Advanced Safeguards Design Using PR & PP Methodology

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Background

- Under the auspices of the Generation IV International Forum (GIF) a Working Group has developed a methodology for the evaluation of Proliferation Resistance and Physical Protection (PR & PP) for Gen IV nuclear energy systems
- Consensus approach to methodology development has been achieved: many stakeholders have been involved, including IAEA, Japan, USA, ROK, France, EC, Canada, and UK
- USA sponsorship by NNSA and DOE/NE
- Markov tool presented here sponsored by DOE/NE; *focus of application is PR*

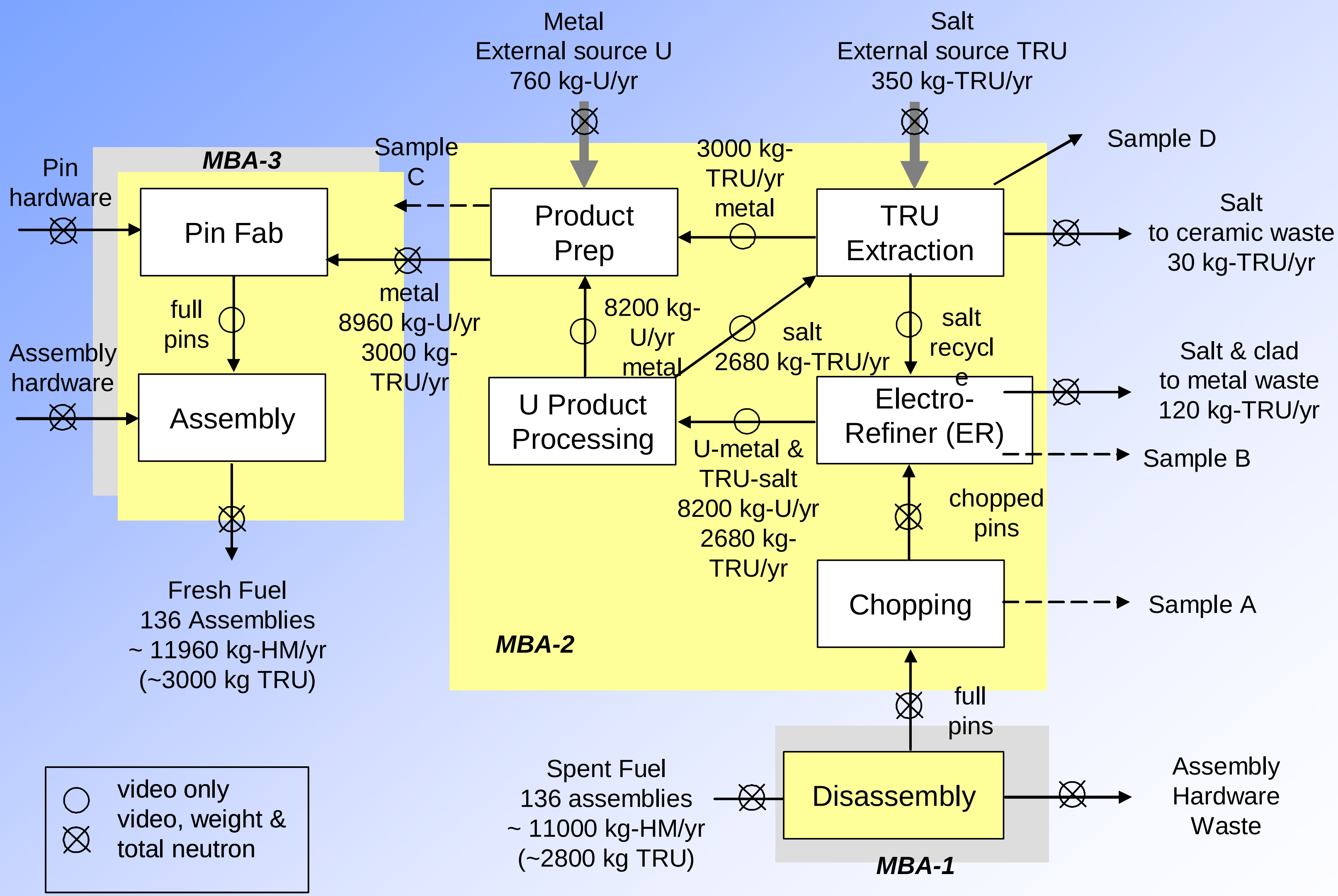
Background (cont'd)

- The Working Group has developed an evaluation framework, characteristic threats, measures with corresponding metrics, and several proposed ways for evaluation of scenarios or pathways.
- A sample case was formulated (Example Sodium Fast Reactor, or ESFR), and a portion of the system (a part of the pyroprocessing facility) has been evaluated

