IAEA 60 Years
Atoms for Peace and Development

Industrial and Environmental Applications of Electron Accelerators: Prospects and Challenges

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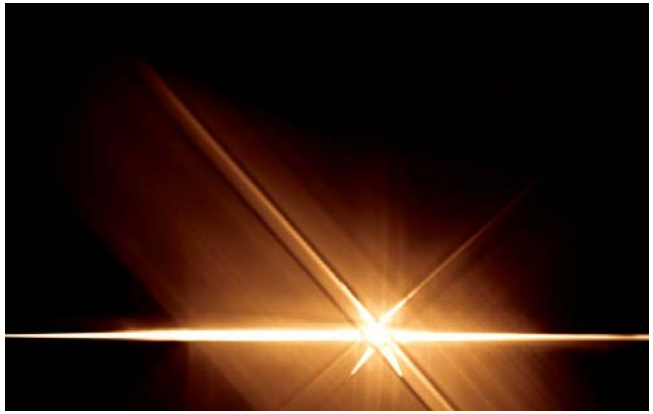
EuCARD-2 Workshop with Industry - 8-9 December 2016 Warsaw, Poland

Greetings from the IAEA

Outline of the presentation

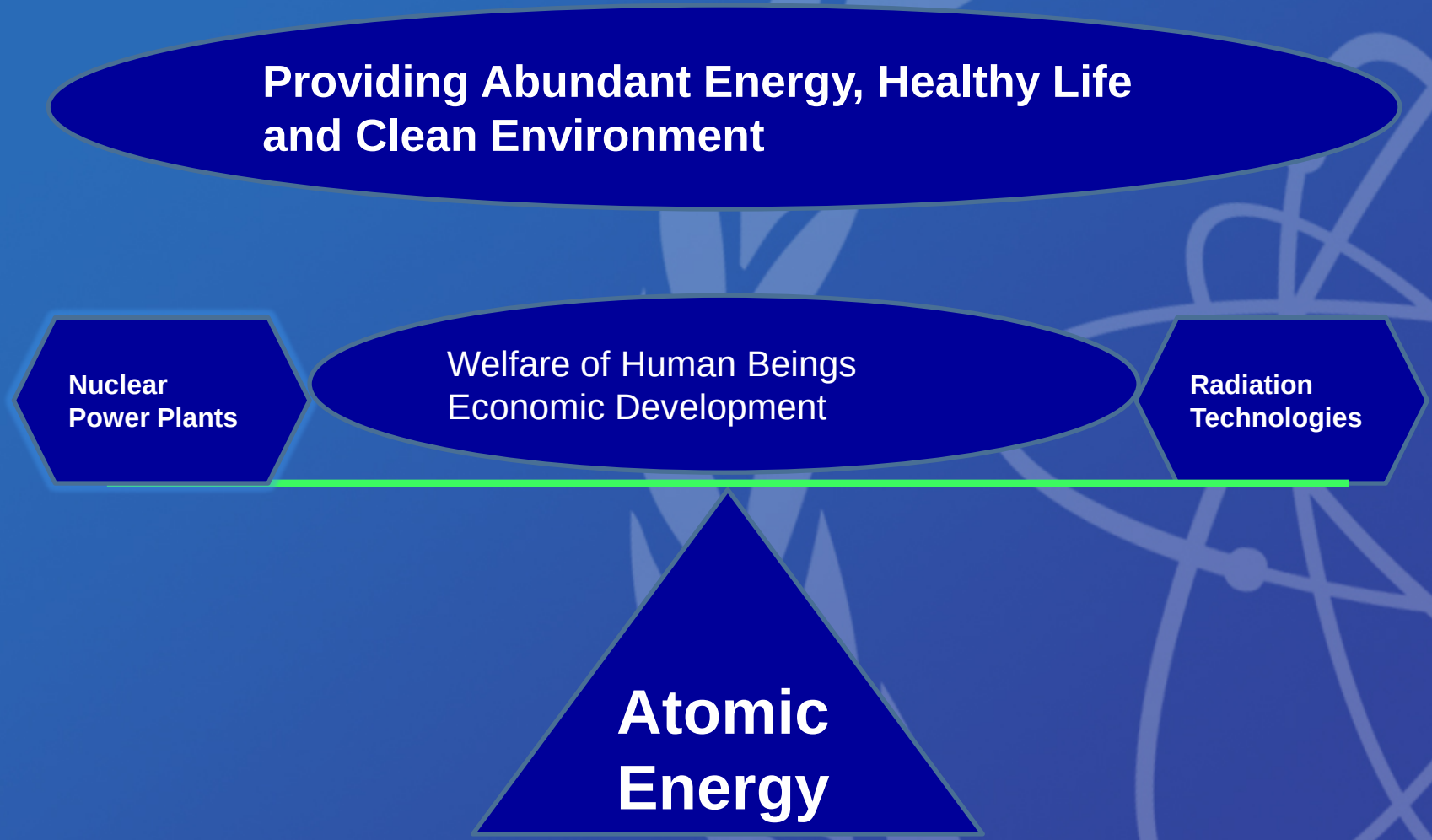
- Scale of economic utilization of radiation technologies
- What makes them so useful?
- Why Electron Beams are preferred sources?
- Opportunities and Challenges for the EB technologies
- Role of IAEA

Questions?



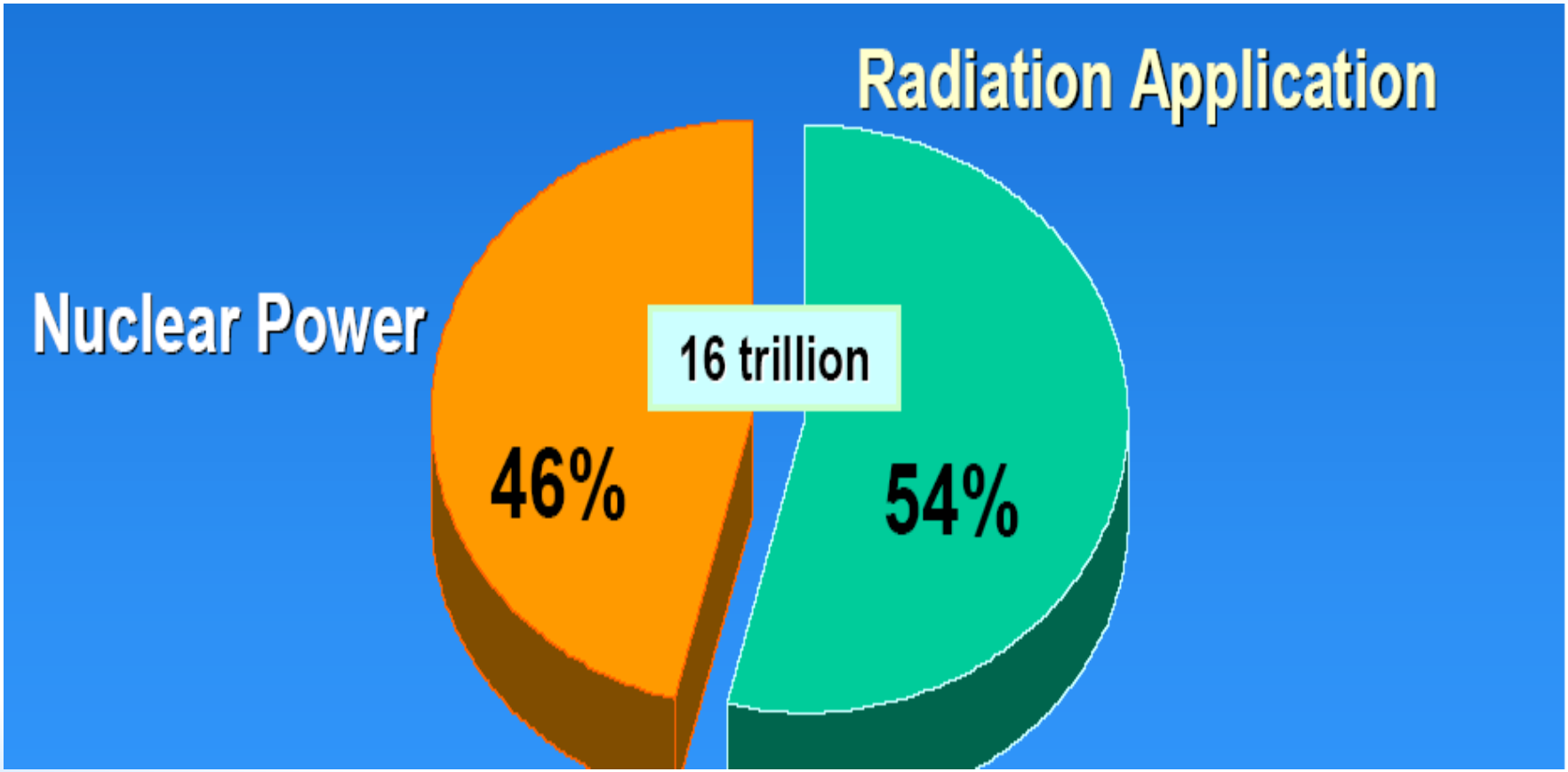
IAEA 60 Years
Atoms for Peace and Development

