Energies for the Future

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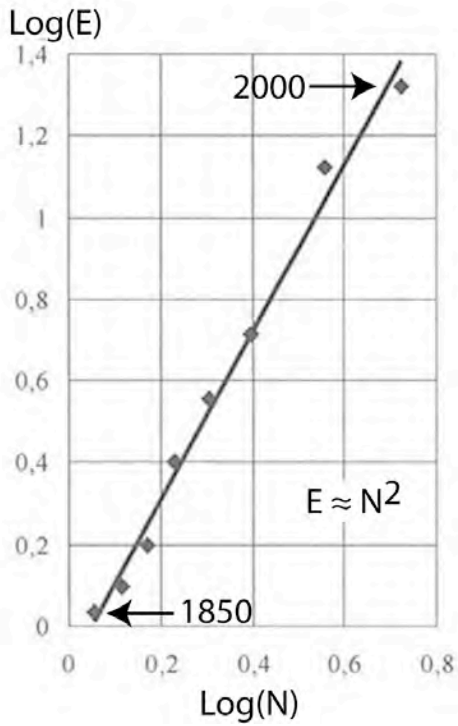
The population "explosion" and the Demographic Transition

- Every second, 21 people are born and 18 die, a net gain of 3 people/s. Every day the population increases by 0.22 million people. The growth rate has been incessantly rising and it is currently approaching 90 million/year, with the rapid blowup of a population explosion.
- Such an immense growth of the human species is one of the most extraordinary evolutions of the planet Earth and no doubt it is conditioning the future of man as well as the one of any other animal and vegetal species.
- Within the 4300 millions of years of the life of the solar system, the "homo sapiens", its speech, language and fire all go back to far less than one million years from today.
- The total number of individuals which have ever lived on earth is estimated between 70 and 150 billions. Because of the exponential growth, as many as 6 to 10 % of all human beings are alive today.

- At the beginning of the 19th century (population : 10^9) the average power was about 1kW/p, about 1/2 of a HP, 10 x his own human power.
- Since 1850, energy has grown twice as fast as population, i.e. $E \propto N^2$.



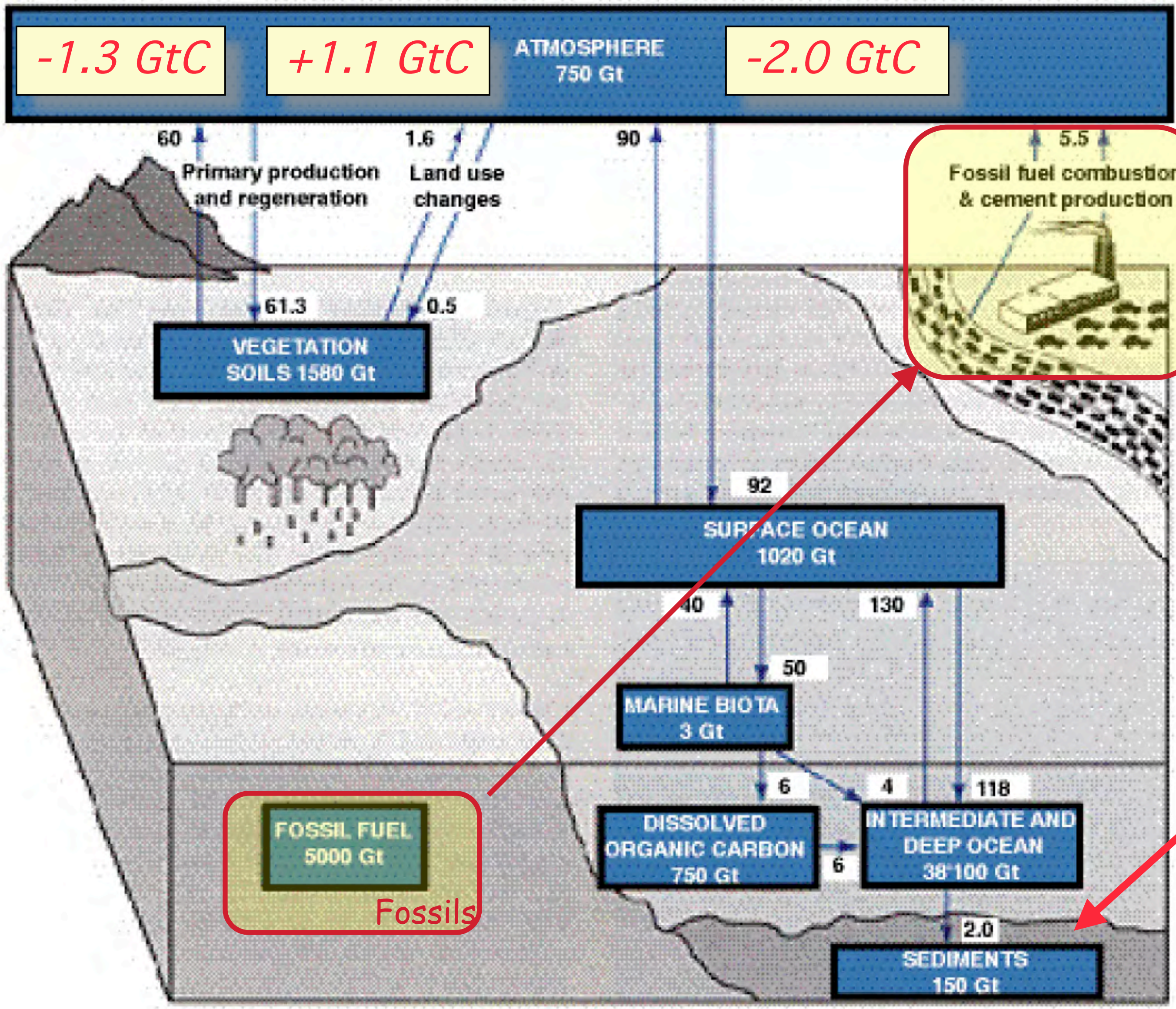
Year	Population Billions	Energy TWatts·Year
1850	1.13	0.68
1870	1.3	0.79
1890	1.49	1.0
1910	1.70	1.60
1930	2.02	2.28
1950	2.51	3.26
1970	3.62	8.36
1992	5.32	13.3
2000	6.10	14.5
2020	7.32	20.9

- During the last 79 years, the global population grew by 3.42 times and the energy production increased 11.7 times.
- In 2000 mankind consumed 14.5 Twatt x year, a pro capite equivalent to 2.3 ton of coal, of the same order of the pro-capita nuclear weapons or of the energy required to launch each human being into space. For the US ≈ 14 t/y/p.

The dangers of an unlimited coal utilization

- Some of the world's biggest economies rely on coal. For instance, it provides almost 50% of USA's and Germany's electric power, 70% of India's and 80% of China's, a livelihood for billions of people, with a secure, domestic energy. But it produces twice the CO2 of NG.
- Is there a way of reconciling coal and climate ? Politicians' hopes are very high. The job is huge if one thinks that already today about 20 billion tons of CO2 are produced every year,
- At the present rate CO2 is enough to fill with super-fluid CO2 at >100 atm. the lake of Geneva (80 km^3) every 4 years
- The lake Michigan, the third largest Great Lake by surface area and the sixth largest freshwater lake in the world (2600 km of shoreline) after 1200 Gt of fossils (60 years at today's consumption)

Where is CO2 going ?



Adapted from Climate Change 1994, published by the IPCC

1 ppmv CO_2 = 2.1 GtC

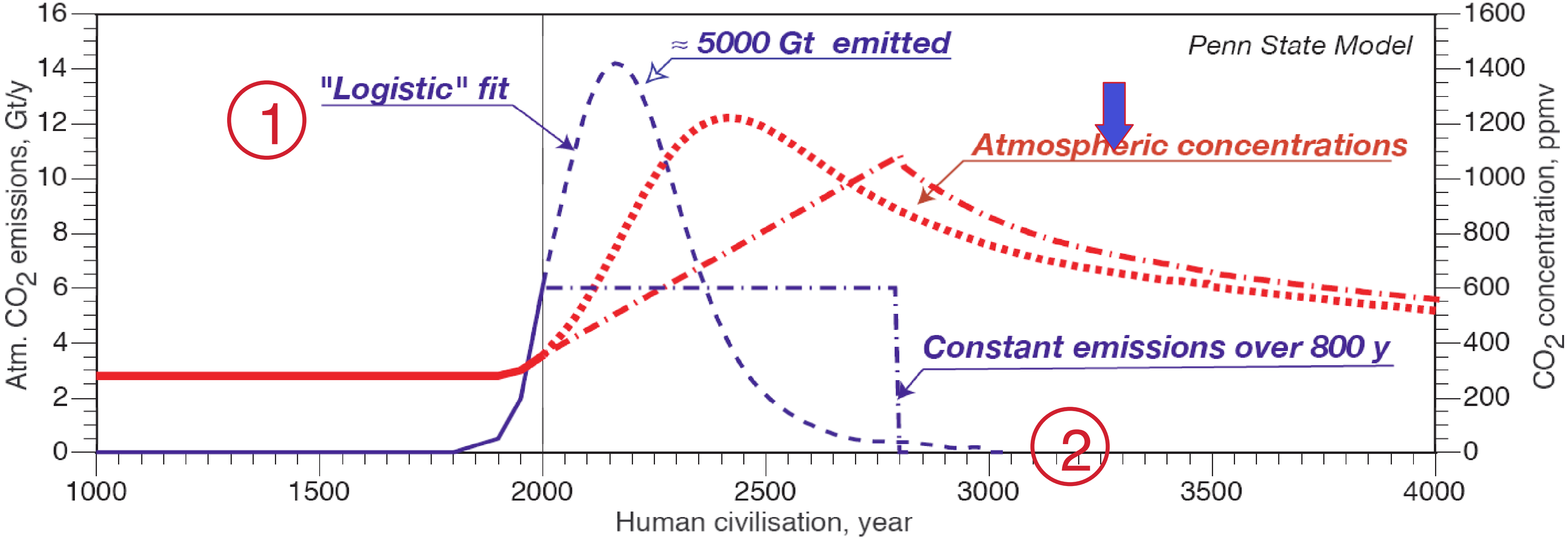
Antropogenic effects

Ultimately most of the CO2 excess will have to be carbonized in the deep oceans

-2.0 GtC into Carbonates

- Oil and Natural gas (about 500 Gton each) are expected to reach their limits sooner rather than later, due both to an increase of consumption and the progressive reduction of easily available resources.
- However there is plenty of cheap and readily available Coal. The known reserve is about 5000 Gton and it could be up to 20'000 Gton.
- Coal or Shales can be eventually converted to liquids (methanol or ethanol) to replace Oil and to gas (Syngas,Towngas and so on) to replace NG. but they require about twice as much CO2 than Oil or gas.
- We recall as an example Germany during the last world war, with a massive use of gasoline from Coal in order to replace the wartime shortage of Oil.
- *There are sufficient amounts of Coal for half a millenium at twice the present level of (fossil) energy consumption*.

Assume that a major fraction of fossils are burnt….



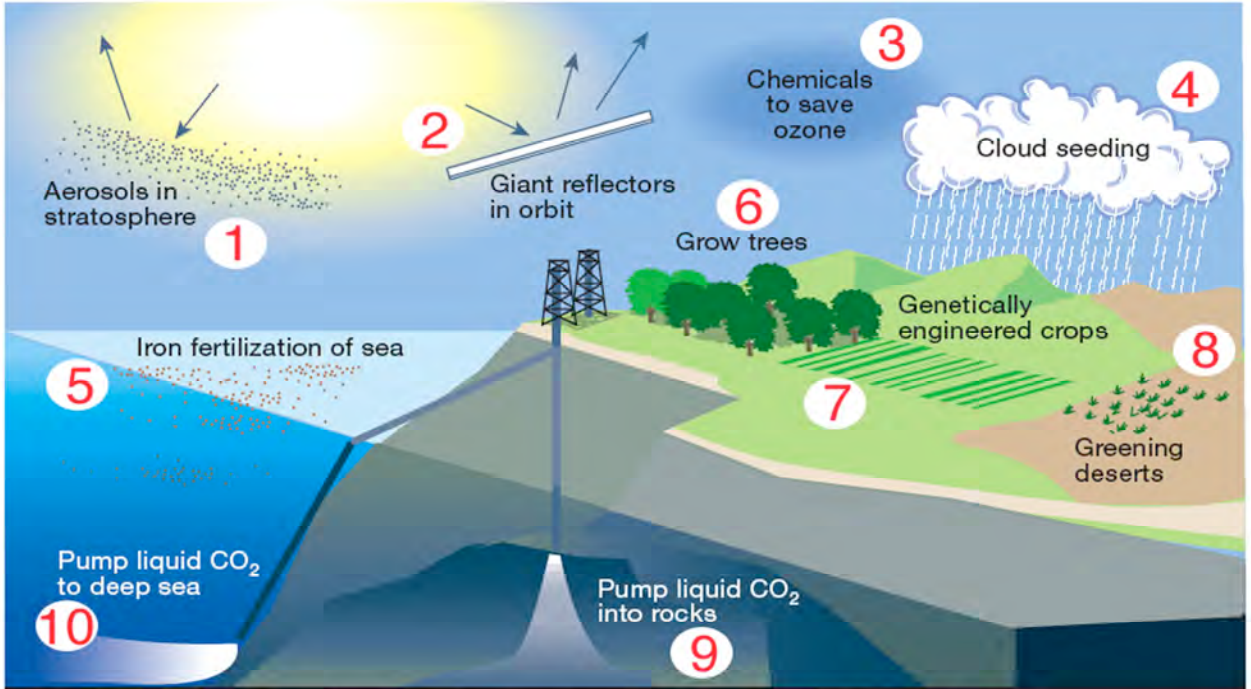
- Technological improvements will, no doubt, will introduce other forms of energy: but the planet will continue notwithstanding to burn fossils for a long time to come, especially in those parts of the planet where the technological change is the slowest.
- We have not yet reached public awareness and concern for CO2 as for the production of long-lived nuclear waste, f.i. the Plutonium lifetime is 26 kyr, while mean lifetime of fossil CO2, including its long lasting tail, will reach about 30–35 kyr.*For 5000 Gt,* survival is *17-33%* after 1 ky, 10–15% after 10 ky and 7% after 100 ky.

Is there a way out ?

- Global warming and pollution are direct consequences of our growing population and economies. Investing now in devices which conserve energy is worthwile, but also new alternatives must be vigorously pursued.
- There are today only few possible alternatives to the dramatic "business as usual approach", all requiring a vast R&D :
  - *INEVITABLE USES OF FOSSILS*, but mitigating the global warming of the atmosphere. On a longer timescale:
  - *NEW ENERGIES from the SUN :* Solar energy may be either used directly as heat, hydrogen or PV or indirectly through hydro, wind, bio-mass and so on.
  - *a NEW NUCLEAR*, but on a longer timetable and with due consideration for its problems. Practical examples are natural Uranium (U-238) or Thorium (fission) and Lithium (fusion) all adequate for many thousand of years at several times the present energy consumption.

Geo-engineering for fossil CO2 recovery ?

1. *Aereosols in the stratosphere*
2. *Reflectors in orbit*
3. *Ozone preservation with chemicals*
4. *Cloud seeding*
5. *Iron fertilisation of sea*
6. *Grow trees*
7. *Genetically modified crops*
8. *Greening deserts*
9. *Pump liquid CO_2 into rocks*
10. *Pump liquid CO_2 to deep seas*

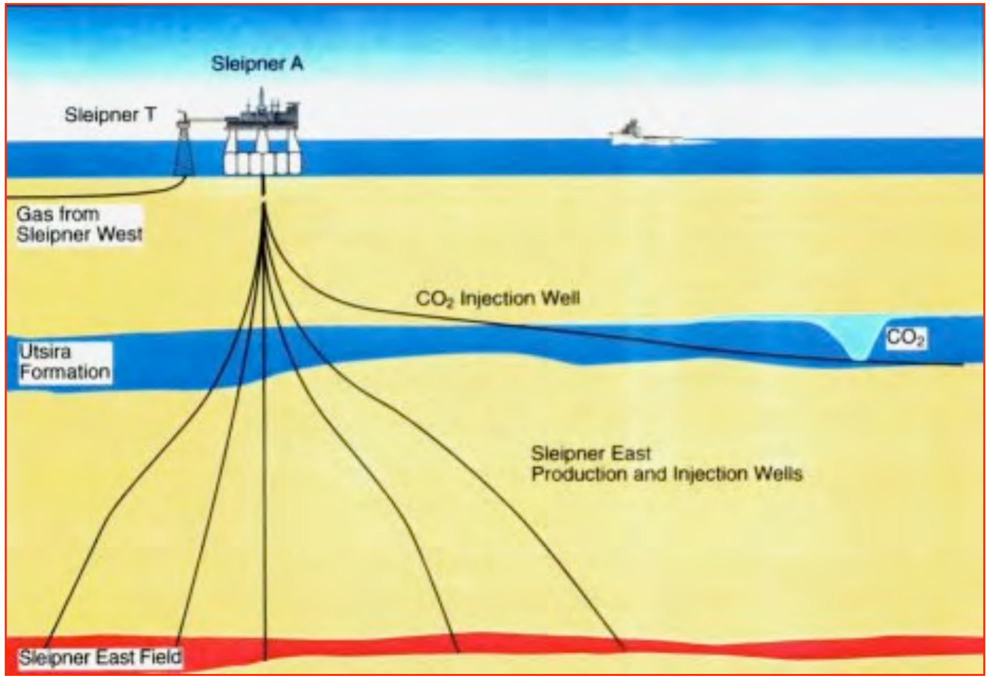


Schematic representation of various climate-engineering proposals (courtesy B. Matthews).