Objectives

- To demonstrate how the PR&PP methodology can be useful early in the design of safeguards systems of advanced nuclear energy systems
- The ESFR pyroprocessing unit is used as the example system and a *Markov* model approach is applied to the definition and evaluation of proliferation scenarios that could be impeded or prevented by advanced safeguards

ESFR Pyroprocessing Unit



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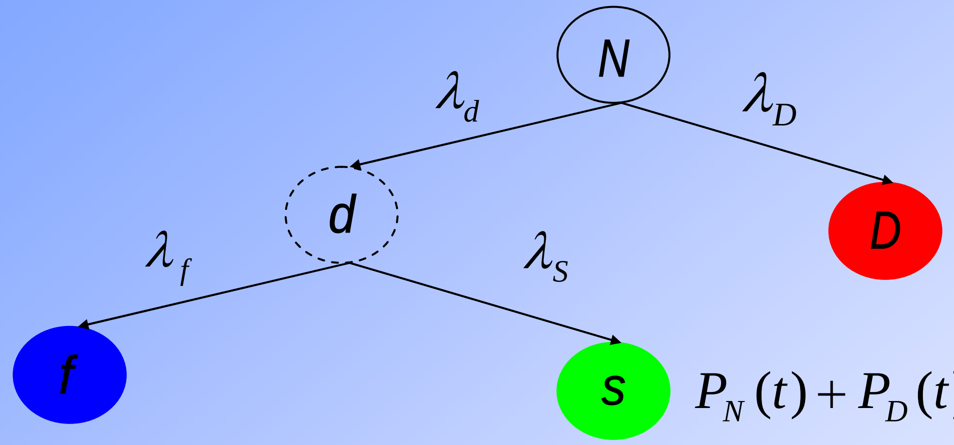
PR & PP Paradigm and Markov Formulation

Generic PR & PP Paradigm	Threat →	Response →	Outcomes
Markov Model Formulation	■ Assumes proliferator targets ■ A particular MT (Material Type) ■ Sufficient resources to carry out missions	■ Defines pathways to proliferation based on material stocks and flows design features ■ Assumes safeguards approaches, false alarm, and intrinsic barriers ■ Assumes the existence of clandestine facilities in which material can be processed and weapons can be fabricated	■ Calculates ✓ Detection probability at each stage of potential proliferation ✓ Probability of technical failure of the proliferator ✓ Probability of proliferation success ■ Can Calculate ✓ Least time to proliferation ✓ Least cost to proliferation

Application to Proliferation Resistance Evaluation (2): Diversion Scenario



$$P_N(t) + P_D(t) + P_s(t) + P_f(t) = 1$$

State Definition:

N: Normal operation (determined by nature of individual facility)

D: Diversion activities are detected, which is the goal of protectors (determined by safeguards approaches) *

d: Material diverted to clandestine facilities for further processing (intermediate state)

s: Successful processing after diversion, which is the goal of proliferators *

f: Failure during diversion and during processing after diversion (determined by available resources of the proliferators) *