Two axes of atomic energy



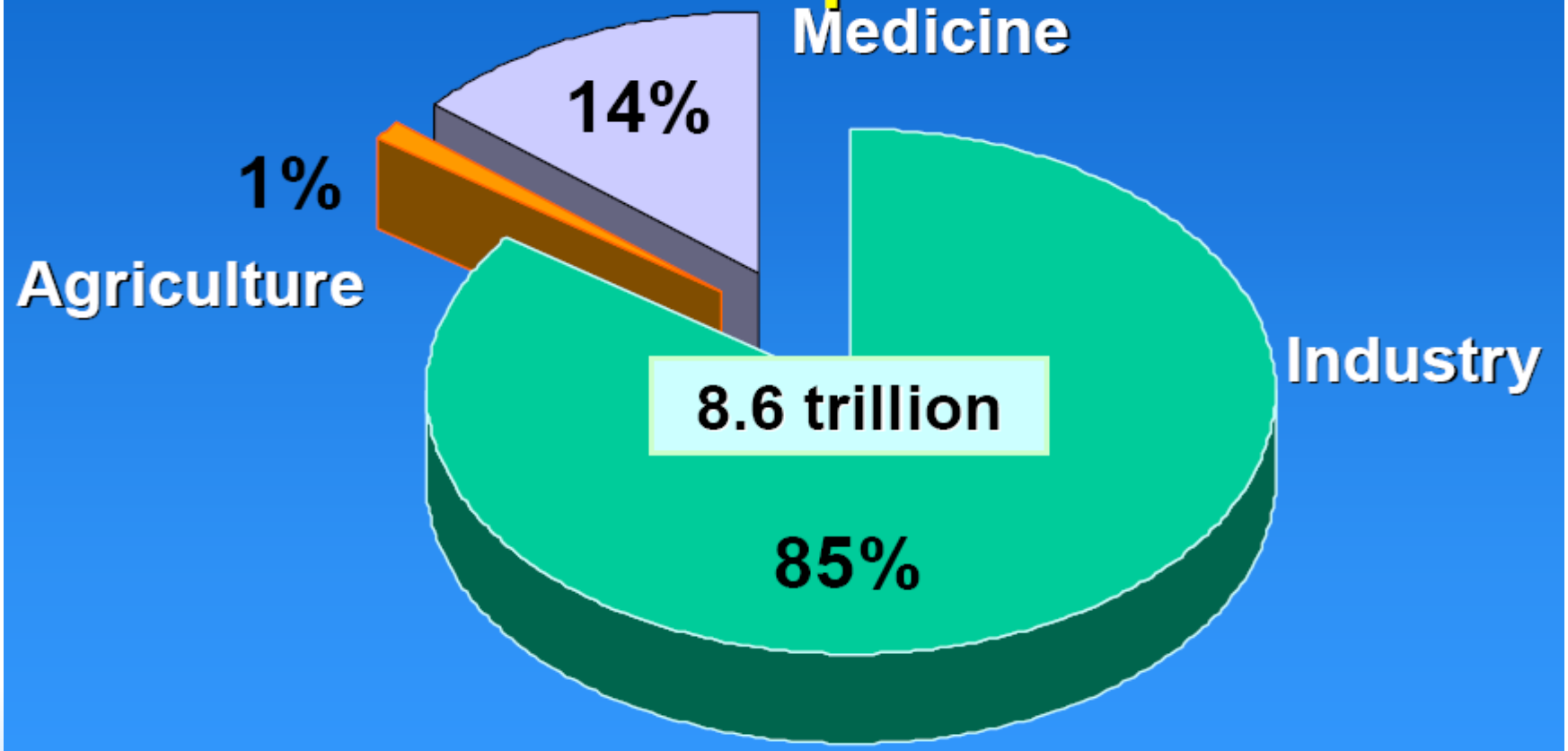
Economic Scale of Nuclear Power and radiation Technology in Japan (1997)

3.2% of the GDP 494 trillion Japanese Yen



J.Nucl.Sci.Tech. 39(2002)1002-1113

Breakdown of Economic Scafe of Radiation Application in Japan



J.Nucl.Sci.Tech. 39(2002)1002-1113

Overall Impact of Nuclear Technology in the United States (using multiplication economic model)

	1991		1995	
	Sales($B)	Jobs(M)	Sales($B)	Jobs(M)
Radiation Technology	257	3.7	331	4.0
Nuclear Power	73	0.4	90	0.4
Total	330	4.1	421	4.4

Reference : Global 2003, November 16-20, 2003

Sustainable Development Goals

IAEA 60 Years Atoms for Peace and Development

Atoms for Peace and Development

The Golden Rule!

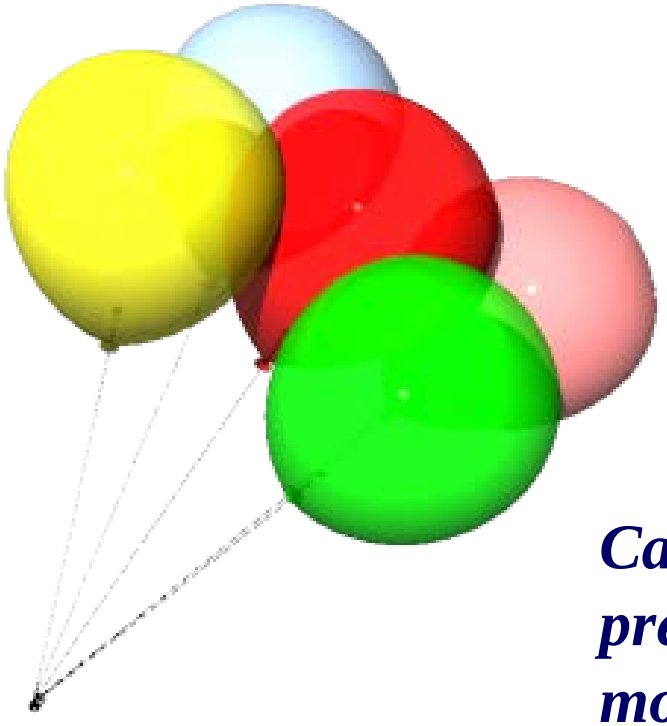
HEAT

BEAT

&

HOPE!!

Conventional curing leaves toxic residues!!



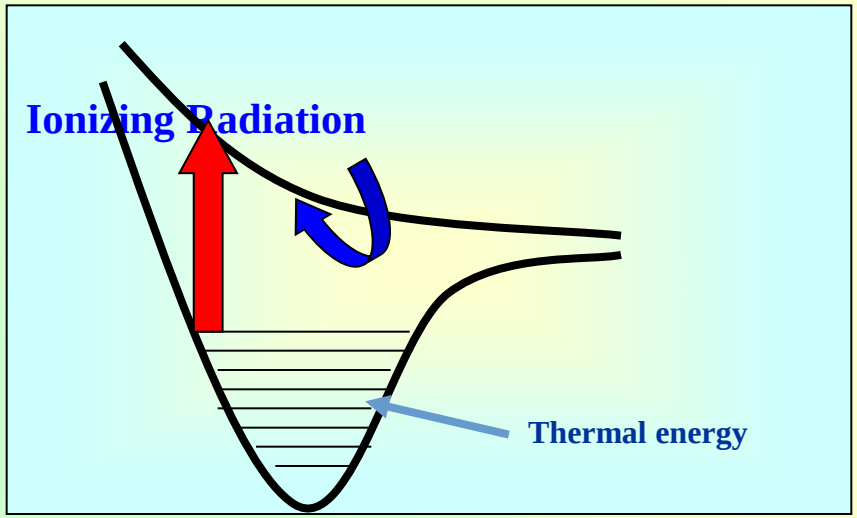
Carcinogenic nitrosoamines are present in high concentrations in most of the rubber products

Expectations from new technologies

- **Energy Saving**
- **Must provide superior products**
- **Environment friendly**
- **Cost effective**
- **Public acceptance**

How is Radiation Different from Thermal energy ?

Thermal energy **is very strongly coupled to Translational, Rotational and Vibrational modes of the energy absorber. Ionization, bond rupture and other processes leading to chemical reactions occur only in the high energy region of the Maxwellian tail.**



Ionizing radiation **is almost entirely absorbed by the electronic structure of absorber which increases the energy level of its orbital electrons.**

Effective, Efficient generator of reactive Species.

Energy in the form of large quanta can have more pronounced chemical effects than energy in the form of small quanta

Comparison of Energy Input of Thermal and Radiation Vulcanization of Rubbers

Rubber Vulcanization at 80 kGy = 80 J/g

Thermochemical vulcanization of rubber at 150 C to achieve the same crosslinking = 281 J/g

Radiation vulcanization is 3-6 times more energy efficient!

Ref: V.S.Ivanov, Radiation Chemistry of Polymers, Utrecht (1992)

Energy Demand to Dry/Cure Coatings

System	Solvent	Solvent	Water	EB cure
Solids	30%	40%	40%	100%
Diluent	heptane	toluene	water	none
Boiling Point,	98 ^{0}C	111 ^{0}C	100 ^{0}C	-
Vapour pressure at 20 ^{0}C	35 mm Hg	22 mm Hg	17 mm Hg	-
Heat of vapourization (cal/gm diluent)	76	88	540	-
Energy to dry 1g dried coating	740	555	3390	30 at 30 kGy

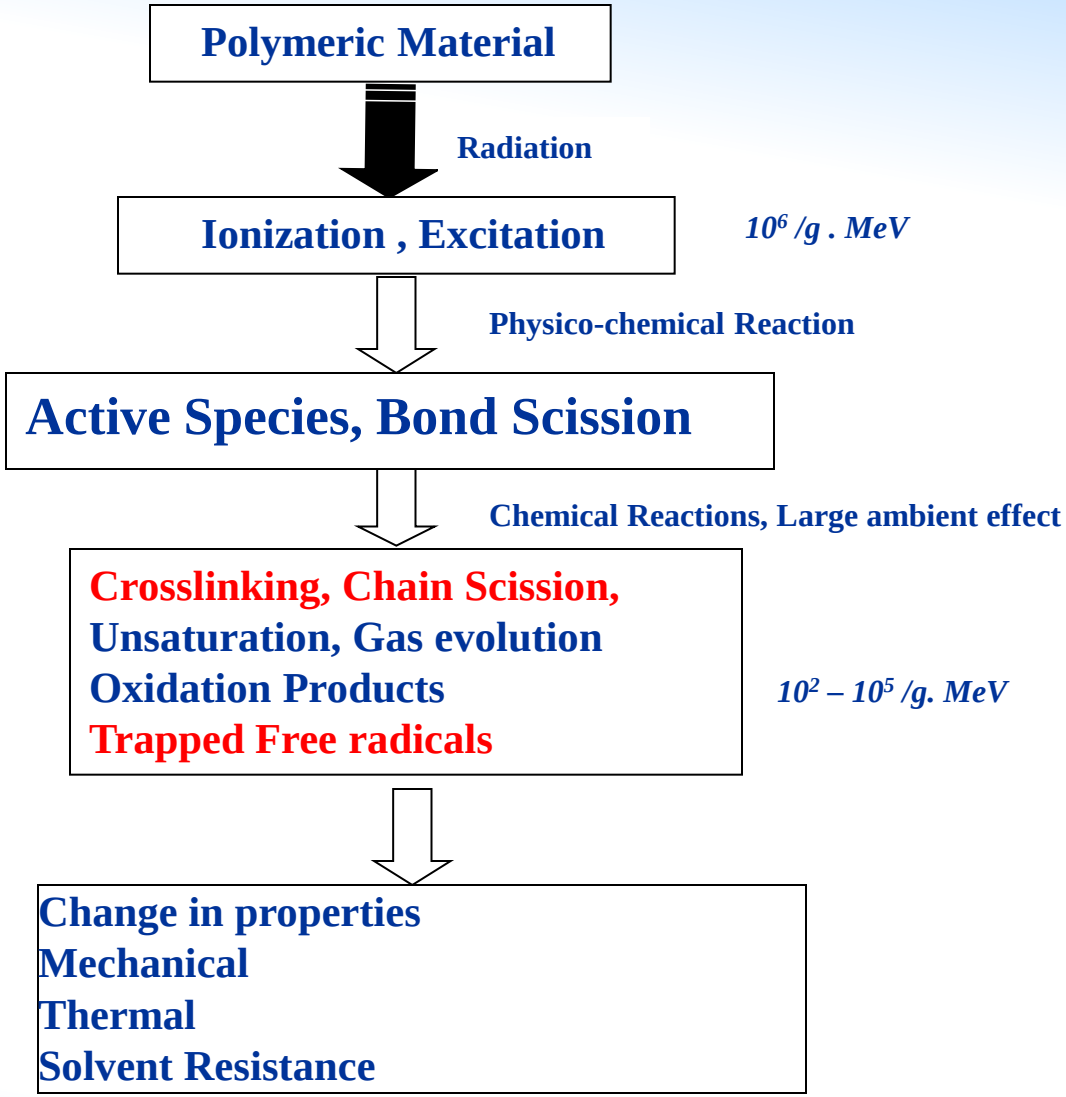
What kind of reactions are amiable with radiation processing?

