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# Challenging Problems of the Chernobyl Cooling Pond Monitoring and Modeling

**RIC 2011**
**International Panel Discussion on Radionuclide Sources and Migration in the Subsurface**

March 10, 2011

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**Lawrence Berkeley National Laboratory**

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- Vyacheslav Shestopalov, Dmitri Bugai, Alexander Skalsky, and Mark Zheleznyak, National Academy of Sciences of Ukraine
- Oleg Voitskhovich, Ukrainian Hydrometeorological Institute, CMSET
- Valery Kashparov, Institute of Agricultural Radioecology, Ukraine
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**Acknowledgement of Support**

- **DOE-EM:** Kurt Gerdes
  Skip Chamberlain
  Mark Williamson
- **IAEA:** Horst Monken-Fernandes

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## RIC Questions

### Monitoring

- How were monitoring systems designed and used to detect abnormal and routine releases to the subsurface?
  - Was atmospheric deposition monitored?
  - Was contamination of surface water and bottom sediments monitored?
  - Were the saturated and unsaturated zones monitored?
- What specific monitoring data (e.g., hydraulic, radiochemical, geochemical, geophysical, meteorological) and analyses were used to test the conceptual models?

### Modeling

- What was learned in the testing of conceptual site models?
- What role did modeling have in estimating and confirming radionuclide migration behavior, and in assessing vulnerabilities to environmental resources?

Concluding Notes and Potential Use of the Chernobyl Cooling Pond Monitoring and Modeling as Case Studies

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## General Information about the Chernobyl Accident and Chernobyl Cooling Pond

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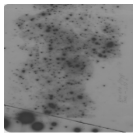
## Chernobyl Accident

Chernobyl Exclusion Zone

Radioactive releases to the atmosphere consisted of gases, aerosols and finely fragmented fuel.

- Fuel particles—finely dispersed, low volatility, settled primarily within the ChEZ
- Condensed components—from radioactive gases, settled primarily along the atmospheric flow pathways
- Hot particles—fuel particles, uranium dioxide, with a specific activity >$10^5$ Bq/g, size 1 to 100 µm, surface density ~ 1,600 per $m^2$, to ~0.5 m depth



Autoradiography of CP sediments Ukr. Institute of Agricultural Radioecolgy

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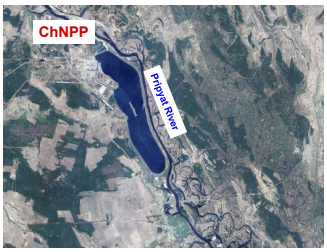
## Chernobyl Cooling Pond




### Sources of Contamination

- Dispersed fuel particles
- Heavily contaminated water from the reactor basement and soils.
- Total radioactivity >200 TBq, including $^{137}$Cs-80%, $^{90}$Sr-10%, $^{239,240,241}$Pu-10%
- Routine releases of contaminated water into the pond

- Area ~ 22 km$^2$ , ~1.5 × 10$^8$ m$^3$ of water
- Water is pumped from the Pripyat River to the Cooling Pond

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## Cooling Pond Decommissioning

- Separating the inflow and outfow channels from the pond
- Declining the pond water level and exposing highly contaminated bottom sediments
- Remediation of the residual bottom sediments.

After A. Antropov, Chernobyl NPP

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- How were monitoring systems designed and used to detect abnormal and routine releases to the subsurface?
  - Was atmospheric deposition monitored?
    - Post-accident monitoring of aerosol distribution along with modeling studies were used to assess the atmospheric deposition.
    - Resuspension of radionuclides has been thoroughly studied.
  - Was contamination of surface water and bottom sediments monitored?
    - Monitoring of contamination of surface water and bottom sediments since mid-1986.
  - Were the saturated and unsaturated zones monitored?
    - Post-accident network of groundwater wells, surface sampling stations, and research sites.

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- **What specific monitoring data and analyses were used to test the conceptual models?**
  - **surface water and groundwater monitoring,**
  - **tracer and pumping tests,**
  - **radiochemical, geochemical, meteorological measurements,**
  - **pilot cooling pond drawdown,**
  - **resuspension monitoring,**
  - **monthly sampling and radioactive analysis of water from the input and output canals.**

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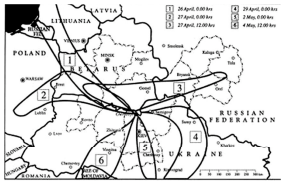
## Atmospheric Deposition




- ~27% of the volatile Cs and I was initially deposited within 80 km (USSR State Committee, 1986).
- The major part of radioactivity in Western Europe was associated with particles of <2 μm.

