Accelerator Driven Systems (ADS)

Fusion-Fission Workshop

Richard Sheffield
Los Alamos National Laboratory
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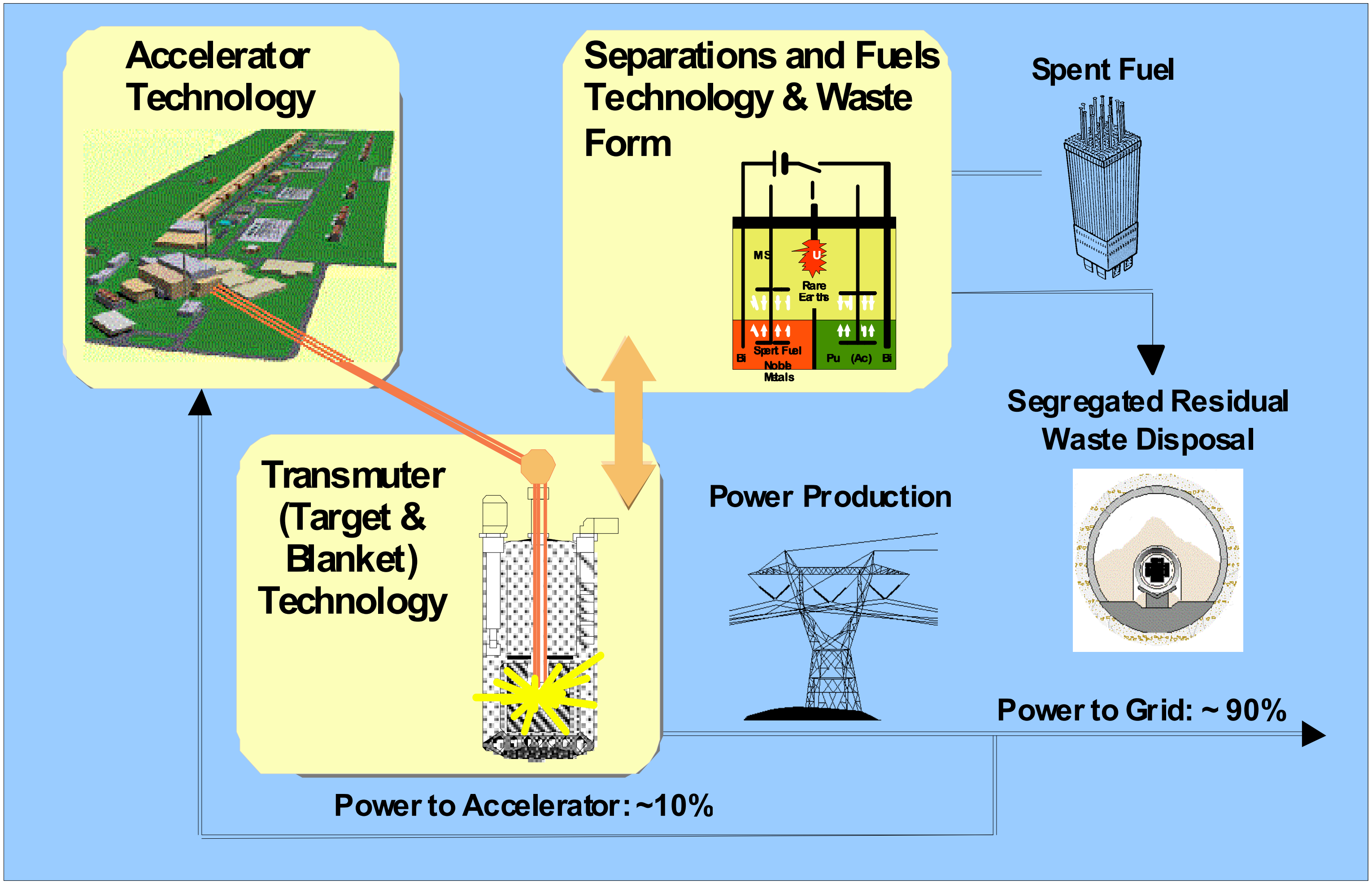
Operated by Los Alamos National Security, LLC for NNSA

Outline

- **Impact of Accelerator Transmutation**
  - **The why and how of an accelerator based transmuter**
  - **The why not and why "why not"**
- **Overseas efforts**

Accelerator Transmutation Includes Three Major Technology Elements: Separations, Fuels & Waste Forms, Accelerators, and Transmuters



Accelerator Technology

Separations and Fuels Technology & Waste Form

Spent Fuel

Segregated Residual Waste Disposal

Transmuter (Target & Blanket) Technology

Power Production

Power to Grid: ~ 90%

Power to Accelerator: ~10%

Subcritical Reactor Operation Capability Adds Flexibility

- **Can drive systems with low fissile content (Th or M.A.) or high burden of non-fissile materials**

- **Can operate with fuel blends (Pu and M.A. wo/ U or Th) that could make critical systems operate in an unsafe regime, i.e. avoid prompt critical abnormal accident and leads to bounded rather than exponential power density responses to reactivity changes. *Addition of U to gain stability produces more Pu.***

