DOW CENTRE FOR
SUSTAINABLE ENGINEERING INNOVATION
UQ School of Chemical Engineering

Chemicals: Creating a compelling nuclear value proposition through co-production

Eric McFarland

Sustainable Engineering Innovation: Novel applications of science and technology to promote increasing human prosperity while creating and maintaining the conditions under which humans and nature can coexist in productive harmony.

Goal: Enable the world's democratic nations to lead the adoption of economically and environmentally sustainable nuclear power.

Outline

- Why most western democracies are not aggressively adopting nuclear power.
- A change in tactics and strategy?
- Co-production of chemicals as a business model today.
- Specific examples.

World Nuclear Association

Representing the people and organisations of the global nuclear profession

Nuclear Basics | Information Library | Our Association | Press and Ev

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Non-Power Nuclear Applications | Economics of Nuclear Power | Energy Subsidies and External Costs | Energy Security | 1995-2012 | Challenge: NPP investment cost uncertainty | Challenge: Construction Risk

The Economics of Nuclear Power

(Updated 16 February 2015)

- **Nuclear power is cost competitive with other forms of electricity generation, except where there is direct access to low-cost fossil fuels.**

Which is everywhere!!!!

Today's Costs

Sanmen I and II

Westinghouse AP 1000 x 2 **$5.9 B**
Chicago Bridge&Iron EPC

(2 x 1100 $MW_{e\text{-}net}$) ~ **$2.7/Watt**

Capacity factor 90% → $3.00/$Watt_{out}$

Construction time ~ 60 months.
Capital delay factor: $1/(1+0.10)^5$ ~ 1/1.6

Today's Costs

Taishan I and II

French EPR (Areva) $7.5 B

(2 x 1660 $MW_{e\text{-}net}$) ~ $2.2/Watt

Capacity factor 90% → $2.50/$Watt_{out}$

Construction time ~ 40 months.

Capital factor: $1/(1+0.10)^{3.5}$ ~ 1/1.4

Feb 2012

But ……..in the US

Vogtle 3 & 4

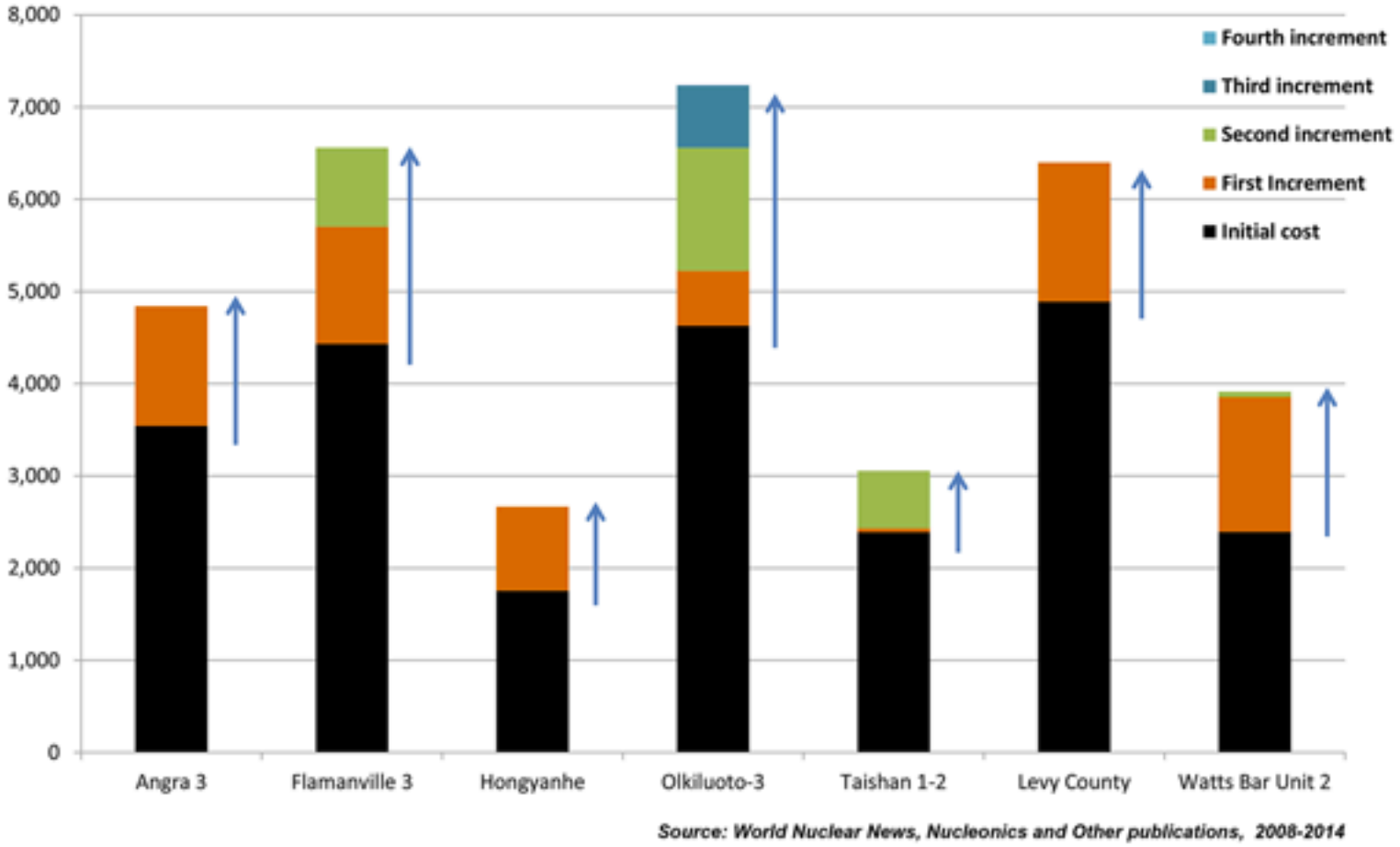
Westinghouse AP 1000 x 2 $15.5 B
(2 x 1100 $MW_{e\text{-}net}$)

Major Construction time ~ 72 months.
Capital factor: $1/(1+0.10)^6$ 1/1.8

Capacity factor 90% → $7.80/Watt$_{out}$

~ $7.80/Watt$_{out}$ x 1/4Y x 1000/8760 ~ $0.22/kWh

Challenge: Construction risk



Coal and Gas will remain inexpensive
~ $3-5/GJ ~ $0.02/kWh$_{th}$ ~ $0.06/kWh$_{el}$

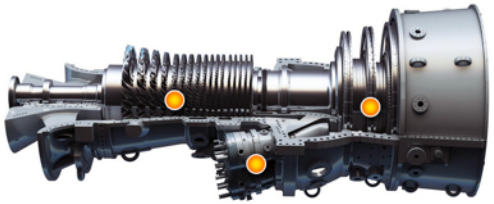
Total Project Capital Costs $0.60 - $1.50/Watt

Major Construction time ~ 24-30 months.
Capital factor: $1/(1+0.10)^{2.5}$ ~ 1/1.3

@ $1/W x 1/4Y x 1000/8760 ~ $0.03/kWh

Outputs of Coal and Natural Gas Power Plants is Simply Heat at a capital ~$0.3/$W_{th}$!

Turbine Gas (>1500 C) → Steam (~ 600 C)



Coal (1700 C) → Steam (~ 600 C)

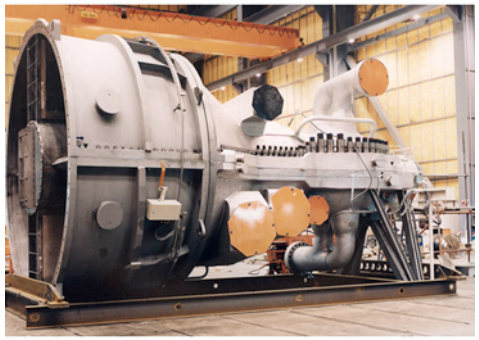
Bharat Heavy Electricals Limited; Telangana India
Super Critical Coal Fired Plant - $600M/800MW ~ $0.75/$W_e$

Doosan Heavy Industries; Binh Thuan, Viet Nam
Coal Fired Plant - $1500M/1200 MW ~ $1.25/$W_e$

Ansaldo Energia: Batna, Algeria
Open cycle natural gas - $216M/340MW ~ $0.62/$W_e$

SSE : County Wexford, Ireland
Combined cycle natural gas - $449M /460 MW ~ $0.98/$W_e$

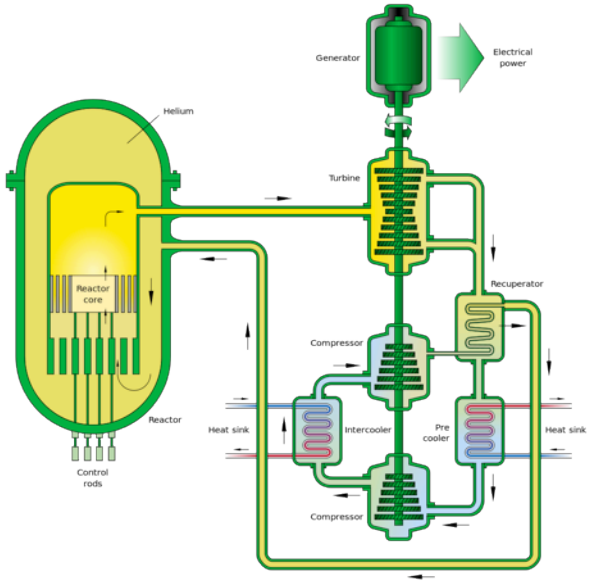
Moundsville, West Virginia, USA
Combined cycle natural gas - $615M /549 MW ~ $1.12/$W_e$

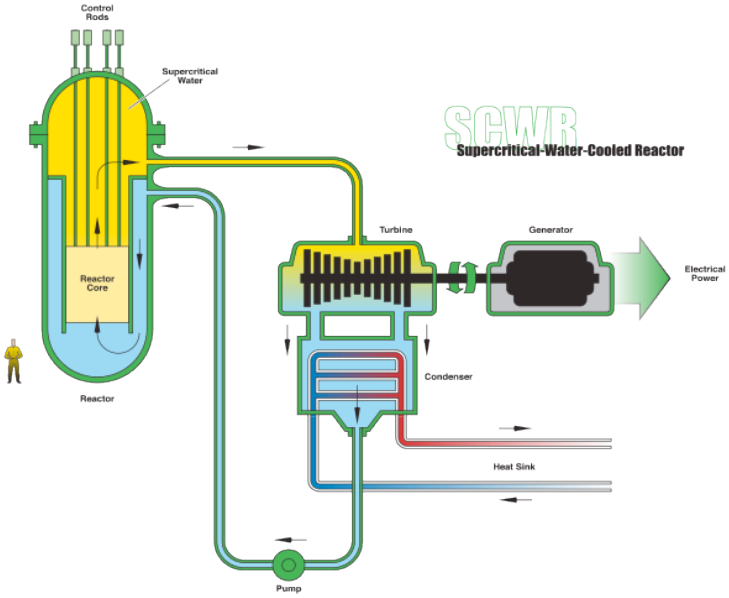


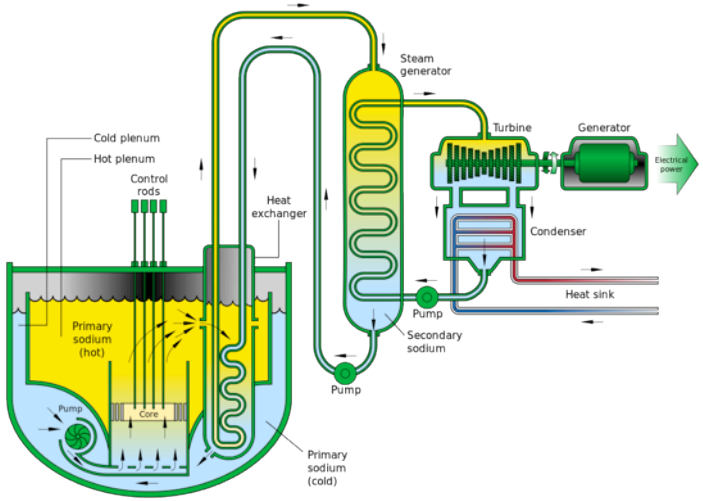
Global Efforts in Advanced Nuclear Reactor Technologies

Gen VI Reactors; Safer, More fuel efficient (less waste)

But…… producing electricity without major capital cost reductions







Gen VI Reactors: Proposed to Co-produce Desalinated Water

Use the heat source to make drinking water?

Energy and Power Engineering, 2013, 5, 26-35
http://dx.doi.org/10.4236/epe.2013.51004 Published Online January 2013 (http://www.scirp.org/journal/epe)

Scientific Research

Comparison of the Cost of Co-Production of Power and Desalinated Water from Different Power Cycles

P. Asiedu-Boateng[1,2], B. J. B. Nyarko[2], S. Yamoah[1], F. Ameyaw[1], K. Tuffour-Acheampong[1]

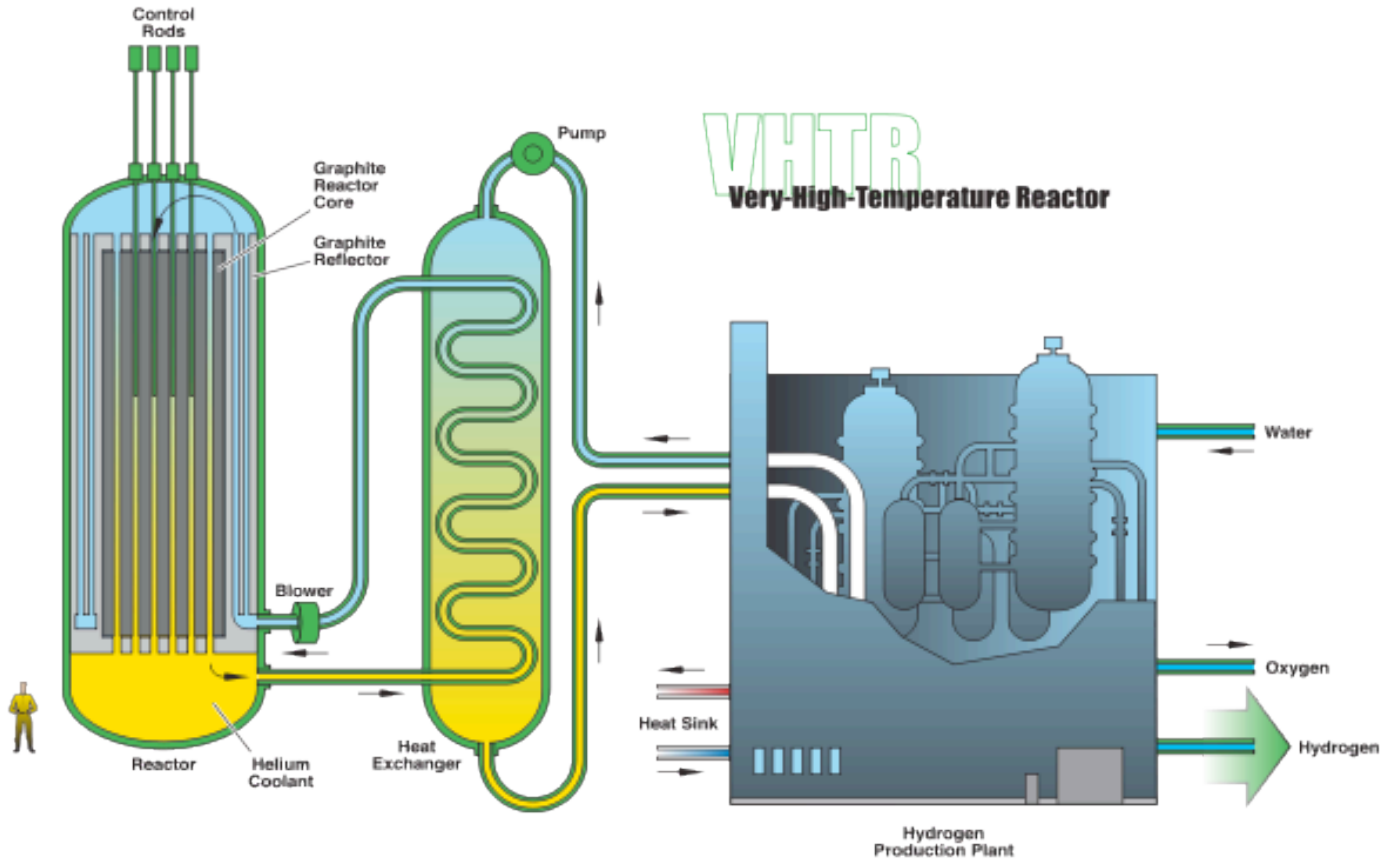
BN350 Reactor, Kazakhstan 1000 MW_{th}
150 MW_e + desalination plant 120,000 m^3/d

1000 MW_{th} (333MW_e)
→ @$0.05/kWh **$83M/year**

1000 MW_{th} (150MW_e ,120,000 m^3/d)
→ @$0.05/kWh, **$38M/year**
Water @ $1/$m^3$
→ 0.12M/day x 0.9 * 365 ~ **$40M/y** water

VHTR Gen VI Reactors for Hydrogen Production

Heat source to "break" water ?



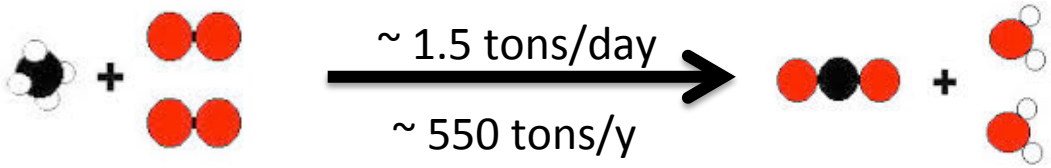
Electricity
@ \$0.05/kWh$_{el}$~ \$0.02/kWh$_{th}$~ \$3-5/GJ$_{th}$

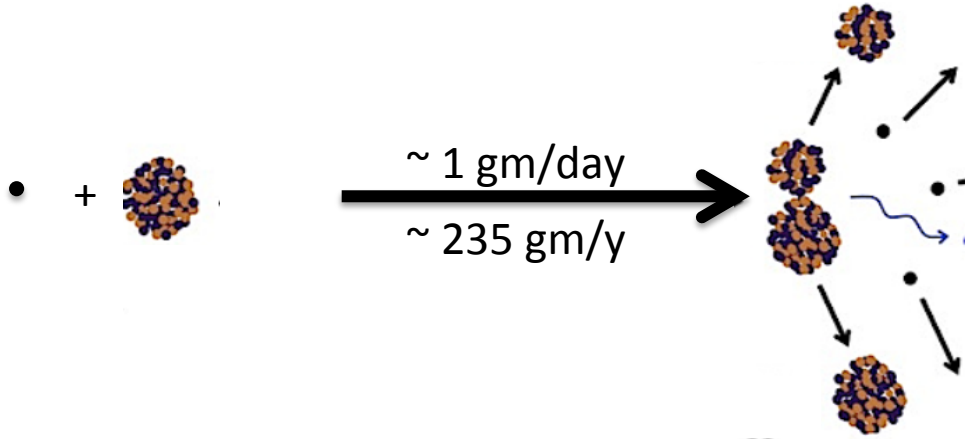
$H_2O \rightarrow H_2 + O_2$
@ \$0.5/kg and ~ 250 kJ/mole ~ \$4/GJ

The Electric Power Production Process: It's just steam!

Inputs → Process → Products

1 MW_{th} —0.3*eff*→ 300 kW_{el} —300*.9*24*365*0.10/kWh→ $250k/y rev





~ $0.5 - $1.2 M max capital

(~$1.5- 4/$W_e$)

Lessons Learned from Biofuels

Biomass → Sugar/Oils → ~~Fuels~~
→ **Chemicals**

Biomass → → → → **Chemicals**

Unique Chemicals

Make Money !

