Nuclear Safety and Security

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Pillars of Development

Energy

Seek to attain energy independence
and promote efficient utilization

Environment

Conserve and minimize the impact
on the environment

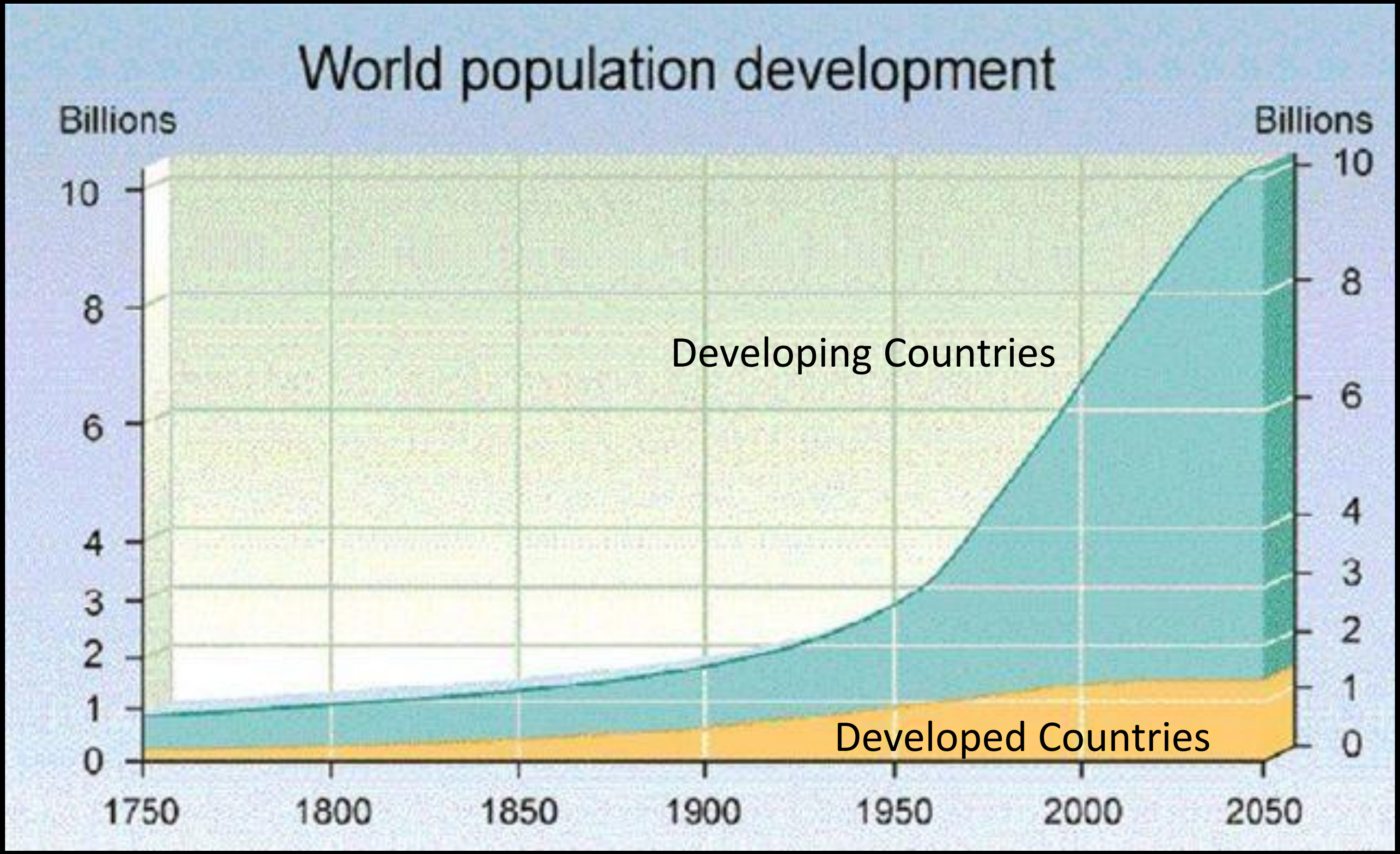
Economy

Enhance the national economic development
through the use of technology

Society

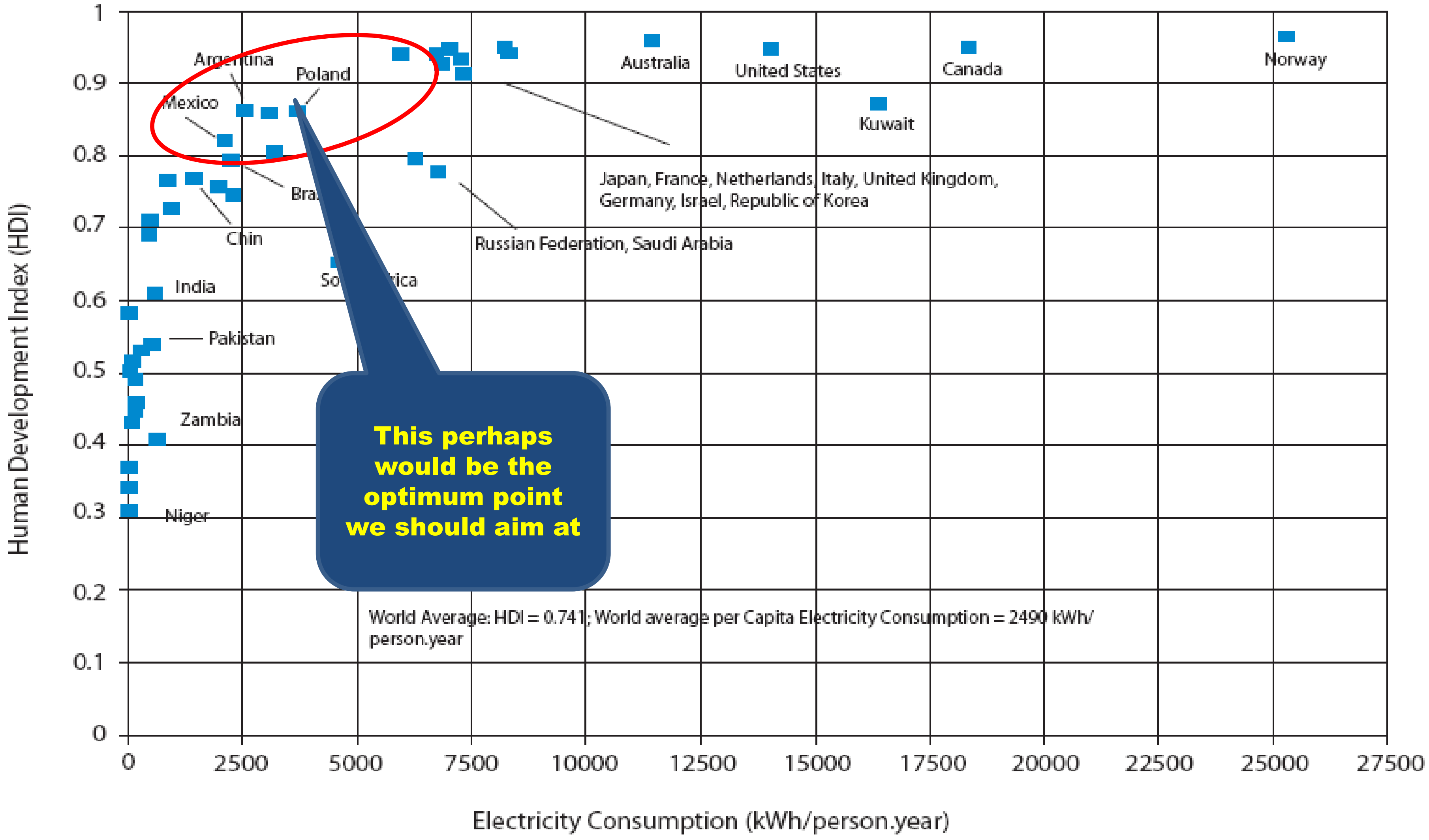
Improve the quality of life for all

Our World



The population is likely to grow to about ten billion by the end of 2050 and the climate changes are threatening to deprive the under-privileged more than those who are doing well in the world.

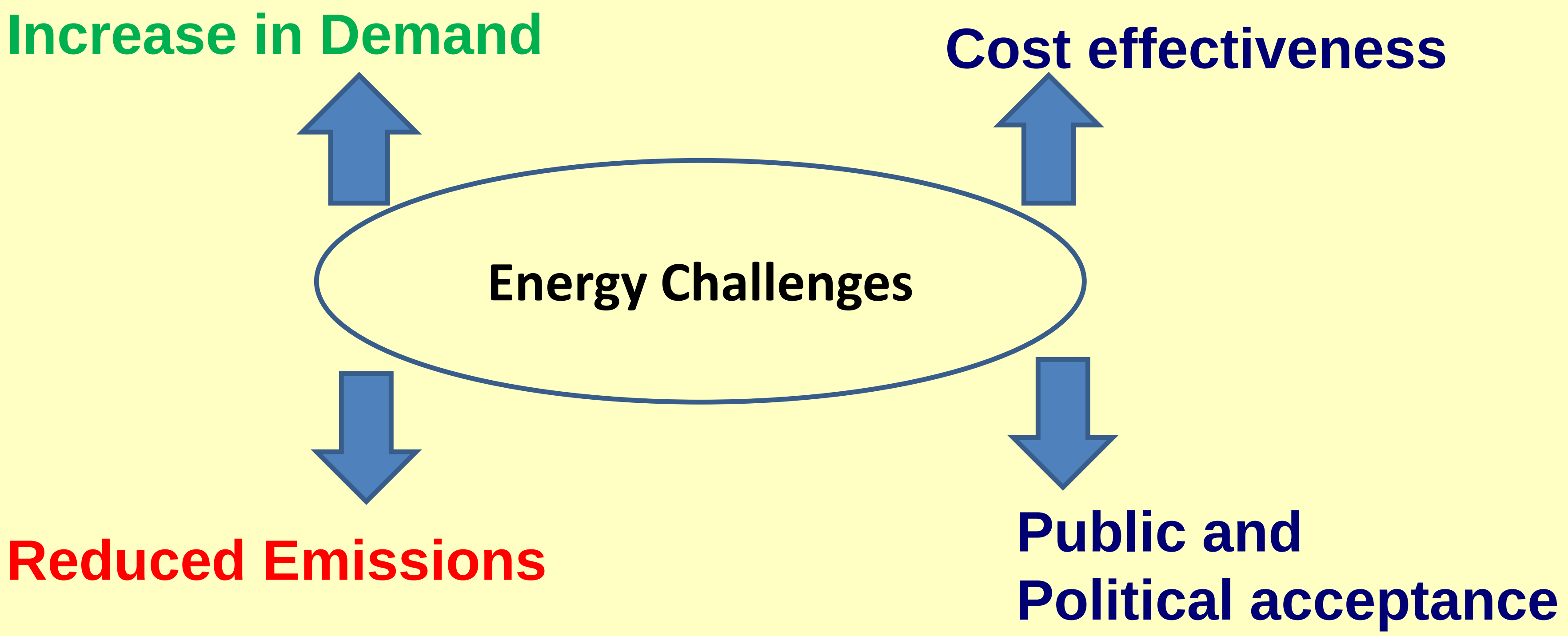
Human Development Index & Electricity Consumption