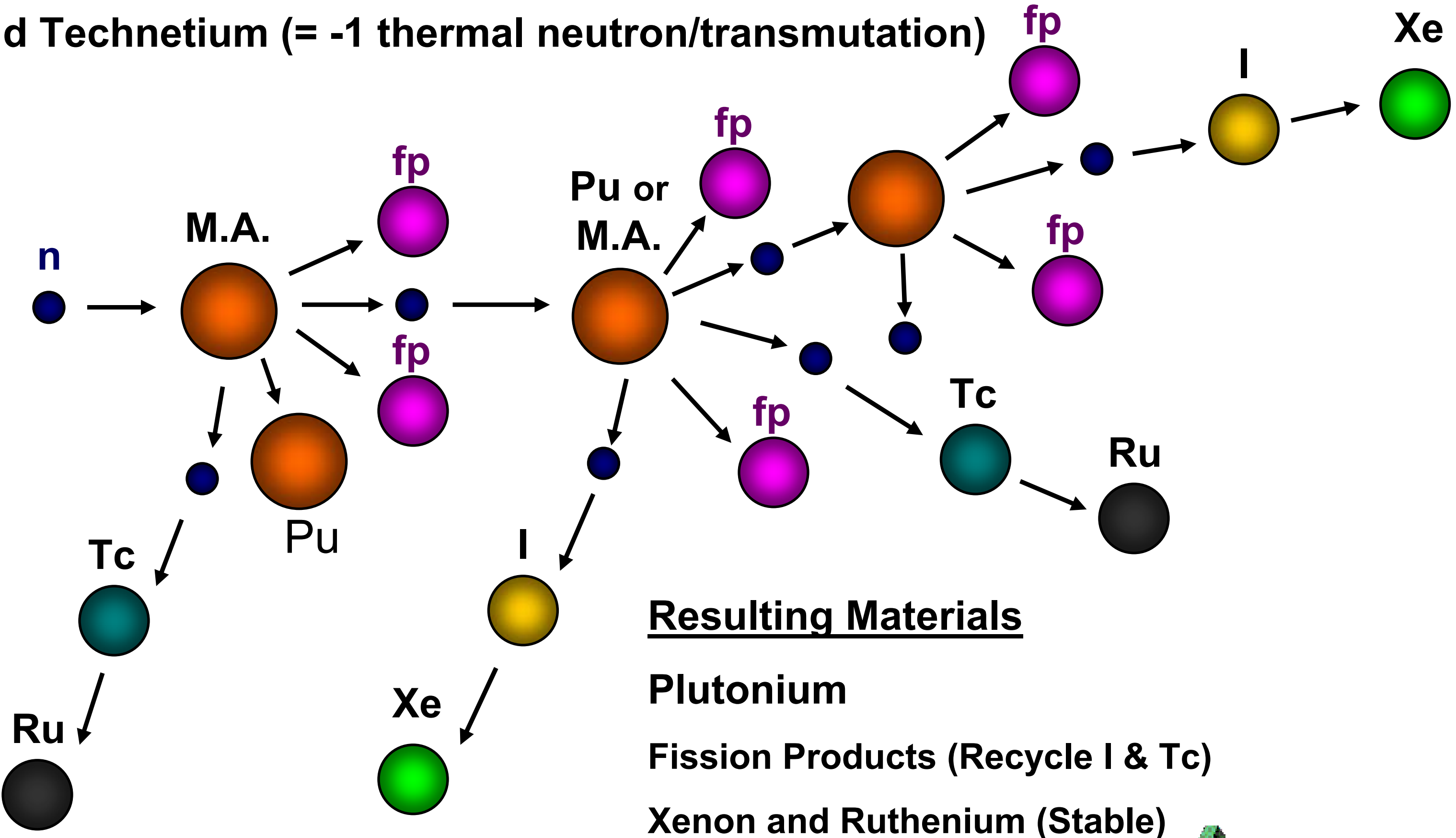
- **Can compensate for large uncertainties or burnup reactivity swings**

An Actinide Transmuter Must Take Into Account Neutron Leakage and Capture

Minor Actinides (= ~2-1 neutrons/fission: 3-1 for fast neutrons)

Plutonium (= 3-1 neutrons/fission)

Iodine and Technetium (= -1 thermal neutron/transmutation)



<u>Resulting Materials</u>

Plutonium

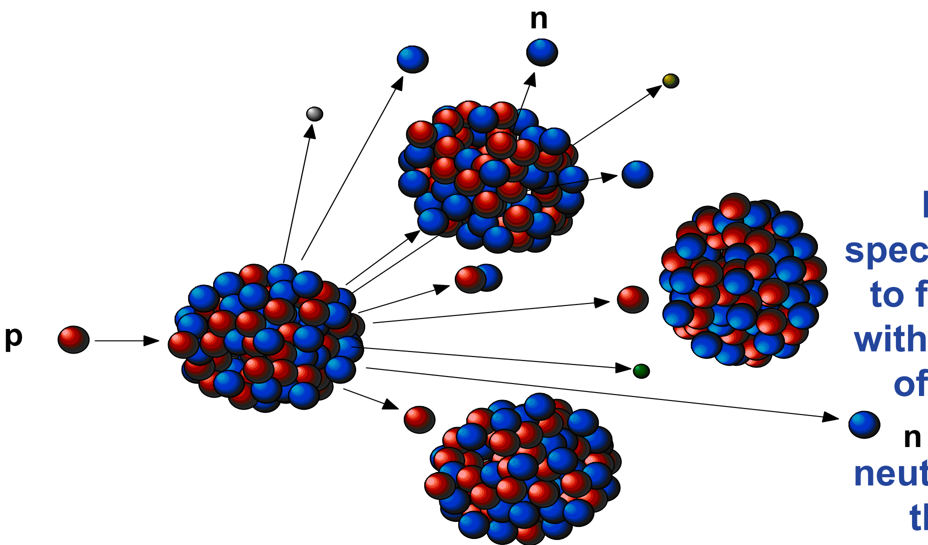
Fission Products (Recycle I & Tc)

