Presentation 8 – Mary Ann Parkhurst

Estimating Depleted Uranium Aerosol Doses and Risks:

An Overview of the Capstone Depleted Uranium Aerosol Study and the Capstone Human Health Risk Assessment

Research Advisory Committee on Gulf War Veterans' Illnesses
April 7, 2005

Mary Ann Parkhurst
Battelle/Pacific Northwest National Laboratory
Richland, Washington

Study Objectives

- Generate data to fill knowledge gaps about aerosols created by perforation of armored vehicles with DU munitions
- Apply data in dose and risk assessment of DU aerosol exposures
  - Retrospective assessments
  - Prospective assessments

Data to Be Generated

Underlying question: Are health risks high enough to warrant changes in

- Medical policy for treatment?
- Monitoring?
- Protective Measures?

Peer Review Committee

Dr. Roy Reuter, Team Coordinator
Dr. Arthur Upton—Radiobiology
Dr. John Doull—Toxicology
Dr. Rogene Henderson—Inhalation Toxicology
Dr. David Hoel, Health Physics, Industrial Hygiene
Dr. Morton Lippmann—Air Sampling
Dr. Paul Strickland—Toxicology
Dr. Wes Van Pelt—Health Physics
Dr. Paul Baron—Aerosol Physics
Dr. Tony James—Health Physics, Computer Modeling
Dr. Wesley Bolch—Health Physics, Computer Modeling

Capstone DU Aerosol Study

- Large-scale field testing of aerosols generated by perforation of armored vehicles with depleted uranium (DU) penetrators
- Highest priority on aerosols created inside vehicle at time of and immediately after perforation
- Fired at ballistic turrets and hulls
- Collected aerosol and deposited particulate material
- Characterized chemical composition and particle size collected over first 2 hours

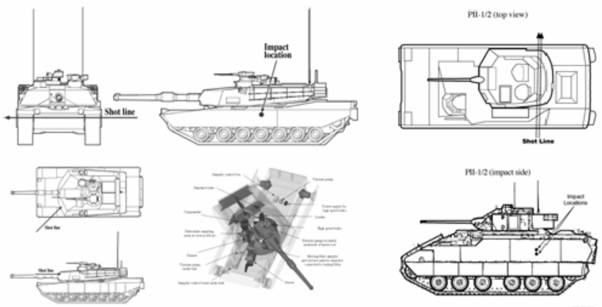
Field Tests

- **Phase I – Abrams tank with conventional armor**
  - Crossing shots (4)
  - Breech shots (2)
  - Hull shot (1)
- **Phase II – Bradley Fighting Vehicle**
  - Crossing shots (2)
  - Turret/breech shot (1)
- **Phase III – Abrams tank with DU armor**
  - Armor packaged shots (2)
- **Phase IV – Abrams operational tank**

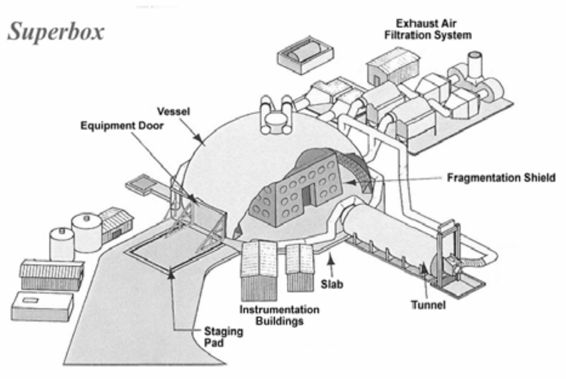
Abrams Tank– with Conventional or DU Armor

Bradley Fighting Vehicle—Conventional Armor

Perforation Shot Lines



ATC SUPERBOX FACILITY



ATC SUPERBOX SHOT

Sampling Environments

- **Interior (primary sampling)**
  - Turret air (and passenger compartment in Bradley) immediately after shot
  - Periodically up to 2-hr post shot
  - During recovery operations
  - Turret interior surfaces
- **Exterior (secondary sampling)**

Sampler Requirements

- **Survive a high energy environment**
  - Robust aerosol samplers
  - Physical shielding against immediate pressure and temperature pulses and fragments
  - Sampler Redundancy
- **Accommodate computerized time sequencing control**
- **Overall sampling rate <200 Lpm**

Interior Sampling Equipment Selected

Filter Cassettes

(IOMs): used for time-sequenced sampling

- stainless steel
- Gelman Supor membrane discs
- Replaced with Zefluor filters

Interior Sampling Equipment Selected (Cont.)

