Current Research in Fate & Transport of Chemical and Biological Contaminants in Water Distribution Systems

Session 2C
Modeling, Ecological Restoration / Systems Assessment

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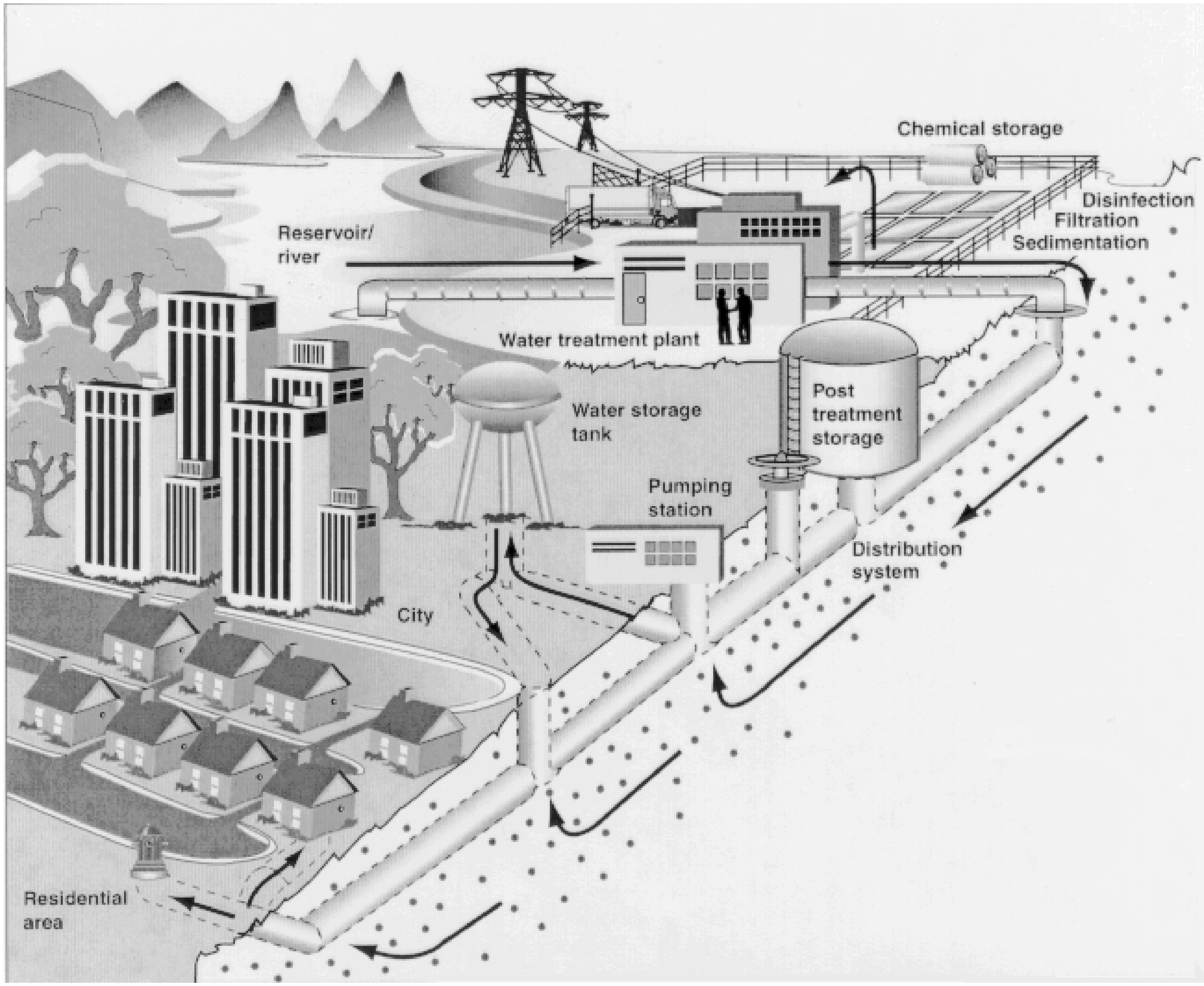
Engineer Research and Development Center

Team

- Product Development Team:
  - USA-ERDC: V. Van Blaricum, M. Ginsberg, V. Boddu
  - EPA: J. Herrmann, S. Clarke, K. Fox, R. Murray
  - ECBC: V. Rastogi, A. Turetsky, A. Pappas
  - Hach HST: M. Gibson, D. Kroll
  - AwwaRF: G. Welter, F. Blaha
- CRADA - ERDC-CERL, ECBC, Hach HST
- Other Partners:
  - Sensors (SBIR & commercial partners)
  - Water treatment (SBIR & commercial partners, CHPPM)
  - Decontamination methods (EPA, AwwaRF)
  - Control systems (Commercial Partners & ERDC, CHPPM)
  - Updated fate and transport physics for simulation (ERDC lead, UIUC, AwwaRF, EPA, ECBC, CHPPM)
  - Test bed facilities at ECBC for experimental verification against live CB agents (ECBC, ERDC, Hach HST, EPA.)

Threats and Vulnerabilities



- Threat to Water Potability
- Threat to Fire Suppression
- Lack of system redundancy
- Large area subtended by the system
- Treatment chemicals
- Lack of anti-tampering devices currently built-in
- Control systems (SCADA)

The Threat – Current Estimates

- AwwaRF Project 1812
  - 279 Documented incidents from ~1960's to present
  - 19 deaths, 166 illnesses confirmed

- GAO Report GAO-03-29
  - 75% of experts (32/43) identify the water distribution system as being most vulnerable (as opposed to source waters or other system components, treatment chemicals, etc.).

The Threat – Current Estimates

- Recent Incidents

1. February 2002 – Al Qaeda arrested with plans to attack U.S. embassy water in Rome with "cyanide".
2. December 2002 -- Al Qaeda operatives arrested with plans to attack water networks surrounding the Eiffel Tower neighborhoods, Paris
3. April 2003 -- Jordan foils Iraqi plot to poison drinking water supplies from Zarqa feeding U.S. military bases along the Eastern desert.
4. September 2003 -- FBI bulletin warns of Al Qaeda plans found in Afghanistan to poison U.S. food and water supplies.