- Many of these ideas are unrealistic at the first sight, like for instance the proposal for huge reflectors in space (2)
- Notwithstanding they evidence the extreme difficulty in facing the consequences of growing fossil emissions.
- These considerations should foster a serious debate on maybe other, truly innovative ideas on the planetary scale.

Clean coal: a reality or an illusion ?

- Sequestration (CCS) is seriously considered: inject the CO2 down into the earth or at the bottom of the ocean.
- Already used by the oil industry, but at the level of few million tons/y.
- Some $3.4 Billion have been already spent by USA and similar incentives have been given by EECC and elsewhere.



- But so far CCS will be incredibly costly to build and to operate, reducing electric plant's efficiency by at least 20-40%.
- Many methods are not applicable to CCS.
- How long will it stay down there ? CO2 is a very volatile and chemically dangerous material. If it escapes at a concentration of > 10% it causes sudden death in less than 4 minutes.

A pssible alternative: NG to H2 transformation ?

- H2 production is 1.9×10^{11} Nm^3/y, 17 Mton/y, energetically equivalent to ≈ 5% of the world oil production (84 MBOL/d)
- Steam methane reforming (SMR) is the most common and least expensive method of producing commercial H2 as well as in the industrial synthesis of ammonia (10^8 t/y) from H2.
- The process is undertaken mostly starting from NG with 700 - 1100 °C with energetic efficiencies of NG to H2 of 70 – 80%.

$$CH_4 + H_2O \rightarrow CO_2 + 4H_2$$

- The main inconvenience is the associated large CO2 production of 29.25 $kgCO_2/GJH_2$.
- An alternative with no CO2 emissions is the one in which NG is heated enough to split spontaneously NG into H2 + carbon.

$$CH_4 + heat\left[at\ \ 1600\ \ °C\right] \rightarrow C + 2H_2$$

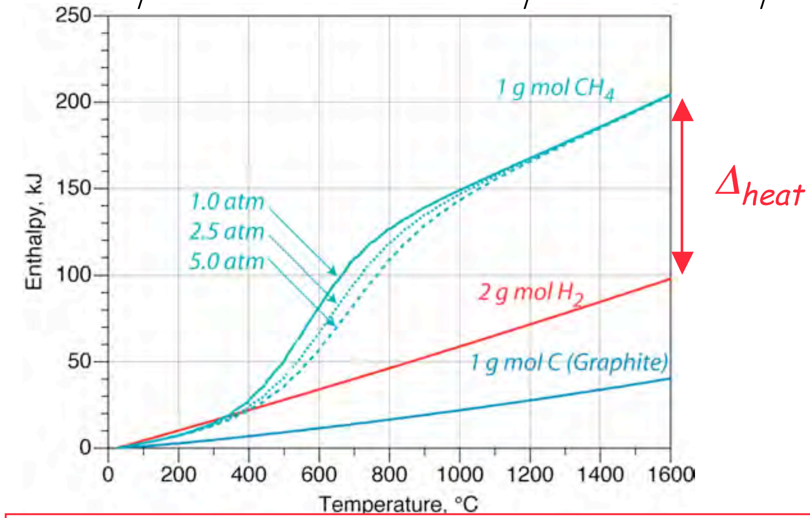
- *As a main result, the H2 yield for a given NG is halved*

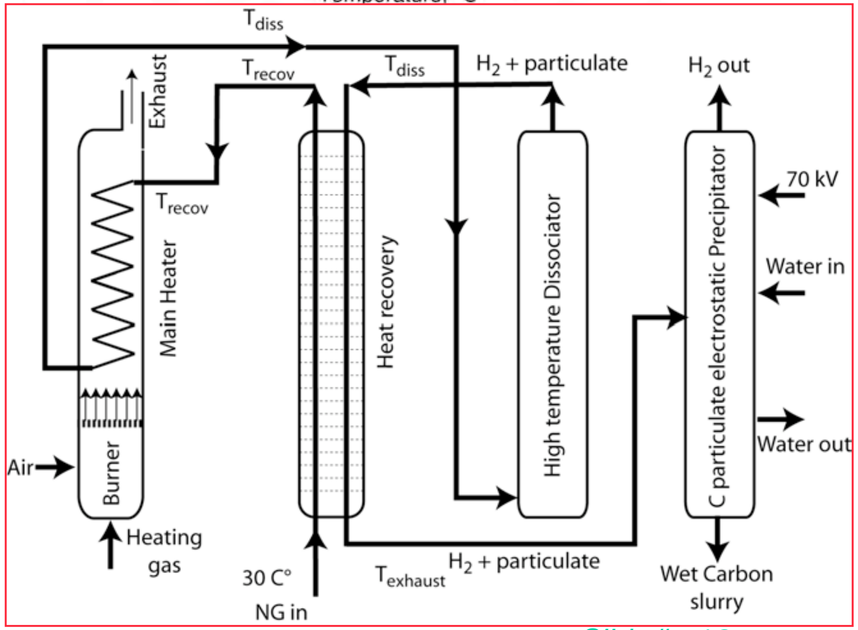
Principle of NG to H2 dissociation with no CO2 (CIEMAT)

- The device is a simple graphite tube dissociator heated at very high temperature
- Natural gas is introduced at high temperatures and flow rates in the reactor to activate fast, spontaneous pyrolytic dissociation.
- A dense black smoke streams from the outlet end of the reactor and it is found to consist of carbon black and hydrogen.
- Carbon black particles are extremely fine and difficult to filter.
- Carbon black is recovered and separated (bag or precipitator).

CH_4 Δ_{heat} Black C $2 \times H_2$

$$890\,kJ/mol + 76kJ \rightarrow 394\,kJ/mol + 752\,kJ/2mol$$





Universal behavior of different measurements

CIEMAT + U.P.M TEAM
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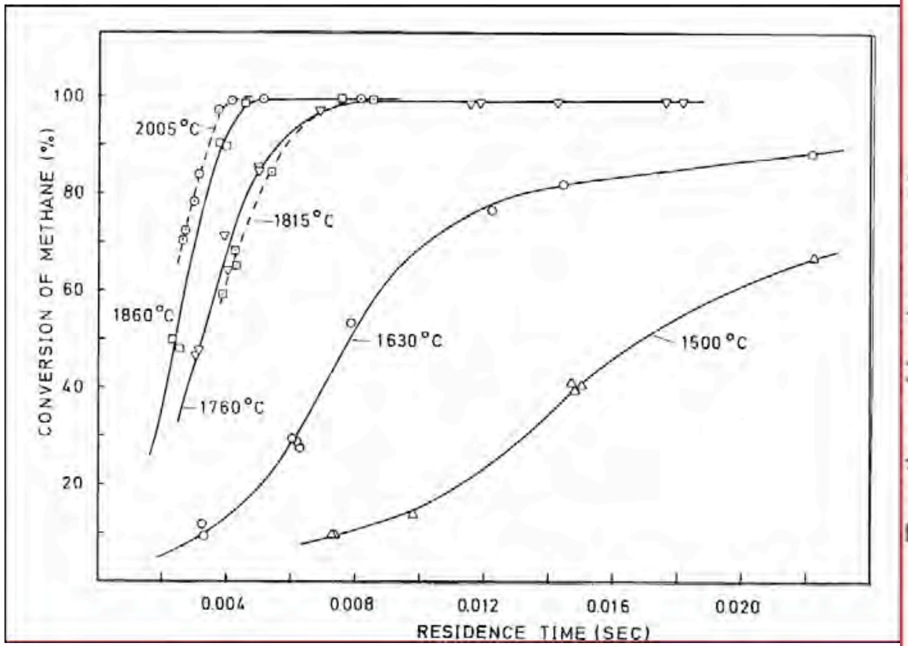
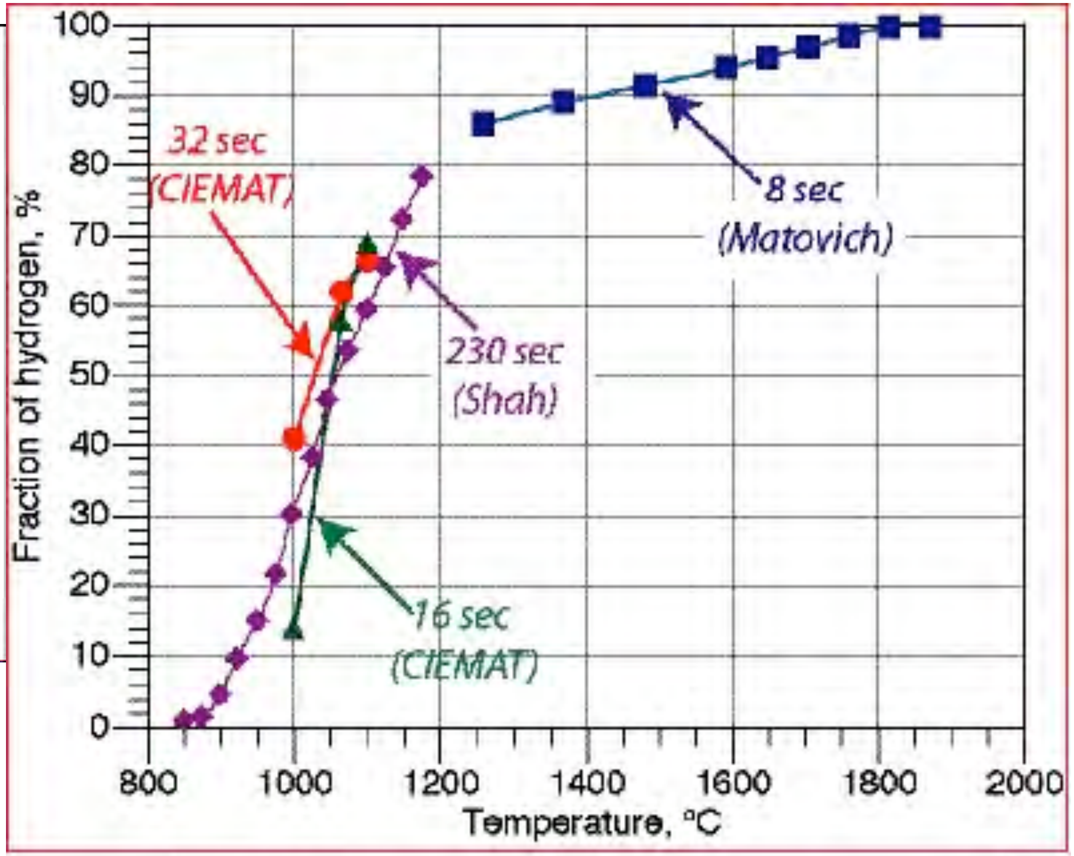




- Extremely fast conversion time of methane splitting.

Remarkable, over-all agreement

A "Hydrogen " economy ?

- Oil and NG are not only our main energy sources: they are also essential materials for a great variety of products (for example many petrochemical and chemical products including synthetic materials, plastics, pharmaceuticals, etc.).
- Given by nature as a gift, they are being used up rather rapidly and become significantly depleted and increasingly costly. We need to search for new sources and solutions.
- Much has been said about a future "hydrogen economy". Hydrogen is indeed clean, giving only water and energy.
- Governments and some major industries seem to be committed to develop the "hydrogen economy" (see for example the statements by President Bush's January 2003 State of the Union message and President Prodi's talks at the EEUU).
- It is clear, however, that in order to achieve this, new ways without CO2 must be found to make it feasible.

Hydrogen is only an energy carrier

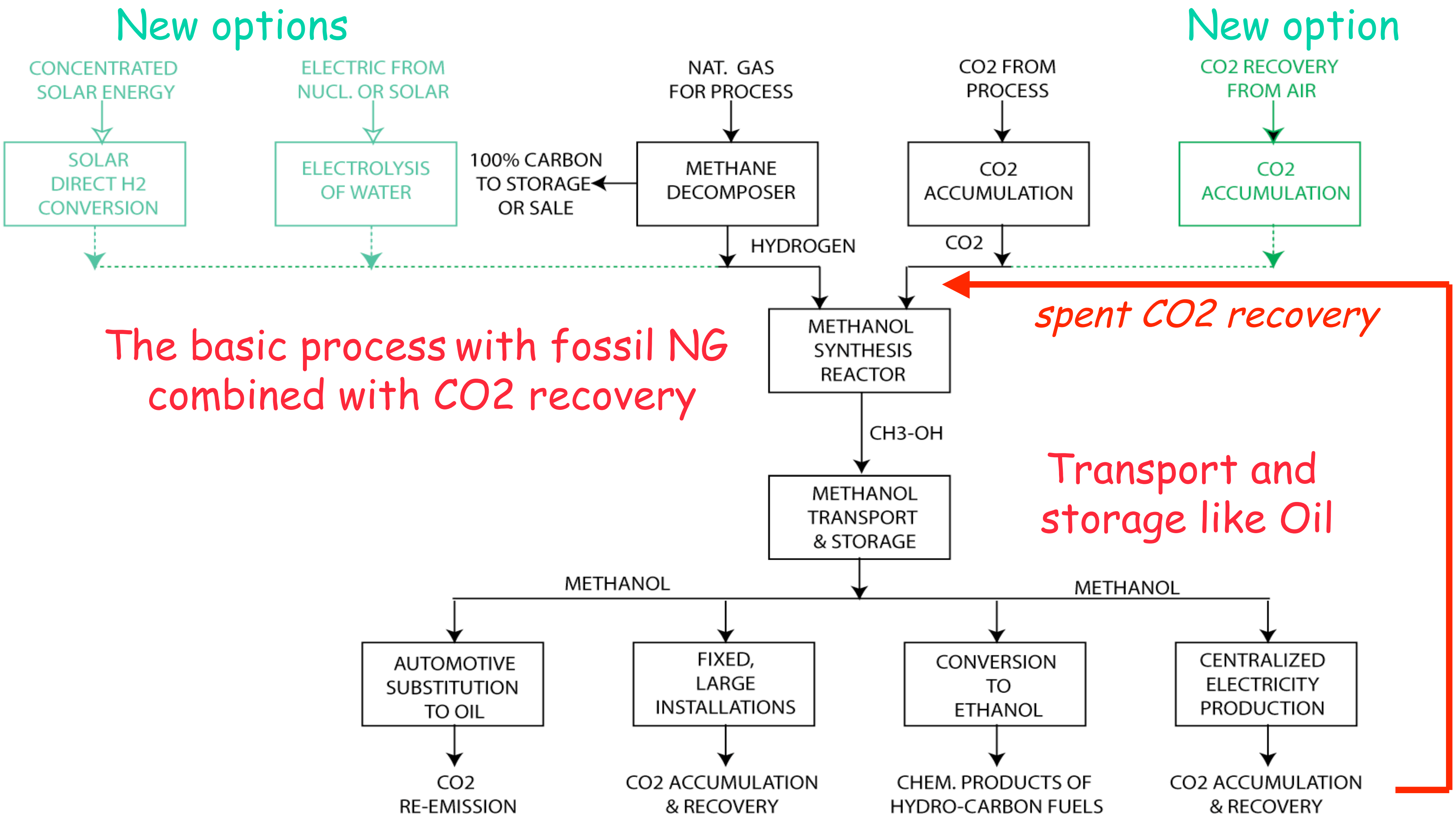
- However, hydrogen is not a natural energy source on our planet (in contrast to the sun and stars) and it may be presently generated for instance from natural gas or coal.
- Handling of this volatile and explosive gas is difficult, dangerous and costly, necessitating high pressure equipment and the use of special materials. No infrastructure exists for it and its costs, without a doubt, will be prohibitive.
- Even with the greatest care, any leaks would represent extreme explosion hazards, limiting wide use by consumers.
- The new sources of H2 must avoid the associated production of CO2 in the process, since its increase in the atmosphere is considered a major man made cause for global warming.

Methanol or Ethanol (not hydrogen) is the future !

