Lecture 19: Biological Effects of Radiation

I. Radiation Chemistry

Interaction of Radiation with Matter:
Emphasis on effect of medium on incident radiation

Biological Effects of Radiation:
Emphasis on effect of radiation on medium

\[
dE/dx \propto AZ^2/E \quad \text{for charged particles}
\]
\[
dE/dx \propto \mu E_\gamma \quad \text{for photons}
\]

A. Chemical Species Formed in Medium

1. Cation-Electron Pairs
   a. Gases and Liquids \( \Rightarrow \) mobile ions – facilitates detection
      
      \[\text{e.g., } CH_4 \xrightarrow{hv} CH_4^+ + e^-\]
      
      biological systems: alters electrolyte balance

   b. Solids \( \Rightarrow \) trapped electrons and lattice defects
      modified conduction bands: impurities, Si bit upsets

2. Free Radicals
   Bond cleavage \[\text{CH}_4 \xrightarrow{hv} \text{CH}_3 + \text{H}\]
   a. Radioanalysis: Decomposition of compounds; esp. \( H_2O \), by radiation
      \[H_2O \rightarrow \text{H} + \text{OH}\]
      \[\text{OH} + \text{H} \rightarrow H_2 \quad \text{\{reducing agent\}}\]
      \[\text{Body mostly } H_2O\]
      \[\text{Body mostly } H_2O\]
      \[\text{Body mostly } H_2O\]

   b. Compounds
      \[C_xH_yO_z \xrightarrow{hv} \text{CO}, H_2O, H_2, \text{ etc.}\]
      recombinants may alter properties – negative or positive
      - Negative: biological alterations (DNA)
      - Positive: cross-linking of polymers (Cook, Inc.)

\[\text{can improve qualities of polymers}\]
3. **Excited Atoms and Molecules**

a. **Excitation**

<table>
<thead>
<tr>
<th>Excitation</th>
<th>Fluorescence</th>
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</table>

Resonance stabilization; aromatic hydrocarbons highly susceptible to excitation (good scintillators)

b. **Application**

Scintillation detectors (both liquid and solid)

Widely used in biochemistry and medical sciences for counting $^3$H, $^{14}$C, $^{32}$P

![Chemical structures]

- anthracene
- phenanthrene
- stilbene

and derivatives

**B. Radiation Dosimetry**

DOSE – Quantity of Radiation Exposure

1. **Rad** – Basic unit of radiation dose measurement

(Gray – SI unit) = Gy

a. **Definition:**

\[
1 \text{ rad} = 10^{-2} \text{ J/kg} \quad \text{of absorbed material} = 100 \text{ ergs/g} = \frac{\Delta E}{\text{mass}}
\]

\[
10^{-2} \text{ J} \quad \text{1 kg} \quad 1 \text{ eV} = 1.60 \times 10^{-19} \text{ J} \quad 1 \text{ Gy} = 1 \text{ J/kg} = 100 \text{ rads}
\]

(1) Charged particles

E = energy of particle if stopped

\( (dE/dx)(\Delta x) \) if transmitted
Photons
\[ \Delta E = \mu E_r/cm^2 \]

b. Example: A 2.0 g sample absorbs 1.0 \( \mu \) Ci of 100 keV electrons in 10.0 min. What is the dose in rads?

\[ \Delta E = (1.00 \times 10^5 eV)(1.60 \times 10^{-19} J/eV)(3.70 \times 10^4 dps)(600 s) \]

Energy/particle Number of particles
\[ \Delta E = 3.6 \times 10^{-7} J \]

Dose = \[ \frac{\Delta E}{\text{mass}} = \frac{3.6 \times 10^{-7} J}{2.0 \times 10^{-3} kg} \times \frac{kg}{10^{-3} J} = 1.8 \times 10^{-2} \text{ rads} = 18 \text{ mrad} = 1.8 \times 10^{-4} \text{ Gy} \]

