The R and D program at CEA

4 major topics :

1 - Subcritical core :

Physics :
- the MUSE experiments (2000 - 2003),
- nuclear data measurements and evaluation,
- code validation,
- safety and kinetics of subcritical cores.

Fuel : Common activity with critical reactors for transmutation (homogeneous recycling, targets, dedicated fuels).

2 - Target

Physics :
- Spallation physics (experiments on spallation product distribution, etc ...).
- Code system : SPARTE (intranuclear cascade, intermediate energy data, nuclei evolution, particle transport $E < 150$ MeV).

2 - Target (follows)

Materials : Mostly Pb/Bi.

The ISTC-559 1 MWt target.

Loops for corrosion, purification studies PLOMBIERES at Cadarache, to be built.

Effects of irradiation (neutrons, protons).

Choice of 9Cr martensitic steel.

Design : Methods and codes for design.

⇨ Global validation envisaged (the MEGAPIE project at PSI : 1 MWt Pb/Bi flowing target, to be put in the SINQ installation by the end of 2003).

A preliminary experiment foreseen on embrittlement with 72 MeV protons (PSI cyclotron injector) : LISOR experiment.

3 - Accelerator

Most of the studies on linear accelerator with supraconductive cavities (above 150 ÷ 200 MeV).

The IPHI project (Final objective : ~ 20 mA - E_p : ~ 600 MeV ÷ 1 GeV).

The project is conducted jointly by CEA and CNRS.

4 - System studies

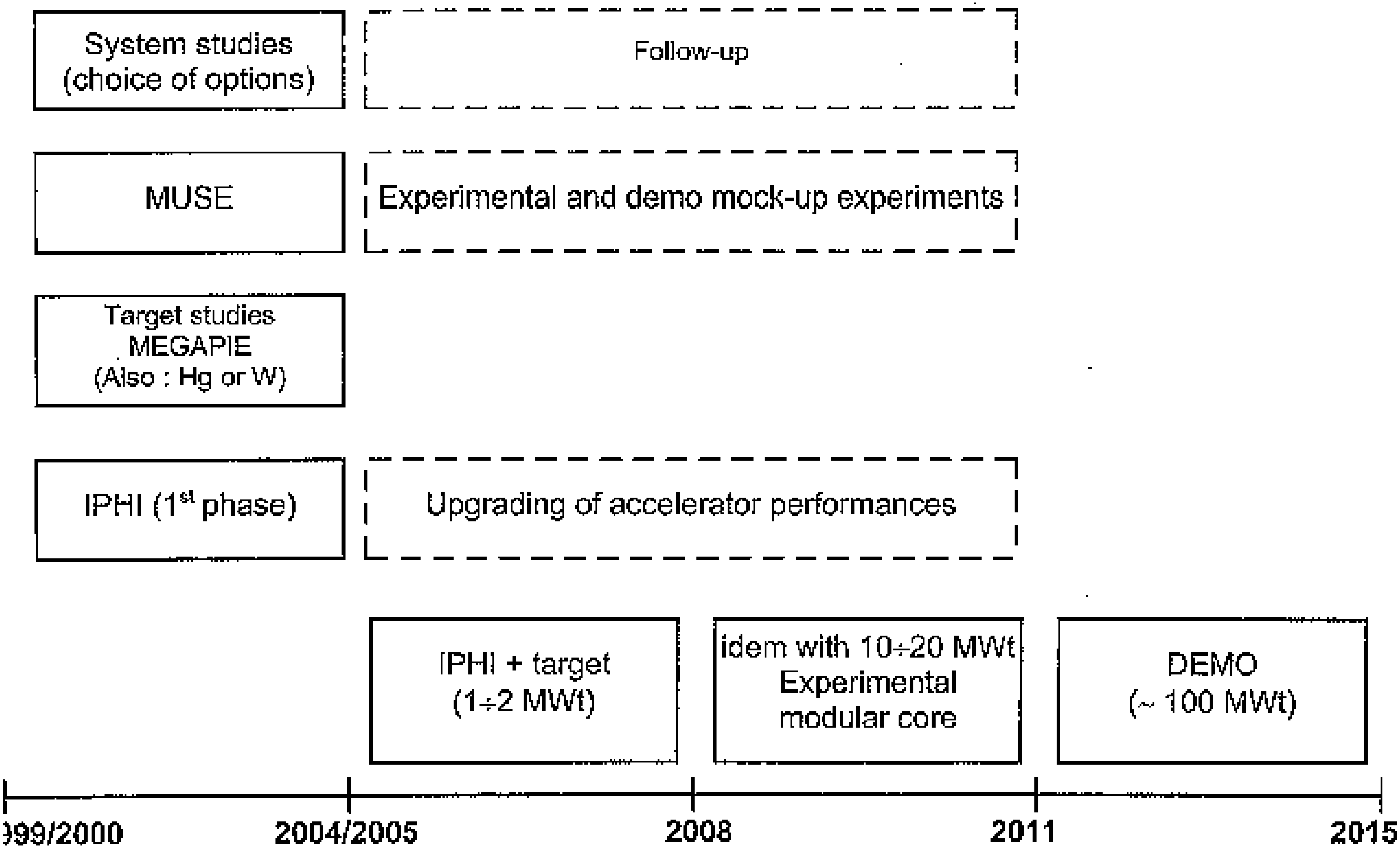
Images for demo plant (~ 100 MWt) :