- Organic ethanol from bio-mass has been very extensively used as organic substitute to Oil for almost all its applications. See f.i the Brazil's pioneering work.
- Very large amounts of fossil NG are available: their cost at the point of production is usually very low (0.5 $/GJ); most of its added cost is transport with pipelines or liquefaction.
- A spontaneous, local conversion of fossil NG into H2 and black carbon without CO2 emissions is readily performed.
- Assume that we recover CO2 as a chemical material and to recycle it from some conventional source of concentrated CO2 waste, already "paid for" by the savings due to the CO2 conversion of the previous application (two for one).
- CO2 and H2 can produce methanol or ethanol + water, a liquid substitute to gasoline in all distant transport applications; if in a concentrated source, it could be indefinitely recycled.

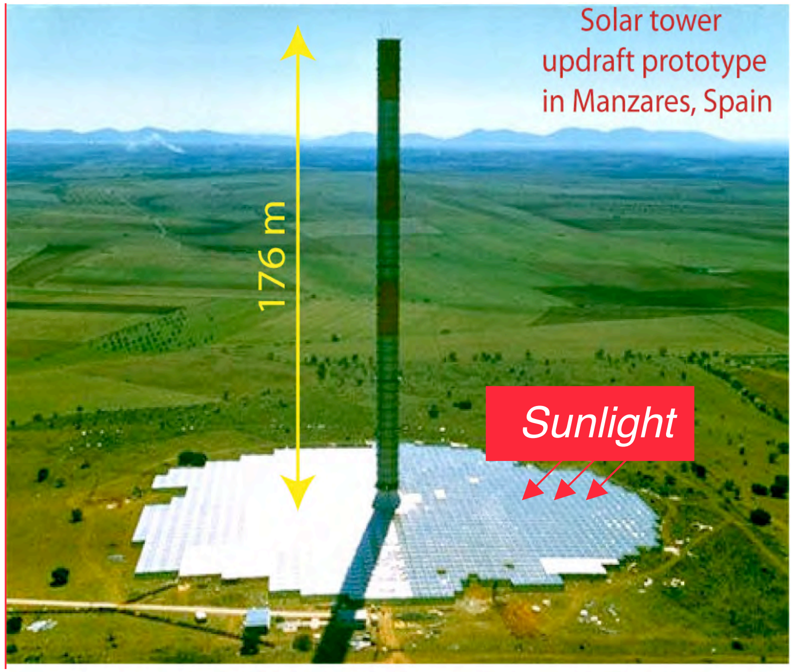
$$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O \qquad CH_3OH + 3/2O_2 \rightarrow CO_2 + 2H_2O$$

Alternate processes with CO2 preservation



New Option:recovering spent CO2 from the atmosphere ?

- According to this alternative to sequestration,the atmosphere of the planet would act as a temporary storage and transport.
- Air extraction is an appealing concept, because it separates the location of the CO2 source from its disposal. CO2 can be recovered from any product (including cars, airplanes, flames, fires, heating, etc), located far away from the sources.
- These dedicated sinks should behave like "synthetic trees", removing the CO2 of the air (≈360 ppmV).
- A solar tower ("solar chimney") is a air collector and a central updraft tube generating a strong convective flow through a chemical sorbent. Cold CO2 and sorbent combine. CO2 is recovered at high temperature



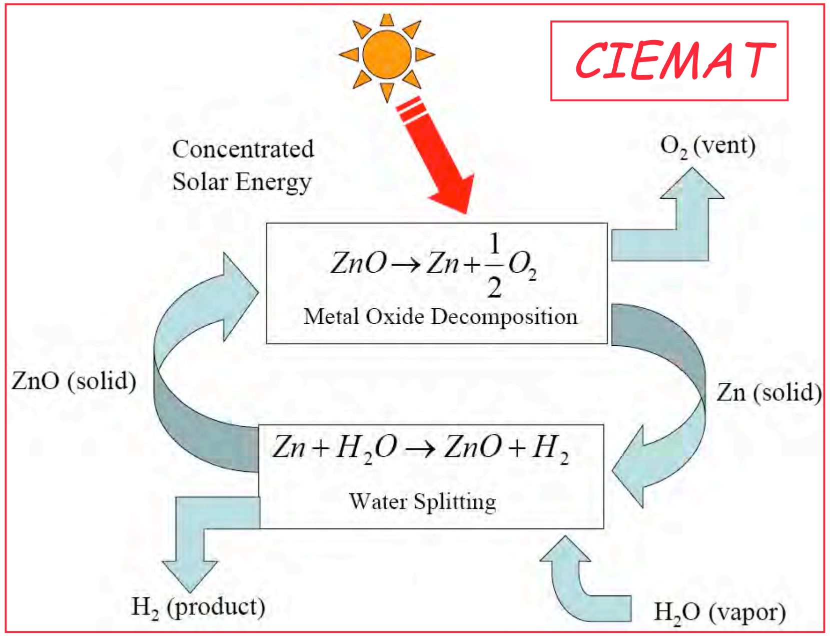
(Haaf et al. 1983, Schlaich et al, 1990)

CO2 from air: a dream or a reality ?

TOWER PARAMETERS		
Height tower	500.	m
Radius tower	55.	m
Diameter collector	4300	m
Area collector	14.5	km2
Peak solar power	900. 0	W/m2
Tower wind efficiency	1.635	%
AIR:-WIND ENERGY PRODUCTION		
Wind speed	79.73	km/h
Air mass	321.6	ton/s
Air mass /m2/sec	26.6	kg/m2/s
Kinetic air theor. power	78.9	MW
Wind turbine conversion eff	0.50	
Actual Wind power	39.43	MW
Fract. windy hours	2190	/y
Electric Wind energy yearly	86.36	GWh
CO2: ACCUMULATION		
CO2 volumic	0.36E-03	ppv
CO2 volume/sec	96.47	m3/s
CO2 mass/sec	0 .193	ton
CO2 mass/h	694.6	ton
Effective CO2 mass/y	1.52	Mton/y
EQUIVALENT COAL BURNING		
Electric coal burning equiv to Wind	0.108	Mton/y
Wind CO2/Coal CO2 (same electric energy)	14.03	

New Option: Direct Hydrogen production without CO2 (cont)

- Hydrogen can be produced directly from water dissociation with the help of high temperature (solar) heat.
- But a spontaneous dissociation of water into H_2 and O_2 is only possible at temperatures above 3000 °C, far too high to be of practical use. Several simple thermo-chemical processes are under development in which concentrated solar heat, at temperatures of the order 1200 °C, splits H_2O into H_2 and O_2.
- Some optimal processes are oxi-reductions of ZnO/Zn, Fe_3O_4/FeO and Fe_2O_3/Fe_3O_4. They are cycles with a high efficiency, large scale and environmentally attractive.
- The accumulated hydrogen energy in good sunny regions is in practice about 50% of the incoming solar.



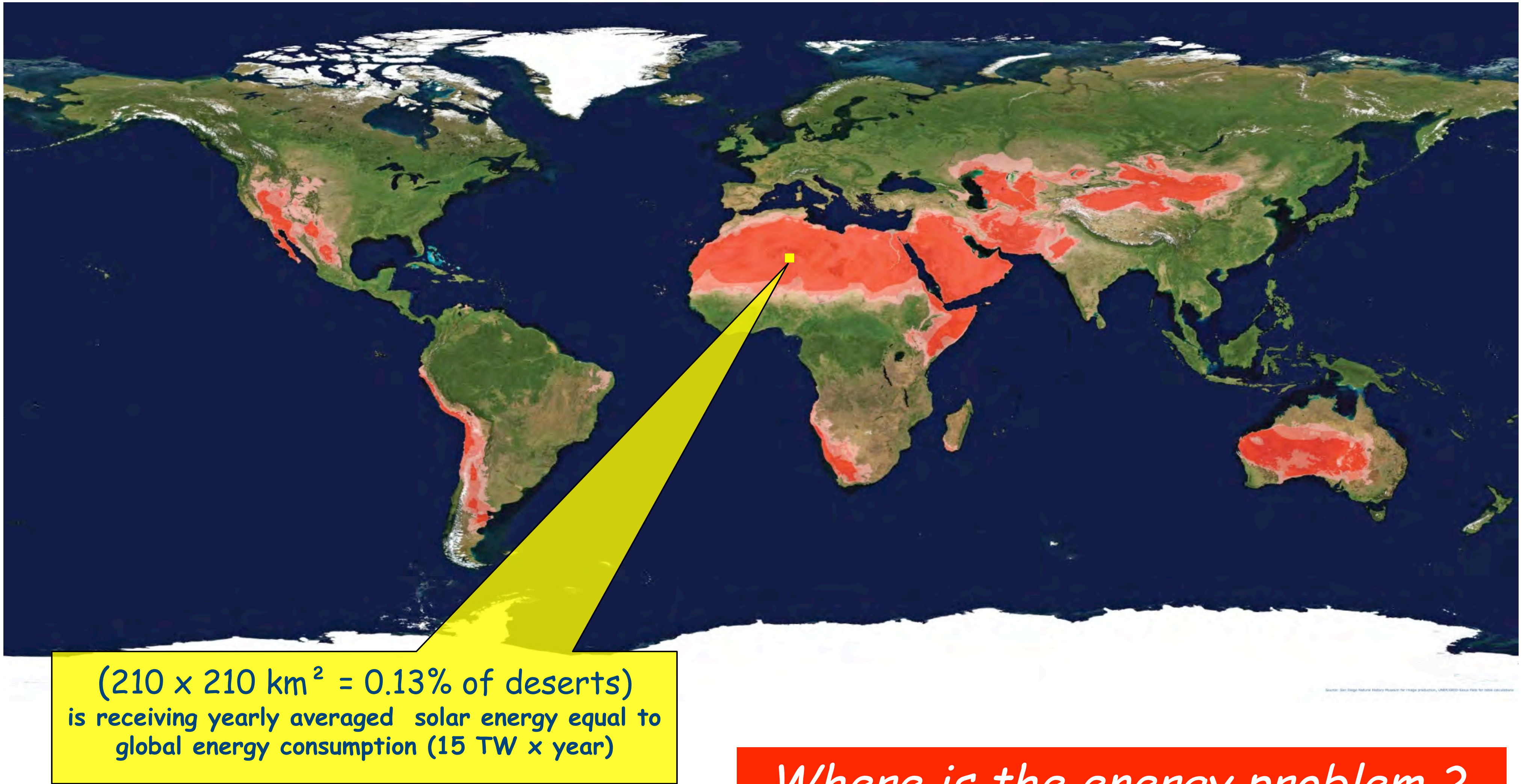
New energies: which ones ?

- Only two natural resources have the capability of a long term energetic survival of mankind. They are both necessary:

1. **Solar energy**. The world's primary energetic consumption is only 1/10000 of the one available on the surface of earth of sunny countries. Solar energy may be either used directly as heat or PV or indirectly through hydro, wind, bio-mass and so on. *If adequately exploited, solar energy may provide enough energy for future mankind.*

2. **A new nuclear energy.** Energy is generally produced whenever a light nucleus is undergoing fusion or whenever a heavy nucleus is undergoing fission. Practical examples are *natural Uranium (U-238),Thorium (fission) and Lithium (fusion) both adequate for many thousand of years at several times the present energy consumption*.

Solar energy in the "sunbelt"

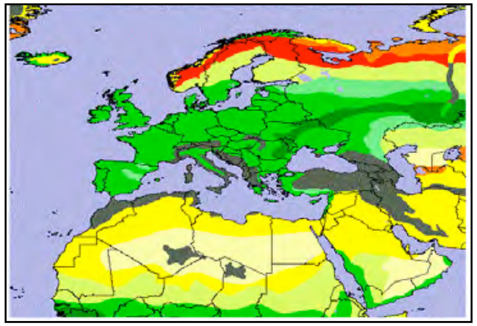
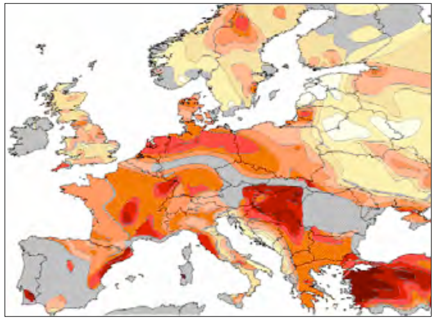
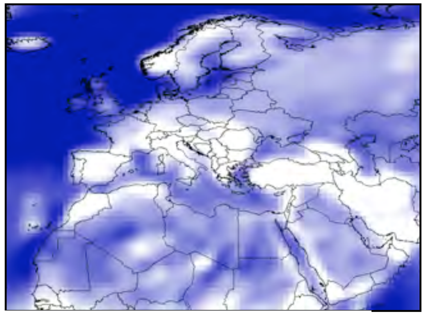
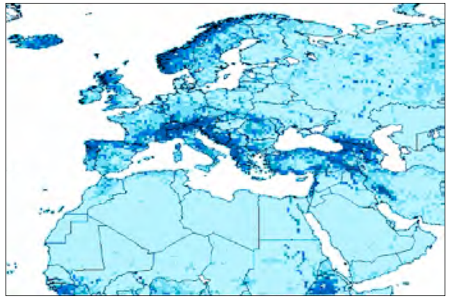


Where is the energy problem ?

Gerhard Knies, ISES-Rome CSP WS 2007

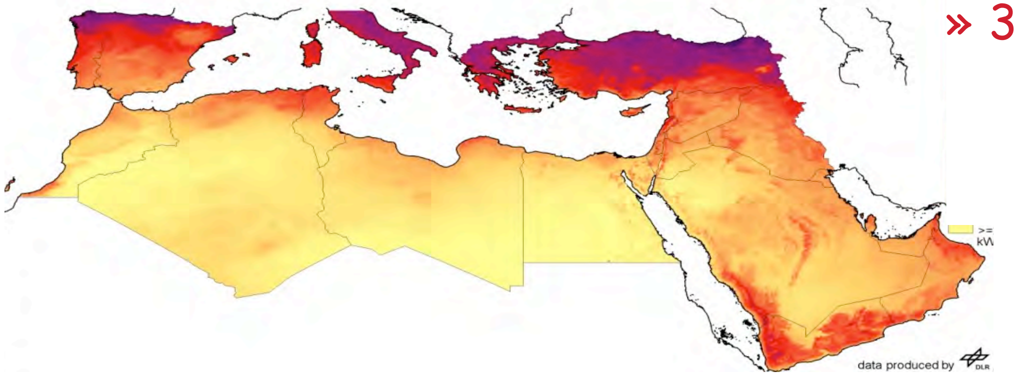
Biomass	Geothermal	Wind	Hydropower

Typical Yield

≈1 $GWh_{el}/km^2/y$	≈1 $GWh_{el}/km^2/y$	≈ 30 $GWh_{el}/km^2/y$	≈ 30 $GWh_{el}/km^2/y$
			
890 TWh_{el}/y	750 TWh_{el}/y	1700 TWh_{el}/y	1090 TWh_{el}/y

Economic potentials

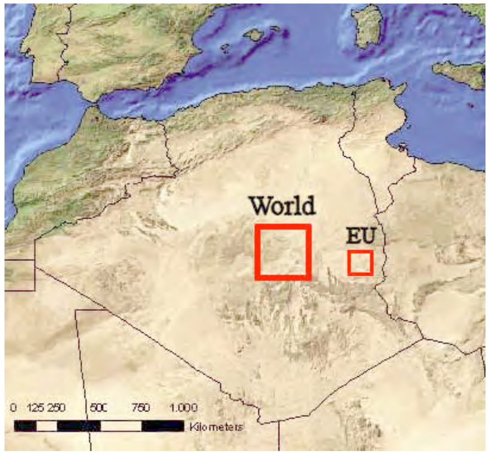
Typical yield CSP, PV≈250 $GWh_{el}/km^2/y$



Economic potentials > 600 000 TWh_{el}/y

Demand of electric power:

- » 7 500 TWh/y Europe + Desert 2050
- » 35 000 TWh/y world-wide 2050



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The earliest ideas for CSP(concentrating solar power)

Painting Title : Burning Mirrors, Stanzio della Mattematica, 1587-1609
Artisit: Parigi, Giulio (1571-1635)