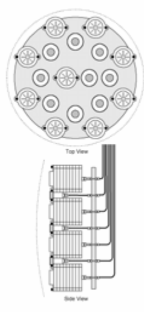
Cascade Impactors:

used for time-sequenced sampling

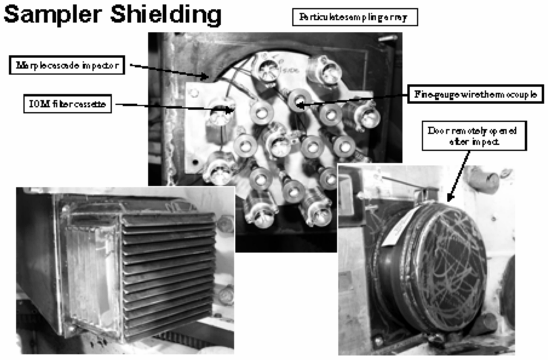
34-µm, 8 stage, inlet modified, with backup filter

- Effective cutoff diameter at 2 Lpm: 21, 15, 10, 6, 3.5, 1.6, 0.9, 0.5 µm, respectively
- Mixed cellulose ester substrate
- Medium of 0.8-µm pore size

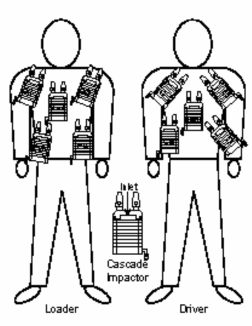
Sampling Arrays—Placed at Commander, Driver, Gunner, and Loader Positions (Right and Left Scout in BFV)



Sampler Shielding



Phase IV Samplers



Interior Sampling Equipment Selected (Cont.)

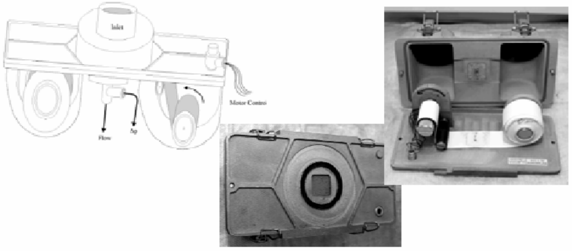
5-stage SRI cyclone train

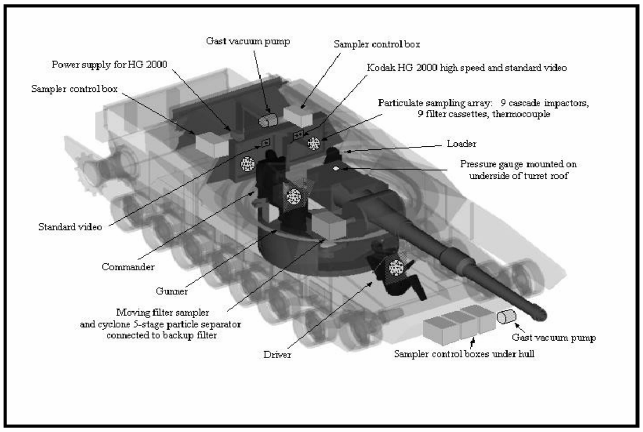
- Stage cutoff diameters of aerodynamic diameters (μm) at 10 Lpm flow rate: 10, 4.3, 2.9, 2, 1.2 (<1.2 backup filter)

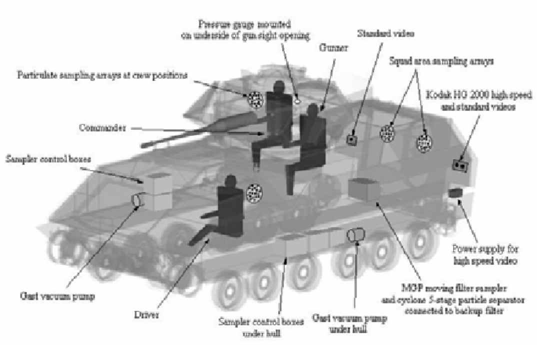
Used for bulk aerosol sampling

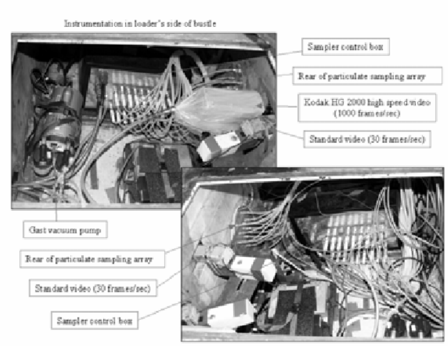
Interior Sampling Equipment Selected (Cont.)