Army Relevance

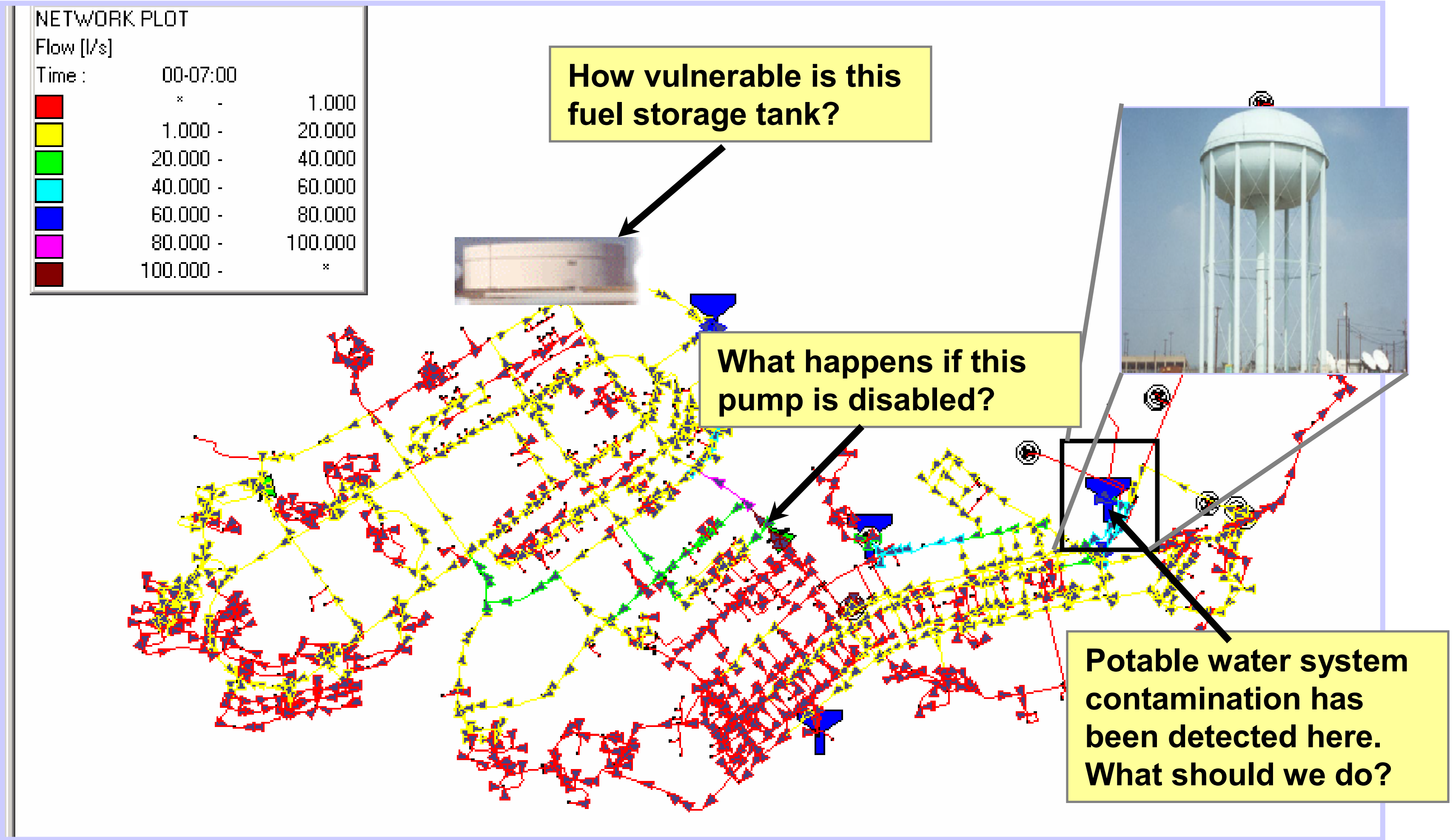
CINC's and services are required by DoDD 2000.12 and DoDI 2000.16 standard 26, to conduct a higher headquarters vulnerability assessment of their installations AT programs every three years.

Dynamic Simulation tools can be used to support the Joint AntiTerrorism Guide (JAT Guide)

Installation Management Agency (IMA) – Force protection officer supports requirements for mitigation of terrorist threats to utilities (Feb '04)

Force Protection

Utility systems are potential targets to terrorists.