*: absorbing states and $P_D(\infty) + P_s(\infty) + P_f(\infty) = 1$

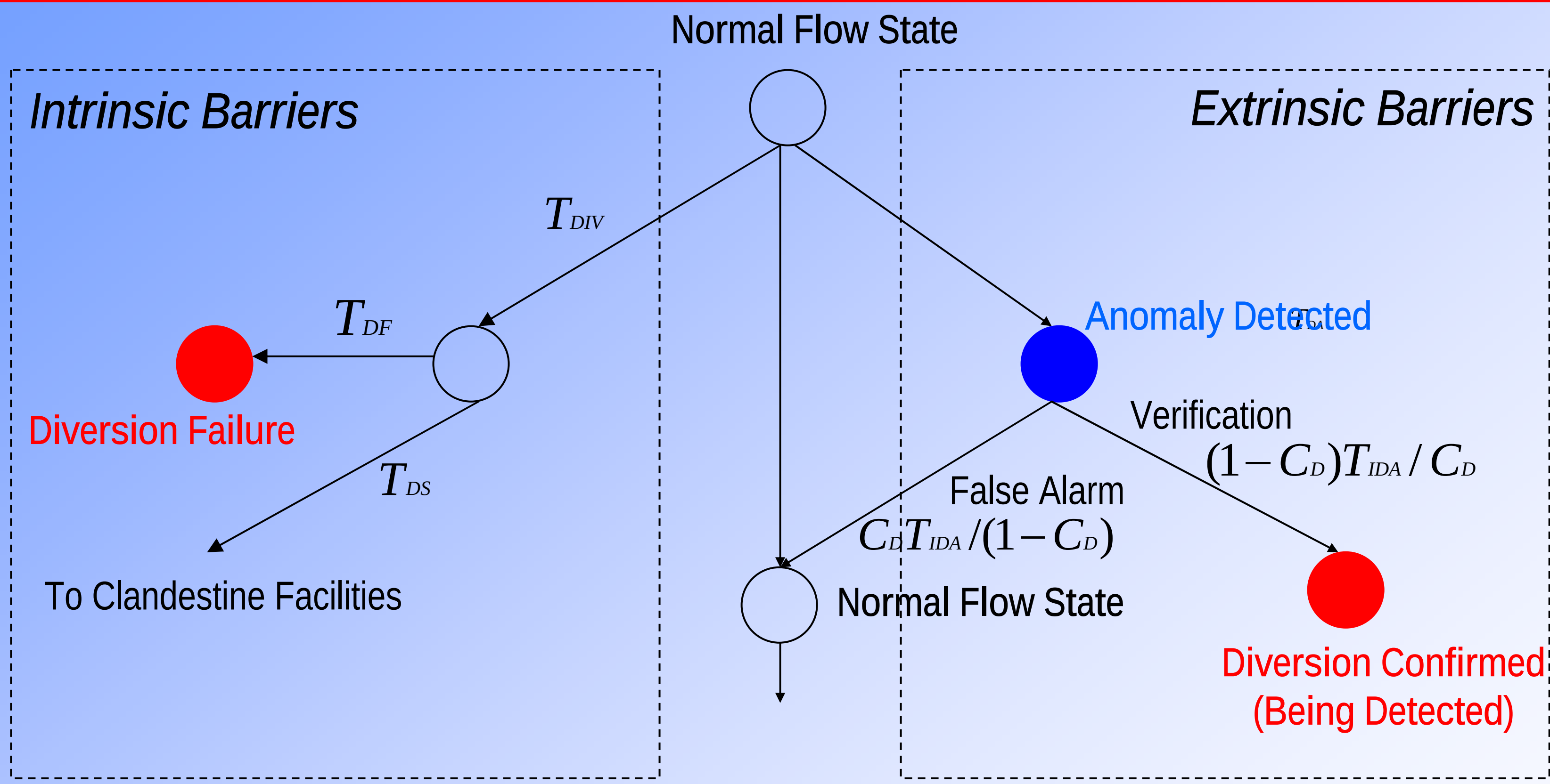
Features Modeled

- Composite safeguards modeling
- Safeguards uncertainty modeling
- False alarm modeling
- Concealment scenarios
- Intrinsic barrier modeling
- Human factors

Classification of Generic Safeguards Approaches

- Audit of nuclear material accounting records or reports
- Material verification: a physical inventory verification of all nuclear material
- Surveillance and real-time monitoring system: surveillance camera is assumed to be available where the diversion may occur and real-time monitoring systems are available in certain facilities
- Containment: it is assumed that the IAEA's metal cap seal is used on the reactor vessel, shipping casks, and safeguards equipment. The seal must be replaced and returned to the laboratory for tampering analysis

A Summary of Intrinsic / Extrinsic Barrier Modeling



False Alarm Modeling

- Consideration of false alarm effects: indicates sensitivities of safeguards approaches
- Additional time is required to verify whether it is caused by a diversion or not in case of false alarms
- Extra time required for further verification is proportional to confidence levels C_D of specific safeguards approaches
- Data of safeguards confidence levels can be collected from field experiences