Production rate (kw-hr) = 3.74×10^{-4} G.M.f kg

where f is efficiency of radiation absorption

- **G-value (yield) of reaction should be very high**
- **M - (mol. wt. of product) should be high**
- **Small change produced should have very large effect on the properties**
- **Value addition to the product is very high**

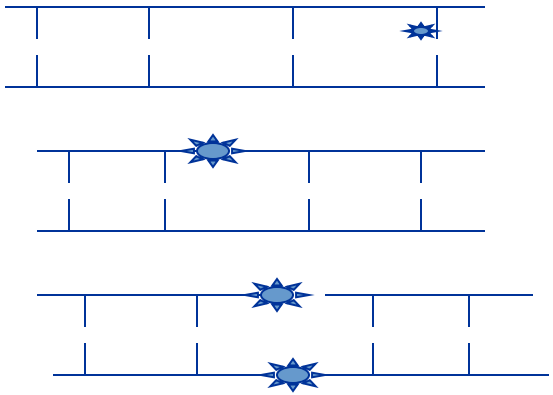
Radiation Effects on Polymers in Solid State



Schematic of Radiation Effects on Polymers

Effect of radiation on DNA

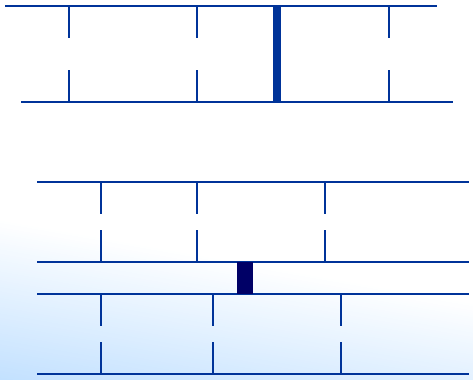
Direct effect as well as indirect effect through water radiolysis products



Base Pair damage

Single strand break

Double strand break



Intra molecular crosslinking

Intermolecular crosslinking

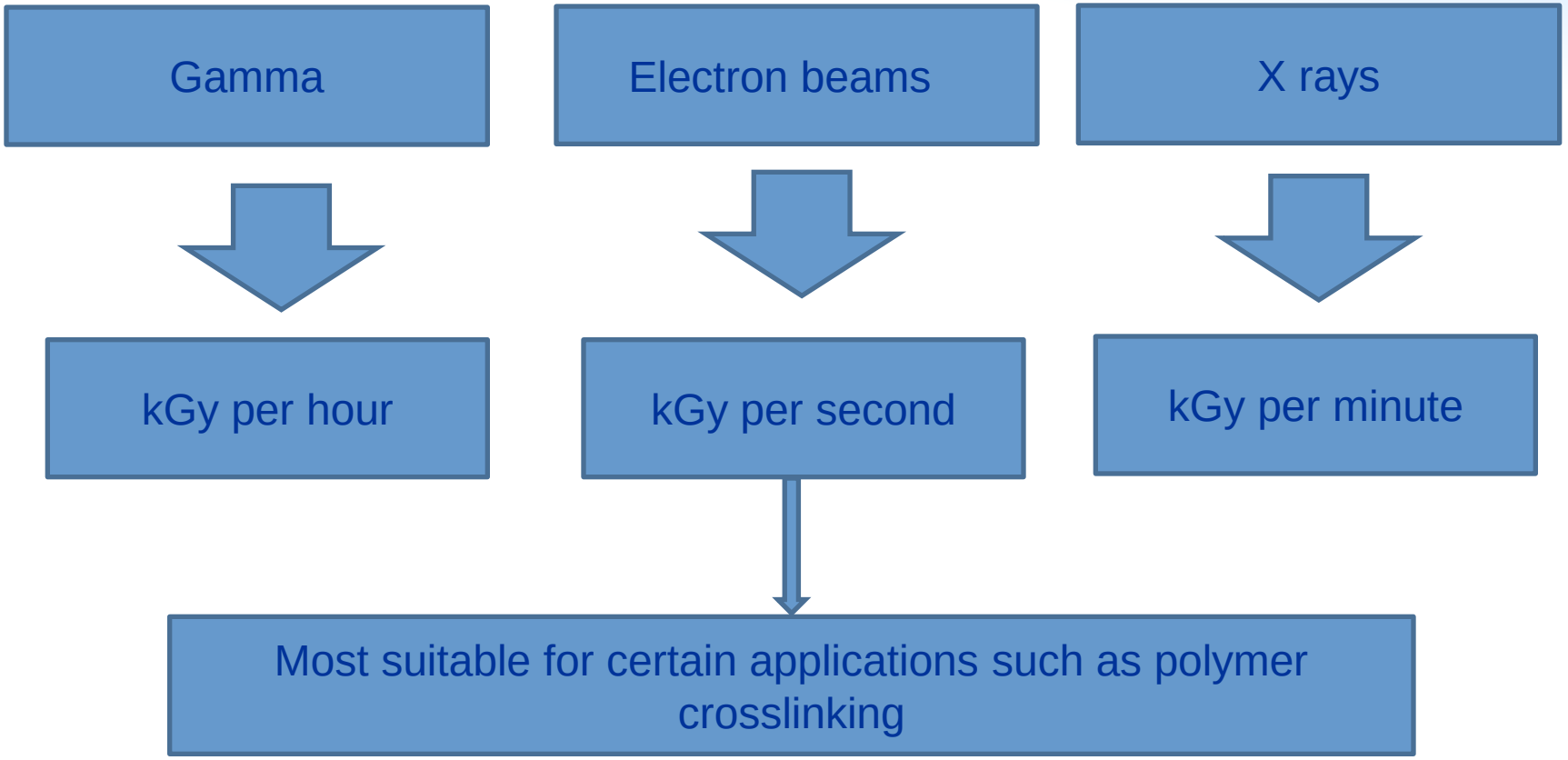
Radiation Chemistry Based Applications

Radiation Biology Based applications

Applications of Radiation Technology

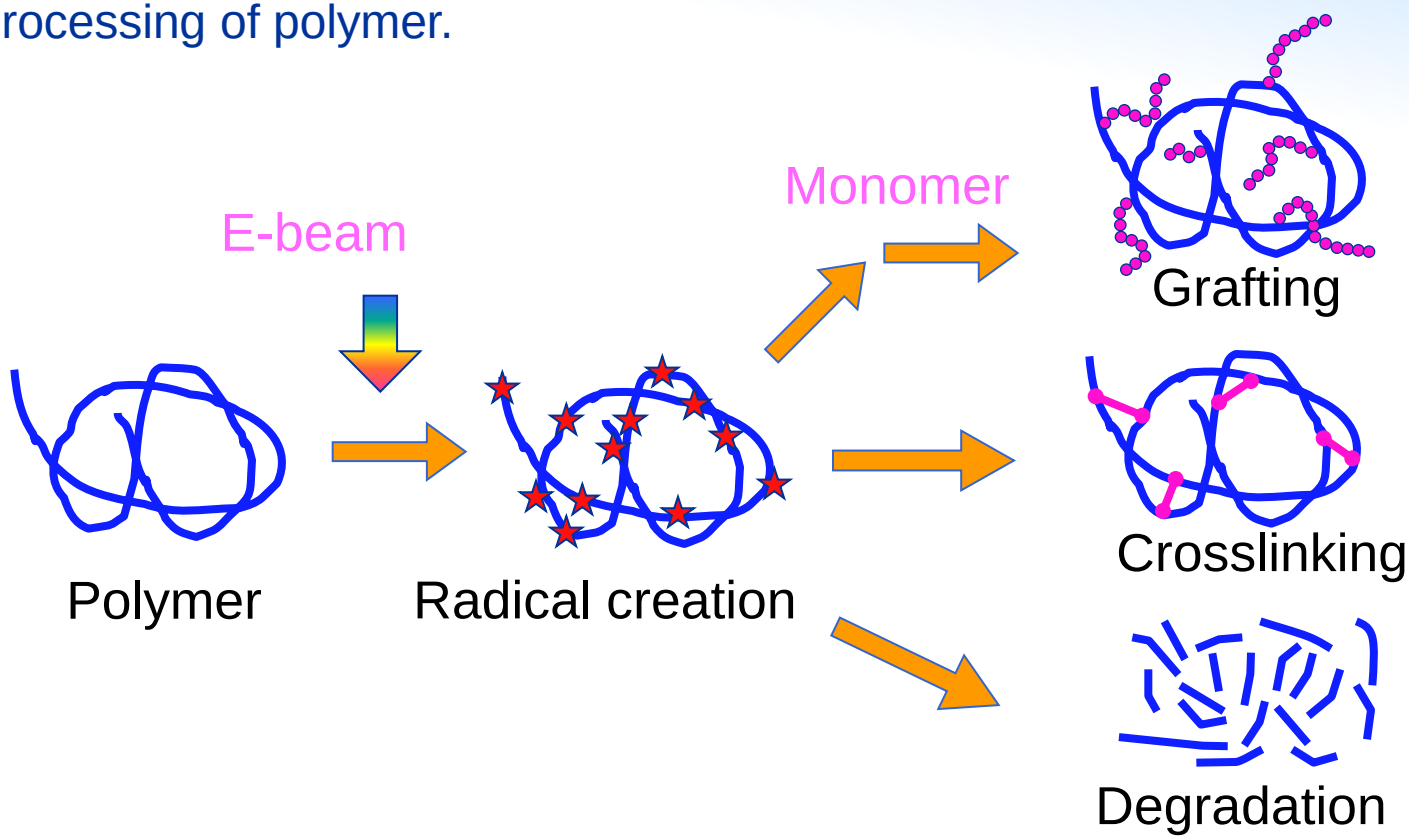
- *Crosslinking of polymers*
- *Degradation of high molecular weight materials*
- *Curing of polymer coatings*
- *Graft polymerization*
- *Sterilization of medical products*
- *Food irradiation*
- *Sewage Sludge Hygienization*