2. Biologically Permissible Doses
   a. Depends on type of radiation
      - charged ions: \( dE/dx \) high; range low
      - \( \beta\pm \): \( dE/dx \) intermediate; same for range
      - \( \gamma \), n: low \( dE/dx \); long range
   b. Quality Factor (QF), or Relative Biological Effectiveness (RBE)

\[ \begin{align*}
\text{x-rays, } \gamma\text{-rays} &= 1 \\
\beta\pm &= 1 \\
\text{thermal neutrons} &= 5 \\
\text{fast neutrons} &= 10 \\
\text{protons} &= 1-10 \text{ (depending on energy)} \\
\text{\( \alpha \)'s} &= 1-20 \text{ (depending on energy)} \\
\text{heavy ions} (Z \geq 3) &= 20 \\
\text{or fission fragments} &
\end{align*} \]

TAKE UPPER LIMIT TO BE SAFE

c. Dose Equivalent
\[ \text{rem} = \text{rads} \times \text{QF} \]

We'll use these;

d. SI Unit: Sievert SV
\[ 1 \text{ SV} = 100 \text{ rems} = \text{Gray} \times \text{RBE} \]

Not these,

e. Previous Example: apply to other particles
\[
\begin{align*}
dose (e^-) &= 18 \text{ mrad} \times 1 = 18 \text{ mrem} \\
dose (\gamma) &= 18 \text{ mrad} \times 1 = 18 \text{ mrem} \\
dose (\text{slow n}) &= 18 \text{ mrad} \times 5 = 90 \text{ mrem} \\
dose (\text{fast n}) &= 18 \text{ mrad} \times 10 = 180 \text{ mrem} \\
dose (\alpha') &= 18 \text{ mrad} \times 20 = 360 \text{ mrem}
\end{align*}
\]

3. Radiation in the Environment

Basis for setting standards; easy to measure

a. Natural Average $\approx 360 \text{ mrem/y at sea level}$

Sources:

b. National Background
   - Cosmic rays:
     Altitude-dependent; increases with elevation
   - $^{40}K(87\text{Rb})$:
     Ubiquitous (and it's everywhere, too!)

   - U/Th and decay products (esp. Rn gas):
     Geology-dependent (Rockies, Sri Lanka, Brazil)

c. Anthropogenic
   - Medical and diagnostic
   - Fallout from nuclear weapons tests
   - Jet Travel (enhanced cosmic-ray exposure)
   - Nuclear applications: TV, smoke detectors, (Fiesta ware), cigarette smoke [archaic: Ra dial watches, shoe x-rays]

d. Dose Computation Table

CONCERNS ABOUT RADIATION MUST BE TAKEN IN THIS CONTEXT
Radiation is in every part of our lives. It occurs naturally in the earth and can reach us through cosmic rays from outer space. Radiation may also occur naturally in the water we drink or the soils in our backyard. It even exists in food, building materials, and in our own human bodies. Fill out the chart below to see how much radiation you receive in a year.

Cosmic radiation at sea level (from outer space)
What is the elevation (in feet) of your town? Idaho Falls 4736 feet
Up to 1000 (add 2 mrem) 1000-2000 (add 3 mrem) 2000-3000 (add 5 mrem) 3000-4000 (add 15 mrem)
4000-5000 (add 25 mrem) 5000-6000 (add 28 mrem) 6000-7000 (add 40 mrem) 7000-8000 (add 53 mrem)
above 8000 (add 70 mrem)

Terrestrial (from the ground):
What region of the US do you live in?
Gulf Coast (23 mrem) Atlantic Coast (23 mrem) The Colorado Plateau (90 mrem)
Elsewhere in the US (46 mrem)

Internal radiation (in your body):
From food and water, (e.g. potassium)
From air, (radon)

Do you wear a plutonium powered pacemaker? No (0 mrem) Yes (100 mrem)
Do you have porcelain crowns or false teeth? No (0 mrem) Yes (.07 mrem)

Travel Related Sources:
Add 1 for each 1000 miles traveled by jet this year:
Are X-ray luggage inspection machines used at your airport?
No (0 mrem) Yes (.022 mrem)
Do you use gas lantern mantles when camping? No (0 mrem) Yes (.003 mrem)