Xenon and Ruthenium (Stable)

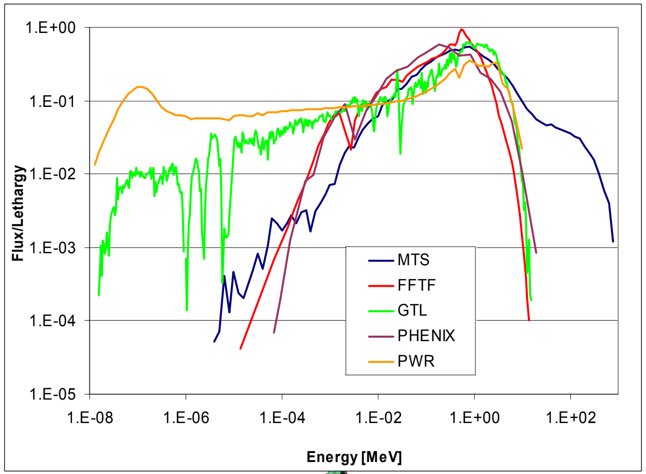
Accelerators Produce Neutrons by Spallation

- **Incident protons strike tungsten nuclei, knocking out other energetic particles**

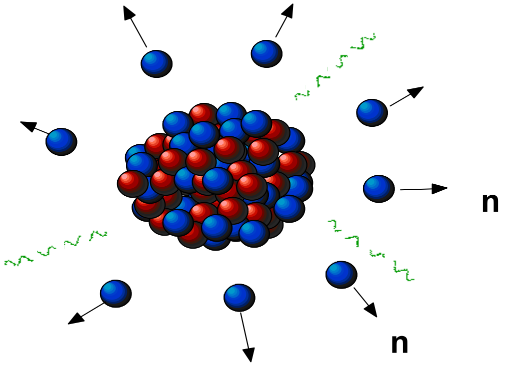
- **Knocked out particles hit other tungsten nuclei creating a ‘cascade’**



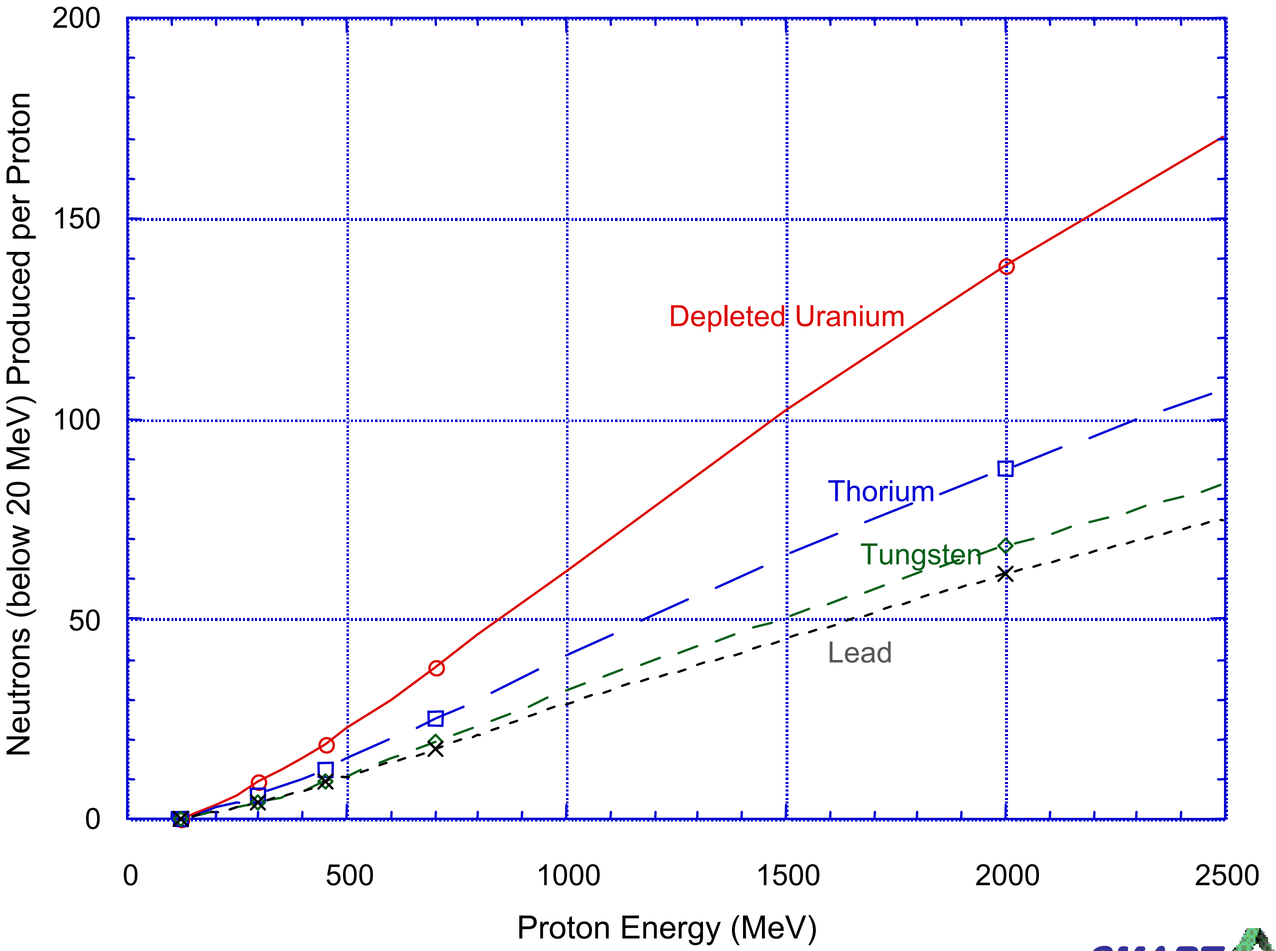
MTS neutron spectra is similar to fast reactors, with the addition of high energy “tail” (6% of neutrons greater than 10 MeV).