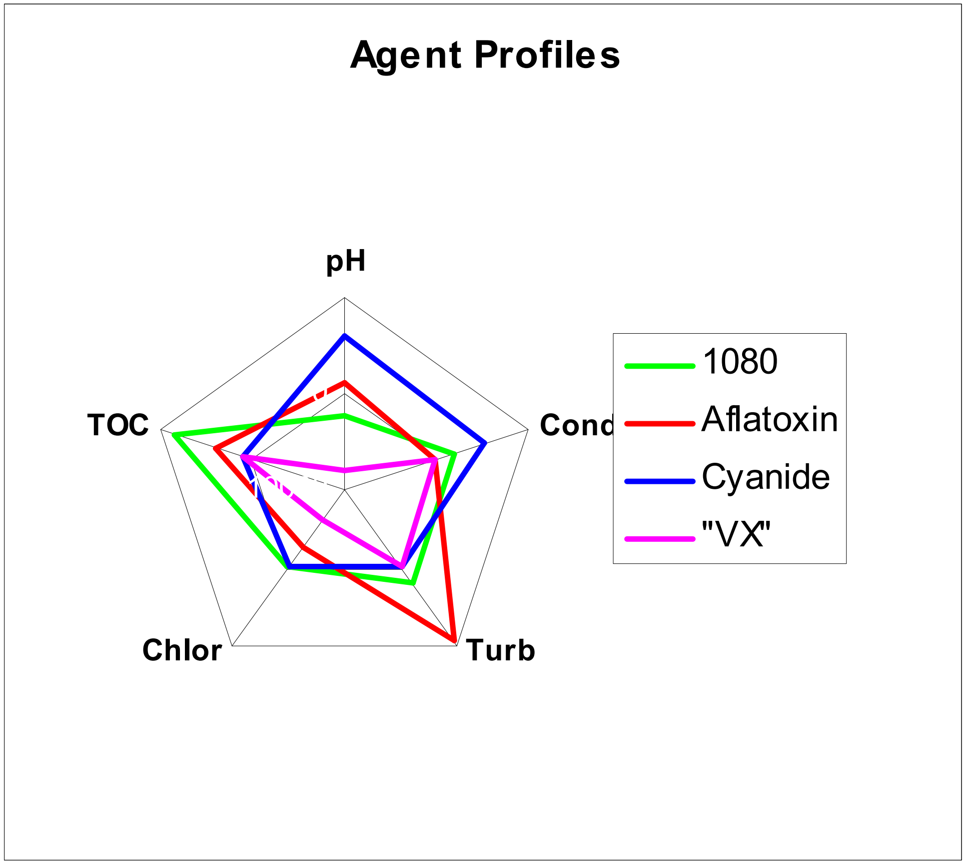


Problem

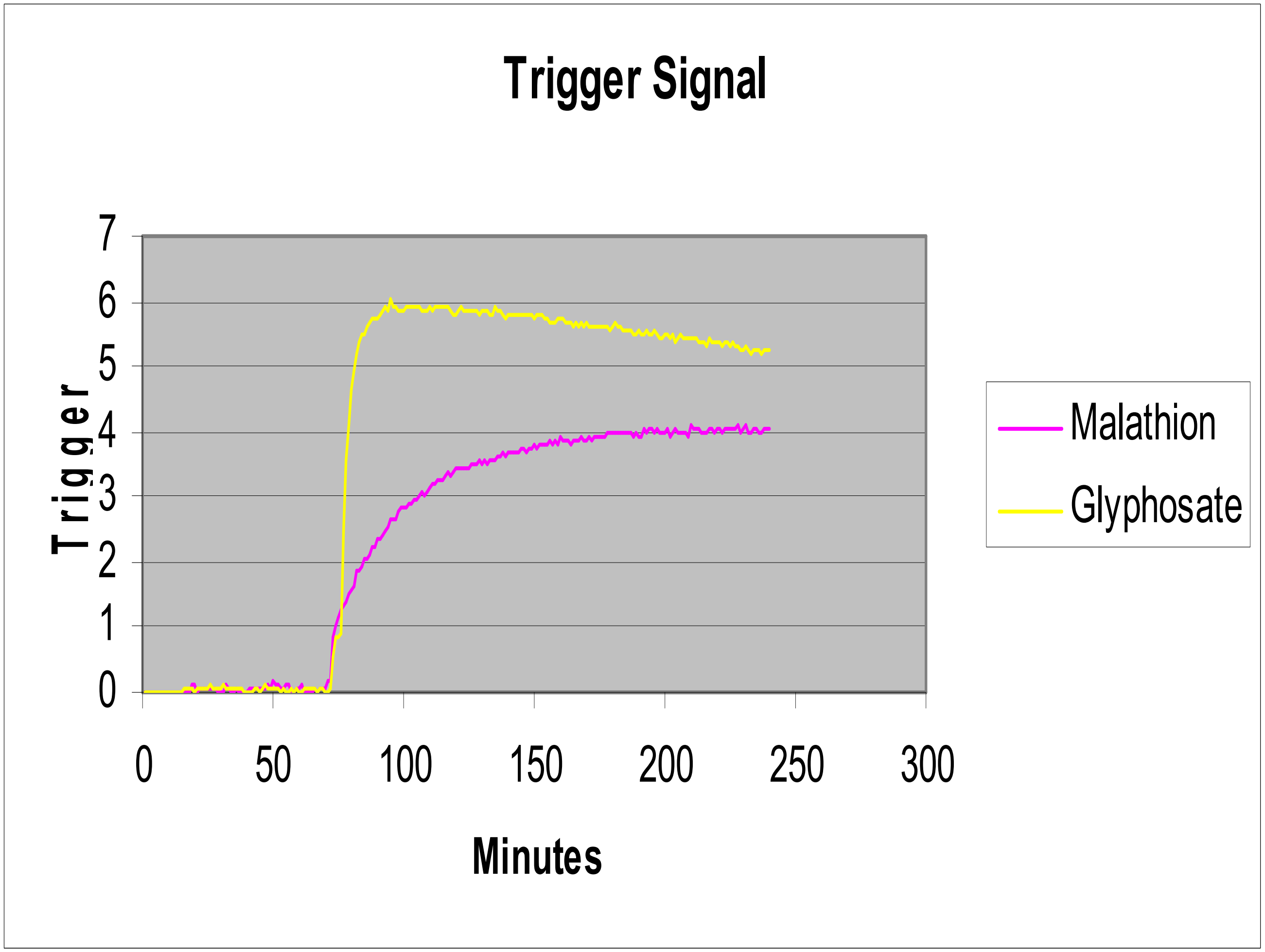
- Water Security has 4 primary components
  - Detection
    - No single sensor can determine the contaminant type and amount released into the system.
  - Modeling - better models of contaminant fate & transport are required to:
    - Preplan response to attack
    - Monitor the progress of an actual attack
  - Countermeasure - “Green” methods (that do not produce additional toxins) are required to
    - Water treatment
    - Pipe Decontamination - 5% of the attack can cause 95% of the cleanup cost
  - Emergency Response
    - Coordination of these resources

Approach: Detection

- Coordinate testing of Hach HST sensor capable of determining contaminant type from water quality data
- Hach sensor is equipped with a library of water quality responses to ~100 classes of agent.
- Contaminant is detected and identified by monitoring the water parameters: ORP, TOC, chlorine, pH, etc. as a generalized vector. Two test runs were conducted at ~70 minutes as the loop is dosed with…
  - Malathion
  - Glyphosate



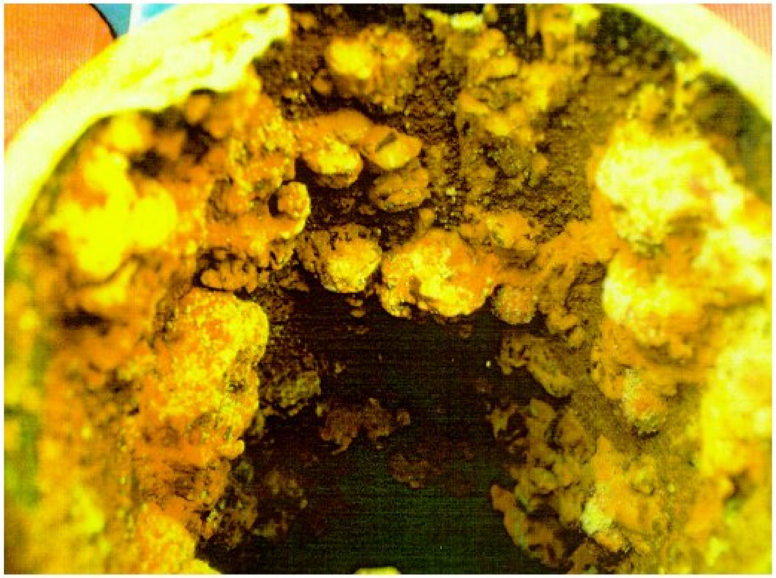
Agents at 1 mg/L, LD50(2%) Trigger Strongly

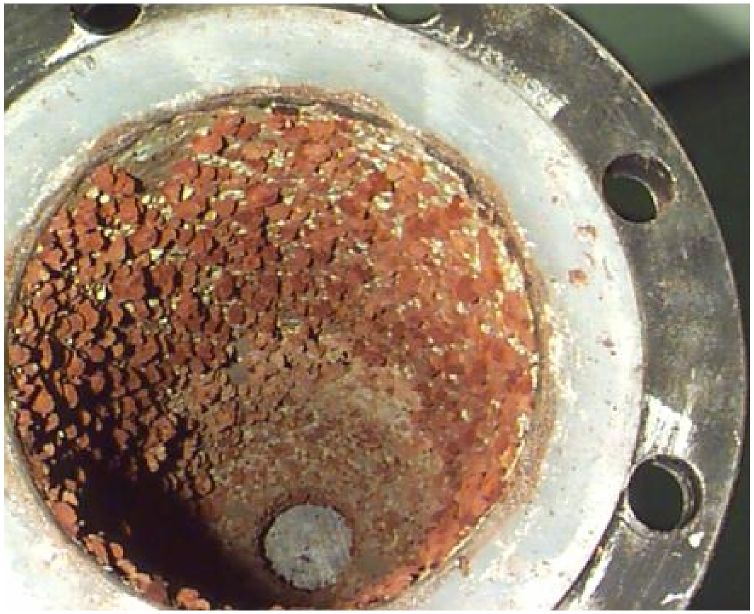


Trigger Threshold= 1.0

S&T Knowledge Gap in the Physical and Chemical Models Embedded in Current Simulations

- Any interaction between the contaminant and the pipe wall will prolong the the CB attack
- Surface roughness from scale or corrosion slows transport and inhibits decontamination.
- Biofilm - Biological contaminants may settle in the biofilm and continue to release bio-toxins.