Miscellaneous Sources:
Weapons test fallout
Do you live in a stone, brick, or concrete building? No (0 mrem) Yes (7 mrem)
Do you wear a luminous wristwatch (LCD)? No (0 mrem) Yes (.06 mrem)
Do you watch TV? No (0 mrem) Yes (1 mrem)
Do you use a computer monitor? No (0 mrem) Yes (.1 mrem)
Do you have a smoke detector in your home? No (0 mrem) Yes (.008 mrem)
How many medical x-rays do you receive per year? (40 mrem each)
How many nuclear medical procedures do you receive per year?
(14 mrem each)
Do you live within 50 miles of a nuclear power plant?
No (0 mrem) Yes (.009 mrem)
Do you live within 50 miles of a coal fired power plant?
No (0 mrem) Yes (.03 mrem)

**TOTAL YEARLY DOSE (in mrem):**

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**In the United States, the annual average dose per person from all sources is about 360 mrem, but it isn’t uncommon for any of us to receive far more than that in a given year (largely due to medical procedures we may have done).**

American Nuclear Society Annual Radiation Dose Chart
4. **Exposure Limits**

   a. General Population: 500 mr/y
   b. Workers in Radiation-Related Fields
      (1) Periodic: 100 mr/week
      (2) Annually: 5 r/y
      (3) Lifetime: 5 \((N-18)r\) where \(N =\) age
   c. Previous Example: How long can one work with a 1.8 mr/min \(\beta^-\) source before using up the weekly limit?
     
     \[(\text{Time})(1.8 \text{ mr/min}) = 100 \text{ mr} \leq \text{LIMITING DOSE}\]
     
     \[\text{time} = 55 \text{ minutes}\]

5. **Dose Reduction**

   a. Attenuate with absorbers (good for \(\alpha, \beta\); less so for \(\gamma, n\)
   b. Geometry: (i.e., back away).
     
     \[
     \% \text{ exposure} = \frac{(\text{Area exposed})(100\%)}{4\pi R^2}, \text{where } R \text{ is distance from the source}
     \]

   Source

   \[\begin{array}{c}
   \bullet \quad R_1 \quad \longrightarrow \quad \bullet \quad \longrightarrow \quad \bullet \\
   \text{Dose (2)} = \frac{\text{Area} / 4\pi R_2}{\text{Area} / 4\pi R_1}, \left(\frac{R_1}{R_2}\right)^2
   \end{array}\]

   i.e., exposure decreases as the square of the separation distance

   c. Earlier Problem:
   If the dose rate of 1.8 mr/min is measured at 20.0 cm, what will the dose rate be at a distance of 40.0 cm?

   \[
   \frac{\text{Dose (40 cm)}}{\text{Dose (20 cm)}} = \frac{(20)^2}{(40)^2} = \frac{1}{4}
   \]
Dose (40 cm) = \frac{1}{4} (1.8 \text{ mr/min}) = 0.45 \text{ mr/min}

6. Radiation Dose Monitoring

a. Dosimeter: Device for measuring total integrated doses;
   depends on calibrated, radiation-sensitive chemical reaction (redox)
   \[
   \begin{align*}
   \text{H}_2\text{O} & \xrightarrow[\text{hv}]{} \text{H}_2\text{O}_2 \\
   \text{Fe}^{2+}(aq) & \xrightarrow[\text{hv}]{} \text{Fe}^{3+}(aq)
   \end{align*}
   \]
   \text{instantaneous, but integral}

b. Film Badge: Integrated dose for long-term monitoring; x-ray film;
   Boron-loaded for neutron sensitivity.
   integral, requires processing

c. Survey Meter – differential, instantaneous, audio, doesn't integrate

d. Common sense

C. Biological Effects of Radiation

   Depends on:

   1. Properties of Radiation
      - QF
      - Energy – E, dE/dx, \mu E_\gamma
      - Amount –dN/dt
      - Half-life – t_{1/2}

   2. Nature of Exposure
      a. External – burns (esp. uv); skin cancer; extremities vs. torso; SF and \alpha
         negligible (air stops); \gamma, \beta, n penetrate
b. Internal
Ingestion, Inhalation; all types dangerous, esp. $\alpha$ (large $dE/dx$)
Depends on:
(1) Rate of Excretion (e.g. $18 \ y \ 244\text{Cm}$)