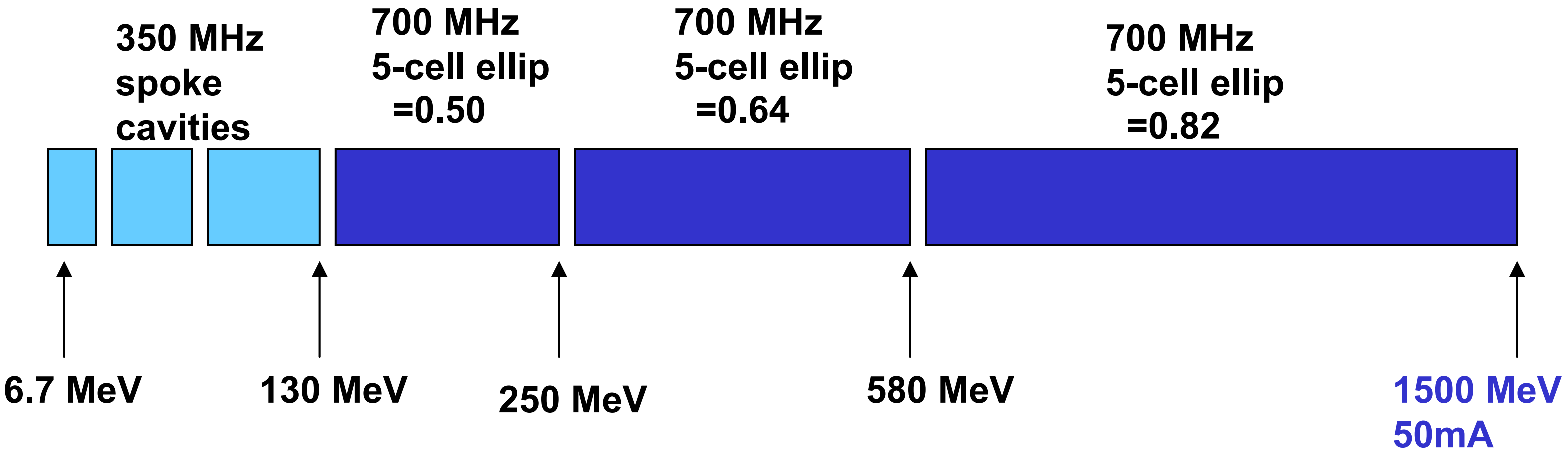
- **The residual nuclei then ‘cool’off by emitting other neutrons and and gamma rays in a process called evaporation.**



Spallation Efficiently Produces Neutrons For Transmutation



The Accelerator Preliminary Design is Based on the Technologies Developed for the APT Program