- fast spectrum, gas cooling,
- idem, Na cooling (back-up),
- idem, Pb/Bi cooling (studied at ANSALDO - Italy).

Also : Step by step approach, with intermediate step at 10 ÷ 20 MWt (experimental reactor), with irradiation capabilities.

Scenario studies : motivations for ADS :

- double strata,
- Pu and MA management.

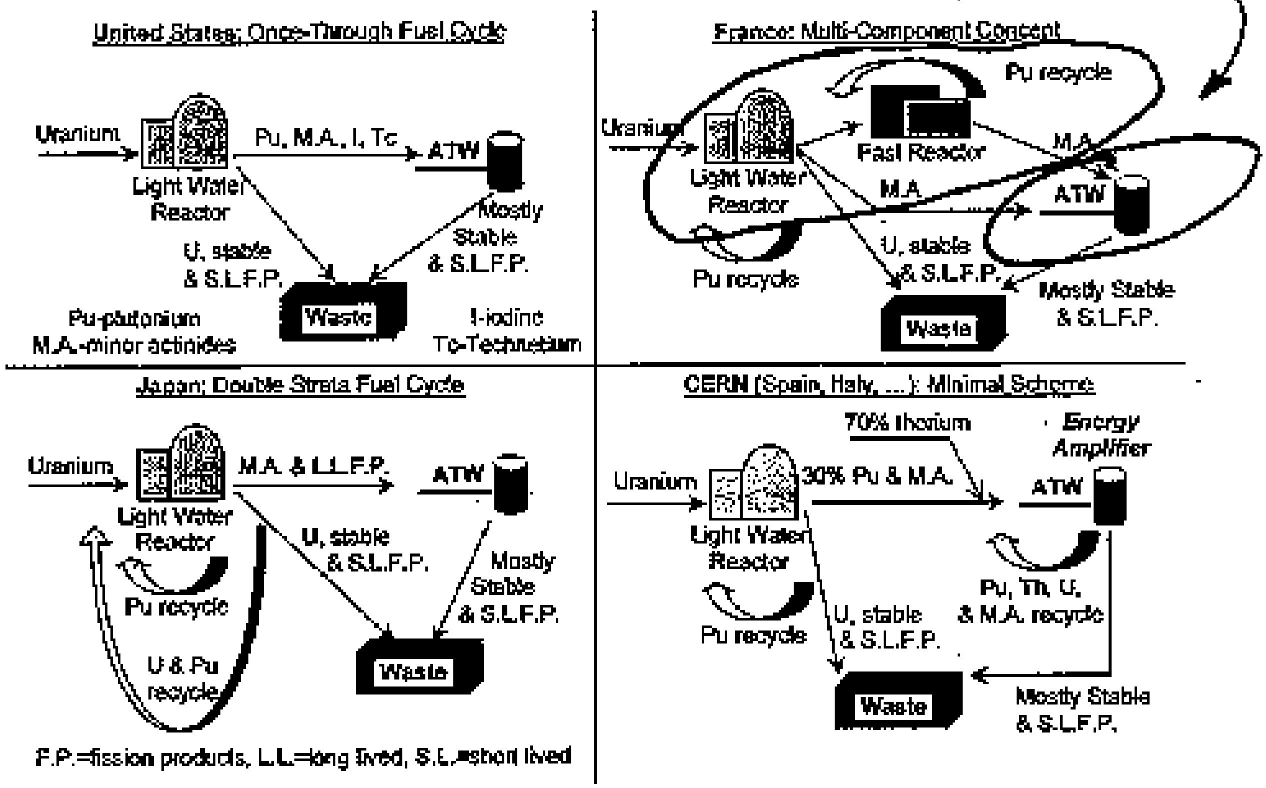

System studies (choice of options)
Follow-up
MUSE
Experimental and demo mock-up experiments
Target studies MEGAPIE (Also : Hg or W)
IPHI (1st phase)
Upgrading of accelerator performances
IPHI + target (1÷2 MWt)
idem with 10÷20 MWt Experimental modular core
DEMO (~ 100 MWt)
999/2000
2004/2005
2008
2011
2015

Calendar for demo deployment

	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14
End of Motivation study		↓														
Technical options - Preliminary safety options - First feedbacks (materials, mock-ups etc)				2												
End of feasibility study (phase A)						4										
End of Definition study (phase B)								6								
Start « realisation phase » (development and construction)									7							
Validation of spallation source													11			
End construction																14

Figure 9-1. International Fuel Cycle Applications of ATW Concepts.

also: double strata



Within the U.S., current policy is to not reprocess spent fuel, implying that plutonium is waste and is to be discarded. In contrast, Japan, France, and Russia view plutonium as fuel and therefore an asset, which leads to a different application of ATW technology. In the "double-strata" concept in Japan, an ATW is seen as a way to optimize a transition from MOX recycle to MOX and uranium recycle, to minimize, and eventually almost eliminate, radioactive waste. ATW is used alongside LMRs. The French concept employs an ATW as a back end to a mix of reactor types that includes LWRs, MOX-fueled LWRs, and breeders. The European group at CERN advocates an "Energy Amplifier" implementation of ATW; they envision the use of the waste stream from the uranium-plutonium fuel cycle as part of a means to transition to a thorium-uranium-233 cycle that may have non-proliferation and waste disposal advantages.

