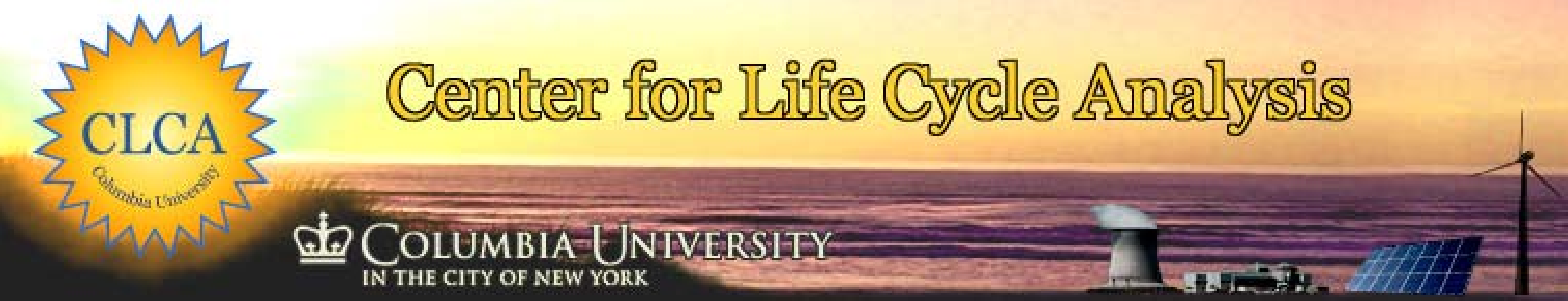

Photovoltaics
Life Cycle Analysis

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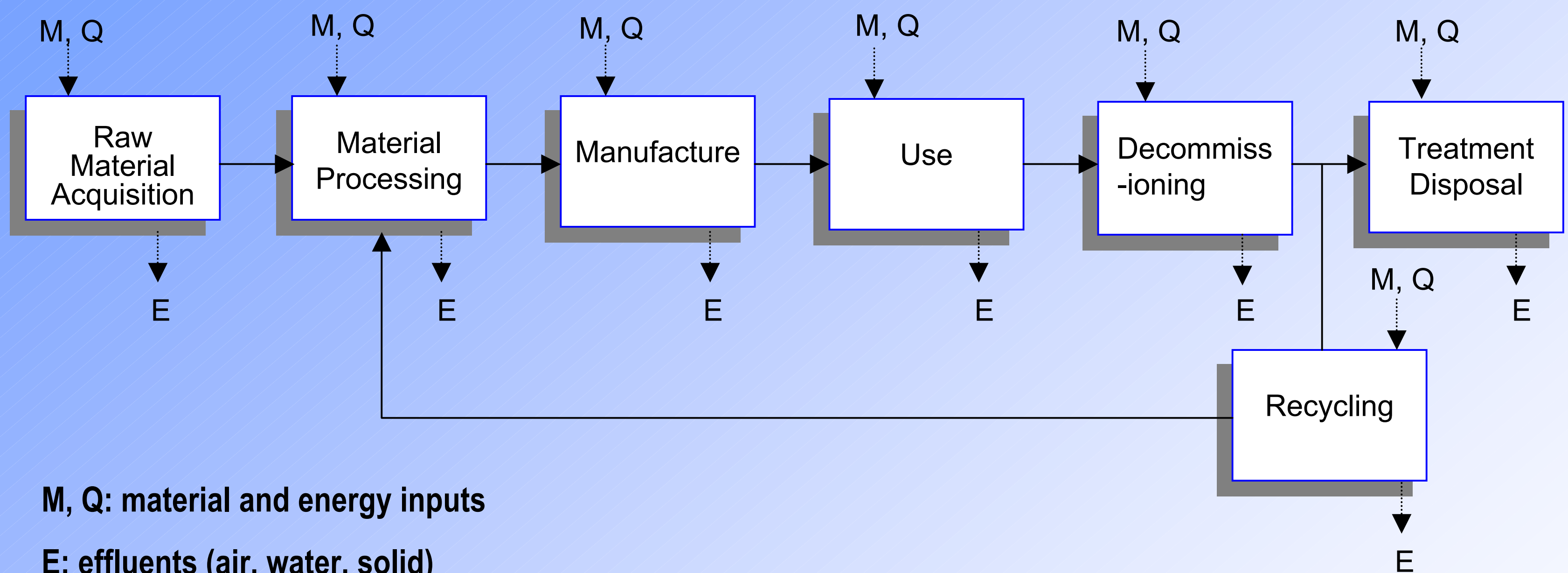
BROOKHAVEN NATIONAL LABORATORY

The Life Cycle of PV



Photovoltaic modules

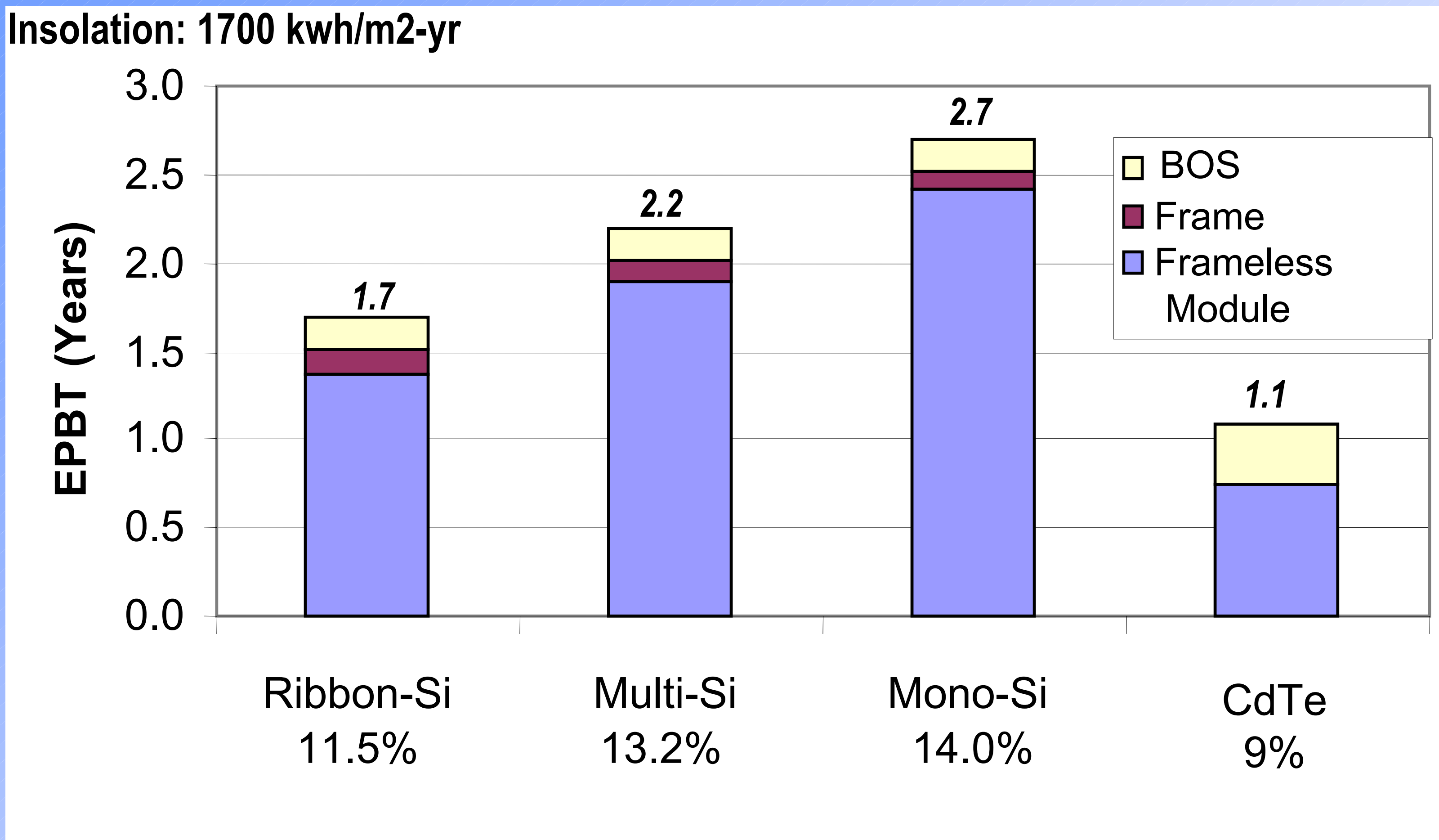
Balance of System (BOS)
(Inverters, Transformers, Frames, Metal and Concrete Supports)

Sample Metrics of Life-Cycle Performance

- Energy Payback Times (EPBT)
- Greenhouse Gas Emissions (GHG)
- Toxic Gases & Heavy Metal Emissions
- Risk Indicators

Energy Payback Times (EPBT)

2004-2005 Status: Crystal Clear & BNL Studies



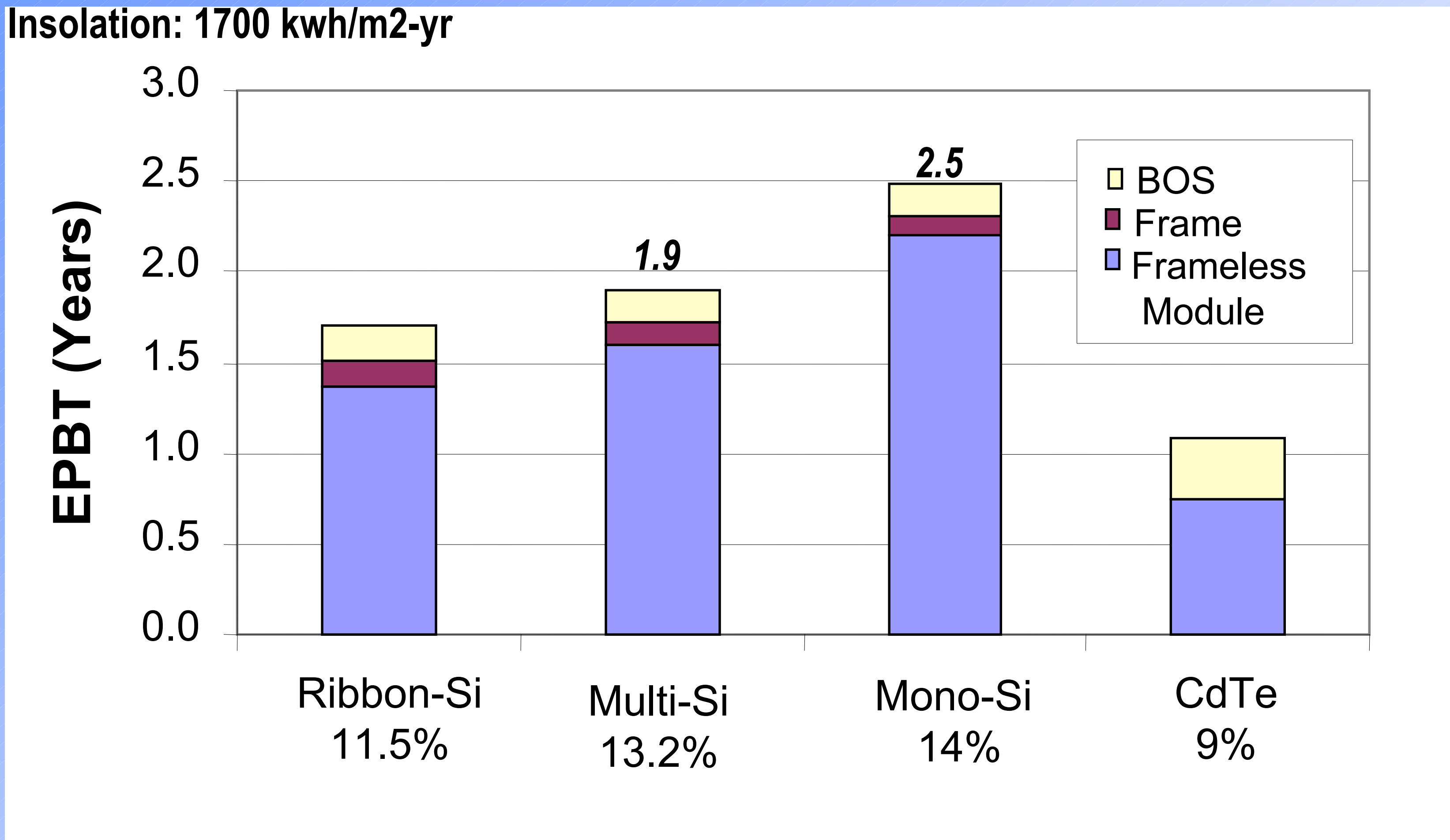
-Alsema & de Wild, *Material Research Society, Symposium vol. 895, 73, 2006*