Difference in dose rates



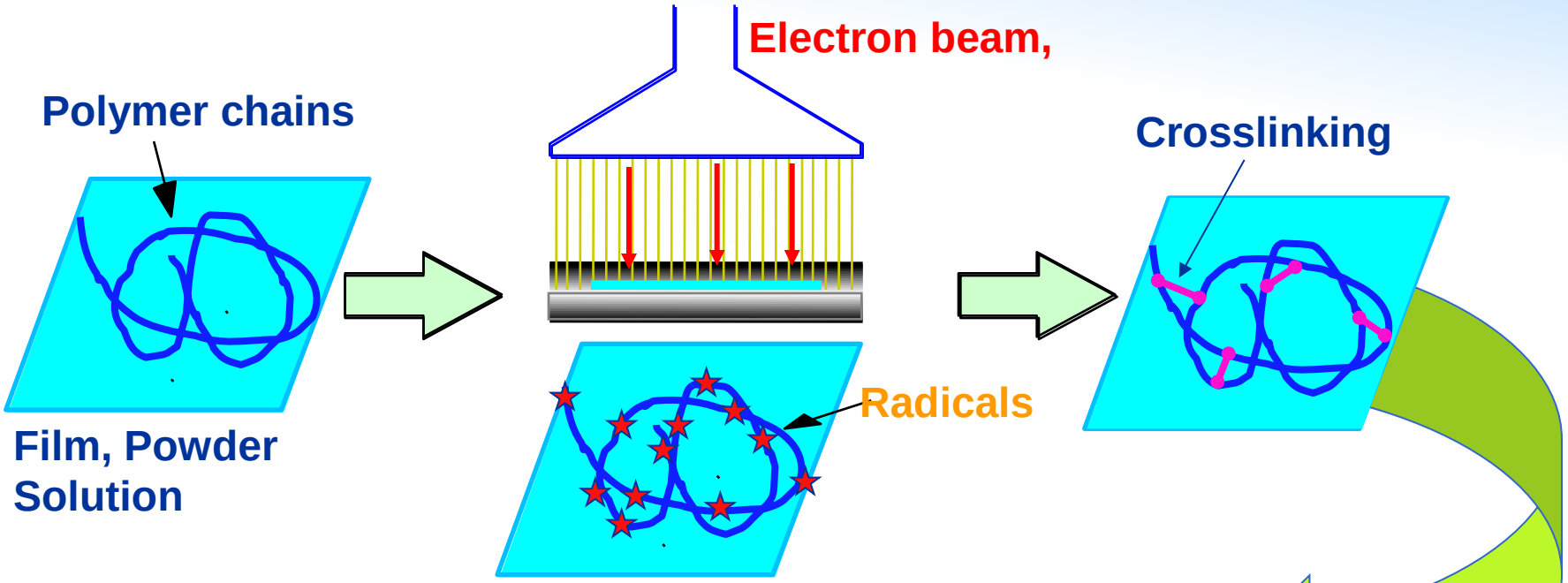
EB processing of polymers

Grafting, crosslinking, and degradation are major reactions in radiation processing of polymer.



- Grafting : Any shapes (membrane, cloth, and fiber)
- Crosslinking : Any states (solid and sticky liquid)
- Degradation : w/o Chemicals

Radiation Crosslinking

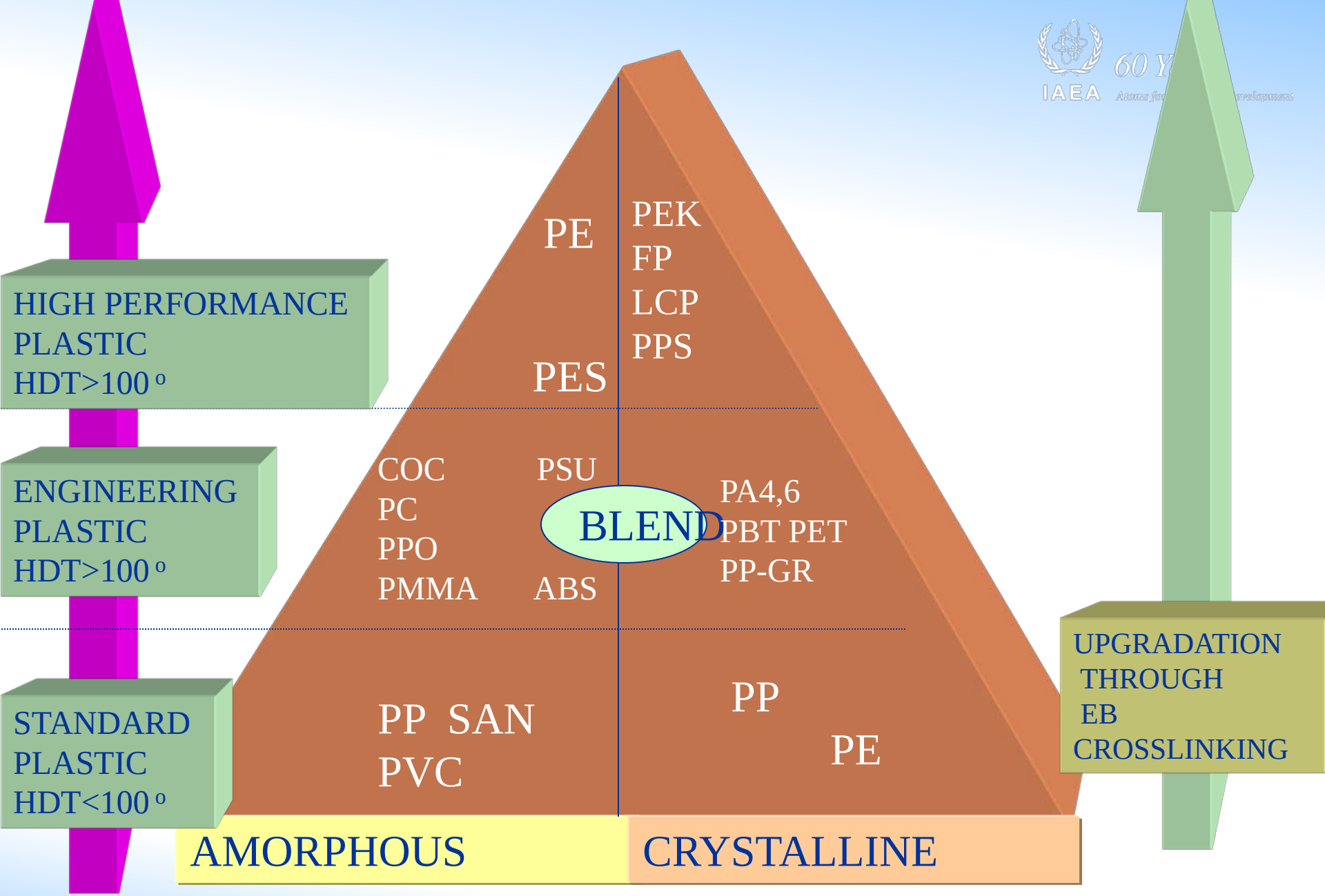


Advantages

- Clean
- Without heat
- Keep shape
- High speed

Improvement by crosslinking

1. Heat stability
2. High strength
3. Processability
4. insoluble


HIGH PERFORMANCE PLASTIC HDT>100 °
ENGINEERING PLASTIC HDT>100 °
STANDARD PLASTIC HDT<100 °
PE
PEK
FP
LCP
PPS
PES
COC
PSU
PC
PPO
PMMA
ABS
BLEND
PA4,6
PBT PET
PP-GR
PP SAN
PVC
PP
PE
UPGRADATION THROUGH EB CROSSLINKING
AMORPHOUS
CRYSTALLINE

Main Applications for Modified Polymer by Radiation

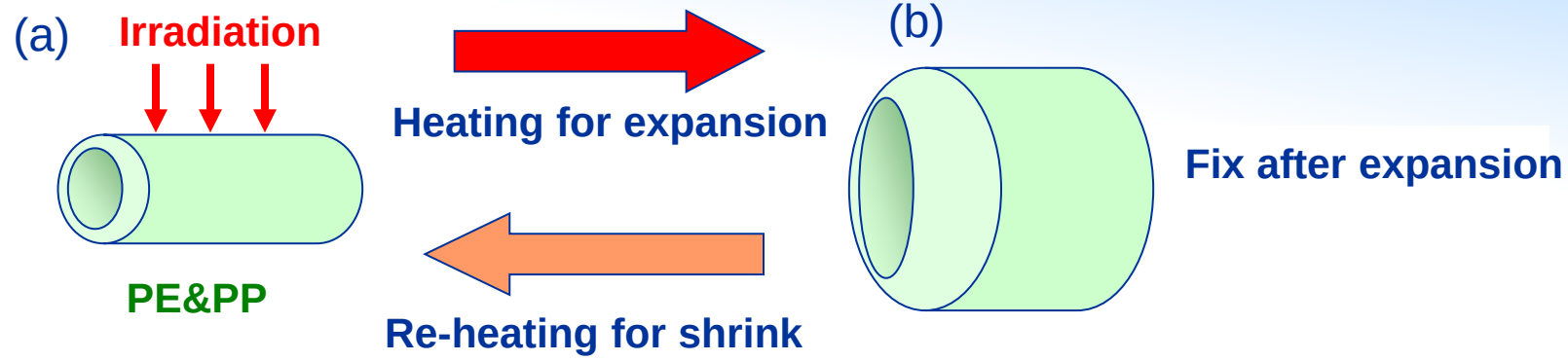
- Wire & cable
- Heat shrinkable material
- Polyethylene foam
- Medical device
- PE packaging film
- Battery membrane
- PTC

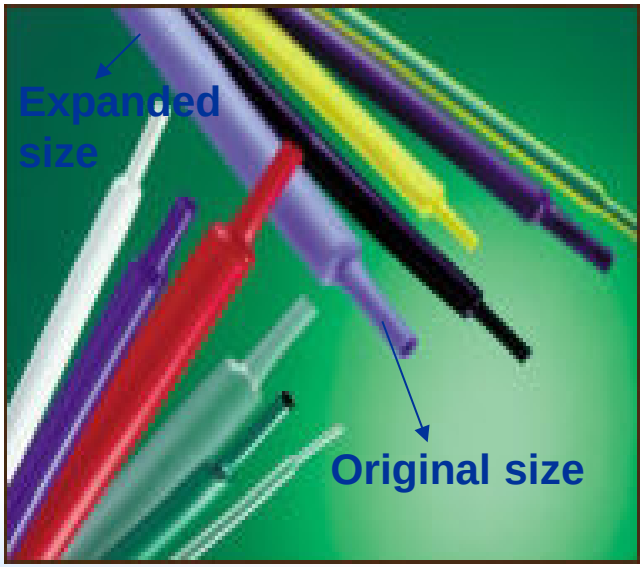
Applications of Radiated Wire & Cables

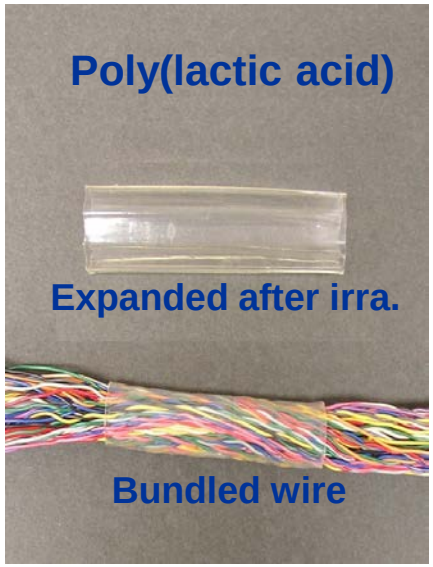
- Automobiles
- Railways
- Aerospace
- Power Industry
- Photovoltaic
- Electronic Appliances