- **The major atmospheric radionuclide migration processes are:**
  - Convection by wind,
  - Deposition--aerosol falls onto the ground due to the gravity,
  - Resuspension--aerosol on the ground is lifted in the air by the wind or some other reasons.
  - Fallout.

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## Network of Monitoring Stations and Wells

- **40 cross sections and aerosol sampling stations;**
- **138 groundwater monitoring wells;**
- **4 stations for sampling surface water and bottom sediments**

**Chernobyl Ecocenter, S. Kireev.**

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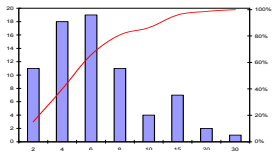
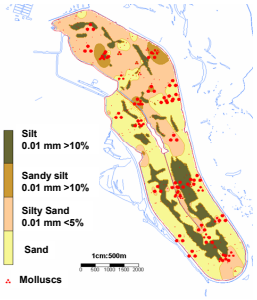
## Types of Bottom Sediments

| Depths, м | 0-4 | 4-7 | 7-10 | > 10 |
|---|---|---|---|---|
| Area (sq. km) | 3.56 | 16.4 | 2.2 | 4.0 |
| Average depth, m | - | 1.8 | 4.3 | 26 |
| Maximum depth, m | - | 6.0 | 19.0 | >100 |



Hot particles, µm

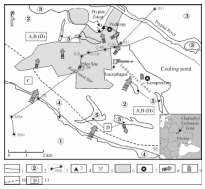



After O. Voitsekhovich



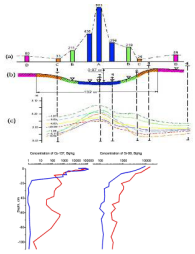
## Unsaturated Zone Studies

NASU Vadose zone pilot Site within the "Red Forest" waste dump area



$^{137}Cs$ and $^{90}Sr$ distribution with depth Veresok site (Shestopalov, 2009)

Accumulation of radionuclides in local land-surface depressions



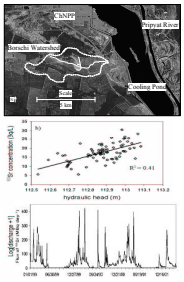


- center of the depression;
- depression border.



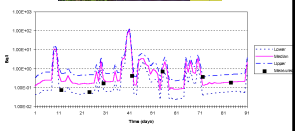
## Surface Water Monitoring

Borschi watershed



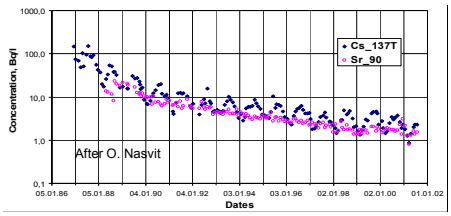

Freed et al., Seasonal Changes of the $^{90}Sr$ Flux in the Borschi Stream, Chernobyl, ERSP, 2003

Ilya River Watershed



Simulation by RIVTOX of $^{137}Cs$ concentration on suspended sediments at outflow from the Iliya River (after O. Voitsekhovich and M. Zheleznyak)

## Time trend of $^{137}Cs$ and $^{90}Sr$ concentrations in the Chernobyl Cooling Pond

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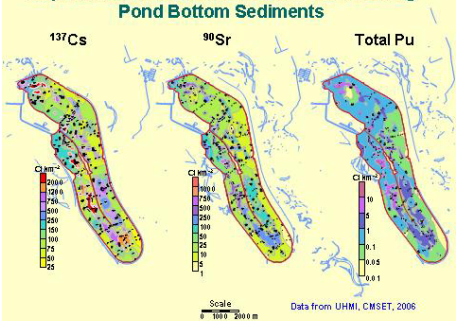
## Maps of Radionuclide Activities in the Cooling Pond Bottom Sediments