-deWild & Alsema, *Material Research Society, Symposium vol. 895, 59, 2006*

-Fthenakis & Kim, *Material Research Society, Symposium vol. 895, 83, 2006*

-Fthenakis & Alsema, *Progress in Photovoltaics, 14, 275, 2006*

Energy Payback Times
Effect of Si Slurry Recycling

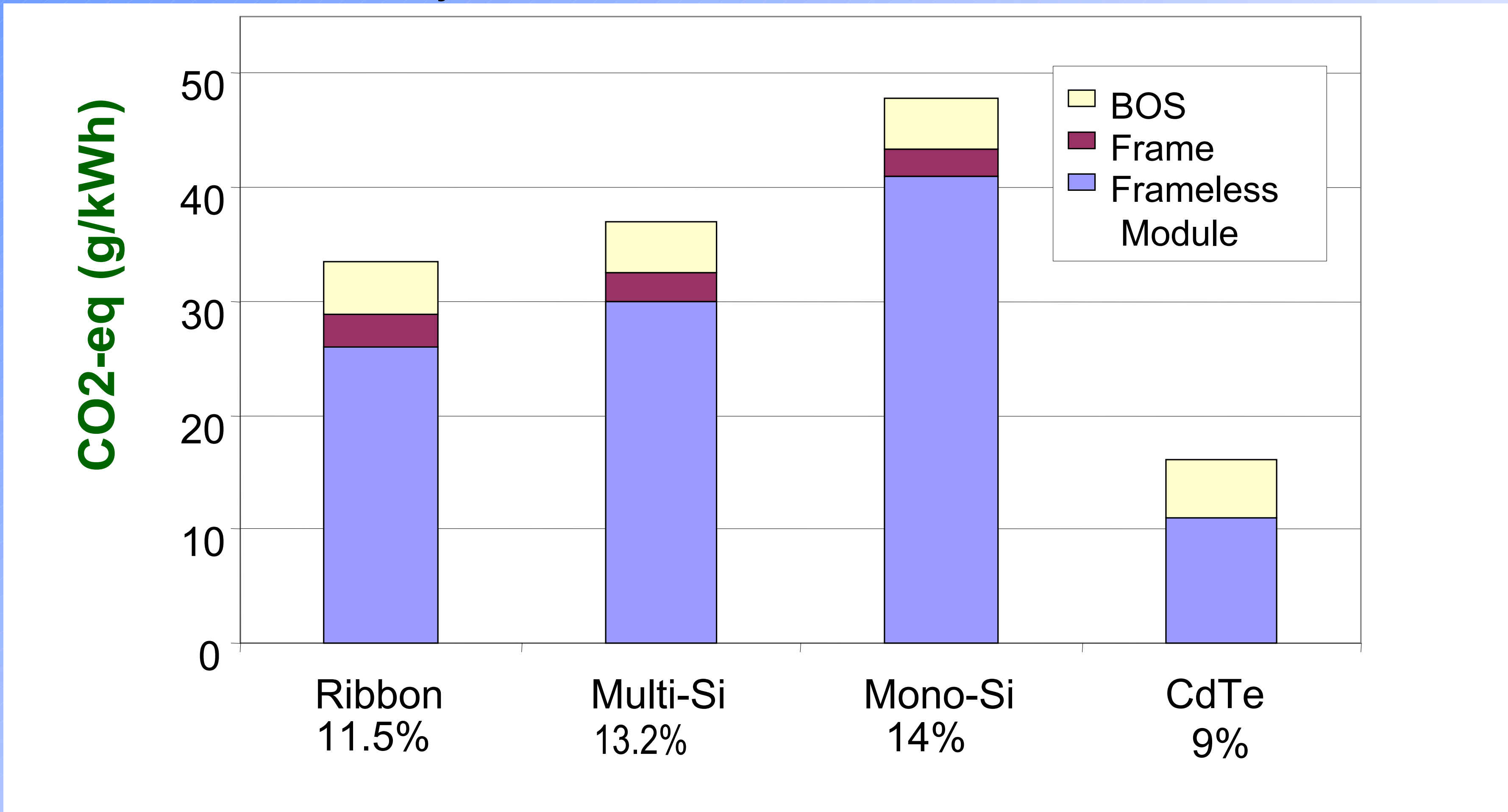


-Alsema , de Wild & Fthenakis, ***21st EU-PV Conference,*** *Aug., 2006*

-**Fthenakis & Alsema,** *Progress in Photovoltaics, 14, 275, 2006*

Life Cycle GHG Emissions –Europe

Insolation: 1700 kwh/m2-yr



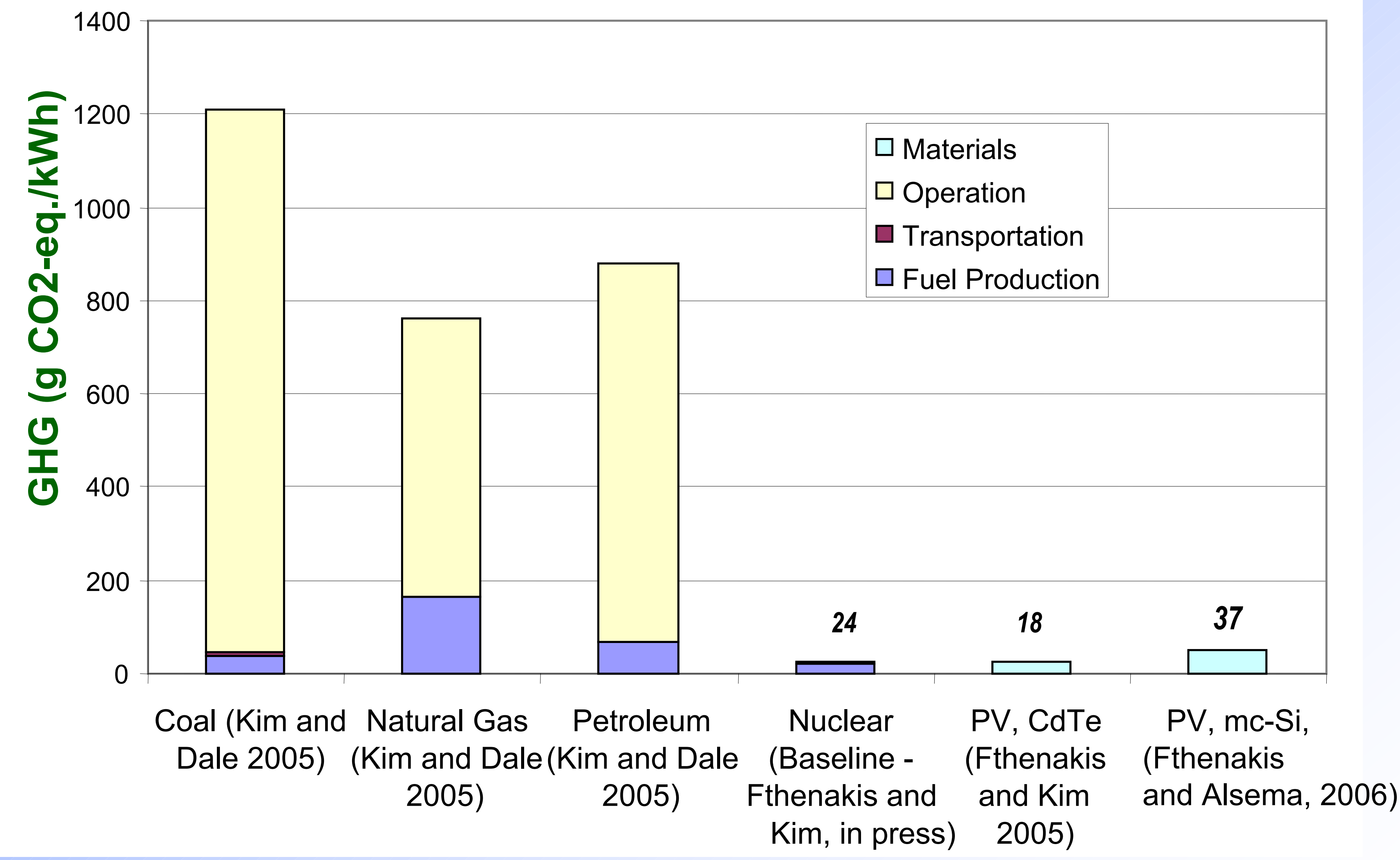
Alsema & de Wild, *Material Research Society, Symposium vol. 895, 73, 2006*

deWild & Alsema, *Material Research Society, Symposium vol. 895, 59, 2006*

Fthenakis & Kim, *Material Research Society, Symposium vol. 895, 83, 2006*

Fthenakis & Alsema, *Progress in Photovoltaics, Accelerated Publication, 14, 275, 2006*