Source: Dr. Steve Chu, Department of Energy, US

Motivation for More & Clean Energy > Better quality of life

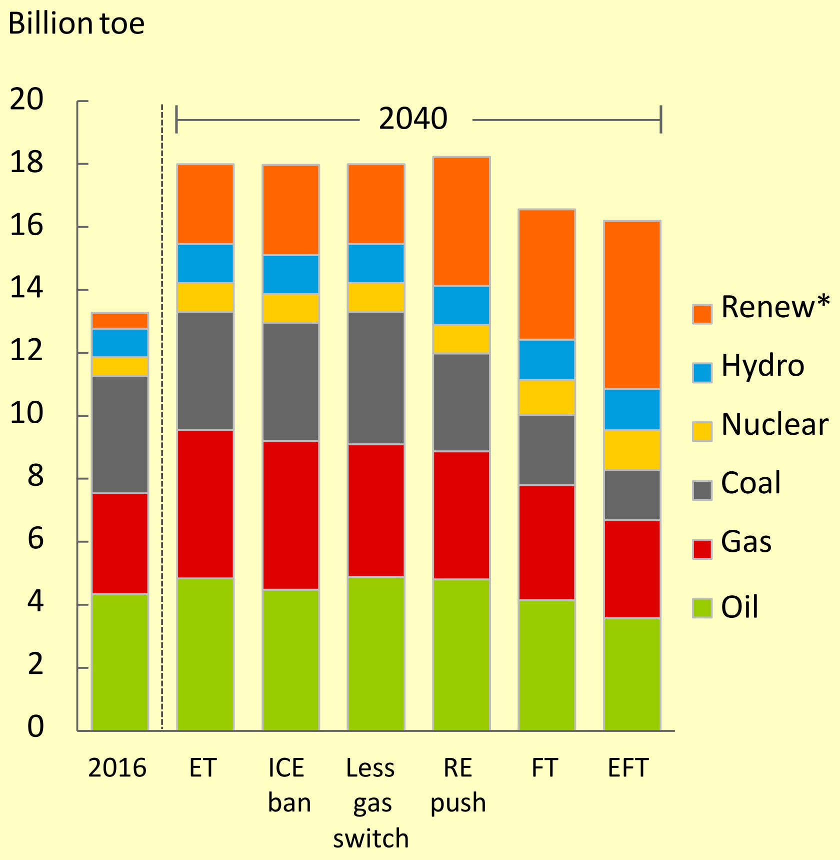
Energy defines the index of quality of life



Energy defines the index of quality of life. But has to meet many challenges

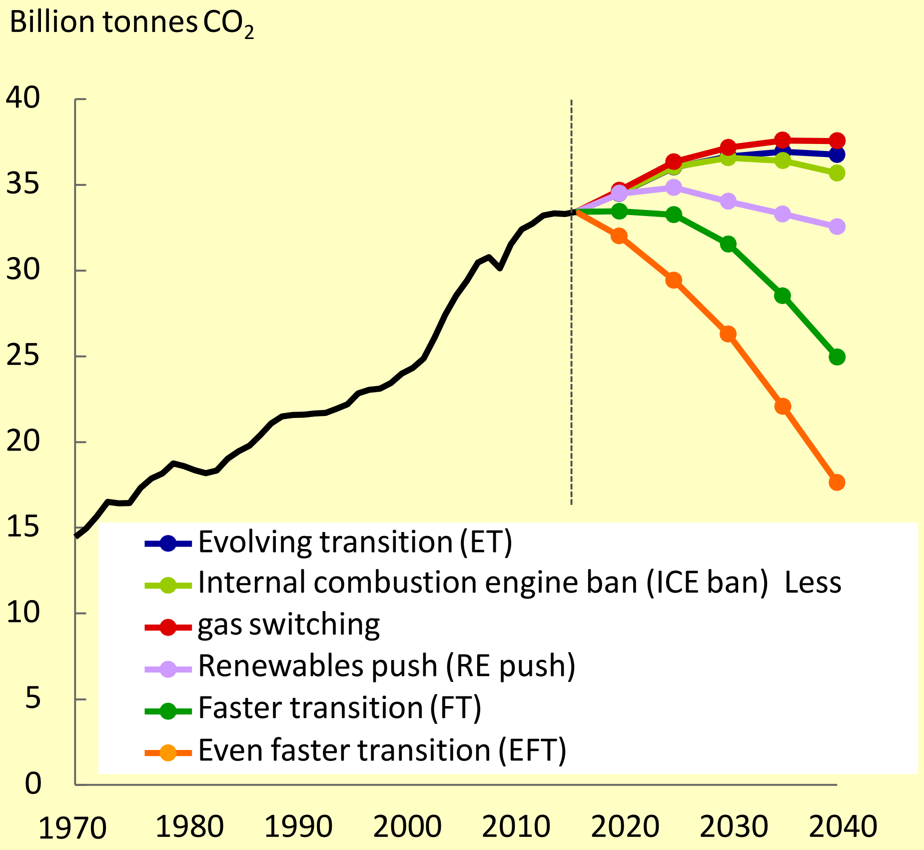
Overview

Primary energy consumption by fuel



*Renewables includes wind, solar, geothermal, biomass, and biofuels

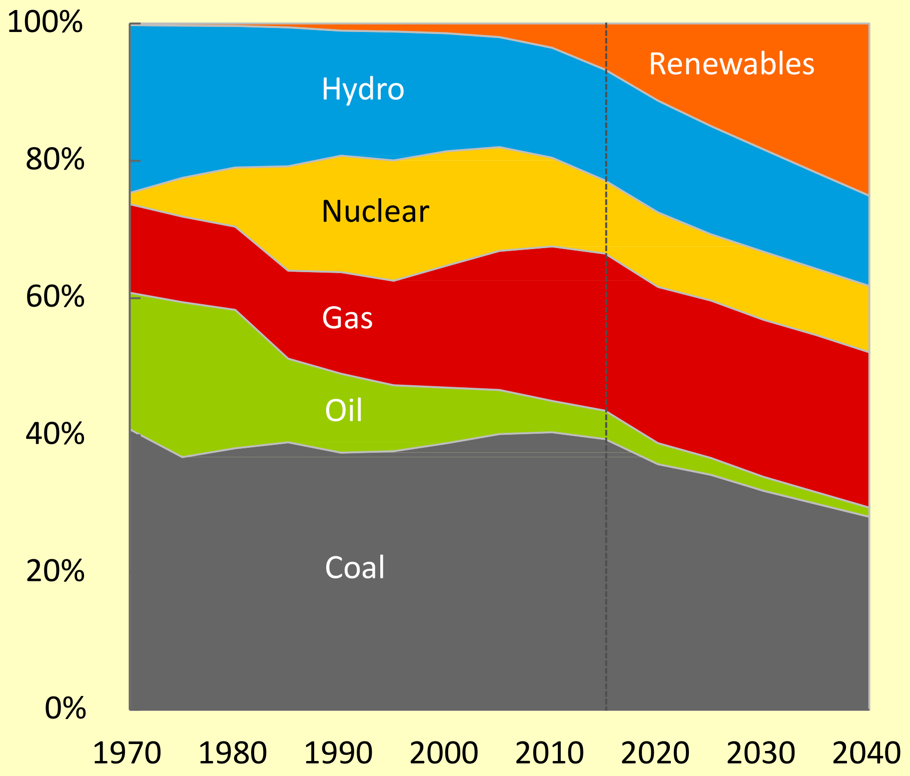
Carbon emissions



Sectors: Power

The world continues to electrify...