Shrinkable Tubes







Applications for Heat Shrink Material

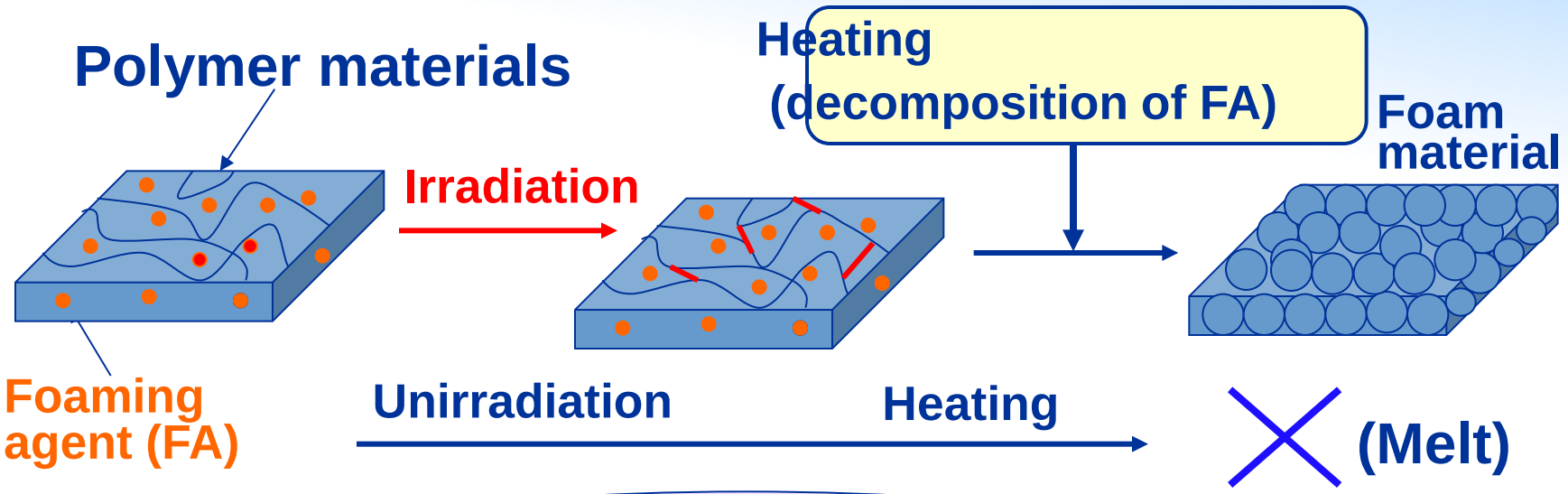
- Automobile
  - wire harness assemblies/ connectors/ terminals/ electronic components/ wire splices/ hose and pipe…
- Railway/Metro
  - track system (Bogl slabs) and train
- Electronics/Appliance
  - Thin wall tubings



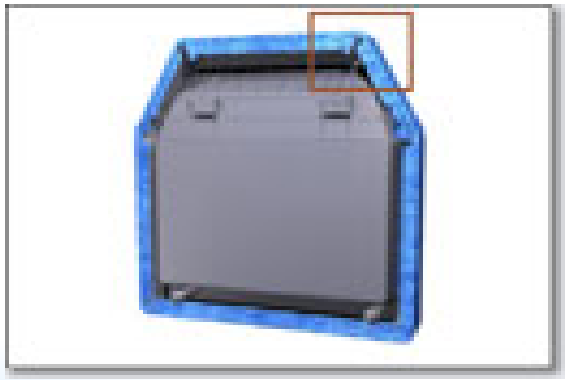

Applications for Heat Shrink Material

- Power Industry
  - terminations, connectors, end cups, bus bars…
- Oil & Gas
  - heat shrink sleeve for protection of the pipeline joints
  - west-east gas pipeline (1 & 2 line are operational 3rd is about complete and 4th, 5th is planned; Inter-city pipeline networks
  - China-Myanmar, China-Russia, China-Central Asia (Turkmenistan, Kazakhstan and Uzbekistan) + Projects in Africa and Middle East
  - current about 60,000 kms， about another 50,000 kms planned for the next 10 years

Polymer Foam of Car



Irradiation ; enhancement of melt strength by crosslinking



Applications for PE Foam

IMRP Shanghai 2013 INTERNATIONAL MEETING ON RADIATION PROCESSING

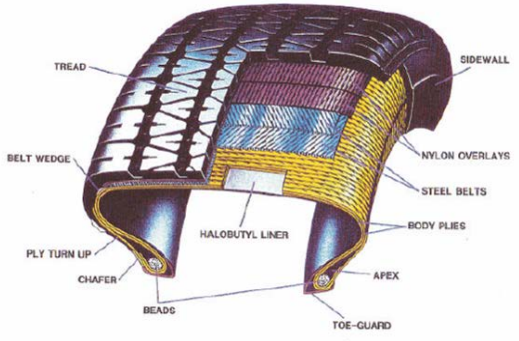
- Automobile industry
- Electronics industry
- Packaging industry
- Air conditioning
- Recreation and sports industry

Radiation Processing of Tires

92% radial tires is processed with EB irradiation

Rubber sheet → **EB irradiation** (Pre-vulcanization) → **Molding of tires**

Molding of tires → **Product (Tire)**



1. Radiation Crosslinking of Polymer Materials

2. Car Parts Produced by Crosslinking technology

- Wire and Cable
- Foam
- Shrinkable Tube
- Tire
- Polyswitch

Electron Beam Crosslinking

Commercial irradiation services being provided for irradiation of diamonds, “O” rings, bushes, heat-shrinkables

New process for irradiation of “O” rings in continuous mode – ease of operation and higher efficiency

Over 10 millions rings processed

Industrial products for EB processing Dim. Stable Automotive components (partial crosslinking)

EB crosslinked HDPE

IARP-2009

High Performance PTFE ＜Crosslinked Product＞

Production process

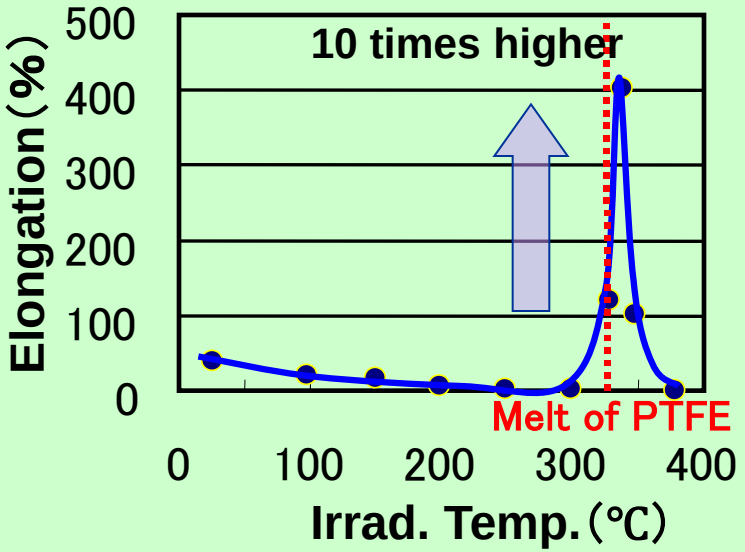
PTFE Powder

⇩ EB irrad. at high temp.