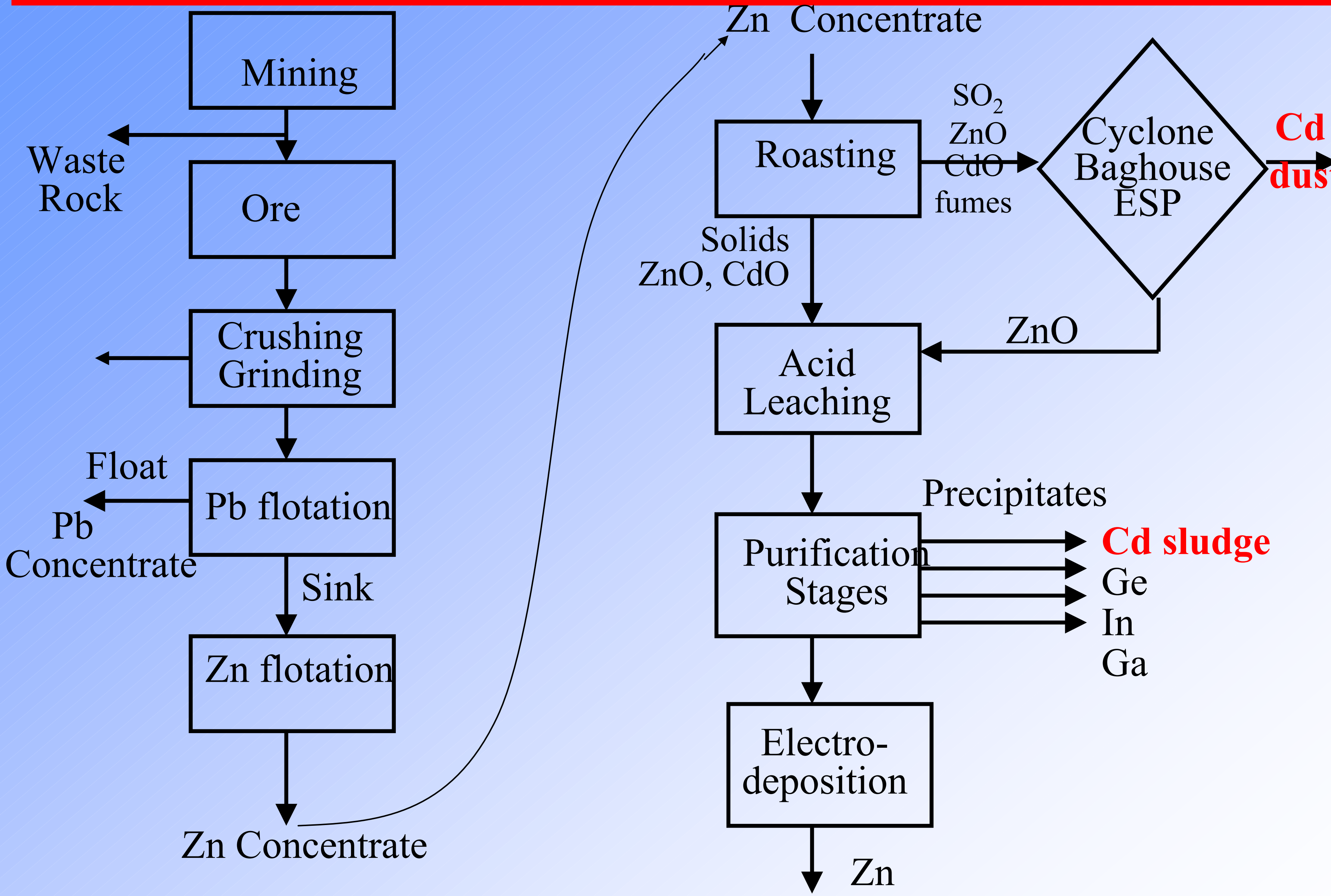
Life Cycle GHG Emissions
–Comparison with Conventional Technologies



Emissions of Heavy Metals -Focus on Cadmium from CdTe PV

1. Mining/Smelting/Refining
2. Purification of Cd & Production of CdTe
3. Manufacture of CdTe PV modules
4. Utilization of CdTe PV modules
5. Disposal of spent CdTe PV modules

Stage 1. Cd Flows in Zn Mining, Smelting & Refining



Fthenakis and Wang., Emission Factors in the Production of Materials Used in Photovoltaics, ***20th EURPVSEC****, 8BO.5.2 , 2005*

Stage 4. Operation of CdTe PV Modules

- **Zero emissions under normal conditions**

  (testing in thermal cycles of –80 C to +80 C)

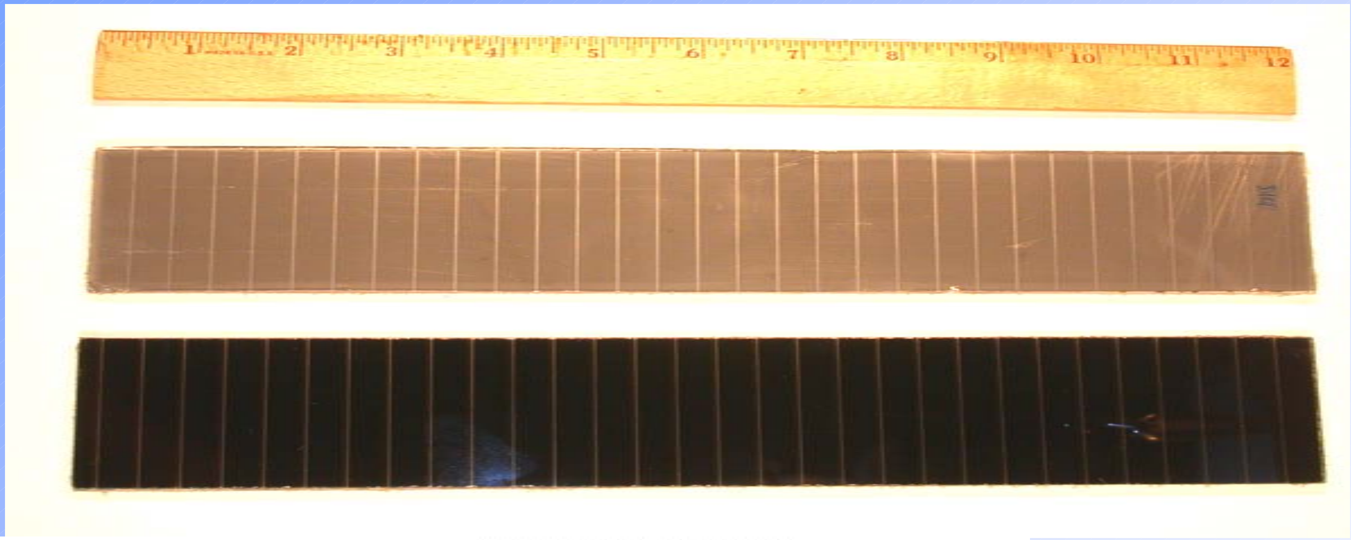
- **No leaching during rain from broken or degraded modules**

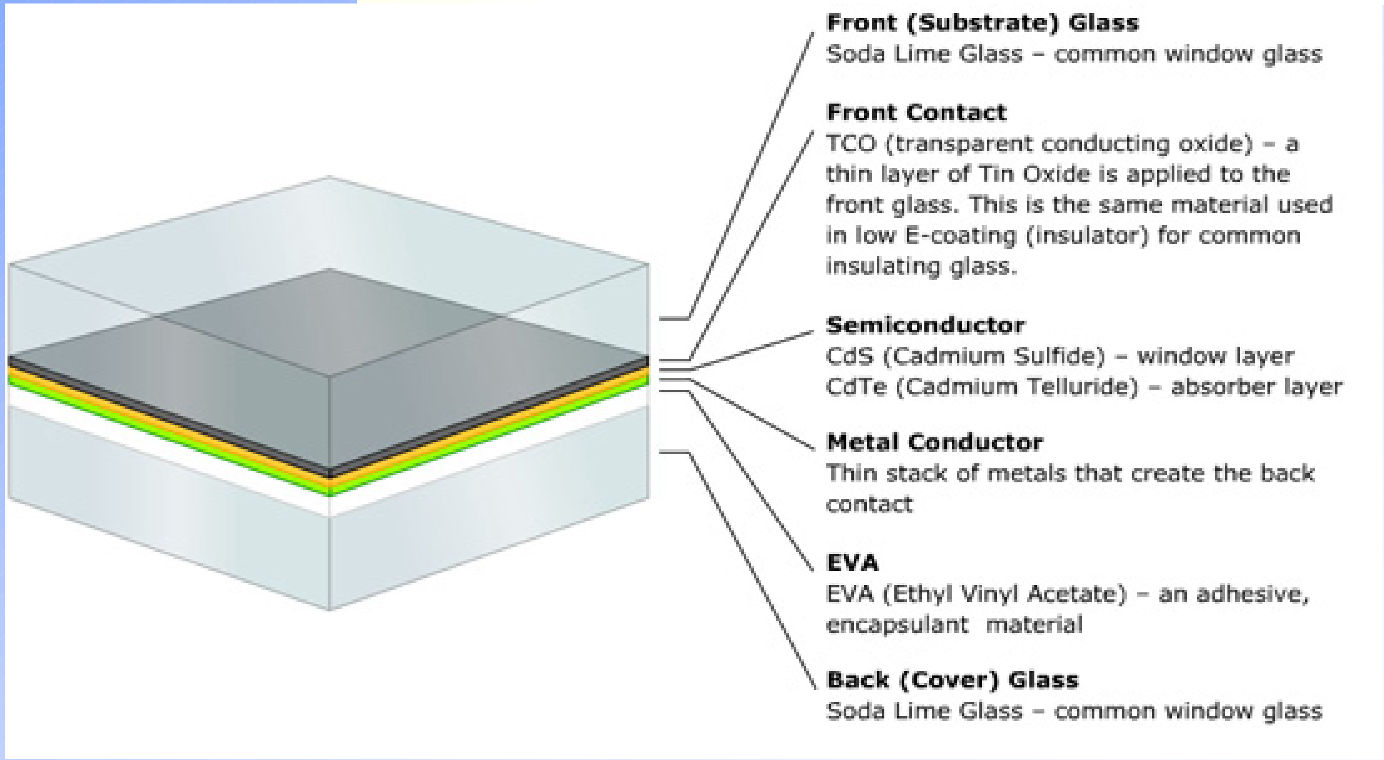
  Steinberger, Progress in Photovoltaics, 1997

- **Negligible emissions during fires**

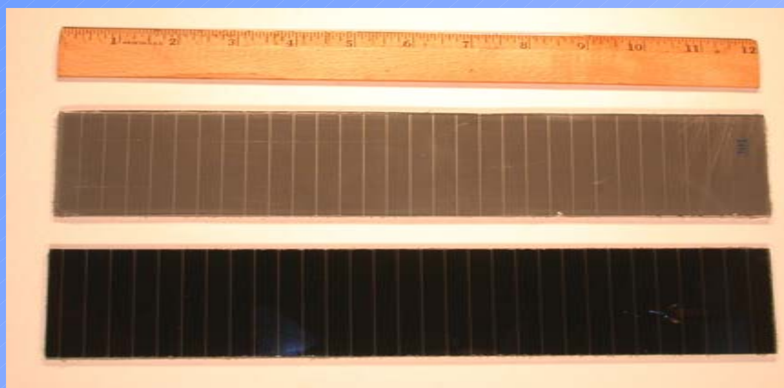
  Fthenakis, Fuhrman, Heiser, Lanzirotti, Fitts and Wang, Progress in Photovoltaics, 2005

CdTe PV sample for Fire-simulation Experiments





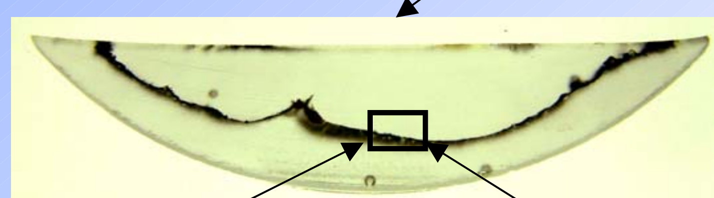
CdTe PV Fire-Simulation Tests: XRF Analysis