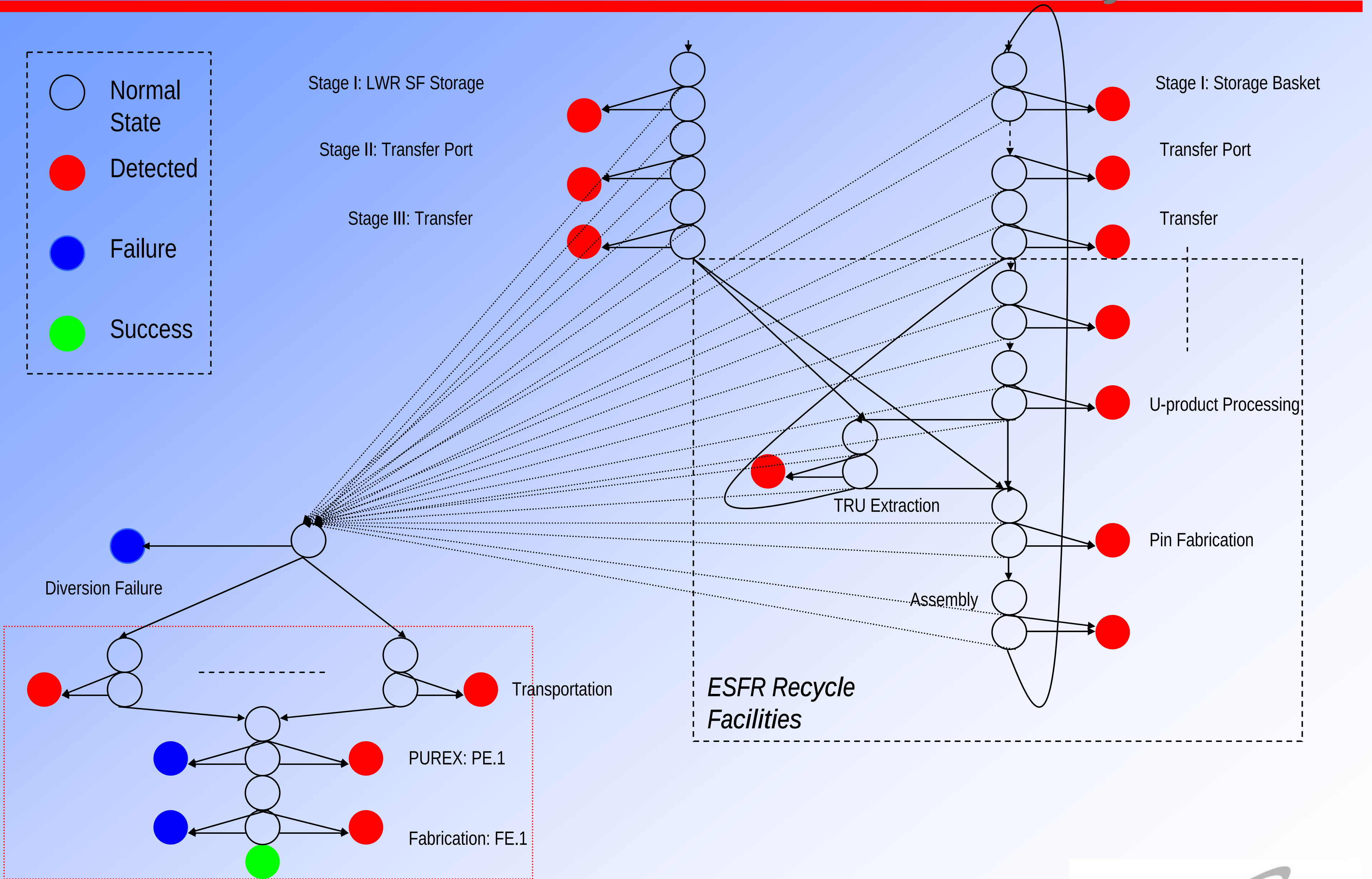
Concealment Modeling

- Purpose of concealment is to defeat some or all of the safeguards approaches associated with specific facilities during diversion
- Introducing diversion-driven anomalies and concealment driven anomalies
- Example concealment scenarios:
  - ✓ Replacement of a spent fuel assembly with a dummy assembly makes diversion undetectable for visual inspection safeguards approach (2B)
  - ✓ If the dummy has a proper neutron source, the diversion is undetectable for neutron monitoring safeguards (3D)
- Markov model provides a natural way to model concealment scenarios considering impacts of success probabilities of concealment on the time parameters of safeguards

Human Performance Modeling

- Human actions involved in every step of safeguards and the focus of human performance modeling is its impacts on safeguards
- Human errors either cause failure of an action or prolong it, depending on whether there are chances to correct errors
- Introduce a parameter, C_H the success probability of a human action, to adjust time parameter associated with human actions

A Markov Model for the ESFR System



PR Measures Calculated Using Markov Model and Material Flow in Demonstration Study

PR Measure	Metric	Obtained From
Detection Probability (DP)	Probability by unit time	Directly calculated from Markov model
Proliferation Failure Probability (PF)*	Probability by unit time	Directly calculated from Markov model
Proliferation Time (PT)	Weeks	Using assumed diversion rate and available material in terms of SQ equivalent
Material Type (MT)	Relative ranking	According to SQ equivalent and composition to assign relative ranking index
Proliferation Cost (PC)	Relative ranking	According to MT index and [OTA 1993]**
Detection Resources Efficiency (DE)	Relative ranking	According to MT index and [OTA 1993]**

*: If technical failure of processing diverted material in clandestine elements is also considered in addition to intrinsic barrier induced diversion failure, the failure rate is modeled according to material type

**: [OTA 1993] Office of Technology Assessment (OTA), *Technologies Underlying Weapons of Mass Destruction*, OTA-BP-ISC-115, U.S. Government Printing Office, 1993