Massive Market Opportunity

Relatively Complex Process

Competing fuels processes less expensive

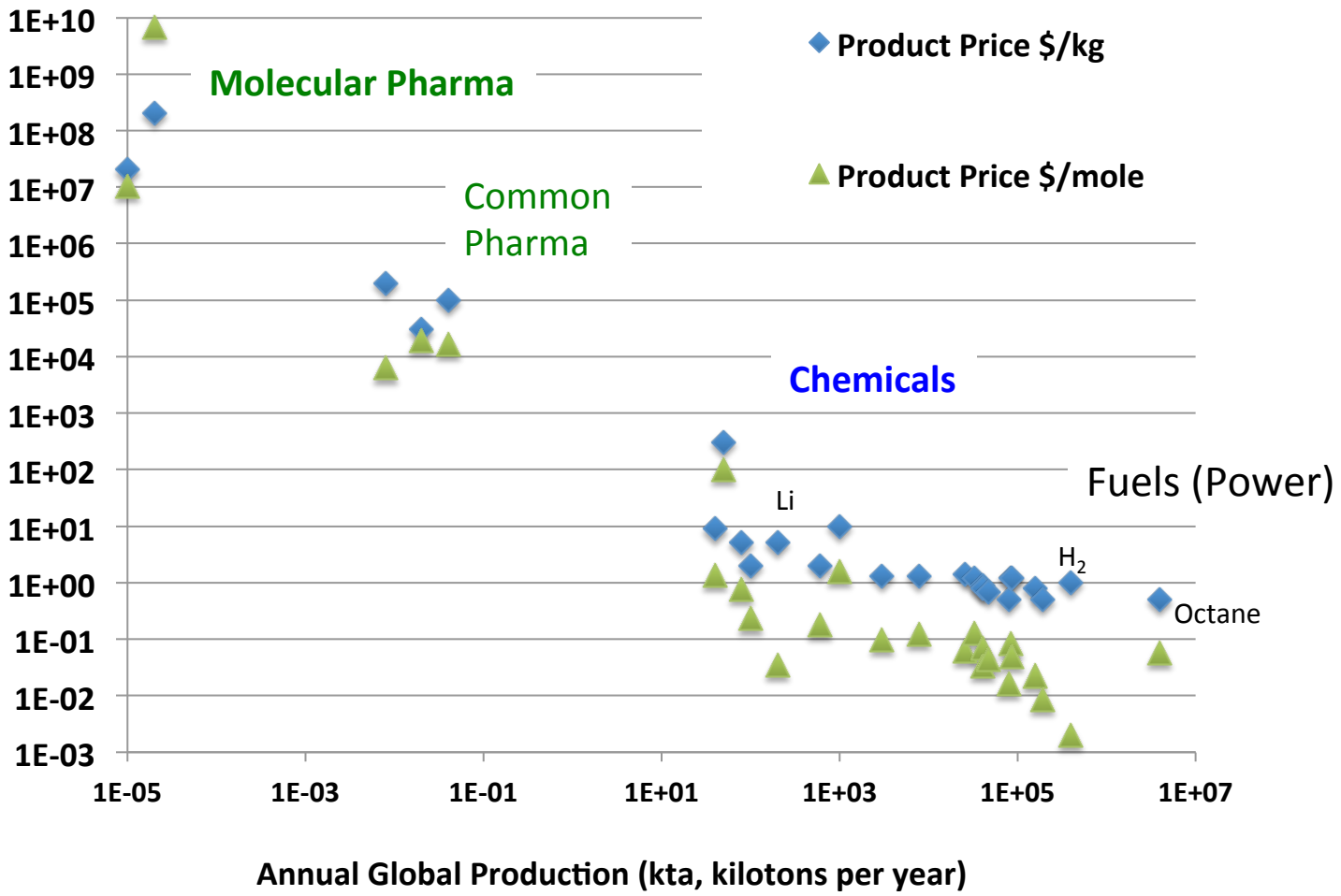
The 30 Hottest Companies in Renewable Chemicals and Biobased Materials

2012-13

BiofuelsDigest

The world's most widely read biofuels daily

Commodity Chemicals ~ 1.5+ times fuels

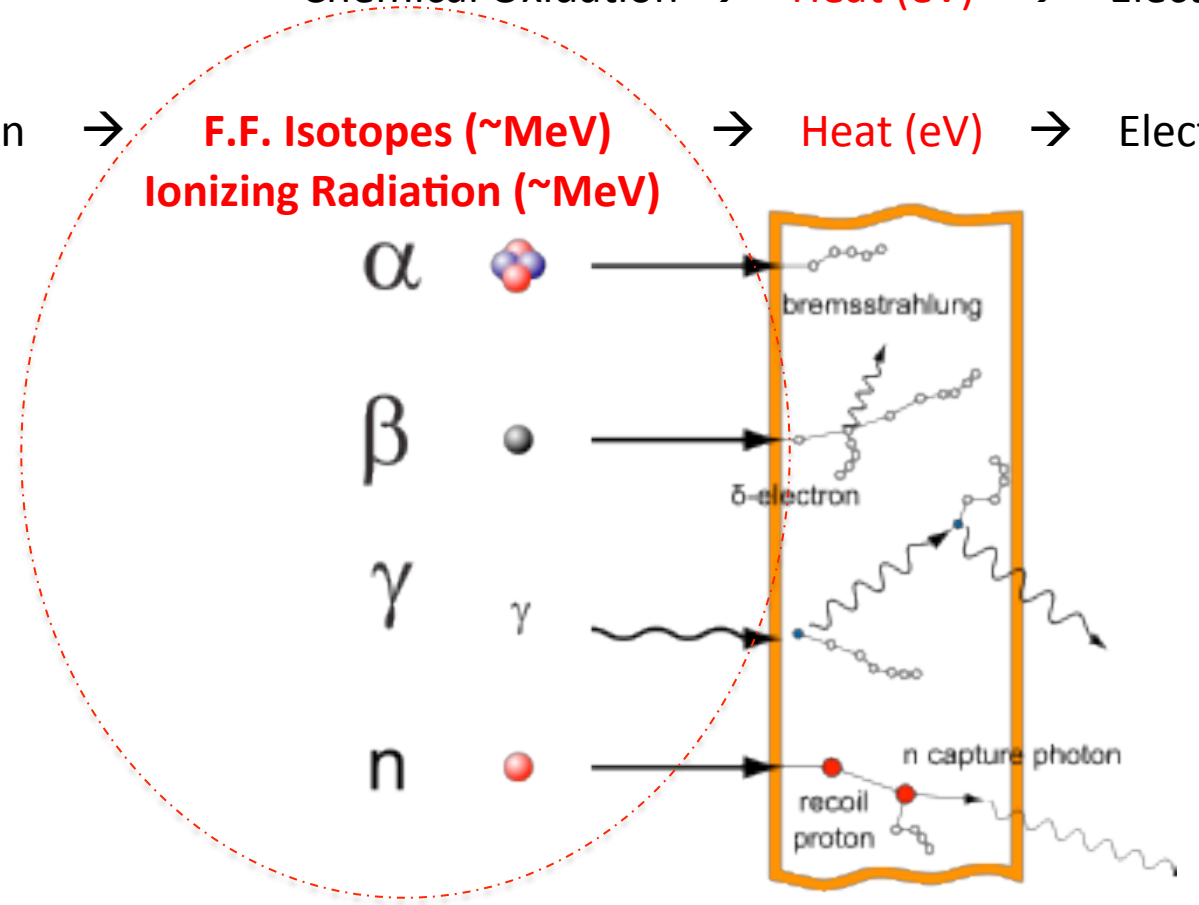


Unique Features of Nuclear Reactions

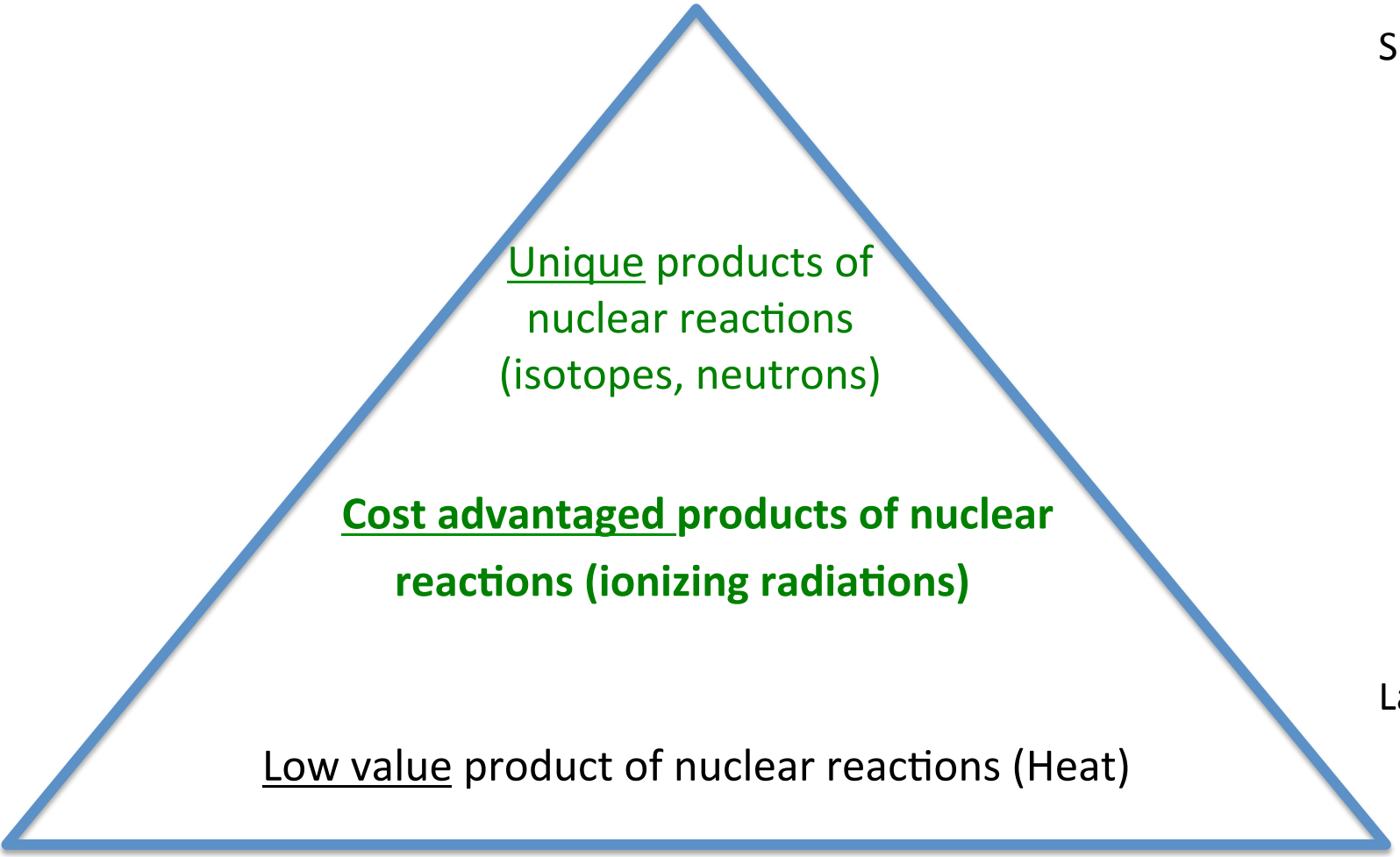
Chemical Oxidation → Heat (eV) → Electricity +/- Thermochemistry

Fission → **F.F. Isotopes (~MeV)** → Heat (eV) → Electricity +/- Thermochemistry

Ionizing Radiation (~MeV)



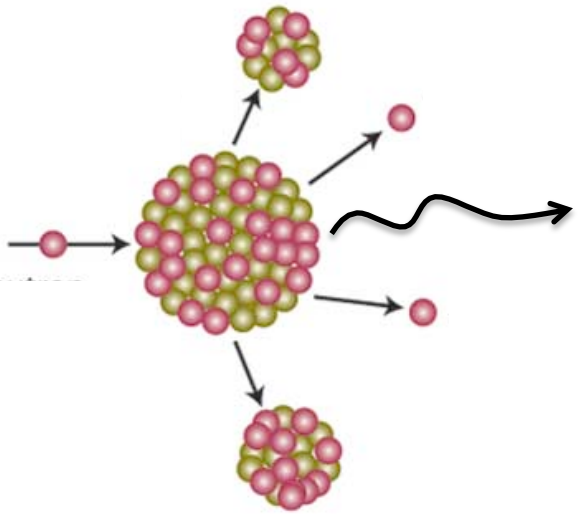
Value Chain of Nuclear Reactions

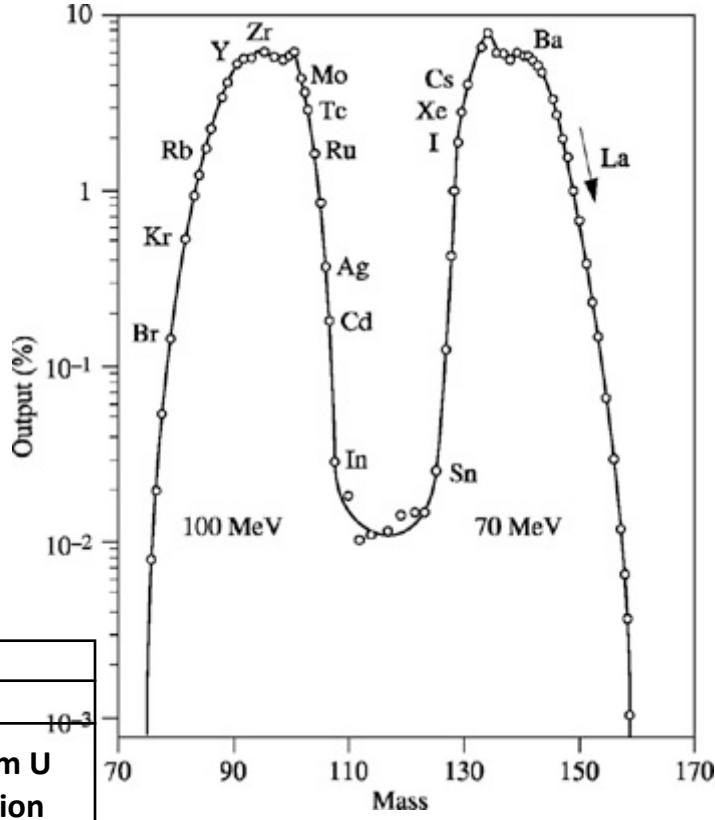


Small Market
High Value

Large Market
Low Value

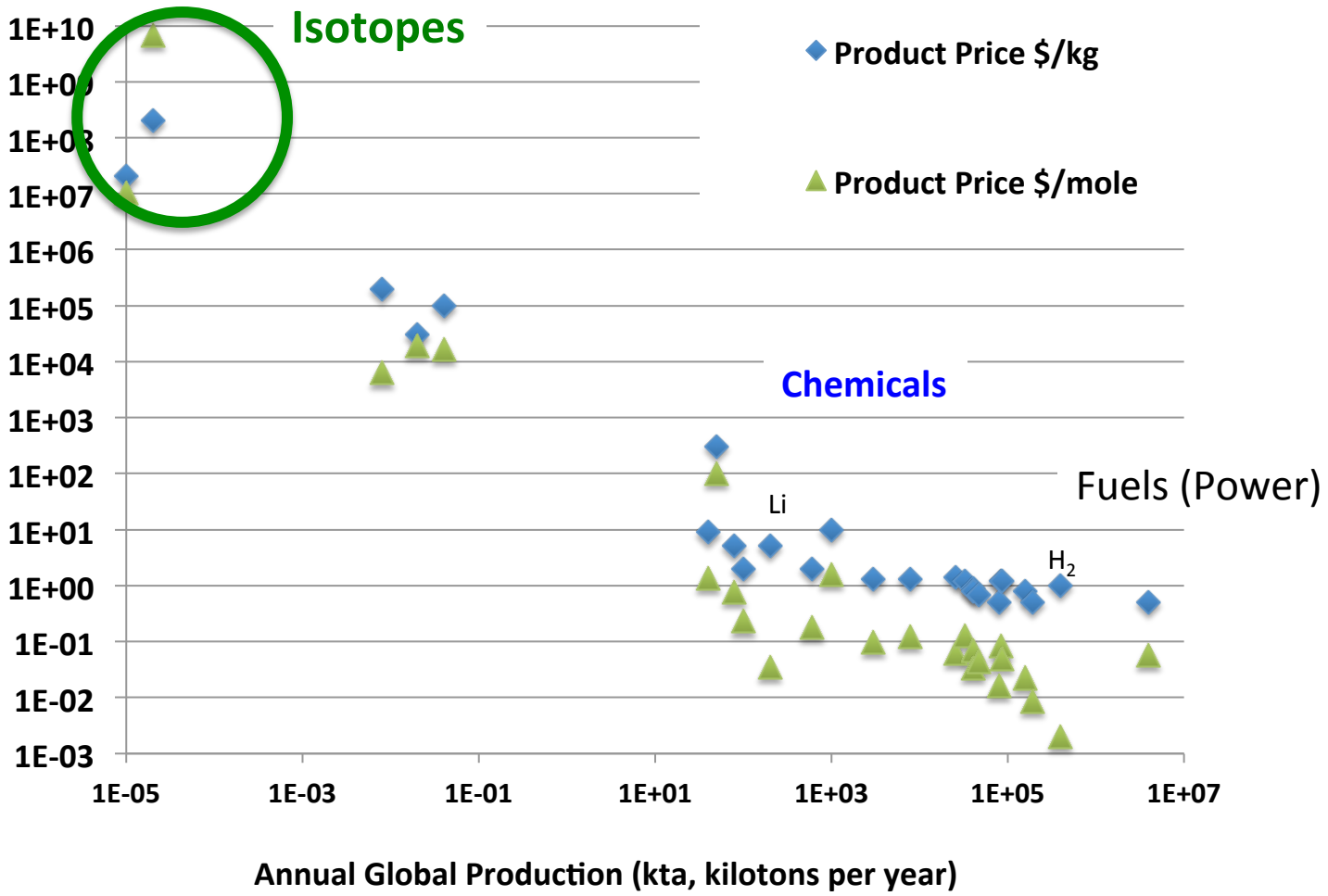
Fission Produces Isotopes ~ 1 gm per MW_{th} per day





						t(days)	
						14	
Isotope	**Price ($/Ci)**	**U 235 fission mass yield %**	**T1/2(hrs)**	**decay constant (day-1)**	**Max SA (Ci/gm)**	**SA (Ci/gm)**	**$/gm U fission**
Mo-99	100	6.1%	66.2	0.251	4.80E+05	14235	$86,833
Sm-153	20	0.2%	46.7	0.356	4.40E+05	3003	$95
I-131	3	2.8%	193.2	0.086	1.24E+05	37144	$3,154
Xe-133	3	6.7%	126.96	0.131	1.85E+05	29546	$5,939
Y-90	1	5.8%	64	0.260	5.40E+05	14190	$820
Sr-89	1	4.7%	1212	0.014	2.90E+04	23930	$1,125