350 MHz
spoke
cavities

700 MHz
5-cell ellip
=0.50

700 MHz
5-cell ellip
=0.64

700 MHz
5-cell ellip
=0.82

6.7 MeV

130 MeV

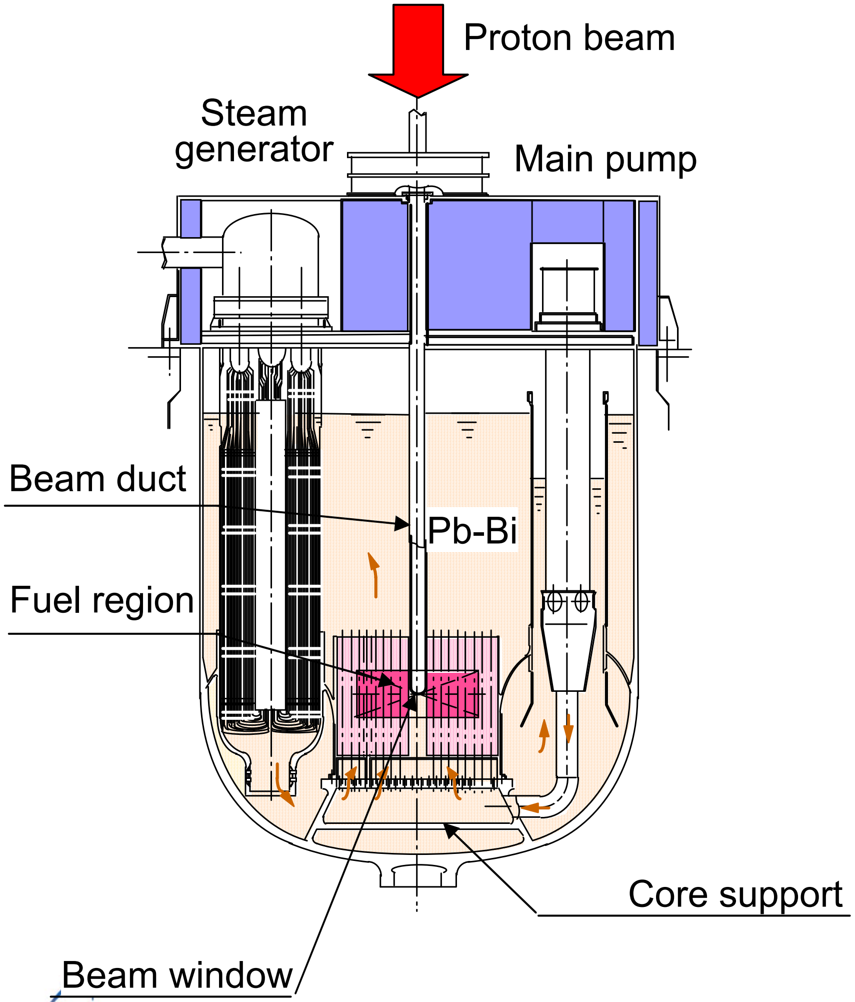
250 MeV

580 MeV

1500 MeV
50mA

- An all-superconducting linac that reduces cost and improves performance and reliability (i.e. beam continuity).
- Most accelerator design issues have been addressed
- There may be other upgrades to include (such as higher power klystrodes?)

High Intensity Proton Accelerator Project in JAERI/Tokai: Preliminary Design of the Target



- Proton beam : 1.5GeV 22 - 30MW
- Spallation target : Pb-Bi
- Coolant : Pb-Bi
- Subcriticality : $k_{eff} = 0.95$
- Thermal output : 800MWt
- Core height : 1000mm
- Core diameter : 2440mm
- MA initial inventory : 2.5t
- Fuel composition :

  (40%Pu + 60%MA) Mono-nitride
- Transmutation rate :

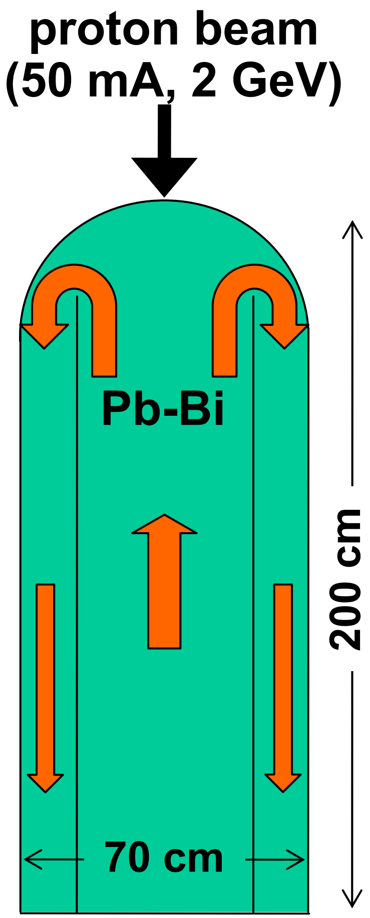
  10%MA / Year (10 units of LWR)
- Burn-up reactivity swing :

  +1.8% k/k

Activities on Nuclear Transmutation H. Oigawa Group Leader, Transmutation Experiments Group

A 70-cm-diam liquid Pb-Bi spallation target can handle a 100-MW (50 mA at 2 GeV) proton beam

- Rastered beam spot footprint of 50 cm diameter has a current density of 25 μA/cm^2
- Target container will have a ≥16-month lifetime
- A target diameter of 70 cm provides a 10-cm “buffer” for beam misalignment, return flow, etc.
- For a 200 °C temperature rise (200 °C inlet, 400 °C outlet), Pb-Bi flow rate is 350 liter/s and velocity 1.8 m/s, within allowable erosion limits
- Russia used Pb-Bi to cool 155-MW reactor cores whose sizes were similar to this target
- Generates 2x10^{19} neutrons/s with very good source-blanket coupling efficiency (~90%)



Past Issues with ADS Technology and Budget Limitations Effectively Eliminated an ADS System as a Component of US Fuel Cycle

- Concerns about faults/trips by reactor designers
  - Effect of transients on materials
  - Effect of transients on fuels
  - Quality of electrical power delivered to the grid
  - Periodic maintenance
- 1996 National Research Council study was negative
  - Presumed that ADS should eliminate the need for a geologic repository.
  - Accelerator based system was too expensive.

1996 NRC Study Conclusions Was Predicated on Faulty Assumptions

- NRC study specified that a burner needs to eliminate the need for a HLW repository – an impossible requirement. ADS does not preclude the need for a HLW repository, but it does greatly reduce the quantity of HLW per MWe.
- Assumed aqueous processing of very young (hence hot) spent fuel – an unnecessary requirement.
- The aqueous and molten-salt processing separations technology required for an ATW were immature.
- The study assumed a single thermal blanket power of 8 GW – too high.
- Superconducting accelerator has a much lower capital and operating cost than the assumed room-temperature accelerator.
  - 1992 design, 250 mA, 1.6 GeV, 1 MV/m, D_2O moderated 2 x 10^{15} n/cm^2-sec; support ratio between 1:8 to 1:10.
- Of the three options considered, the study concluded that an once-through cycle option was significantly less expensive and risky than either an Advanced Liquid Metal Reactor/Integral Fast Reactor or an ATW.
- JAEA has estimated that an ADS based system will result in a 2-3% increase in electricity cost. The cost included operating cost, partitioning, dedicated fuel fabrication facilities, reprocessing, and decommissioning (electricity is ~ 5¢/kWhr in Japan).