Shares of total power generation



Worst Industrial Accidents in History

Year	Incident	Location	Fatalities
2013	Rana Plaza, Collapse of building containing several factories	Savar, Bangladesh	>1100
1984	42 tons of lethal methyl isocyanate leak, Union Carbide pesticide plant	Bhopal, India	2259 (immediately) ~ 25000 believed to have died since due to exposure
1942	Coal dust and gas explosion in a mine	Benxi Liaoning, China	1549
1986	Chernobyl NPP	Prypiat, Ukraine	31 : radiation 3,940: radiation induced cancer and leukemia
1947	Fire near 2300 tons of Ammonium nitrate on S.S. Grandcamp causes explosion	Port of Texas City, Texas, USA	581
1984	Explosions at a Liquid Petroleum Gas tank farm	San Juanico, Mexico	500
1906	Coal dust explosion	Courrieres, France	1099
1976	ICMESA, a chemical manufacturing plant, releases dioxins (TCDD)	Seveso, Italy	3300 farm animals 80000 animals later slaughtered
1989	Exxon Valdez,:oil tanker, spills 260 thousand barrels crude into sea	Prince William Sounds, Alaska, USA	100000 - 250000 Seabirds

Source: Wikipedia

Nuclear Incidents/Accidents

Date	Location	Description	Fatalities
January 3, 1961	Idaho, US	Explosion at SL1 prototype at the National Reactor Testing Station.	3 All three operators were killed when a control rod was removed too far
January 5, 1976	Jaslovské Bohunice, Czechoslovakia	Malfunction during fuel replacement. Fuel rod ejected from reactor into the reactor hall by coolant (CO_2)	2
March 28, 1979	Three Mile Island, Pennsylvania, US	Loss of coolant and partial core meltdown due to operator errors. There is a small release of radioactive gases. See also Three Mile Island accident health effects.	0

Source: Wikipedia

Nuclear Incidents/Accidents

Date	Location	Description	Fatalities
April 26, 1986	Chernobyl, Ukraine	explosion and meltdown, necessitating the evacuation of 300,000 people from Chernobyl and dispersing radioactive material across Europe	31 direct [19 not entirely related and 15 minors due to thyroid cancer] UNSCEAR UN_Scientific Committee on the Effects of Atomic Radiation
September 30, 1999	Ibaraki Prefecture, Japan	Tokaimura nuclear accident	2 1 exposed beyond permissible limits

UN established Chernobyl Forum involving 7 UN agencies including WHO, UN Environment Programme and IAEA. In 2006, 20 years, later the forum concluded, the total death toll of 56 out of which 34 died fighting the fire.

Source: Wikipedia

Nuclear Incidents/Accidents

Date	Location	Description	Fatalities
August 9, 2004	Fukui Prefecture, Japan	Steam explosion at Mihama Nuclear Power Plant	4
March 11, 2011	Fukushima, Japan	Tsunami flooded and damaged the plant's 5 active reactors, Drowning two workers. One man died suddenly while carrying equipment during the clean-up	2+ (over 1,600 excess deaths due to evacuation)
September 12, 2011	Marcoule, France	One person was killed and four injured, one seriously, in a blast at the Marcoule Nuclear Site. The explosion took place in a furnace used to melt metallic waste	1

Source: Wikipedia

Worldwide Severe Accidents

Aggregate Fatalities : Energy options

(also given is normalised Fatalities)

Energy Chain	No. of Accidents	Total Fatalities	Normalised Fatalities/GWa
Coal	1221	25107	0.876
Coal[a]	177	7090	0.690
Oil	397	20283	0.436
Natural Gas	125	1978	0.093
Hydro	11	29938	4.265
*Hydro-2	10	3938	0.561
Nuclear	1	56	0.006

during 1969-2000

No change in fatalities after Fukushima

[a] Excluding China

*Excluding the Banqio/Shimantan dam burst which resulted in 26000 fatalities

Source: Wikipedia

Safety

Human Reliability Program

Security

Productivity

Quality Assurance

Sabotage

for
- decision making
- compliment security
- improve employee quality

employees who are dishonest, disloyal and unreliable

HRP:
although not a prediction of human behaviour,
an excellent tool for decision making
should compliment security and improve employee quality

Human Reliability Program (HRP)

The HRP is a security and safety reliability program designed to ensure that individuals who occupy positions affording access to certain materials, nuclear explosive devices, facilities, and programs meet the highest standards of reliability and physical and mental suitability

Human Reliability Program Handbook: Department of Energy

HRP

periodic HRP audit

Drug/alcohol rehabilitation

On-going education and training

Recognition of aberrant behaviour

Drug/alcohol screen

Polygraph

Psychological evaluation

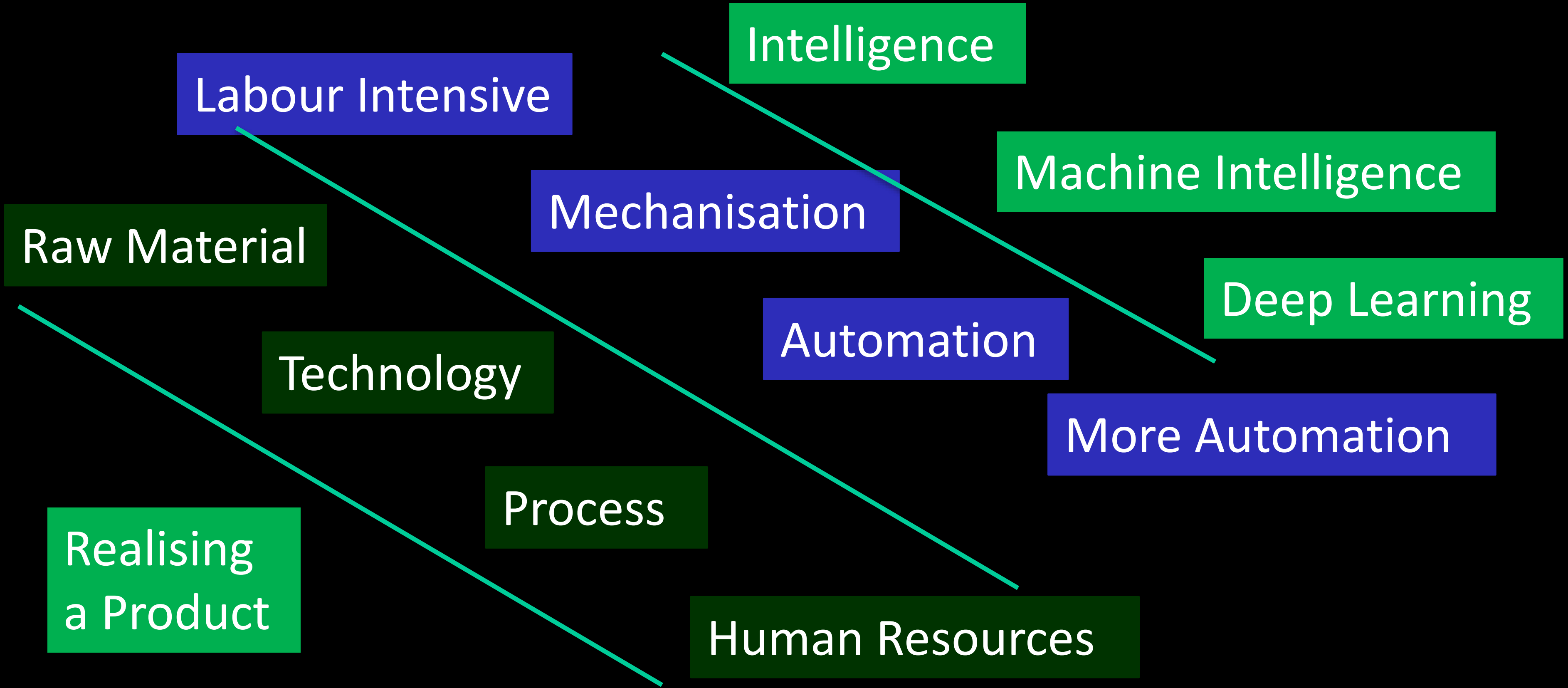
Management Evaluation

Background Checks

Occupational Health examination

Human Reliability Program

Technology


Intelligence
Labour Intensive
Machine Intelligence
Mechanisation
Raw Material
Deep Learning
Automation
Technology
More Automation
Process
Realising a Product
Human Resources

Automation

Automation: Integration of machines into a self-governing systems

Automation has revolutionized wherever it was introduced,
There is scarcely an aspect of modern life that has been unaffected by it

Automation bias: Propensity for the humans to favor suggestions from automated decision making systems and to ignore contradictory information made without automation even when it is correct

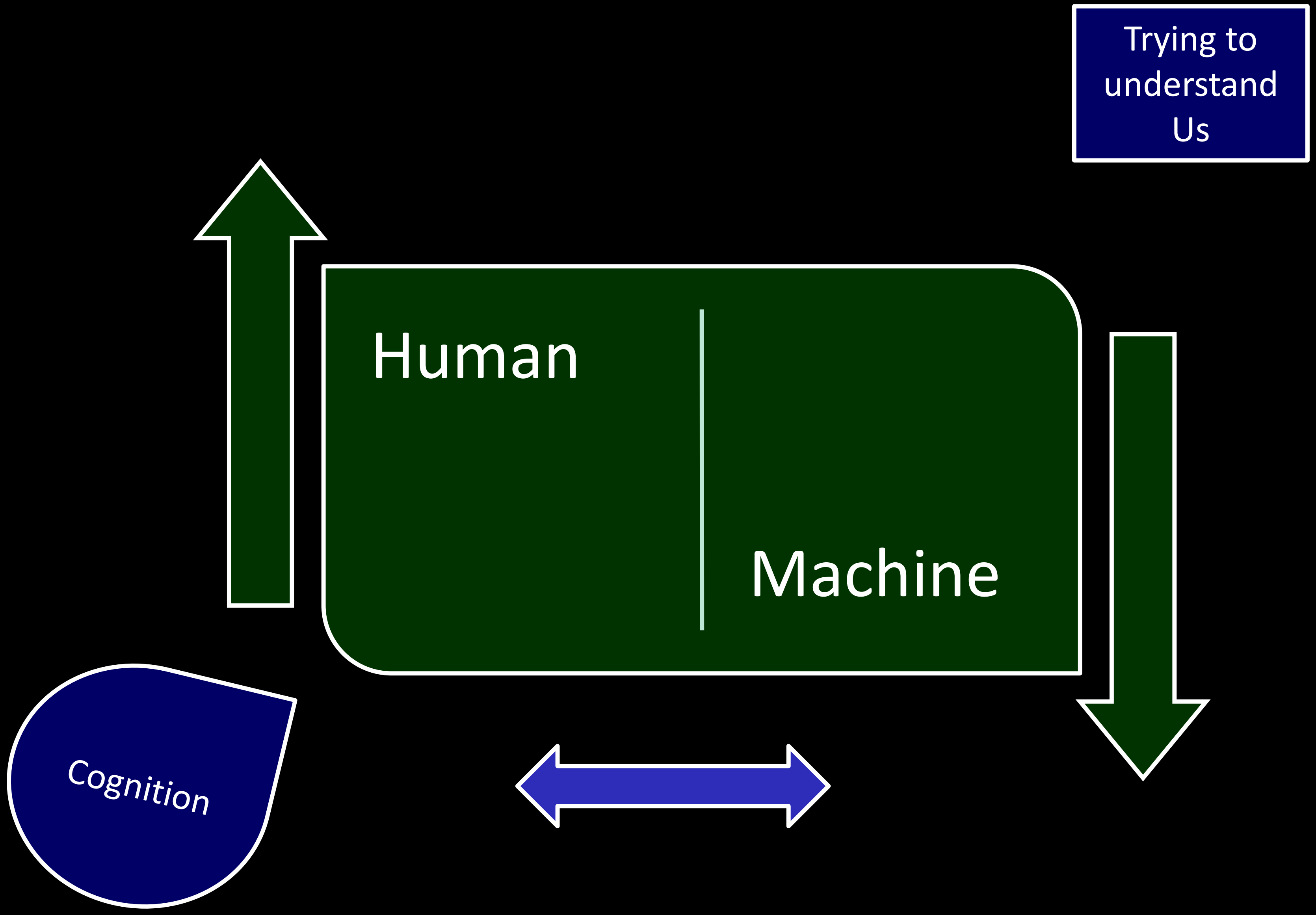
Major concern in aviation, medicine, process control, and military command and control operations.