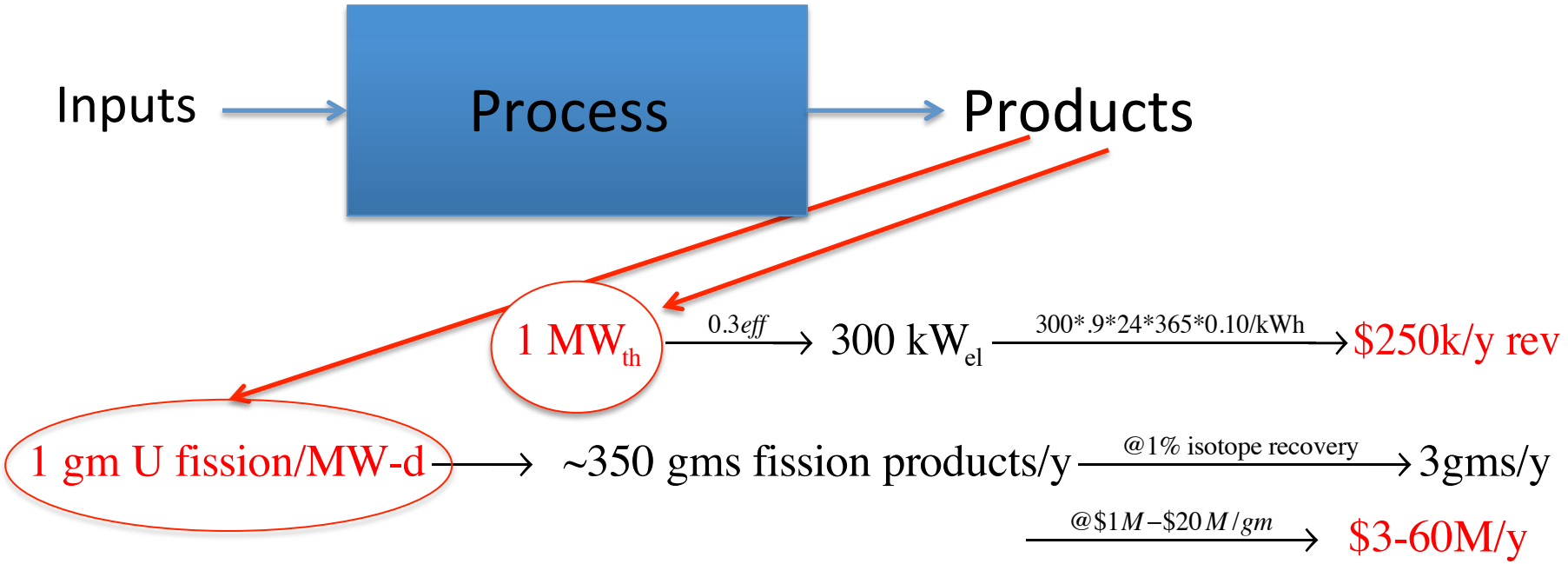
Isotopes: Highest Value



Specialty Isotopes: Medical Isotopes

- Medical isotopes are used to prevent, diagnose and treat disease
- Main isotope supply sources are nuclear reactors and cyclotrons
- Primary product is Mo-99, which decays for use in Technetium-99 (Tc-99m) generators, used in imaging to diagnose heart disease and cancers
- Other Key Reactor Isotopes:
  - Xenon-133 (Xe-133), used in lung scans;
  - Iodine-131 (I-131), used to treat hyperthyroidism, thyroid cancer and non-Hodgkin's lymphoma;
  - Iodine-125 (I-125), used to treat prostate cancer;
  - Yttrium-90 (Y-90), used to treat liver cancer.
- Key Cyclotron Isotopes:
  - Iodine-123 (I-123), used to diagnose thyroid disease;
  - Strontium-82 (Sr-82), used to manufacture rubidium-82 generators, which are used in imaging to diagnose heart disease
  - Thallium-201 (Tl-201), used to diagnose and assess risk of coronary artery heart disease;
  - Palladium-103 (Pd-103), used to treat prostate cancer;
  - Indium-111 (In-111) and Gallium-67 (Ga-67) (both used to diagnose infection and cancer) at our Vancouver facilities

Nuclear Reaction Process for Isotope Production

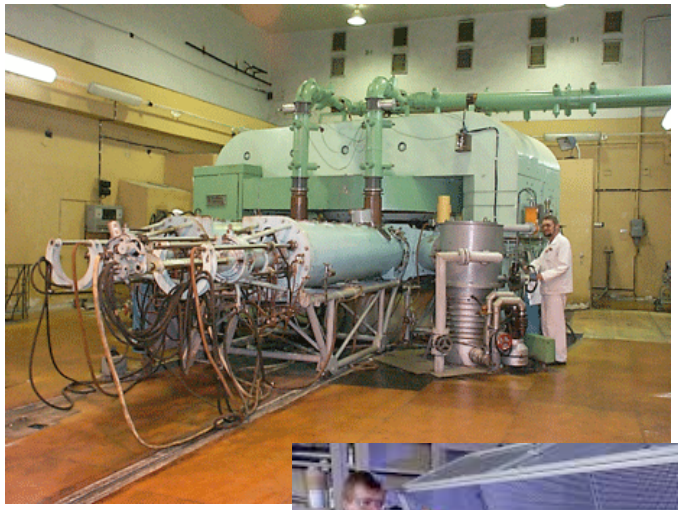


Who wouldn't want to make isotopes ?

Who wouldn't want to make isotopes ?

Know your Competition

Non-reactor sources for nuclear reactions

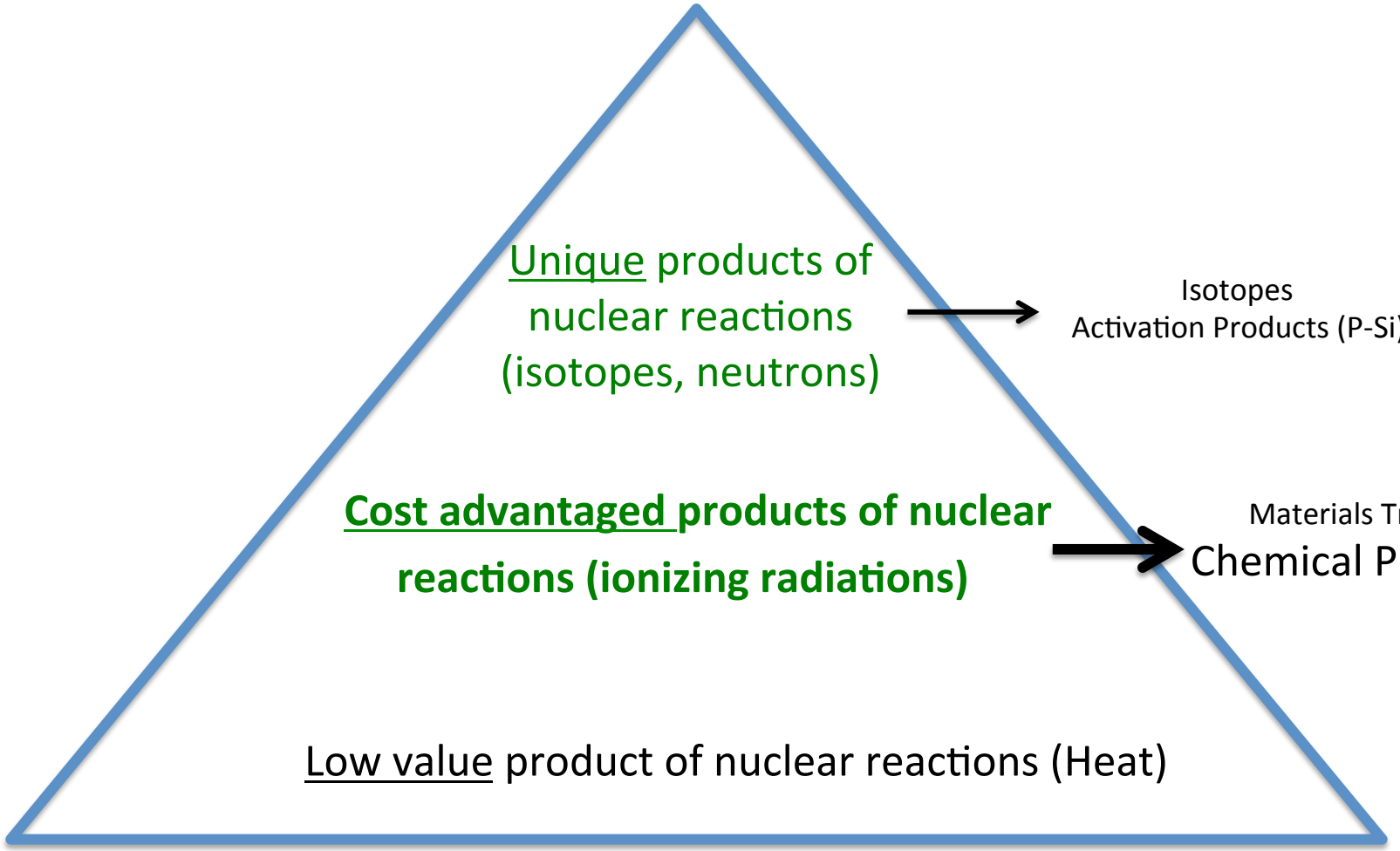


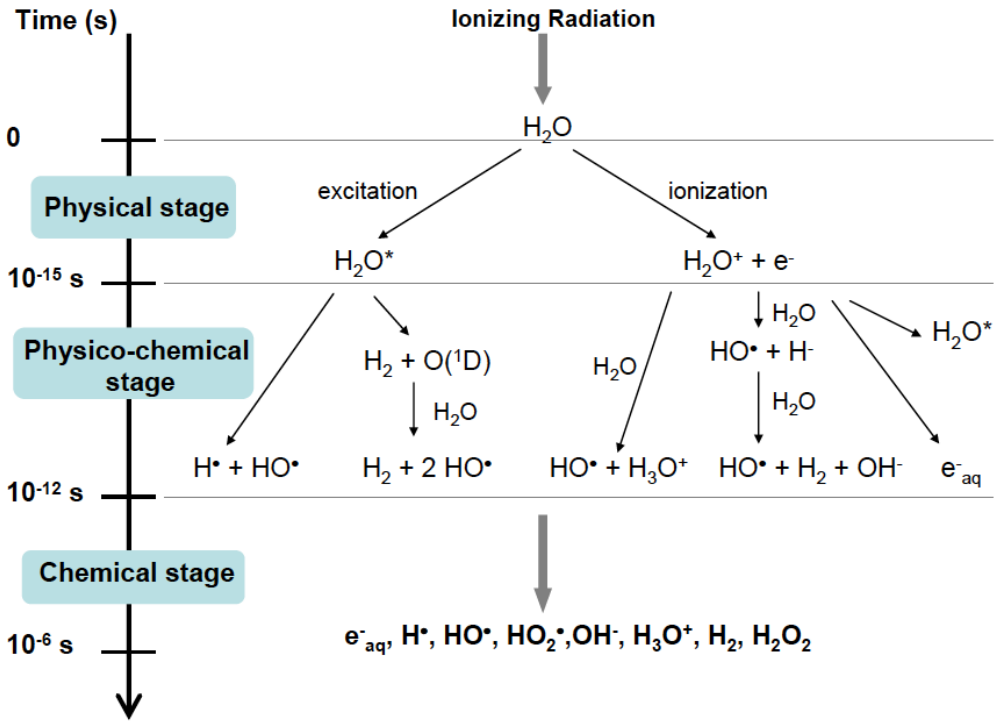
Total Market ~ $10 Billion
20,000 Ci/w

Total Market supported by ~ one power reactor

Isotopes alone will not finance new reactor development

Value Chain of Nuclear Reactions





Debierne, A. Recherches sur les gaz produits par les substances radioactives. Décomposition de l'eau. *Ann. Phys. (Paris)* **1914**, *2*, 97-127.

$$G \equiv \frac{\text{Micromoles product}}{\text{Joules absorbed}}$$

Radiation Chemistry has an enormous history 1914 →

[CONTRIBUTION FROM THE DEPARTMENT OF CHEMISTRY, COLUMBIA UNIVERSITY]

The Photochemical Formation of Phosgene[1]

BY LEWIS FOWLER[2] AND J. J. BEAVER

RECEIVED MARCH 26, 1953

The experimental study of the photochemical reaction $CO + Cl_2 \rightarrow COCl_2$ is extended by investigating the effect of a ten-fold variation in light intensity as well as pressure ratio changes. It is established that the true rate equation followed is $d(COCl_2)/dt = k'(Cl_2)(-1 + \sqrt{k''(CO)I_{abs} + 1})$, and that use of this equation eliminates ambiguities in previously reported data. A convenient and precise method of calculating rate constants based on this equation is derived and applied. Quantum yields as functions of light intensity and reactant pressures are calculated, and found to be about 10^4.

March, 1978] BULLETIN OF THE CHEMICAL SOCIETY OF JAPAN, VOL. 51 (3), 725—728 (1978)

The Formation of Nitrogeneous Compounds in the γ-Radiolyses of Liquid Nitrogen Solutions of Hydrogen, Methane, and Ethane

Keiichi HORIGOME, Shun-ichi HIROKAMI,* and Shin SATO
Department of Applied Physics, Tokyo Institute of Technology, Ookayama, Meguro-ku, Tokyo 152

(Received September 9, 1977)

Polymer Production in the γ Radiolysis of Methane in Liquid Argon[1]

Peter Hamlet,[1c] Jefferey Moss, Jai P. Mittal,[1d] and W. F. Libby
Contribution from the Department of Chemistry, University of California, Los Angeles, California. *Received September 9, 1968*

Gamma-Initiated Iodination of Methane in the Gas Phase

R. VILENCHICH[1] and J. W. HODGINS
Department of Chemical Engineering, McMaster University, Hamilton, Ont.

Kinetics of Sulfochlorination of Cyclohexane in Carbon Tetrachloride Induced by Gamma Radiation

ALFRED SCHNEIDER and JU CHIN CHU
Polytechnic Institute of Brooklyn, Brooklyn, New York

A.I.Ch.E. Journal November, 1964

Yields of Hydrogen Peroxide in the Decomposition of Water by Cobalt γ-Radiation

II. Effect of Chloride Ion

THOMAS J. SWORSKI
Chemistry Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee

Thermochemical vs Radiochemical

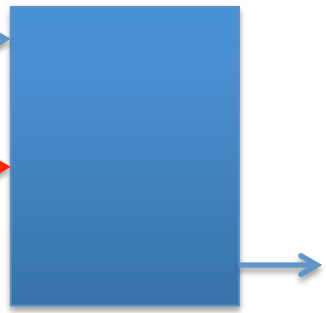
Radiation Yield, G = micromoles product/Joules absorbed

$H_2O \rightarrow H_2 + ½\ O_2$ ΔH=+241kJ/mole

T= 0 C

1 liter/sec

100kW
(heat)



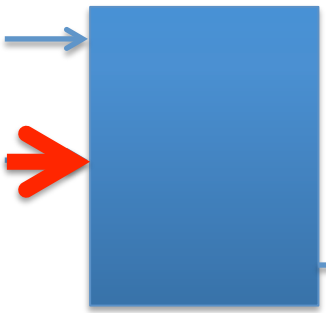
T= 25 C

$H_2O \rightarrow H_2 + ½\ O_2$
Rate ~ 0

T= 0 C

1 liter/sec

100 kW
1MeV gammas



Not at equilibrium:
Reverse rate slow.

T ~ 13 C
Water + 100mM H_2

$H_2O \rightarrow H_2 + ½\ O_2$

G_{H2} ~ 1uM/J x 100,000 J/sec ~ 100mM/s

Higher G's possible for specific reactions

Why use radiation chemistry for synthesis ?

$$A + B \leftrightarrow C + D$$

$$r_{Thermochemical} = r_{forward} - r_{reverse}$$

$$r_{Thermochemical} = \beta(T) e^{-E_A/RT} ([A][B] - [C][D] e^{\Delta G/RT})$$

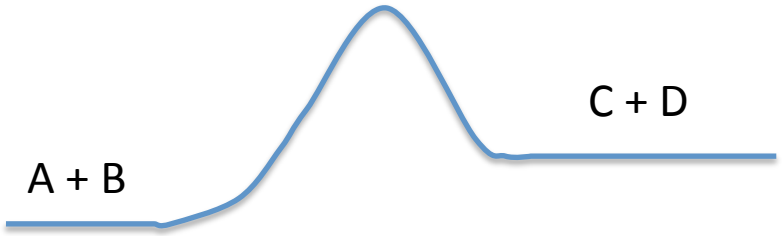
$$r_{Total} = r_{Radiochemical} + r_{Thermal}$$

$$r_{Radiochemical} \sim \sigma\ \Phi\ G \qquad \text{ideally} \sim 0.01 - 100 \text{ moles/liter-s}$$

Operate where thermal (back) reaction is very slow

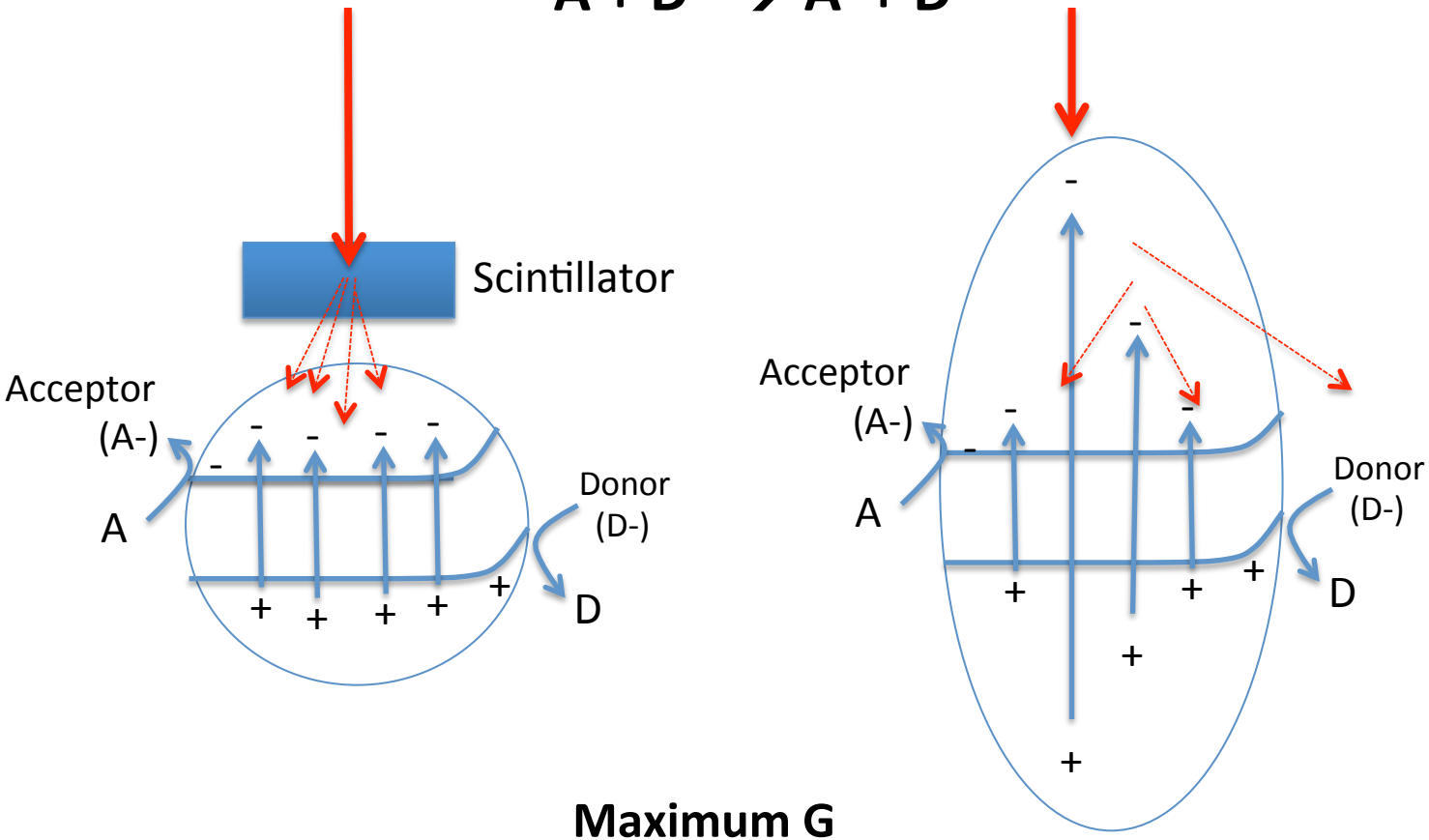
Beat thermodynamics with kinetics

NOT AT EQUILIBRIUM



Photoelectrochemistry (PEC) with Gamma Radiation

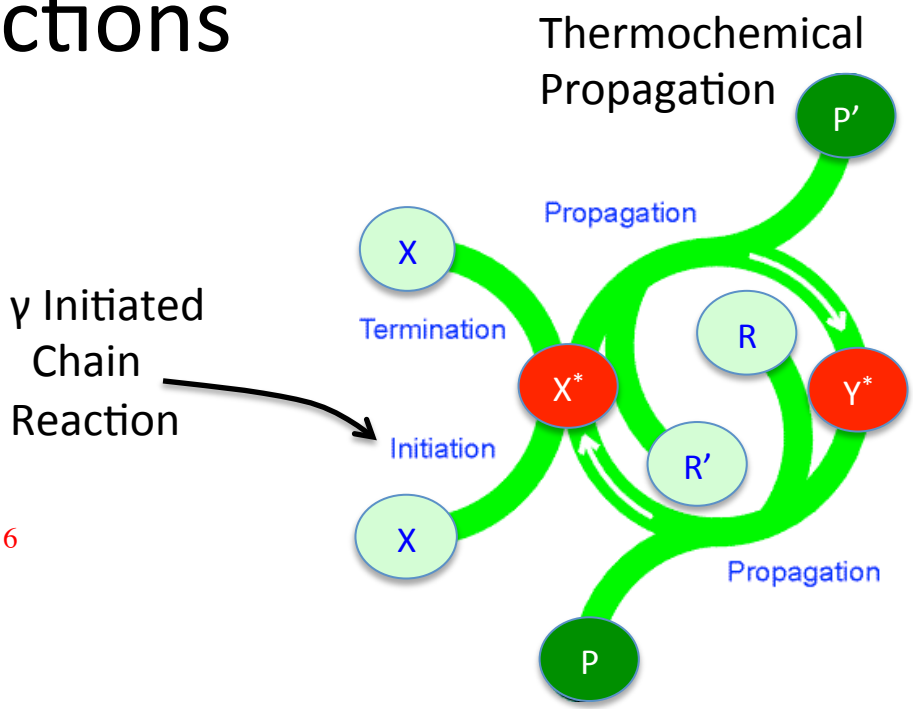
$$A + D^- \rightarrow A^- + D$$



Maximum G

$$G \sim 10/E_{gap}(eV)$$

Enable Chain Reactions



Very High G's Demonstrated ~ 100 -10^6

typical products ~ 0.1 kg/mole

$$G\left(\frac{\mu M}{J}\right) x \left(\frac{10^6 J}{MJ}\right) xMW \left(\frac{10^{-7} kg}{\mu M}\right) x \frac{kt}{10^6 kg} x \frac{31.5 x 10^6 s}{y} \sim 3G\left(\frac{kta}{MW_\gamma}\right)$$