In all cases, the use envisaged for ATW is to destroy the minor actinides which build up in the fuel cycle and hamper efforts to demonstrate acceptability of geologic repositories. Yes!

Table 9-3 International Technology Base – Accelerators

Accelerator Technology	Countries/ Programs				
	U.S.	CERN	U.K.	Switzerland	Germany
LINAC	√LANSCE √APT √SNS √AGS √Fermi	√LINACB			√ESS
CYCLOTRON				√SINQ	
FFAG					
SYNCHROTON	√AGS √AGS-Booster √Fermi	√SPS	√ISIS	√SLS	√BESSY √COSY

Table 9-4 International Technology Base – Waste Transmutation Systems/Programs

Waste Transmutation Technology	Countries/ Programs				
	U.S.	Japan	France	CERN (France, Spain, Italy)	Russia
Accelerator-Driven	√ATW	√ATW	√ATW	√ATW	
Fast-Reactor Based		√ABR	√LMR		√HTGR √LMR
Thermal-Reactor Based	√MOX (Pu disposition)	√MOX	√MOX		√MOX

9.3 International Waste Transmutation Programs

9.3.1 France

The primary French objective is to develop specific technologies as an element of a global waste management strategy. The goal is to keep options open, and be able to reach a waste management decision in the future based on firm technical grounds. This is described as a science-based approach. To this end, France is following a national program to establish feasibility of a large spectrum of partition and transmutation (P&T) strategies.

The French waste management scenario includes a combination of most options: LWR, LWR with MOX, fast reactors (specifically LMR,) and ATW. Presently, the French effort is of the order of ~80 man-year/year for current R&D stage, which includes a large-scale international collaboration (see below).