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Current R&D in Fate and Transport

- Current simulation is limited by inadequate chemical and physical models.
  - Needs interaction between the CB agent and the pipe wall
  - Interactions between CB agents and decontamination agents (ex. Chlorine) need improvement at low concentrations in the water distribution environment.
- Need to translate CBR protection requirements into water distribution requirements
- Updated physicochemical models will be used to improve existing simulations.

Current F&T Issues

- Reaction Rate:
  - Classically - Rate = $k[A]^m[B]^n$
  - Does this continue at low concentrations in the presence of corrosion products, chlorine, biofilm, etc.?
- Wall Interaction
  - DA yields $$\frac{u}{v*} = f\left(\frac{yv*}{\nu}, \frac{y}{e}, \frac{y}{L}\right)$$

    Where u= velocity, y = dist. From wall,

    e = roughness height, nu = viscosity,

    v* = friction velocity = $\sqrt{\tau_0 / \rho}$

    tau = shearing stress, rho = density
  - How common is adhesion to wall material, biofilm, scale, or corrosion products?
  - Hypothesis: Water/Biofilm/Sediment/Pipe equilibrium is related to:
    - octanol / water partition coefficient and molecular weight of the contaminant and the pipe material

Current Model in EPANet 2.0

$$\frac{\partial C_i}{\partial t} = -u_i \frac{\partial C_i}{\partial x} + r(C_i)$$

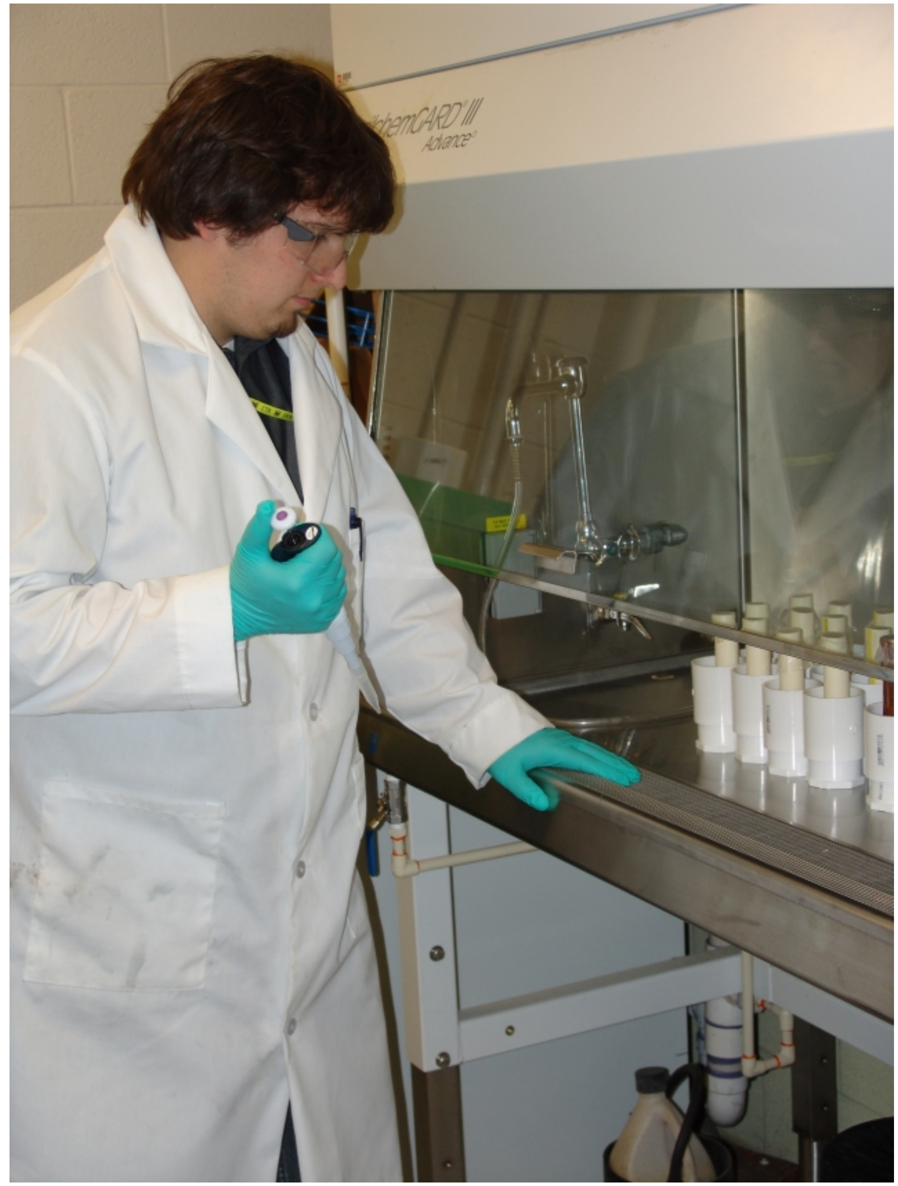
- Advective Transport Equation
  - with u = flow velocity, C_i is concentration, r is the ***pure loss*** term due to bulk interaction and wall interaction
  - The term ‘r’ was limited to pure loss because the simulation was built to track chlorine
  - Conversation with L. Rossman indicates version 3.0 will have more general modeling capabilities to take advantage of our research results.

6.2 In-house Testing

- Pipe types
  - PVC (15 April 2005)
  - Copper (29 April 2005)
  - Cement Lined Ductile Iron
    (Sealed and Unsealed) (25 May 2005)
- Agents - Low concentration
  - Prophos (VX simulant)
  - Ovalbumin (Ricin simulant) - Starts 30 May
- Static testing - Low concentration
  - Prophos @ 400, 200, 100 mg / L

In-House Simulant Static Testing

- VX Simulant Ethoprophos
  - MW = 242 (267.37)
  - H_{ow}= 140 (123)
- Ricin Simulant Ovalbumin
- Pipe: cPVC, Copper, Cement-Lined Ductile Iron (Sealed & Unsealed).
- Measure
  - Time constant & Asymptote
    - During exposure to simulant
    - Then on exposure to fresh water
- HPLC / MS, UV absorption
  - UIUC (A. Scheeline)



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ECBC Live Agent Static Testing

- Static Testing against live agents, (Starts 9 May 2005)
- Dynamic testing with live agents, in meso-scale loops at the ECBC/CERL Test Bed (Starts May 2005)
- Pipe types
  - PVC
  - Cement Lined Ductile Iron
  - CLDI with Sealer
- Agents - Low concentration
  - VX
  - Ricin