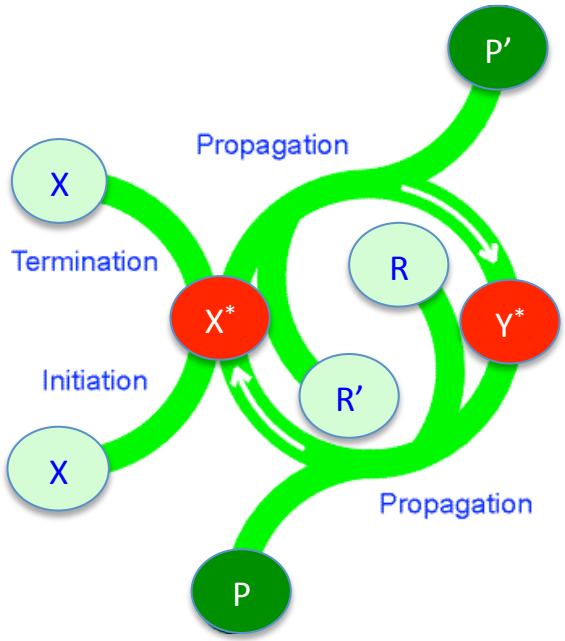
$$\sim 0.1 - 1\text{k}\left(\frac{\text{tons per year}}{kW \ \text{gamma}}\right)$$

Dow Chemical 1963 0.5 kta Ethyl Bromide Commercial Facility

SMALL MOLECULE CHEMICAL PROCESSING

Ethyl Bromide Synthesis

The single most outstanding success in the application of radioisotopes to chemical processing is the Dow Chemical Company's direct addition of hydrogen bromide to ethylene gas (6–9). This is a chain reaction with a *G* value of over 40,000. The reactor shown in Figure 2 contacts ethylene gas with a liquid solution of hydrogen bromide in excess ethyl bromide. A distillation step separates the reaction product from the recycle stream of mainly ethyl bromide. Rising gas bubbles in the cylindrical reactor having cobalt-60 at its axis react essentially completely before reaching the surface. Approximately 3000 curies of cobalt-60 are utilized in the production of in excess of 1 million pounds of product per year. Since going on stream in 1963, the continuously operating plant has required only routine maintenance other than the approximately 20% isotope replacement per year.



Initiation

$$HBr \sim\sim\sim\rightarrow H\cdot + Br\cdot$$

$$C_2H_4 \sim\sim\sim\rightarrow C_2H_2 + 2\,H\cdot$$

$$H\cdot + HBr \rightarrow H_2 + Br\cdot$$

Propagation

$$Br\cdot + C_2H_4 \rightarrow \cdot CH_2CH_2Br$$

$$\cdot CH_2CH_2Br + HBr \rightarrow CH_3CH_2Br + Br\cdot$$

Termination

$$2\,Br\cdot \rightarrow Br_2$$

$$2 \cdot CH_2CH_2Br \rightarrow BrCH_2CH_2CH_2CH_2Br$$

The chemical yield was, depending on reaction conditions, in the range 0.001 – 0.01 mol/J.

$HBr + C_2H_4 \rightarrow C_2H_5Br \quad \Delta H = -80$ kJ/mol

0.003 MCi source ~ 75W ~ 1/100 SF assembly)

$G \sim 10^3 – 10^4$

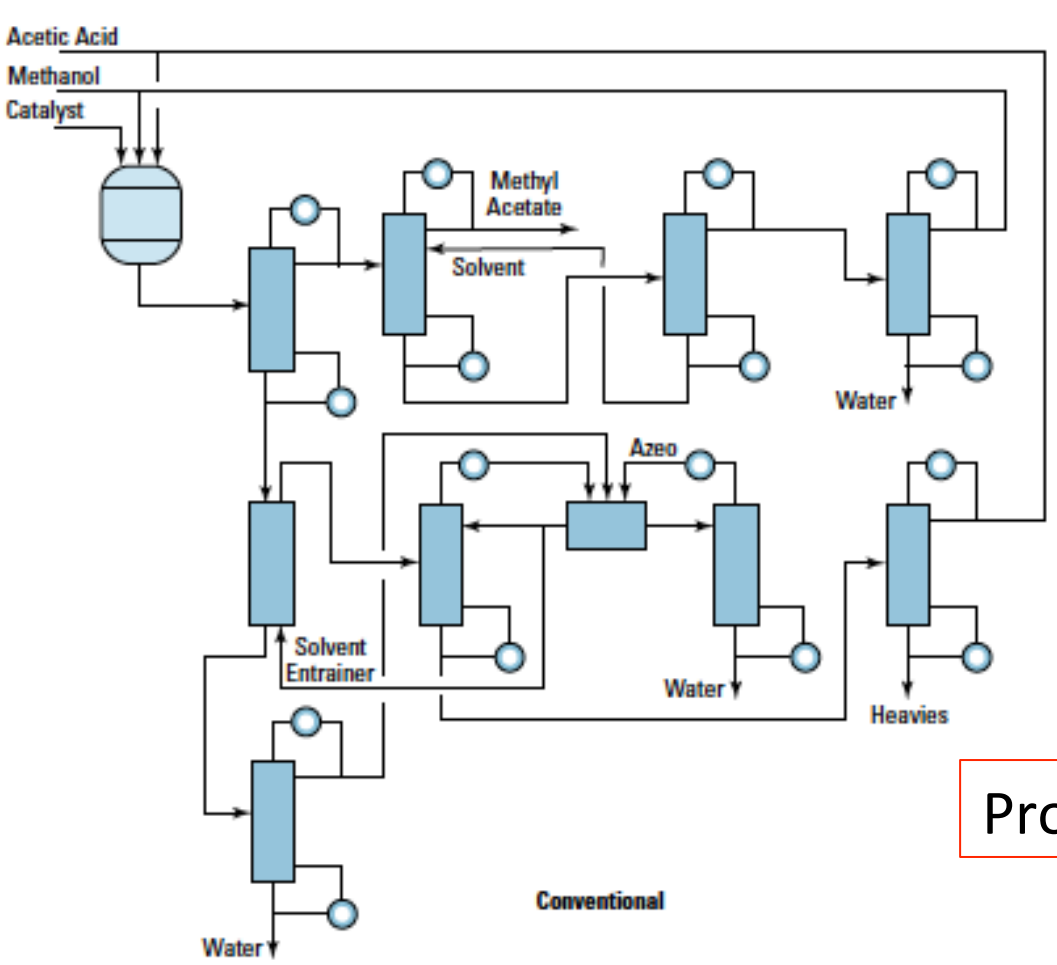
Table I Industrial application of photochemical synthesis[a].

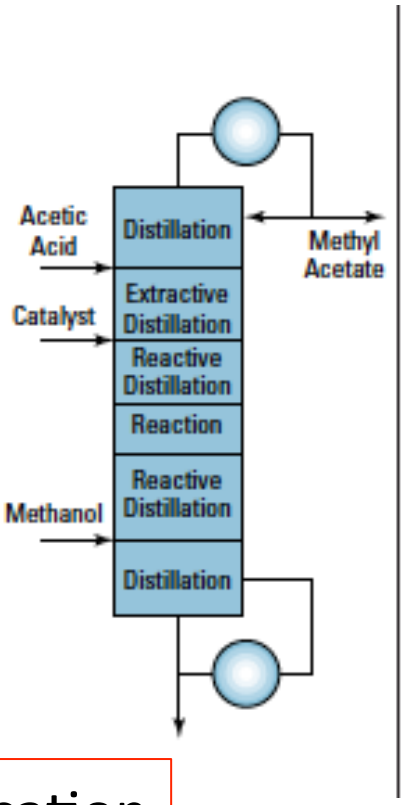
Reaction	Unit production[b]	Lamp[c]
FREE RADICAL REACTIONS		
Photochlorination		
$RH + Cl_2 \xrightarrow{h\nu} RCl$	10,000 Mg/a	7.5 kW(Hg)
$C_6H_6 + Cl_2 \xrightarrow{h\nu} C_6Cl_6$	250 Mg/a	1.5 kW(Hg)
Toluene + $Cl_2 \xrightarrow{h\nu}$ benzyl chloride,[d] benzyl dichloride, benzyl trichloride	~	~
Sulfochlorination		
$RH + SO_2 + Cl_2 \xrightarrow{h\nu} RSO_2Cl + HCl$	250 Mg/a	30 W(Hg)
Sulfoxidation		
$RH + SO_2 + O_2 \xrightarrow{h\nu} RSO_3H \xrightarrow{NaOH} RSO_3Na$	1600 Mg/a	40 kW(Hg)
Photonitrosation		
$c\text{-}C_6H_{12} + NOCl \xrightarrow{h\nu}$ *cyclohexanone oxime* $\xrightarrow{H_2SO_4}$ caprolactam ⟶ Nylon 6	10,000 Mg/a	3 MW(Hg/T1)
$cC_{12}H_{24} + NOCl \xrightarrow{h\nu}$ *cyclododecanone oxime* $\xrightarrow{H_2SO_4}$ lauryllactam ⟶ Nylon-12	8000 Mg/a	≈ 5 MW(Hg(T1))
STOICHIOMETRIC REACTIONS		
7-dehydrocholesterol $\xrightarrow{h\nu}$ *Pre-vitamin-D* $\xrightarrow{heat}$ vitamin-D_3	4 MgA	40 kW(Hg)

Gamma Radiation can be a much cheaper Source of photons!

Challenge of the 21st Century Plant Capital Reduction

Central to economically sustainable chemical processes

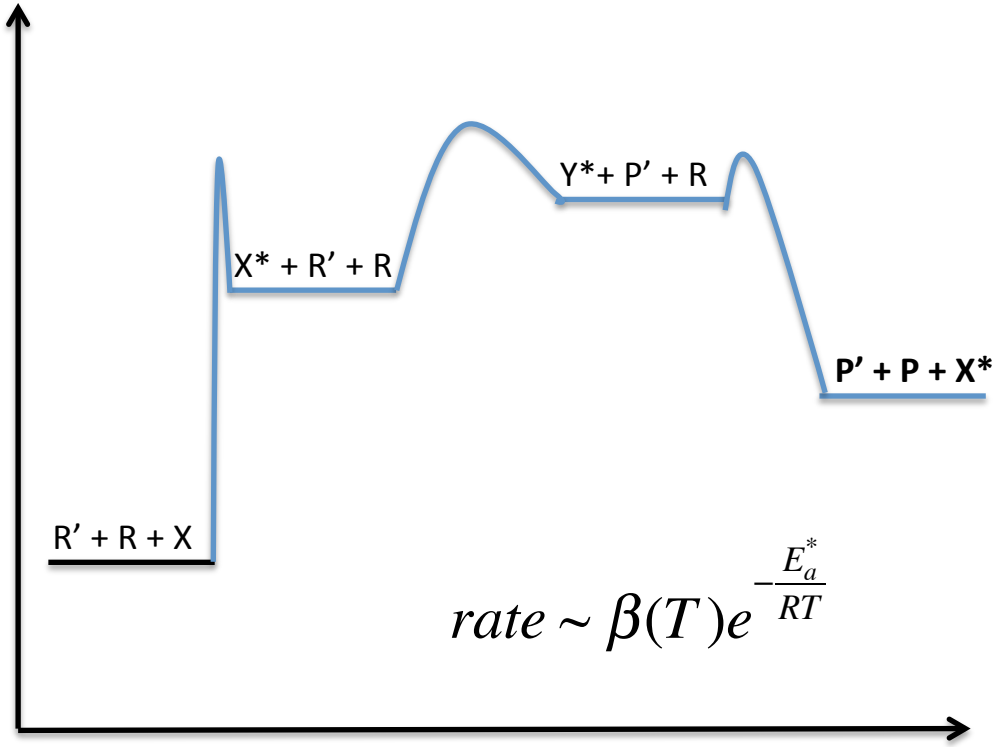




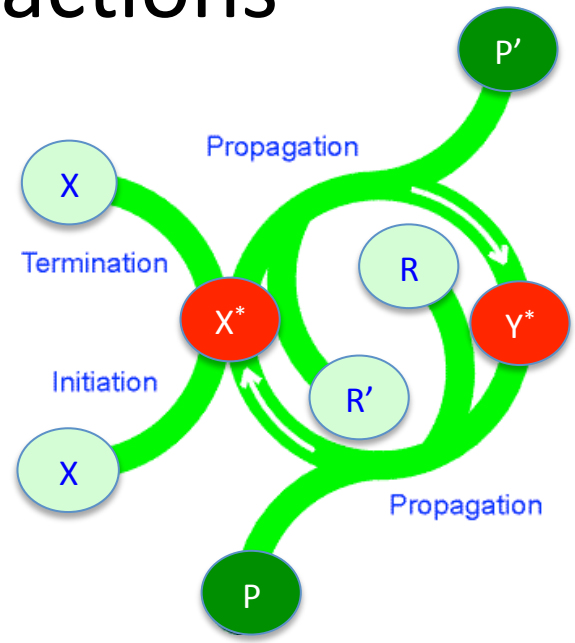
Process Intensification

Integrate, combine, eliminate, simplify → decreased capital, increased safety

Thermochemical Chain Reactions

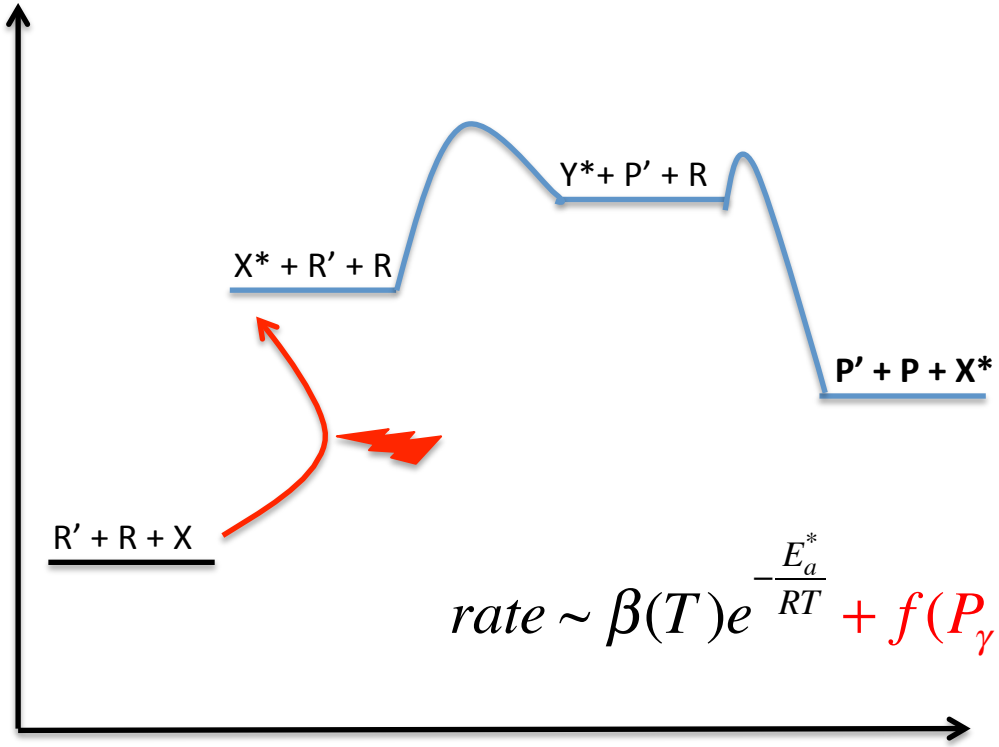


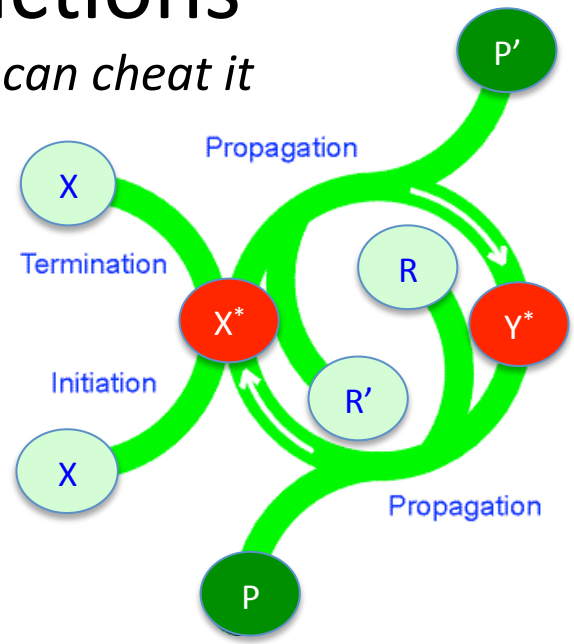
$$rate \sim \beta(T)e^{-\frac{E_a^*}{RT}}$$