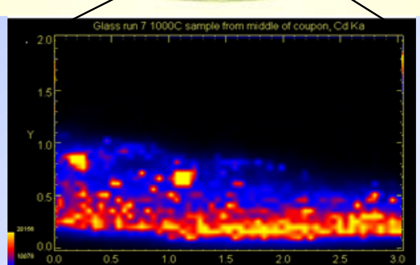


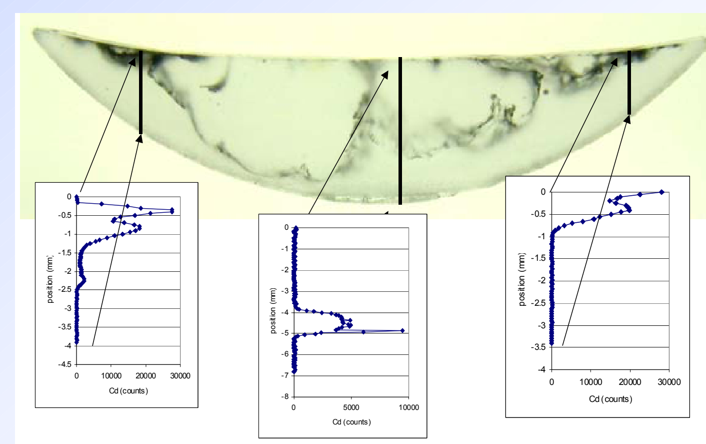
Heat

XRF-micro-spectroscopy -Cd Mapping in PV Glass
1000 °C, Section taken from middle of sample

XRF-micro-probing –
Cd Distribution in PV Glass
1000 °C, right end of sample

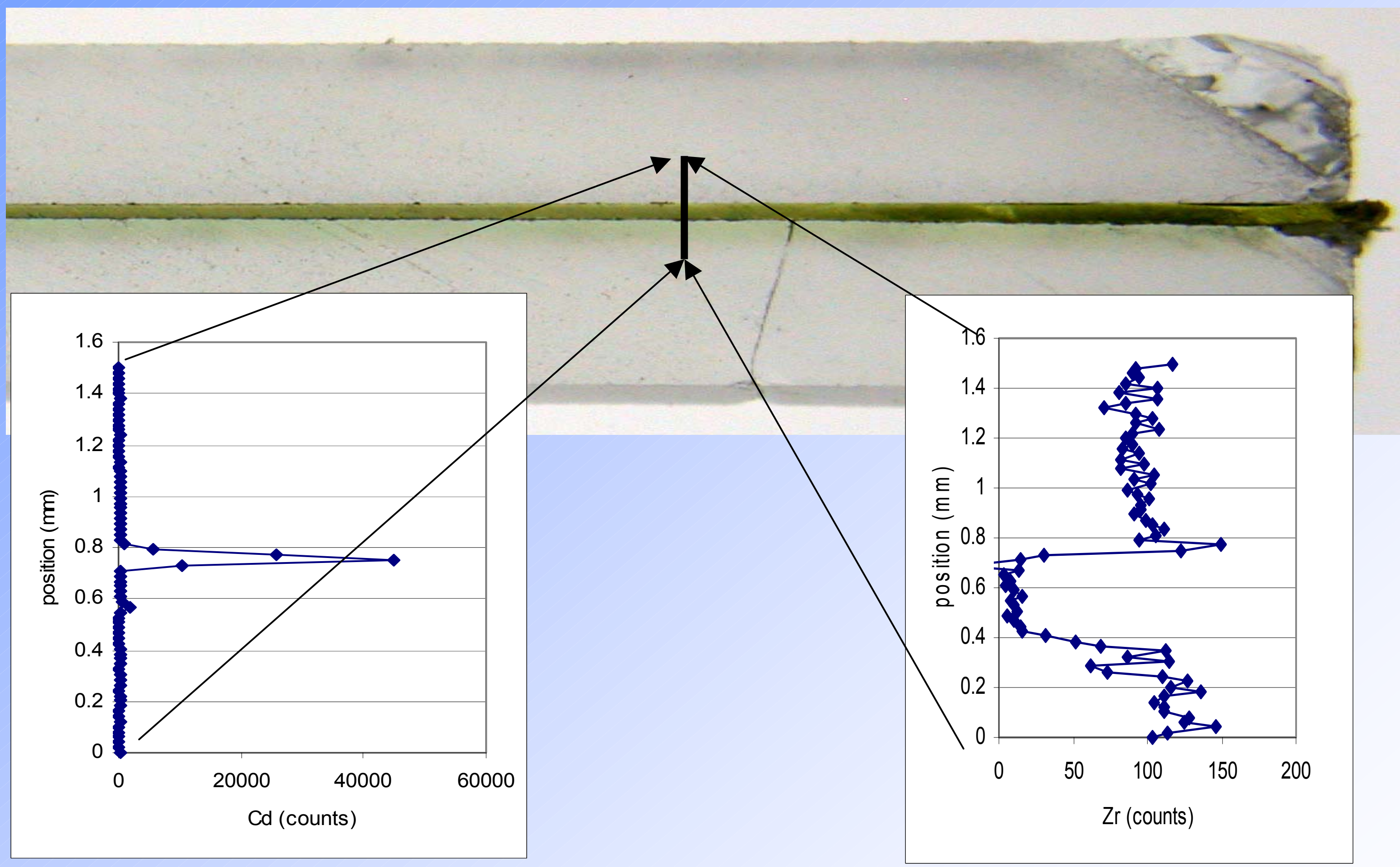




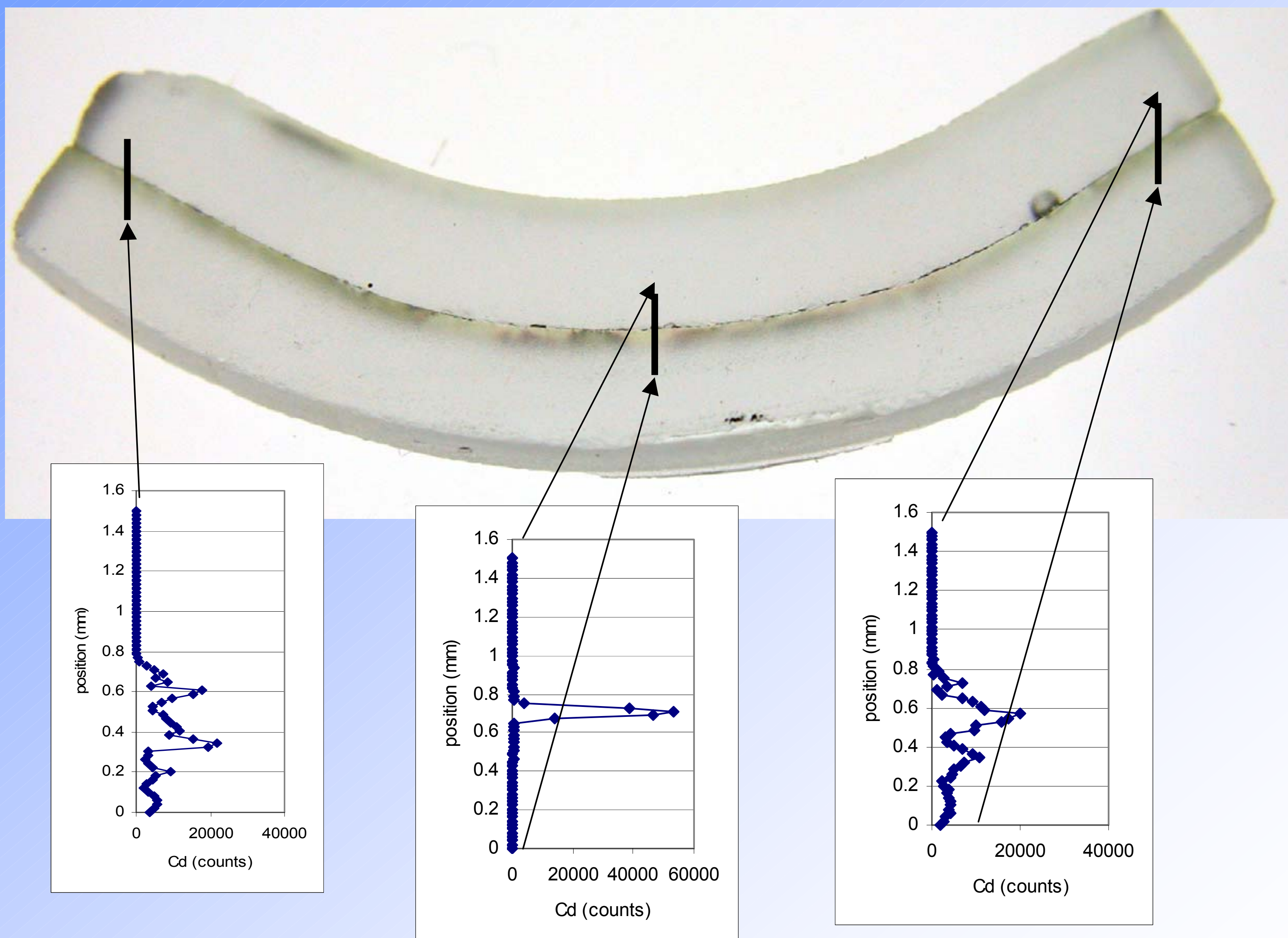


Fthenakis, Fuhrman, Heiser, Lanzirotti, Fitts and Wang, ***Progress in Photovoltaics***, *2005*

XRF-micro-probing -Cd & Zr Distribution in PV Glass Unheated Sample -Vertical Cross Section

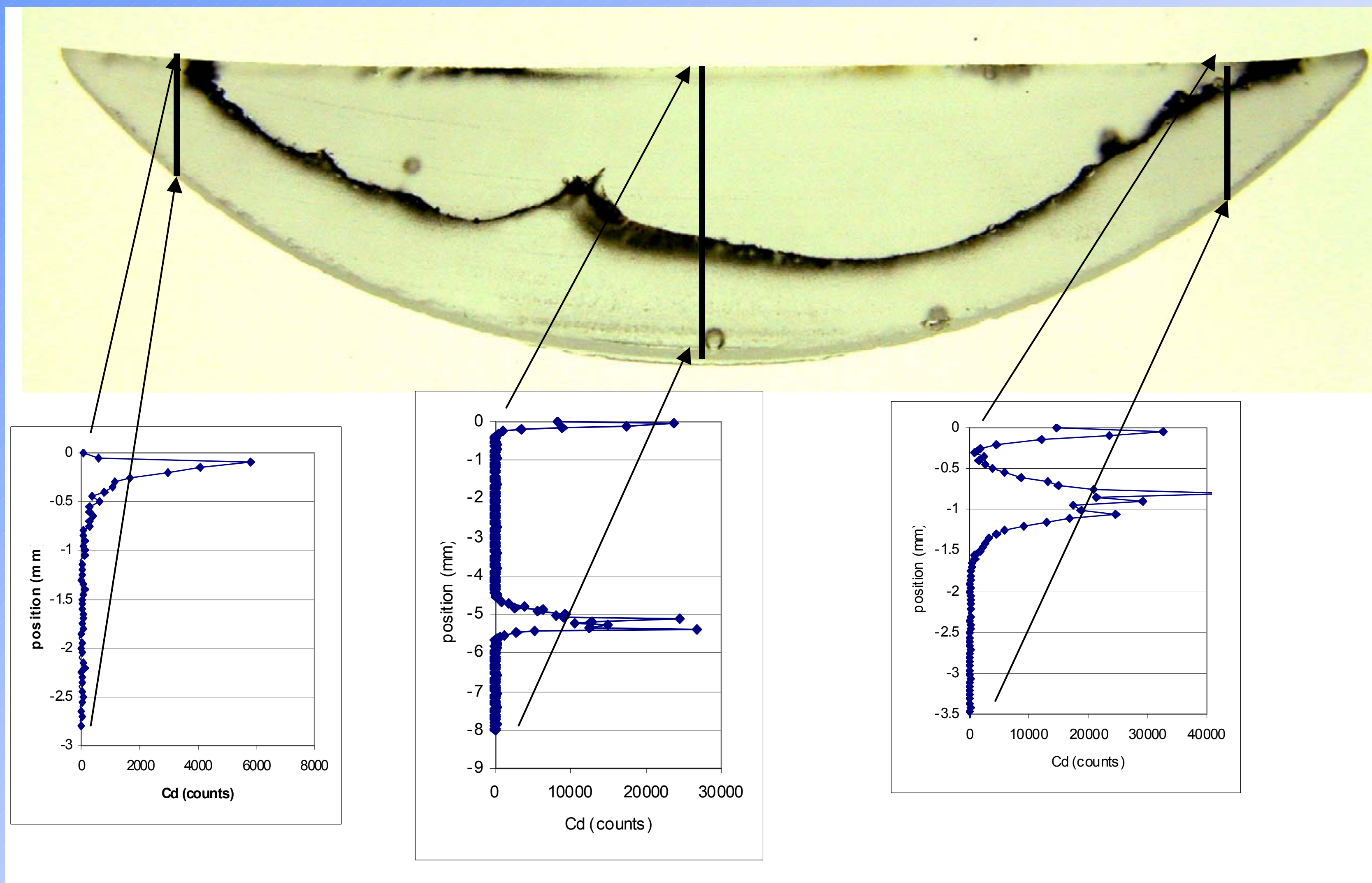


XRF-micro-probe -Cd Distribution in PV Glass
760 °C, Section taken from middle of sample