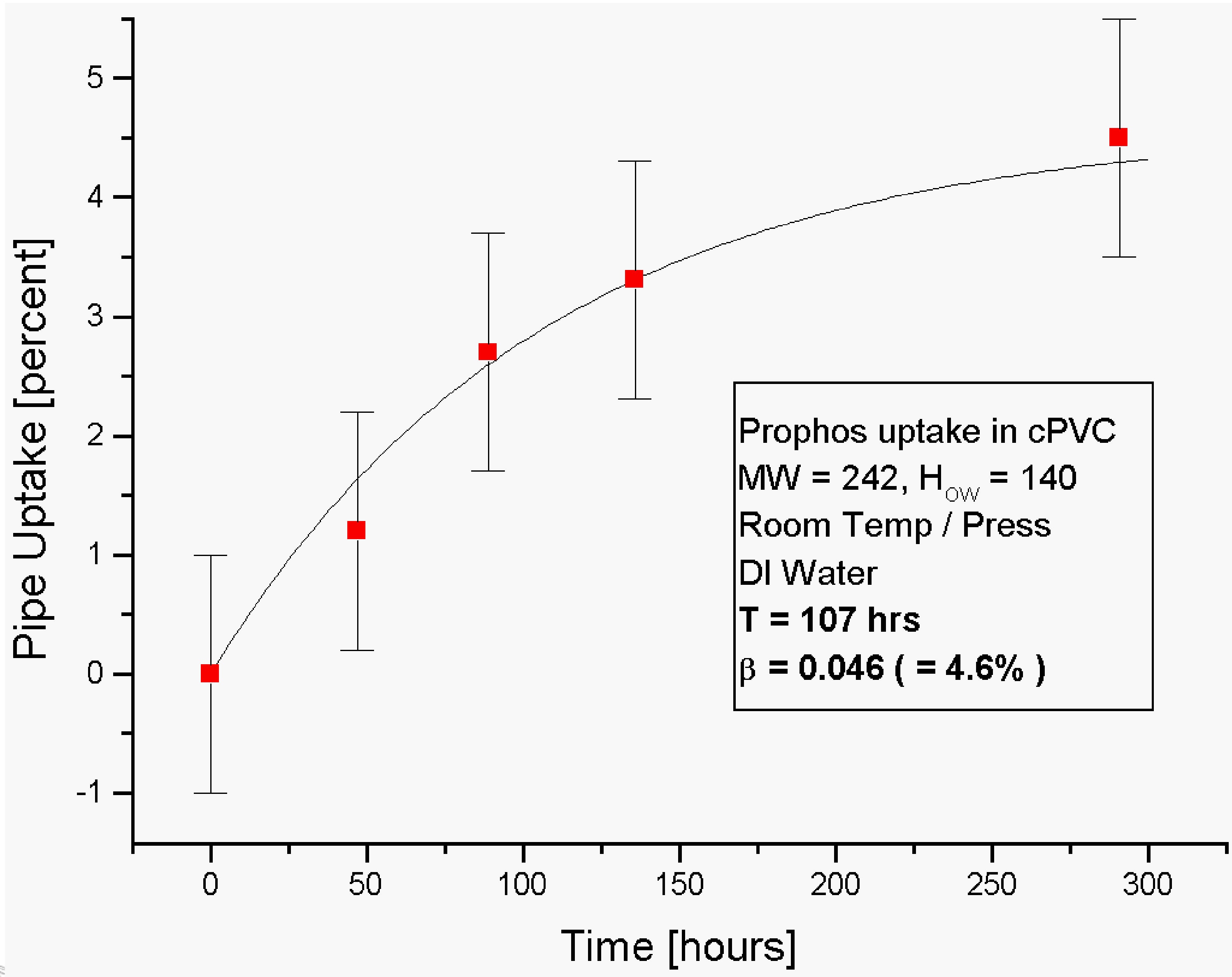
Current Results

$$C(t) = C_0^*\left(\beta\, e^{-t/T} + (1-\beta)\right)$$

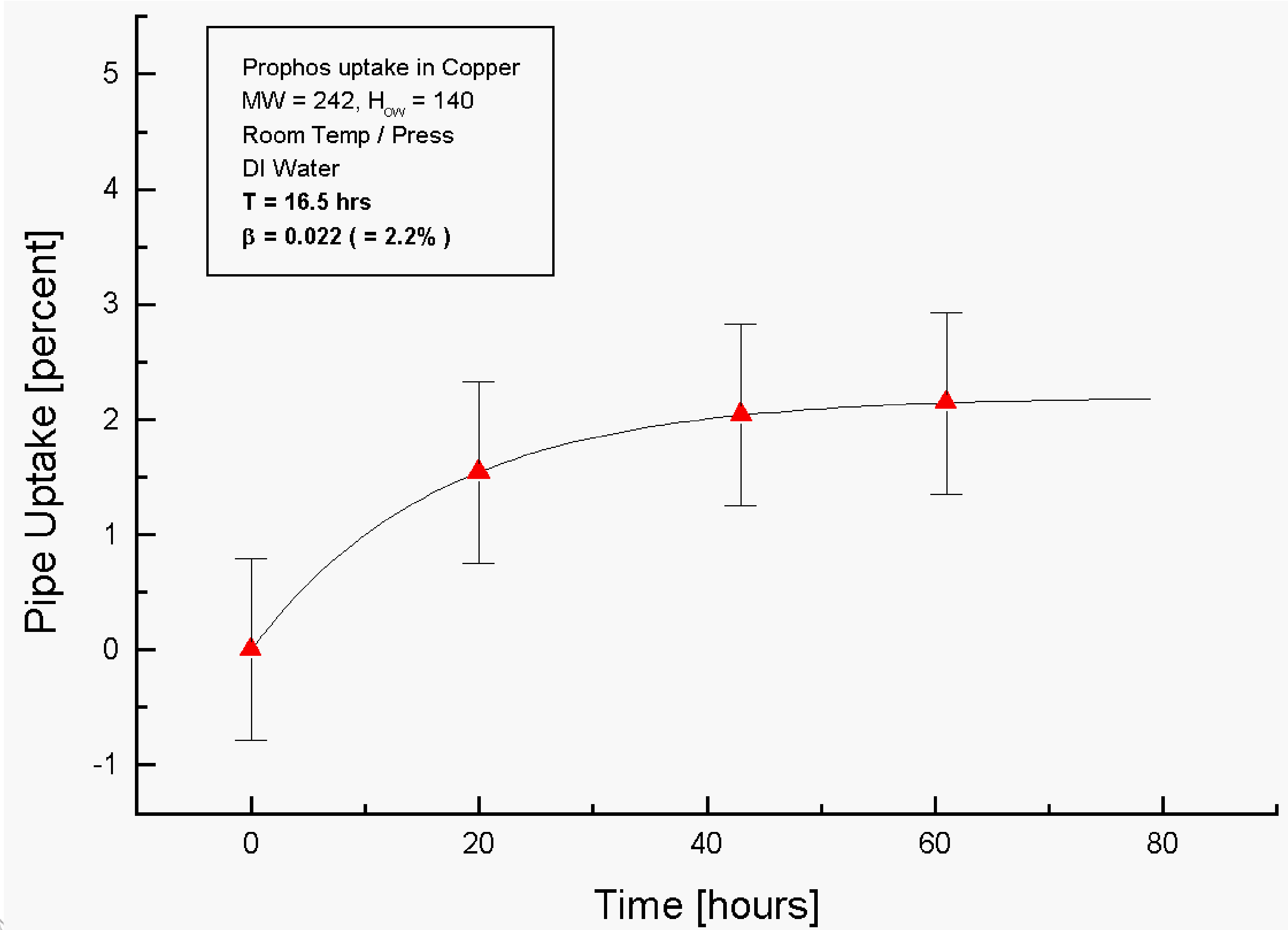
- Where
  - C(t) is the concentration of agent in water
  - C_0* is the initial concentration at the pipe wall
  - Beta is the fraction deposited on the wall at equilibrium
  - Tau is a characteristic time constant.
  - Beta and Tau are the parameters of interest in simulators
- This implies the pipe uptake P(t) is…