Faults/Trips Issues are Manageable

- Quality of electrical power: 1) needed to run through own power interruptions and 2) to put power onto grid:
  - Can now design fault tolerant accelerators
  - Improvements in power storage devices (SC coils:100MW for 100sec, flywheels >MWs, Vanadium Redux Battery >MWs, steam storage capacity)
- Effect of transients on materials and fuels was evaluated at LANL (Maloy)
  - MTS studies and other work shows no significant deleterious effects for core clad or structural materials
  - No concern for metal fuels, slight issue with oxide fuels
- Effect of transients on reactor structures was evaluated at JAEA (Oigawa)
  - Allowable trips based upon:
    - » beam window: 10^5 per 2 yrs of <1 sec
    - » reactor vessel: 10^4 per 40 yrs of 1 sec to 5 min
    - » system availability: 1 per week of > 5 min

Outline

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- <u>Overseas efforts</u>

Overseas ADS Research Covers Many Options

Project	Accelerator power (MW)	keff	Blanket power (MW)	Spectrum Flux (n/cm^2/s)	Target	Fuel	References
JAERI-ADS (Japan 2004)	27 (1.5 GeV, 18 mA)	0.97	800	Fast	Pb-Bi	MA/Pu/ZrN	Ikegami et al. (2004); Kikuchi et al. (2004)
HYPER (Korea)	*15 (1 GeV, 10-16 mA)*	*0.98*	*1000*	*Fast*	*Pb-Bi*	*MA/Pu*	*Yoo (2004)*
XADS Design A (Italy)	3.6 (600 MeV, 3-6 mA)	0.95-0.97	80	Fast 10^{15}	Pb-Bi	U/Pu/MOX	Abderrahim et al. (2004a)
Design B (France)	3.6 (600 MeV, 3-6 mA)	0.95-0.97	80	Fast 10^{15}	Steel	U/Pu/MOX	Abderrahim et al. (2004a)
Design C (Belgium)	1.75 (350 MeV, 5 mA)	0.95	50	Fast 3×10^{15}	Pb-Bi windowless	U/Pu/MOX	Abderrahim et al. (2004b)
INR (Russia)	0.15 (500 MeV, 10 mA)	0.95-0.97	5	Fast	W	MA/MOX	Markov et al. (2003)
NWB (Russia)	3 (380 MeV, 10 mA)	0.95-0.98	100	Fast 10^{14} -10^{15}	Pb-Bi	UO2/UN U/MA/Zr	Pavlopoulos et al. (2003)
CSMSR (Russia)	10 (1 GeV, 10 mA)	0.95	800 cascade scheme	Intermediate 5×10^{14}	Pb-Bi	Np/Pu/MA molten salt	Degtyarev et al. (2005, 2006)

ADS Research Has Continued Overseas

- On-going efforts overseas in ADS/ATW*
  - Europe: Eurotrans – 6M€/yr
  - Have spent 40-50M€ to date + indirect funding
  - Planned costs 700M€ over 12 years with 1/3 Belgium & 2/3 partners;
  - Belgium Parliament has requested an OECD/IAEA review by June

- Other efforts on going in: Asia Japan, China, India, Russia, Sweden

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*ADS/ATW: Accelerator Driven System/Accelerator Transmutation of Waste

SCK•CEN Vision
for Sustainable Nuclear Energy in Europe

- Today's thermal spectrum reactors
  - Needed in the energy mix

  ➔Provide services & support to Gen.II & III NPPs
  - Low efficient use of resources & HLW burden

  ➔R&D on Reduction of HLW burden through P&T and Minor Actinide recycling in fast spectrum dedicated burners (critical or sub-critical) ⇨ MYRRHA
- Fast reactors needed to meet sustainability
  - Closed fuel cycle ⇨ reduce proliferation risk
  - Closed fuel cycle ⇨ better use of resources (U, Th)
  - Reduce the HLW flow

  ➔Move towards fast spectrum reactors and contribute to the demonstrate of GEN.IV concepts ⇨ LFR
- Very long term sustainability through contribution to Fusion systems

Fast Spectrum Experimental Facility needed in Europe

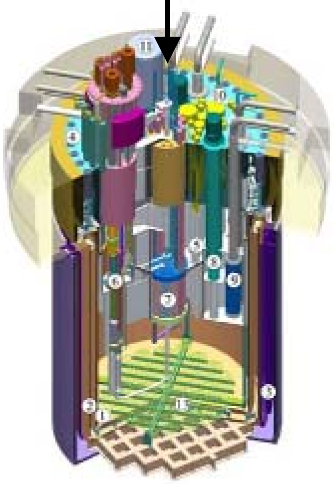
MYRRHA is to be:

- A flexible neutron irradiation testing facility as successor of the SCK•CEN MTR BR2 (100 MW)
- An attractive fast spectrum testing facility in Europe for Gen.IV and Fusion
- A full step ADS demo facility and P&T testing facility
- A technological prototype as test bench for LFR Gen.IV
- An attractive tool for education and training of young scientists and engineers
- A medical radioisotope production facility
- Fundamental research facility at the accelerator