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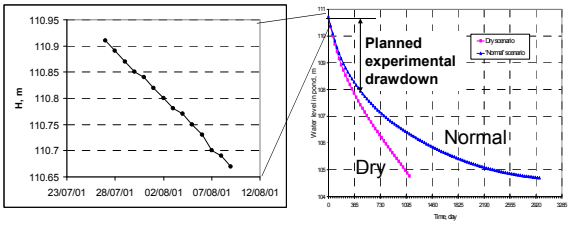
## 2-Week Cooling Pond Drawdown Test for Model Calibration




- Water level decline--24 cm
- Average water losses--4.5 $m^3/s$
- Estimated seepage losses: total - 3.5 $m^3/s$ (incl. ditches), subsurface losses– 1.3 $m^3/s$

Data from NNC-99 report, Bugai et al.

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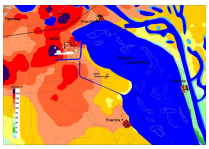
## Radio-Ecological Studies



- No reliable input data and parameters are available for predictions of radioecological consequences of the Cooling Pond decommissioning.
- Additional investigations and development of a standardized approach for decommissioning of cooling ponds of NPP are needed.

After B. Oskolkov

- **RESPOND--Radio-Ecological Study of**
  - Influence of radiation on aquatic systems surrounding Chernobyl;
  - Influence of remediation of the Cooling Pond on the aquatic ecosystem.
- **EU (INTAS); Royal Society**
- **AQUASCOPE--Aquatic modeling study**
- **AQUACURE--Countermeasures**
- **EU INCO - Copernicus**

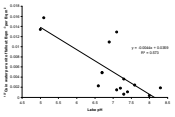
**Jim Smith -- School of Earth and Environmental Sciences, University of Portsmouth, UK**

Biodiversity of the Aquatic Ecosystem and abnormalities of fish

Biodiversity of insects in 9 lakes

Physical and hydrochemical variables were recorded or compiled from existing data

- Lake area and depth
- Conductivity
- pH
- Total hardness
- Phosphate
- $^{137}$Cs load
- Potassium
- Ammonium
- pH

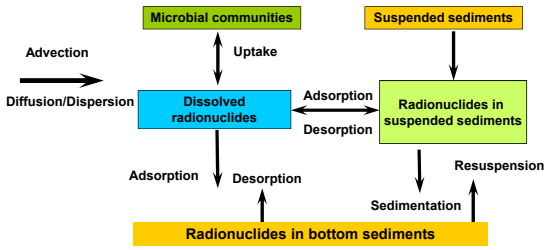


Limited study of heavy metals and organics



- **What was learned in the testing of conceptual site models?**
  - Processes affecting radionuclide transport in the Chernobyl Cooling Pond
  - Conceptual hydrological and geochemical models of the Cooling Pond
  - Geochemical conceptual model of the Cooling Pond bottom sediments
  - $K_d$ depends on the N ammonia concentration
  - Atmospheric deposition and resuspenstion models are needed for
    - estimating source term;
    - deploying field measurement stations;
    - evaluating the consequences of hypothetical emergency scenarios;
    - model and measurements validation.

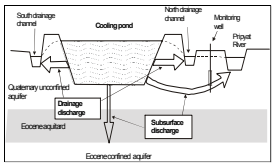
## Processes Affecting Radionuclide Transport in the Chernobyl Cooling Pond



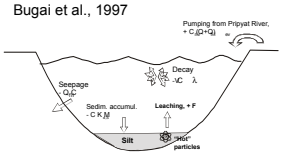

Modified after M.Zheleznyak

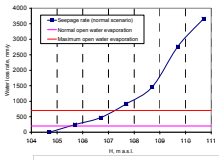


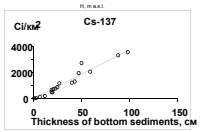
## Conceptual Hydrological and Geochemical Models of the Cooling Pond




Bugai et al., 1997



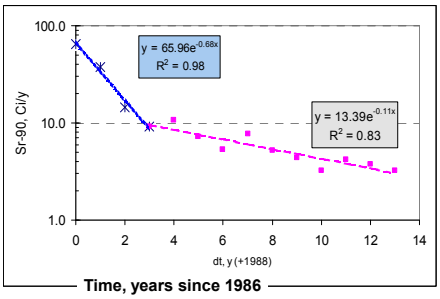




Data from UHMI, CMSET, 2006



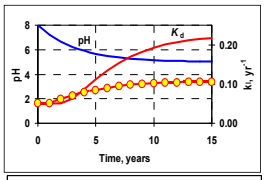
## $^{90}$Sr flux into the Cooling Pond water from the bottom sediments