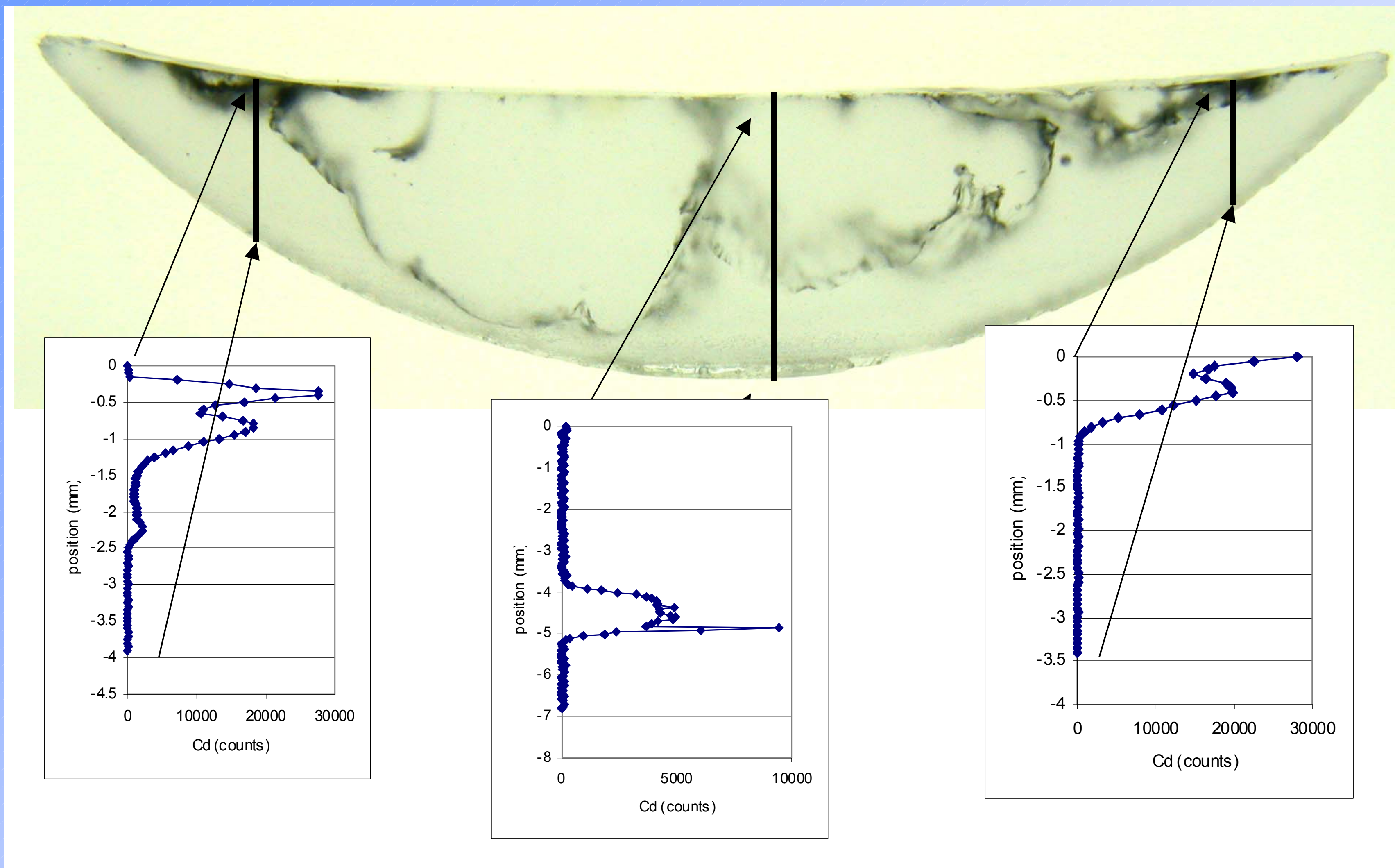


XRF-micro-probe -Cd Distribution in PV Glass

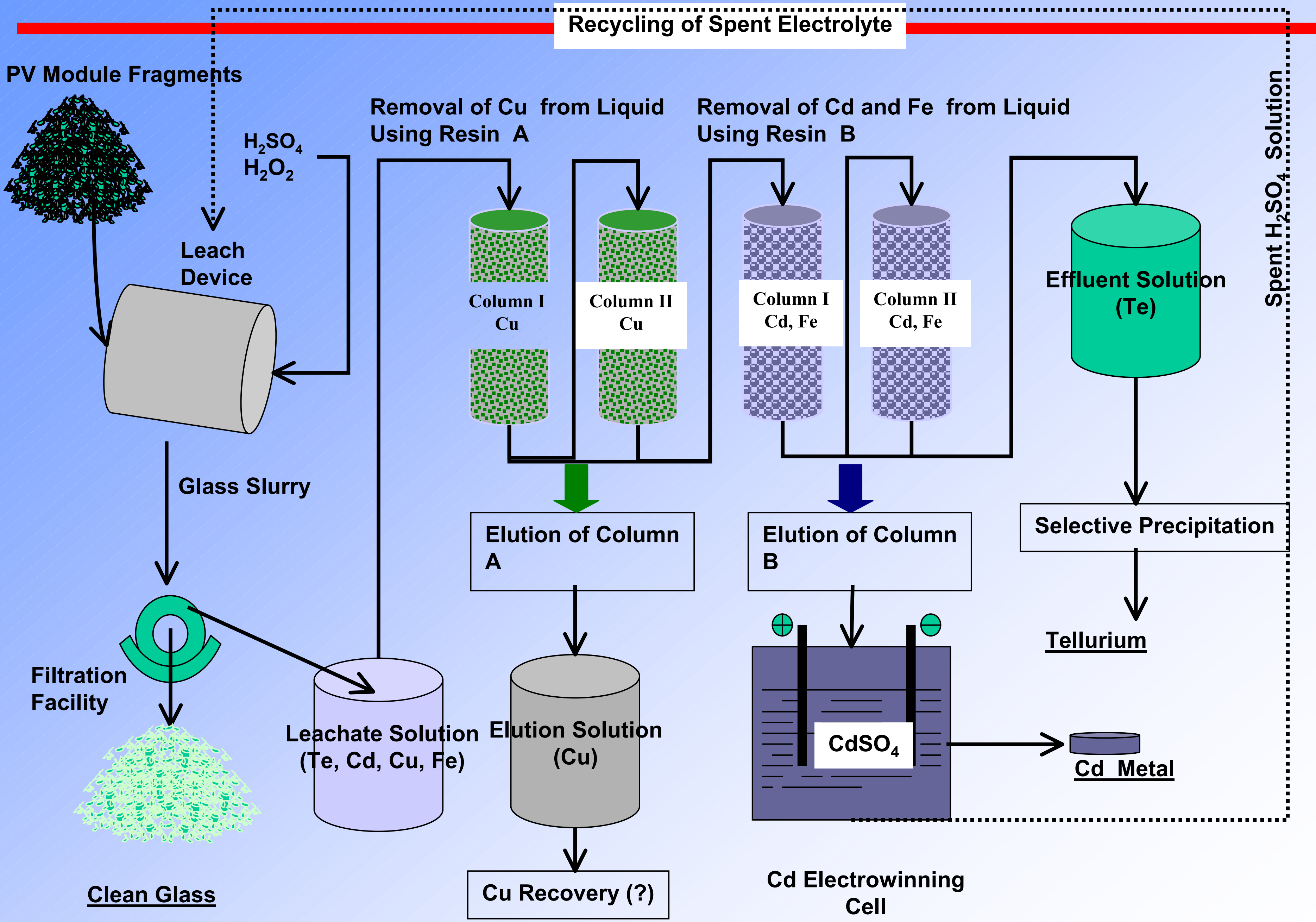
1000 °C, Section taken from middle of sample



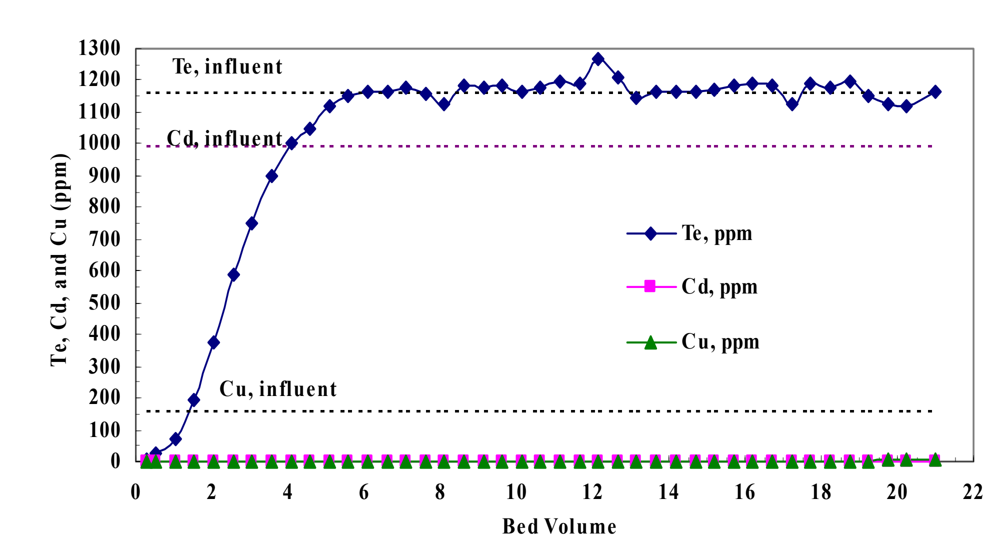
XRF-micro-probing -Cd Distribution in PV Glass
1000 °C, Section taken from right side of sample