$$\frac{P(t)}{C_0^*} = \beta\left(1 - e^{-t/T}\right)$$

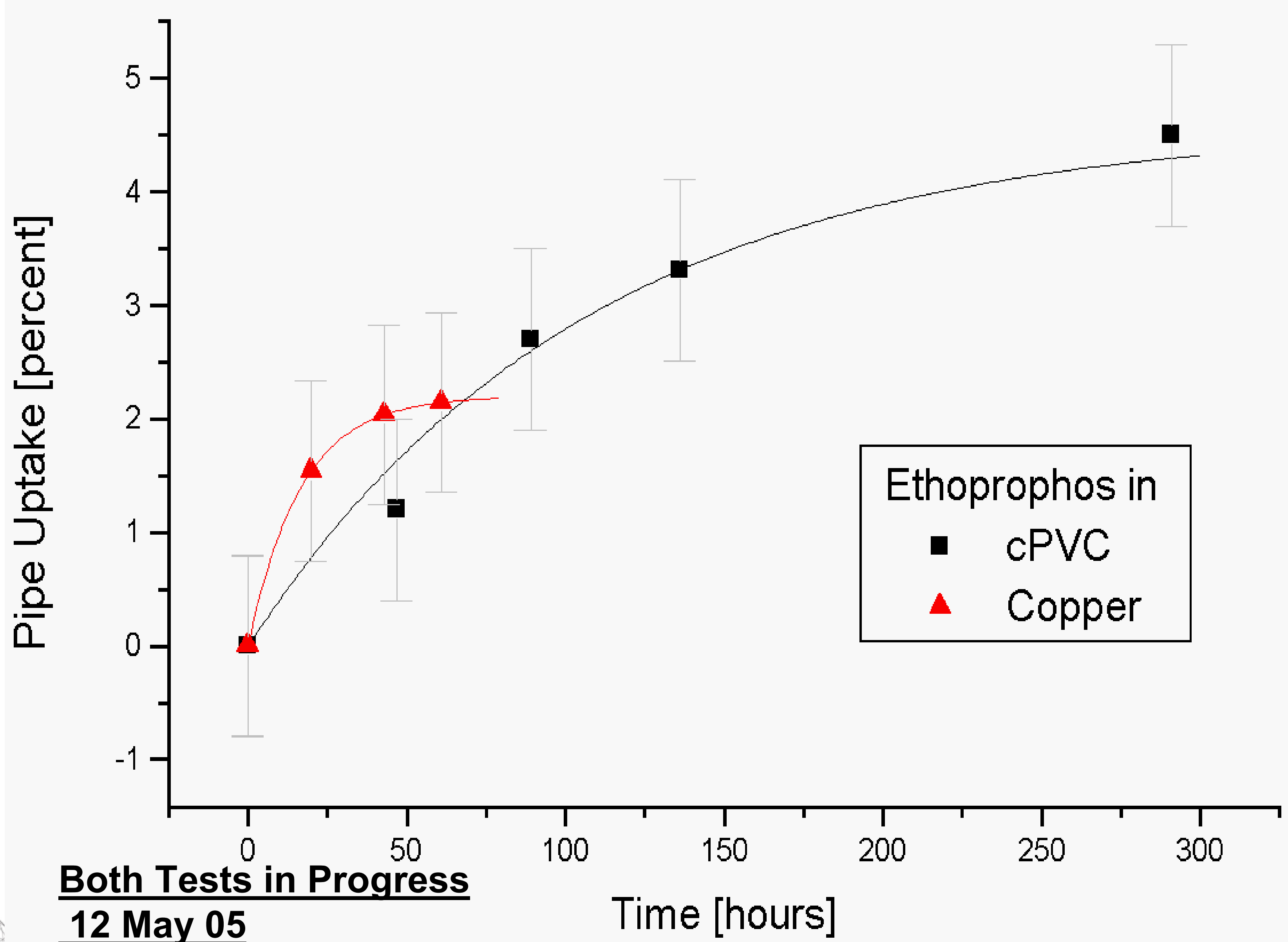
ERDC Static Test - VX Simulant in cPVC



ERDC Static Test - VX Simulant in Copper



VX Simulant in Copper vs. cPVC



Both Tests in Progress

12 May 05

ERDC Analysis of Static Testing

Uptake in 7 days, Time constant in hours

Agent	cPVC	Fe	Cu
Prophos	3.6%, 107	-	2.2%, 16.5
Bacillus	189%	21%	
MS2	30%	3%	
Inorganic As, Sr, Cs, Hg, Co, Tl	1%, ~1	1%	
Chlordane	14%, ~140	6%	
p-DCB	2%, ~73	1%	

Chemical Agent Results

- Percentage uptake on new pipe wall is directly proportional to chemical agent concentration (at moderate or high levels)
  - Preliminary data for VX simulant on cPVC indicates uptake of ~ 5%
- Pipe wall interaction is independent of:
  - pH [7 - 8.9], temperature [4 - 25C]
- Pipe wall interaction is <u>dependent</u> on
  - Pipe type
  - Agent type