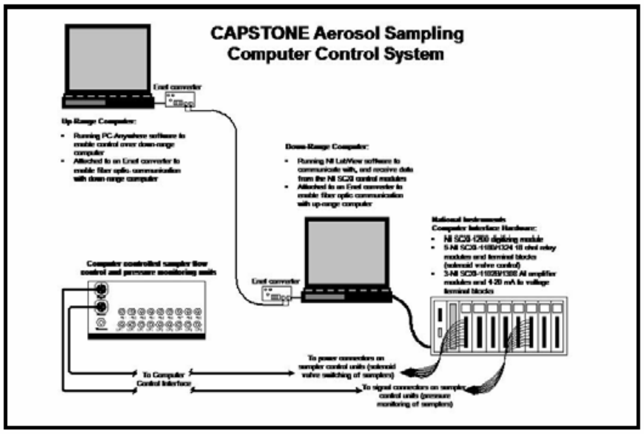
Merlin-Gerin auto-advance moving filter sampler
(AW19 filter tape; 28 Lpm sampling rate; discrete or continuous)
Used for sampling in first few seconds





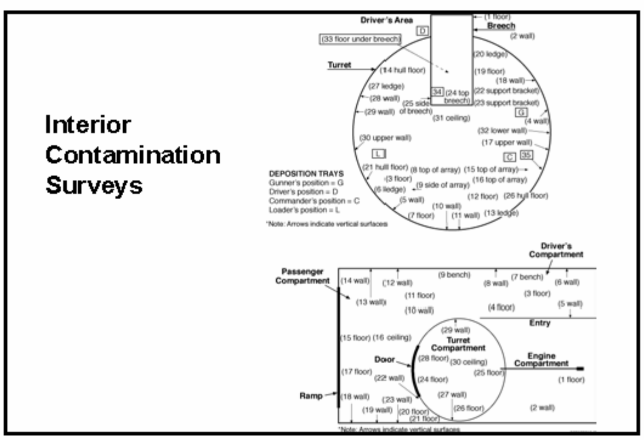


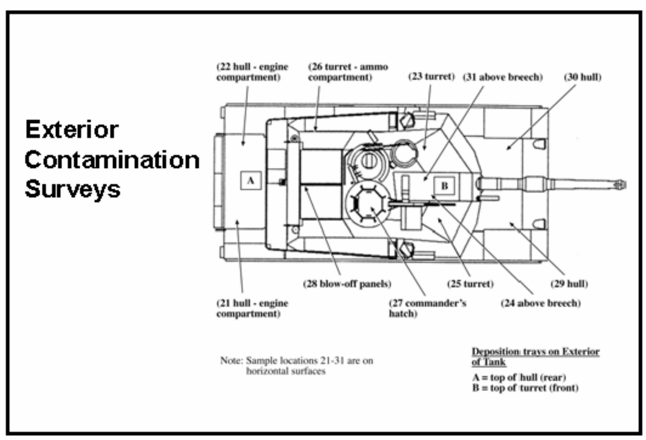




Interior Surface Contamination Sampling

- **Deposition trays**
  - 4 in. by 4 in. aluminum trays (100 cm²)
  - Four on floor near each of 4 sampling arrays
- **Wipe surveys**
  - At least 30 discrete, pre-marked wipe locations
- **Cotton gloves**
  - Worn by sample recovery personnel (over protective gloves)





DU Aerosol Analysis

- **8,000 samples collected**
- **Analysis performed by 4 laboratories**

Laboratory Analysis

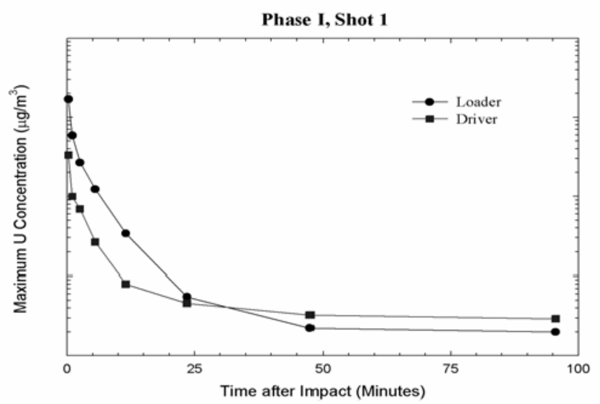
- **Radioactivity on filters, gloves, wipes, cyclone**
  - Alpha/beta counts
  - Gamma counts – cyclones, gloves
- **Chemistry**
  - Uranium analysis
  - DU/U analysis (U235/U238 ratios)
  - Oxide analysis
- **Morphology by scanning electron microscopy**
- ***In vitro* solubility**