(2) Biological Distribution: concentrated or dispersed?
e.g., $^{131}\text{I} \rightarrow$ thyroid ; $^{90}\text{Sr} \rightarrow$ bones ; $^{40}\text{K} \rightarrow$ all body fluids

(3) Biological Susceptibility; genetic differences (e.g., suntans)

D. Clinical Effects: High Levels
1. Somatic vs. Genetic Effects
a. Somatic Effects: Damage to individual irradiated (including fetus in case of pregnancy).
   Short Term – fatal if large enough
   Long Term – positive correlation with leukemia and skin cancer;
   slight(very) negative correlation with other cancer types

b. Genetic Effects: Alterations to genetic material that are transferred to later generations ; DNA alteration
   Hiroshima – Nagasaki survivors – no evidence to support

2. Symptoms: Function of Dose and Dose Rate
a. Leukopenia: serious deficiency of leucocytes in blood; leucocytes maintain the immune system.
   b. $\text{LD}_{50} = 450 \text{ rem}$ ; Exposure time $\lesssim 1 \text{ day}$
      $\text{LD} = \text{lethal dose}$: dose at which 50% of people will die in a few months

3. Hiroshima – Nagasaki
   a. Most deaths caused by fire, not radiation
BIOLOGICAL EFFECTS OF RADIATION

Large Doses

Short Term

Long Term

Small Doses ~ 100 mrem/year

Difficult to assess

Statistics

Radiation Hormesis

Risk Estimates
b. Leukemia statistics confirmed

c. No evidence for genetic effects in 2\textsuperscript{nd} and 3\textsuperscript{rd} generations

d. Correlations

II. Risk Estimates: Dangers of LOW LEVELS of Radiation

A. Fatality Estimates

1. Case: Add 100 mr to average annual exposure for general population
   a. Equivalent to: > 100-fold increase in nuclear power generation spending the entire year in Vail, CO;
      
      << one thermonuclear explosion

   b. Model estimates of death rate due to 100 mr/yr increase:
      
      \begin{align*}
      \text{Absolute risk method: } & \sim 1500 /\text{yr} \\
      \text{Relative risk method: } & \sim 8300 /\text{yr}
      \end{align*}

      delay time \sim 20 \text{ yr}

2. Environmental Factors
   a. Example: CO – <\text{bkg}> \sim 500 mr/yr; cancer rate 46/50
      \(50 = \text{lowest}\)

      \[ \text{PA} – <\text{bkg}. \sim 360 \text{ mr/yr}; \text{ cancer rate 10/50} \]
      \(1 = \text{highest}\)

      Points out synergistic effects due to air and water quality

   b. Kerala Coast (West India): <\text{bkg}> \sim 1–1.5 r/yr. (Th in soil)
      cancer rates normal

      Swiss Alpine villages – same effect

3. Radiation Hormesis

   Theory that small amounts of radiation are beneficial; Mechanism: radiation damage stimulates immune system, leaves the body better prepared to deal with invading organisms.
B. Statistical Significance and the Press

1. Utah: "epidemiological studies show leukemia rates 50% higher downstream from 1950's test site"
   Actual numbers:
   cases reported: 29 (± 5.4)
   cases expected: 19 (± 4.4) \{ i.e., identical at 67% confidence level. \\

In addition, same population sample experienced lower than normal incidence of other types of cancer. Net cancer rate effect ~0

2. Recent reports of “unethical experiments with radiation in the 40's and 50's." Certainly true by today's standards, but concerns for nuclear war created need to know what to expect.

