Modeling Framework for Detecting HEU in Seaborne Containers

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- **Domestic Nuclear Detection Office (DNDO)** and **National Science Foundation (NSF)** jointly conducted the first competition in 2007. Projects funded in this round of competition are called Class of 2007.
- TAMU team (led by Nuclear Engineering Dept) submitted a large-size grant proposal (5-year, $7.5 M). **In Class of 2007, two large-size grants were awarded (TAMU and UC Berkeley)**.
- The first year fund comes from NSF and the funds in years 2-5 are from DNDO.
- **Director** for the overall project is **Dr. Warren (Pete) Miller** (member of National Academy of Engineering).

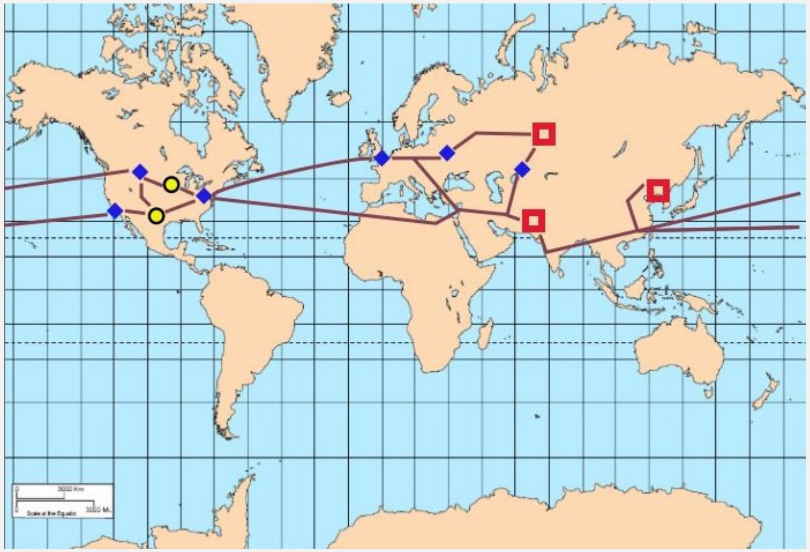
- **Create a framework for development and evaluation of detector systems**

- **The framework will integrate detector sensor concepts, forward radiation transport computational models, inverse analysis, systems and risk analysis, and social science/policy aspects**

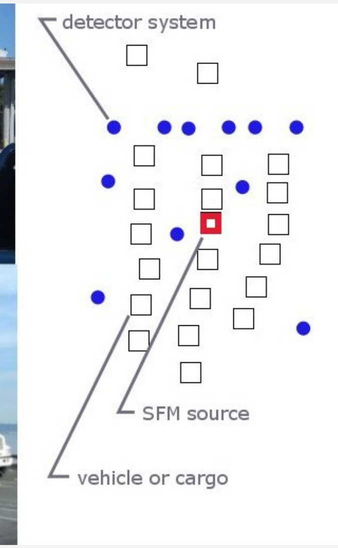
- **Conduct basic research programs in detector concepts, radiation transport, inverse problem solutions, and systems analysis, informed by relevant social science/policy factors.**