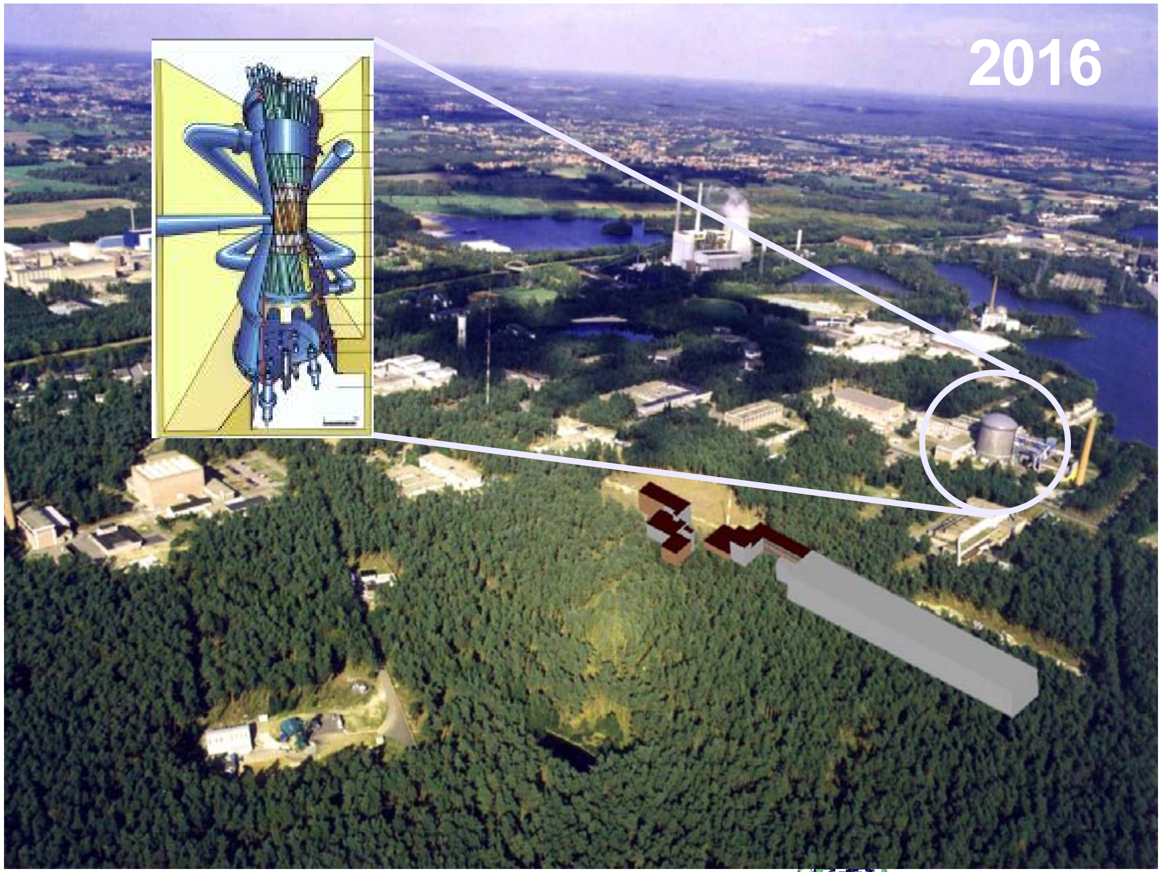
MYRRHA = Accelerator + Reactor to Replace BR2