Fuel reprocessing is based on "wet" technologies, but pyrometallurgical technologies are being considered. Sodium, LBE and gas are being pursued as coolant options.

→ focus on double strata

no!

As presently envisioned, the French ATW program would use Thorium + Minor Actinides as fuel to produce electric power as well as waste transmutation. There is presently R&D underway to identify fuel forms, which includes inert matrices. There are no plans to transmute T_c and I other than carry over into the fuel, i.e., no separation of T_c and I is envisaged. decision for construction of a demo plant will be reached in the year 2006.

no! separation is studied

9.3.2 European "Energy Amplifier" (CERN, Italy, Spain & France)

The European "Energy Amplifier" is a concept that originated in CERN, and it involves a cooperation between Italy, Spain, and France. The objective of the Energy Amplifier concept is dual: (1) burn actinides, and (2) power production through a Thorium cycle. R&D resources are pooled between the different countries to reduce overall R&D cost. The Energy Amplifier concept has received strong support from the European Union, with the goal of helping members solve their various nuclear waste problems. The size of the present effort is hard to quantify, but it is expected to be larger than 100 man-year/year in the near future.

convergence is on DEMO (~100 MW) with standard fuel!

The Energy Amplifier Concept is an accelerator-driven subcritical pile using Thorium + Minor Actinides fuel. The primary target and coolant option is molten Pb-Bi, but other options such as Pb, Na, or gas-cooling are being considered. Fuel reprocessing is not part of the present program.

Current demo plans include a small-scale fissile target in CERN by 2003. LAESA (Spain) is also proposing to build an Energy Amplifier demo facility using a 380 MeV 5 mA cyclotron with a molten Pb-Bi target and a 10 MW sub-critical pile (k_{eff}=0.9).

9.3.3 Japan

Japan has active R&D efforts in the areas of fast LMRs and fast-reactor actinide burners. Even though a long-term HLW strategy has not yet been fully defined, Japan is pursuing a combination of LWR, LWR-MOX, LMR, Actinide Burner, and ATW. They have active R&D projects to examine a long term P&T strategy for long term HLW disposal.

Present plans include a Test facility in ~2009. The decision point for implementing a P&T strategy is ~2030.

Japan is pursuing nitride fuels composed mostly of minor actinides. Coolants considered are LBE, Na, He, and Pb. Their processing technology is aqueous based, but significant research into pyrometallurgical processes is being conducted.

- Convergence points :
  - Despite the fact that in France the MA (and LLFP) elimination (e.g. in the "double strata" approach) is the main motivation, Pu with MA management is also considered
  - For both application, a fast neutron spectrum is preferred
  - Also: solid fuel
  - We agree on the relevance of key fuel issues
  - Acqueous process for front end (spent fuel treatmt) and possibly pyroprocess for irradiated ATW fuel
  - Preference for LINAC option (20 ÷ 40 mA goal)
  - A ≈ 2008 horizon for most key choices (with intermediate step at ≈ 2004 horizon)
  - A ≈ 2015 target for DEMO start-up (followed by up-grade)
  - Agreement on many R and D issues (e.g. need for neutronics validation exp., MUSE at MASURCA, and target facilities for early test of LBE and W concepts - In our case: the MEGAPIE exp with PSI ⇒ 1MWt experiment in LBE)

Different appreciation :

- Difficulty and timescale for fuel development
  ⇒ Availability of facilities
  - Basic properties assessment
  - Fabrication of fuel with large MA amounts
  - ⇒ Irradiation facilities
  - Extent of PIE programs

- Fuel transient behaviour in representative conditions (LBE loop? In what reactor? TREAT? Elsewhere?)

- Difficulties related to LBE technology demonstration:
  - Need for preliminary embrittlement experiments
  - Oxygen control systems
  - Alternate coating methods
  - "small" vs "large" vessel circulation
  - natural convection

- Inspection in Service issue (of relevance also for Na). R and D needs in this field?

- Recriticality issues, connected with high density fuel and fast spectrum.

- Time needed to validate materials for window under representative conditions (e.g. test of some spallation product implantation in steels, like S, P)

- schedule for accelerator development: how to freeze design with respect to reliability issue? Reliability demonstration at what step? Extrapolability?