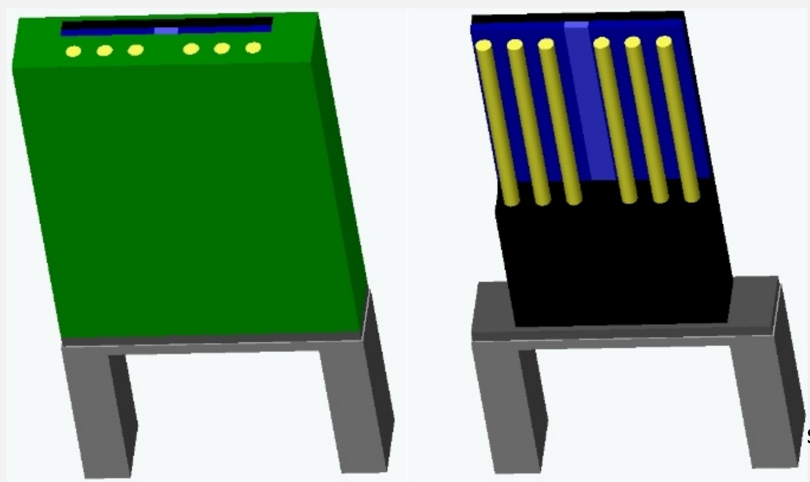
Three Scales of Global Detection System

Global Network & Distribution



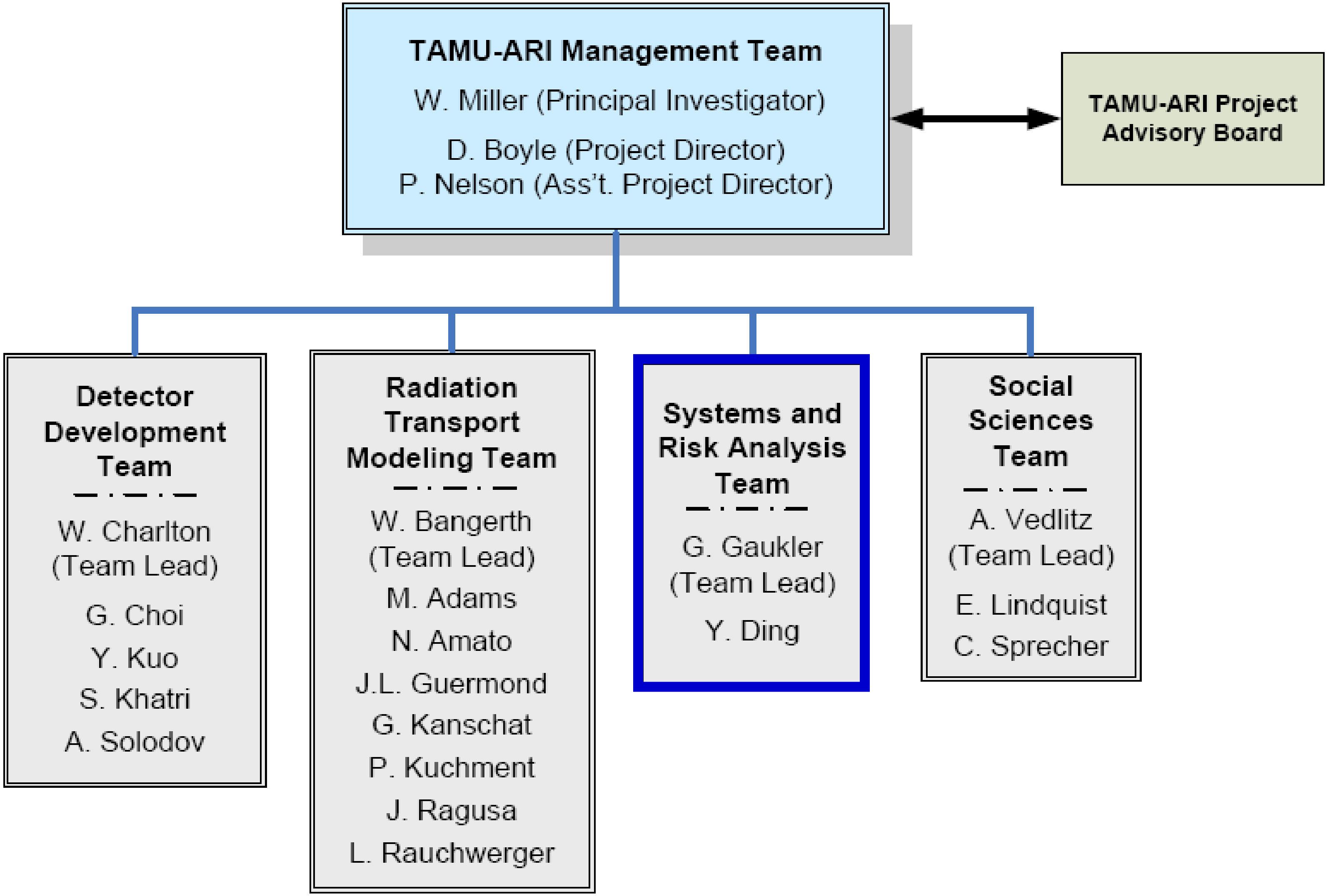
Detection & Inspection Policy

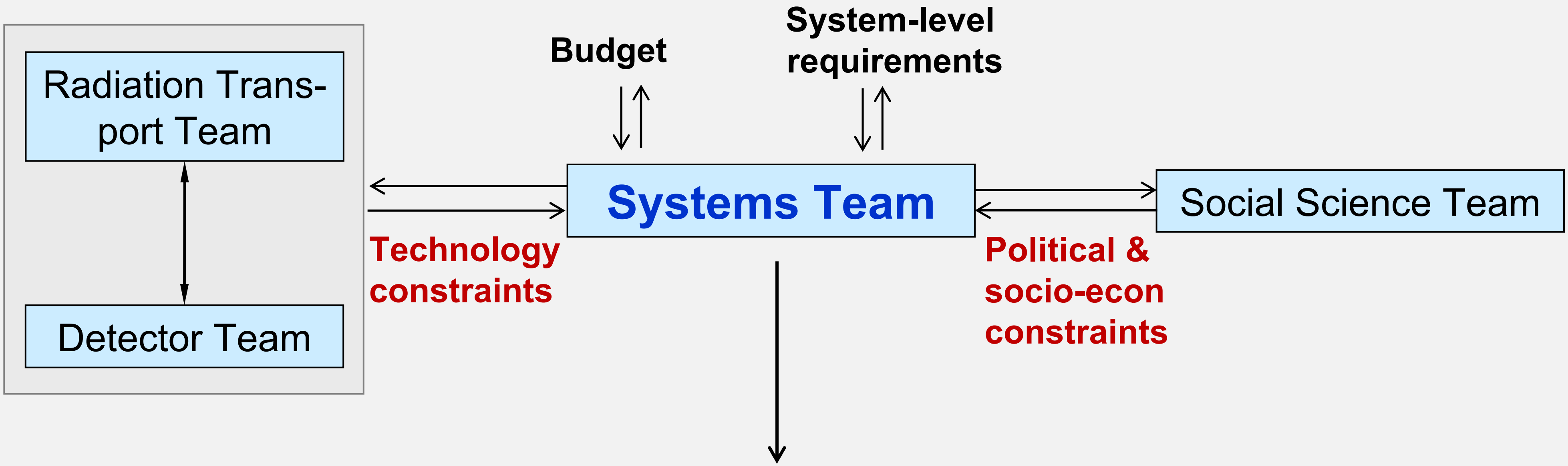




Detector Technology

Research Teams





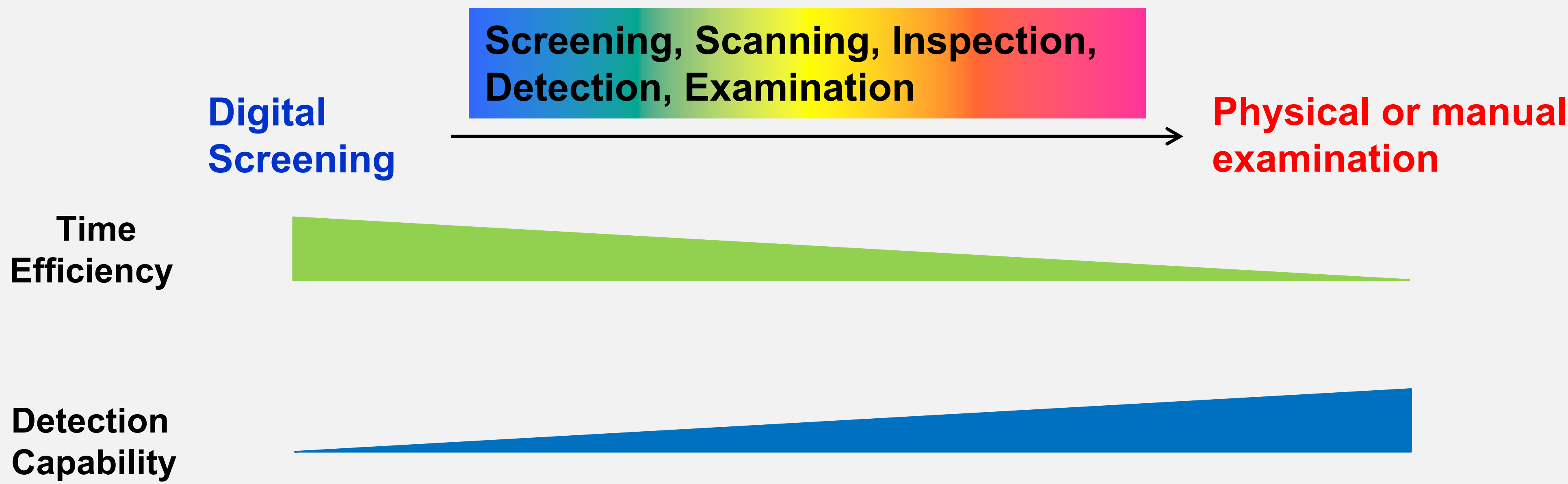
Charge to the System Engineering Team

(1) Design of a robust, re-configurable network of nuclear materials detectors across the US and allied countries,

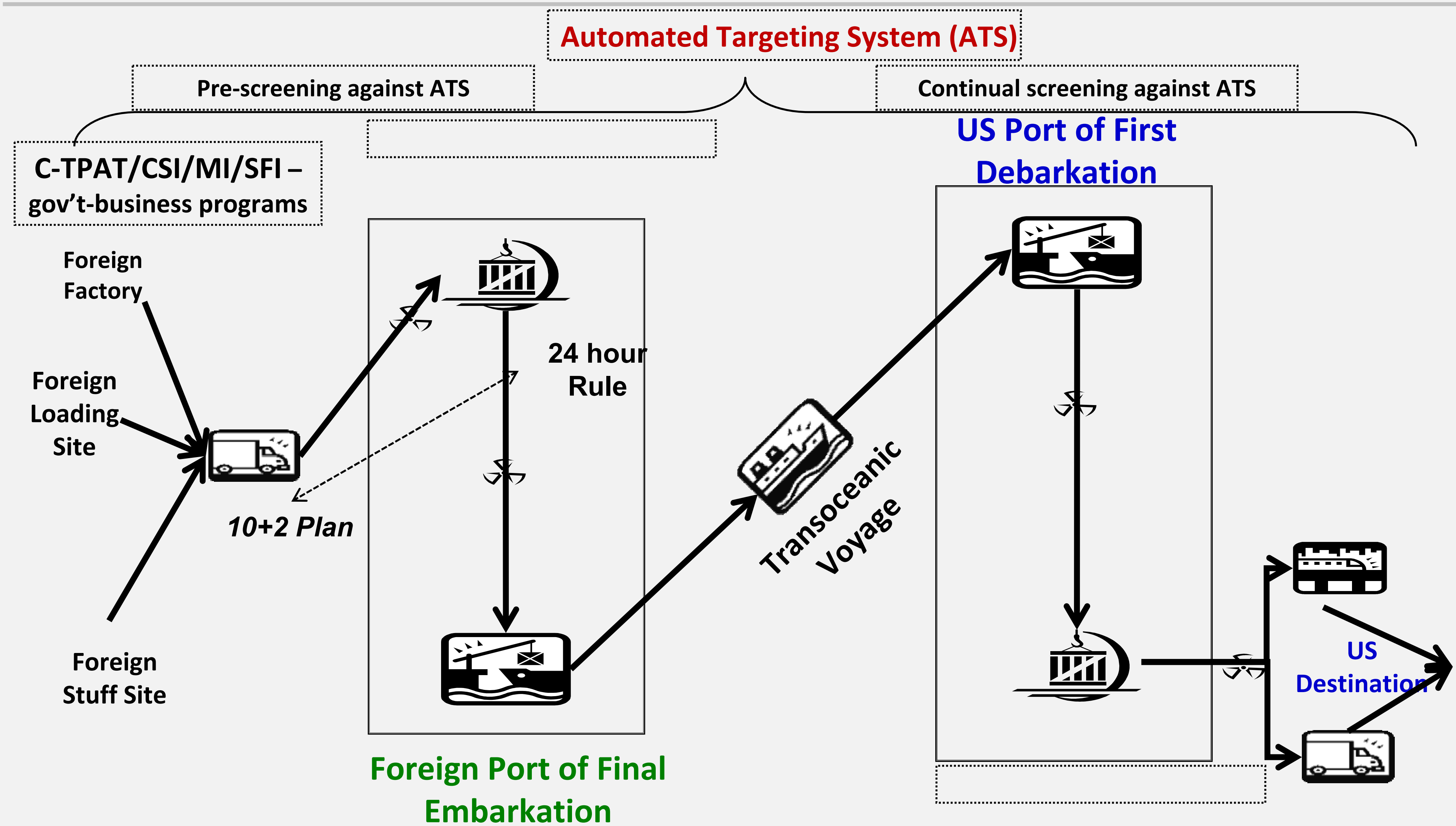
(2) Dynamic screening of shipping containers based on chain-of-custody and geopolitical information, and

(3) Developing strategies for sequential screening of containers at the same or different interdiction points.

- After the project got started in September 2007, the Systems team spent the first half year to understand the current practice of container inspection at sea ports.
- We went through the information in the public sources (primarily in the congressional hearings and news reports).



Current Practice | **Global Detection Concept**



Automated Targeting System (ATS)

- **Identify ‘high-risk’ containers**
  - Customs established criteria and automated targeting tools for identifying “high-risk” shipments
  - Ships are assessed for risk using general intelligence information and advance manifest data
  - Digitally screening in the container shipment database

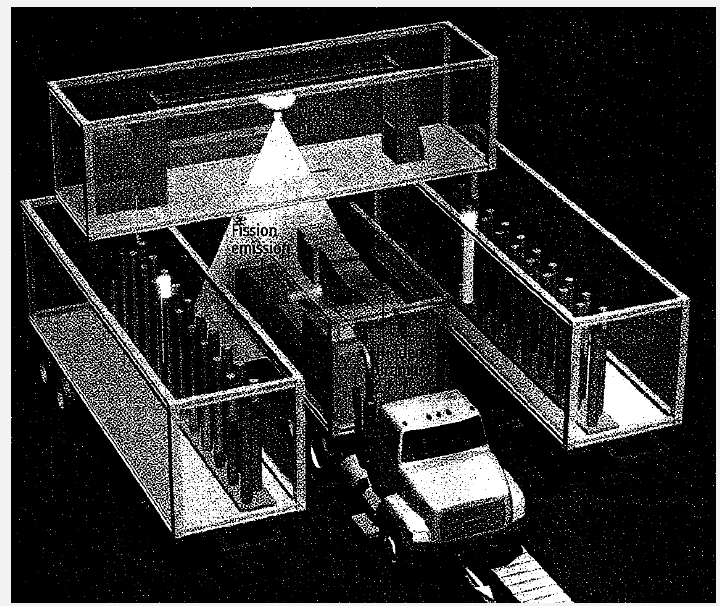
- **Treat ‘high-risk’ containers different from ‘low-risk’ containers**
  - e.g. different detection technology, requirement to passively scan at foreign port, etc.