Photochemical Chain Reactions

Don't Really Beat Thermodynamics, But…you can cheat it

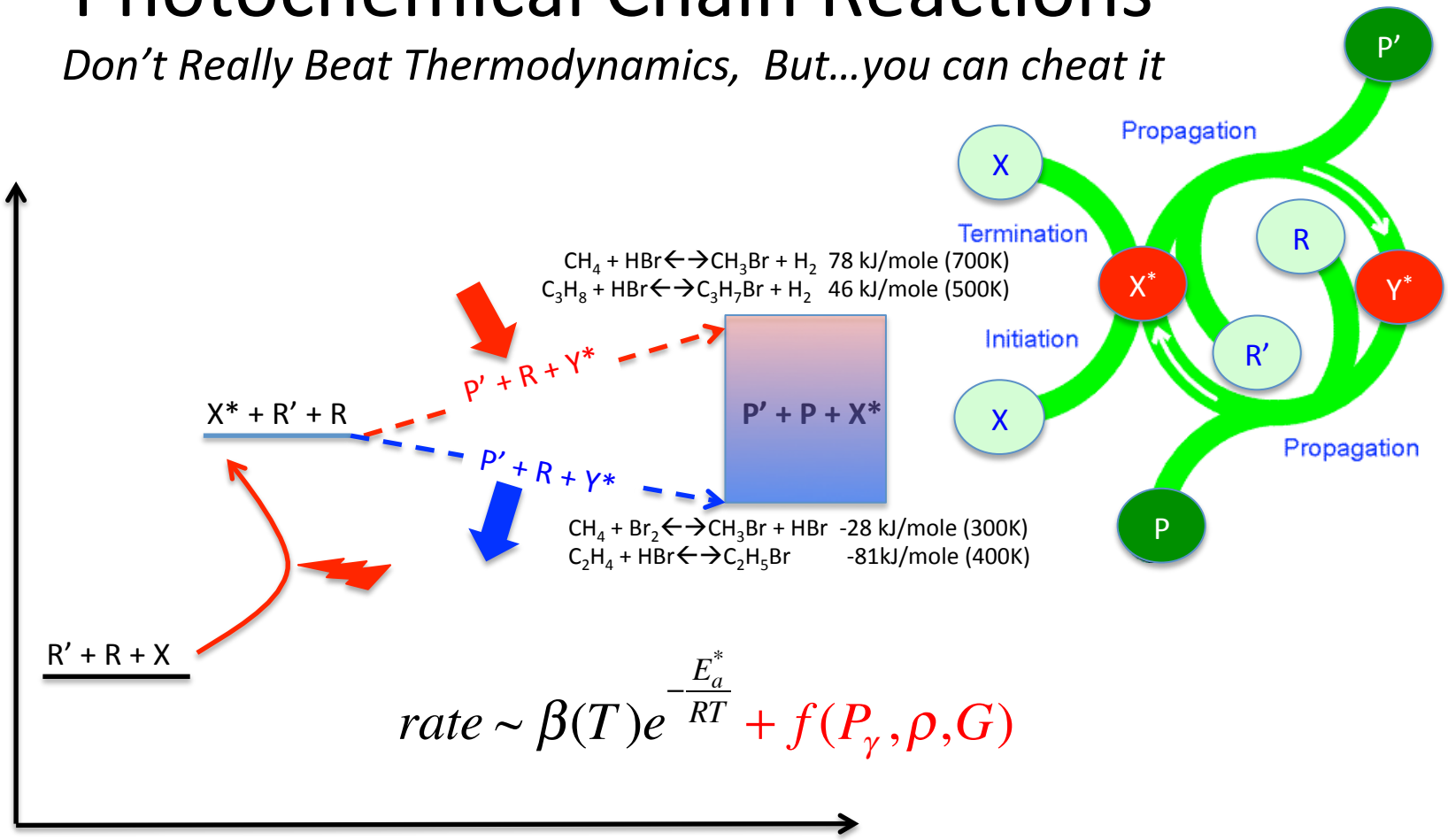




$$rate \sim \beta(T) e^{-\frac{E_a^*}{RT}} + f(P_\gamma, \rho, G)$$

Photochemical Chain Reactions

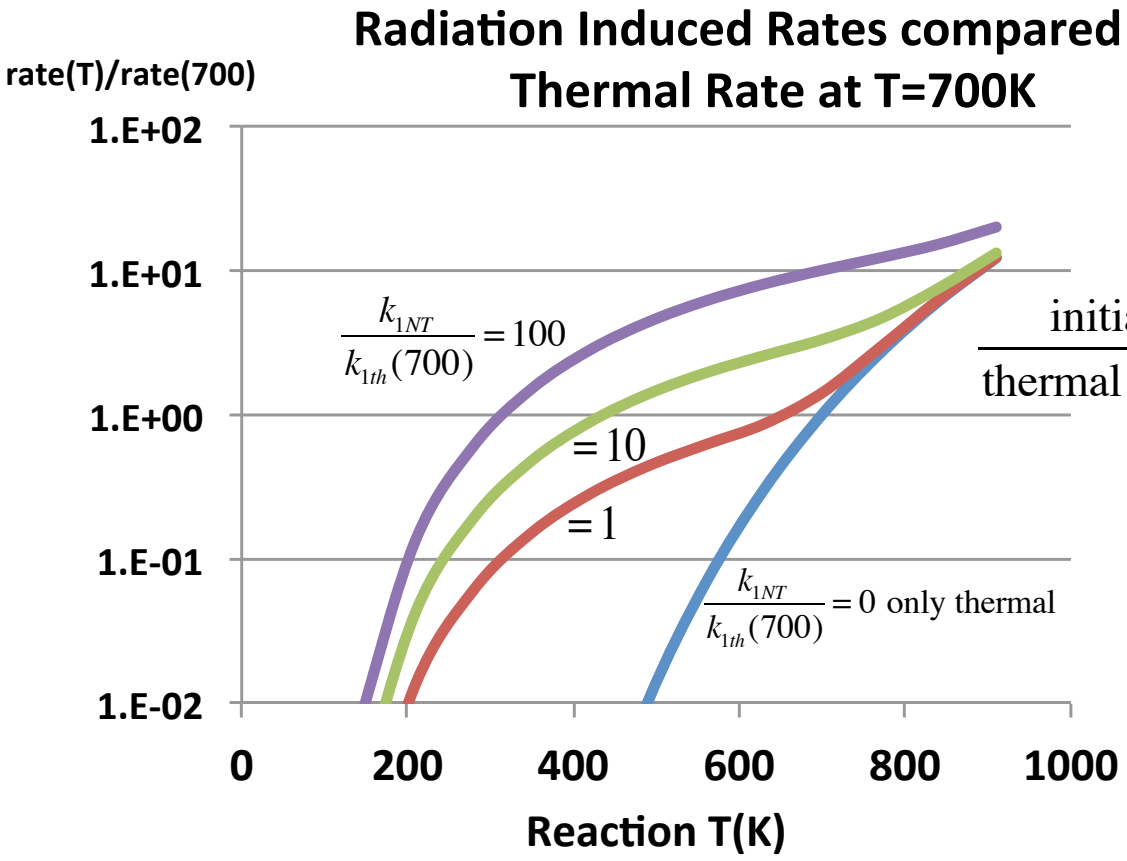
Don't Really Beat Thermodynamics, But…you can cheat it



$$rate \sim \beta(T)e^{-\frac{E_a^*}{RT}} + f(P_\gamma, \rho, G)$$

Gamma Induced Chain Reaction Rates Equivalent to Thermochemistry at Higher T

Modest G can allow 200-300 K lower temperatures, increased selectivity!



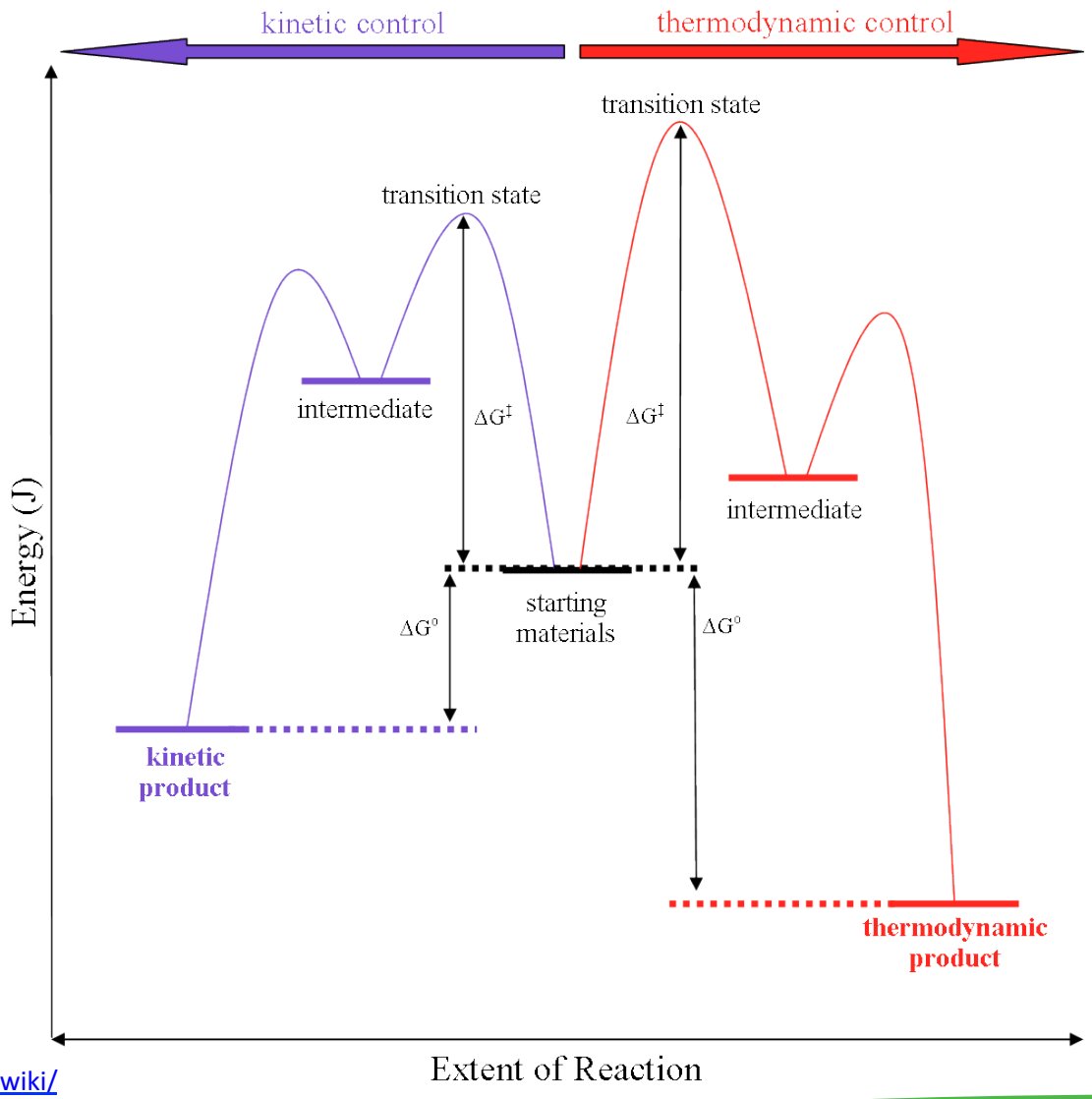
$$\frac{\text{initiation rate with } \gamma\ (T)}{\text{thermal initiation rate (T=700K)}} = \frac{k_{1NT}}{k_{1th}(700)}$$

$$k_{1NT} \sim G\ x\ Flux$$

$$E_{A1} = 1eV$$

$$E_{A2-4} = 0.1eV$$

Less byproducts (cost) can be achieved by kinetic control of reaction

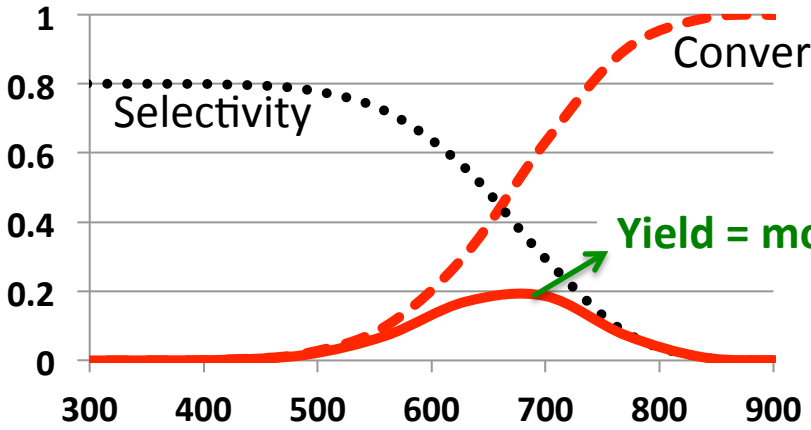


http://commons.wikimedia.org/wiki/
File:Thermodyamic_versus_kinetic_control.png

Allow reactions to be performed under conditions minimizing byproducts and facilitating separations

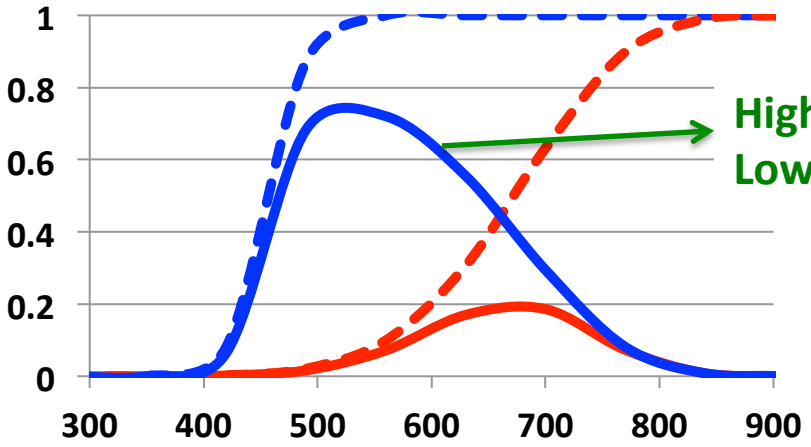
Process Intensification → Reduced Capital

Thermochemical
Single Pass



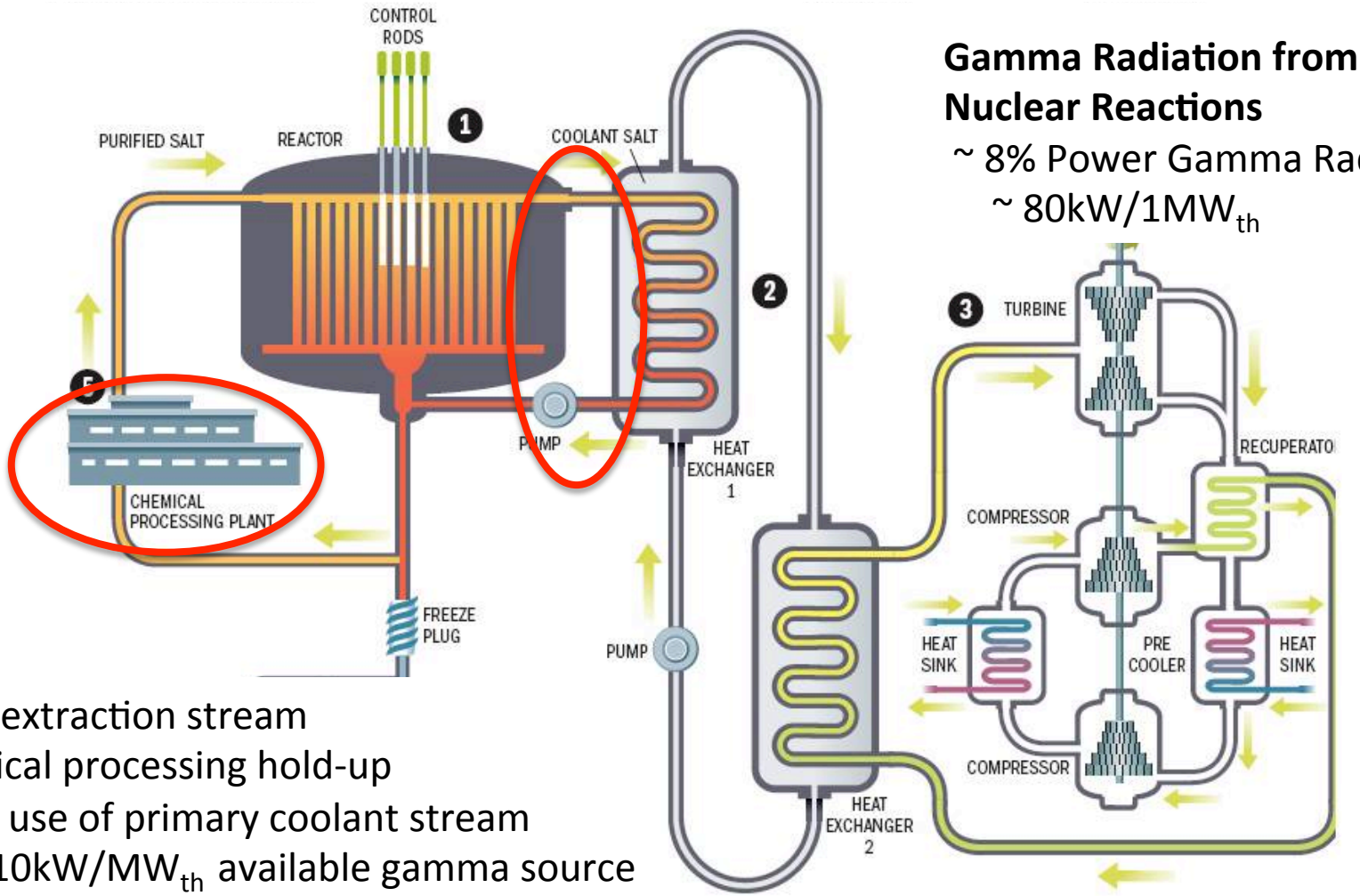
Yield = moles prod/moles reactant ~ $

Radiation Chemical
Single Pass



Higher Yield $$
Lower Temp $$

Gen VI Reactors: The Molten Salt Reactor is Uniquely Suited for Chemical Production Using Outside Core Fuel Loop (isotopes, gamma source)