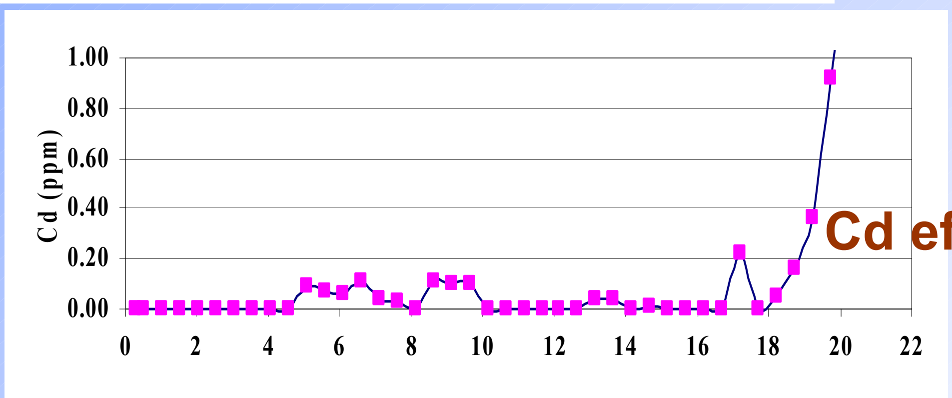
Stage 5. Recycling of Cd and Te from Spent CdTe PV Modules



CdTe Recycling: Separation of Te and Cd



Cd separation 99.99%



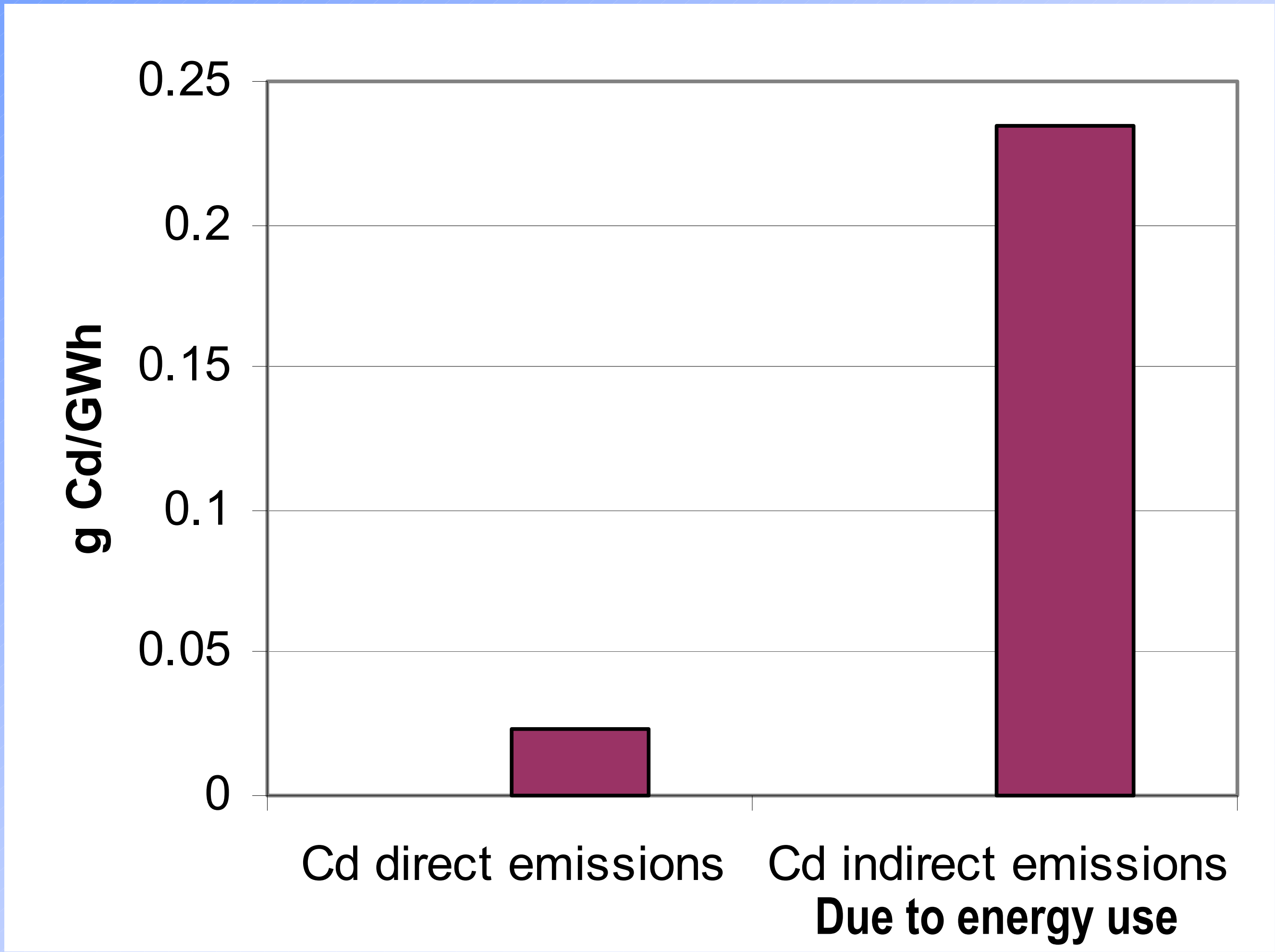
Cd effluent concentration <0.3 ppm

Fthenakis and Wang, Patent Application # 60/686,911, 2, 2005

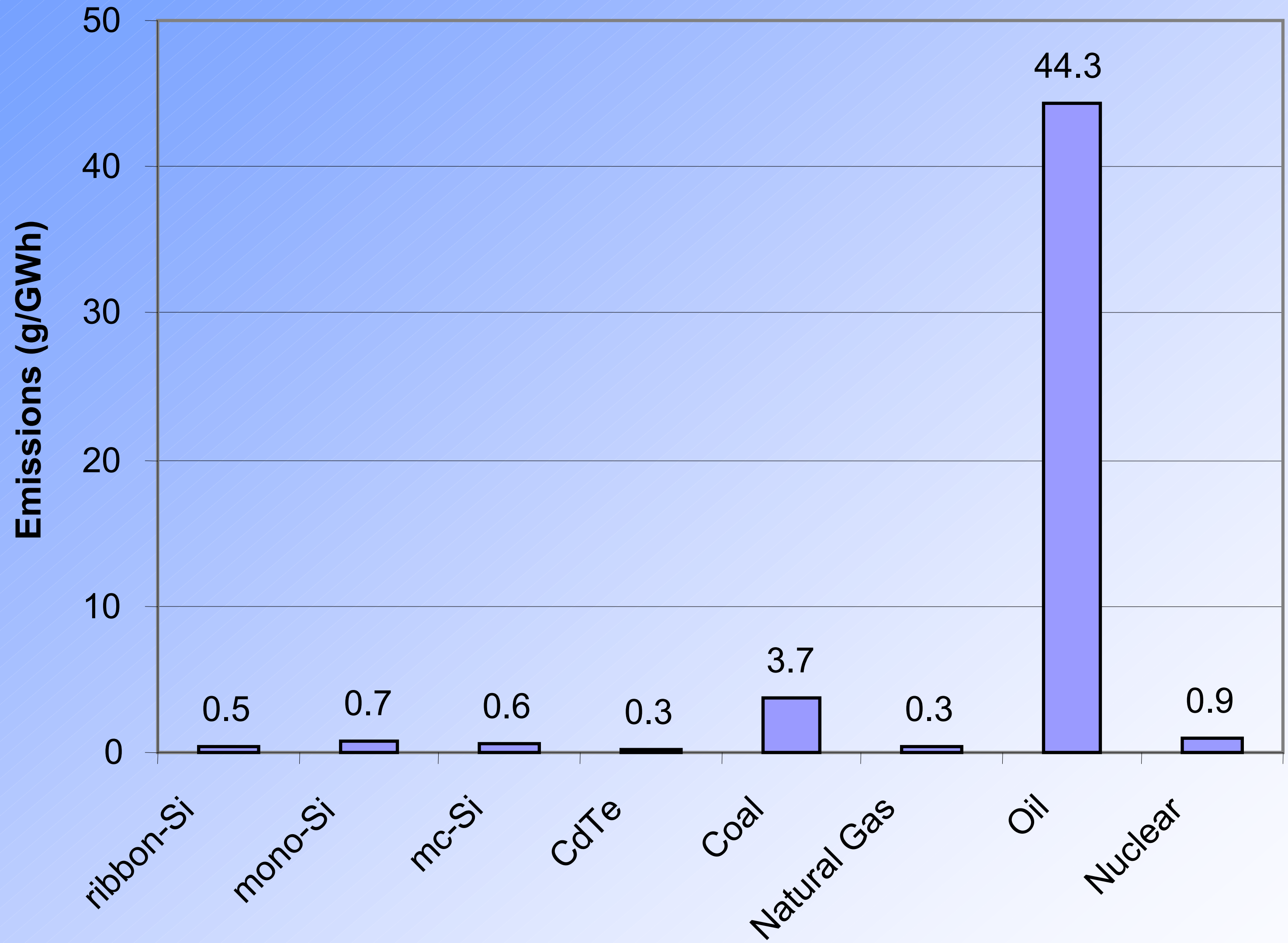
Atmospheric Cd emissions from the Life-Cycle of CdTe PV Modules –Direct Emissions

Process	Cd Emissions (g /GWh)
1. Mining/Smelting of Zn	3.2×10^{-4}
2. Purification/CdTe Production	1.5×10^{-2}
3. Module Manufacturing	3.9×10^{-3}
4. Operation (accidents)	6.0×10^{-5}
5. Recycling	-
TOTAL Life-Cycle Emissions	**0.02**

Total Life-Cycle Cd Air emissions in CdTe PV



Life-Cycle Cd Emissions from Electricity Use (European electricity grid)