❑ Passive radiation detector

- Passively detect level of neutrons and gamma rays. **Fast and commercially available.**

❑ Active radiation detector

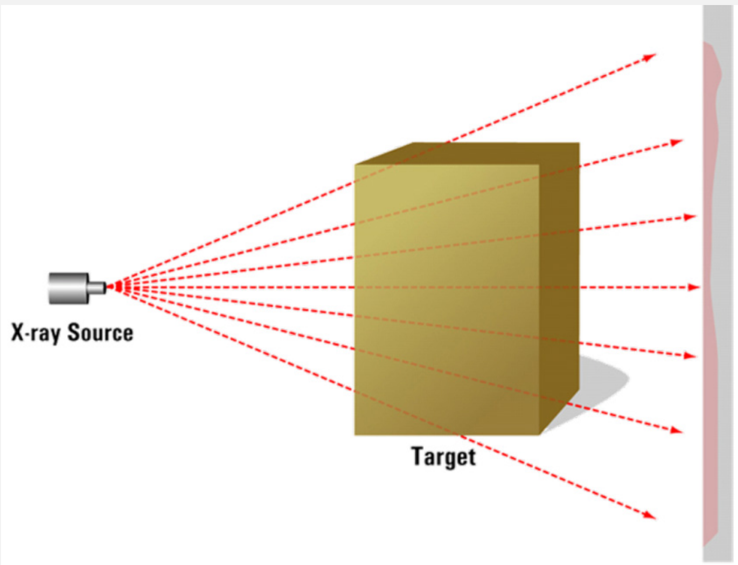
- Bombard the cargo with neutron/gamma rays to cause the materials under interrogation to react and emit more neutrons/gamma rays. **Slow and still in prototype.**



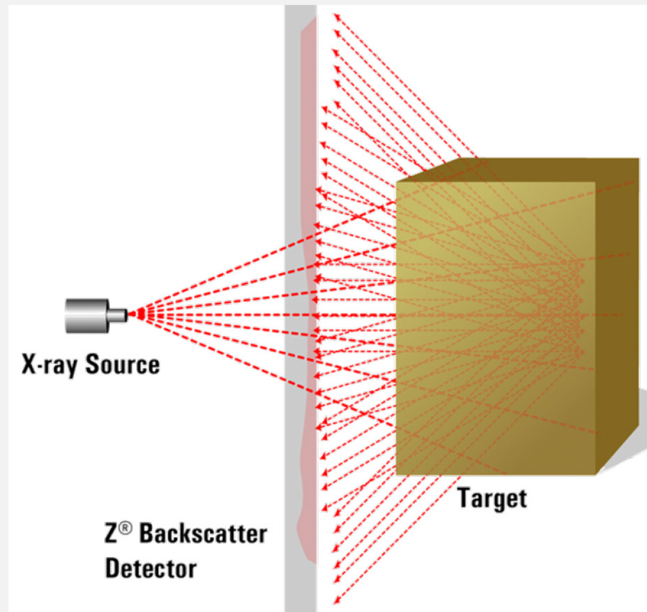
- X-ray imaging of cargo contains.

  - High energy X-ray machine, also labeled as **NII** (Non-Intrusive Inspection) imaging. Slow but high-resolution.

  - Medium energy X-ray machine. Fast but lower-resolution.



Transmission X-Ray



Backscatter X-Ray

Level of Inspection Efforts

Amount of US inbound cargo at the **debarkation** port = Y_{debk}; 100% Y_{debk} **screened** by ATS

15% **85%**

non-CSI ports (Y_{NCSI})

??

CSI ports (Y_{CSI})

"high risk" containers, $Y_{HR} \approx 1\%$ of Y_{debk}

48% of Y_{HR} (labeled as Y_{HRR}) requested for **examination** at overseas ports

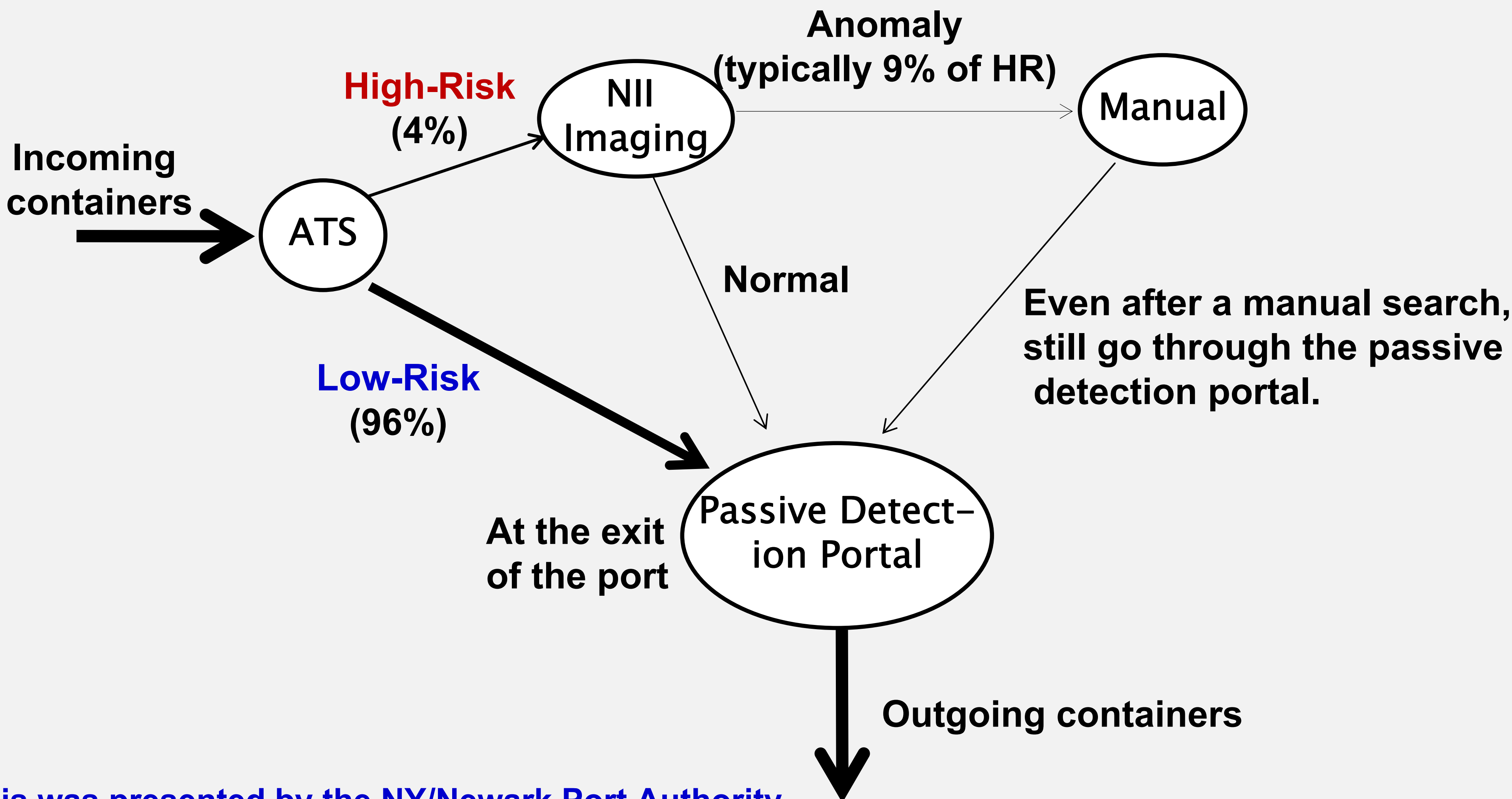
83% of Y_{HRR} (37% of Y_{HR}) are actually examined overseas; 17% of Y_{HRR} are examined only at US ports.

Amount of US inbound cargo at the **embarkation** port = Y_{embk}; assume that $Y_{embk} = Y_{debk}$

5% in 2005, 37% in 2006, and 93% in 2007 of Y_{embk} are **examined**, the target is 98% at top 22 US ports by the end of FY 2007.

100% of the **high-risk** containers are **examined** at the US ports.