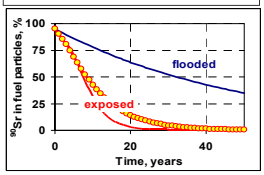



Time, years since 1986

## Geochemical Processes and $K_d$ Parameters of the Bottom Sediments

- Low DO and high pH cause a very slow dissolution of fuel particles in bottom sediments.
- Vegetation and microbiological activity will acidify newly formed soils, causing the dissolution rate to increase.
- Fuel particle dissolution will take ~15–25 years in exposed sediments, and ~100 years in flooded areas.
  - Bulgakov et al., 2009




A. Konoplev et al. 2009

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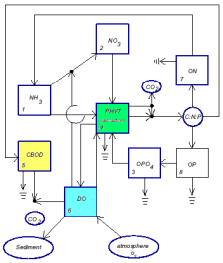
## Water Quality Analysis Simulation Program (WASP)--EPA framework for modeling contaminant fate and transport in surface water.




$K_d$ depends on the N ammonia concentration (M. Zheleznyak et al., (2005)—INTAS-2001-0556 Project Report "Radionuclide and Sediment Transport Modelling Within the Cooling Pond Ecosystem")

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- **What role did modeling have in estimating and confirming radionuclide migration behavior?**
  - Areal extent of residual ponds and exposed bottom sediments under different climatic scenarios
  - Optimal time trend of the water level drawdown
  - Impact of cooling pond drawdown on the radwaste disposal sites
  - Contaminant travel time from the Cooling Pond to the Pripyat River through groundwater and surface water and a cascade of the Dnieper River reservoirs
  - Risk assessment and economical analysis of decommissioning, remediation and Monitored Natural Attenuation

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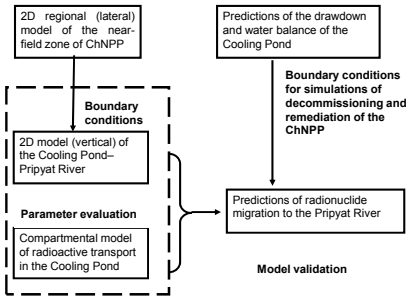
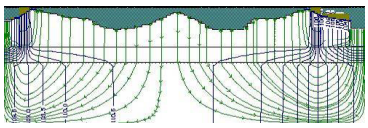
## Modeling Approach for Predictions of the Chernobyl Cooling Pond Decommissioning and Remediation





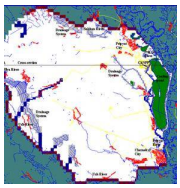

- **VisualModflow and MT3D96 codes**
- **Regional model of the Chernobyl Exclusion Zone and a 2D cross-section model**

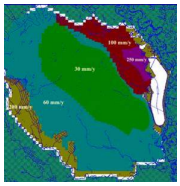
**Pond**



After Bugai et al.

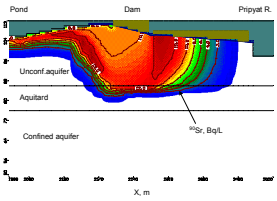
**Infiltration model**



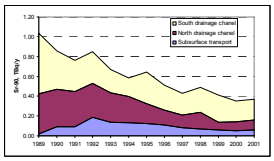




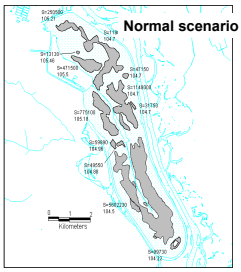
## $^{90}$Sr Concentration in Groundwater between the Pond and the Pripyat River (5 years)

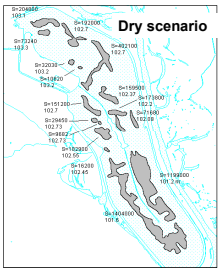



## $^{90}$Sr discharge from the Cooling Pond to the Pripyat River



## Expected Areal Distribution of Exposed Sediments During the Pond Water-Level Drawdown




Exposed area 58%. Under water in bottom sediments will remain: $^{137}$Cs- 78%, $^{90}$Sr--74%, Pu-85%