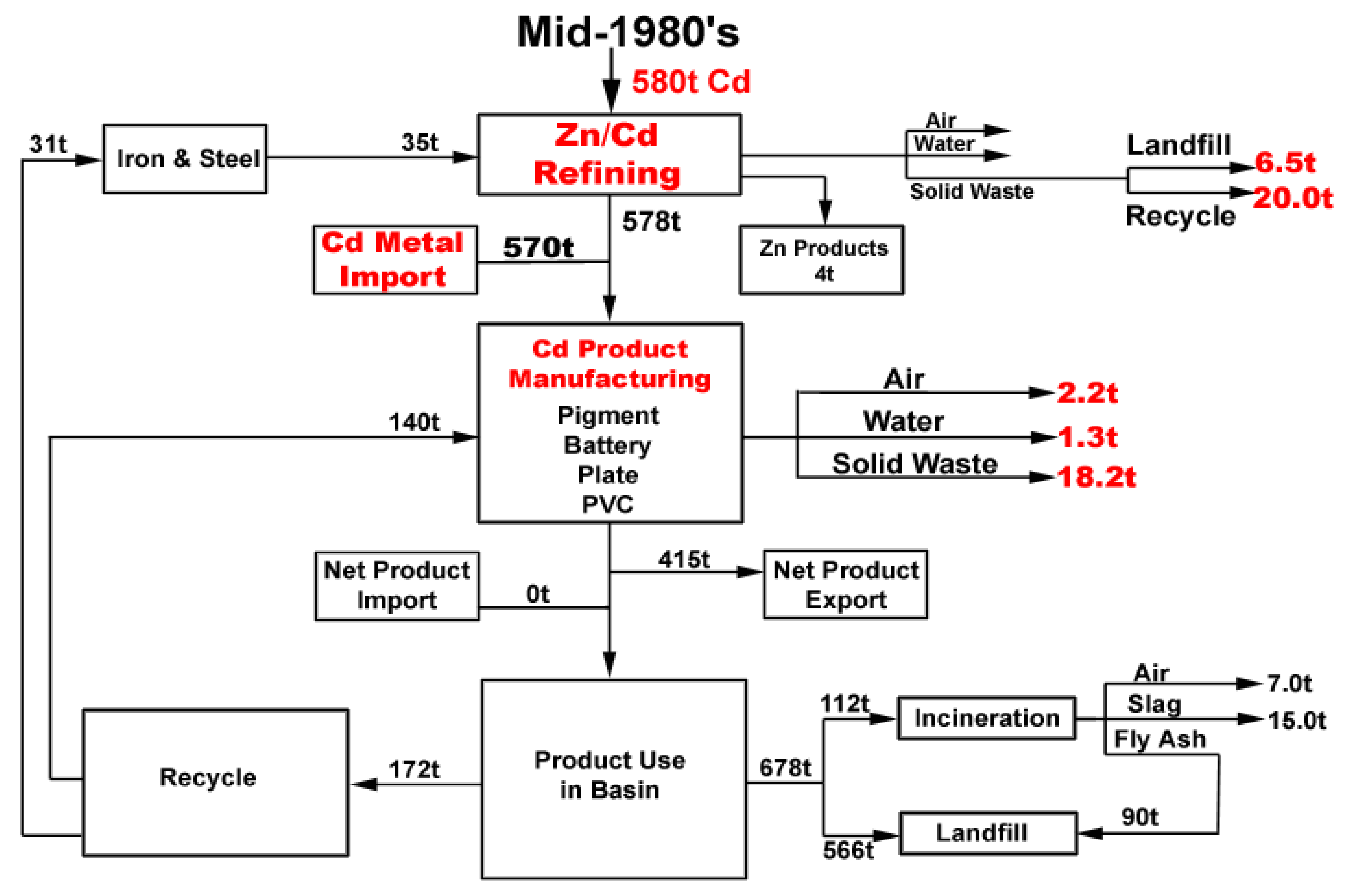


Cd Use in CdTe PV Production

Cd is produced inevitably as a byproduct of Zn production and if not **used**, it may be **discharged** into the environment

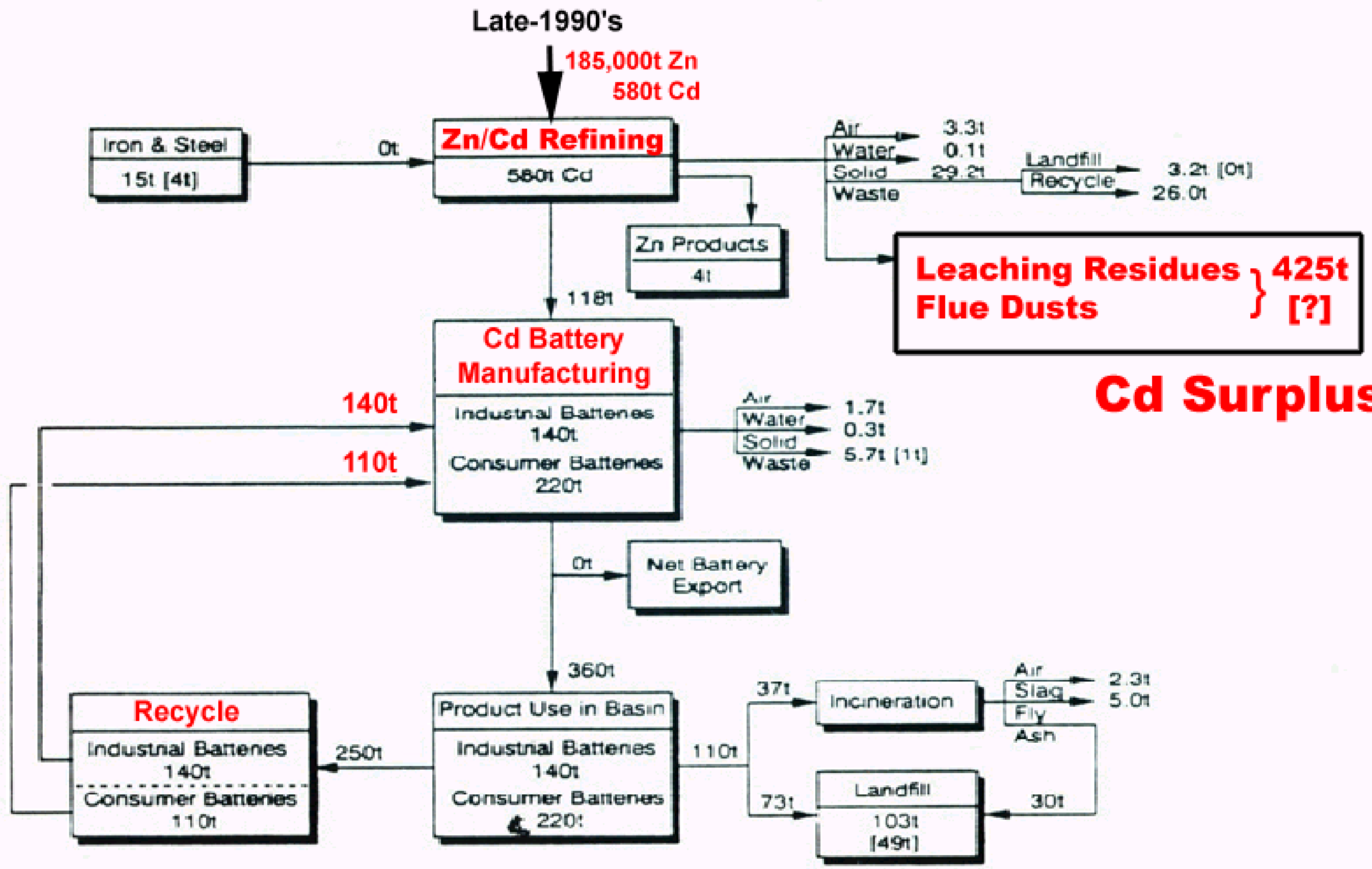
- Above statement is supported by:
  - US Bureau of Mines reports
  - Rhine Basin study (the largest application of Systems Analysis on Industrial Metabolism)

Cd Flow in the Rhine Basin



Source: *Stigliani & Anderberg, Chapter 7, Industrial Metabolism, The UN University, 1994*

Rhine Basin: Cd Banning Scenario



Source: *Stigliani & Anderberg, Chapter 7, Industrial Metabolism, The UN University, 1994*

Cd Use & Disposal in the Rhine Basin: The effect of banning Cd products

"So, the ultimate effect of banning Cd products and recycling 50% of disposed consumer batteries may be to shift the pollution load from the product disposal phase to the Zn/Cd production phase. … it indicates that ***if such a ban were to be implemented, special provisions would have to be made for the safe handling of surplus Cd wastes generated at the Zn refineries!***

One possible option would be to allow the production and use of Cd-containing products with inherently low availability for leaching. *The other option, depositing the Cd-containing wastes in safely contained landfills, has other risks"*

Source: *Stigliani & Anderberg, Chapter 7, Industrial Metabolism, The United Nations University, 1994*

Risk Analysis in a Life Cycle Context

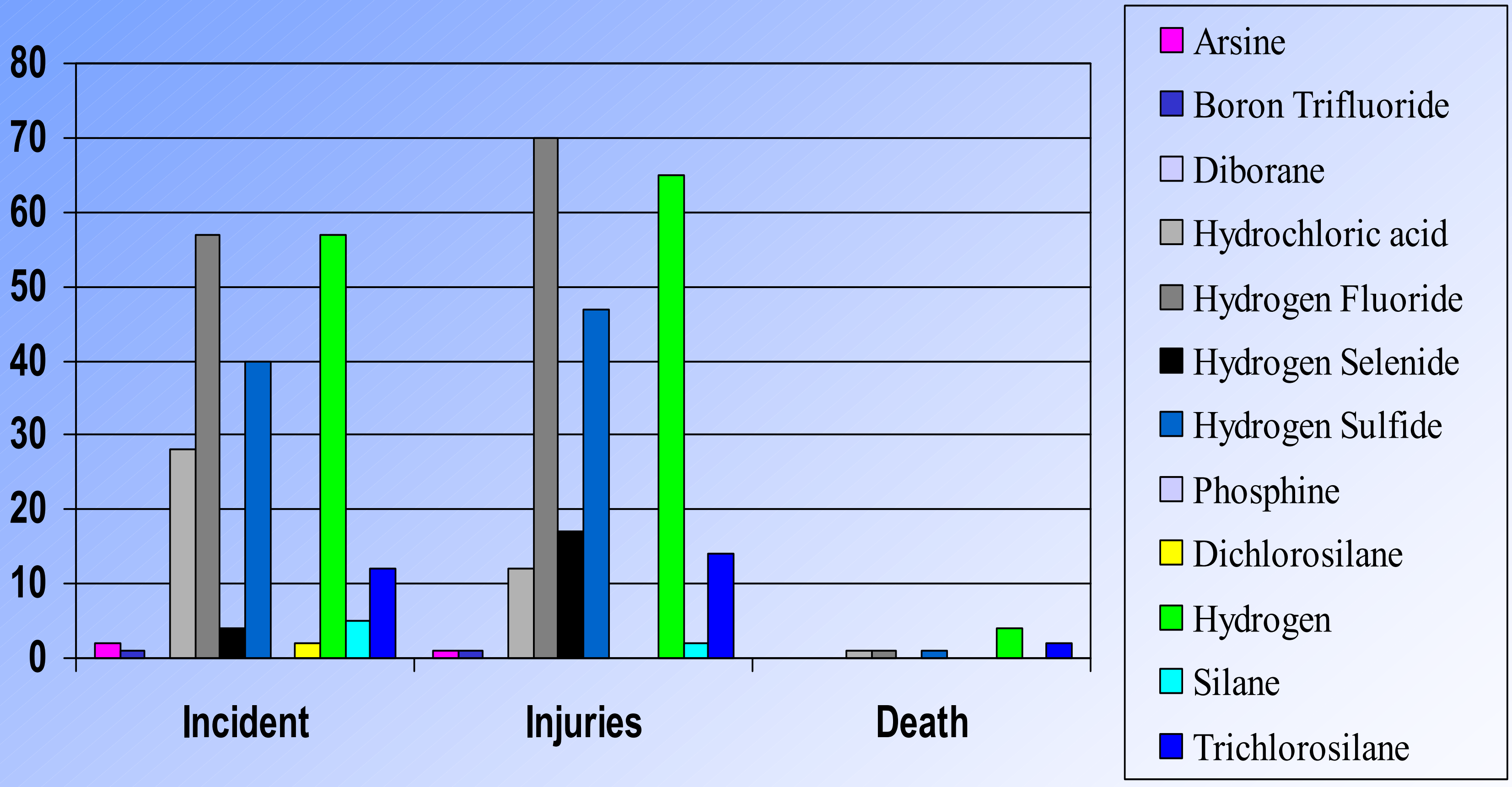
Hazardous Substances in PV Module Manufacturing

Substance	Source
Arsine	GaAs MOCVD
Boron Trifluoride	Dopant
Diborane	a-Si dopant
Hydrochloric acid	Cleaning agent – c-Si
Hydrogen Fluoride	Etchant – c-Si
Hydrogen Selenide	CIGS selenization
Hydrogen Sulfide	CIS sputtering
Phosphine	a-Si dopant
Hydrogen	a-Si deposition/GaAs
Silane	a-Si deposition
Trichlorosilane	Precursor - c-Si