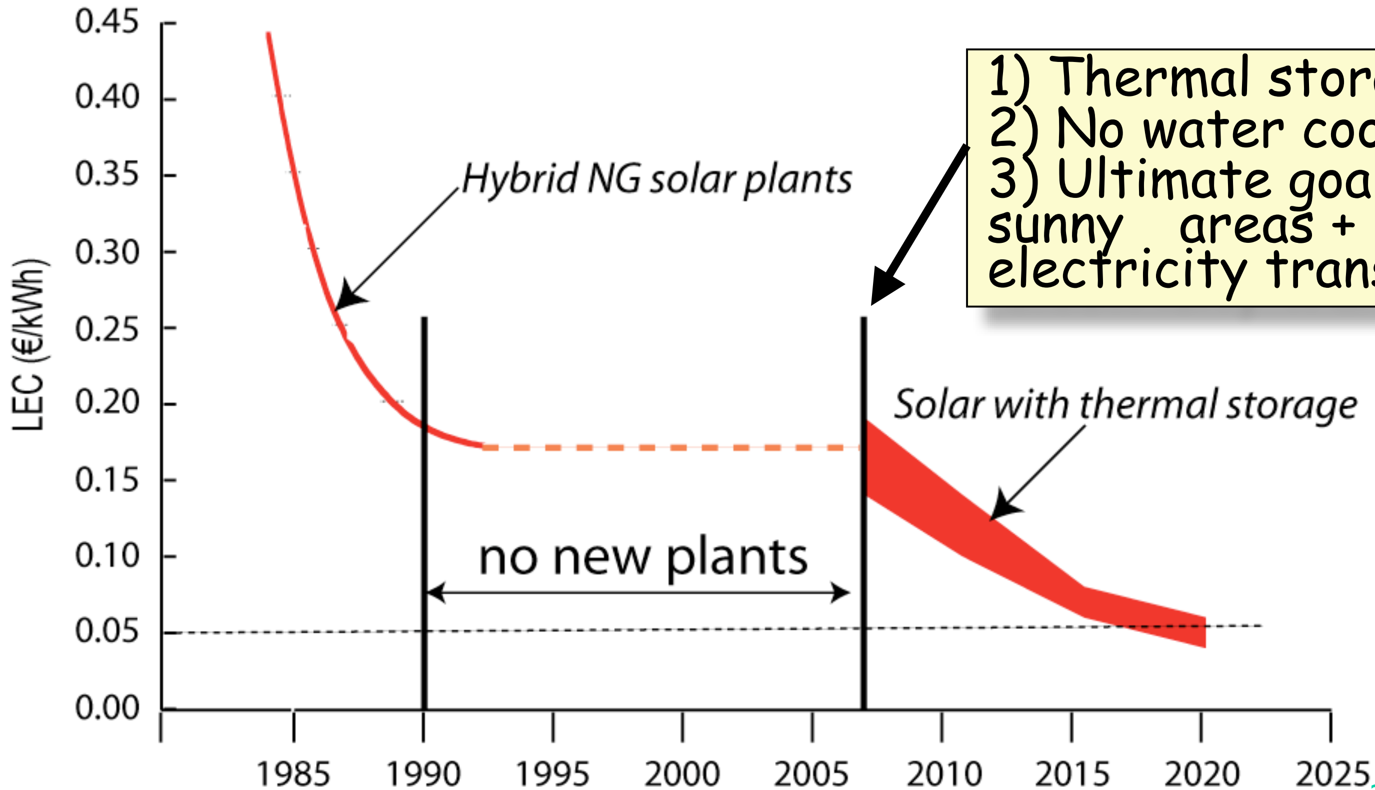
According to the tradition, Archimedes destroyed the Roman fleet at the siege of Syracuse in 213 BC by the application of directed solar radiant heat concentrating sufficient energy to ignite wood at 50 m.

*We believe that the combined effort of some 440 men, each wielding a 1 m² metal mirror, could ignite a 1*0.5 m area of a wooden hull at a distance of 50 m. A much smaller corps-say 50 men- could inflict severe burns upon selected enemy personnel*

The first solar facility to produce electricity was installed in 1912 by Shuman in Maady, Egypt.
The parabolic mirror trough concentrates sunrays on a line focus in which a tube was situated containing water that was brought to evaporation.
It produced 55 kWatt of electric power.

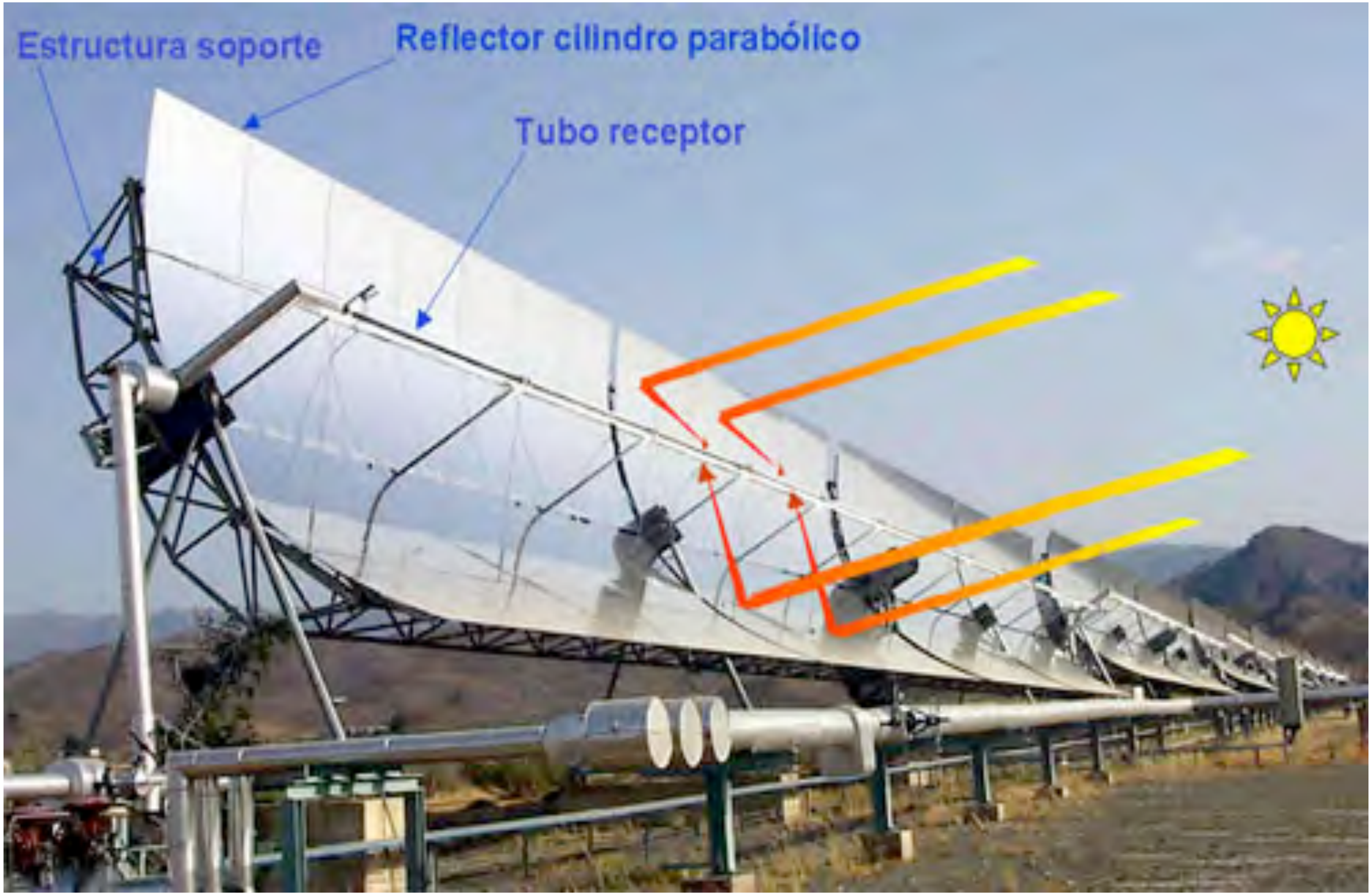
The revival of Archimedes

- The first modern power plants were developed over 20 years ago and were based on hybrid NG-Solar operation.
- No new CSP plants were developed during the last 15 years.
- The new plants now under construction are instead pure solar unit with energy storage to cover the variability of the flux



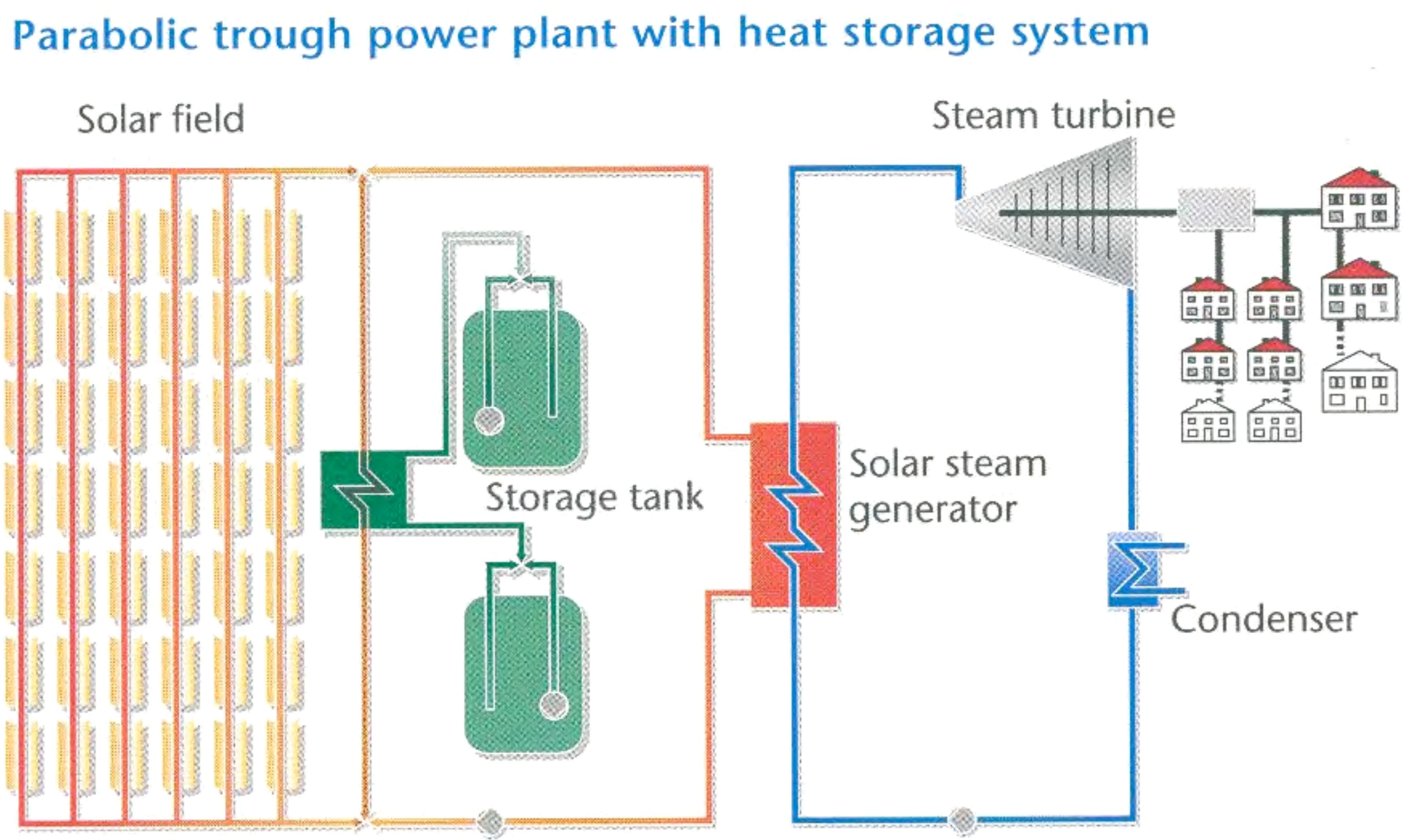
1) Thermal storage
2) No water cooling
3) Ultimate goal:desertic sunny areas + HVDC electricity transport

Principle of modern CSP

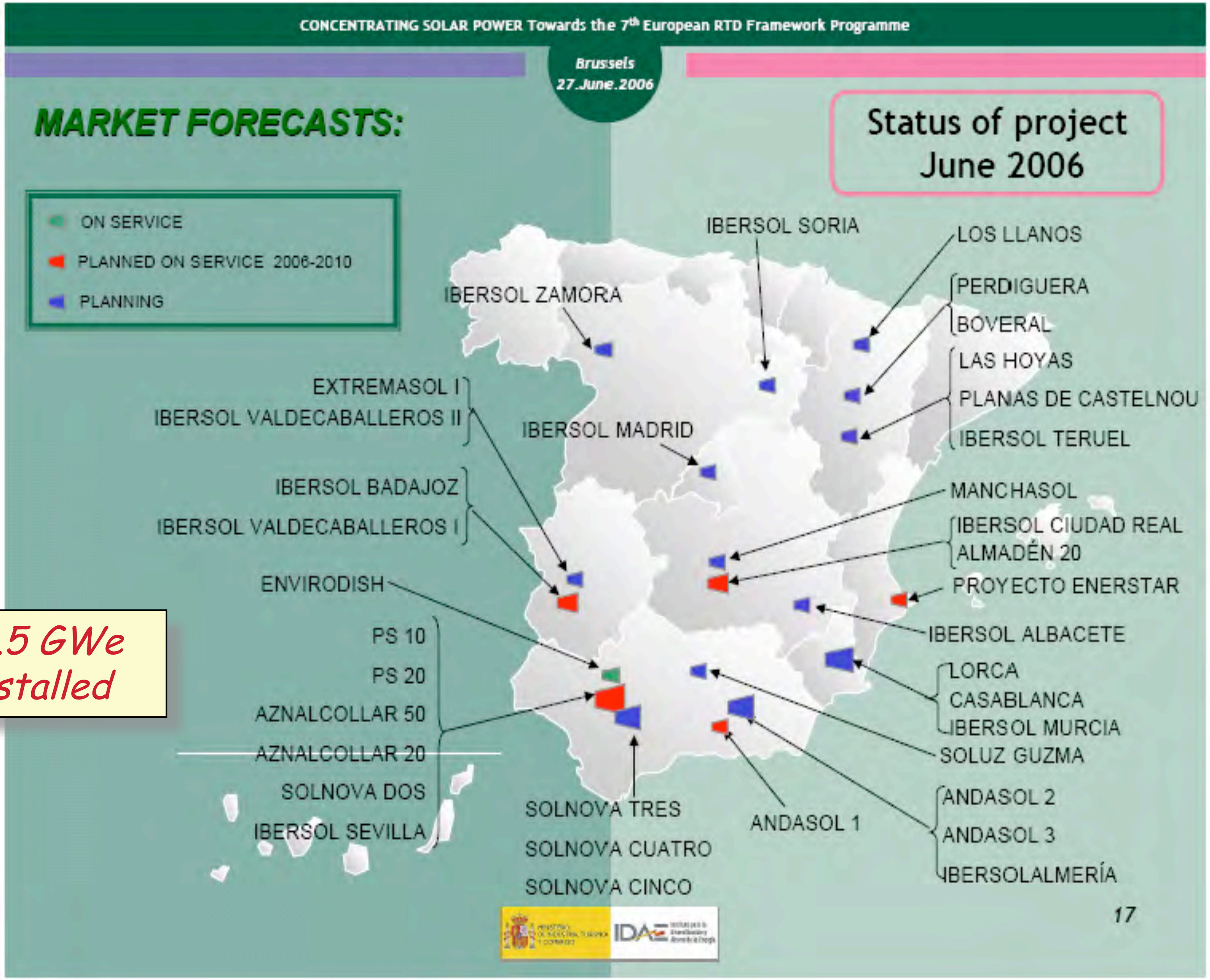


CSP modern power plant

- Utility scale plant with conventional power block
- 2000 - 7000 full load hours using thermal storage
- LECs today: 13 - 20 ct/kWh, future: 5 - 10 ct/kWh



The leading role of CSP in Spain: June 2006



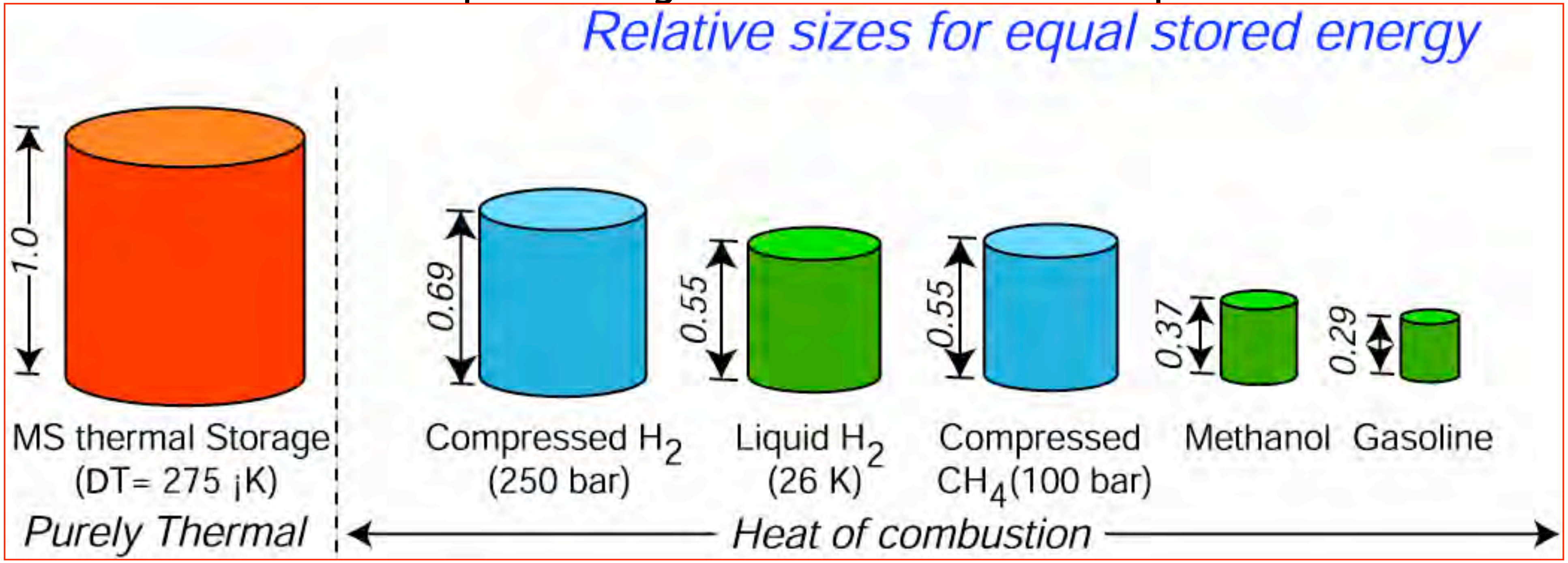
About 1.5 GWe to be installed

Nevada Solar 1 in the USA (2007)

- Generating Capacity 64 MW (Nominal)
- 357,200 m2 of Solar Field
- Annual Production > 130,000 MWh
- Construction in less than 18 months,
- 1.6 million man-hours
- *Capital investment : ≈ 250 Millions USD*

The storage of energy

- Indeed any primary main form of energy, in order to be realistically capable to counteract fossils and their emissions must be available *whenever it is needed by the user and not according to the variability of the source*.
- It is possible to insure the continuity of utilisation of CSP plant with the addition of a thermal liquid storage, in the form of a cheap molten salt.