3. Electromagnetic radiation: 36,000 electrical workers in southern California – normal cancer rates; similar Swedish study – same result

C. Relative Risks in Context
1. Major causes of death due to cancer
2. Total risk tables
Hiroshima-Nagasaki Survivor Leukemia Statistics
(18 year study)

<table>
<thead>
<tr>
<th>Dose (rems)</th>
<th>No of Cases</th>
<th>Deaths</th>
<th>Person-Yrs ÷ 1000</th>
<th>Rate (per $10^5$ p-yrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 +</td>
<td>1460</td>
<td>22</td>
<td>26.7</td>
<td>81.6</td>
</tr>
<tr>
<td>100-199</td>
<td>1677</td>
<td>10</td>
<td>30.2</td>
<td>33.1</td>
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<tr>
<td>50-99</td>
<td>2665</td>
<td>7</td>
<td>48.3</td>
<td>14.5</td>
</tr>
<tr>
<td>10-49</td>
<td>10,707</td>
<td>17</td>
<td>195.4</td>
<td>8.7</td>
</tr>
<tr>
<td>0-9</td>
<td>43,830</td>
<td>34</td>
<td>795.6</td>
<td>4.3</td>
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</table>

$LD_{50} = 450$ rem
No detectable genetic effects
## Clinical Effects of High-Level Radiation

<table>
<thead>
<tr>
<th>Subclinical Dose (rems)</th>
<th>Therapeutic Dose</th>
<th>Lethal Dose</th>
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<tr>
<td>0-100</td>
<td>200 – 600</td>
<td>1000 – 5000</td>
</tr>
<tr>
<td>100 – 200</td>
<td>600 – 1000</td>
<td>&gt; 5000</td>
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<tr>
<td>200</td>
<td></td>
<td>5000</td>
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<table>
<thead>
<tr>
<th>Symptoms</th>
<th>Critical Period</th>
<th>Therapy</th>
<th>Prognosis</th>
<th>Recovery Time</th>
<th>Death Rate</th>
<th>Prognosis</th>
<th>Recovery Time</th>
<th>Death Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>none</td>
<td>none</td>
<td>7 Reassurance; surveillance</td>
<td>Good</td>
<td>1-12 mo.</td>
<td>none</td>
<td>Excellent</td>
<td>—</td>
<td>none</td>
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<tr>
<td>leukopenia</td>
<td>none</td>
<td>6 Bone marrow transplant</td>
<td>Guarded</td>
<td>long</td>
<td>none</td>
<td>Good</td>
<td>1-12 mo.</td>
<td>none</td>
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<tr>
<td>hemorrhage</td>
<td>4-6 weeks</td>
<td>Blood transfusions; balance electrolytes</td>
<td>Unfavorable</td>
<td>rare</td>
<td>90 - 100%</td>
<td>Guarded</td>
<td>1-12 mo.</td>
<td>90 - 100%</td>
</tr>
<tr>
<td>infection</td>
<td></td>
<td>Balance</td>
<td></td>
<td></td>
<td>90 - 100%</td>
<td>Unfavorable</td>
<td></td>
<td>90 - 100%</td>
</tr>
<tr>
<td>Diarrhea</td>
<td>5-14 days</td>
<td>Sedation</td>
<td></td>
<td></td>
<td>90 - 100%</td>
<td>Unfavorable</td>
<td></td>
<td>90 - 100%</td>
</tr>
<tr>
<td>Convulsions</td>
<td></td>
<td>electrolytes</td>
<td></td>
<td></td>
<td>90 - 100%</td>
<td>Unfavorable</td>
<td></td>
<td>90 - 100%</td>
</tr>
<tr>
<td>fever</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>90 - 100%</td>
<td>Unfavorable</td>
<td></td>
<td>90 - 100%</td>
</tr>
<tr>
<td>electrolyte imbalance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>90 - 100%</td>
<td>Unfavorable</td>
<td></td>
<td>90 - 100%</td>
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<table>
<thead>
<tr>
<th>Prognosis</th>
<th>Recovery Time</th>
<th>Death Rate</th>
</tr>
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<tbody>
<tr>
<td>Excellent</td>
<td>—</td>
<td>none</td>
</tr>
<tr>
<td>Good</td>
<td>1-12 mo.</td>
<td>none</td>
</tr>
<tr>
<td>Guarded</td>
<td>1-12 mo.</td>
<td>none</td>
</tr>
<tr>
<td>Unfavorable</td>
<td></td>
<td>90 - 100%</td>
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<table>
<thead>
<tr>
<th>Recovery Time</th>
<th>Death Rate</th>
</tr>
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<tbody>
<tr>
<td>2 wk</td>
<td>2 D</td>
</tr>
<tr>
<td>2 mo.</td>
<td>2 mo.</td>
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<tr>
<td>RISK FACTOR</td>
<td>ANNUAL DEATHS*</td>
</tr>
<tr>
<td>---------------------------</td>
<td>----------------</td>
</tr>
<tr>
<td>Smoking (1E)</td>
<td>434,000</td>
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<tr>
<td>Alcohol</td>
<td>105,000</td>
</tr>
<tr>
<td>Secondary Smoke</td>
<td>53,000</td>
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<tr>
<td>Motor Vehicles</td>
<td>49,000</td>
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<tr>
<td>AIDS</td>
<td>31,000</td>
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<tr>
<td>Homicides</td>
<td>22,000</td>
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<tr>
<td>Electric Power</td>
<td>14,000</td>
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<tr>
<td>Cocaine/Crack</td>
<td>3,300</td>
</tr>
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<td>Motorcycles</td>
<td>3,000</td>
</tr>
<tr>
<td>Swimming</td>
<td>3,000</td>
</tr>
<tr>
<td>Surgery</td>
<td>2,800</td>
</tr>
<tr>
<td>Heroin/Morphine</td>
<td>2,400</td>
</tr>
<tr>
<td>x-rays</td>
<td>2,300</td>
</tr>
<tr>
<td>Railroads</td>
<td>1,900</td>
</tr>
<tr>
<td>Aviation (not commercial)</td>
<td>1,400</td>
</tr>
<tr>
<td>Large Construction</td>
<td>1,000</td>
</tr>
<tr>
<td>Bicycles</td>
<td>1,000</td>
</tr>
<tr>
<td>Hunting</td>
<td>800</td>
</tr>
<tr>
<td></td>
<td>:</td>
</tr>
<tr>
<td>Nuclear Power</td>
<td>100</td>
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<td></td>
<td>:</td>
</tr>
<tr>
<td>Skiing</td>
<td>20</td>
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</tbody>
</table>