Developing AI : How do we select reliable individuals to develop AI applications?
If once the algorithm is biased it stays that way
until it is realised that it is biased

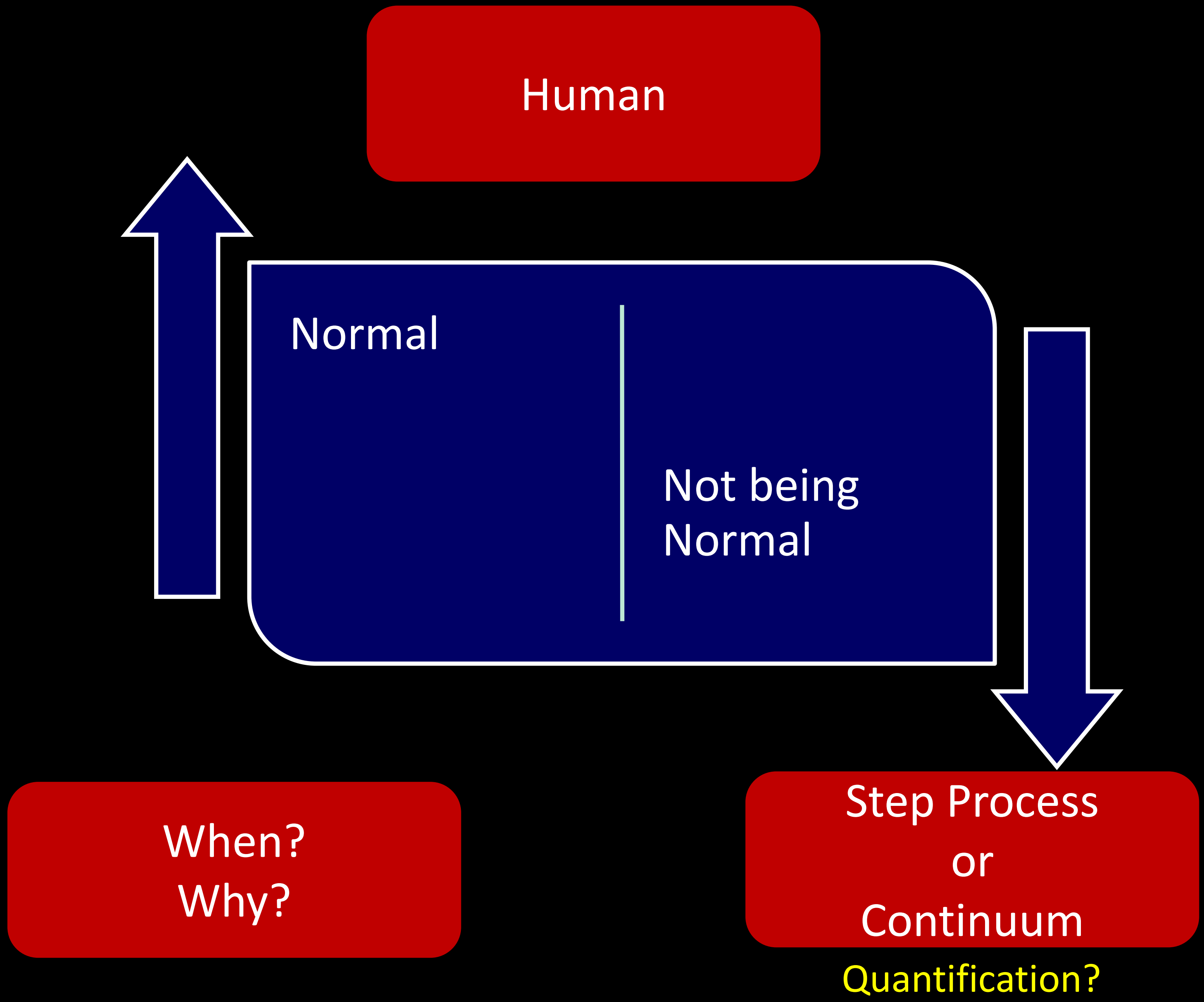
AI systems are reflecting the existing prejudices in the system,
Instead of eliminating them.

https://pdfs.semanticscholar.org/8580/dc7ba0f0d7eb1c2495ceb23af9491a805849.pdf

HRP



HRP


Human
Normal
Not being
Normal
When?
Why?
Step Process
or
Continuum
Quantification?

HRP

management evaluation
appropriate background investigative requirements
occupational health examination and laboratory testing
drug/alcohol screening
psychological testing and interviews
polygraph examination
job related aberrant behaviour recognition
on-going education and training
document control
drug/alcohol rehabilitation

Symptomatic?

Can we go beyond?

HRP

Aviation
Nuclear
Chemical
Mining
Transport

Human Reliability

Can we find the Common Thread

Afterall we are trying to understand us?

Isn’t it the real challenge?

Understand and Accommodate Diversity

Can We?