- Thermal storage process is very efficient (less than 1% loss per day).

Molten salt performance

Cost estimates are for complete systems with power conditioning sub-systems (PCS), controls, ventilation and cooling, facility, and balance of plant.

	Type of storage	Cost for a 200 MW plant ($/kWh$_{electric}$)	Operation Lifetime (years)	Storage efficiency (%)	Operating temperature (C°)
Molten-Salt	HQH	**30**	30	99	567
Synthetic-Oil	HQH	**200**	30	95	390
Pumped hydro	ELE	**500 to 1600**	30	70	N/A
Compressed air	ELE	**----**	30	60	N/A
Superconducting	ELE	**> 1,000**	30	90	cryogenic
Battery Storage	ELE	**500 to 800**	5 to 10	76	N/A

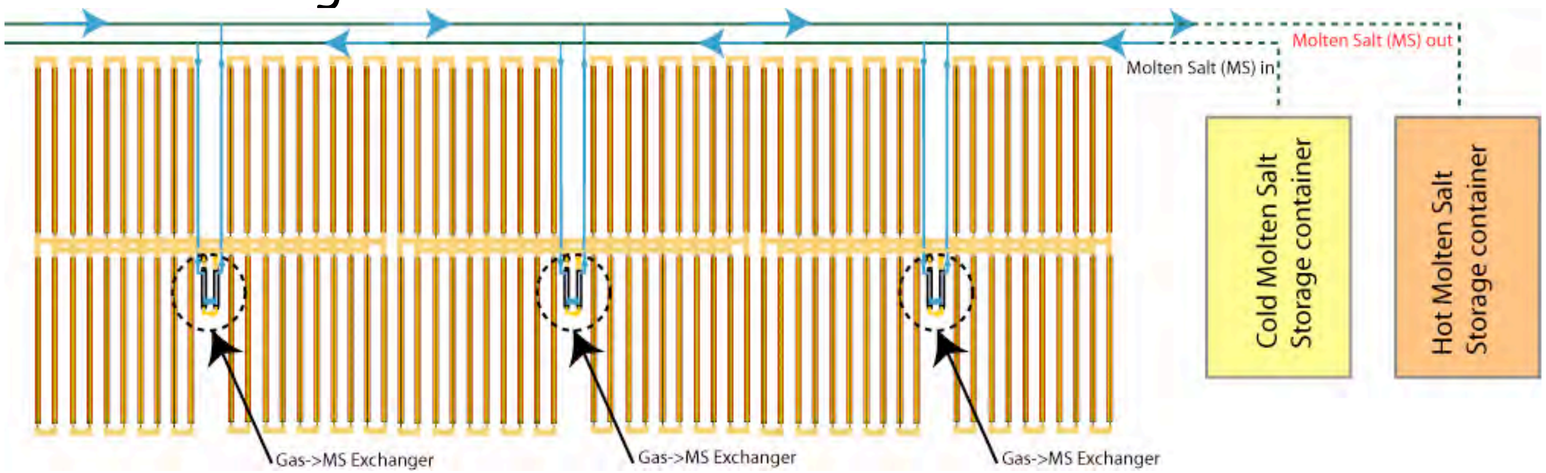
Solar troughs: evolution in the heating medium

- A number of different fluids have been used as filling in order to realise the heat transfer. In particular they include:
  - A low cost mineral oil, up to temperatures of the order of 400 °C. Such oil is highly flammable and considered toxic in many countries;
  - superheated steam with significant improvements over the mineral oil. The main drawback of this solution is the complex thermal response at high pressures
  - A molten salt, f.i. a eutectic mixture of Na and K nitrates, environmentally benign and not toxic. The liquid must remain all times above freezing above 200 °C.
  - Dry compressed air or CO2. The environmental impact is strongly reduced in comparison with other known methods because of the harmless nature of the heat carrying medium.

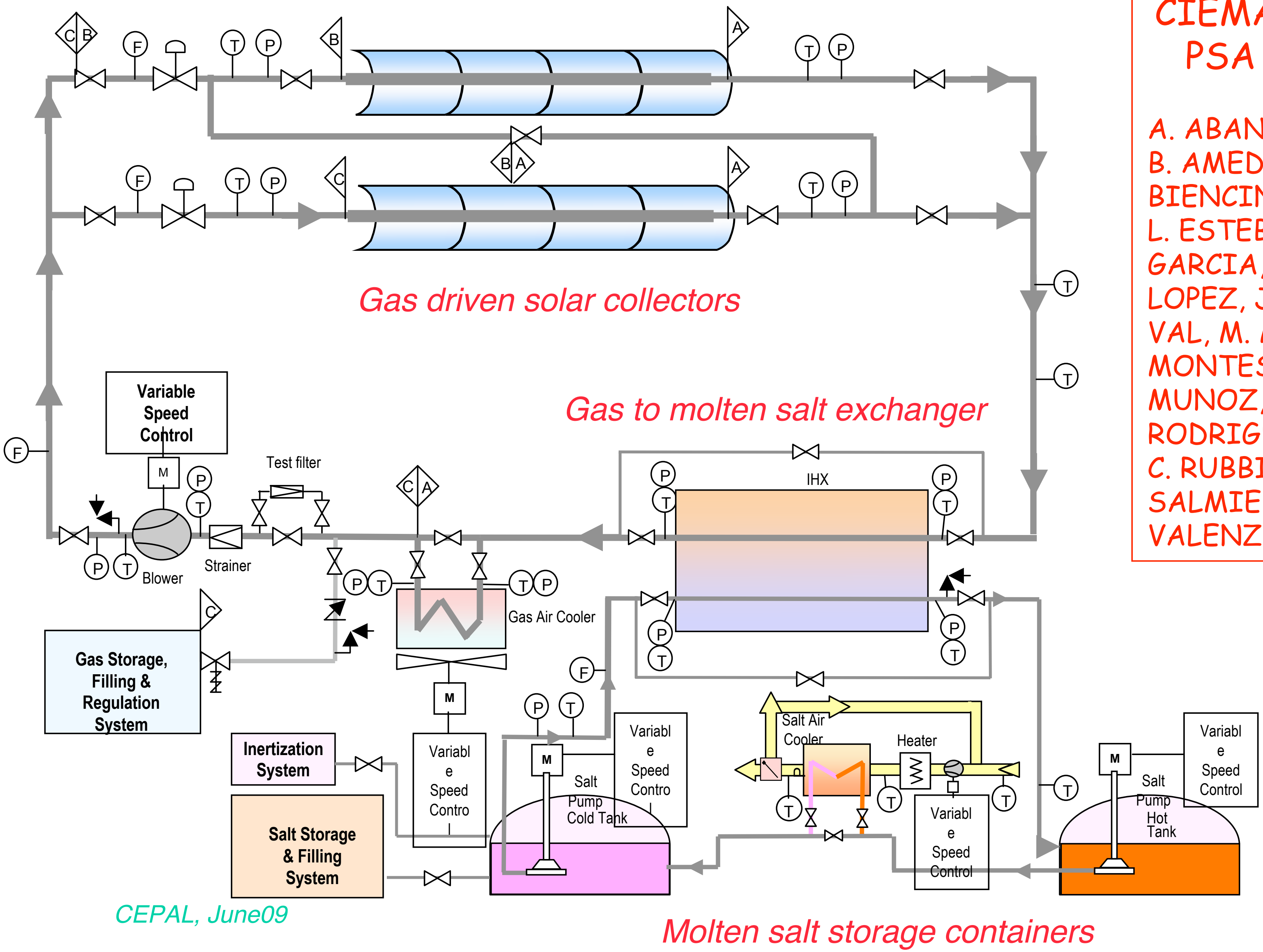
Solar troughs:cooling with a gas ?

- A new development at CIEMAT is the use of a suitable dry gas instead of a liquid or water-steam as a heat-carrying medium, in order to collect the radiating solar heat with the highest thermal efficiency.
- A number of gases are considered. Amongst widely available commercial gases, Air, He and CO_2 are candidates with similar performances.
- The easy operability of such a (inert) gas driven system ensures an unparalleled robustness of the necessarily very extensive and complex array of collecting pipelines, ease of maintenance are of primary importance.
- The heat transport needs storage with molten salt. An optimized system has many relatively small, locally distributed gas => molten salt modular heat exchangers. Final collection and storage is performed with the help of a pair of large molten salt storage containers.

Typical size of local mini heat exchanger: 7 ÷ 10 MWatt(t).



Gas driven test facility in Almeria



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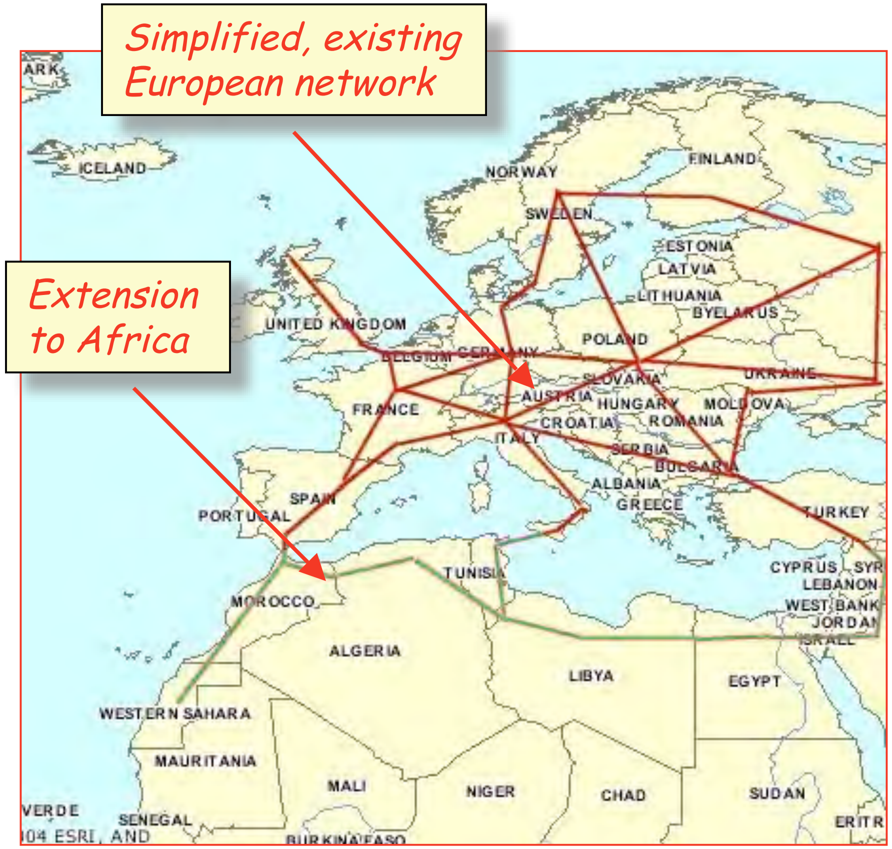
Planned EURO-MED electricity interconnection

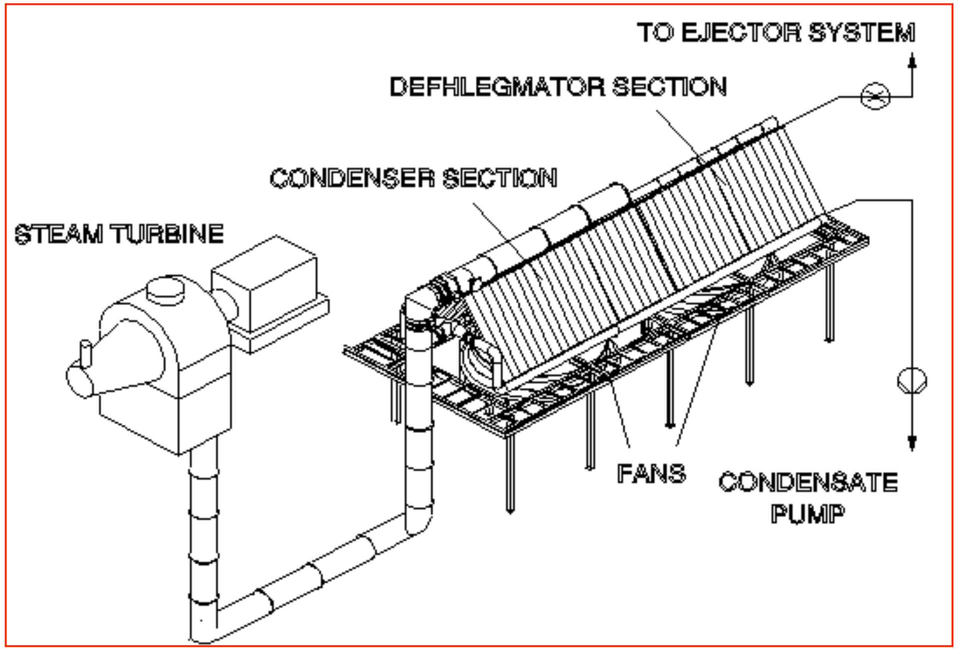
- The planned EURO-MED electricity interconnection permits to produce from the Sahara large amounts of solar electricity toward the Pan-European network
- Transport of electricity from far regions is both economically and technically feasible. About 60 GWatt of electric capacity in over 80 projects of long distance electric transport are now in operation, based on High Voltage direct current transmission lines (HVDC).
- For instance, for a distance of 1000 km over land plus 100 km over water, the cost is of the order of 0.6 ÷ 1.0 ¢/kWatth. The cost of marine cable portion is about ten times larger for unit length.



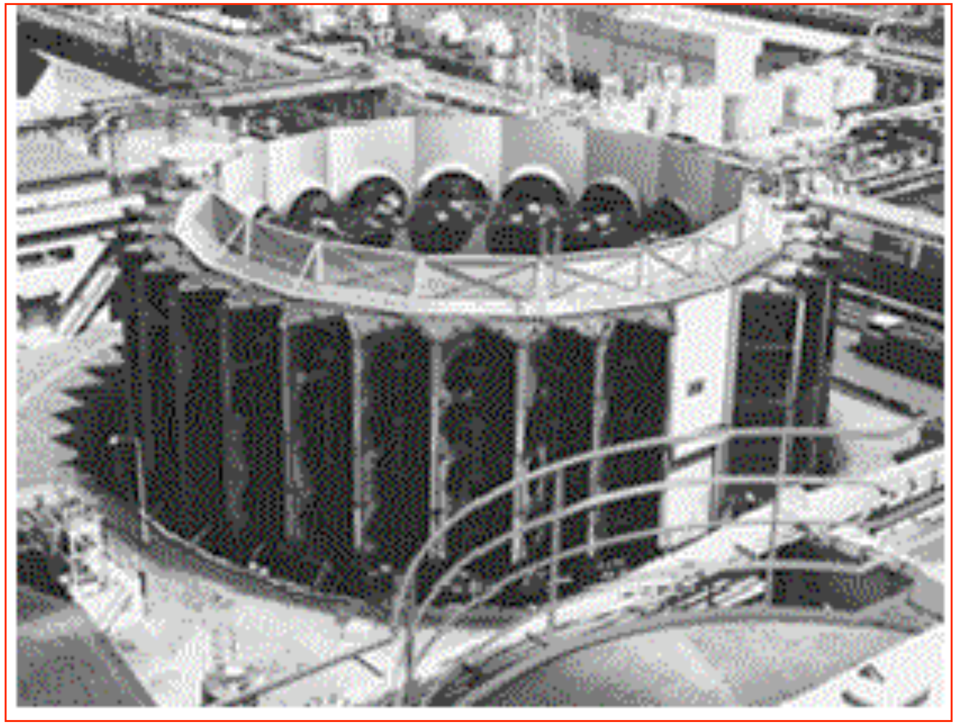
The electric link could be easily extended to the *now extremely poor areas of Mali, Niger,Chad and Sudan, Eritrea etc*. where the richness of the sun energy could become a valuable, new export item.

