model #5
Proliferation Risk
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1940
1950
1960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

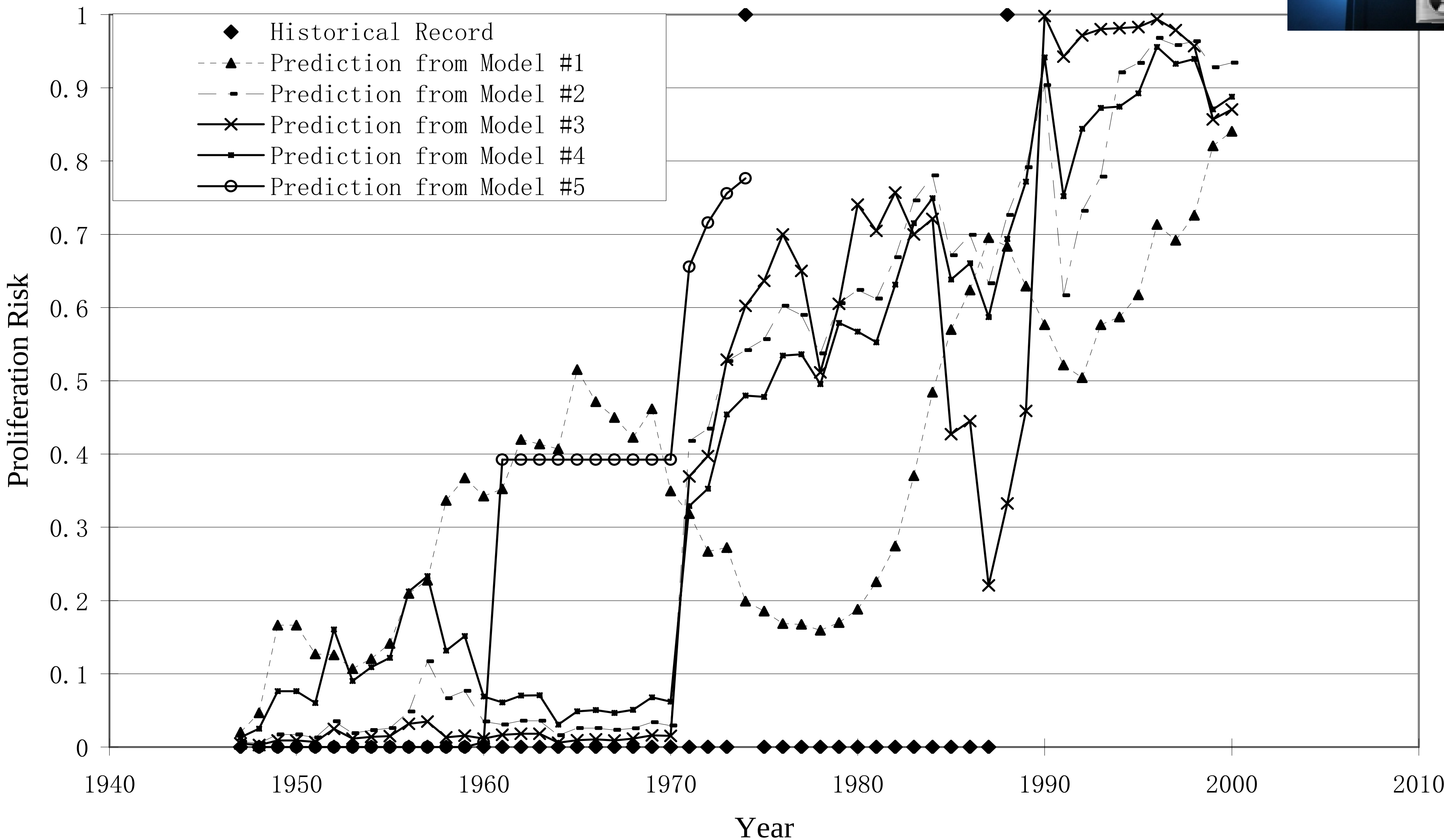


Comparison of Predicted Probability and Historical Records
Country I; Level: Explore
Historical Record
Prediction from Model #1
Prediction from Model #2
Prediction from Model #3
Prediction from Model #4
Prediction from Model #5
Proliferation Risk
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1940
1950
1960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