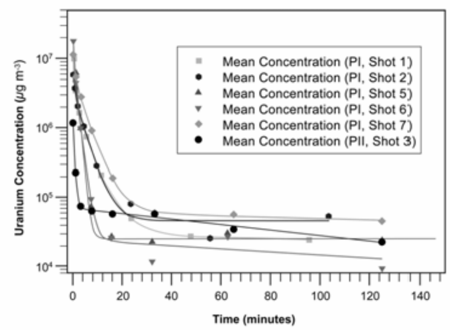
Example of Filter Cassette Samples Collected

Mass Concentration

**Uranium Mass Concentration (µg/m^3)
(adjusted for ingrowth) =**

$$\frac{\text{[Sample Mass (Max U µg) – Field Blank (Max U µg)]}}{\text{[Sample Volume (L) x 1.0 E-3 m}^3\text{/L]}}$$





DU Aerosol Summary Table

Shot Description	Mean DU Concentration (g/m^3)					
	10 sec	30 sec	1 min	30 min	1 h	2 h
Retrospective						
Abrams—crossing hull	11	9.0	6.0	0.11	0.057	0.047
Bradley—turret and passenger comp't	3.0	2.7	2.2	0.13	0.049	0.024
Prospective						
Abrams—crossing turret	8.8	7.9	5.7	0.15	0.064	–(a)
Abrams—crossing turret into breech	16	12	6.4	0.020(b)	0.029	0.019
Abrams—into DU armor	10	7.9	4.2	0.049	0.017	0.013
Abrams—into DU armor (PIV-4; with ventilation)	0.092	0.14	0.22	0.011	--(a)	--(a)

(a) Averages not extrapolated past last sample.
(b) Samplers for both shots showed similar pattern in large reduction from 1 min; most 30 min DU concentrations were lower than at 1 h.

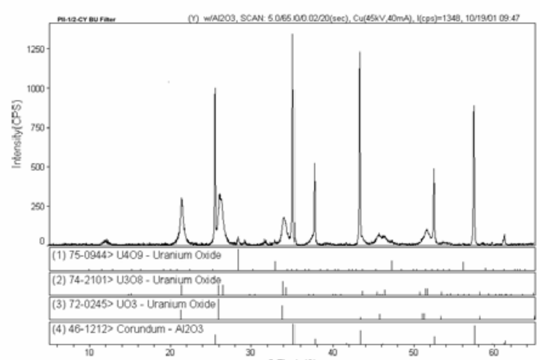
Cyclone Residues

Chemical Composition of Total Aerosol Mass

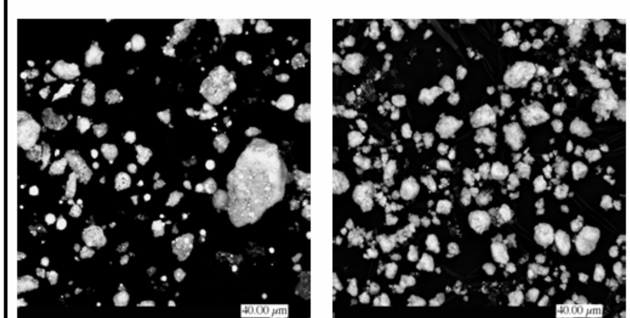
- **DU Concentration**
  - 38 to 54% in the Abrams BHT/hull, conventional armor
  - 43 to 72% in the Abrams BHT/turret shots, conventional armor
  - 60 to 72% in the Abrams BHT/turret shot, DU armor)
  - 18 to 29% in the Bradley BHT/passenger compartment shots
- **Other Metals Concentration**
  - Mostly aluminum and iron
  - Some titanium, zinc, and copper
  - Additional trace metals

DU Particle Composition and Morphology

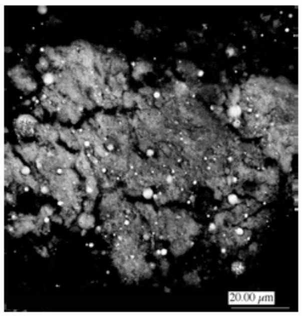
- **DU oxide using X Ray Diffraction**
  - Predominant phase was U_3O_8/UO_3 believed to be primarily hyperstoichiometric forms of U_3O_8
  - U_4O_9 also present especially in larger particles
  - A small amount of schoepite ($UO_3 \cdot 2H_2O$) found in several samples
- **Morphology examined using scanning electron microscopy**
- **Composition of individual particles analyzed using energy dispersive spectroscopy**