Sample Results of PR Evaluation of ESFR Facilities Using PR Measures *

Stages	DP	PF**	PS***	MT	PC	DE	PT (weeks)****
ESFR SF Disassembly	0.68	0.031	0.0027	ESFR SF (pins): 0.5	0.5	0.5	40.1
Chopping	0.78	0.025	0.0022	ESFR SF (chopped pins): 0.5	0.5	0.5	40.1
Electro-refiner	0.72	0.121	0.0016	Combined U-metal and TRU-salt: 0.7	0.7	0.7	37
U-product Processing	0.72	0.021	0.0003	TRU-salt: 0.7	0.7	0.7	515
TRU Extraction	0.41	0.061	0.0058	TRU metal ingots and salt: 0.2	0.2	0.2	28
Product Preparation	0.64	0.287	0.017	ESFR FF (metal): 0.4	0.4	0.4	53.2
Pin Fabrication	0.93	0.035	0.005	ESFR FF (pins): 0.4	0.4	0.4	38.1
Assembly	0.96	0.036	0.005	ESFR FF (assembly): 0.4	0.4	0.4	38.1

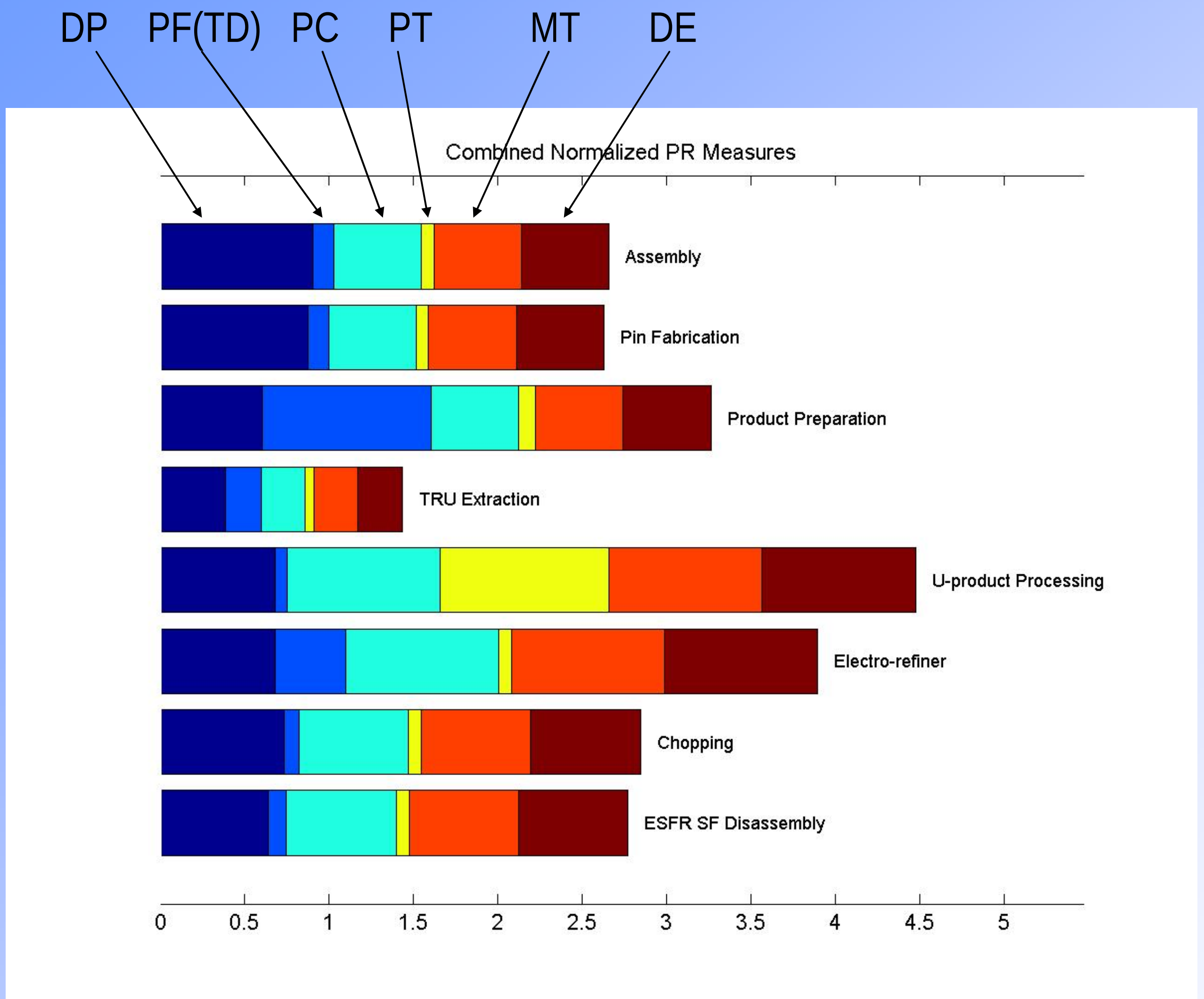
*: All probabilistic measures are evaluated at the end of diversion time