Comparison of Predicted Probability and Historical Records
Country I; Level: Pursue



Comparison of Predicted Probability and Historical Records
Country I; Level: Acquire



Main variables affecting the "explore" decision

- Economic openness (proliferation inhibitor)
- Growing GDP (proliferation inhibitor)
- Frequent dispute involvement (proliferation promoter)
- Prevalence of democracy in the region (proliferation inhibitor)
- Industrial development capacity (proliferation promoter)
- Growing GDP per capita (proliferation promoter)
- Five-year changes in economic openness (proliferation promoter)

Main variables affecting the "pursue" decision

- Spent fuel reprocessing capability (proliferation promoter)
- Dry spent fuel storage capability (proliferation inhibitor)
- Uranium enrichment capability (proliferation inhibitor)
- Presence of Additional Protocol (proliferation inhibitor)
- Five year changes in economic openness (proliferation promoter)
- Economic openness (proliferation inhibitor)
- Frequency of dispute involvement (proliferation promoter)
- Heavy water production capability (proliferation inhibitor)
- Prevalence of democracy in the region (proliferation inhibitor)
- NPT membership (proliferation inhibitor).

Main variables affecting the “acquire” decision

- Spent fuel reprocessing capability (proliferation promoter)
- Heavy water production capability (proliferation inhibitor)
- Uranium enrichment capability (proliferation promoter)
- NPT membership (proliferation inhibitor)
- Economic openness (proliferation promoter)
- Industrial development capacity (proliferation promoter)
- Five year changes in economic openness (proliferation inhibitor)
- Uranium ore production capability (proliferation promoter)
- Population size (proliferation promoter)
- Dry spent fuel storage capability (proliferation promoter)
- Frequency of dispute involvement (proliferation promoter).

Observations

- A country's decision to "explore" nuclear proliferation appears to be mainly controlled by its security environment and industrial and economic development status.
- Data on a country's nuclear fuel cycle capabilities was not found to be essential in predicting the 'explore" decision.
- For the "pursue" and "acquire" decisions, accounting for the nuclear fuel cycle capability of the nation was important in improving the predictions of nuclear proliferation.
- Predictions made without using the fuel cycle capability data often produced false positive warnings.

Observations

- Due to the empirical nature of the study, the results obtained were strongly affected by the quality of the data recorded during the period included.
- For example, results indicating that having a heavy water production capability, uranium enrichment capability, or dry spent fuel storage capability as proliferation inhibitors are an artifact.

Summary

- This study indicated that predictive models can be useful in providing warnings for potential nuclear proliferation attempts.
- In general, the event history analysis (based on using the log-logistic model) seems to be a more reliable modeling approach to predict nuclear proliferation.
- Proliferation prediction results from the multinomial logit model may be less reliable in representing time-evolving effects of different proliferation variables.
- Nonetheless, in terms of using the predictive models for warning against proliferation attempts, each of the models developed in this study seems to have some merit as shown in the results.
- It would be prudent to use the models in an inclusive way to stay on the conservative side.

Discussions

- This study did not examine the issue of what probability of proliferation should be considered to constitute a warning.
- At this point, interpreting the results with qualitative understanding seems more appropriate than putting an arbitrary threshold for warning.
- Using the trend of the results obtained from predictive models along with an understanding of the historical and political context of each country’s situation should be considered when arriving at a realistic warning level.

Discussions

- One of the possible applications of the developed methodology is to prioritize the use of resources for safeguards monitoring.
- Because of the competing demands on IAEA's resources, efforts must be prioritized among the countries and technologies of interest.
- For the greatest effectiveness, the bulk of the monitoring resources and activities should be focused on states that present the most risk with fewer resources expended in inspecting low-risk installations.

Future Work

- Consider human resource data
- Expand the database beyond 2000
- Combine with fuel cycle facility nonproliferation characteristic data
- Implementation into a different modeling approach (e.g., Bayesian Belief Network)

Team Members

- Jun Li, PhD, Former student, NCSU, Research Associate, University of North Carolina, Chapel Hill
- Stephen Skutnik, Doctoral student, NCSU
- David N. McNelis, PhD, NCSU/University of North Carolina, Chapel Hill

Questions?