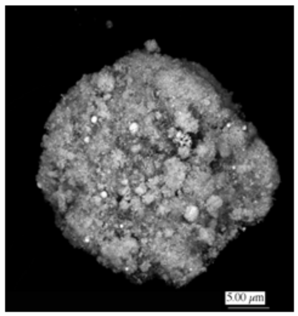


Stages 1 and 4 Distributions

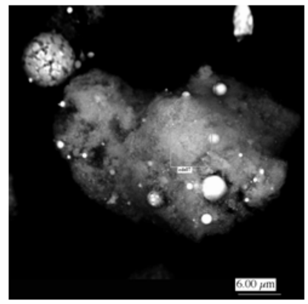


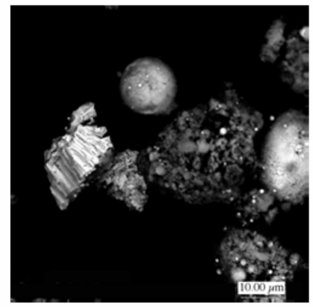
Typical U Aggregates



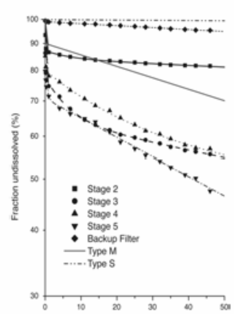


Less Dense Aggregates

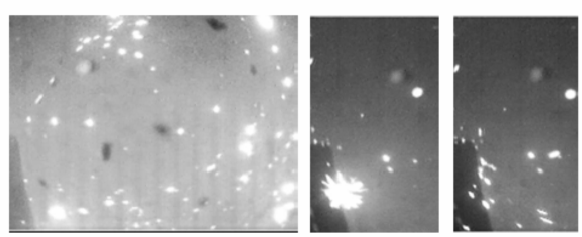




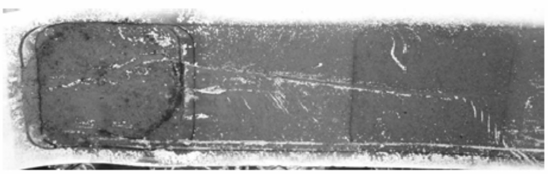
In Vitro Solubility in Simulated Lung Fluid



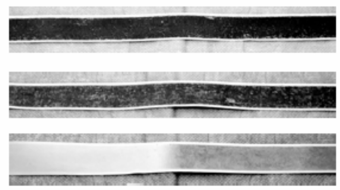
Transient Fireflies

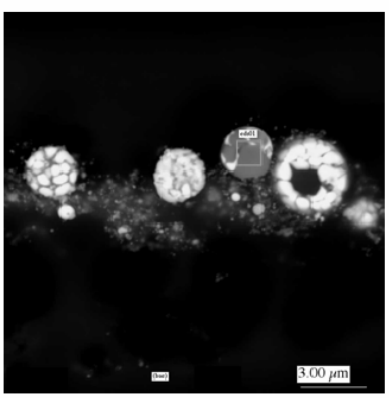


Moving Filter Residues—Discrete Interval Sampling



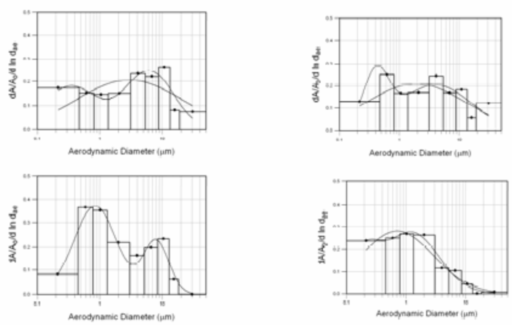
Moving Filter Residues—Continuous Time Sampling

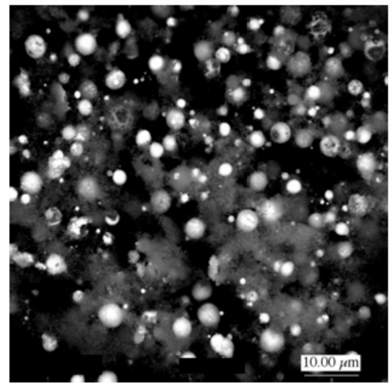




Example of Cascade Impactor Samples Collected: Respirability of Particles

AMAD Graphs: 10 sec, 1 min, 3 min, 33 min





General Characteristics of Particle Size Distributions

- **Particle size distributions changed as a function of time with larger particles settling out more quickly**