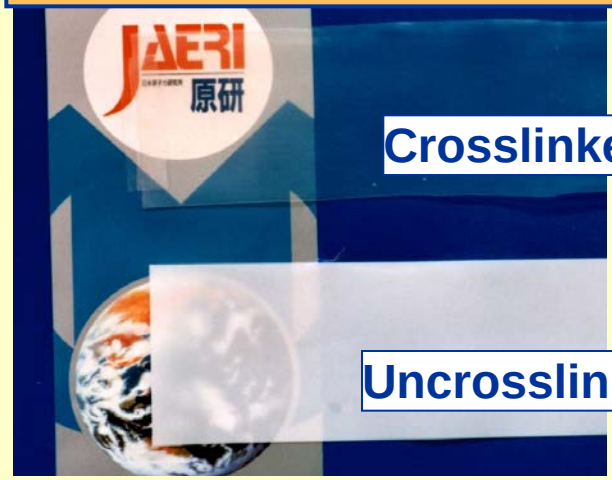
Crosslinked PTFE Powder

⇩ Moulding・Heat press

Crosslinked PTFE sheet



Synthesis of transparent sheet

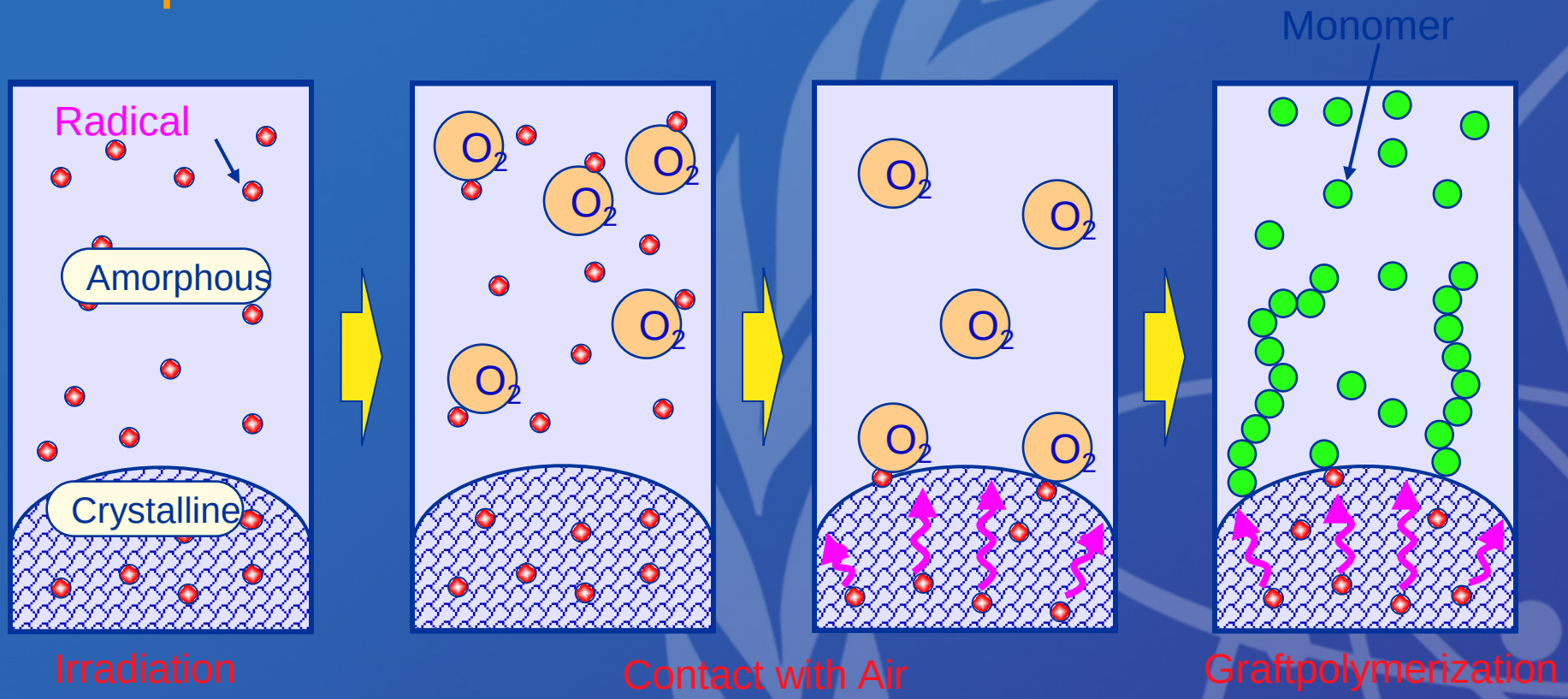


Abrasion resistance:10^3 times higher

Bearing seal

O-ring, Flange

Mechanism of graftpolymerization on pre-irradiation method

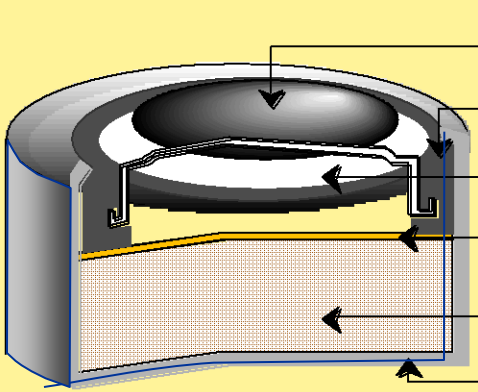


Grafting is initialed on surface of crystalline part and polymer propagate in amorphous phase.

Important factor for high yield: Radical number and diffusion of monomer

Separator membrane for button-shaped battery

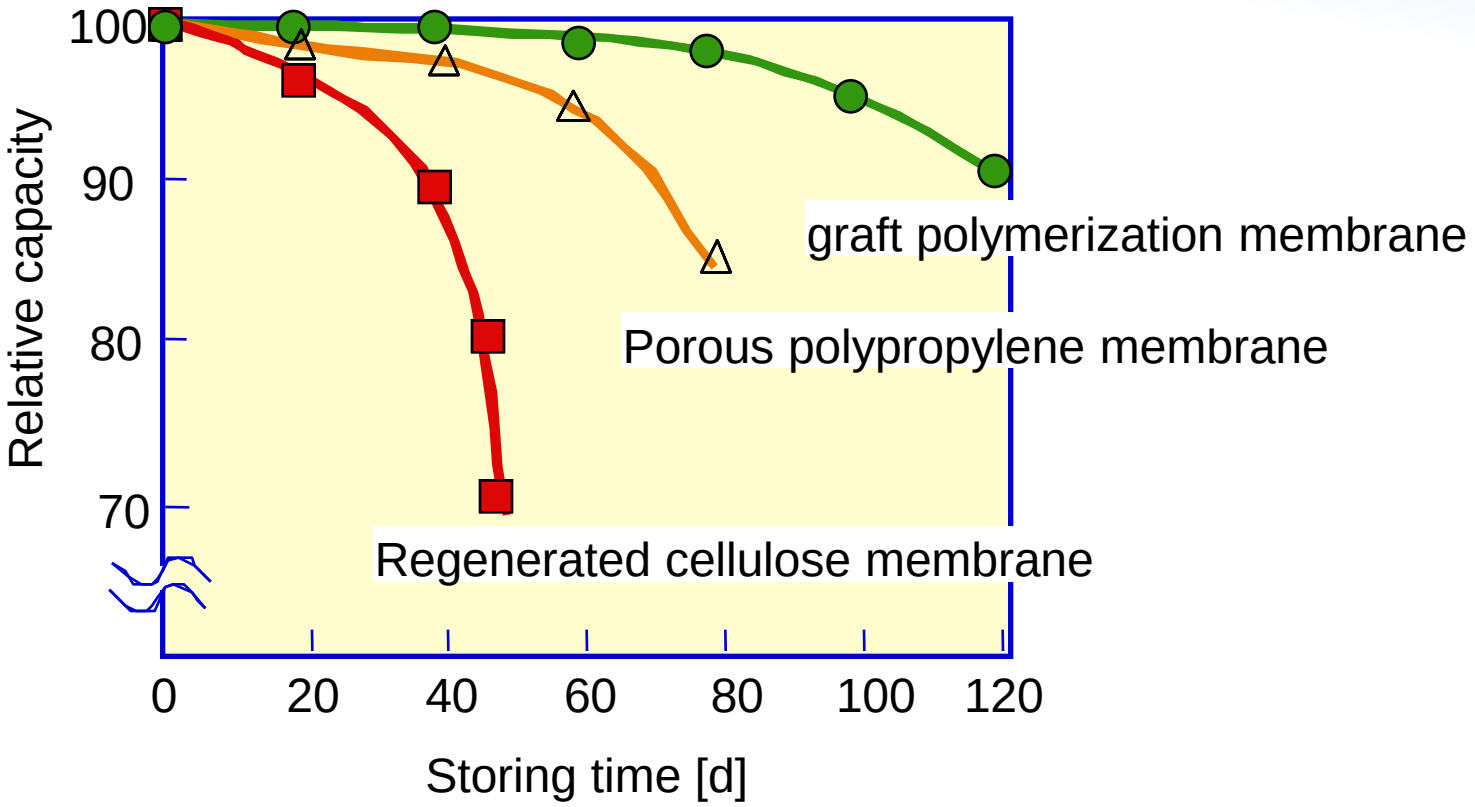
Annual production: 1 billon pieces



Cross section of battery

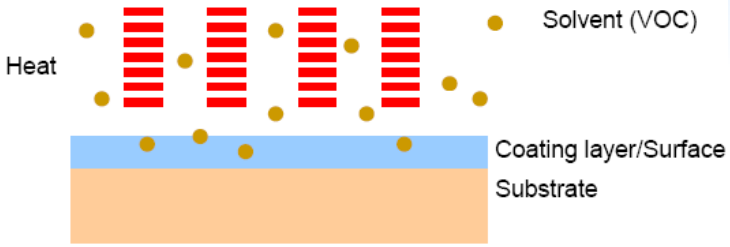
Electro conductive membrane synthesized by grafting on polyethylene, 25 μ thick

Various separator membranes in button-shaped battery



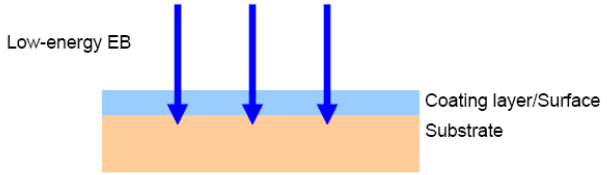
Accelerating test for storing battery at 60˚C

Thermal drying for Curing



- Well-established process. Solvents required.
- VOC (Volatile Organic Compound) + CO_2
- Larger energy (heat sauce) required

Low-energy EB for Curing



- Just gives energy to surface area. No VOCs.
- Smaller size for inline, continuous process.
- High dose rate: high speed process

Comparison of solvent based drying and EB system

System	Solvent	EB Curable
Coating solid conc.	60%	100%
Dried coat wt., g/m2	20 g	20 g
VOCs/m2, sol. Den.0.9	12 g	0 g
Force air system energy demand, kJ/m2	328 kJ	NA
Total EB energy demand, kJ/m2 30kGy at 70% electric input to effective EB	NA	0.86 kJ
Total energy demand (11200 m2/h production)	3,700.000 kJ	9600 kJ
Total energy demand/hr	1030 kWh	2.67 kW/h

Ref: A.J.Berejka, RADTECH (2003)

EB Lamination

- Paper board + Film
- Instant cure of adhesive
- No aging time
  - Reduce lead time

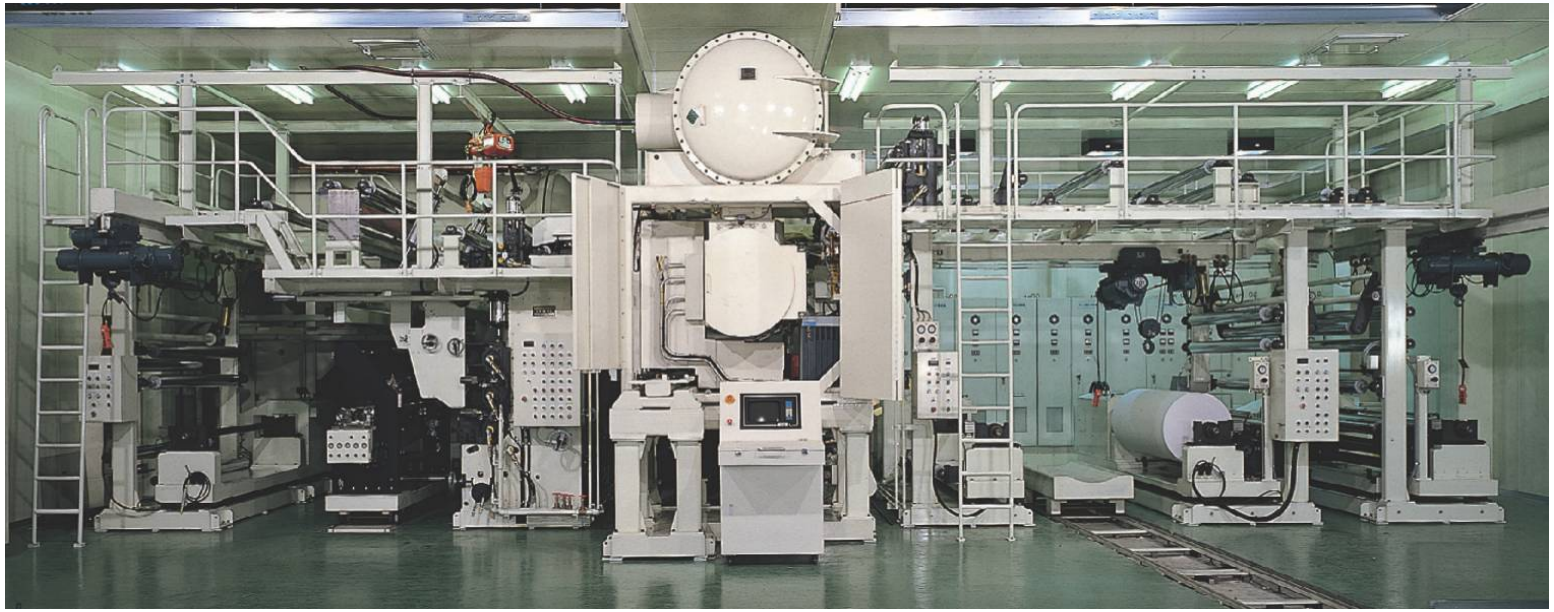
<http://www.packworld.com/>

EB lamination process can be used not only for packaging, but also for industrial materials.