Solar Electricity production without water ?

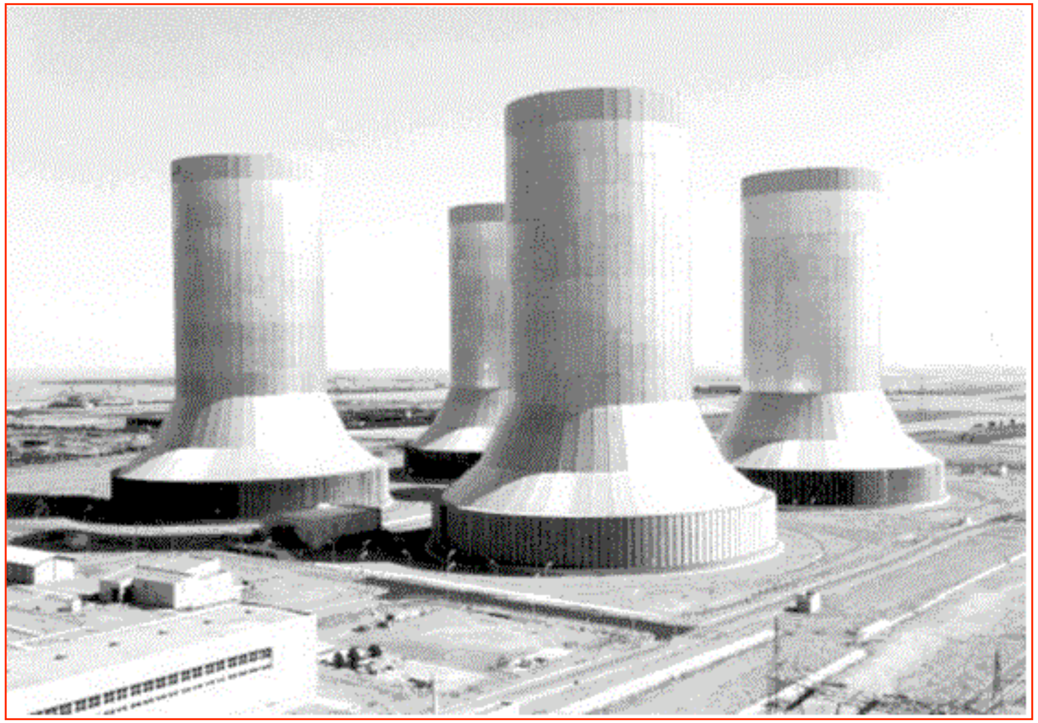
- Conventional cooling methods of thermal power plants are extremely water intensive processes. A 200 $MWatt_e$ CSP plant requires water equivalent to the consumption of a town of 100'000 inhabitants. The annual water consumption is 3×10^6 m^3/y.
- Solar plants (troughs and towers) are particularly effective in hot, deserted areas in several locations in the world: f.i. several areas in Sahara are ideal for CSP with a solar DNI of ≈ 2900 $kWh/m^2/y$ (10.4 GJ/m^2) and small seasonal variations.
- In completely arid inland areas, "dry cooling" is needed, either "direct" or "indirect", - in which an intermediate heat transfer medium , water between steam and air.
- Dry cooled plants introduce:
  - A energy production penalty with respect to wet cooling of ≈ 5% for a 110 °F (43 °C) day.
  - Installation are of larger size (2÷3 x) and more costly, For instance a 150 MW wet plant costs typically 5 M$: a dry plant has 2÷3 times this cost.
- These factors are acceptable in the case of CPS plants in the desert.



Practical examples



Mechanical Draft Indirect Dry Cooling System for the 60 MWe Power Unit of the Kaneka Chemical Works (Japan)

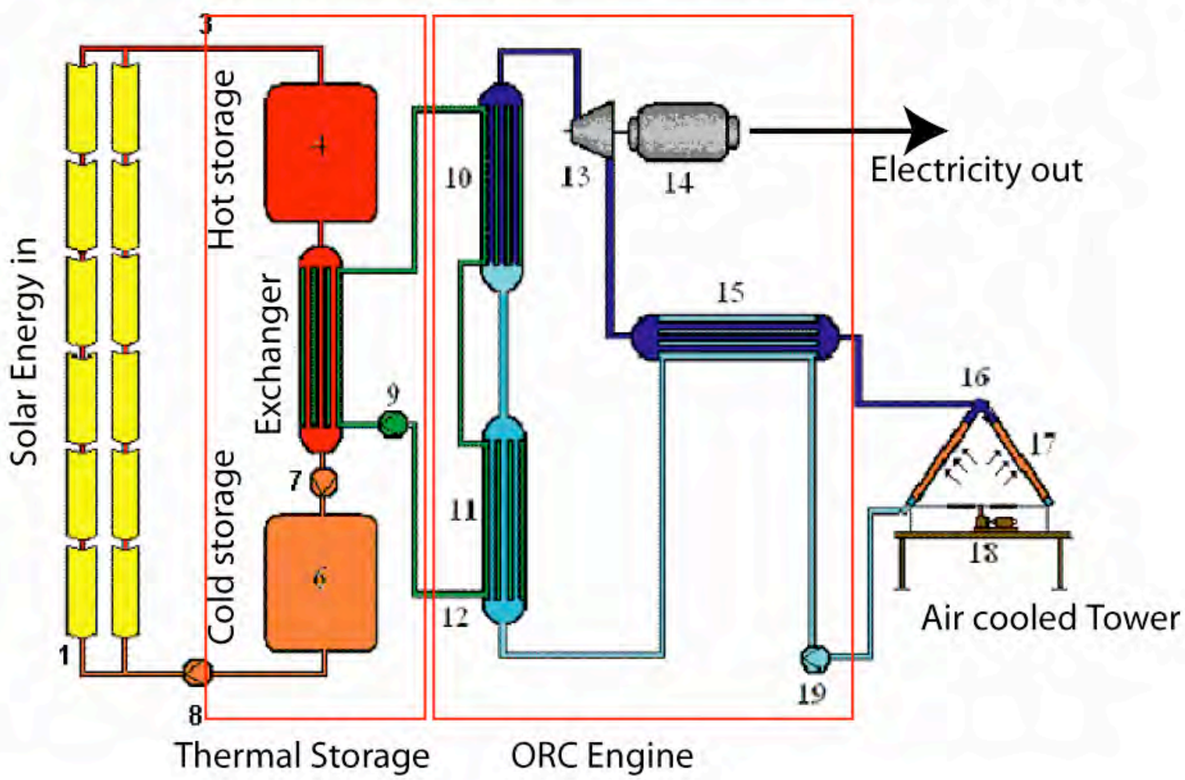


Earthquake Proof Natural Draft Towers for the Dry Cooling HELLER System of the 4 x 250 MWe Shahid Rajai PP (Iran)

Small CSP units disconnected from network

- An important application of CSP with a very wide potential market is distributed generation with storage. These units are best suited to provide electricity to remote but sunny locations, where connection to the general network is either difficult or too expensive.
- Plants could provide the continuous supply of the basic electricity needs for 100-kW$_e$ to 10-MW$_e$.
- The electrical efficiency of such ORC generators is of the order of 20%.

Rankine cycle with an organic fluid (ORC for Organic Rankine Cycle)



These ORC units are extremely reliable and require little or no maintenance

Why CSP technology?

- ***An environmentally friendly technology***
  - The plant produces energy with no emissions or pollutants. No toxic, readily flammable or otherwise harmful materials are used and it will introduce no hazards or other inconveniences (noise) to the population.
  - The energy pay-back time of the system is of the order of only 6 months, less than 2% of the produced energy over the life expectancy, much smaller than the one of photo-voltaic panels. At the end of their lifetime, most of the materials can be either recycled or recovered.
- ***A short construction time and a long life span***
  - Because of the simplicity of design, a power plant can be realistically constructed in about three years. The life span of the installation is approximately 25 ÷ 30 years. The final dismantling is cheap and simple, and the land can be reused without limitations.
- ***Advanced R&D stage and short time to market***
  - Hybrid solar/fossil versions of this technology (354 MWatt) have been in commercial operation at Kramer Junction (USA) for more then 15 years.
  - The advanced designs, in addition to a general reduction in cost, may introduce higher temperatures and an extensive energy storage which permits solar-only operation.

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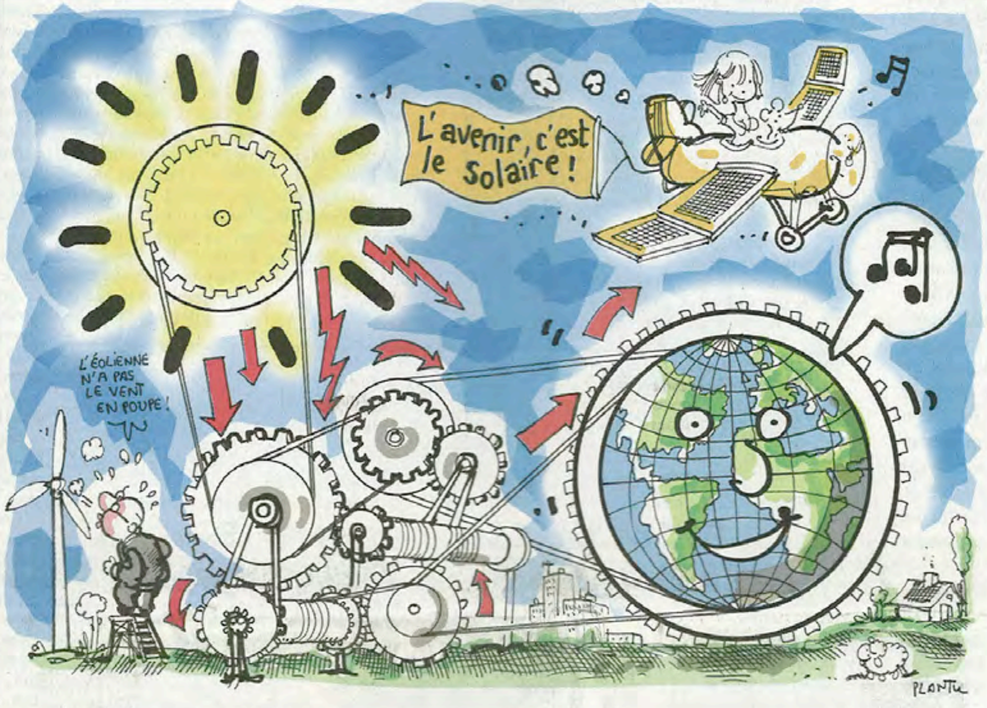
Le solaire s'impose comme l'énergie du futur

Electricité Le secteur photovoltaïque croît au rythme de 40 % par an



New, practically inexhaustible energies from Nuclei

Nuclear energy without U-235 ?

- Today's nuclear energy is based on U-335, 0.71 % of the natural Uranium, fissionable both with thermal and with fast neutrons.
- A massive increase of this technology (5 ÷ 10 fold), such as to counterbalance effectively global warming is facing serious problems of accumulated waste and of scarcity of Uranium ores.
- In the sixties,"atoms for peace" promised a cheap, abundant and universally available nuclear power, where the few "nuclear" countries would ensure the necessary know-how to the many others which have renounced to nuclear weaponry.
- Today, the situation is far from being acceptable: the link between peaceful and military applications has been shortened by the inevitable developments and the corresponding widening of the know-how of nuclear technologies.
- For the nuclear penetration to become freely and abundantly available in all countries, some totally different but adequate nuclear technology must be developed.

New, virtually unlimited forms of nuclear energy

- Nuclear energy is produced whenever a light nucleus is undergoing fusion or a heavy nucleus is undergoing fission.
- Particularly interesting are fission reactions in which a natural element is firstly bred into a readily fissionable element.

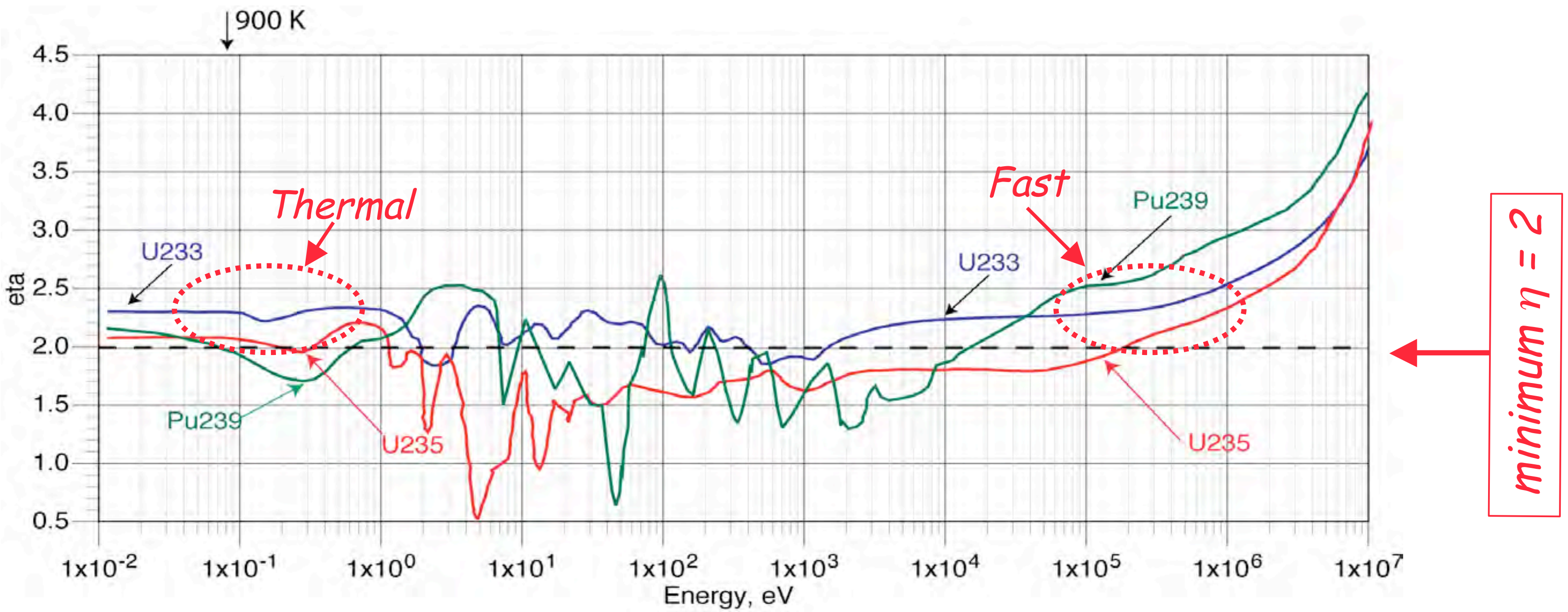
$$^{232}Th + n \rightarrow {}^{233}U; \quad {}^{233}U + n \rightarrow fission + 2.3n \quad (Th \ \ cycle)$$

$$^{238}U + n \rightarrow {}^{239}Pu; \quad {}^{239}Pu + n \rightarrow fission + 2.5n \quad ({}^{238}U \ \ cycle)$$

- The main advantage of these reactions, in which U-235 is absent, is that they permit an essentially unlimited energy supply, during millenia at the present primary energy supply, comparable to the one of Lithium driven D-T Nuclear Fusion.
- However they require substantial developments since two neutrons (rather than one) are required to close the cycle.

Thermal and fast options

- Most of the present day reactors operate with thermal(ized) neutrons, for which a well established technology exists.
- A Uranium (U-238) breeder will not operate with thermal neutrons, since there Pu-239 has η <2. Very fast neutrons are mandatory.
- A Thorium (Th-232) breeder can instead operate both with thermal and fast neutrons.