- Relevance of shielding issues

- Relevance of fuel cycle impact issues (doses to workers, transport, criticality-safety etc)

⟹ - A major point: Approach to DEMO ↷

a - "5% to full power" approach

b - step by step approach

"step by step" approach:

~5 y
- (critical experiments with external source) => MUSE exp
- Accelerator (already existing) + target (1 MW: the MEGAPIE exp)
- (Accelerator + target + subcritical blkt ≈ 100 kW: the JAERI approach)

~6÷7 y
- Accelerator (in-house) + target + sub. blkt ("standard" fuel)
  ≈ 1 MW ≈ 10 MW
  + MA/Pu fuel irradiation experiments

- Accelerator + target + DEMO ("standard" fuel)
  ≈ 2÷5 MW ≈ 100 MW

[illegible]

- The step by step approach, is closer to a science-based approach
The objective is the demonstration of the scientific feasibility and performance of an Accelerator-Driven-System, quite independently from application
- A construction-driven approach can make the final objective more difficult to meet.

Finally, there are different approaches on how to present the performance of the system, e.g. in terms of radiotoxicity/activity/volume reduction (How to account for TRUs which stay in the cycle etc) the radio-toxicity of a waste. This is a product of the decay rate and the biological effect of the nuclide. The biological toxicity of ingested spent fuel nuclides with and without the actinides present is shown in Figure 8-1 (Van Tuyle 1998). This illustrates the dominance of short lived fission products in spent fuel in the early time (few hundred years) and the dominance of long lived actinides at longer times. ATW provides the potential to eliminate most of the actinide inventory and thus greatly reduce the long time hazard. In a repository, this allows a robust engineered system to effectively isolate the waste during the first hundreds or thousands of years, and reduces the demand for isolation at very long times. This demand for high confidence in isolation for 10^4 – 10^6 years represents a technical challenge unprecedented in human experience. To the extent that ATW moderates this demand for very long-term isolation, the confidence in repository safety is improved.