Gamma Radiation from Nuclear Reactions

~ 8% Power Gamma Radiation

~ 80kW/1MW$_{th}$

Xe/Kr extraction stream

Chemical processing hold-up

Direct use of primary coolant stream

~ 5 - 10kW/MW$_{th}$ available gamma source

Molten Salt has Technical Challenges

but the isotopes are dissolved and we can get them

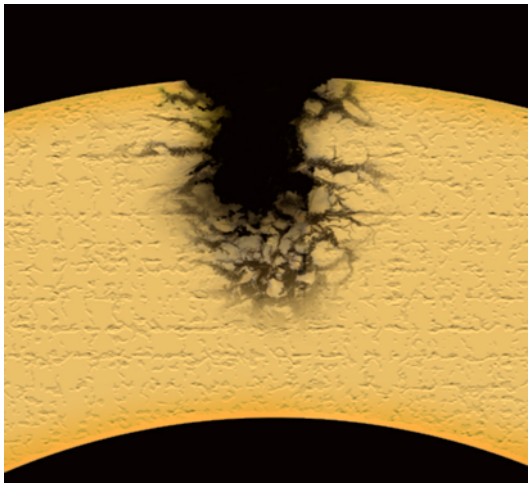
Low Pressure
High Heat Capacity

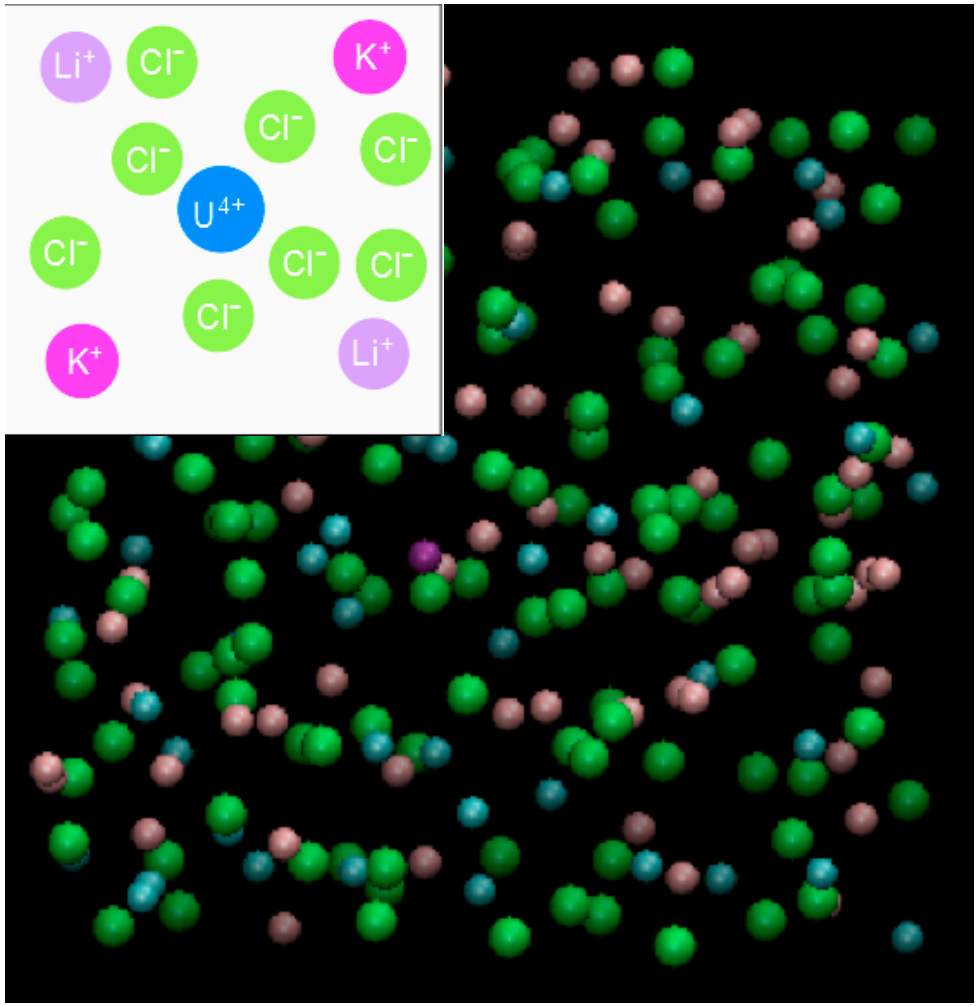
$LiF\text{-}BeF_2\text{-}ThF_4\text{-}UF_4$

$LiF\text{-}BeF_2\text{-}ZrF_4\text{-}F_4$

$LiF–ZrF_4$

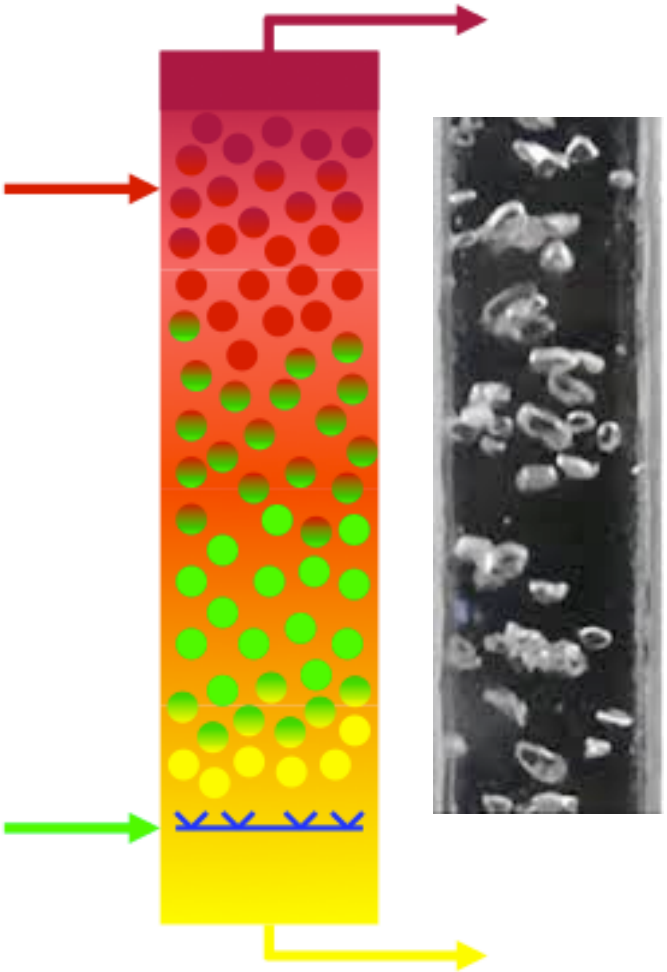
Corrosive



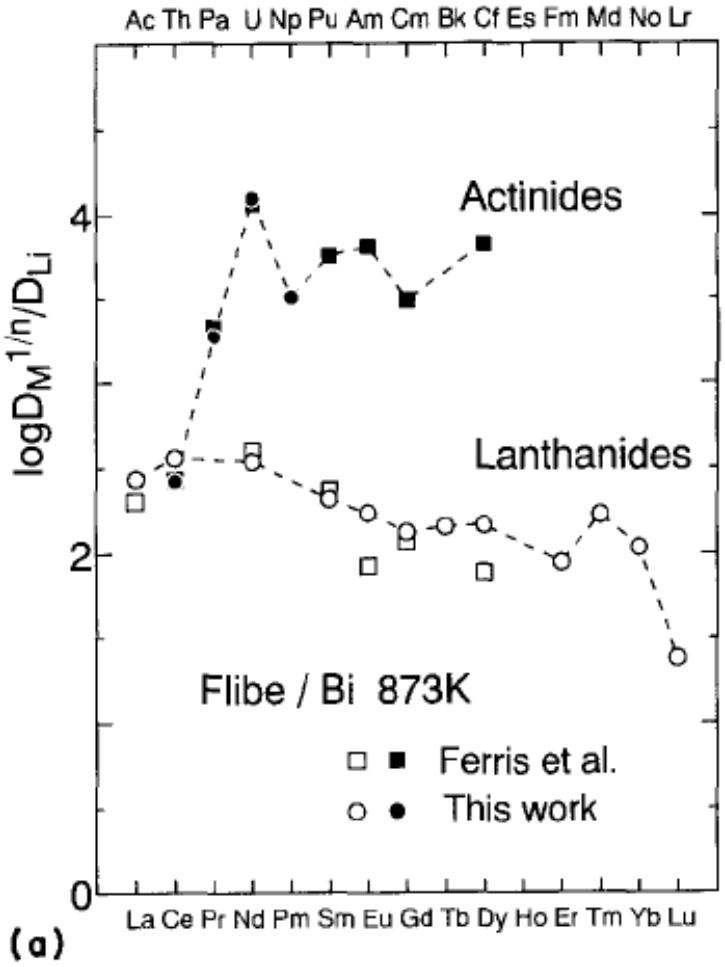


L-L Extraction Technology Exists

Salt←→Metal



H. Moriyama et al.

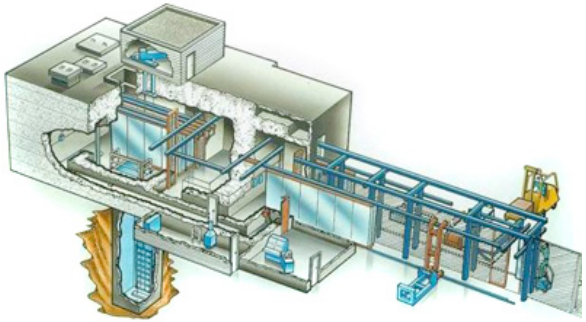


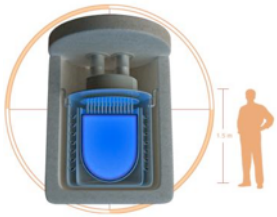
Journal of Alloys and Compounds, 213/214 (1994) 354–359
JALCOM 4099

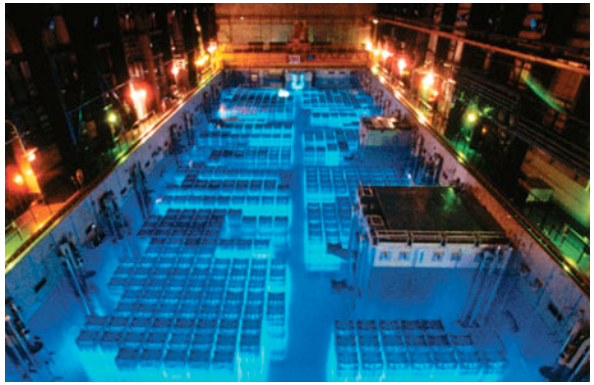
Our Approach: Start With Highest Value Products at Small Scale

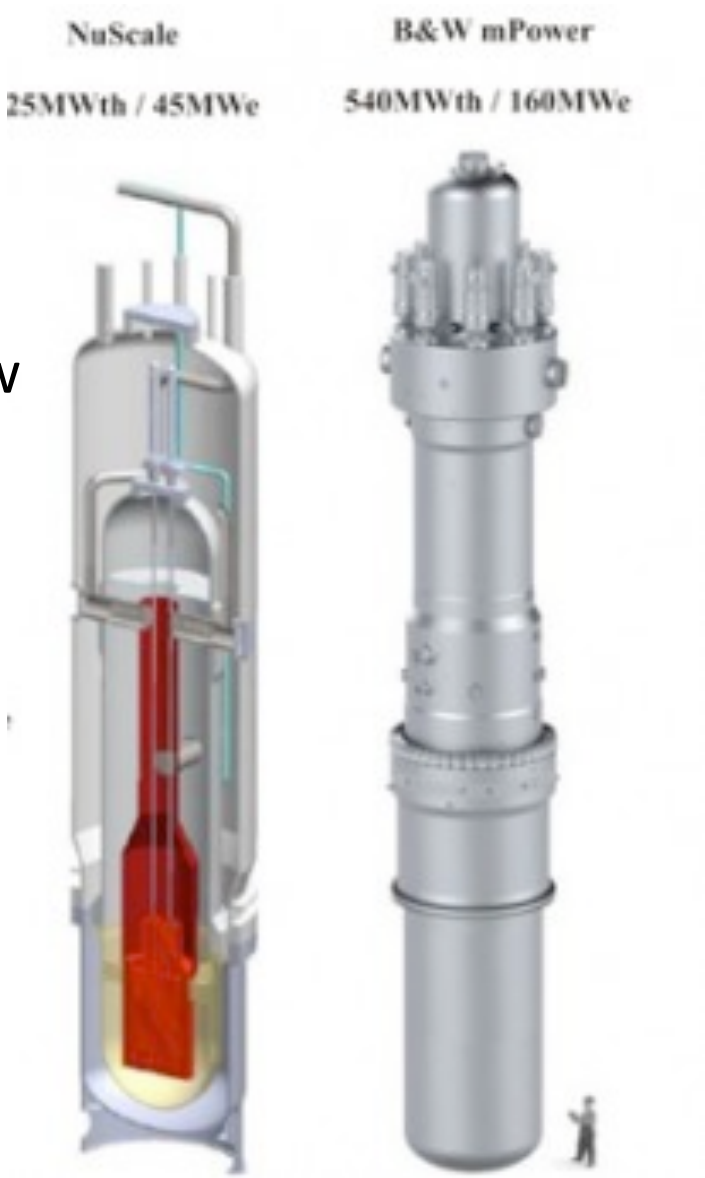
(under the regulatory radar)

Today ---------- -> Tomorrow

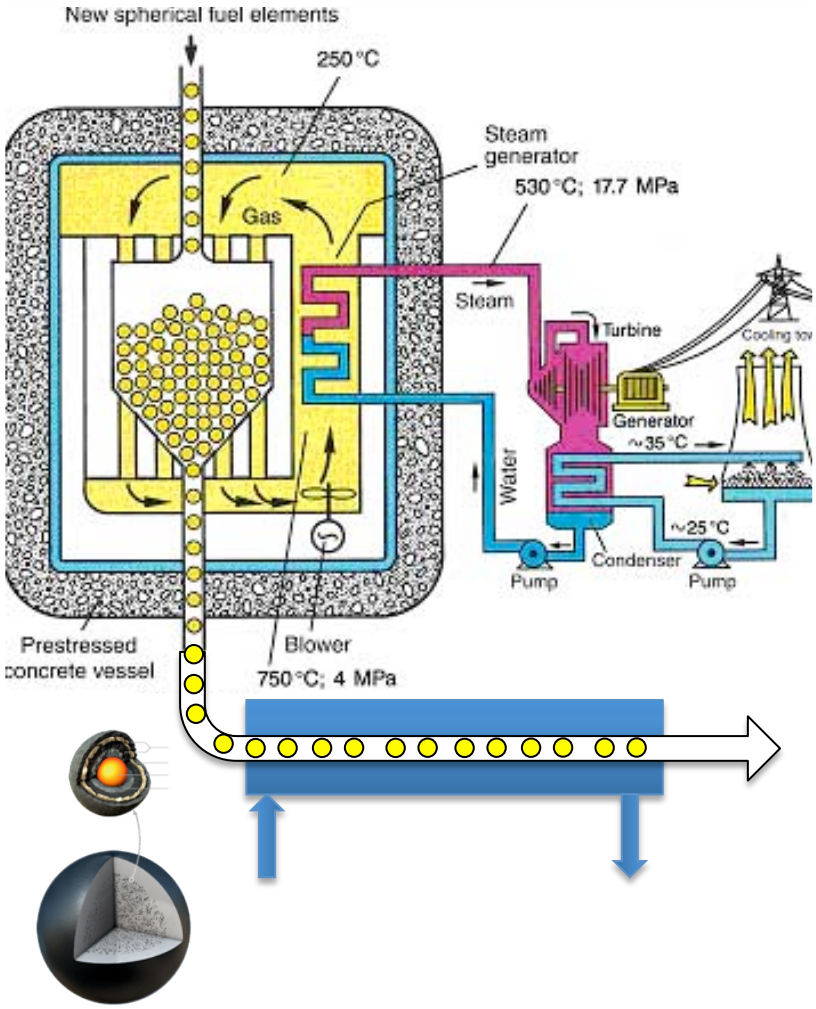


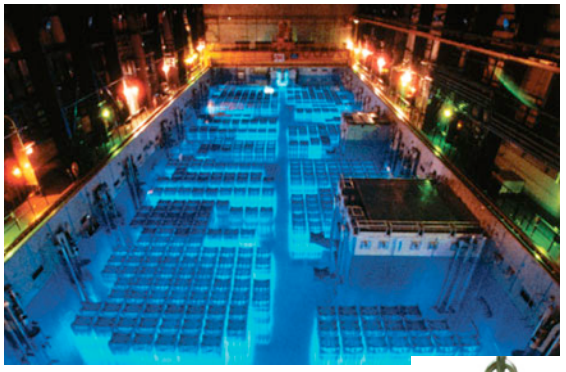






Spent Fuel as Gamma Source





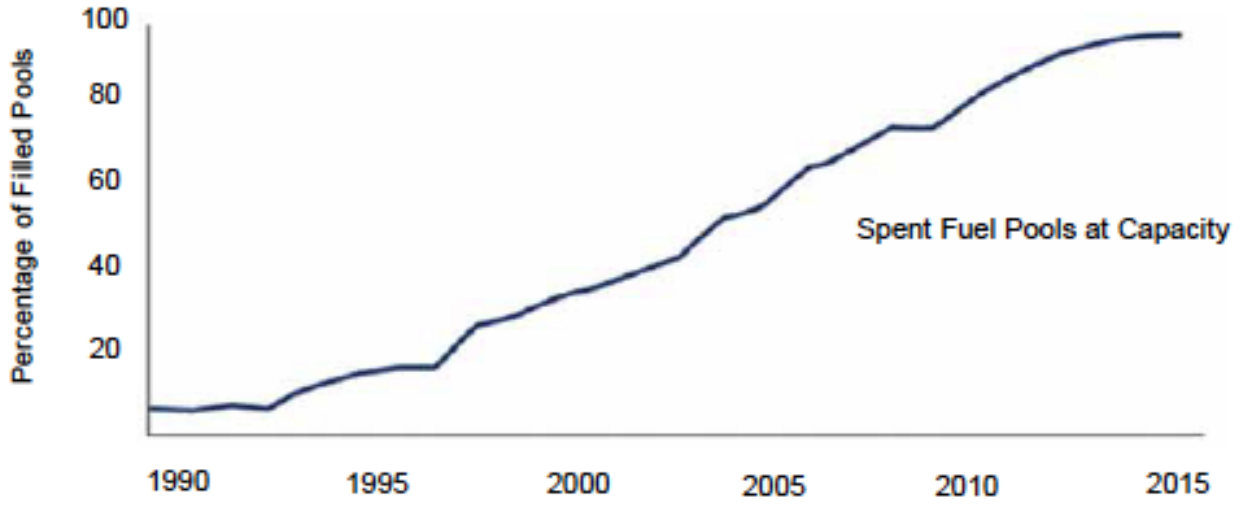
60 assemblies per year removed in typical 1GWe reactor

At 1-4 years after shutdown (0.1% power)
~ 15kW per assembly (50% gamma, 50% beta)
At G=10 → ~ 0.25 kta per assembly
~ 3000 W/m^2

U.S. ~ 218,700+ Spent Fuel Assemblies;

12 Billion Curies; 65 kilotonnes of U

Figure 12: High-Density Spent Fuel Pools at U.S. Nuclear Reactors are Soon to Reach their Maximum Capacity



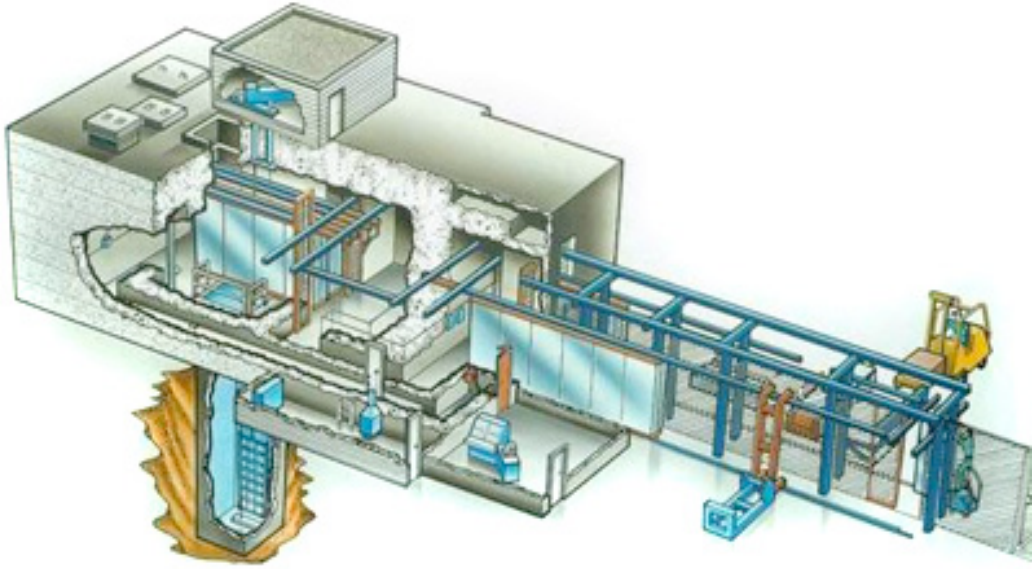
Source: *Power Magazine*, May 2010. Available on line: http://www.powermag.com/nuclear/The-U-S-Spent-Nuclear-Fuel-Policy-Road-to-Nowhere_2651_p6.html

In the US, there is more than 2 kta of new U waste generated each year (~36 tons/GW-y) 75% is stored in pools, 25% in dry casks.