**: PF consists of failure probabilities during diversion and processing in clandestine facilities;

***PS is not one of the PR measures and PS=1-DP-PF at steady state

****: PT is the time to successfully divert 1 SQ equivalent material and the time of processing in clandestine facilities

Sample Results of PR Evaluation of ESFR Facilities: Bar Diagram Representation

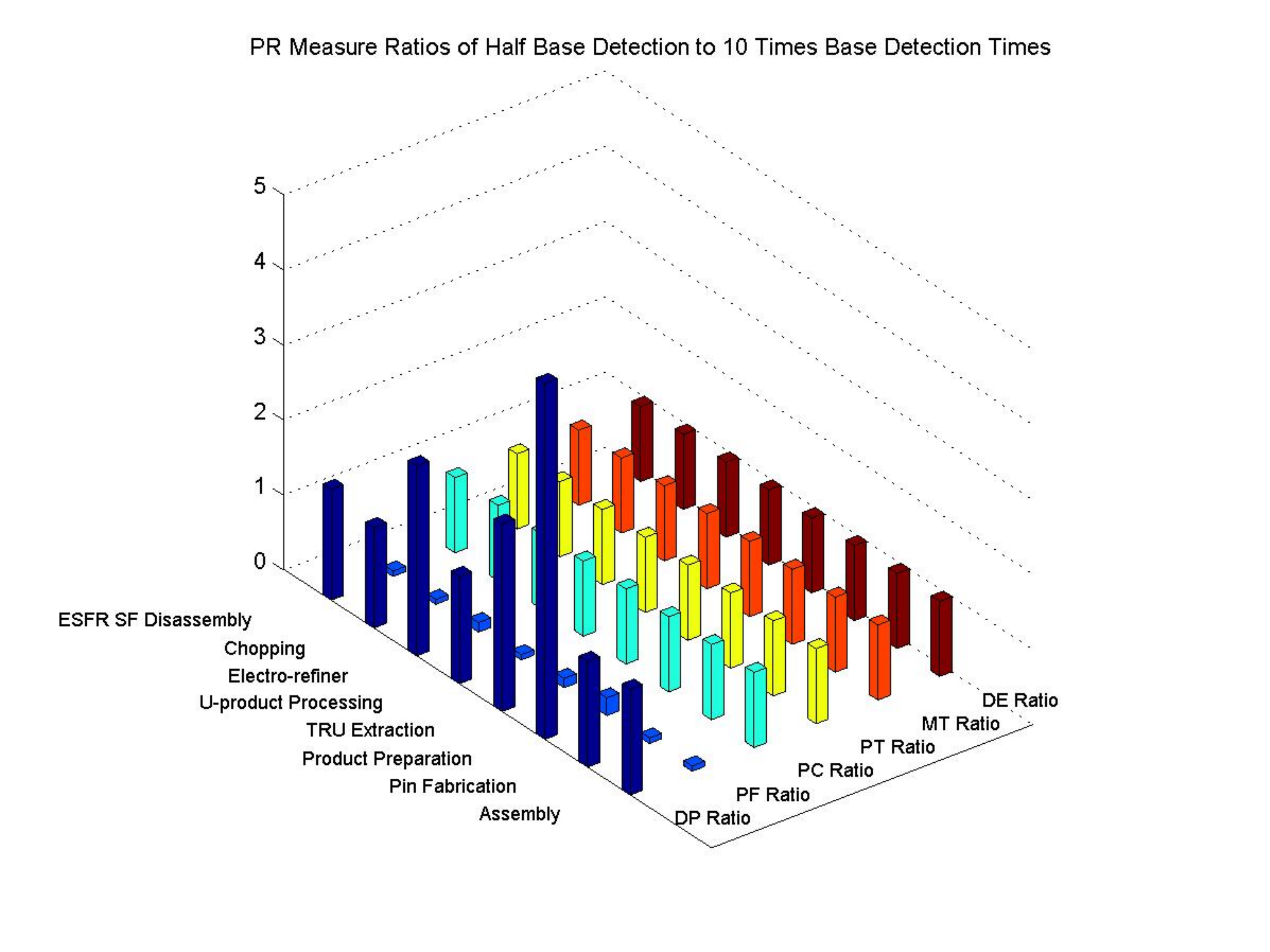


Each of the six PR measures is normalized with respect to the eight ESFR recycle facilities.

A larger bar is interpreted as being more proliferation resistant.