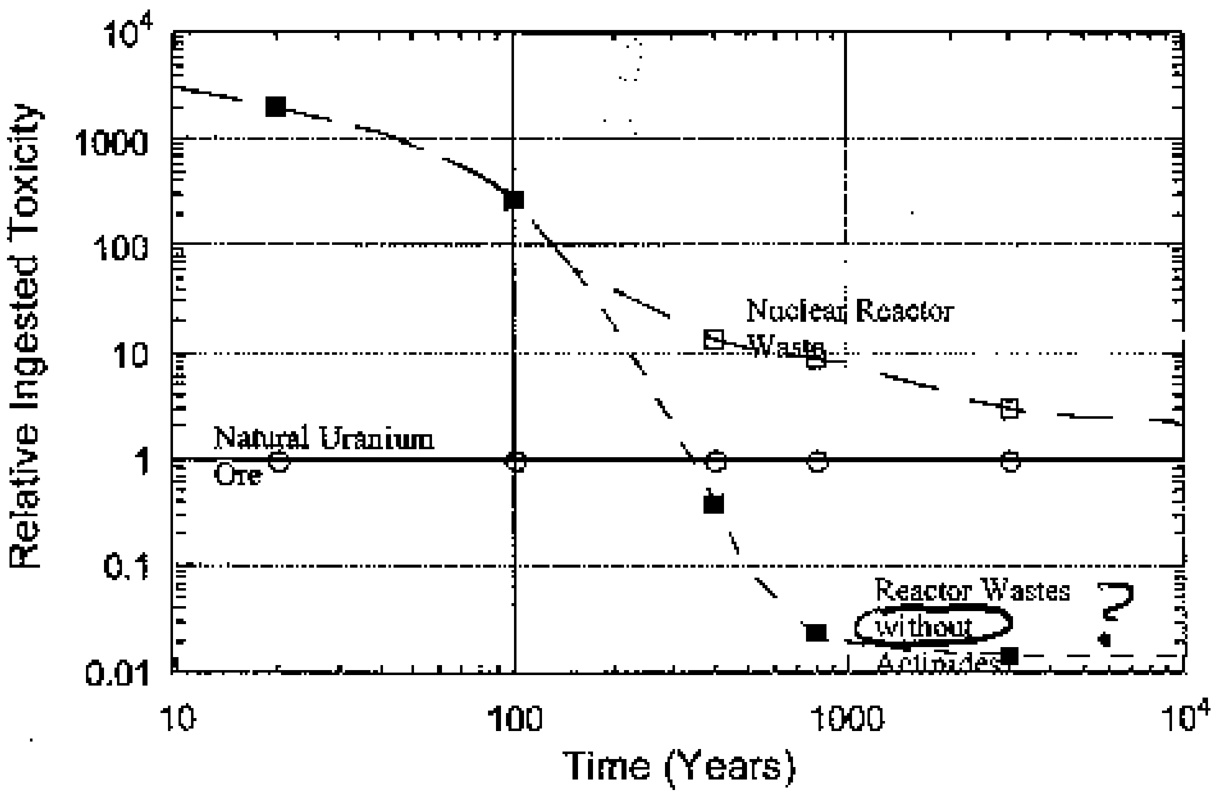


Figure 8-1. Relative Ingestion Toxicity of Spent Fuel With and Without Removal of the Actinides.

Another measure of the impact from inventory reduction can be seen from the results of Total System Performance Assessment for the "Viability Assessment of a Repository at Yucca Mountain" (USDOE 1998). Through a complex synthesis of mechanistic models, probabilistic models and expert judgement, the "base case" performance of a repository is represented in a curve of "Dose Rate" to an exposed population versus time for each of the most important radionuclides. As seen in Figure 8-2 (USDOE 1998, Section 4.2.3), this dose rate (for this