Method for Estimating Accidental Risks

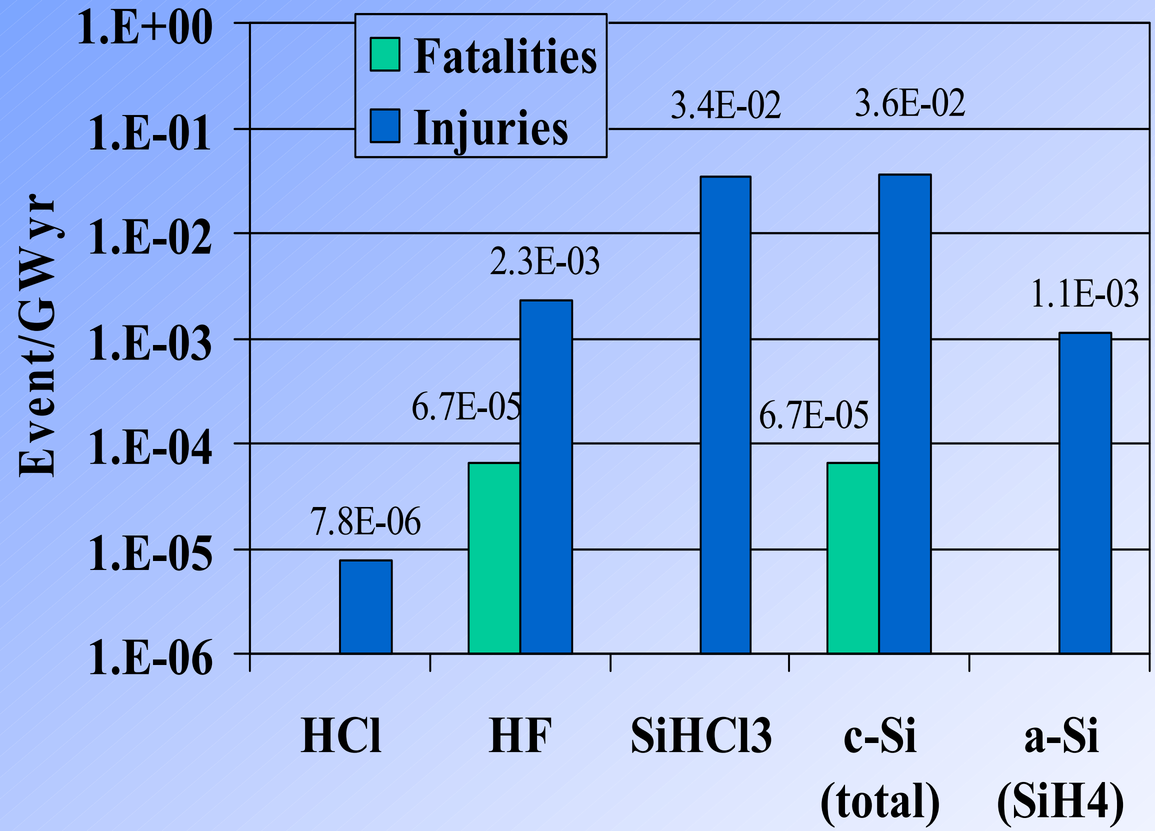
- We examined the risks related to the production, distribution and use of each substance in the whole U.S. industry based on the database of the EPA Risk Management Program (RMP)

Number of Reported Events in the U.S.
US-EPA RMP Database (1994-2004)



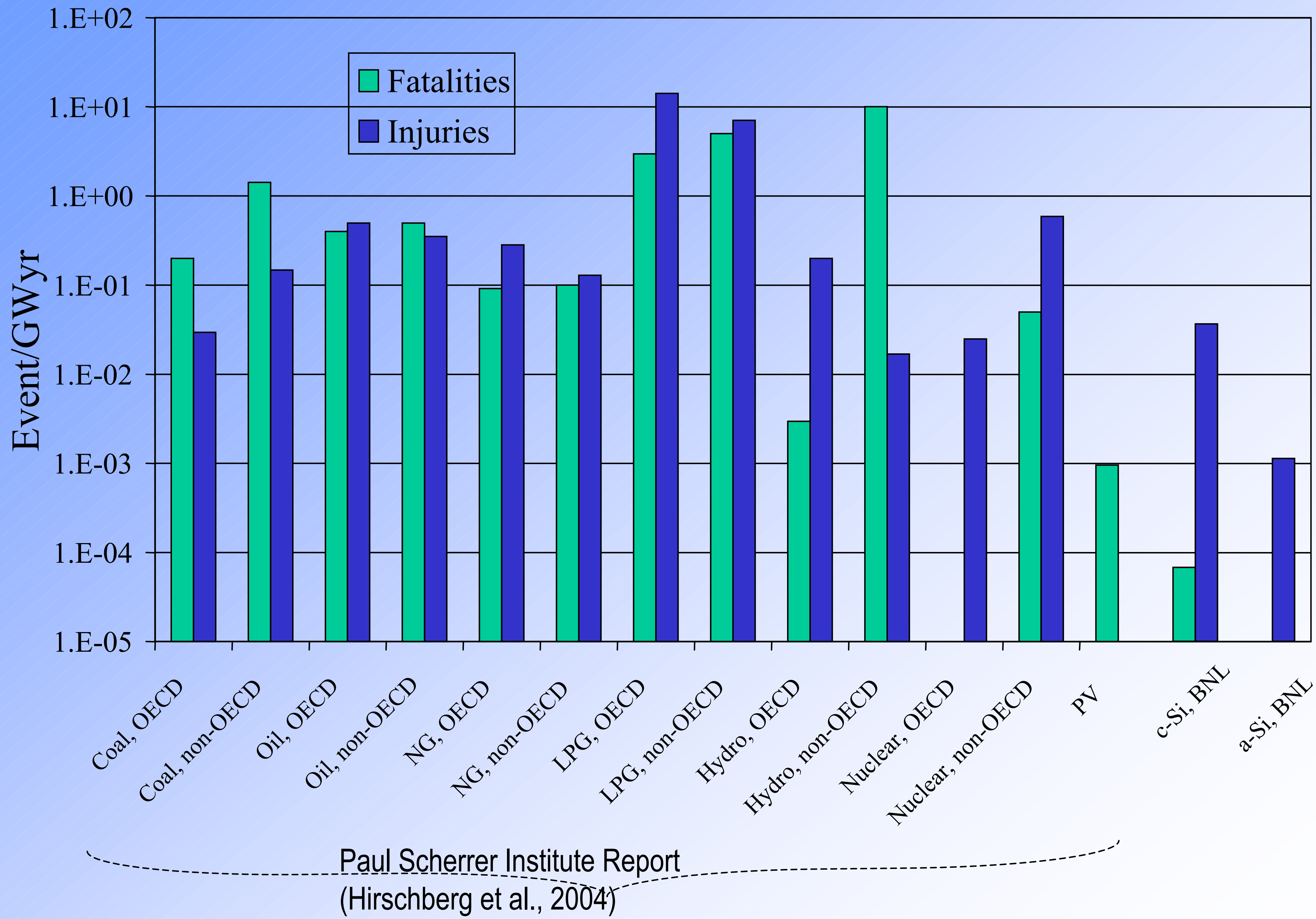
Estimated PV Risks by Chemical

Derived from US-EPA RMP Database (1997-2004)

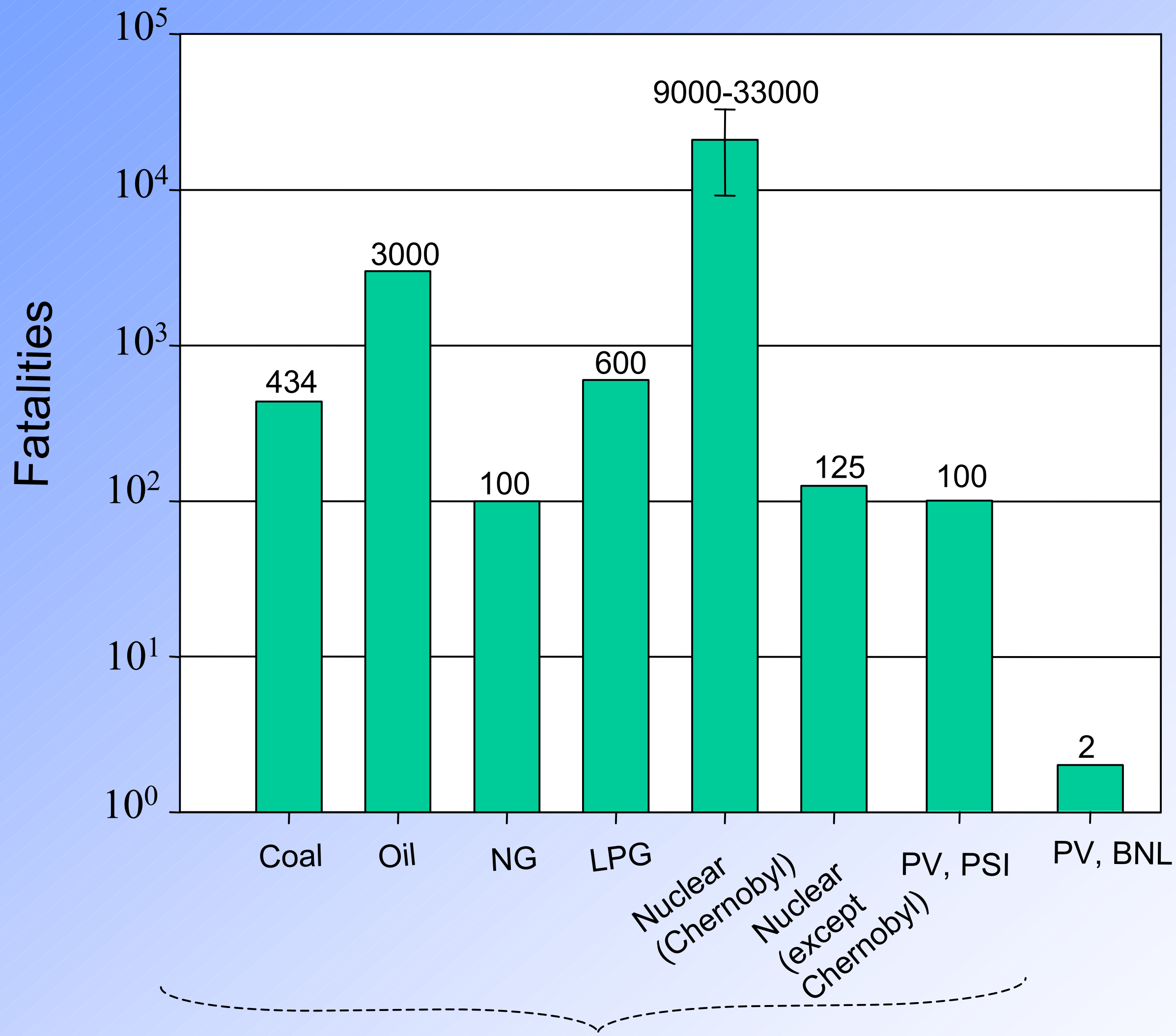


Insolation = 1800 kWh/m2/yr; performance ratio = 0.8.

Comparison of Risk Estimates



Comparisons of Estimated Maximum Consequences



Paul Scherrer Institute, German Case
(Hirschberg et al., 2004)

Conclusions

- A Life Cycle Framework is necessary for a complete description of the Sustainability of Energy Technologies
- Cadmium and other heavy metal emissions are negligible in comparison to the heavy metal emissions from the fossil power plants that PV will displace
- Modern PV Technologies have Low Energy Payback Times and low GHG emissions
- PV is also much safer than conventional electricity generation technologies

www.clca.columbia.edu
www.pv.bnl.gov

Brookhaven National Laboratory