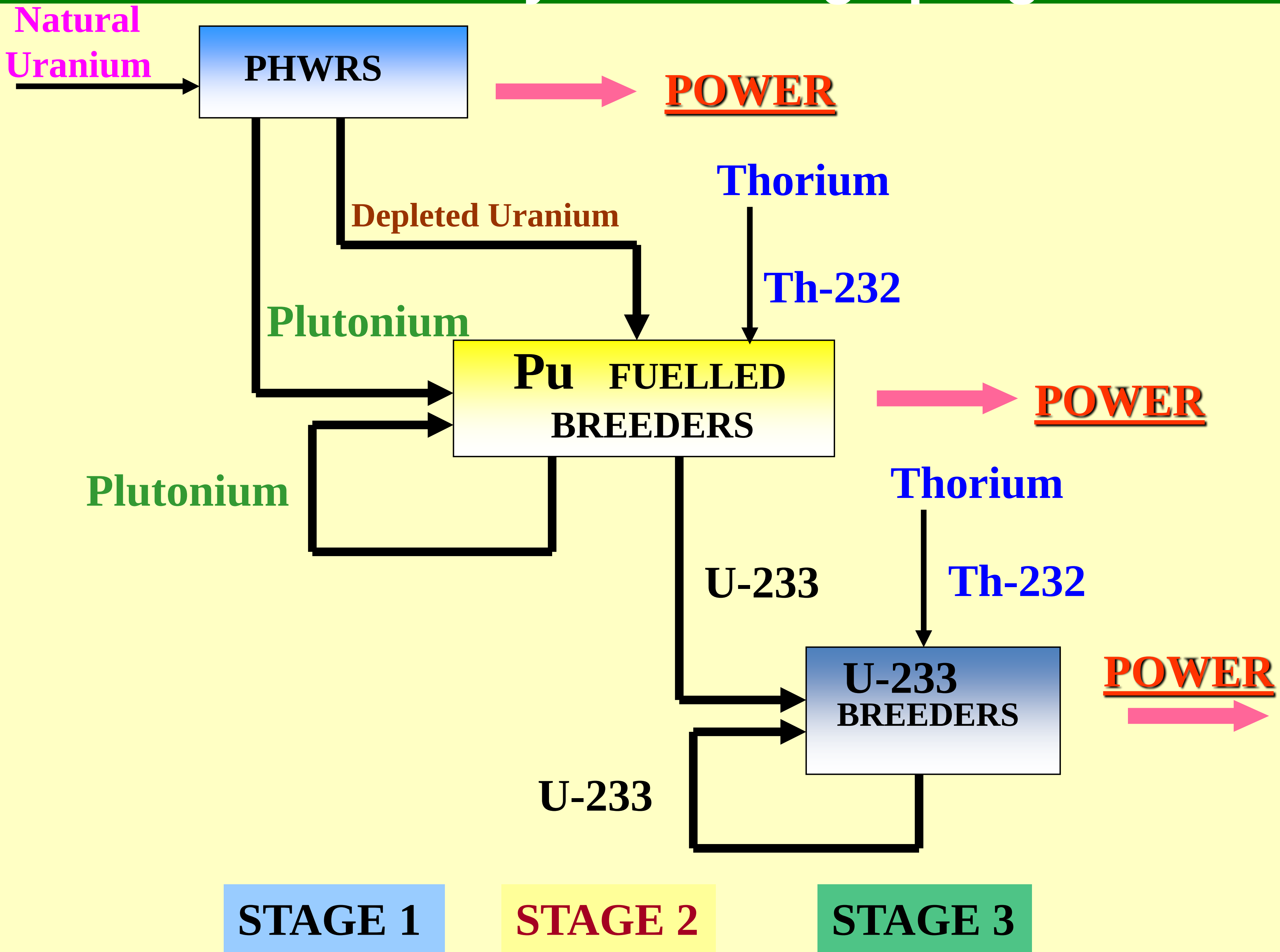
Attributes of Nuclear Technology

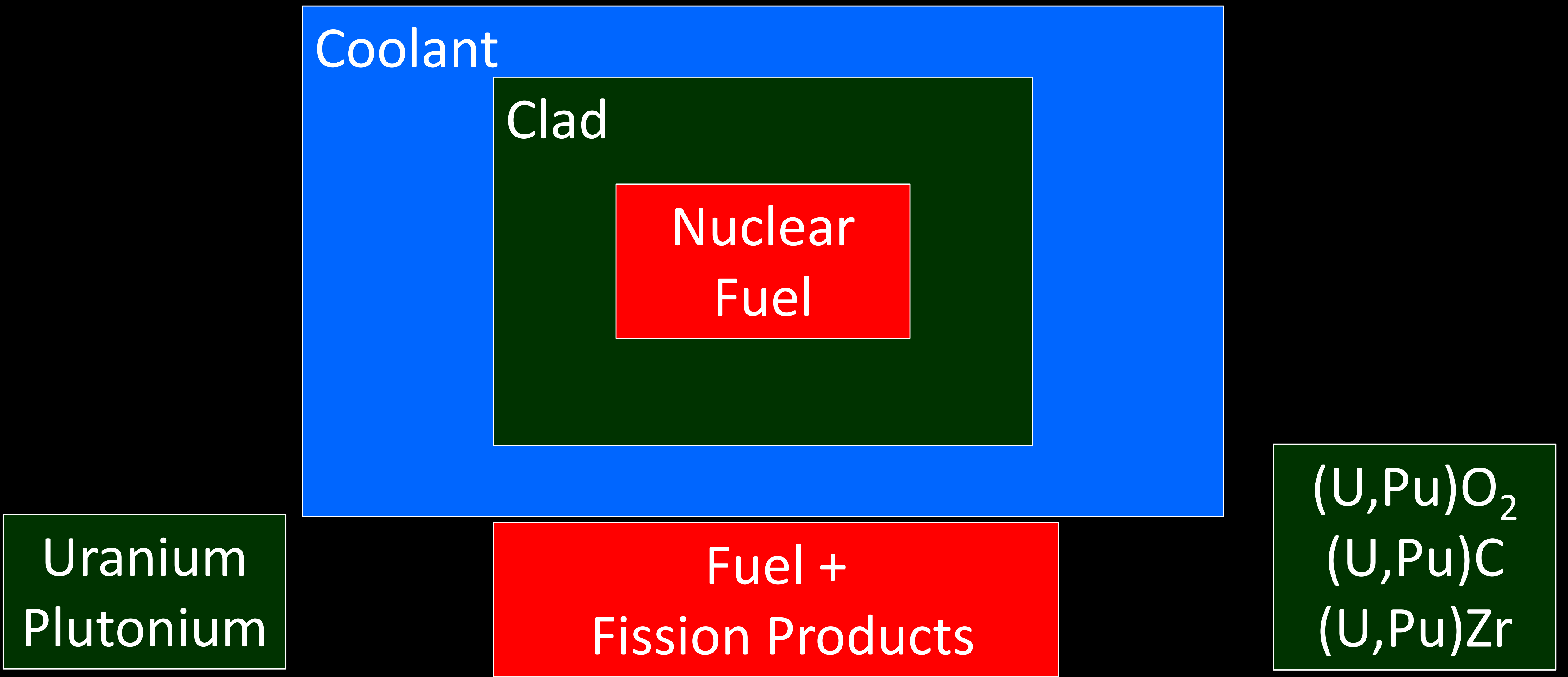
- **Nuclear technology is knowledge intensive**
- **Needs well trained Human Resource and strong industrial infrastructure for its exploitation**
- **Needs synergistic pursuit of basic research and technology development**
- **Needs Multi-Disciplinary approach to problem solving**
- **Requires safety analyses encompassing the entire gamut of engineering issues**

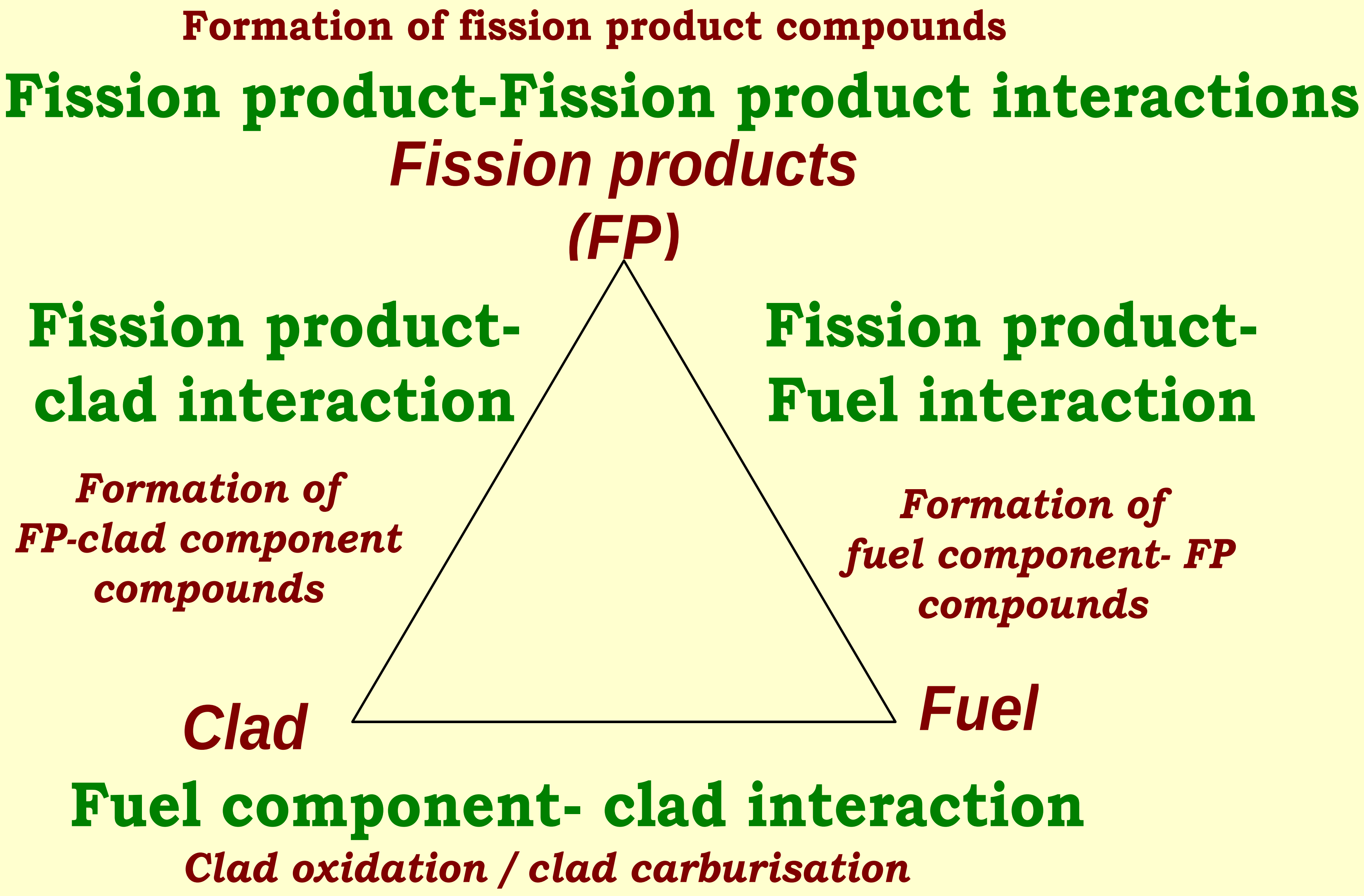
Hire and train approach –
to produce Industry Ready Human Resources

Practicing professionals as faculty –
Tacit , Explicit and Implicit Knowledge is transferred

Closed Fuel Cycle: 3 Stage program




Coolant
Clad
Nuclear Fuel
Uranium Plutonium
Fuel + Fission Products
$(U,Pu)O_2$
(U,Pu)C
(U,Pu)Zr


Formation of fission product compounds
Fission product-Fission product interactions
Fission products (FP)
Fission product-clad interaction
Formation of FP-clad component compounds
Fission product-Fuel interaction
Formation of fuel component- FP compounds
Clad
Fuel
Fuel component- clad interaction
Clad oxidation / clad carburisation

Thermo-chemical Investigations on Nuclear Materials

Driving force for these interactions?
Reason for a particular interaction becoming dominant ?