Proton beam

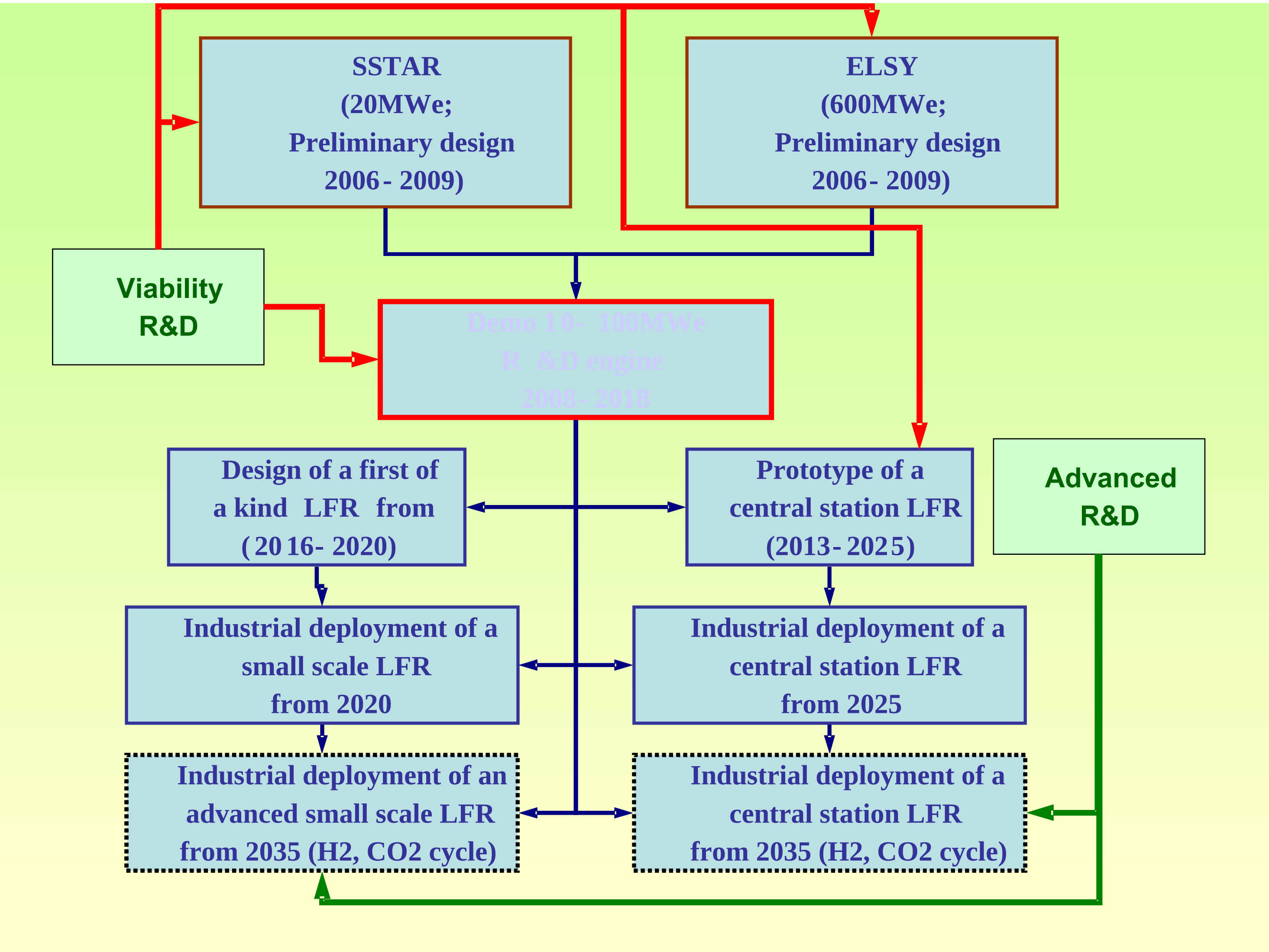
multidisciplinary



Research tool



Link ADS – Gen. IV LFR



SSTAR
(20MWe;
Preliminary design
2006 - 2009)

ELSY
(600MWe;
Preliminary design
2006 - 2009)

Viability
R&D

Demo 10 - 100MWe
R &D engine
2008 - 2018

Design of a first of
a kind LFR from
(2016 - 2020)

Prototype of a
central station LFR
(2013 - 2025)

Advanced
R&D

Industrial deployment of a
small scale LFR
from 2020

Industrial deployment of a
central station LFR
from 2025

Industrial deployment of an
advanced small scale LFR
from 2035 (H2, CO2 cycle)

Industrial deployment of a
central station LFR
from 2035 (H2, CO2 cycle)

Some key dates (1/2)

- Presently : MYRRHA serves as basis of XT-ADS development
  - FP6 integrated project EUROTRANS (48 partners)
  - Runs until March 2009 => Extension +1 year
- End 2008 ➔ submit Preliminary Decommissioning Plan to the waste management authorities – ONDRAF/NIRAS.
- 2009 – 2013 ➔ work in parallel on:
  - 2009 – 2011 : detailed engineering design (FP7 CDT)
  - 2012 – 2013 : -drafting of technical specifications
    -publication of call for tenders
    -awarding of manufacturing contracts
  - 2009 – 2011 : testing of innovative components
    (accelerator, spallation target and reactor)
  - 2009 – 2013 : licensing and permit
    ➔ obtain the authorization of construction at the end of 2013

Some key dates (2/2)

- 2014 – 2016 : construction of components & civil engineering works on the Mol site.
- 2017 : assembling together the different components
- 2018 – 2019 : commissioning (at progressive levels of power).
- 2020 : MYRRHA full Power operation

Summary of costs

- A Business Plan has been issued in April 2007
- The total investment costs expressed in current value (2007), spread over 12 years, amounts to: ~700 M€ including contingencies (under revision)
- This includes:
  - Total investment
  - Project management costs
  - Licensing costs
- MYRRHA project is up for funding for 1/3 by Belgium and 2/3 by international partners

A Subcritical System Requires An External Neutron Source, And The Choice Will Be Made On Safety And Cost Effectiveness

- Each system will have its own unique safety basis considerations, but any system that has large quantities of fissionable material will have to meet reactor class safety regulations and will be evaluated against conventional reactors (and their 50 years of operational experience). The further the design is from existing reactor designs, the more design and testing that will be required.
- Any system with large reactivity swings will have the neutron source operate at low power for a significant period of the time, thus the resources spent to enable operation at high powers are inefficiently used.
- Any system with a high neutron multiplication, k_{eff} close to 1, significantly reduces the fraction of total neutrons provided by the source
  - significantly reduces the cost of the neutron source relative to overall system cost.
  - since cost will certainly be a big factor then the implication is that a sub-critical system will be viewed as a reactor first and the neutron source viewed as an appendage - but with a large (and negative from a conventional reactor engineer) design impact

General Comments

- Invariably either compromises in operation or added expense is incurred in multifunction devices as compared to single function systems, for example, is the focus power production or waste transmutation.
- No substantive physics difference is expected in neutronics when comparing different neutron sources
  - differences in geometry will have substantial design impact
  - any advanced, novel fuel scheme can, in general, work equally well for any the external neutron source systems.
- If power production then availability should be comparable to LWRs, now better than 90% including all maintenance and refueling (took 50 yrs).

Each system Will Have Its Unique Design Considerations

As an example, an ADS will have a tube for propagating the beam to the spallation target. For top penetration, the coolant would fill the tube to the level of the liquid metal coolant and so would act like a reflector more than an absorber – the design must ensure that the core does not go into prompt criticality.

Any External Source Will be Evaluated by Production Rate (n/s) and Capital and Operations Cost

- **2-Gev, 100 MW spallation source produces ~2.4×10^{19} n/s, approximately comparable to a 60 MW fusion device and compatible with 6 GWth and k_{eff} of 0.95.**

- **Accelerator cost ~$2.4B (including spallation target and 30% contingency)**

Conclusion on Accelerator Based Transmuters

- A clear path exists to implementing the accelerator technology
- The major issues are in fuels and chemistry
- Production of electricity is optional (but would pay for the facility and associated operational costs)
  - Since only two transmuters are required for the present LWR fleet then the incremental electrical cost will be a few percent*.
  - Over the next three decades a reasonable expectation is that:
    - Accelerator faults can be reduced to an acceptable level through technology improvements
    - High-capacity energy storage systems will see significant improvements driven by alternative energy sources, such as solar and wind.

*Assuming reprocessing is funded separately as part of a new nuclear fuel cycle