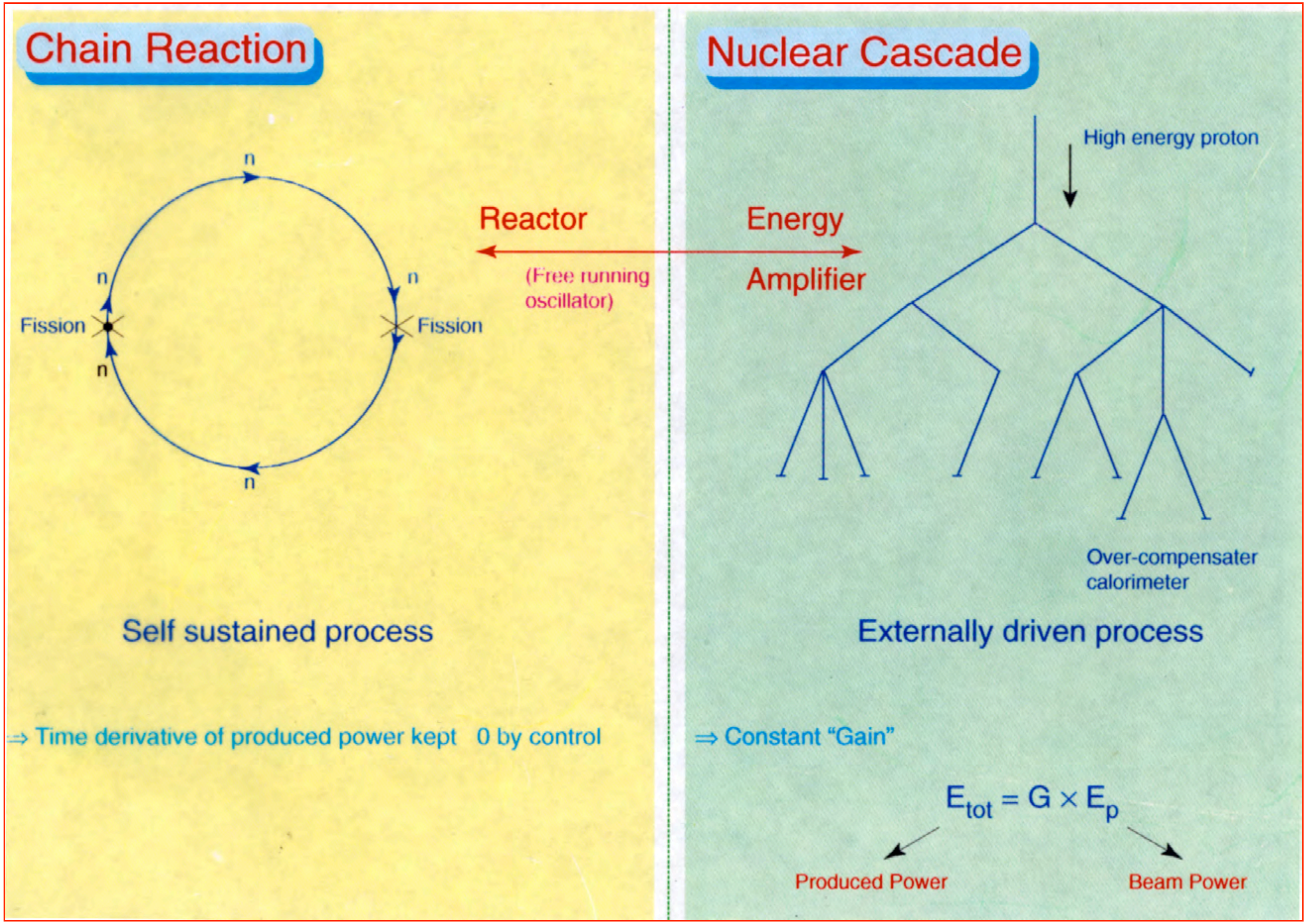
A new concept: the Accelerator driven system

- This very small neutron excess is essentially incompatible with the requirements of any critical reactor without U-235. An external neutron source must be added to ensure the neutron inventory balance. This is both true for Fission (Th and/or Depleted U) and D-T Fusion starting from Lithium.
- The development of modern accelerators has permitted the production of a substantial neutron flux with the help of a proton driven high energy spallation source.
- Let k_{eff} be the neutron multiplication coefficient of an ADS (k_{eff} =1 for a critical reactor). In a "sub-critical" mode, k_{eff} <1 neutrons are produced by a spallation driven proton beam source and multiplied by fissions. The nuclear power is then directly proportional to the proton beam power with a gain G:

$$G = \frac{\chi}{1 - k_{eff}} \quad ;\chi \approx 2.1 \div 2.4 \quad for \;\; Pb - p \; coll. > 0.5 \;\; GeV$$

G = 70-80 for K_{eff}=0.97 and G = 700-800 for K_{eff} = 0.997 (very large)

Critical(reactor) and sub-critical (energy amplifier) operation



The thorium driven fast EA

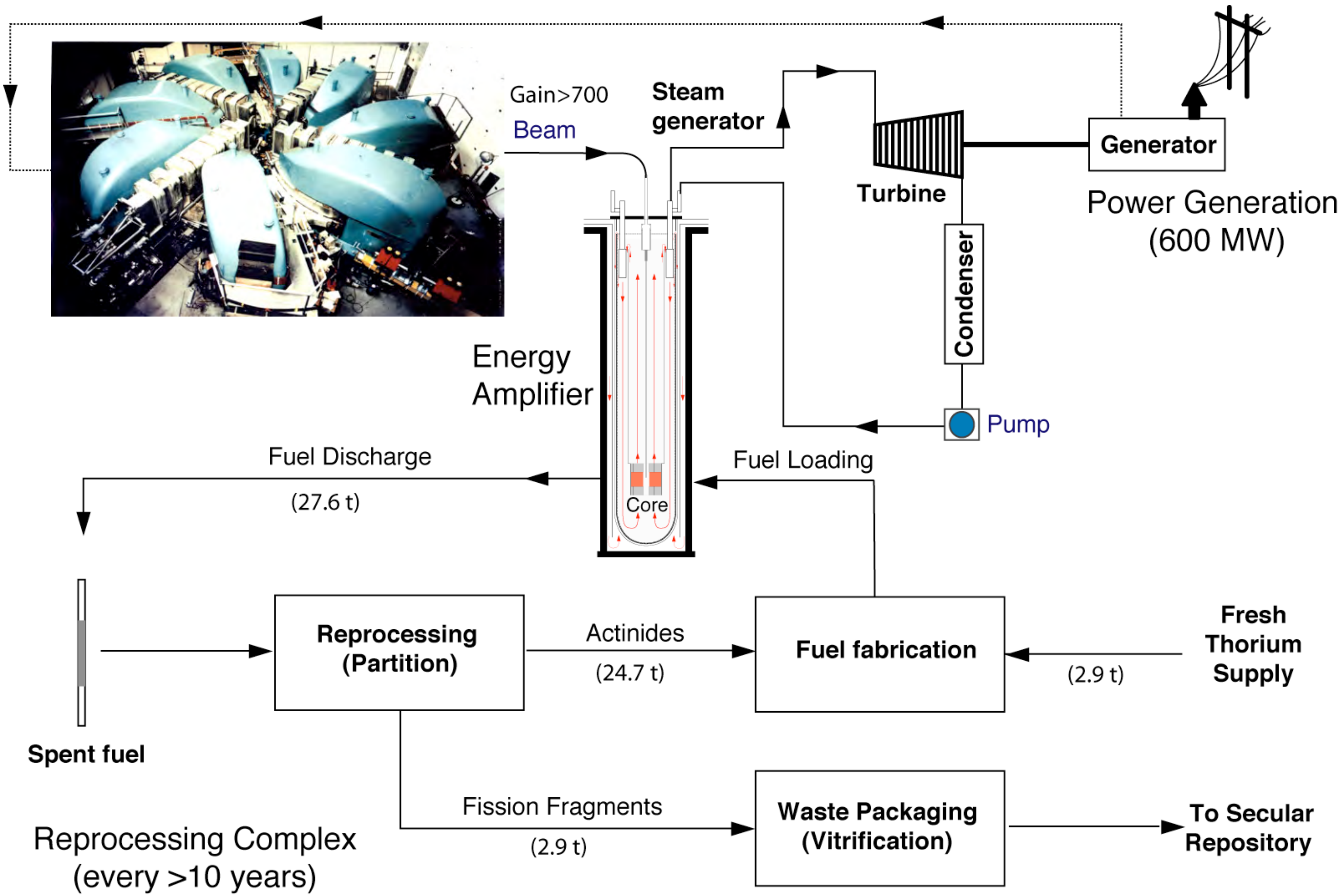


Figure 1

The Energy Amplifier

- **Closed cycle**: all actinides are recycled indefinitely unmixed. The only "waste" are fission fragments and structural materials which are relatively short-lived
- **Fast neutrons** and fuel cycle based on **Thorium**
- **Lead** as target both as neutron moderator and as heat carrier
- **Subcritical system** driven by a proton accelerator.
- **Deterministic safety** with passive elements to eliminate
  - Prompt criticality
  - Meltdown
  - Decay heat
  - Seismic protection

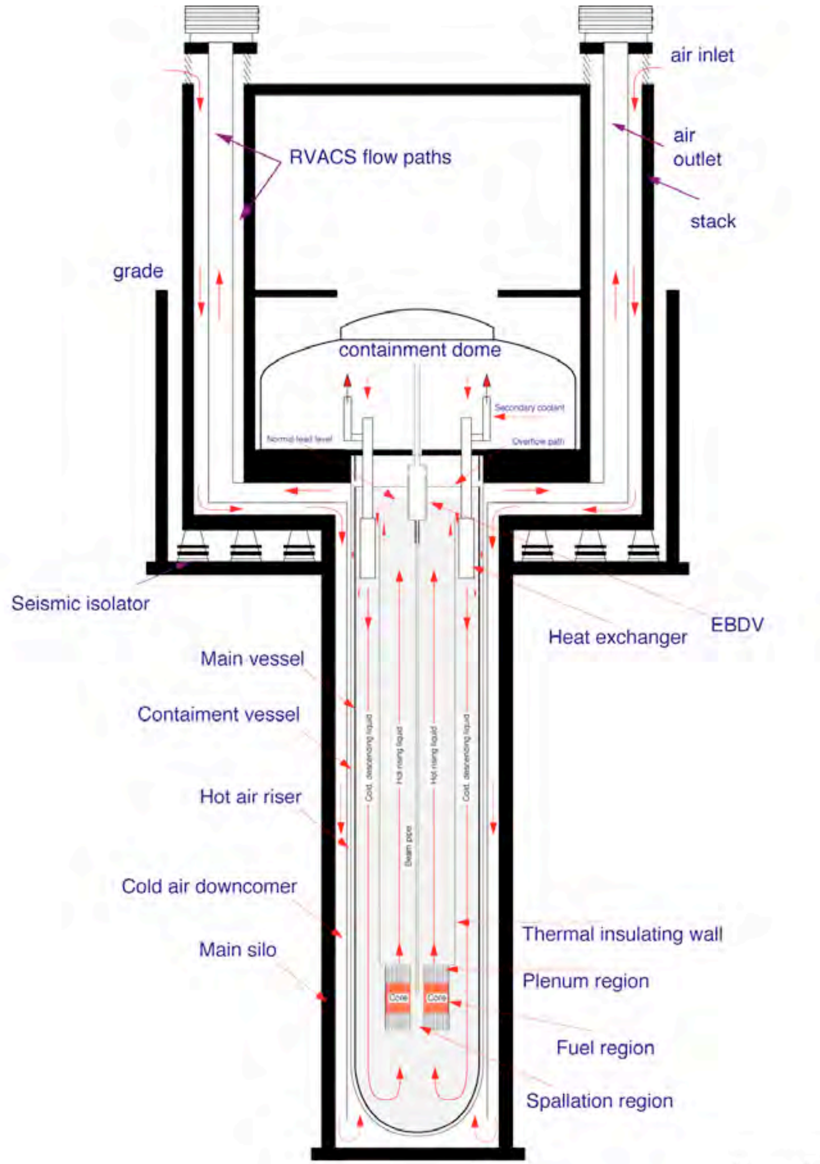
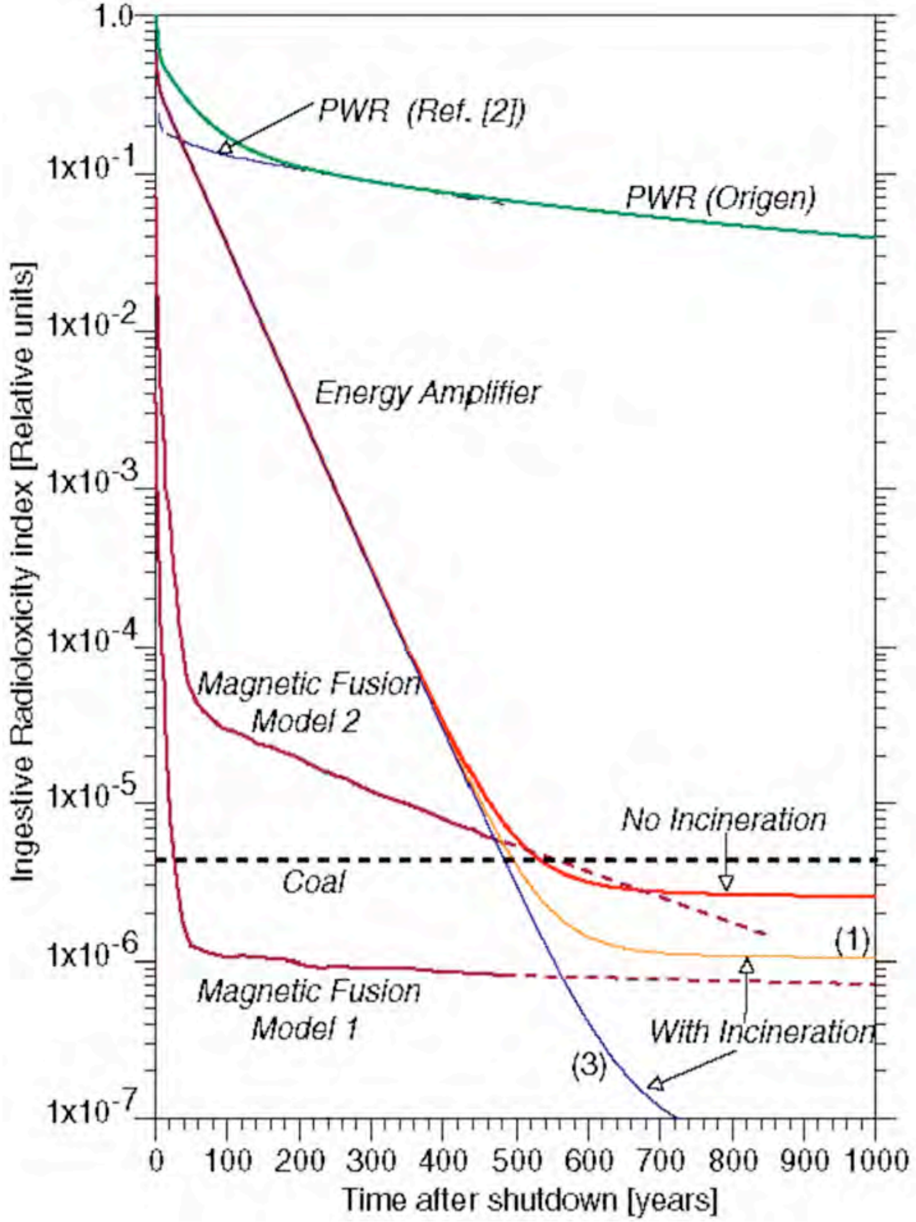


Figure 4.1a

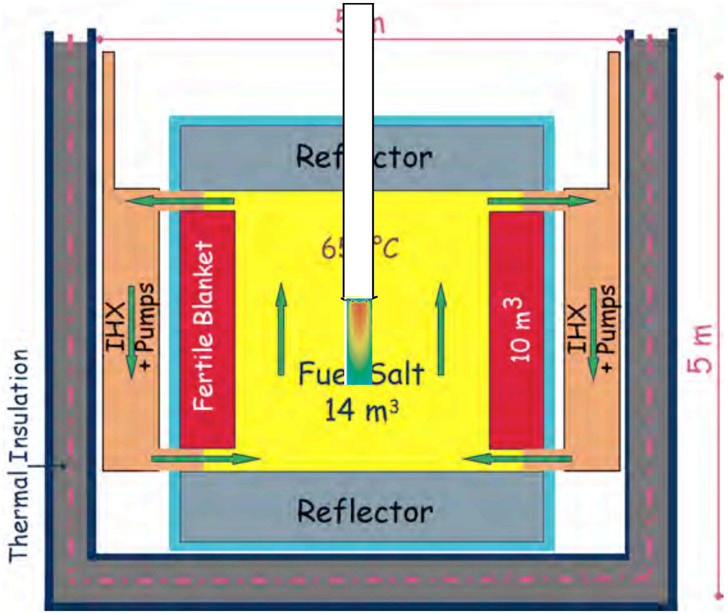
Short duration of nuclear waste and Fuel reprocessing