EB Curing Over-coat of Decorative Paper for Furniture and Flooring in Japan

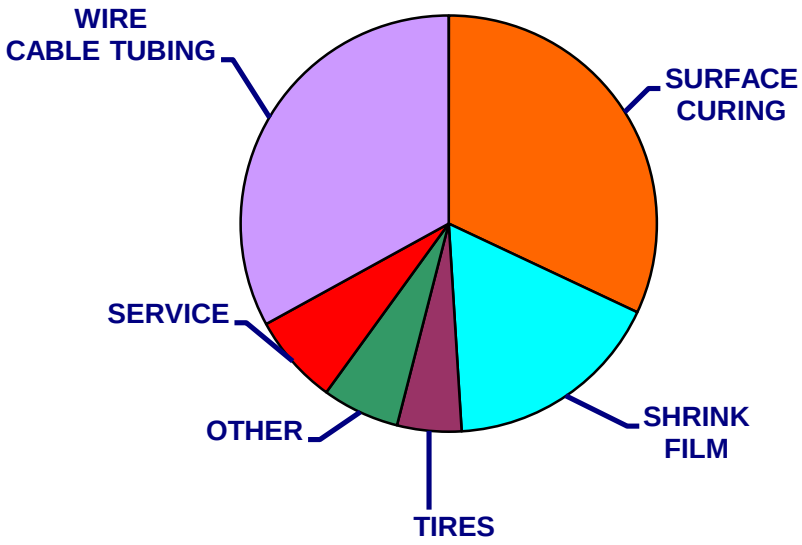
- EB processing has following advantages over UV or thermal curing :
  - Higher hardness and scratch resistance
  - Higher chemical resistance
  - Less energy consumption
  - Non-solvent process

Coating/Laminating Line with an EB System



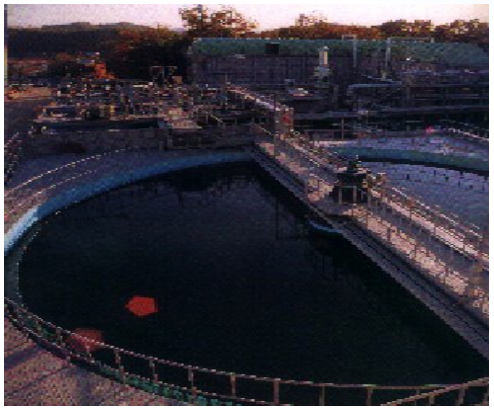
- EB System (Up to 300kV, 165 cm width)
  - Gravure coaters / Laminators

A GLANCE AT ESTABLISHED EB APPLICATIONS



Radiation Technology Applications towards Better Environment

Flue gas Purification



Wastewater Treatment

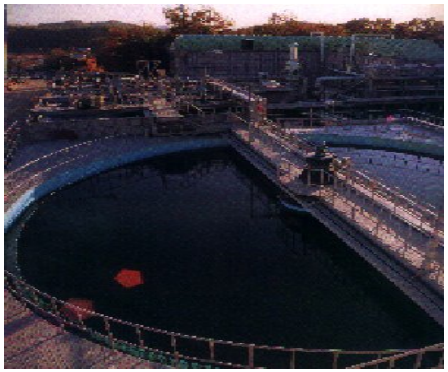
Sludge Hygienization

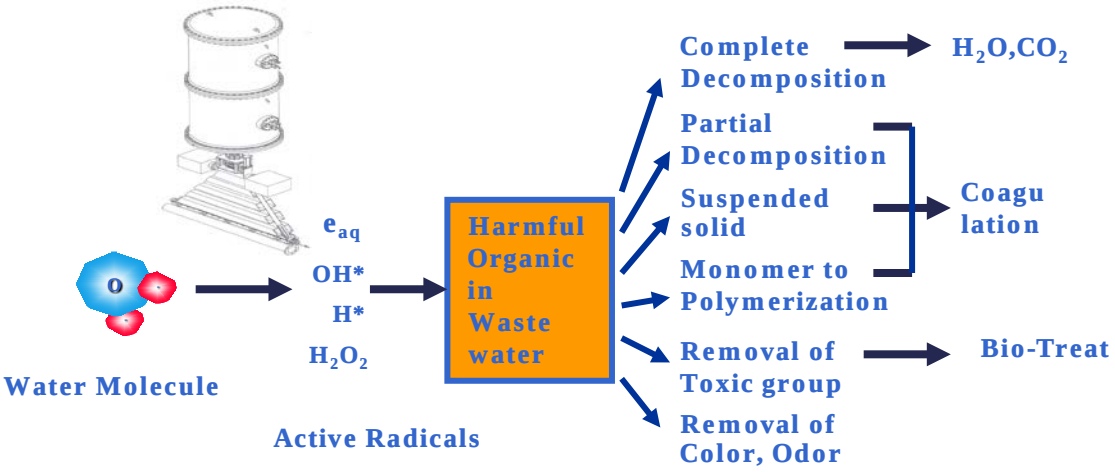
Radiation Treatment of Flue Gases for Cleaner Environment

- Removal of SO2 and NOx in one step
- By-product is useful fertilizer
- No secondary waste
- Complementary to the CO_2 sequestration
- Fully developed proven technology unit set up in Poland with IAEA assistance.

- **IAEA projects for technology deployment**

Radiation Treatment of Waste Water for Cleaner Environment





- *EB facility* in Rep. of Korea set up with IAEA cooperation
- Max. flow rate 10,000m^3/day
- In combination with the existing Biological Treatment Facility
- Decrease in the chem. Reagents up to 50%
- Efficiency of Biological Treatment improved by 30%
- Decrease in the retention time in Biological Treatment Facility
- *Mobile EB facility developed with IAEA cooperation*

Hygenization of Bio-solids

Utilization of enriched Hygienized sewage sludge and water for growing grapes in Gujarat in the area where most of land has very low fertility

IAEA INITIATIVES

- **Fostering Relevant Development and Dissemination of information, Technology Transfer**
  - Coordinated Research Projects
  - Thematic Meetings
  - Collaborating Centres
  - Publication of Technical Reports
  - IAEA Workshops/Schools
  - Support to Conferences/Meetings

IAEA Coordinated Research Projects

- **Radiation Treatment of Wastewater for Reuse with Particular Focus on Wastewaters Containing Organic Pollutants (2010-2016)**

  ALGERIA, BRAZIL, CHINA, EGYPT,MALAYSIA, KOREA, JAPAN, ITALY,HUNGARY, ROMANIA,POLAND,PORTUGAL, TURKEY, USA

  Radiation Treatment of Emerging Organic Pollutants (2018- proposed)

Monitoring of antibiotics detected in influent of livestock wastewater treatment plant

Compounds (1 차)	Concent. (ng/mL)	Frequency
Acetaminophen	62.41~1352.90	5/18 (27.8%)
Sulfamethoxazole	-	0/18 (0 %)
Sulfathiazole	105.22~146.45	3/18 (16.7%)
Sulfamethazine	1.23~58.68	4/18 (22.2%)
Trimethoprim	-	0/18 (0%)
Lincomycin	16.09~511.46	11/18 (61.1%)
Oxytetracycline	728.84~7413.10	12/18 (66.7%)
Chlortetracycline	420.68~70866.50	14/18 (77.8%)
Acetyl salicylic acid	0.21~294.02	16/18 (88.9%)
Erythromycin-H_2O	-	0/18 (0%)
Tylosin	0.48~16.20	10/18 (55.6%)
Formaldehyde	2.78~257.36	17/18 (94.4%)
Glutaraldehyde	1.13~13.24	10/18 (55.6%)

Compounds (2 차)	Concent. (ng/mL)	Frequency
Acetaminophen	7.32~97.7	2/19 (10.5%)
Sulfamethoxazole	-	0/19 (0%)
Sulfathiazole	3.86~1082.60	13/19 (68.4%)
Sulfamethazine	0.40~299.82	9/19 (47.4%)
Trimethoprim	0.43	1/19 (5.3%)
Lincomycin	0.50~333.77	13/19 (68.4%)
Oxytetracycline	515.36~12171.89	9/19 (47.4%)
Chlortetracycline	0.12~34111.47	19/19 (100.0%)
Acetyl salicylic acid	0.04~690.43	18/19 (94.7%)
Erythromycin-H2O	-	0/19 (0%)
Tylosin	0.46~8.03	12/19 (63.2%)
Formaldehyde	0.70~346.22	18/19 (94.7%)
Glutaraldehyde	0.75~9.61	15/19 (78.9%)

Ref: Dr. M. J.Lee, Korea Atomic Energy Research Institute (2014), 3rd IAEA CRP Meeting, Budapest, Hungary

Radiation Sterilization of Life Saving Equipment

About 180 gamma radiation plants are being used world-over for sterilization of medical products

Increasing Use of Electron Beams for Radiation sterilization

Food Irradiation

One Process:

Multiple Uses

Sprout

Onion, Potato,
Ginger, Garlic

Quarantine

Fruits

Cereals, Pulses,
Dry Fruits

Bacteria Reduction

Chicken, Meat, Fish

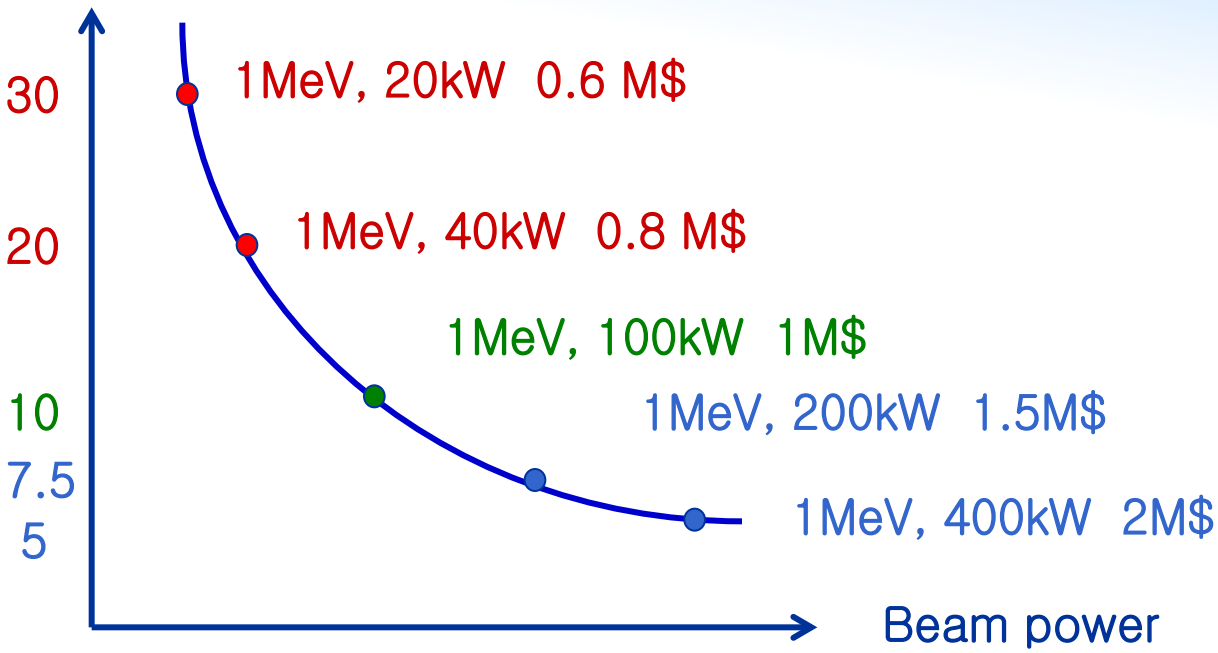
Spices

Comparison of gamma with accelerators

	Med. Energy			High Energy	C0-60	Remarks
Energy (max.)	1.0MeV	**1.0MeV**	2.5MeV	10MeV	1.25MeV*	
Power Source	DC Transformer			Klystron	Isotope	
Beam Current	**100mA**	**400mA**	**50mA**	**1mA**	**-**	
Power (max.)	**100kW**	**400kW**	**100kW**	**10kW**	**1MCi**	**1MCi≈15kW**
Power Consumption	125kW	**500kW**	125kW	110kW		Machine only
	140kW	**650kW**	140kW	170kW	10kW	Overall
Energy Efficiency	**~80%**			**~10-20%**	**-**	**To beam**
Window size (mm)	900~1800	**1500~1800 X 3**	900~1800	600~800		
Shield Thickness	**90Cm**	**1.0meter**	**1.8meter**	**3 meter**	**3~5 meter**	**In concrete**
Co-60 equivalent	**6.7 MCi**	**27 MCi**	**6.7 MCi**	**0.67 MCi**	**1MCi**	**1MCi≈15kW**
Theoretical Throughput	2500kg/min 250kg/min 100kg/min	**10,000kg/min** **1,000kg/min** **400kg/min**	2500kg/min 250kg/min 100kg/min	250kg/min 25kg/min 10kg/min	375kg/min 37.5kg/min 15kg/min	at 1kGy at 10kGy at 25kGy

Slide Courtesy : Dr. Bumsoo HAN, EB TECH

Cost for unit power ($/W)



Beam Power	20kW	40kW	100kW	200kW	400kW	1MW
Total Cost (M$)	0.6	0.8	1.0	1.5	2	2.2*
Unit Cost ($/W)	30	20	10	7.5	5	2.2

Slide Courtesy : Dr. Bumsoo HAN, EB TECH

Production Cost

	Med. Energy			High Energy	C0-60	Remarks
Energy (max.)	1.0MeV	**1.0MeV**	2.5MeV	10MeV	1.25MeV*	
Power (max.)	40kW	**400kW**	100kW	10kW	1MCi	1MCi≈15kW
Initial Investment	1.5M$	**3.0M$**	1.6M$	2.6M$	3.6M$	
Fixed Cost	150k$	**160k$**	160k$	260k$	360k$	
Variable Cost (8,000hr/y)	125k$	**345k$**	125k$	210k$	325k$	
Total	275k$	**505k$**	285k$	470k$	685k$	
Theoretical Throughput	1000kg/min 100kg/min 40kg/min	**10,000kg/min** **1,000kg/min** **400kg/min**	2500kg/min 250kg/min 100kg/min	250kg/min 25kg/min 10kg/min	375kg/min 37.5kg/min 15kg/min	at 1kGy at 10kGy at 25kGy
Production Cost (only Variable cost)	0.26$/ton 2.6$/ton 26$/ton	**0.07$/ton** **0.72$/ton** **1.8$/ton**	0.1$/ton 1.0$/ton 2.6$/ton	1.8$/ton 18$/ton 44$/ton	1.8$/ton 18$/ton 45$/ton	at 1kGy at 10kGy at 25kGy
Production Cost (including both)	0.58$/ton 5.8$/ton 14$/ton	**0.11$/ton** **1.1$/ton** **2.6$/ton**	0.24$/ton 2.4$/ton 5.9$/ton	3.9$/ton 39$/ton 98$/ton	3.8$/ton 38$/ton 95$/ton	at 1kGy at 10kGy at 25kGy

Slide Courtesy : Dr. Bumsoo HAN, EB TECH

Commercial Aspects

- Significant capital investment
  - Electron Beam system is in the range $1-2.5 M
  - Total Facility Cost may cost $5 M
  - Amortization of capital investment is a large component of yearly cost
  - Operational cost specially electricity consumption not so high

Breakeven processing price is usually in the range $ 0.022-0.22 per kg/per kGy

Ref: B.Miller, ISNATT, September 2004

New Developments

High powered machines for X ray generation

5 MeV = 500 kW, X rays @ 8% efficiency = 40 kW
Equivalent of about 3 MCi of Cobalt-60

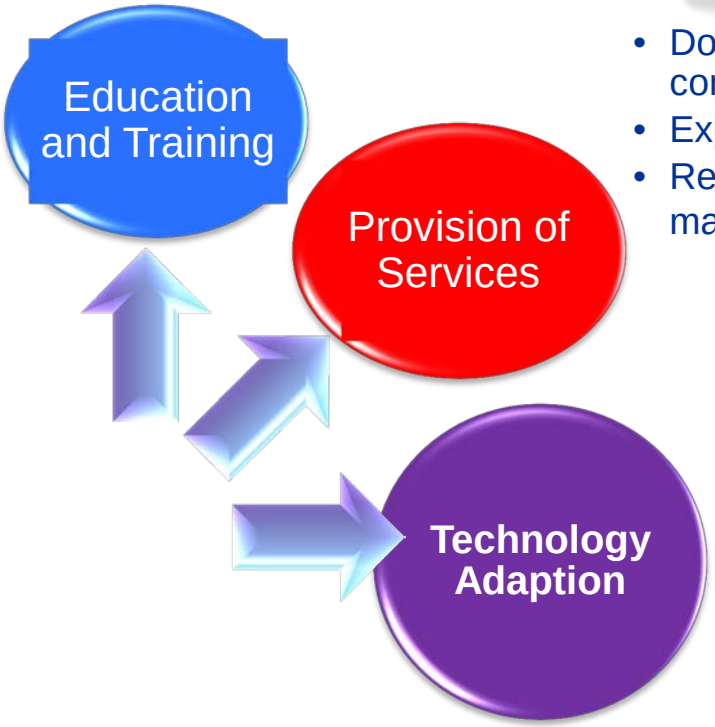
7 MeV= 700 kW, X rays @ 13% efficiency = 91 kW
Equivalent of about 6.5 MCi of Cobalt-60

IAEA Serving Member States: How?

- Guidelines; curriculum
- E-learning
- Specialized training

- Dosimetry inter-comparison
- Expert missions
- Reference materials

- 4 Collaborating Centres
- 5 Coordinated Research Projects per year

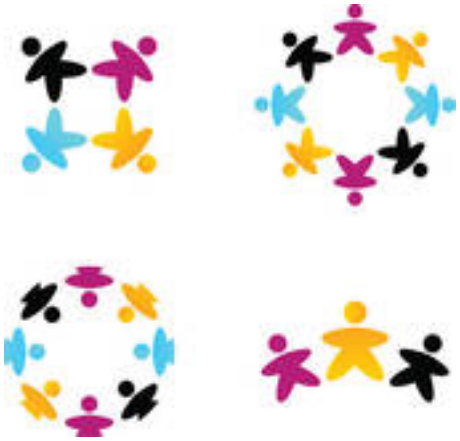


- **TECHNICAL COOPERATION PROGRAMME**
- Setting up radiation facilities
- €39.95 million in 2015 (NA)

What dose IAEA offer? Institutional advantages!

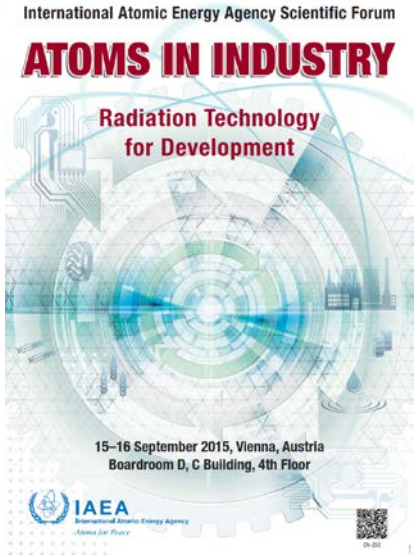
- Global membership (171 MS)and high legitimacy
- Can establish strong collaborations at regional and inter-regional level
- Strong convening power
- Neutrality in assessments and research
- Bottom-up requests to collaborate from partners
- Extensive knowledge networks / centres: academia, private sector, etc.

What does IAEA seek?



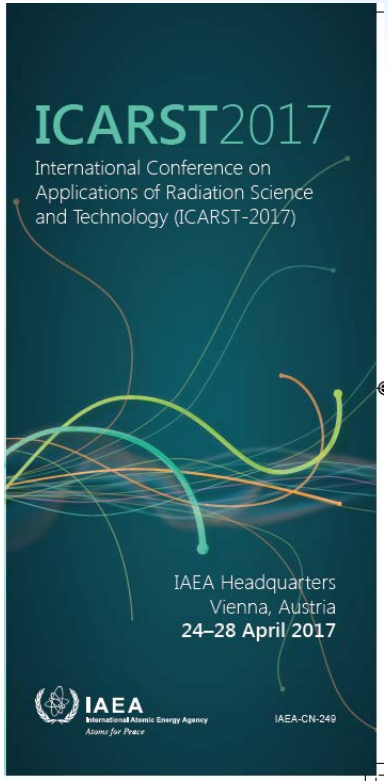
Cooperation!

Scientific Forum 2015



https://www.youtube.com/watch?feature=player_embedded&v=ePiNdzWjoWM

International Conference 2017



Workshop-TM on Applications of Electron Beam Accelerators
19-23 June 2017, INCT, Warsaw, Poland

IAEA 60 Years
Atoms for Peace and Development

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