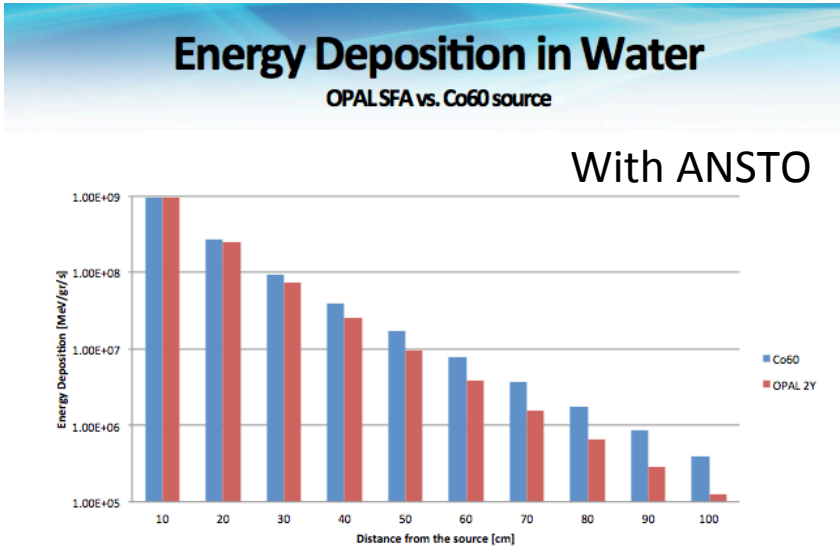
Zero, value is obtained from 12 billion Curies of activity.

Commercial Irradiation Facilities

Available today and useful for cost estimates



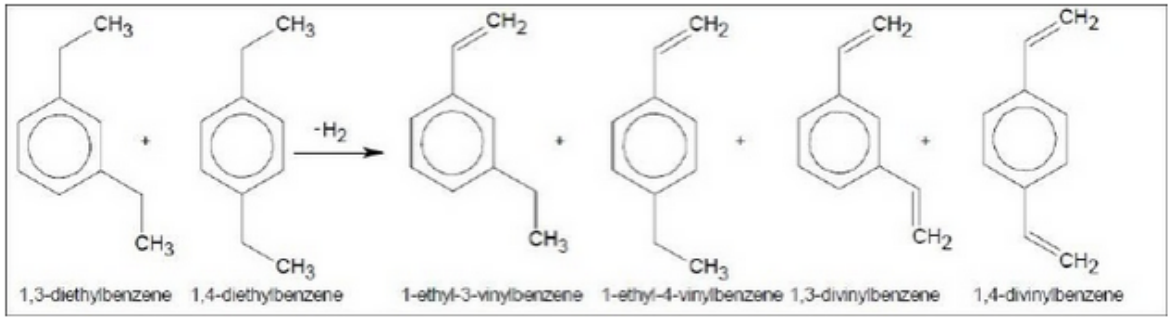
http://www0.tint.or.th/nkc/nkc53/content/nstkc53-077.html



With ANSTO

Small Scale Example: Divinylbenzene ($4-6/kg)

Polymer additive, crosslinking ion-exchange



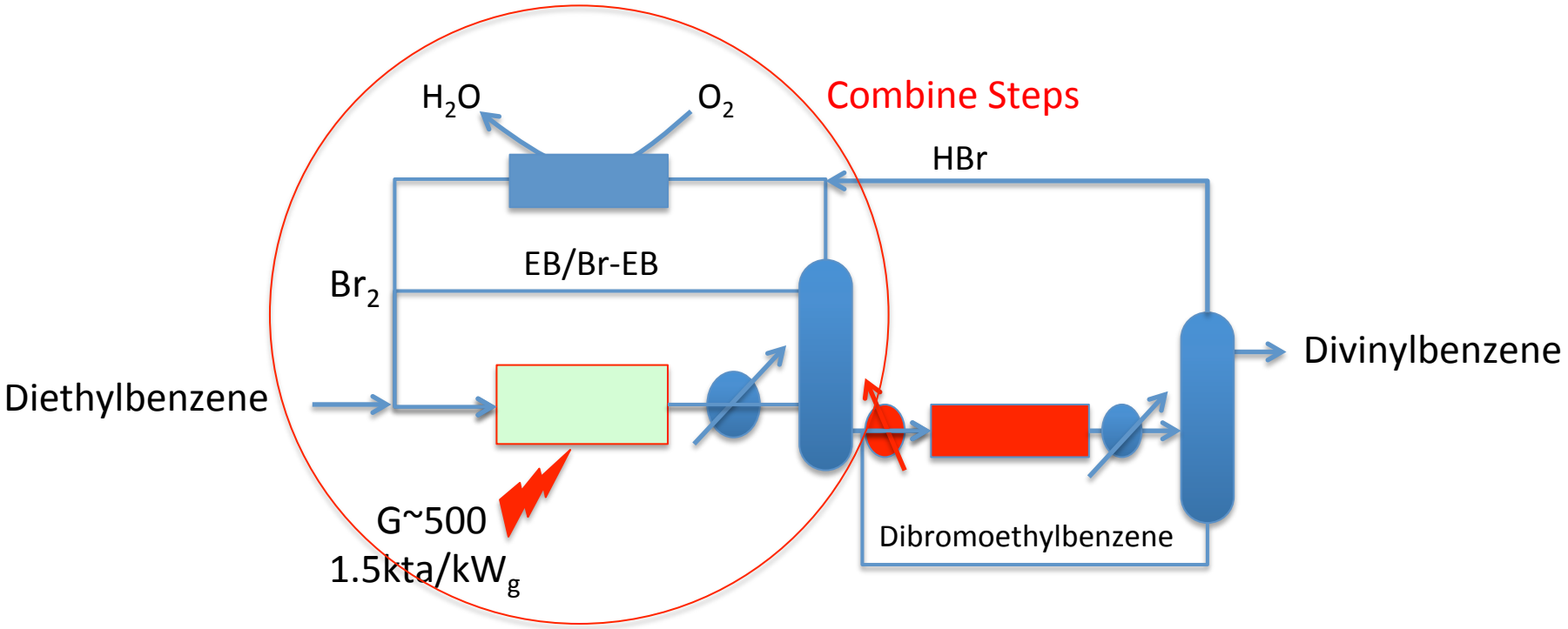
High Temp, Low P reaction
Mixture of DVB + EVB
Difficult Separation
(Low T, High P)

Typical Chemical Analysis and Structural Formulae[1]

Structural Formula	DVB-55	DVB-63	DVB-HP
Total Divinylbenzene[2]	56%	63.5%	80%
Meta:Para Divinylbenzene isomer ratio	2.3	2.3	2.3
Total Ethylvinylbenzene[3]	43.0%	35.5%	19%
Meta:Para Ethylvinylbenzene isomer ratio	2.3	2.3	2.3
Diethylbenzene	<0.05%	<0.05%	<0.05%
Naphthalene	<0.04%	<0.04%	<0.04%
Benzene content	N.D.	N.D.	N.D.
t-butyl catechol inhibitor	900-1100 ppm	—	900-1100 ppm
Color (Gardner)	<4	<4	<4
Polymer	<5 ppm	<5 ppm	<5 ppm

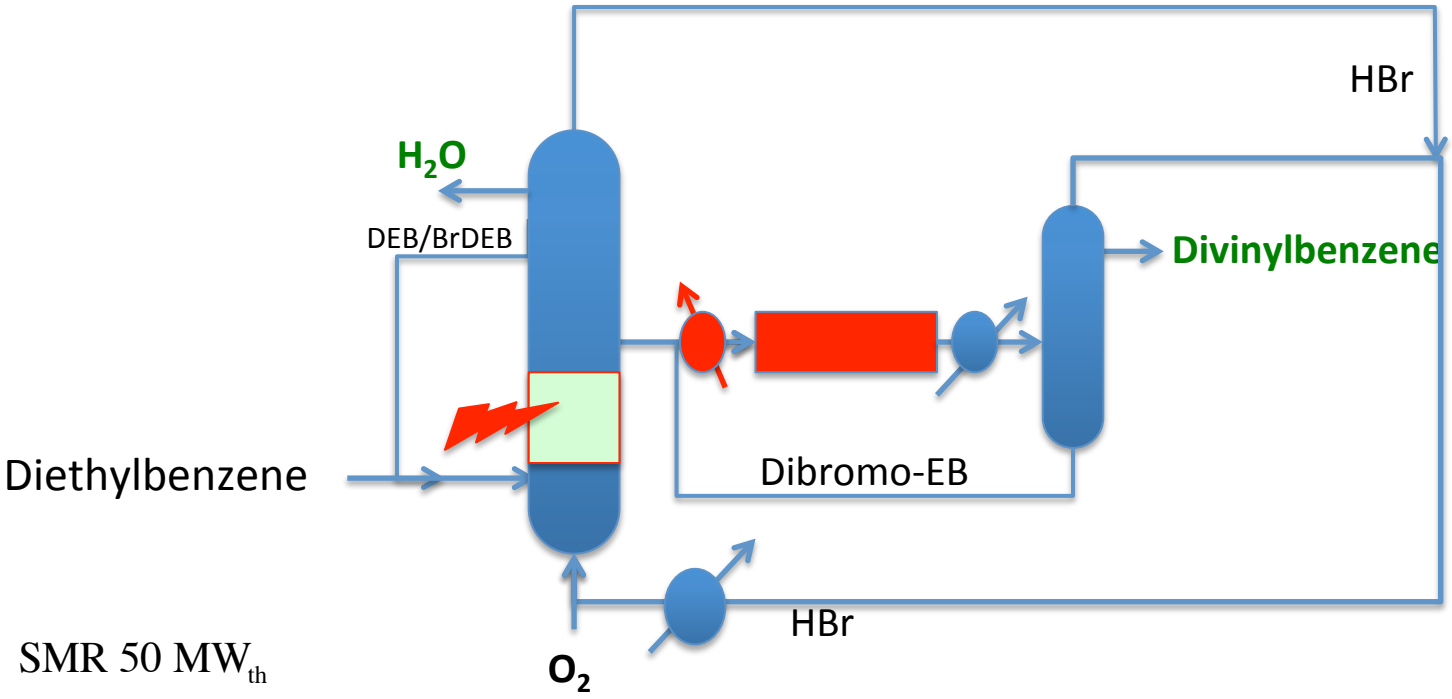
Process Intensification:

Low reaction temperature, easy separations, ~ isobaric



Process Intensification:

Radiation Reactive Distillation with Oxybromination



G~500
1.5kta/kW_g
Revenue
\$7.5M/y/kW_g

SMR 50 MW_{th}

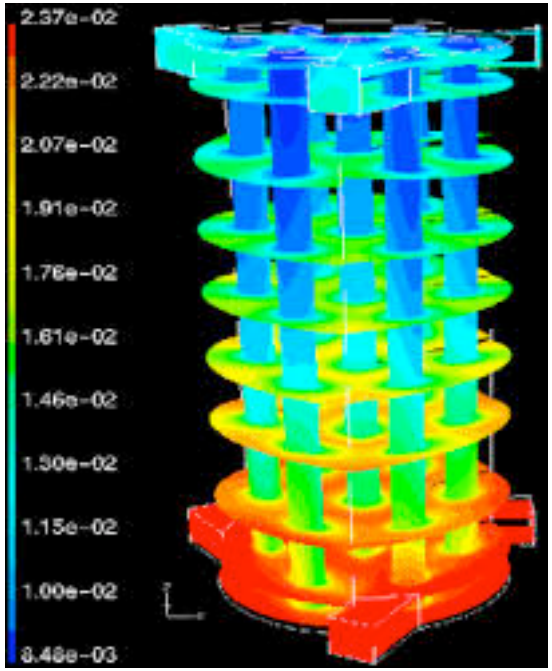
$$50\ MW_{th} \xrightarrow{0.3\,eff} 15000\ kW_e \xrightarrow{300*.9*24*365@\$0.10/kWh\sim} \$12M/y\ revenue$$

$$\xrightarrow{0.08_\gamma} 4\ MW_\gamma \xrightarrow{useful\,12.5\%} 0.5\ MW_\gamma \xrightarrow{G\sim 500\frac{\mu mole}{J}} \sim 750\ kta\ \ (too\ big\ !!)$$

USE ONLY ~ 1% of available gamma's (50kW) ~ 75 kta

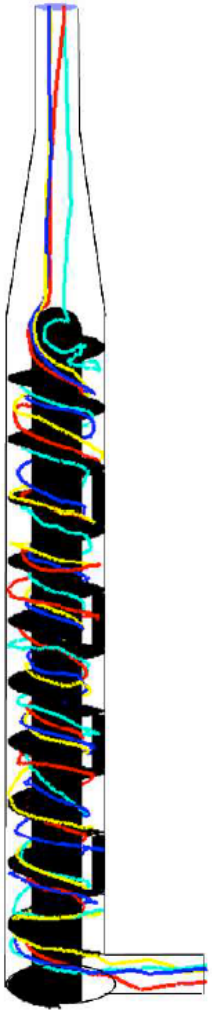
$$\xrightarrow{@\$2000/t} \$\ 150M/y\ revenue$$

Multiscale – Radiation Transport, Reaction-Transport Modeling



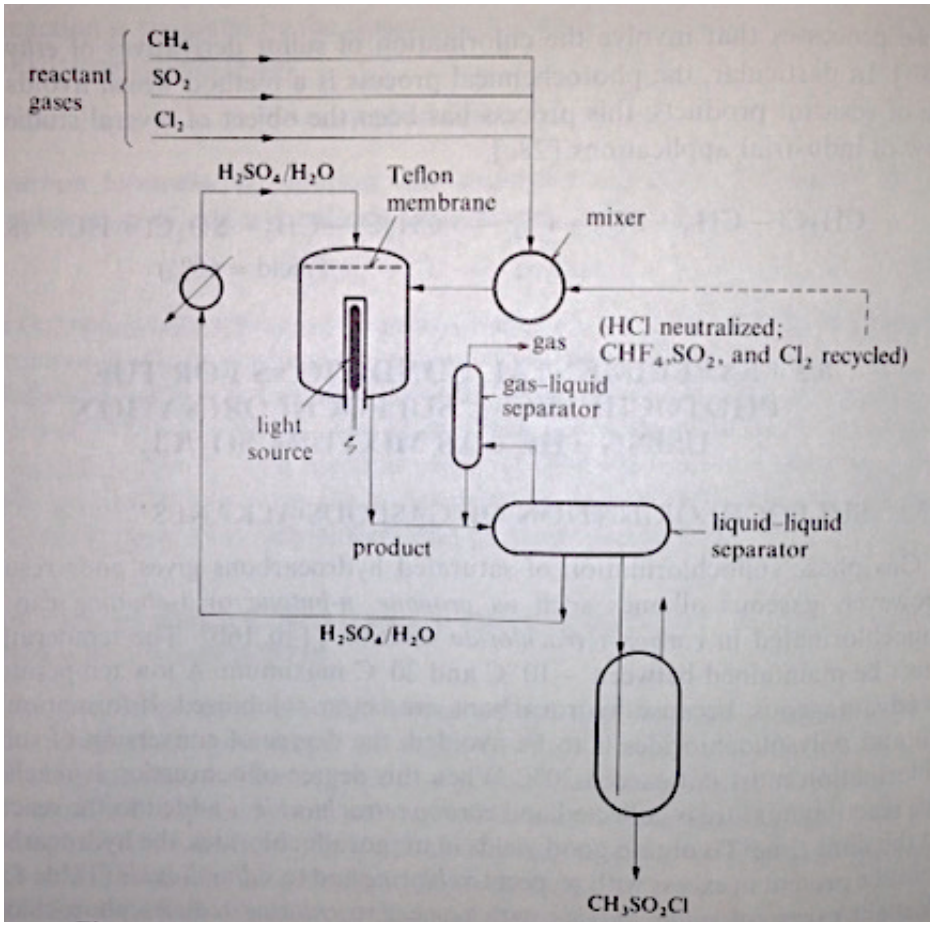
$$\frac{C_{Ao}D_i}{-r_A(C_{Ao})}\nabla^2\hat{C}_i - \frac{C_{Ao}}{-r_A(C_{Ao})\tau}\frac{\partial\hat{v}\hat{C}_i}{\partial\hat{V}} + \hat{r}_i = \frac{\partial\hat{C}_i}{\partial\hat{t}}$$

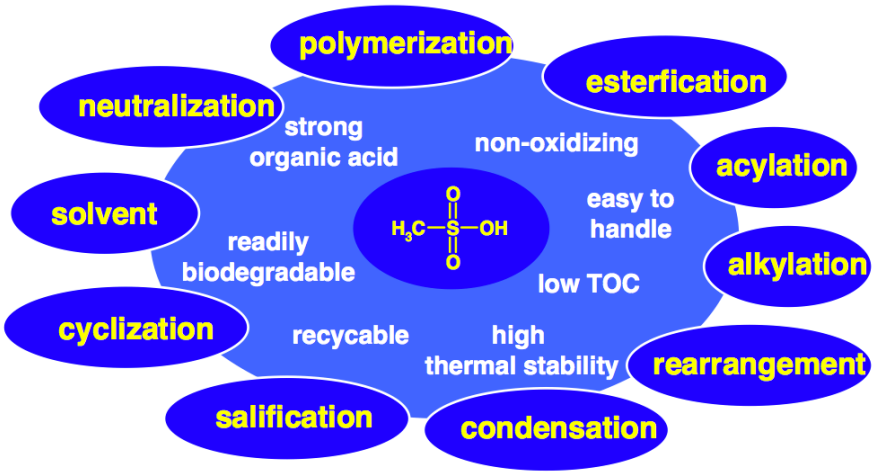
$$\boxed{\hat{r}_i = k(T,\hat{\phi}_\gamma)\hat{C}_i}$$



Medium Scale Example: Alkane sulfochlorides ($2-6/kg)

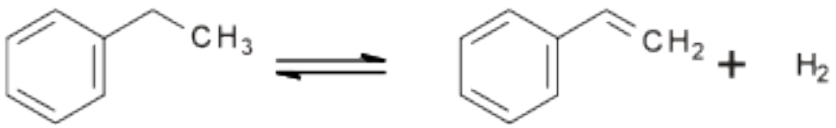
$R\text{-}H + SO_2 + Cl_2 \rightarrow R\text{-}SO_2Cl + HCl$