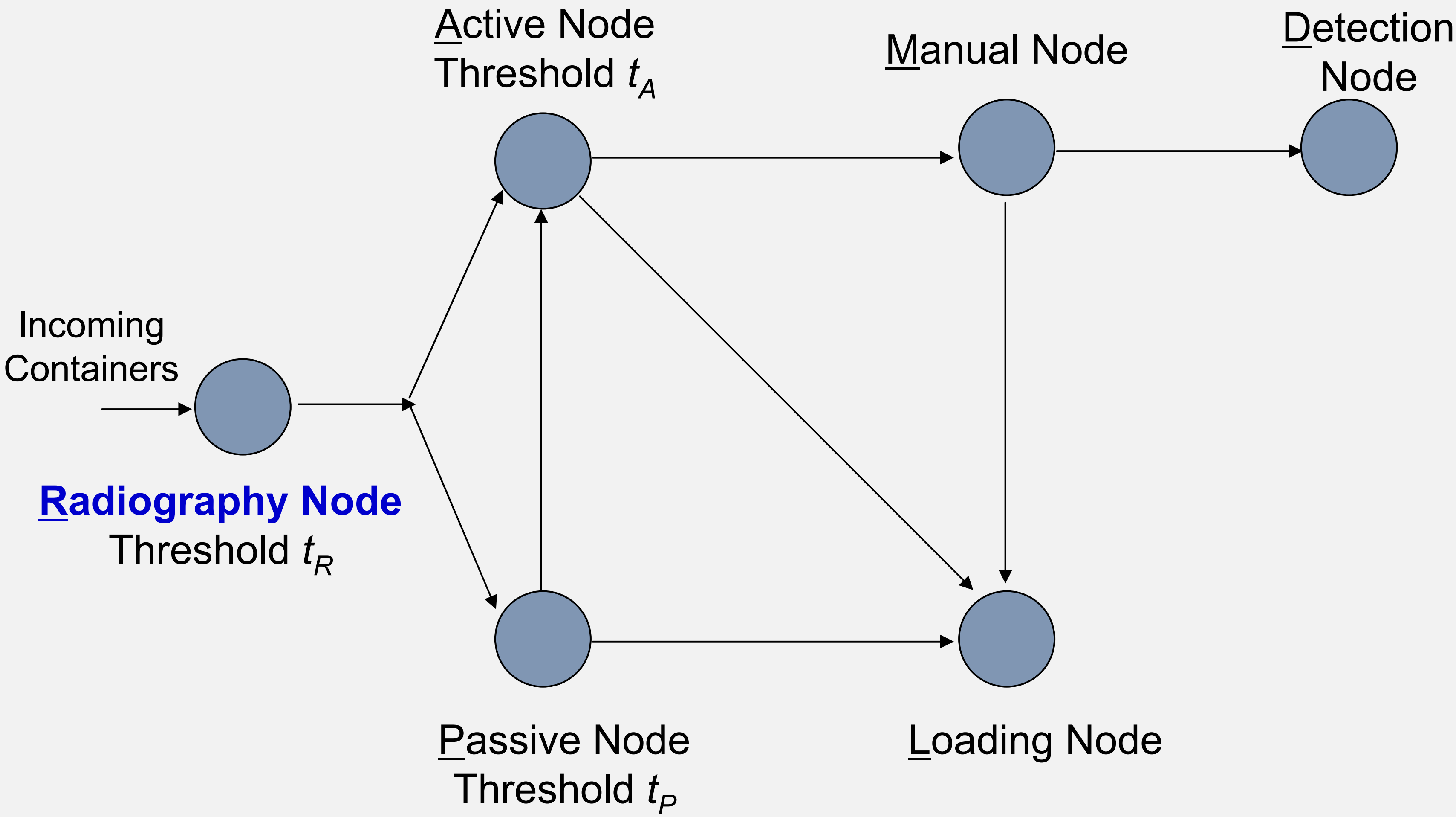
An Actual System at NY/Newark Ports



This was presented by the NY/Newark Port Authority in the 2008 Rutgers Workshop on Port Security

- **The current inspection system is a layered system.**
- **It has the high-throughput components (ATS and passive detectors) and the low-throughput components (NII, active detectors, and/or manual inspection team).**
- **Due to the system throughput constraints, only a small percentage of the containers can be sent to the low-throughput components with high detection power (generally less than 5%).**
- **The success of the current inspection system in detecting illicit nuclear materials depends on (a) the reliability of intelligence (used in ATS), which usually cannot be guaranteed; (b) the capability of passive detectors.**
- **The passive detectors have fundamental difficulties in detecting small-quantity, shielded nuclear materials (especially uranium).**

Introduce a Radiography Node



- **At the R-node, it provides an X-ray imaging of what is inside the container, which is called a container scenario.**

- **Based on a given container scenario, we propose to calculate a hardness measure, which indicates the degree of difficulty that a HEU or a shielded HEU would be successfully detected by a passive detector.**

- **Based on the computing value of hardness, the subsequent inspection path for a given container scenario will be different.**

Technical Feasibility of Radiography Node

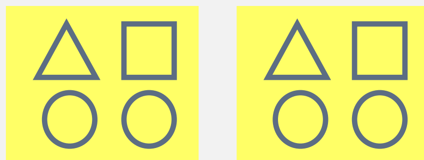
- **Medium energy X-ray machine is technically available and can be operated in a time-efficient way. Its average scanning time of a container is about 45 seconds.**
- **In a few pilot programs, this type of machine is being deployed to inspect seaborne cargo containers. According to a comment made by a DNDO officer during the 2008 Rutgers Workshop, at some Pakistan and Honduras ports as well as the UK South Hampton port, 100% of the US-bound containers are X-ray imaged.**

Z Portal

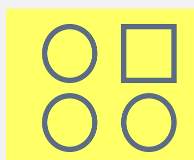
- A **container scenario** describes what is in a container, denoted by q_s.
- In the subsequent calculation, a scenario is mathematically described by the **Z-value matrix** based on a radiographic image.

Different Scenarios

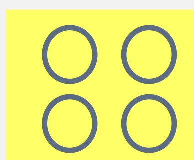
Scenario q_1

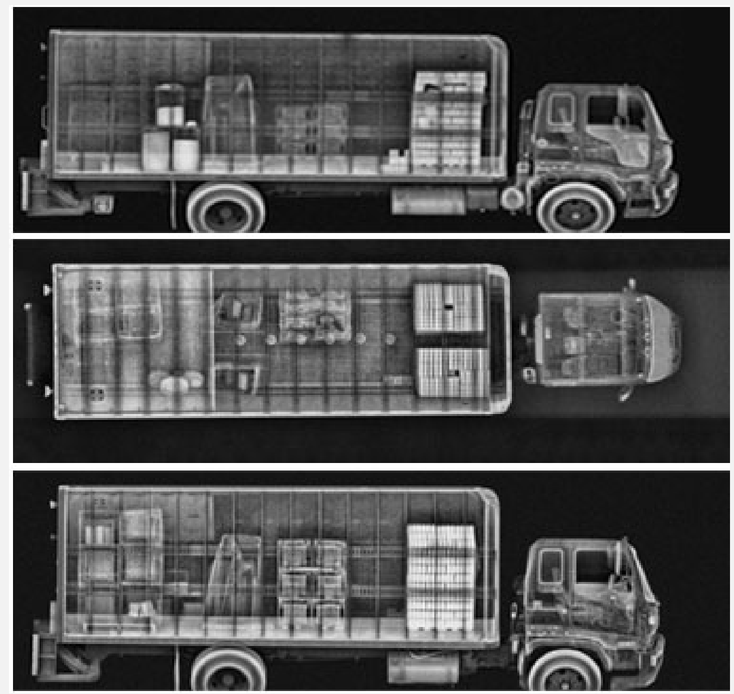


Scenario q_2



Scenario q_3



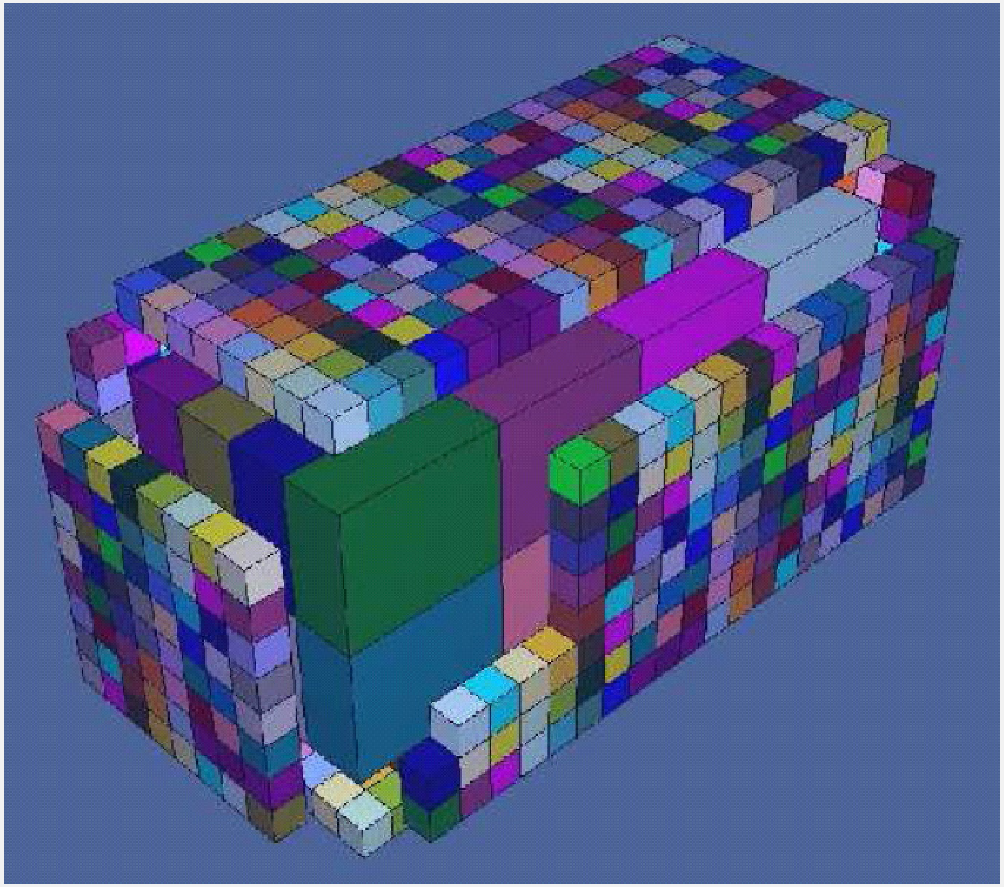


- **Mimicking the response of a passive detector is based on the general-purpose Monte Carlo N-Particle (MCNP) computer simulation.**