Exposure Categories for HHRA

- **Level I (modeling limited to the following)**
  - Personnel in vehicle at time of impact
  - First responders
- **Level II**
  - Personnel whose job functions require them to work in and around vehicles containing DU fragments and particles, usually within hours to few days
- **Level III**
  - Personnel with brief or incidental exposure
  - Includes those entering equipment, downwind of DU impacts and fires

Level I Scenario Development

- **Personnel in vehicle at time of impact**
- **First responders**
  - Stay-time in vehicle
  - Breathing rates
  - Type of breathing (nose/mouth)
  - Individuals' characteristics (Reference Man)
    - Respiratory tract (ICRP-66)
    - Bone (ICRP-70)
    - Other organs (ICRP-23, ICRP-89)

Summary of Level I, In-Vehicle Personnel Exposure Scenarios

Scenario	Time of Exposure	Exposure Duration	Breathing Rate
Crew Inside Vehicle			
A	From impact to exit 1 min post shot	1 min	3 m³/h
B	From impact to exit 5 min post shot	5 min	3 m³/h
C	From impact to exit 1 h post shot	1 h	3 m³/h for first 15 min, 1.5 m³/h thereafter
D	From impact to exit 2 h post shot	2 h	3 m³/h for first 15 min, 1.5 m³/h thereafter
First Responder			
E	Entry 5 min post shot, exit 10 min later	10 min	3 m³/h

Primary DU Aerosol Characteristics used in Intake and Dose Modeling

- **DU concentration as a function of time**
- **Particle size distribution as a function of time**
- ***In vitro* solubility as surrogate for dissolution and transfer of inhaled particles within human body**

Aerosol Concentration (Source Term)

- **DU Concentration over time (IOM)**
- **Particle-size distributions over time (CI)**
  - Also DU concentration
- **CI data selected**
  - IOM conc > CI stages summed conc
  - IOM conc > early time intervals (<10 min)
  - Larger particle sizes collected by IOMs
  - Adjustments for CI wall loss
  - Field blank adjustments to all time intervals except first

Inhalation Intakes

- **Time integral of aerosol concentration times the scenario breathing rate**
- **Statistical approaches**
  - Conventional approach
  - Bayesian approach

Median DU Intakes

Scenarios	Uranium Intake (mg)			
	Abrams Tank: Conventional Armor, No Ventilation	Abrams Tank: DU Armor, No Ventilation	Abrams Tank: DU Armor, EC/NBC Operating	Bradley Vehicle: Conventional Armor, No Ventilation
Most Likely				
A - Crew, exit in 1 min	280	250	10	83
B - Crew, exit in 5 min	590	710	43	220
E - First responders	160	200	27	99
Upper Bound				
C - Crew, exit in 1 h	760	970	91	330
D - Crew, exit in 2 h	780	1000	110	380

Dose Calculations

- **Dosimetry models**
  - HRTM (ICRP-66)
    - Deposition
    - Clearance (mechanical and absorption)
  - GI Tract (ICRP-30)
  - U systemic biokinetic (ICRP-78)
- **DU aerosol solubility in lung/extracelluar fluids**
  - *In vitro* solubility results rather than ICRP-66 defaults (Types F, M, S)

Quantities Calculated

- **Radiological quantities**
  - Committed effective dose – E(50)
    - ICRP-68 with modifications
      - Gonadal $H_T(50)$ – testes only
      - Thymus and uterus eliminated from remainder organs
      - No splitting applied – ET assigned w_T =0.025
  - Organ dose equivalents – $H_T(50)$
    - Lung, BS, ET, kidney, LN-TH, RM, Liver reported
- **Chemical concentration**
  - Peak kidney concentration

Median 50-yr Committed Effective Doses

Scenarios	E(50), rem			
	Abrams Tank: Conventional Armor, No Ventilation	Abrams Tank: DU Armor, No Ventilation	Abrams Tank: DU Armor, EC/NBC Operating	Bradley Vehicle: Conventional Armor, No Ventilation
Most Likely				
A - Crew, exit in 1 min	2.0	2.2	0.090	0.59
B - Crew, exit in 5 min	3.7	6.0	0.44	1.7
E - First responders	0.92	1.9	0.41	0.89
Upper Bound				
C - Crew, exit in 1 h	4.8	8.3	1.02	2.1
D - Crew, exit in 2 h	5.0	8.7	1.20	2.4

E(50) Relative to NRC Occupational Dose Limits

- Annual occupation TEDE limit is 5 rem (10 CFR 20).
- Although the E(50) is different from the TEDE, the concepts are similar, and for radiation protection purposes, can be compared (ICRP [60] 1991).
- The NRC's planned special exposure limit is 10 rem in a year (two times the annual limit, not to exceed five times the annual limit in a lifetime [10 CFR 20.1206]).
- Although the E(50)s exceed the occupational radiation limits for some scenarios, all E(50)s are less than the planned special exposure limit.
- For all scenarios modeled, radiation doses are at levels unlikely to cause adverse health effects.