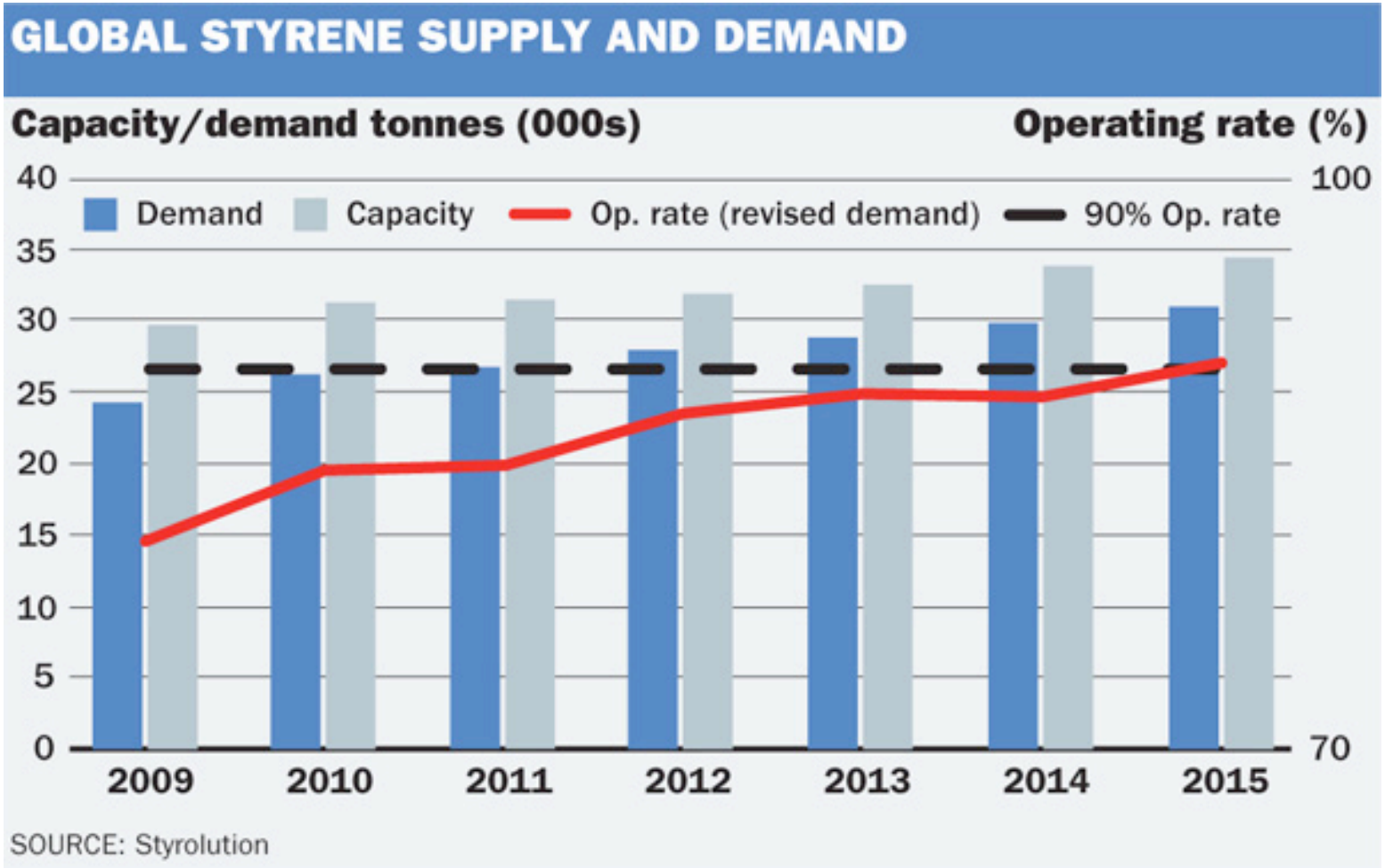


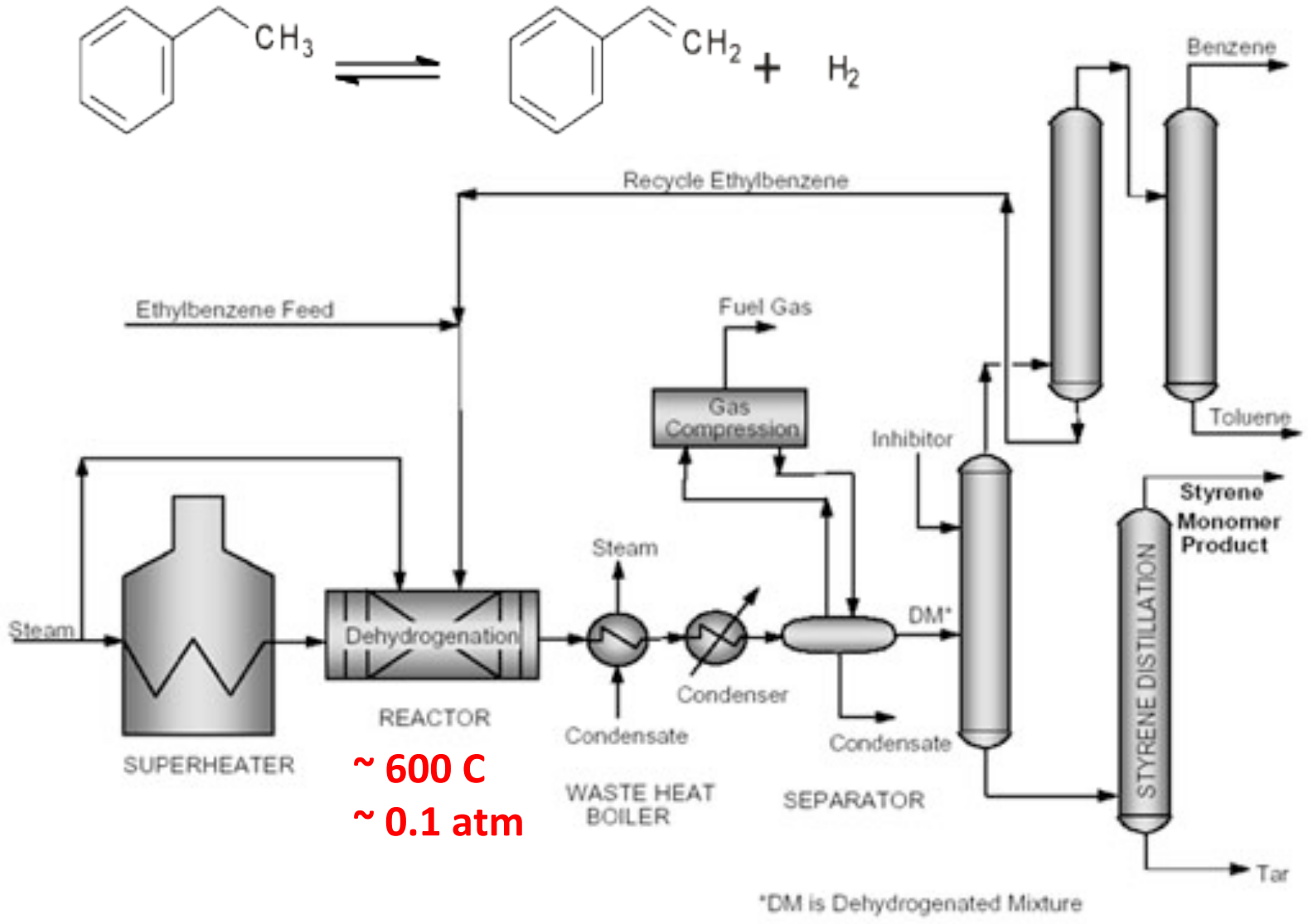
Pilot G ~ 1000

180 W Hg lamp → 9 tons C in product/y



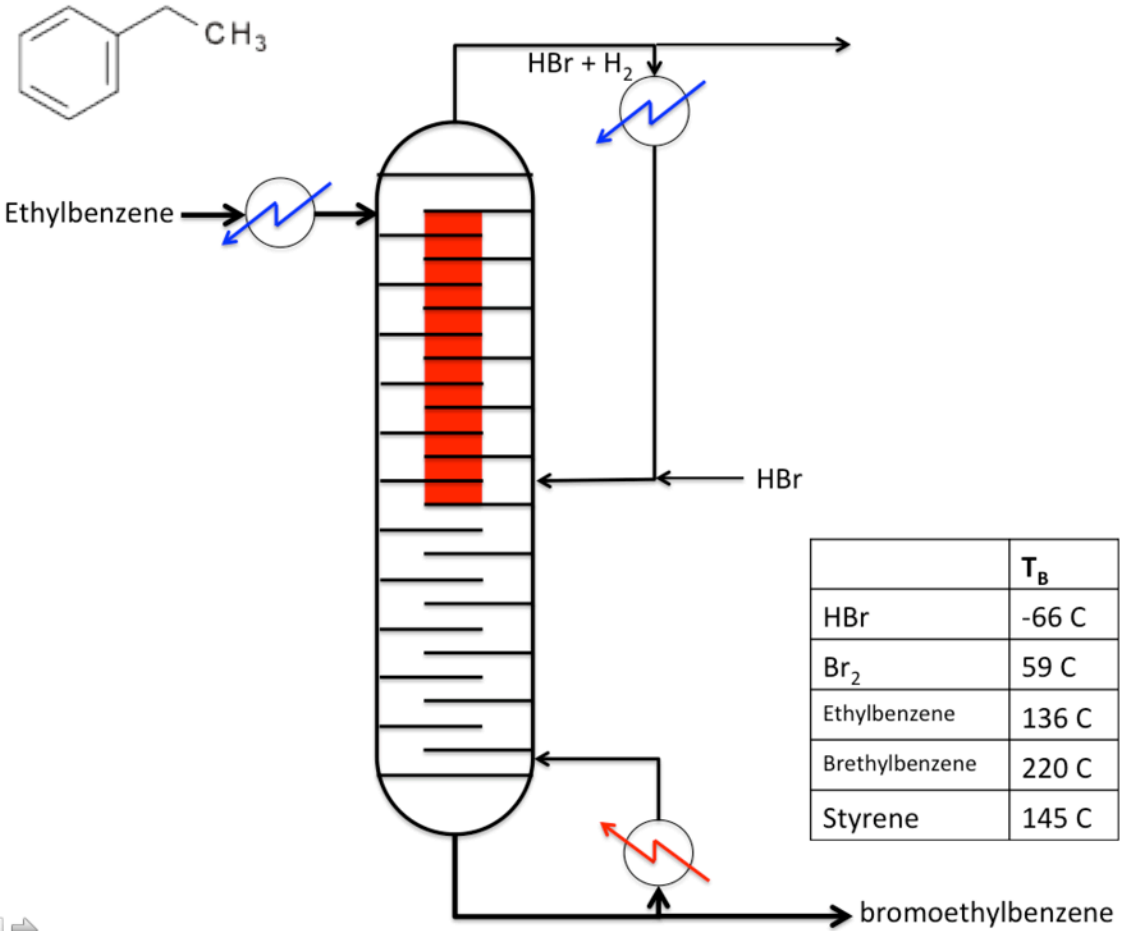
Styrene Large Scale
~ $30B/year 25,000 kta



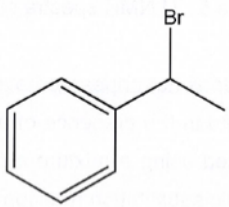

Benzene
Recycle Ethylbenzene
Ethylbenzene Feed
Fuel Gas
Gas Compression
Inhibitor
Toluene
Styrene Monomer Product
Steam
Steam
Dehydrogenation
DM*
Condenser
REACTOR
Condensate
Condensate
STYRENE DISTILLATION
SUPERHEATER
~ 600 C
~ 0.1 atm
WASTE HEAT BOILER
SEPARATOR
Tar
*DM is Dehydrogenated Mixture

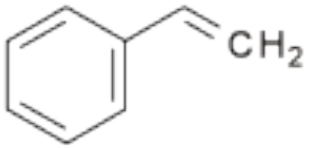
Ethylbenzene to styrene

Radiation reactive distillation



	T_B
HBr	-66 C
Br_2	59 C
Ethylbenzene	136 C
Brethylbenzene	220 C
Styrene	145 C





Gamma Ray Induced Bromination of Ethylbenzene, 20 C, G=500

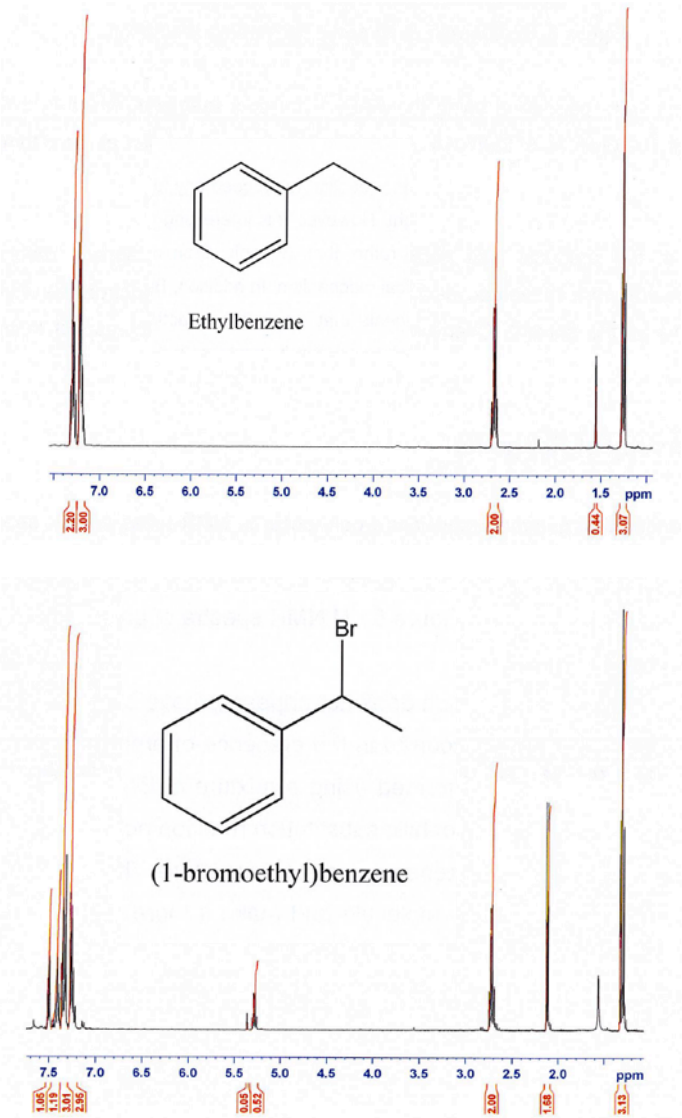
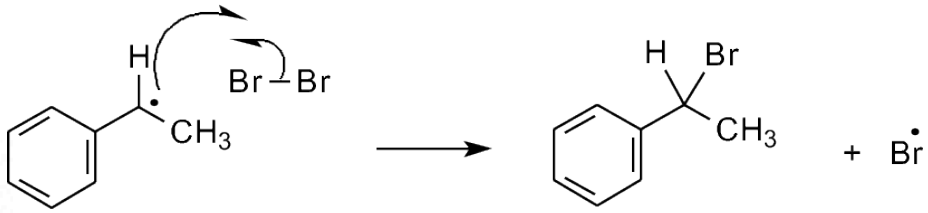


Figure 4: ^{1}H NMR spectra of products from reaction of 1:1 ethylbenzene and Br_2



Goal: Safety, Reduce Capital, ***Maximize Revenue***

$$1\ MW_{th} \xrightarrow{0.3\,eff} 300\ kW_e \xrightarrow{300*.9*24*365@\$0.10/kWh} \$250k/y\ rev$$

$$\xrightarrow{@1\,gm\,fission/MW-day} 356\ gms\ fission\ products/y \xrightarrow{@1\%\ isotope\ recovery} 3gms/y$$

$$\xrightarrow{@\$1M-\$20M/gm} \$3 - 60M/y$$

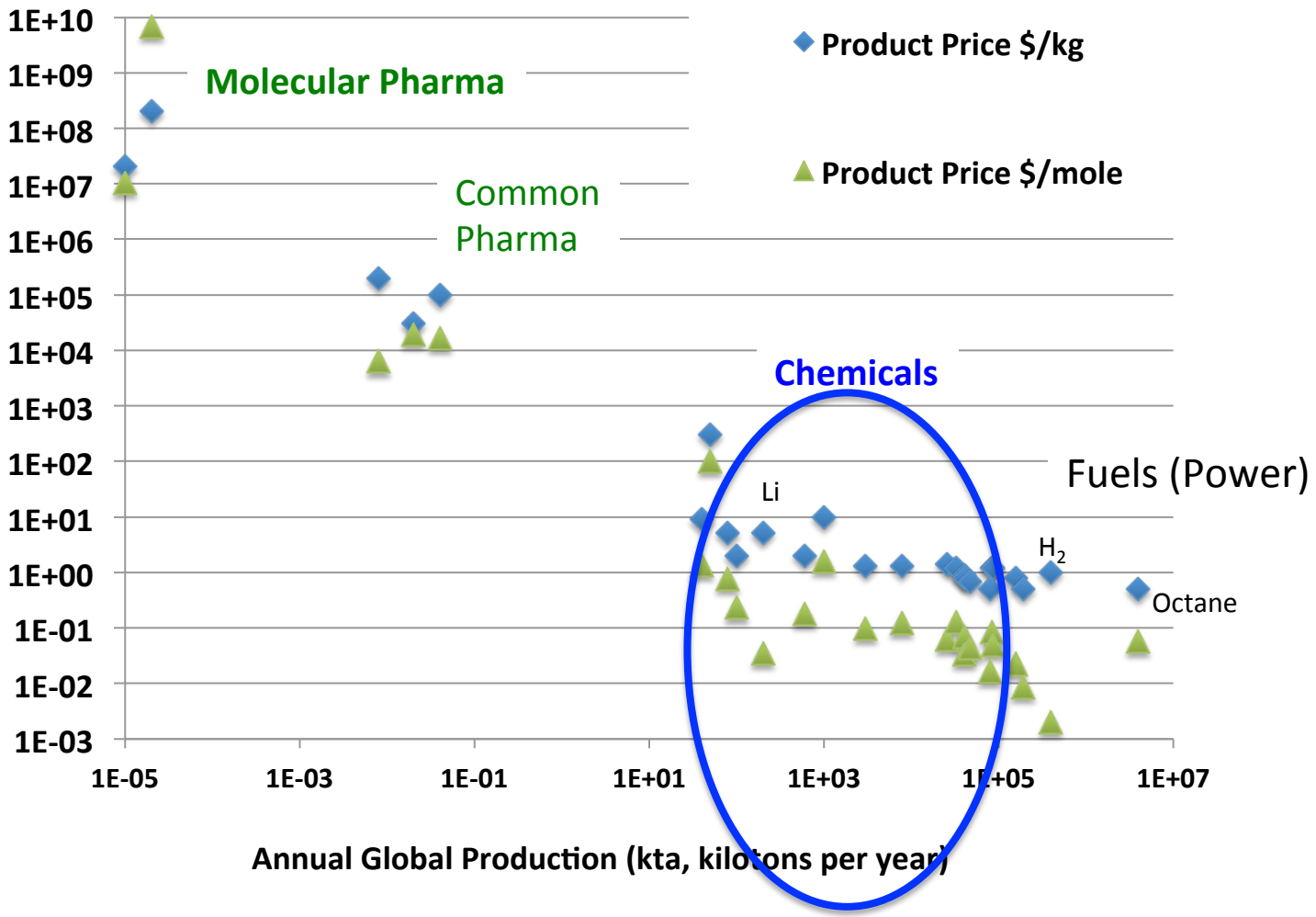
$$\xrightarrow{0.08_\gamma} 80\ kW_\gamma \xrightarrow{useful\,12.5\%} 10\ kW_\gamma \xrightarrow{G\frac{\mu mole}{J}} 3x10^5\ \frac{mol}{y}\ x\ G \xrightarrow{\frac{0.1kg}{mole}} G30\ tons/y$$

$$\xrightarrow{@\$1000/t} G\ x\ \$30k/y$$

For G > 10 Chemical Revenue > Power Revenue

One Large $3GW_{th}$ reactor produces at most ~ $750M in annual power revenue. By use of only, ~ 3 MW of gamma radiation, a 1000 kta, world scale, styrene process could be enabled producing $1B in revenue assuming only G~100

$$1\ \mathrm{GW_{th}} \longrightarrow 300\ \mathrm{MW_e} \longrightarrow 10\ \mathrm{MW_\gamma} \longrightarrow G30\ \mathrm{kta}$$



1 – 100 GW @ G~10

Summary

- **Nuclear power is the only proven technology with the potential for massive production of carbon free electrical energy production.** *Modern designs, advances in waste management, and closed fuel cycles have minimized safety and sustainability risks.*
- **Today, nuclear power is not economically competitive with fossil fuels for power generation.** *We are offering society a money losing proposition that nobody wants.*
- **Co-production of higher value chemicals with relatively large markets may be a means for increasing the value produced by a nuclear power facility and improve the overall economics.**
- **There is tremendous opportunity for engineering innovation in creating new reactor designs and new, cost effective, chemical processes based on nuclear reactions.**

We need smart young people to think differently.