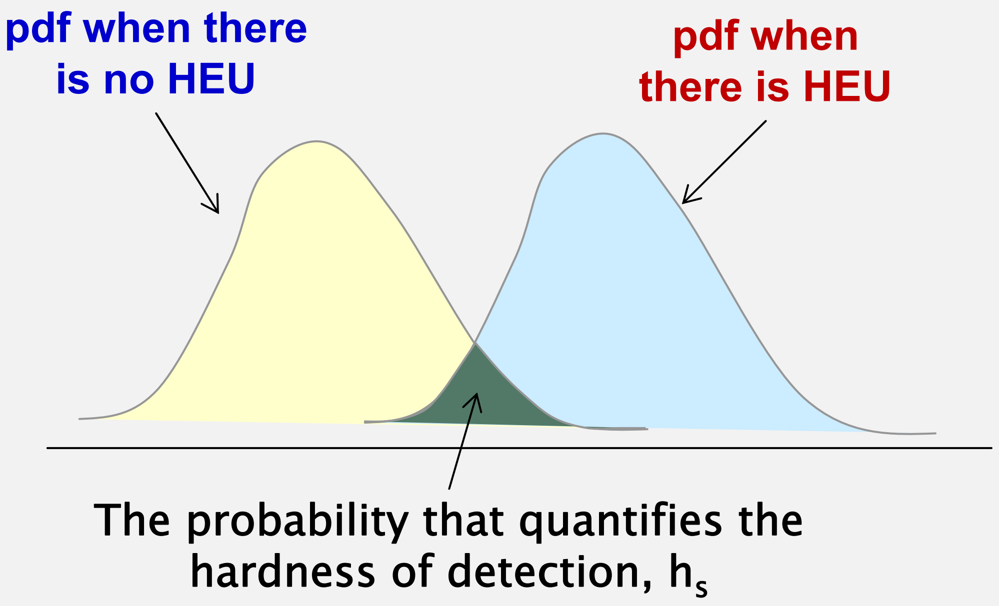
- **MCNP is used for neutron, photon, electron, or coupled neutron/photon/electron transport;**
- **Treats an arbitrary three-dimensional configuration of materials in geometric cells;**
- **Suited to the needs performing radiation shielding, detector simulation studies, and etc.**

- **Input: Z-value matrix**
- **Output: distribution of the amount of photons we expect to detect for a given scenario q_s with HEU and without HEU**

- A 3-D model of a container used in the MCNP code



- The hardness of detection is the misclassification probability of not being able to detect a certain amount of (shielded) HEU for a given scenario.



- Choose the threshold for hardness, t_R
  - $h_s > t_R$, sent to **A-node**
  - $h_s < t_R$, sent to **P-node**

- **Inputs: container traffic information (arrival rate and container scenario information) and detector capability (service rate, detection power, and number of each type of detector);**

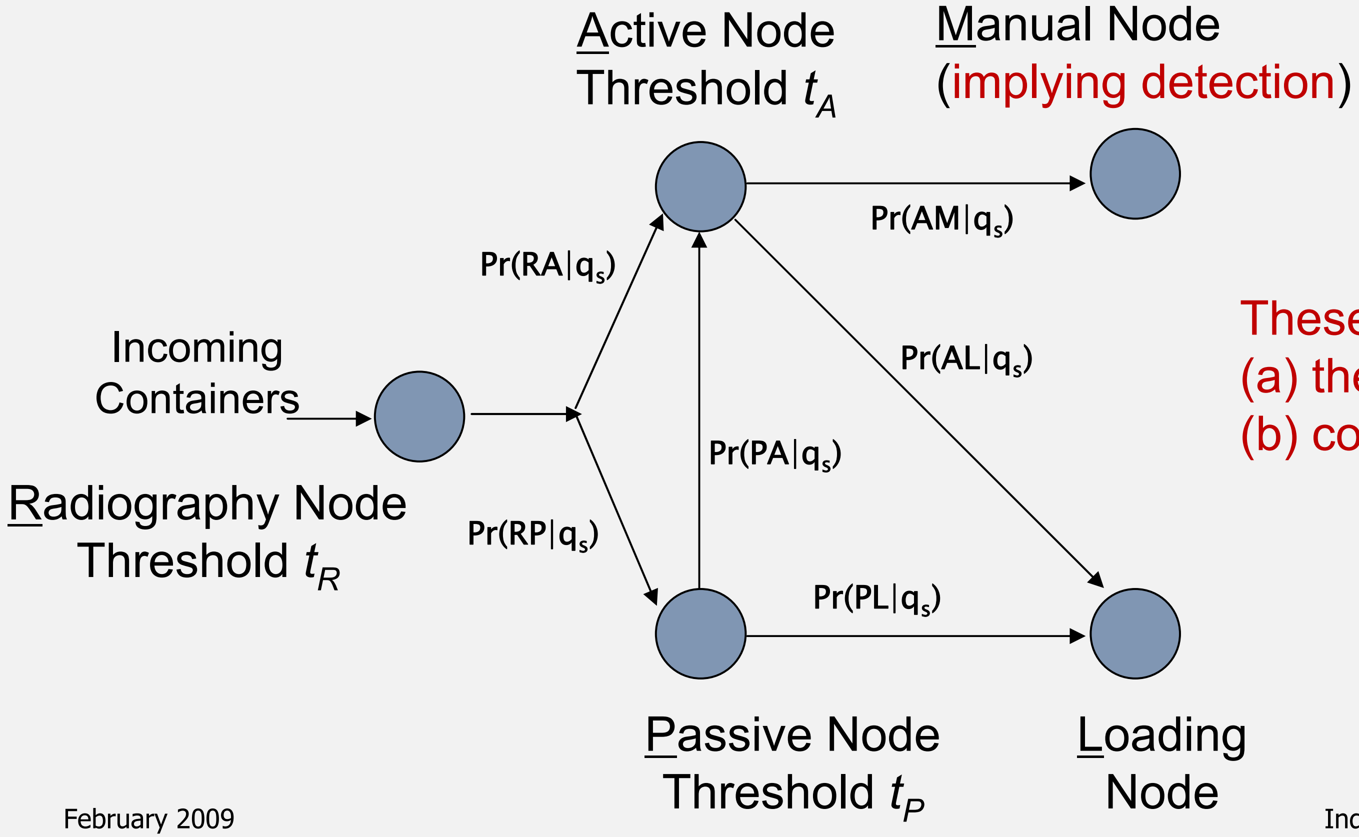
- **Performance indices: detection probability (i.e., a container having HEU eventually arrives at the D-node) and system throughput (i.e., how long a container stays in the inspection system).**

- **Decision variables or inspection policies: t_R, t_P, and t_A.**

- **Assume manual detection can always find illicit nuclear materials. Denote by q_s^{HEU} a container scenario with the presence of a known quantity of HEU. What we want to compute is**

$$Pr(q_s^{HEU} \text{ arrives at M-node})$$

- **Model the probabilities for a container q_s to take a specific pathway**



These probabilities are decided by
(a) the three inspection thresholds
(b) container scenarios.

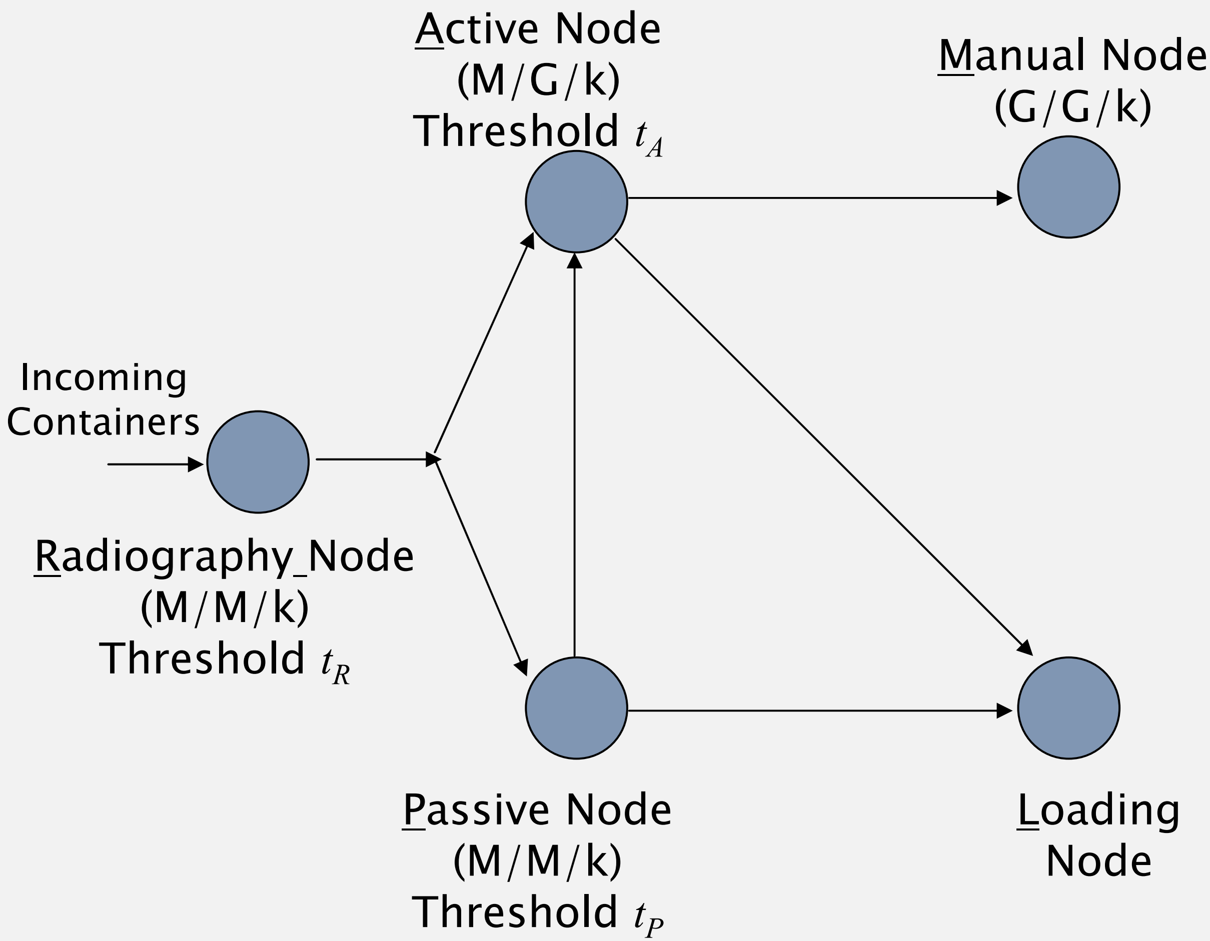
- **Detection Probability for a given scenario**

$$Pr(q_s^{HEU} \text{ arrives at M-node}) := Pr(s \text{ arrives at M}|q_s^{HEU})$$
$$= Pr(RA|q_s^{HEU}) \cdot Pr(AM|q_s^{HEU}, RA)$$
$$+ Pr(RP|q_s^{HEU}) \cdot Pr(PA|q_s^{HEU}, RP) \cdot Pr(AM|q_s^{HEU}, RP, PA)$$

- **Given the prior probability, $Pr(q_s^{HEU})$, that container scenario q_s contains HEU, the overall detection probability is**

$$DP = \sum_s Pr(s \text{ arrives at M}|q_s^{HEU}) \cdot Pr(q_s^{HEU})$$

- **Model each node using a queuing model.**



- Model each node using a queuing model.