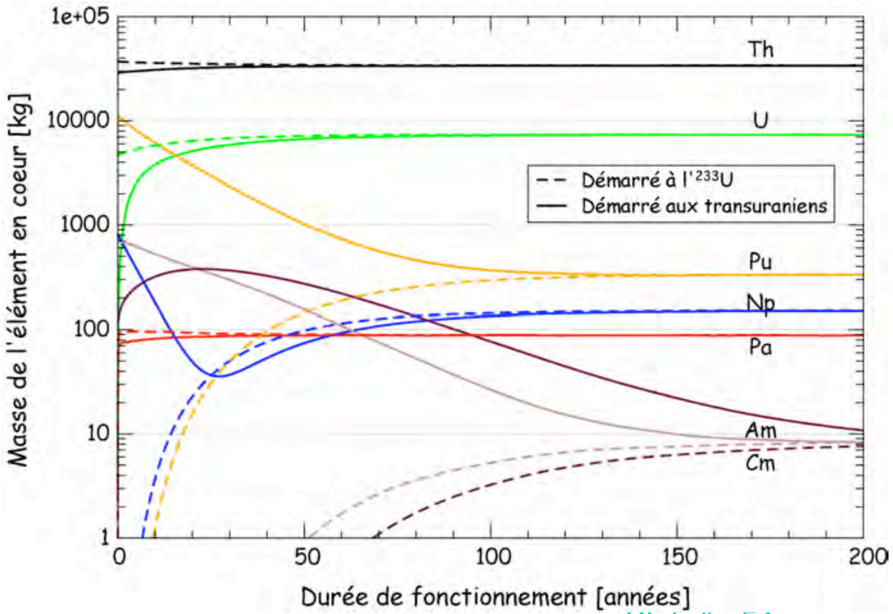
- An uninterrupted operation of about 10 years, in which
  - the only waste are Fission fragments Their radio-activity of the material is intense, but limited to some hundreds of years.
  - Actinides are recovered without separation and are the "seeds" of the next load, after being topped with about 10 ÷ 15 % of fresh breeding element (Th or U-238) in order to compensate for the losses
  - A small fraction of Actinides is not recovered and ends with the "waste"
- *The cycle is "closed" in the sense that the only material inflow is the natural element and the only "outflow" are fission fragments.*



Thermal (Molten salt) Thorium breeder (Alvin Weinberg)

- Liquid Fuel: LiF, $(NL)F_4$, BeF:
- NL from 6,5% to 20 %.
- Volume : 20 m³, Temp.: 630°C,
- Power : 2.5 GW_{th} = 1 Gw_{ele}
- A molten salt reactor's fuel is continuously reprocessed by an adjacent chemical plant on line. *All the salt has to be reprocessed every 10 days*. Reprocessing is based on fluorination:
  - Fluorine removes U233 from the salt.
  - A molten bismuth column separates Pa-233 from the salt before decay.
  - A fluoride-salt system distills the salts. Each salt has a distinct temperature of vaporization.
  - The light carrier salts evaporate at low temperatures, and form the bulk of salt.
  - The thorium salts must be separated from the FP which become "waste"
- The amounts recovered are about 800 kg of waste per year per GW generated.





Thorium molten salt reactors (TMSR)

- In 2002 a 1000 MWe Thorium MSR was designed in France with a fissile zone where most power would be produced and a surrounding fertile zone where most conversion of Th-232 to U-233 would occur.
- The FUJI MSR is a 100 MWe design operating as a breeder and being developed internationally by a Japanese, Russian and US consortium.
- It is not a fast neutron reactor, but epithermal (intermediate neutrons). The value of η is small and closer to 2.
- A major fraction of Xe and of Pa-233 to U-233 conversion must be recovered by the on-line purification plant, (not clearly shown as yet).
- A possible but exotic sub-critical scenario is also shown.

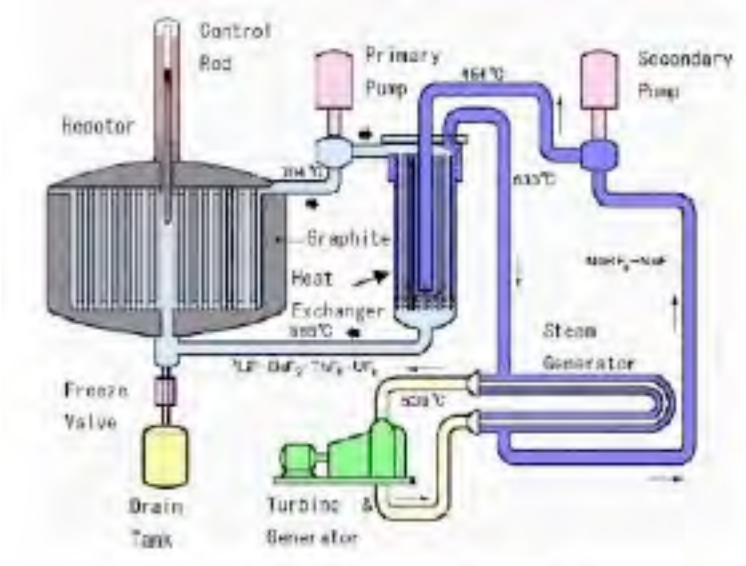
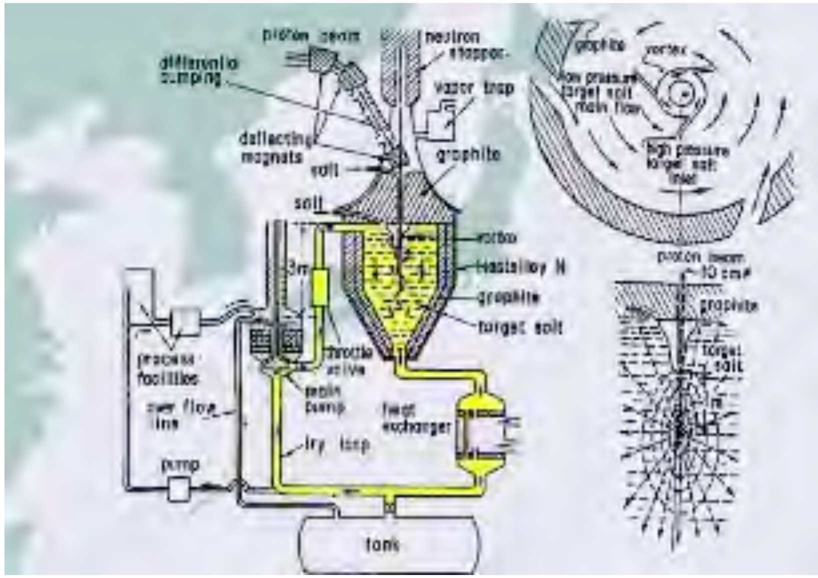
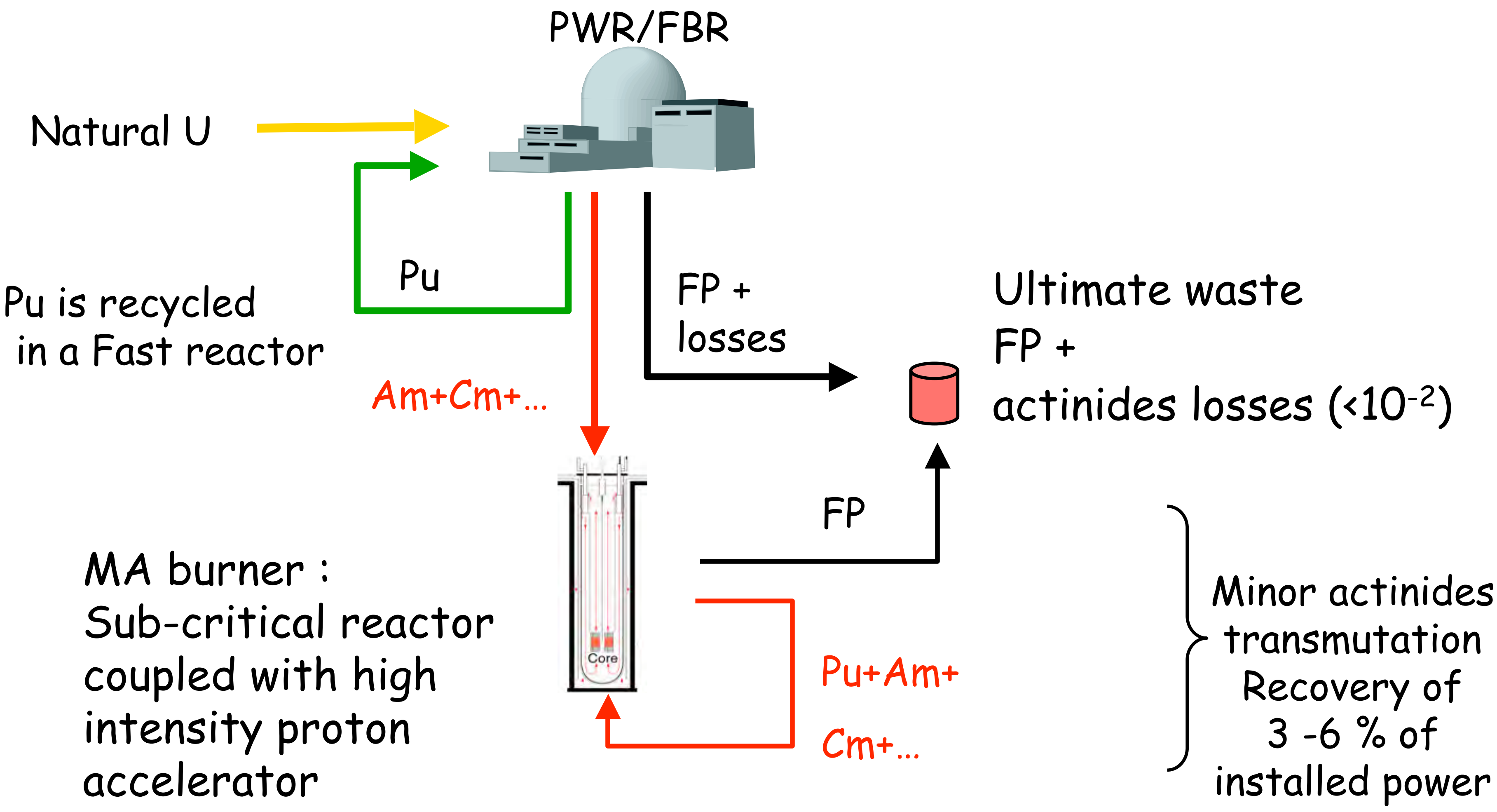


FIG. [illegible] Simplified schematic diagram of FUJI

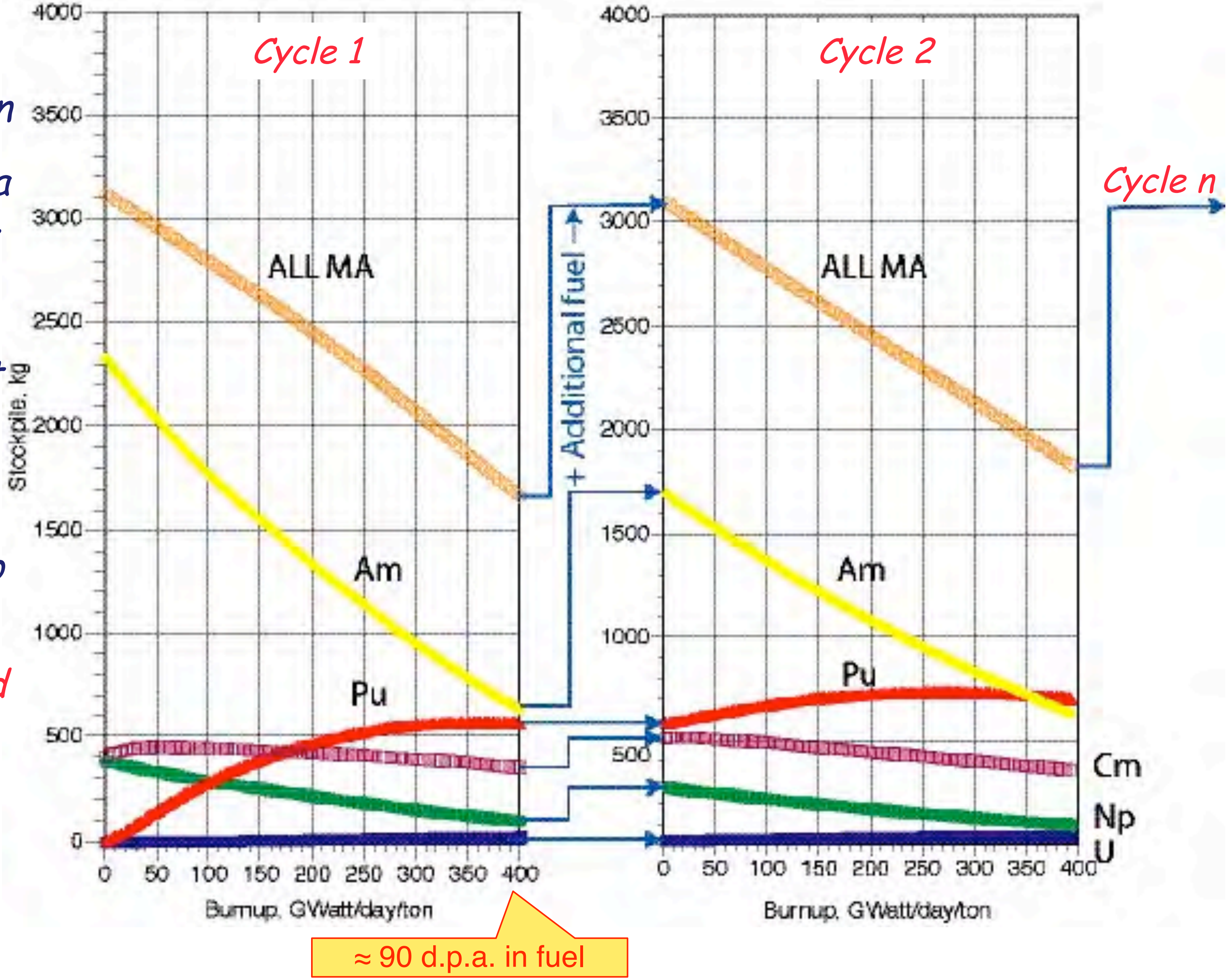


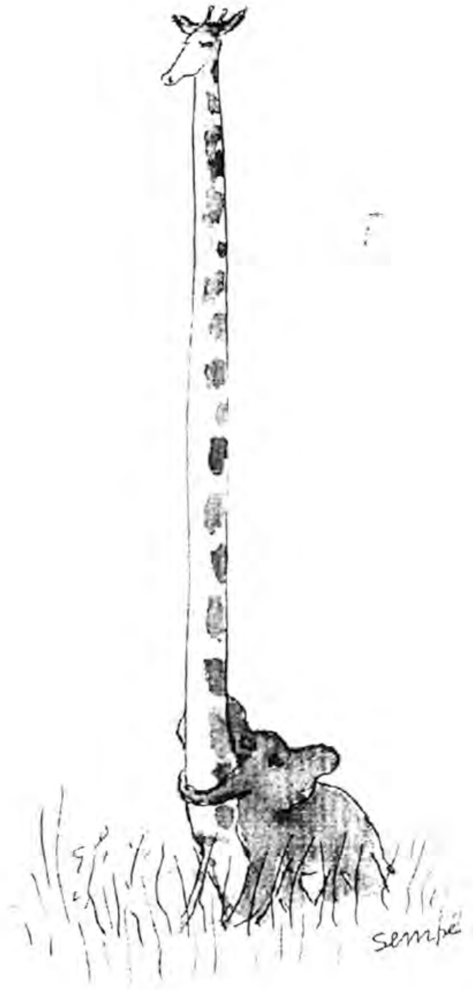
Transmutation of waste of minor actinides



Cyclic time evolution of the MA's stockpile in a EA

- *About 3.1 ton of h.m. MA's are burnt for about 400 GW d/t, in a sub-critical molten Pb fast reactor and a neutral matrix of Zr.*
- *The burnup is normalized to the MA h.m. The final MA h.m. mass is 1.7 t*
- *At each subsequent cycle additional fuel is added to the surviving MA's, topping each cycle to 3.1 ton of h.m.*
- *The cycle is indefinitely repeated*
- *Secondary Pu and U are generated and incinerated during the cycles.*
- *No appreciable Bk, Cf, Es etc. are produced*





Le couplage d'un accélérateur et d'un réacteur nucléaire : un accouplement contre nature ou l'avenir de l'énergie nucléaire ?

*The coupling of an accelerator and of a nuclear reactor:
a mating against nature or the future of the nuclear energy ?*

Thank you !