Sensitivity analyses by varying different parameters were also performed

Sample Results of PR Sensitivity: Variation of Safeguards Parameters



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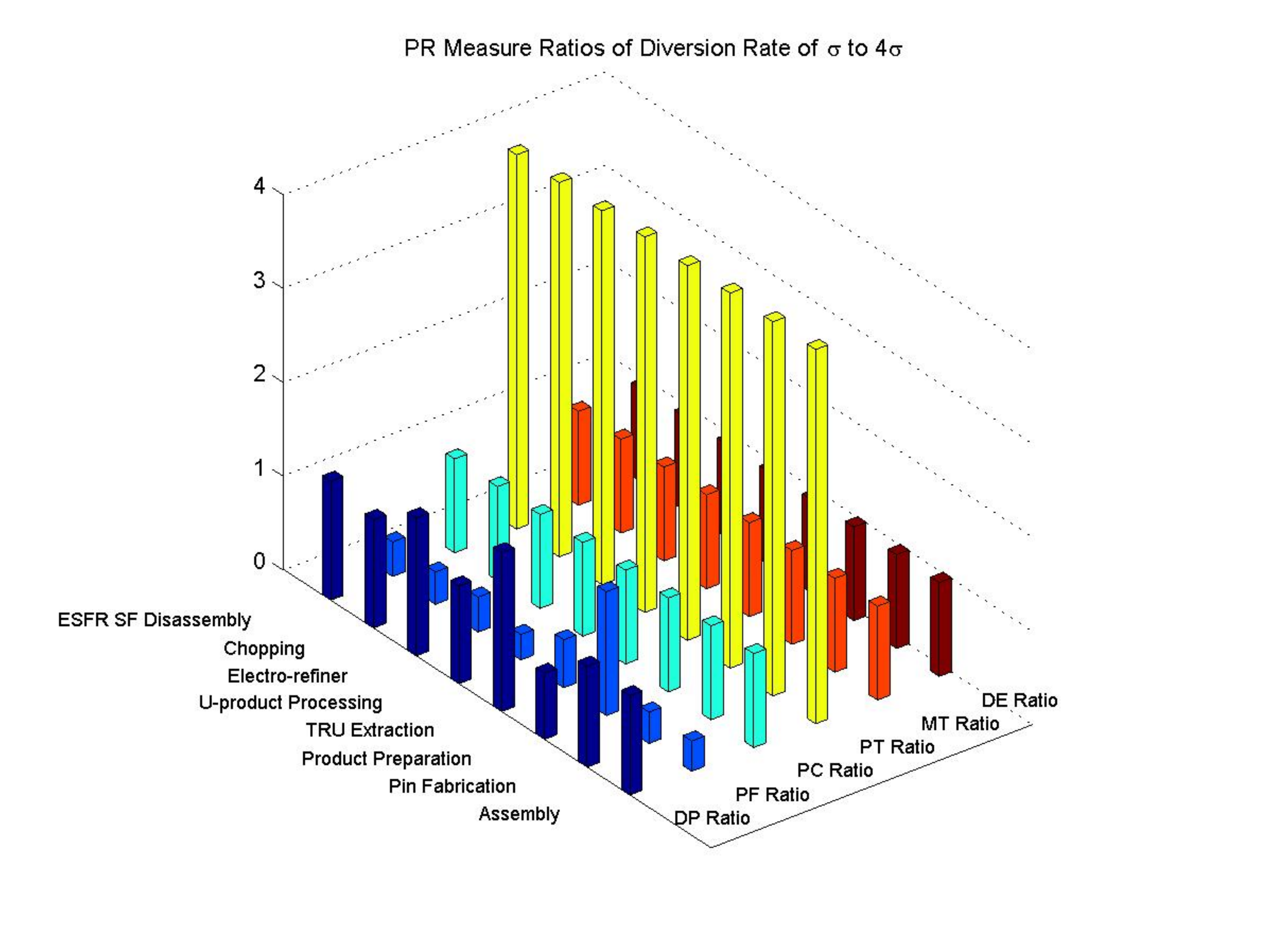
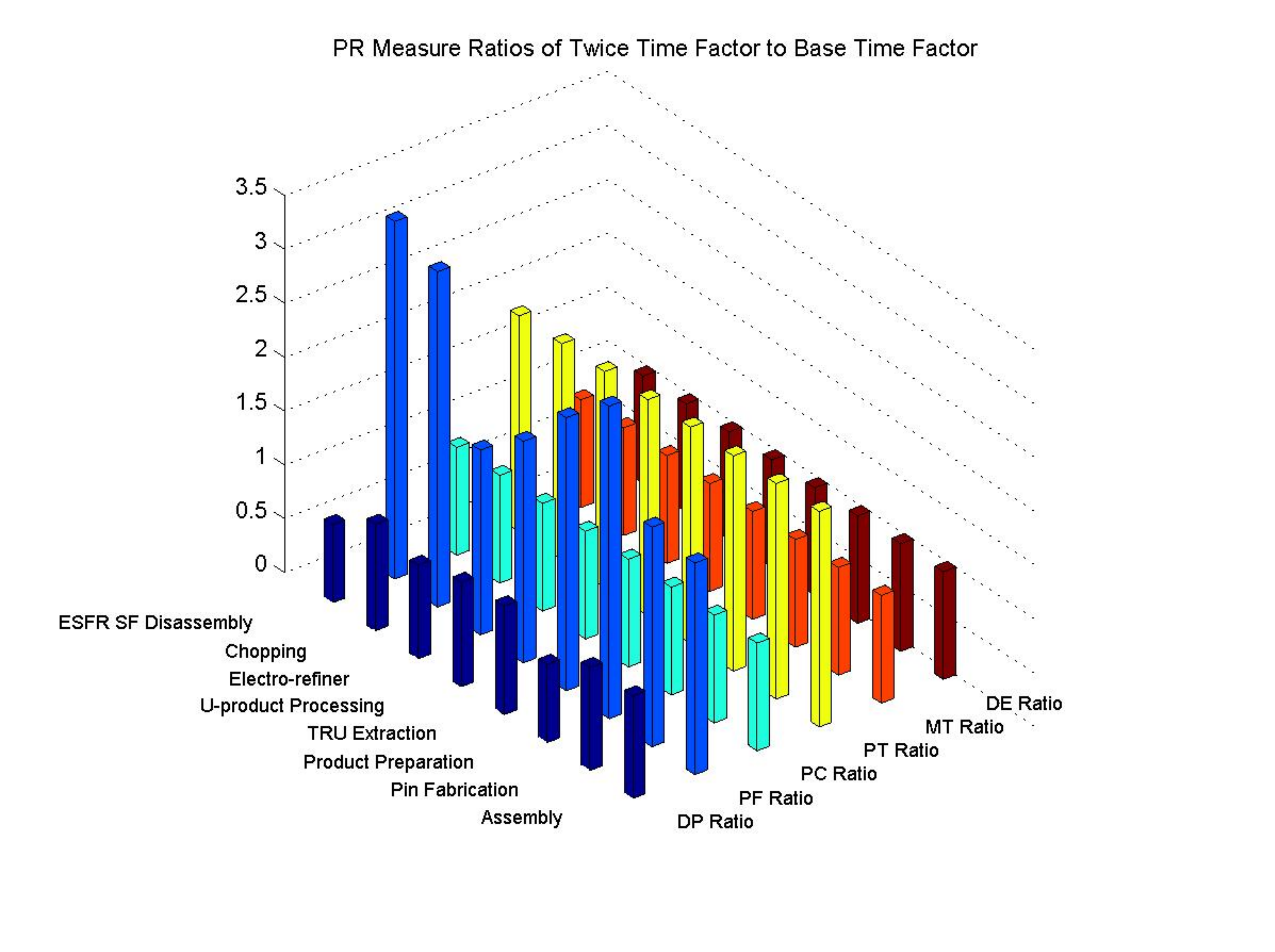
Sample Results of PR Sensitivity: Variation of Diversion Rates