Median 50-yr Committed Equivalent Doses to the Lung

Scenario	Lung $H_T(50)$, rem			
	Abrams Tank: Conventional Armor, No Ventilation	Abrams Tank: DU Armor, No Ventilation	Abrams Tank: DU Armor, EC/NBC Operating	Bradley Vehicle: Conventional Armor, No Ventilation
Most Likely				
A – Crew, exit in 1 min	14	18	0.66	5.2
B – Crew, exit in 5 min	32	44	3.3	14
E – First responders	8.8	14	3.1	6.7
Upper Bound				
C – Crew, exit in 1 h	38	60	7.6	20
D – Crew, exit in 2 h	39	61	8.7	22

$H_T(50)$ Relative to NRC Occupational Dose Limits

- Annual occupational radiation dose limits include a 50 rem committed dose equivalent (10 CFR 20).
- Although the HT(50) is different from the committed dose equivalent, the concepts are similar, and for radiation protection purposes, the two quantities can be compared (ICRP [60] 1991).
- Except for the case in which an Abrams tank was perforated through DU armor and the stay-time was 1 to 2 h, the predicted doses to the organs were less than this occupational limit.
- For all scenarios modeled, organ doses are at levels unlikely to cause adverse health effects.

Radiological Dose to Risk

- **ICRP-60/NCRP-115 approach**
- **Cancer mortality risk coefficients**
- **Summed organ risk approach (non-uniform irradiation)**

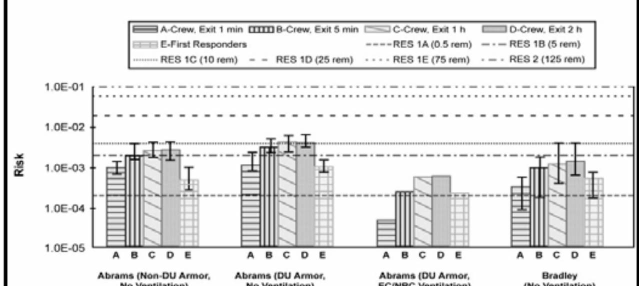
Median Lifetime Risk Increase of Fatal Cancer from DU Inhalation

Scenario	Lifetime Risk Increase of Fatal Cancer (%)			
	Abrams Tank: Conventional Armor, No Ventilation	Abrams Tank: DU Armor, No Ventilation	Abrams Tank: DU Armor, EC/NBC Operating	Bradley Vehicle: Conventional Armor, No Ventilation
Most Likely				
A – Crew, exit in 1 min	0.11	0.12	0.0049	0.034
B – Crew, exit in 5 min	0.20	0.32	0.025	0.099
E – First responders	0.050	0.10	0.023	0.052
Upper Bound				
C – Crew, Exit in 1 h	0.27	0.44	0.057	0.12
D – Crew, Exit in 2 h	0.28	0.45	0.065	0.14

Radiological Risk

- "Generic" lung cancer mortality risk coefficients were based on alpha emitters.
- Lifetime cancer mortality risks calculated using the Linear No-Threshold model of effect, thought to be protective of health.
- For rapid exits (1 min or less), the risks are slightly greater than the risks associated with the annual general population dose limit of 0.5 rem.
- For all vehicle types, the estimated risks at the 90th percentile are below or slightly exceed (by less than 10%) the risks associated with planned special exposures.
- Risks for first responders are below the risks associated with the occupational limit of 5 rem/yr.

Median Radiation Risks w/ 10th & 90th Percentiles for All Phases and Scenarios (Compared to Radiation Standards and Emergency Guidelines)



Development of a Risk Model

- **Goal: Predict the severity of renal effects following an acute exposure to uranium**
- **Methodology: Develop a model that was based upon documented renal effects in humans following acute uranium exposures, and the calculated kidney burdens**
  - **27 cases were selected**
  - **clinical symptoms or the biochemical indicators of renal dysfunction**
  - **peak renal concentrations of uranium in the kidneys**
    - Fisher *et al* (1990) [health effects in workers following an accidental exposure to uranium hexafluoride]
    - The Royal Society (2002) [renal effects occurring within a few days after acute uranium exposures]