Interactions guided by Relative Thermodynamic stabilities

Fuel-Fission Product-Clad Interaction

Complexity of Irradiated Fuel Systems lies in the continuous change in the amounts of the constituents

Importance of a particular equilibrium gets altered depending upon the extent of accumulation fission products

Host of Thermo-chemical Properties needs to be obtained

Fuel-Clad
Chemical Interaction
in
Mixed Oxide Fuels

Post-irradiation examinations

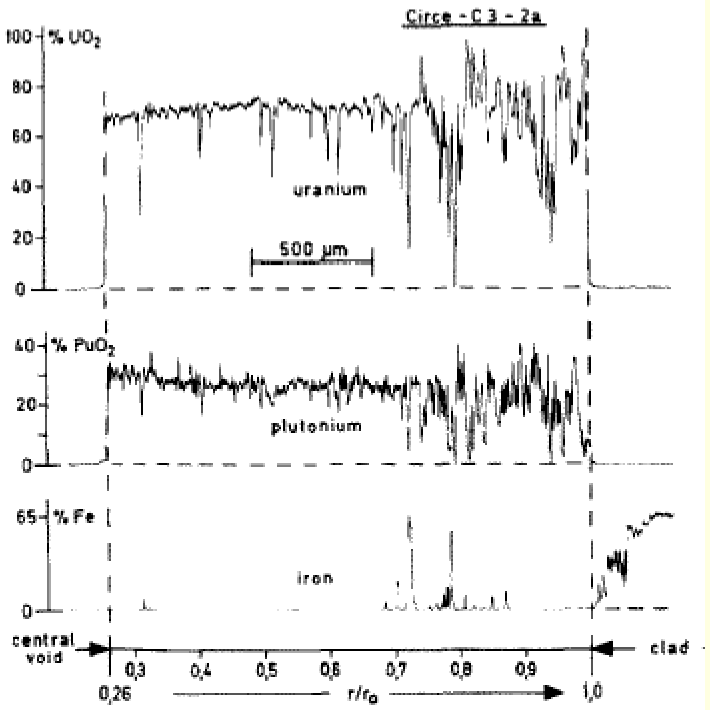
- Broad based matrix attack as well as IGA
  - the largest crack or penetration ~ 1/3 of clad thickness

- Fission products at the fuel-clad interface and in the grain boundaries of the cladding material
  - Cs, I, Te, Mo, Pd

- Clad components in the fuel matrix
  - transport into or onto the fuel

O. Götzmann, H. Kleykamp / Post irradiation examination of simulated fission product

Microstructure of the attacked s.s cladding showing Fe-Cr-Cs-I-Te-0 phases (dark grey) and metallic Mo-Ni precipitates.



Radial concentration profiles of uranium and plutonium in the fuel and of iron in the cladding and in the metallic precipitates

out-of-pile simulation experiments

- clad safe with stoichiometric and sub-stoichiometric fuel - inference applicable to reactor system?
- clad compatible with pure Cs (i.e. without oxygen impurity); attack takes place in presence of O or moisture
- shallow or negligible clad attack with pure Te

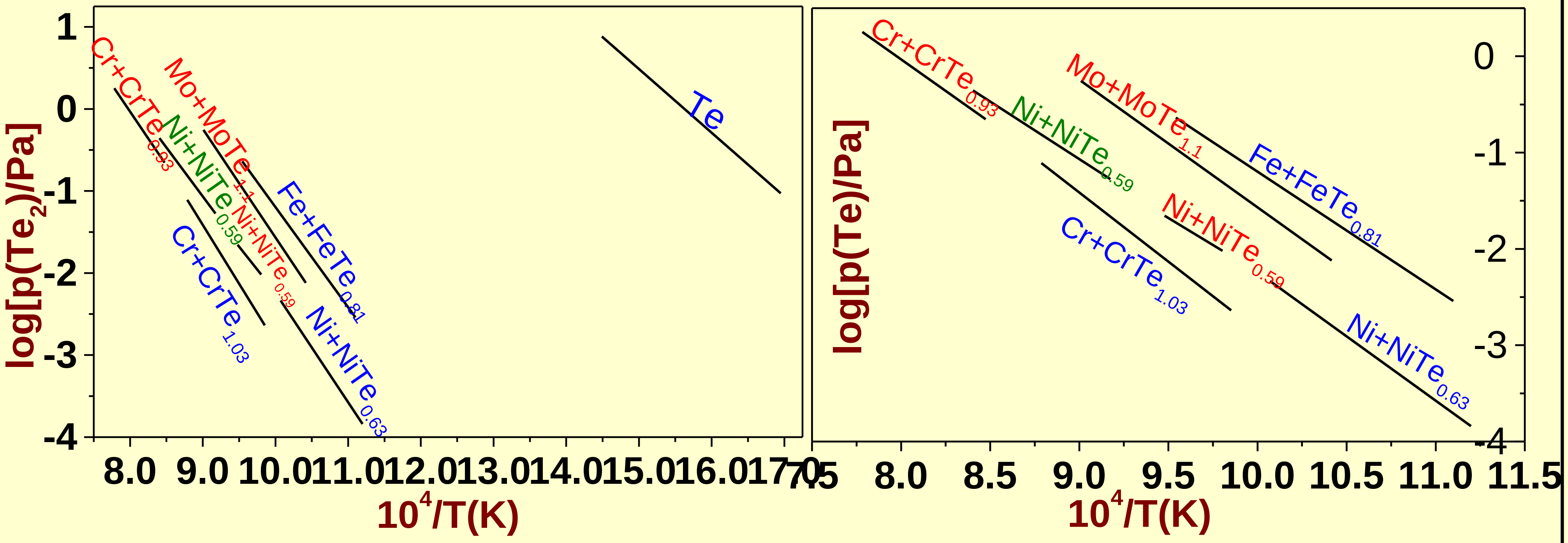
Cs, I, Te, Mo, Pd and Oxygen

Knudsen Effusion Mass Spectrometry

Extensive investigations on M-Te systems

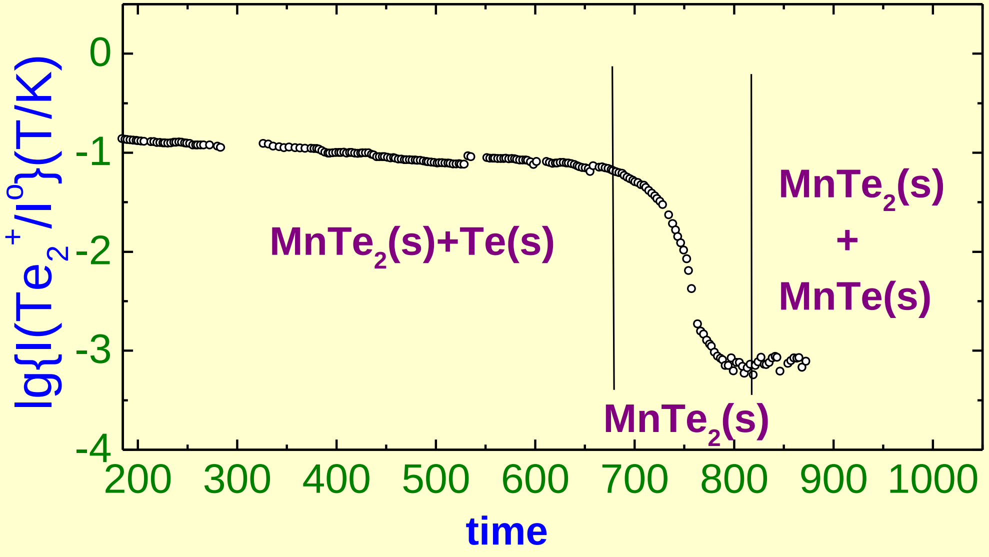
M: component of SS-clad   Te:corrosive fission product

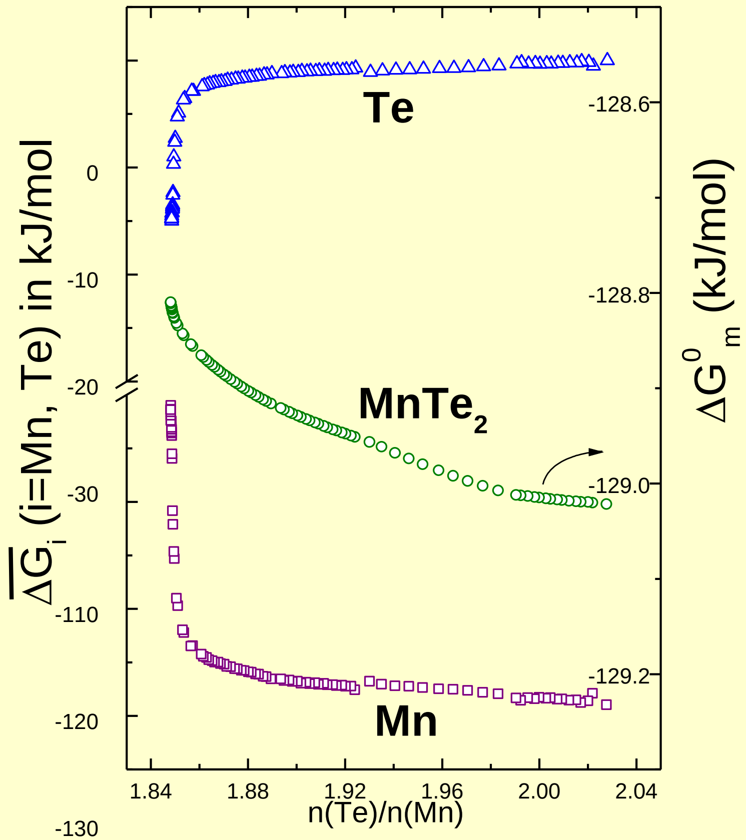
Fe-Te, Ni-Te, Cr-Te, Mo-Te, Mn-Te



Knudsen Effusion Mass Spectrometry

Homogeneity ranges of non-stoichiometric metal Tellurides





FeTe : $FeTe_{0.81}$-$FeTe_{0.94}$

CrTe : $CrTe_{1.03}$ and $CrTe_{0.93}$

Mo_3Te_4: $MoTe_{1.1}$ – $MoTe_{1.3}$

MnTe : $MnTe_{0.8}$

$MnTe_2$: $MnTe_{1.87}$-$MnTe_{2.03}$

T.S. Lakshmi Narasimhan, M. Sai Baba, R.Balasubramanian, S. Nalini and R. Viswanathan
J.Chem. Thermodynamics 34(2002) 103-117

Homogeneity ranges of non-stoichiometric metal Tellurides and Thermodynamic data

System	Phase	Homogeneity range Formula		$\Delta_f G°$ (kJ/mol) at 298.15 K	
		M-rich	Te-rich	M-rich	Te-rich
Fe-Te	$FeTe_{1-x}$	$FeTe_{0.81}$	$FeTe_{0.94}$	-21.1	-29.7
Cr-Te	$CrTe_{1-x1}$	$CrTe_{1.03}$		-70.3	
	$CrTe_{1-x2}$	$CrTe_{0.93}$		-55.7[a]	
Mo-Te	Mo_3Te_4	$MoTe_{1.1}$	$MoTe_{1.3}$	-65.4	-67.0
Mn-Te	$MnTe_{1-x}$	$MnTe_{0.8}$		-90.0	
Mn-Te-O	$Mn_6Te_5O_{16}$			-2835.4[b]	