Sample Results of PR Sensitivity: Variation of Intrinsic Barrier Parameters



Implications for Safeguards Designers and Inspectors

- Based on the assumed safeguards designs for the example ESFR recycle facility, detection probabilities of all diversion scenarios are very high, and further increase in detection probabilities may be difficult
- IAEA may inspect facilities more frequently but significant increase in the detection probabilities is not expected (for this hypothetical example)
- Chances of being detected will increase with prolonged diversion time. This can also be achieved by increasing intrinsic barriers

Implications for System Designers

- Material properties such as radiological level and physical form are inherent in the design of the facilities
- Therefore intrinsic barriers can only be improved by design features of facility
- By inspecting the sensitivity of the technical difficulty (TD) that uses proliferation failure probability as the metric to various design alternatives, the designer can then optimize the physical and intrinsic barriers for facilities

Observations from Markov Results

- Safeguards have significant impacts on both Detection Probability and Proliferation Failure probability (however, in different directions, i.e., Detection Probability and Proliferation Failure probability do not increase simultaneously but their sum increases) and no impact on other measures
- Diversion rates above certain value do not have significant impacts on Detection Probability (due to uncertainty model for MUF safeguards) but do on Proliferation Failure probability and Proliferation Time
- Intrinsic barriers have significant impacts on Proliferation Time and Proliferation Failure probability and less impact on other measures
- Generic approaches to modeling intrinsic barriers, false alarms, extrinsic barriers, concealment approach are integrated in Markov approach

Summary

- The Markov approach is capable of capturing a global picture of the system as well as details of the system such as intrinsic barriers, false alarms, extrinsic barriers, concealment, and human factor
- Proliferation resistance of each facility in the ESFR system is identified and sorted using bar diagram visualization of normalized PR measures
- Results calculated by explicitly modeling interactions between system features allows the safeguards to be designed and evaluated in an integrated manner
- Sensitivity analyses such as variation of individual safeguards approach parameters are easily performed to provide insights