Acute Human Exposures to Uranium

Intake Route (n)	Chemical Form	Intake (mg U)	Peak µg U/g kidney	Effect	Reference
Ingestion	Acetate	8500	100	+++	Pavlakis et al. 1996
Dermal	Nitrate	130	35	+++	Zhao and Zhao 1990
Inhalation	Tetrafluoride	920	10	++	Zhao and Zhao 1990
Injection (2)	Nitrate	11 -16	4 - 6	+	Luessenhop et al. 1958
Dermal	Nitrate	10	3	++	Butterworth 1955
Inhalation	Hexafluoride	24	2.5	+	Fisher et al. 1990a
Injection	Nitrate	5.9	2	+	Luessenhop et al. 1958
		5.5	2	-	
		4.3	1.5	-	
Inhalation (3)	Hexafluoride	40-50	1.2 - 4	+	Kathren and Moore 1986
Inhalation (7)	Hexafluoride	11 - 18	1.1 - 1.9	-	Fisher et al. 1990a
Ingestion	Nitrate	470	1	+	Butterworth 1955
Inhalation	Hexafluoride	20	1	-	Boback 1975
Inhalation (5)	Hexafluoride	6 - 8.7	0.62 - 0.9	-	Fisher et al. 1990a

Modified from the Royal Society, 2002

Renal Effects Groups (REGs)

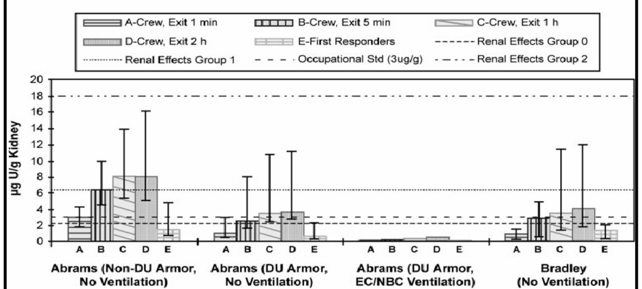
REG	Effects	D (range)	µg U/g kidney
0	No effect	≤ 0.0	≤ 2.2
1	Transient	> 0.0 – 2.0	> 2.2 – 6.4
2	Protracted	> 2.0 – 4.0	> 6.4 – 18
3	Severe	> 4.0	> 18

Median Peak Kidney Uranium Concentrations

Scenarios	Peak Kidney Uranium Concentrations (µg U/g Kidney)			
	Abrams Tank: Conventional Armor, No Ventilation	Abrams Tank: DU Armor, No Ventilation	Abrams Tank: DU Armor, EC/NBC Operating	Bradley Vehicle: Conventional Armor, No Ventilation
Most Likely				
A - Crew, exit in 1 min	3.0	1.1	0.05	1.0
B - Crew, exit in 5 min	6.4	2.6	0.23	2.9
E - First responders	1.5	0.67	0.14	1.4
Upper Bound				
C - Crew, exit in 1 h	8.2	3.5	0.46	3.5
D - Crew, exit in 2 h	8.0[a]	3.7	0.56	4.0

(a) The sampler data used to calculate Scenarios C and D differed slightly and was responsible for the lower dose for the longer exposure time.

HHRA Median Peak Kidney Burdens w/ 10th & 90th Percentiles for All Phases and Scenarios (Compared to Renal Effects Groups and Occupational Guideline)



DU Health Risks in Perspective

- ODS incidents involved crews of 6 Abrams tanks and 14 Bradley Fighting Vehicles—104 survived.
- Of those struck by DU fragments, most continue to be medically monitored. To date, no clinical symptoms of DU toxicity have been observed in this group.
- Crewmembers in these vehicles were exposed to DU oxide aerosols in addition to any DU fragments resulting from impact.
- Uranium is a much-studied material and its toxicity is relatively well known. Although some risk may exist, no compelling evidence from human epidemiologic studies associate natural or DU uranium with an increased cancer risk.

The Bottom Line—Radiological Effects

- For all vehicle configurations and modeled exposure times, except for the *unventilated* Abrams tank perforated through DU armor, predicted radiation doses were within U.S. (routine) occupational limits.
- For the *unventilated* Abrams tank perforated through DU armor, short exposures (about 1 min) were within routine occupational limits, and exposures up to 2 h were within the emergency or planned special exposure limits.
- ***For all vehicle configurations and exposure times modeled (up to 2 h), predicted radiation doses are not likely to cause adverse health effects.***

The Bottom Line—Toxicological Effects

- In the case of the *unventilated* Abrams tank perforated through conventional armor, the potential exists for short-term adverse kidney effects for exposures 5 min or longer.
- In all other cases, ***predicted uranium concentrations in the kidney are not likely to cause adverse chemically-induced health effects.***


CAPSTONE
Aerosols