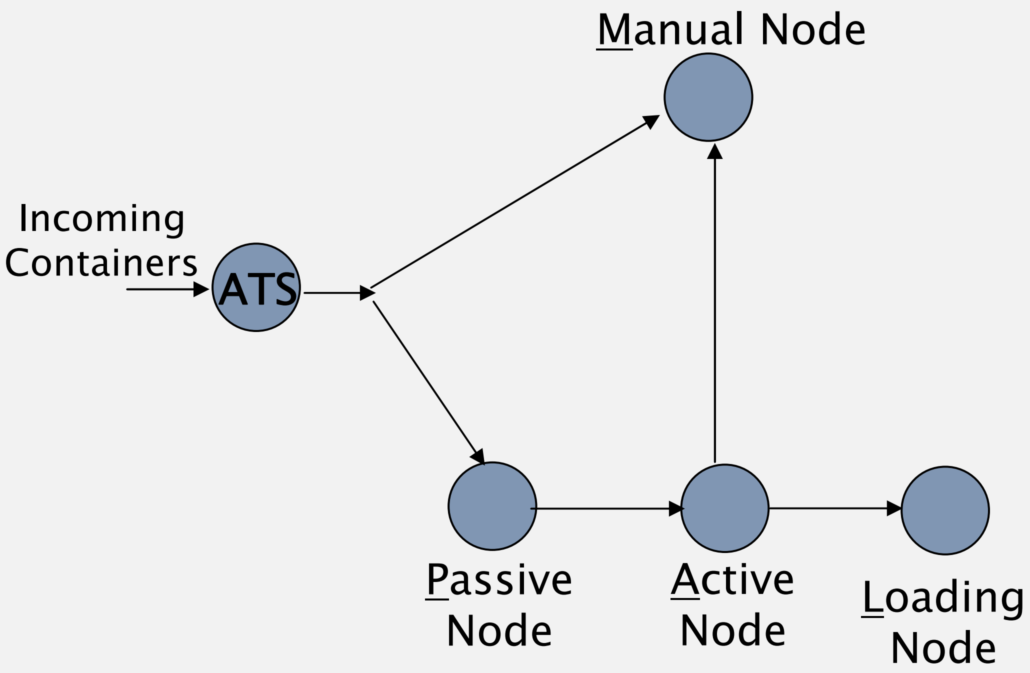
- For each path, calculate the expected time in system
- For each container scenario q_s, calculate the probability that the container follows any given path (similar to what is done when modeling the detection probability).
- Then, calculate the expected time in system for a given scenario q_s

- Model yields:
  - Expected time in system for a given container
  - Expected time in system for a “random” container
  - Expected queue lengths at nodes

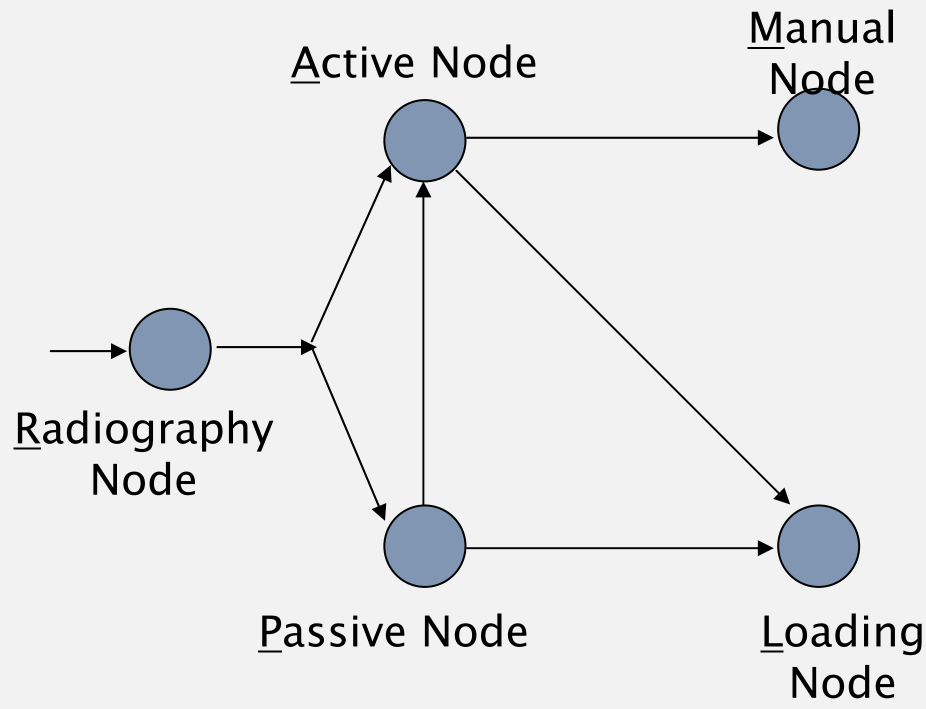
For a given technology set:

- Choose operational thresholds t_R, t_P, t_A
- Tradeoff between detection probability and system throughput for containers
- Constrained optimization, or efficient frontier generation

Numerical Examples — Systems to Be Compared



ATS Based System
(current practice)



Radiography and Hardness Based System
(proposed)

- **First container scenario**: only low z-value contents (e.g., cotton); thus, lowest hardness value.
- **Second container scenario**: a mix of medium z-value materials (e.g., concrete, plastic, wood) and low-z value materials; low hardness value.
- **Third container scenario**: some high z-value contents (iron), mixed with medium and low z-value materials container; high hardness value.
- **Fourth container scenario**: a container has **NORM** (Naturally Occurred Radioactive Materials) in it; the highest hardness value.

- In a container having HEU, **one (1) kg HEU** (30% of U-238 and 70% of U-235) with **one (1) cm** lead shielding is placed in the center of the container.

- In order to compare with the ATS system, we need to adopt a **trustworthiness measure** of the intelligence (McLay et al. 2008).

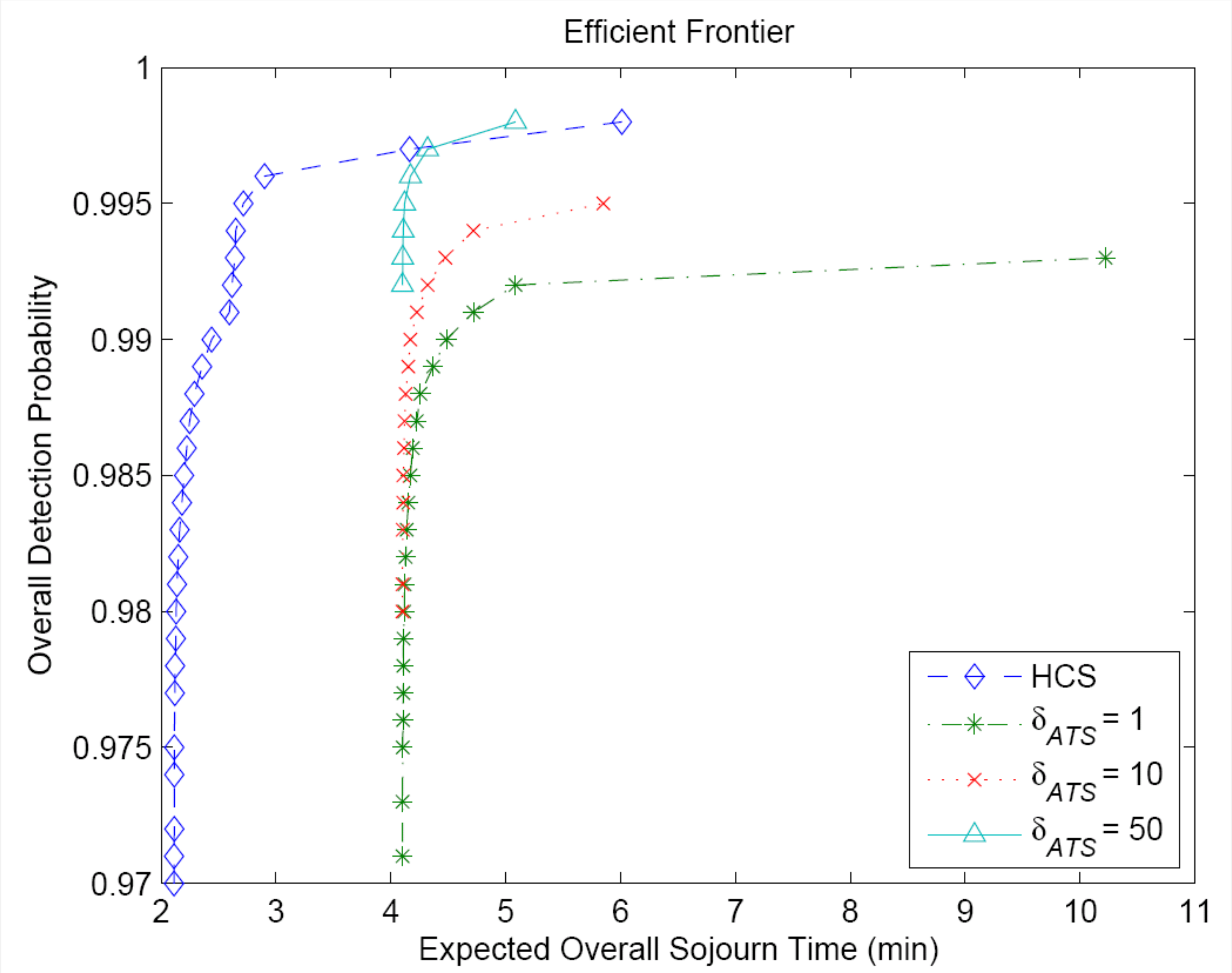
- Denote by HR = High Risk and LR = Low Risk, and define