*Sources: US Center for Disease Control; National Safety Council, National Center for Health Statistics; Insurance Actuarial Tables
National Policy Statements

95.2 STATEMENT ON POWER LINE FIELDS AND PUBLIC HEALTH

(Adopted by Council 23 April 1995)

Physicists are frequently asked to comment on the potential dangers of cancer from electromagnetic fields that emanate from common power lines and electrical appliances. While recognizing that the connection between power line fields and cancer is an area of continuing study by research workers in many disciplines in the United States and abroad, we believe that it is possible to make several observations based on the scientific evidence at this time. We also believe that, in the interest of making the best use of the finite resources available for environmental research and mitigation, it is important for professional organizations to comment on this issue.

The scientific literature and the reports of reviews by other panels show no consistent, significant link between cancer and power line fields. This literature includes epidemiological studies, research on biological systems, and analyses of theoretical interaction mechanisms. No plausible biophysical mechanisms for the systematic initiation or promotion of cancer by these power line fields have been identified. Furthermore, the preponderance of the epidemiological and biophysical/biological research findings have failed to substantiate those studies which have reported specific adverse health effects from exposure to such fields. While it is impossible to prove that no deleterious health effects occur from exposure to any environmental factor, it is necessary to demonstrate a consistent, significant, and causal relationship before one can conclude that such effects do occur. From this standpoint, the conjectures relating cancer to power line fields have not been scientifically substantiated.

These unsubstantiated claims, however, have generated fears of power lines in some communities, leading to expensive mitigation efforts, and, in some cases, to lengthy and divisive court proceedings. The costs of mitigation and litigation relating to the power line cancer connection have risen into the billions of dollars and threaten to go much higher. The diversion of these resources to eliminate a threat which has no persuasive scientific basis is disturbing to us. More serious environmental problems are neglected for lack of funding and public attention, and the burden of cost placed on the American public is incommensurate with the risk, if any.