[a] 1232.5 K [b] 900 K

Tellurium induced clad attack in mixed oxide fueled FBRs

At the Fuel-clad interface

$Cs_2Te/MO_{2\pm x}/Cs_2MO_4$ $[M=U_{0.75}Pu_{0.25}]$

Fuel : hypo-stoichiometric, stoichiometric and hyper-stoichiometric

$[\Delta\mu\ (Te)]_{fuel}$ at 1000 K

O/M	$\Delta\mu\ (O_2)/(kJ/mol)$		$\Delta\ \mu\ (Te)/(kJ/mol)$	
	21 % Pu	27 % Pu	21 % Pu	27 % Pu
1.9998	- 565.0	-556.6	-238.9	-230.6
1.9999	-553.4	-545.1	-227.4	-219.0
2.0000	-450.9	-444.1	-124.8	-118.0
2.0001	-348.3	-343.1	-22.3	-17.0
2.0002	-336.8	-331.5	-10.8	-5.5

Thermodynamic modelling

Tellurium induced clad attack in mixed oxide fuelled FBRS

At the clad

$[M]_{ss}/MTe_x$

$[\Delta\mu\ (Te)]_{clad}$ at 1000 K

M	a(M)		Δμ (Te)kJ/mol	
	SS 316	D-9	SS 316	D-9
Formation of MTe_x				
Fe	$8.52x10^{-1}$	$8.79x10^{-1}$	-30.7	-31.0
Cr	$3.11x10^{-1}$	$2.36x10^{-1}$	-54.0	-51.8
Ni	$6.15x10^{-1}$	$6.03x10^{-2}$	-44.9	-14.4
Mo	$3.99x10^{-2}$	$6.56x10^{-2}$	-17.4	-21.2
Mn	$1.45x10^{-2}$	$8.49x10^{-3}$	-71.4	-65.8

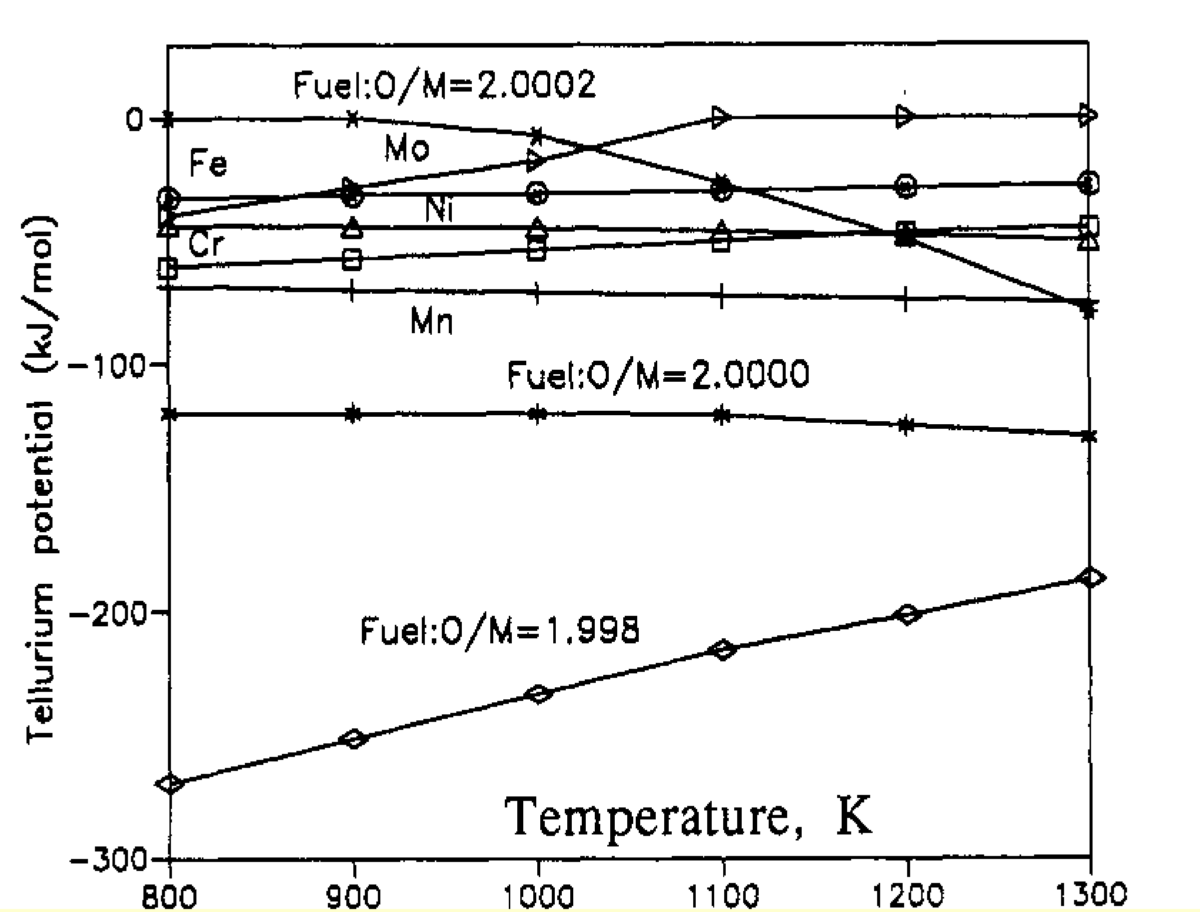
Thermodynamic modelling

Tellurium induced clad attack mixed oxide fueled FBR

At the clad — $[M]_{ss}/MTe$

At the Fuel-clad interface — $Cs_2Te/MO_{2\pm x}/Cs_2MO_4$ $[M=U_{0.75}Pu_{0.25}]$

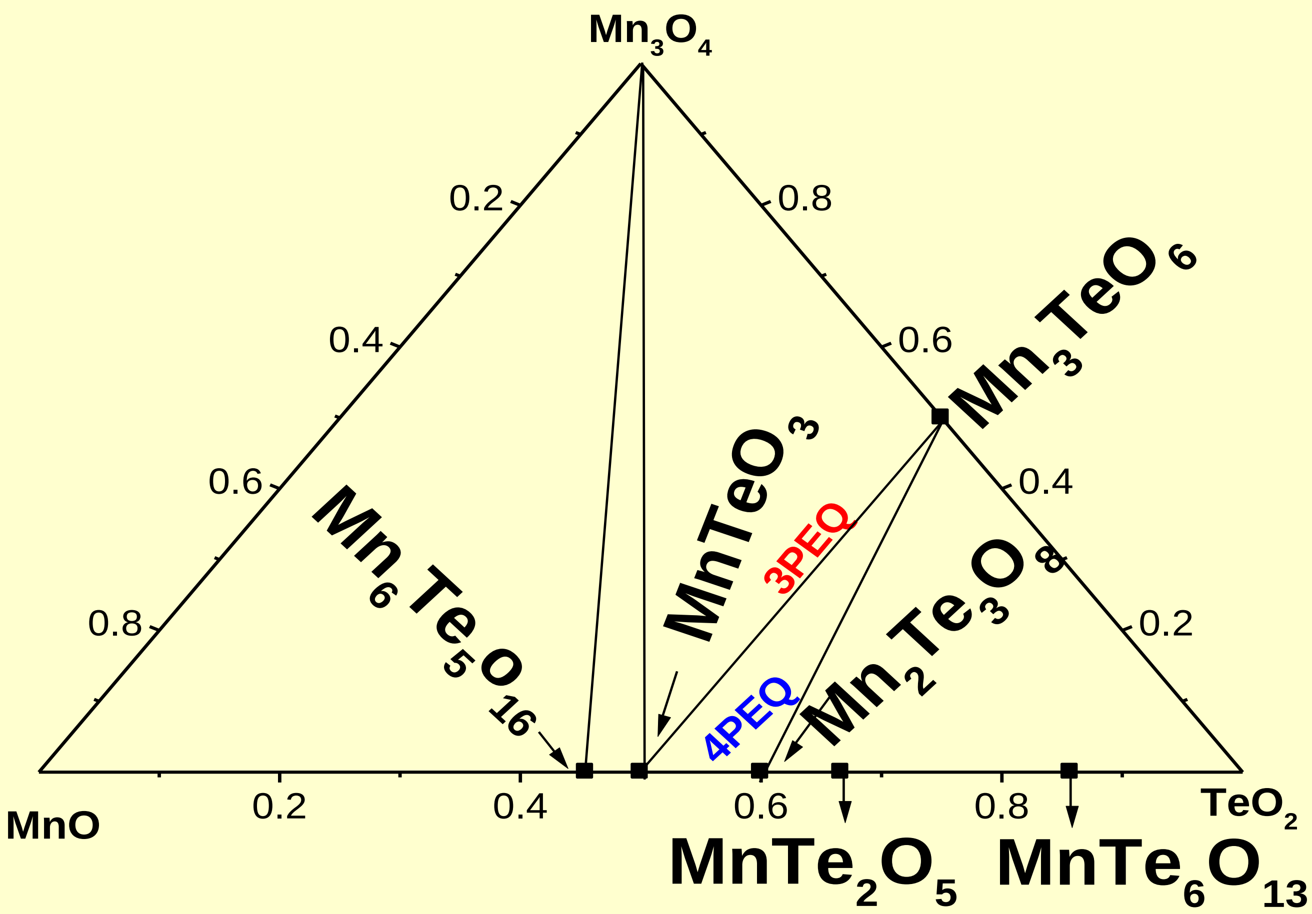
Fuel : hypo-stoichiometric stoichiometric and hyper-stoichiometric



Te-attack is likely in the case of hyper-stoichiometric fuels

MnTe likely telluride to be formed

Study of M-Te-O systems (M: SS component)



Phase diagram & Thermodynamic data determined for the first time for Mn-Te-O system

Te-Induced clad attack

Tellurium potential required for the formation of binary metal tellurides will exist when the O/M of the mixed oxide becomes >2.000

Threshold chemical potential of Te $[\Delta\mu(Te)]_{clad}$ for $M_zTe_xO_y$ formation:

$[\Delta\mu(Te)]_{clad}$ calculated as per the equilibrium

$$z\,[M]_{SS} + x\,[Te] + (y/2)\,[O_2] = M_zTe_xO_y(s)$$

The tellurium potential required for the formation of MnO-rich Mn-Te-O compound, $Mn_6Te_5O_{16}$, was calculated to be –9 kJ/mol at 900 K. This Te-potential is likely to prevail in the fuel-clad gap for fuel with O/M>2.000.