$$\delta_{ATS} = \frac{P(HEU|HR)}{P(HEU|LR)}$$

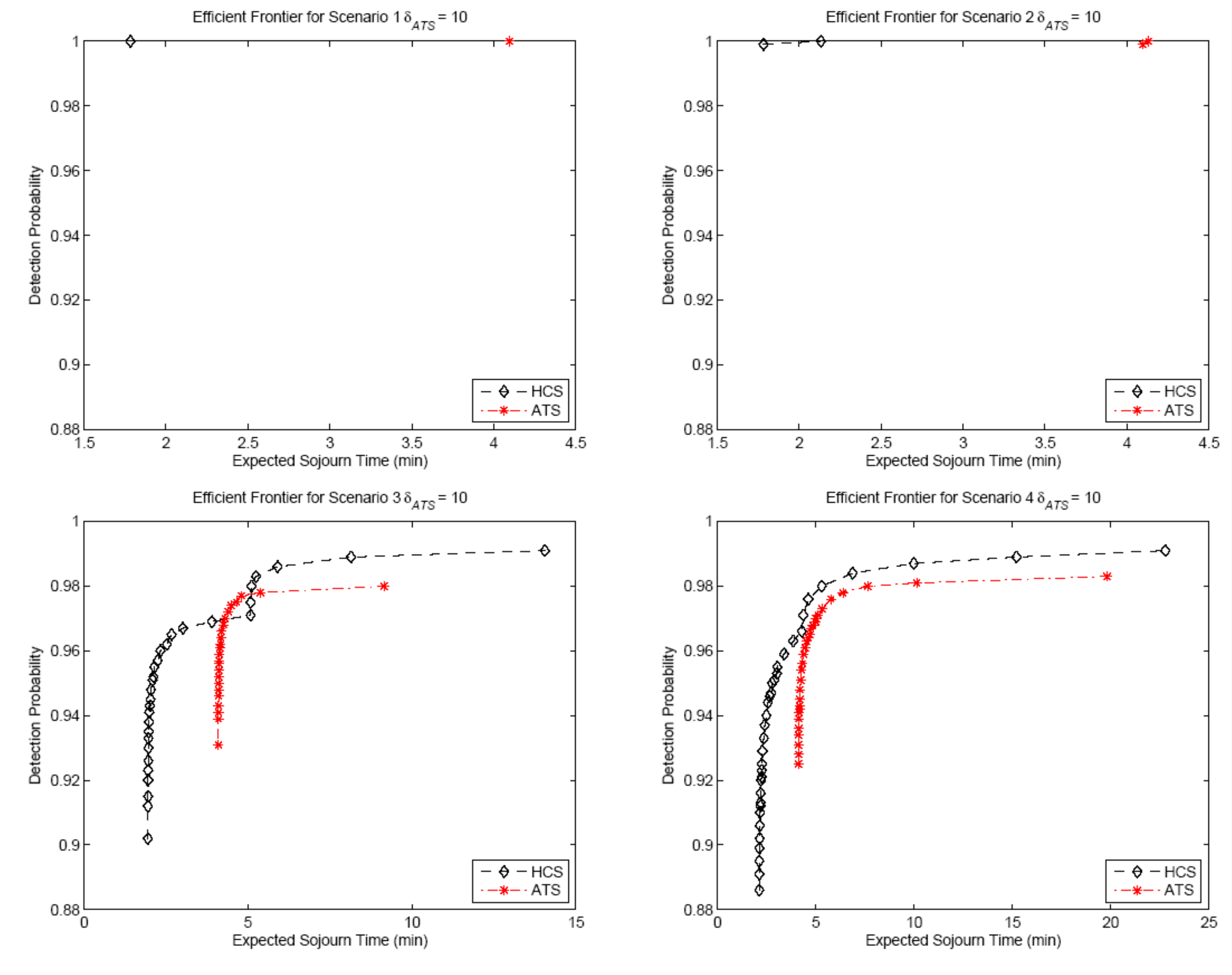
- δ_{ATS} indicates how much more likely a container indeed has HEU in it when the intelligence assigns the container as "High Risk." The larger the δ_{ATS} is, the more trustworthy (or reliable) the ATS is.

- $\delta_{ATS} = 1$ means that the ATS assignment is the same as doing a random selection.

Efficient Frontiers for Different δ_{ATS}



Different Scenarios when $\delta_{ATS} = 10$



- We advocate calculating a **hardness measure** based on radiography information of the containers before sending them to the subsequent inspection steps. This hardness measure is a new metric introduced in our work and differentiates our framework from others (most notably, Wein et al. 2006).

- Despite the superior performance demonstrated by the proposed inspection system in the four chosen container scenarios, we are not advocating to completely replace the current ATS-based system. It would be sensible to use a **hybrid system** that continues to use the ATS, but complements it with intelligent use of radiography information.

- Our research is summarized in a paper# submitted to the special issue of *Annals of Operations Research* on port security.

- Our future work includes sensitivity analysis of the proposed system, modeling gaming behavior of terrorists, and strategic aspects of the detector networks.

Gaukler, Li, Cannaday, Ding, 2009, "Detecting nuclear materials smuggling: using radiography to improve container inspection policies", *Annals of Operations Research*, submitted.

A Few Other Projects

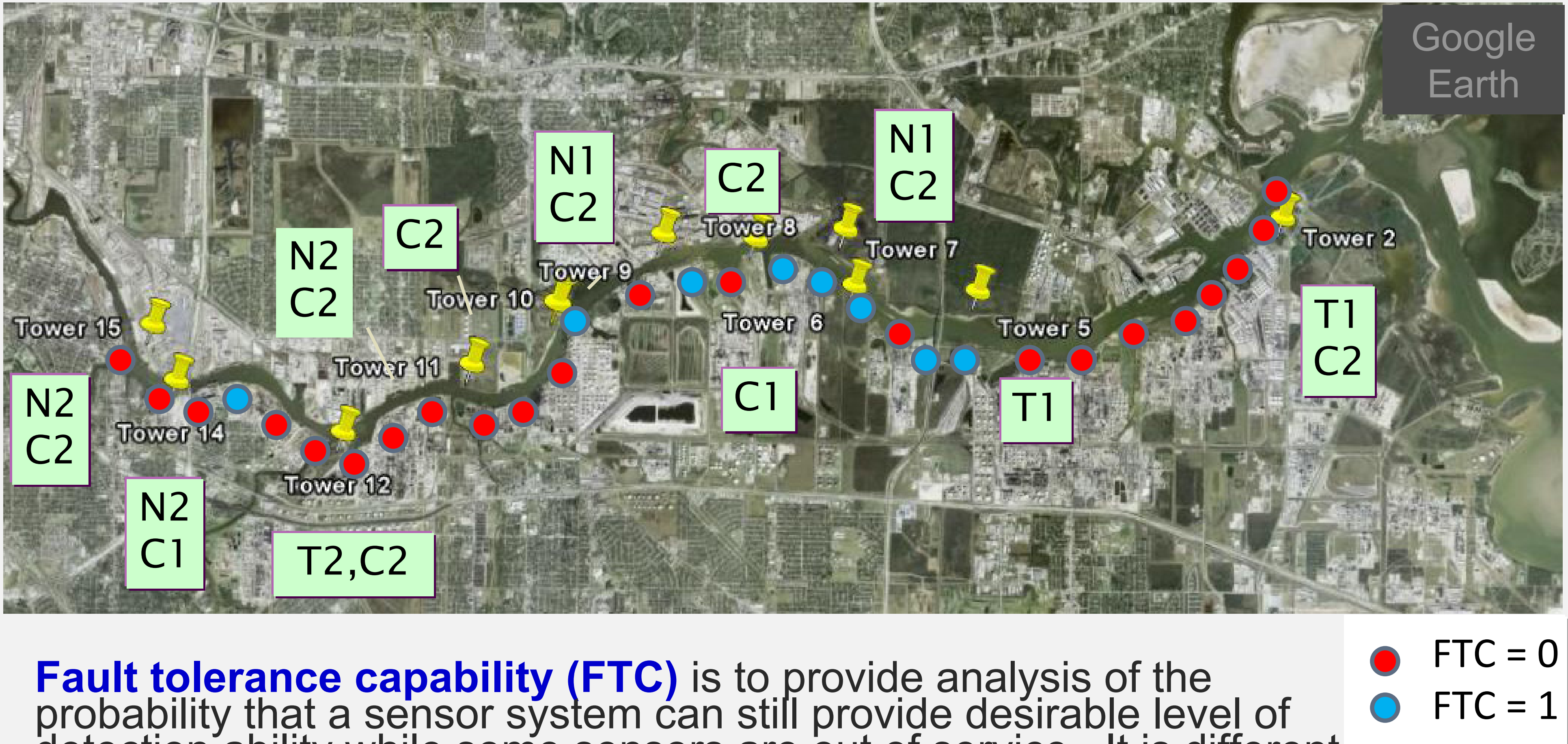
- **Strategic design and tactical operations of surveillance sensor systems in the Houston ship channel**

  - Funded by the National Science Foundation.