Exposed area 80%

Bugai et al. 2006

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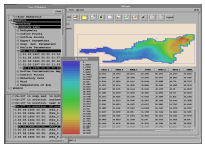
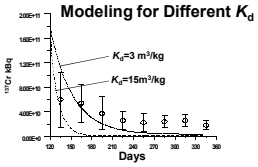
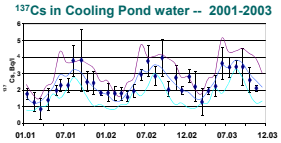
## Radionuclide transport modeling codes RIVTOX, COASTOX and THREETOX



Codes developed at the IMMSP of the National Academy of Sciences of Ukraine




$^{137}$Cs in Cooling Pond water -- 2001-2003




CMSET, 2006

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- What role did modeling have in vulnerabilities to environmental resources?
  - Modeling of dam break and Sr-90 release
  - Possible effects of aerosol dispersion toward surrounding areas and additional soil contamination due to fallout
  - Radio-ecological studies to evaluate biota dose
  - Using RESRAD-BIOTA: A Tool for Implementing a Graded Approach to Biota Dose Evaluation (Argonne Lab)
  - RESPOND-Radio-ecological study of the Chernobyl Cooling Pond and options for remediation

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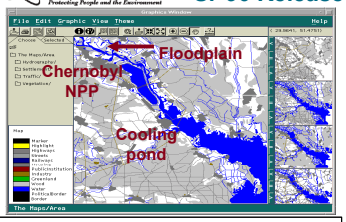
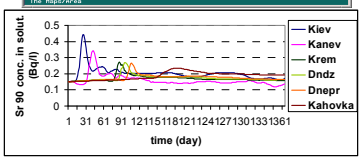
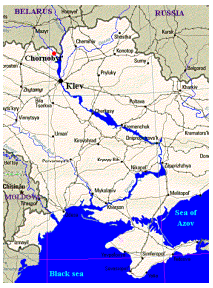
## Modeling of Dam Break and Sr-90 Release




Zheleznyak et al.

**CMSET, 2006**

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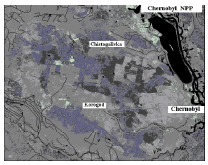
## Simulations of Extreme Climatic Scenarios

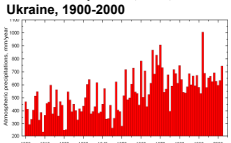
**Increased Fire Risk**




**V.I.Lyalko et al., Satellite monitoring of forest of the Chernobyl disaster… , International Archives of Photogrammetry and Remote Sensing. Vol. XXXIII, Part B7. Amsterdam 2000.**

NAS Ukraine and NA USA Workshop on Water Sector Adaptation for Climate Change, December 2~3, 2009

**Annual Precipitation, Kiev, Ukraine, 1900-2000**



SURFACE FLOODING AT THE NEFTEBAZA FVLRO

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## Assessing Radionuclide Resuspension

- **Controlled fire tests of forest and grassland experimental plots in the ChEZ have been carried out to estimate the radionuclide resuspension, transport and deposition parameters.**
- **The resuspension factor for $^{137}Cs$ and $^{90}Sr$ ranges from $10^{-6}$ to $10^{-5}$ $m^{-1}$, and for the plutonium radionuclides from $10^{-7}$ to $10^{-7}$ $m^{-1}$.**
- **These values are 2 orders of magnitude lower if they are calculated relatively to the total contamination density (including the nuclides in the soil).**
- **The radionuclide fallout along the plume axis is negligible in comparison to the existing contamination.**

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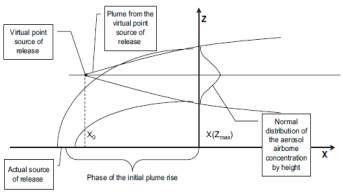
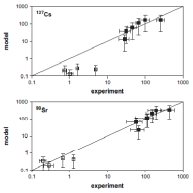
## Modeling vs. Experimental Data for the Grassland Fire




Concept of the virtual point source of the radioactive smoke release.




Experimental and modeling results of the airborne activity concentration (open symbols) in Bq/m$^3$ and the deposition density (closed symbols) in Bq/m$^2$.

V.I.Yoschenko et al., J.Environ.Radioactivity 87, 2006.