Studies on Sodium Fire

Sodium Concrete Interactions:
Qualification of sodium resistant concrete for Reactor application

Development of advanced clad and wrapper materials

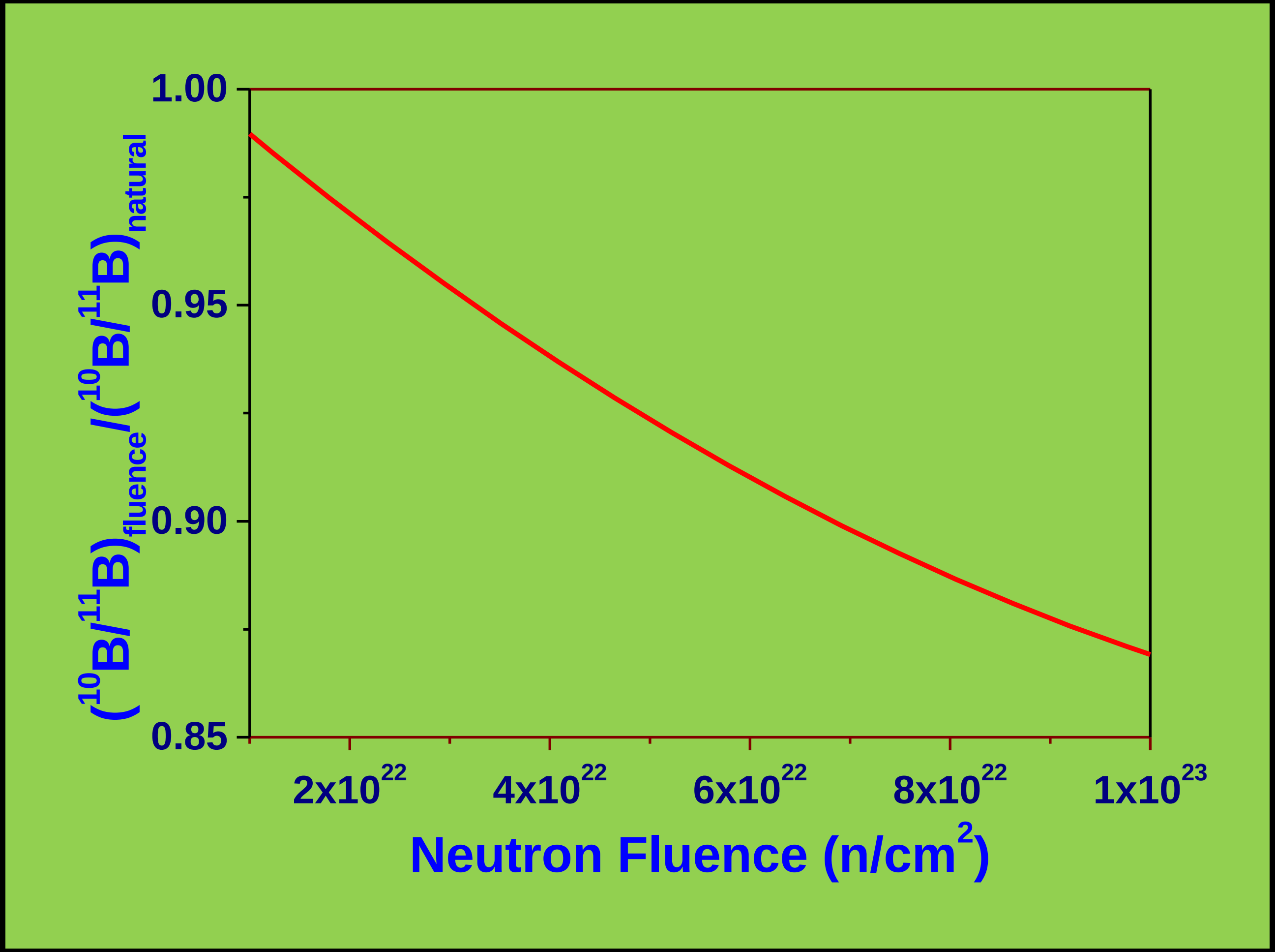
Parameter	Current	Stage-1	Stage-2	Satege-3	Stage-4
Target Burnup GWd/t	100	< 150	> 150	200	200
Fuel	Oxide	Oxide	Oxide	Oxide	Metallic
Clad material	D9	IFAC-1 (D9I)	IFAC-1 (D9I)	F-M ODS steel	F-M ODS steel
Wrapper material	D9	IFAC-1 (D9I)	T9 F-M steel	T9 F-M steel	T91 F-M steel
Linear power, W/cm	450	450	450	500	> 500

Development of structural materials

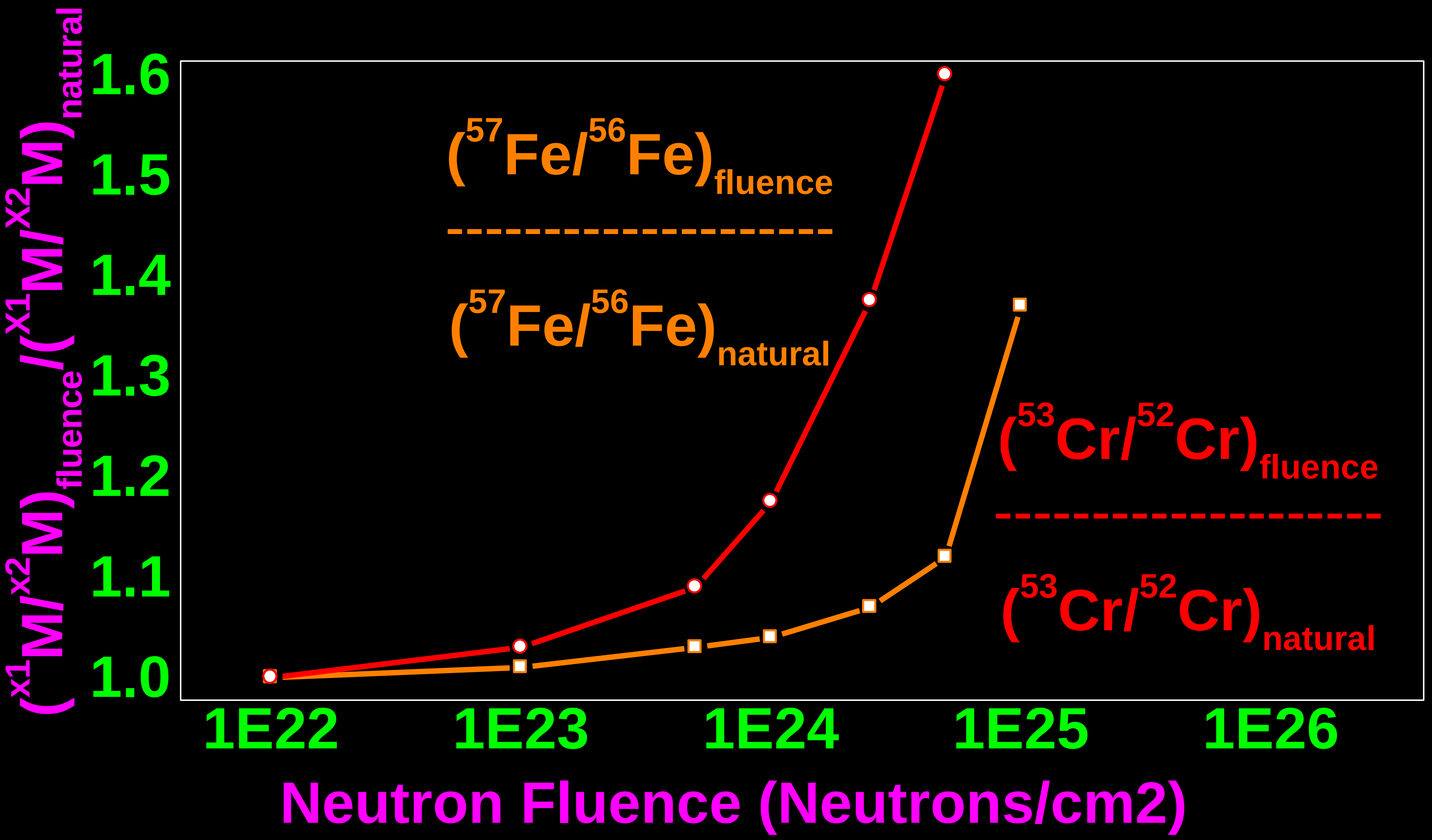
Material	Application
316 LN (0.14N)	Reactor vessels
T23, T24, T91BN	Steam generators

Development of Neutron Fluence Monitors

Variation of($^{10}B/^{11}B$) as a function of fluence



Development of Neutron Fluence Monitors



Why Environment is so important

As we watch the sun go down, evening after evening, through the smog across the poisoned waters of our native earth, we must ask ourselves seriously whether we really wish some future universal historian on another planet to say about us:

"With all their genius and with all their skill, they ran out of foresight and air and food and water and ideas"

or

"They went on playing politics until their world collapsed around them"

U Thant

Thank you
for
Your
Attention