  - Collaborating with Dr. Wil Wilhelm (Texas A&M)

  - Investigate three aspects:
    Strategic sensor placement (Wilhelm),
    Fault tolerance analysis,
    and risk mapping based on incident data.

Surveillance Sensor Systems at Port and Waterway



- **Fault tolerance capability (FTC)** is to provide analysis of the probability that a sensor system can still provide desirable level of detection ability while some sensors are out of service. It is different from sensor reliability.

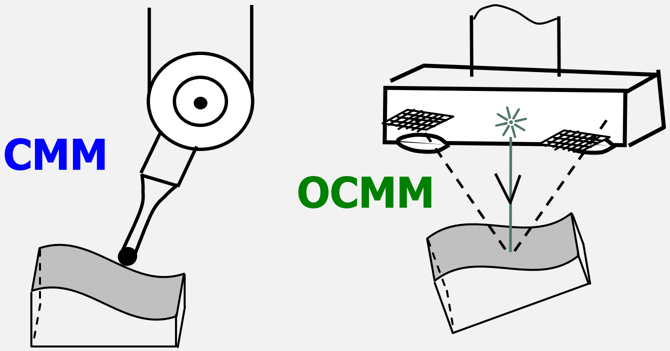
- Our analysis also determines the FTC for individual surveillance points and thus visualize the **FTC pattern** along the waterway.

- **Integrating data from multi-resolution sources for engineering predictions.**

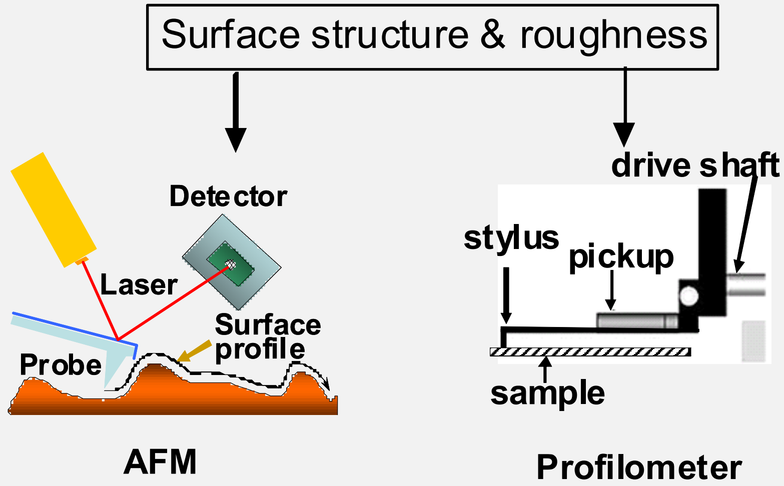
  - ❑ Texas Advanced Research Program (ARP) project
    - Multi-resolution modeling and analysis in material research;
    - Collaborating with Dr. Helen Liang (ME) and Dr. Bani Mallick (STAT)
    - Funded.

  - ❑ NSF Cyber-enabled Discovery and Innovations (CDI)
    - Multiple applications (material, metrology, and fuel cell simulations);
    - Large team effort (one ISE, two ME, two STAT) for four years
    - Pre-proposal submitted.

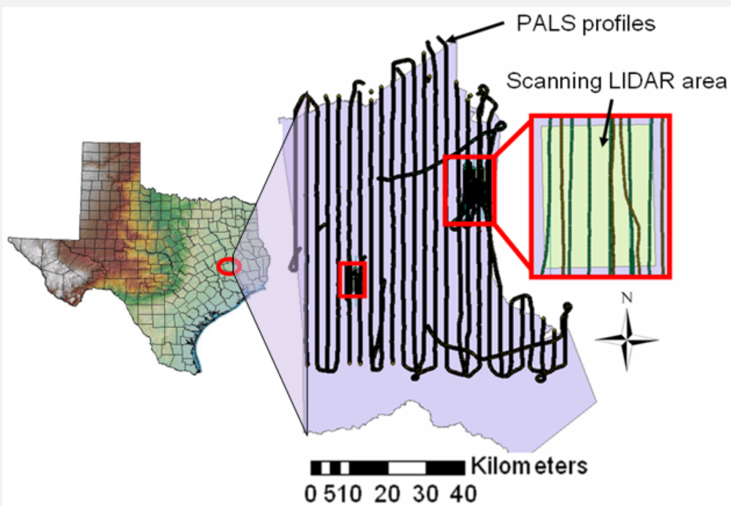
Multi-resolution Modeling and Analysis



In dimensional metrology:
CMM: high resolution (~ 0.5 m^{-6})
OCMM: low resolution (~ 10 m^{-6})



In the material and surface analysis:
AFM: high resolution (nm scale)
Profilomemter: low resolution (µm scale)



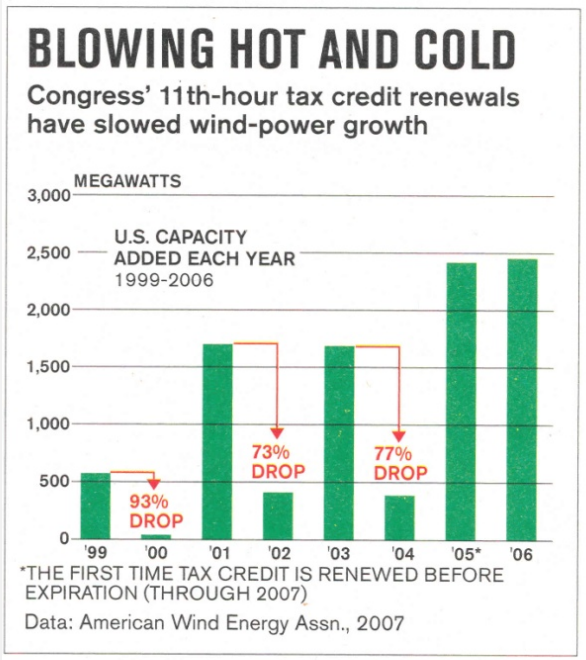
In remote sensing:
Scanning LiDAR: high resolution
PALS LiDAR: low resolution

LiDAR: Light Detection And Ranging

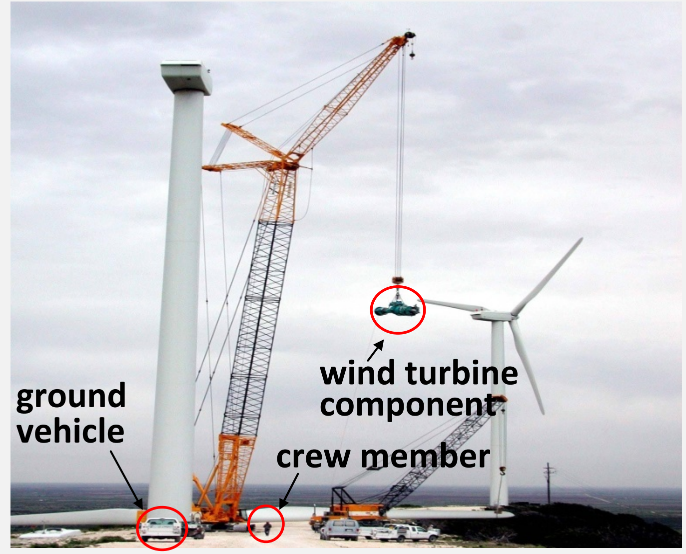
- **Decision, simulation, and optimization for cost-effective maintenance and operations of wind turbine farms.**

  ❑ NSF DDDAS (Dynamic Data Drive Application Systems) project
  - Collaborating with Dr. Jiong Tang (U Conn) and Dr. Lewis Ntaimo (A&M)

  ❑ Opportunity with Vestas
  - Vestas is one of the leading wind energy companies. They decided in June 2008 to establish a research center at Houston.
  - Vestas is in the process of establishing a large-scale research collaboration with A&M's College of Engineering.



From BusinessWeek:
"With the credits due to expire at the end of 2008, costs are rising …" "If the credits aren't renewed by summer, many 2009 projects will dry up … …"



- **Promise**: can produce *three times* as much electricity needed in the US today. **Reality**: currently wind contributes *less than 1%* electricity. **Target**: generate 20% of the electricity for US by 2030.
- The key issue is the cost and marketability. Maintenance cost accounts for a substantial portion (heavy duty equipment and remote location).

System Informatics

EVALUATION

- Redundancy & robustness analysis
- Fault tolerance analysis
  - Port security (NSF)
  - Manufacturing (NSF)

DATA

- Multi-resolution data integration
- Data reduction and novelty detection
  - Waterway security (NSF)
  - Nanotechnology (Texas ARP)
  - Structural health monitoring (NSF)
  - Manufacturing (NSF/Texas ATP)

DECISION

- Stochastic decision making
- Maintenance & inspection policy
  - Wind farm operations (NSF)
  - Port/container security (NSF/DHS)

DESIGN

- Optimal sensor placement
- Data-mining guided heuristic optimization
- Non-redundancy design
  - Port security (NSF/DHS)
  - Manufacturing (NSF/Texas ATP)