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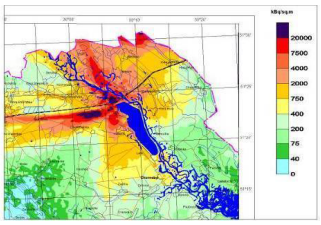
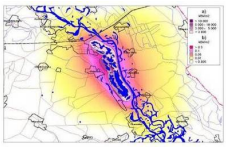
## Long-Term Effect of Wind Resuspension



$^{137}$Cs Contamination of Soil before and after Decommissioning of the Cooling Pond

Possible effects of aerosol dispersion toward surrounding areas and additional soil contamination due to fallout are negligible in comparison to already existing situation.

Kashparov, et all. 2001

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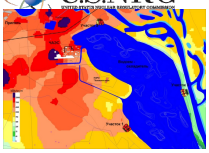
## Radio-Ecological Studies



- No reliable input data and parameters are available for predictions of radioecological consequences of the Cooling Pond decommissioning.
- Additional investigations and development of a standardized approach for decommissioning of cooling ponds of NPP are needed.

After B. Oskolkov

RESRAD-BIOTA: A Tool for Implementing a Graded Approach to Biota Dose Evaluation (Argonne Lab)

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## RESPOND-Radio-Ecological Study of the Chernobyl Cooling Pond and Options for Remediation

- Pond drawdown will negatively impact biodiversity of fish, but may have a positive impact on aquatic insects;
- Complete remediation of the Cooling Pond would significantly damage the ecosystem whilst not significantly reducing doses;
- Phytostabilisation of some small areas may be worthwhile;
- Drawdown of water level should be as slow as practicable;
- Monitored natural attenuation is the most environmentally sound remediation option.

**Jim Smith -- School of Earth and Environmental Sciences, University of Portsmouth, UK**
**Oleg Voitsekhovich – Ukrainian Hydrometeorological Institute, Kiev, Ukraine**

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## Concluding Notes and Examples of Potential Use of the Chernobyl Cooling Pond Monitoring and Modeling as Case Studies

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## Concluding Notes from Monitoring and Modeling Studies

- The post-Chernobyl accident studies clearly indicate the need for measurements of radionuclide concentration in the air, surface water and groundwater to go hand-in-hand with collecting meteorological data and modeling studies.
- Models complement measurements and measurements correct and strengthen models.
- Actual requirements will change with the scale and character of the emission.

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## Potential Use of the Chernobyl Cooling Pond Monitoring and Modeling Results

**(1) Evaluation and modeling of hydrologic and biogeochemical processes for unsaturated-saturated soils and bottom sediments, including parameter estimation, aleatory, epistemic, and scenario uncertainties;**

**(2) Design and implementation of appropriate site characterization and monitoring techniques for highly contaminated sols and groundwater - geophysical monitoring, natural and radioactive isotopic methods, remote sensing;**

**(3) Assessing the efficacy of different remediation approaches according to applicable regulations, such as NEPA and CERCLA, and monitored natural attenuation.**

**(4) Validation of numerical codes--DOE ASCEM project, NRC/EPA/USGS Integrated Environmental Models, U.S. Army Engineer Research and Development Center (ERDC) codes.**

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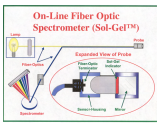
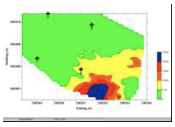
## Testing of Remotely Operated Field Monitoring Techniques

**Savannah River Site**

- ADCON Telemetry-a real-time soil moisture monitoring system (D-Area Phytoremediation).
- FDTAS-tritium analysis system in surface and groundwater in near real time.
- Sol-Gel Indicators for Process and Environmental Measurements




**INL Soil and Surface Assay Systems for Gamma, Beta, and Alpha Radiation Sources**



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## Case Studies to Test Modeling Techniques

- **DOE ASCEM** project--testing/validation of high performance computing capabilities, parameter estimation, uncertainty quantification, data management, visualization and site application approaches.
- **NRC/EPA/USGS** integrated environmental modeling collaborative projects.
- **U.S. Army Engineer Research and Development Center (ERDC)--**Gridded Surface Sub-surface Hydrologic Analysis (GSSHA) and the Contaminant Transport, Transformation, and Fate (CTT&F) modeling system.

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