High Concentration Mini-Loop at ECBC

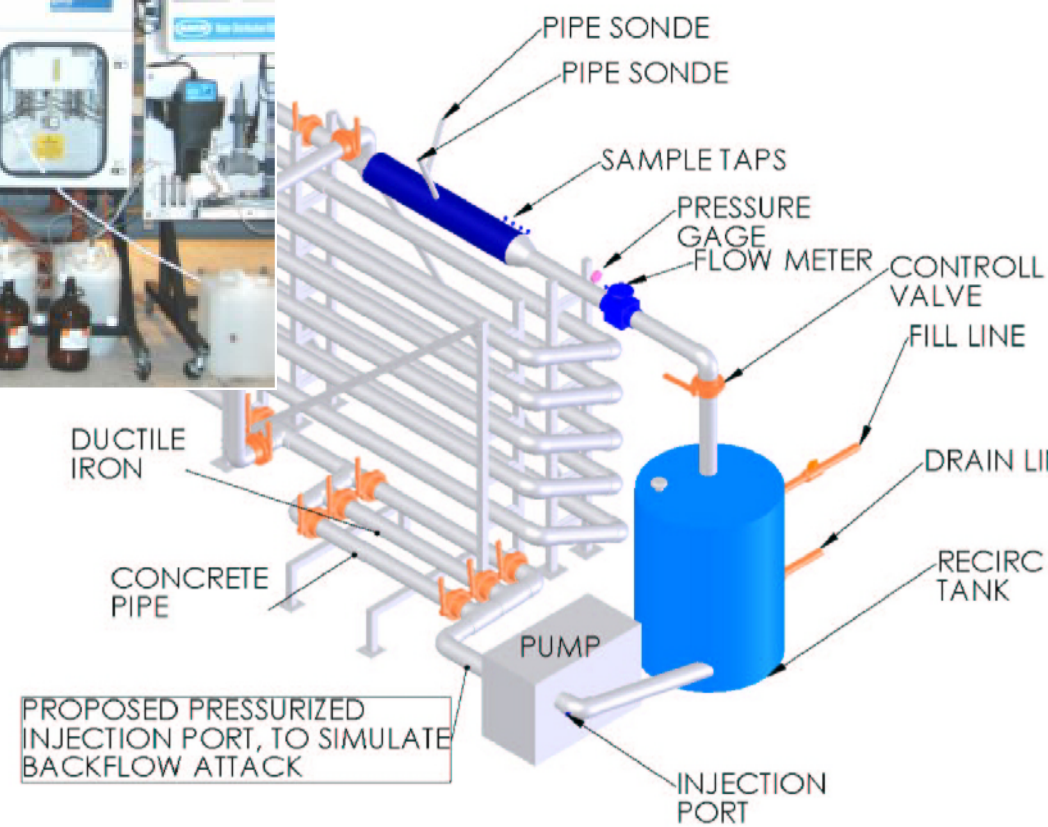
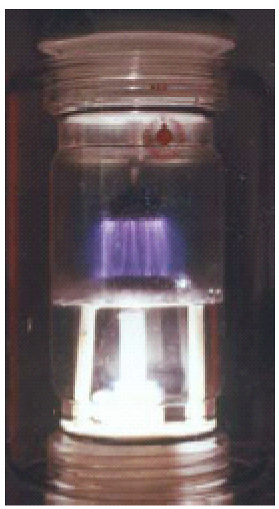


Photo of Large Test Loop at ECBC

Approach: Countermeasures

- Develop new “green” countermeasures that do not produce toxic by-products, including:
  - UV
  - E-Beam
  - Pulsed Corona Discharge



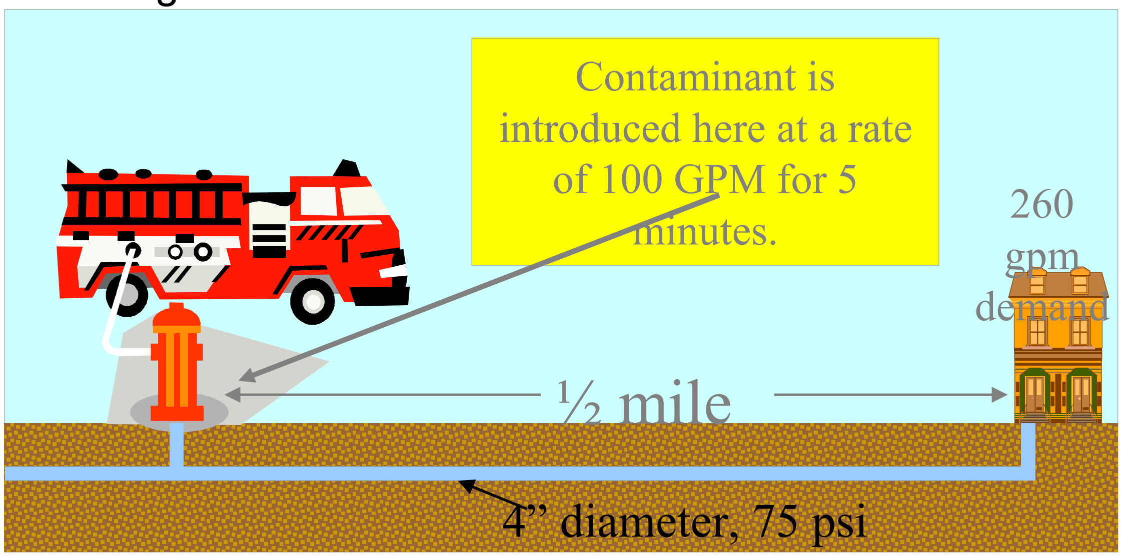
R&D Simulation of Fate & Transport of a CB Agent in a Water Distribution System

Scenario:

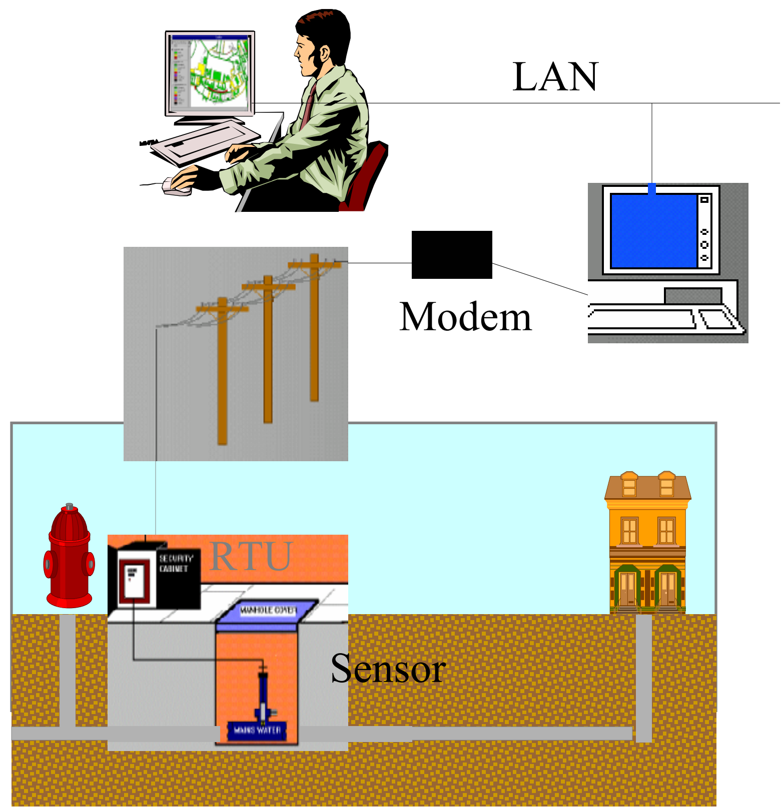
- DoD and municipal water systems are vulnerable to terrorist threats
- System-specific response to threats/ emergencies (such as chem/bio attack) is often unknown
- Limited methods for detecting chem/bio agents

Response:

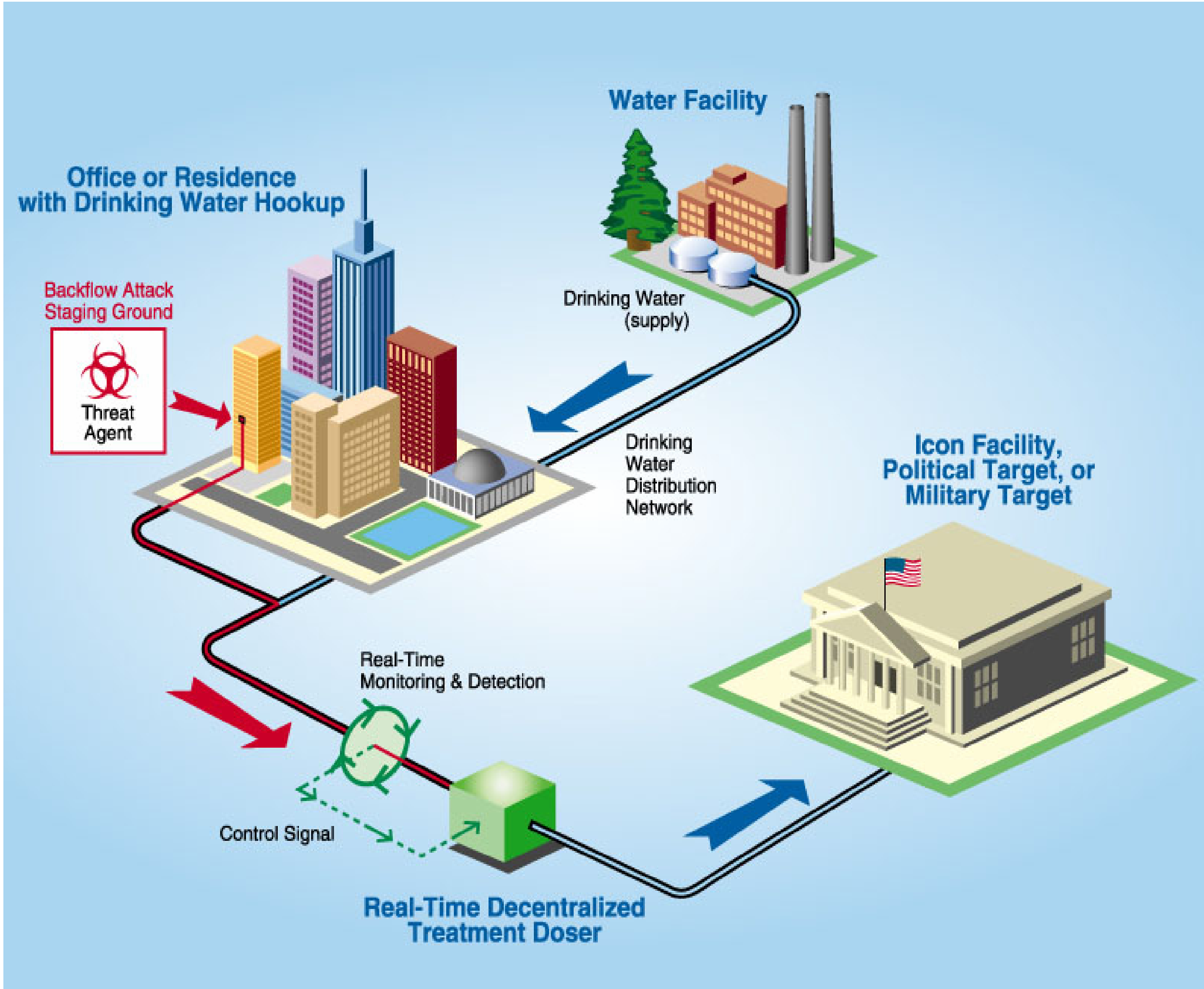
- Sensor-enabled dynamic models coupled with countermeasures

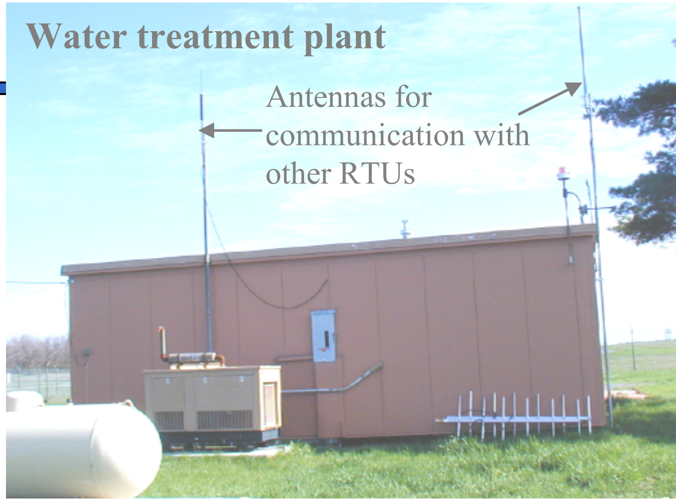


How long before it reaches the building? What will its concentration be? When will the concentration return to zero?

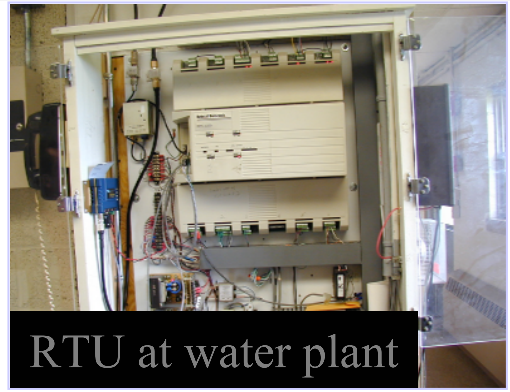


Integrated System Protection



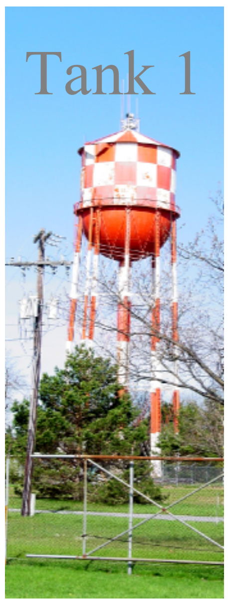


Water treatment plant

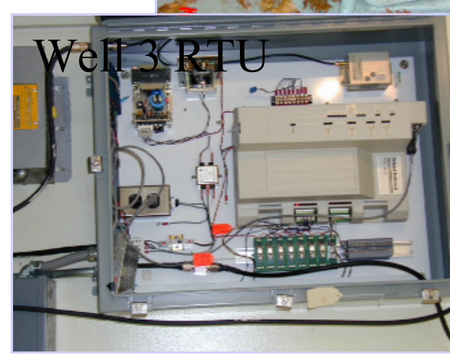

RTU at water plant


Ground storage reservoir


Tank 1 water level sensor at water plant


Tank 1


Flow meter at water plant


Well 3 RTU

FORT DRUM PILOT TEST

Technology Transfer

- Transfer rate constants for CB Agent F&T in various pipe types to enhance engineering simulation
- EPANet 3.0 updated by EPA office of Water Security (POC L. Rossman) Fall 05
- Updated EPANet 3.0 embedded in the Ft. Future Virtual Installation FY06.
- Additional plans
  - ACSM / IMA - Force Protection (P. Hoffman)
    - Vulnerability Assessment of Critical Facilities
  - DTRA - Nationwide network of sensors with integration with ASOCC or CATS.
  - CHPPM - Soldier health, sensors, and fate of agent.
  - Congressional line-item with Hach HST for field implementation of sensors