Figure 1. Reference ATW plant sized to process 10,155 tonnes of spent fuel

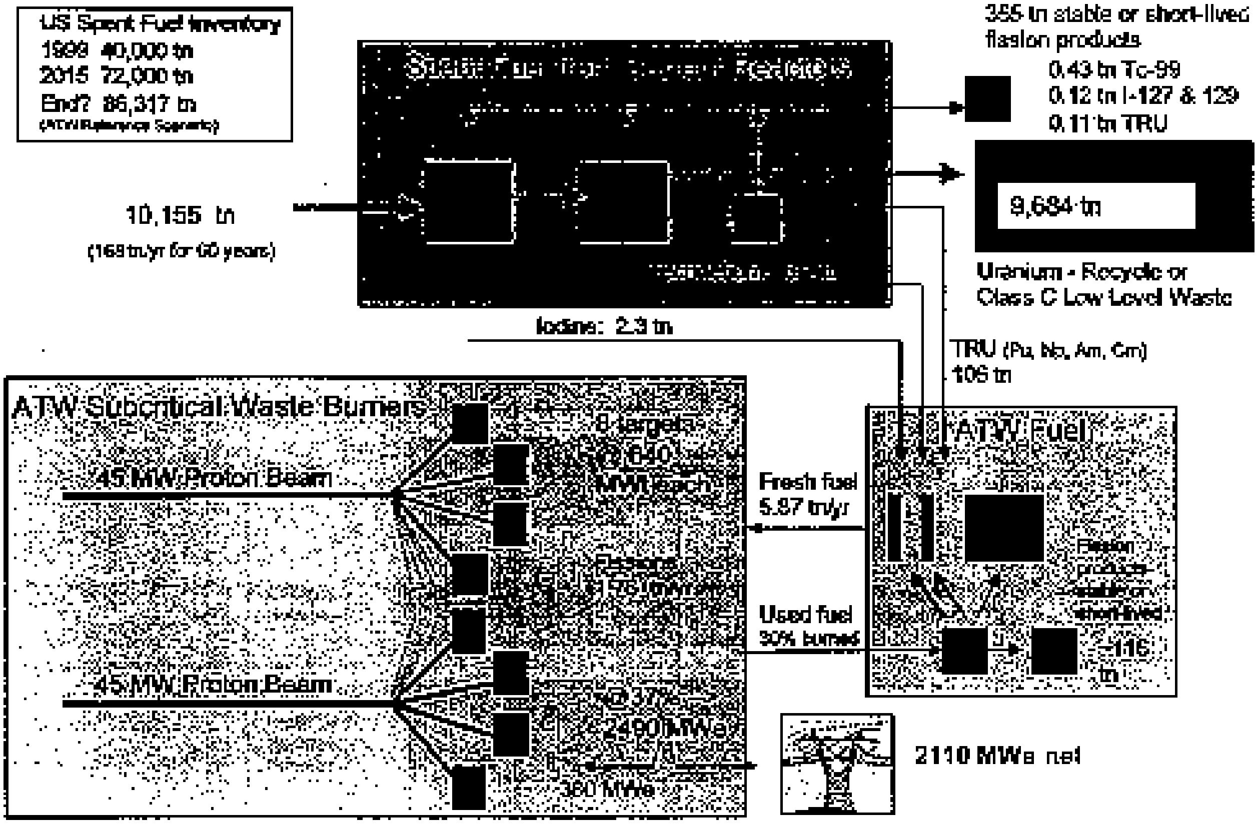
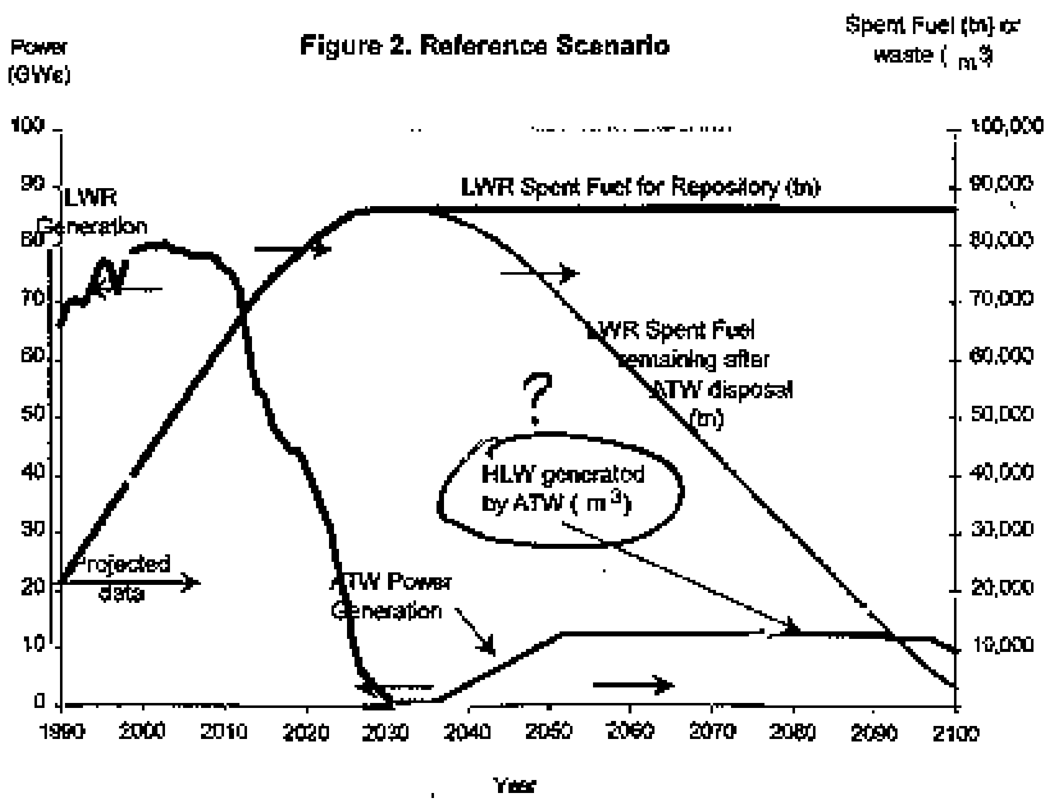


Figure 2. Reference Scenario



Questions :

- Trade studies : 1st phase : one, two, more years ?
  objectives ?
- Need for "motivation" studies ?
  critical vs subcritical cores for transmutati
- Need to clarify "subcriticality" vs "safety" issue ?
- Need to clarify the question : "A DEMO for what purposes" ?

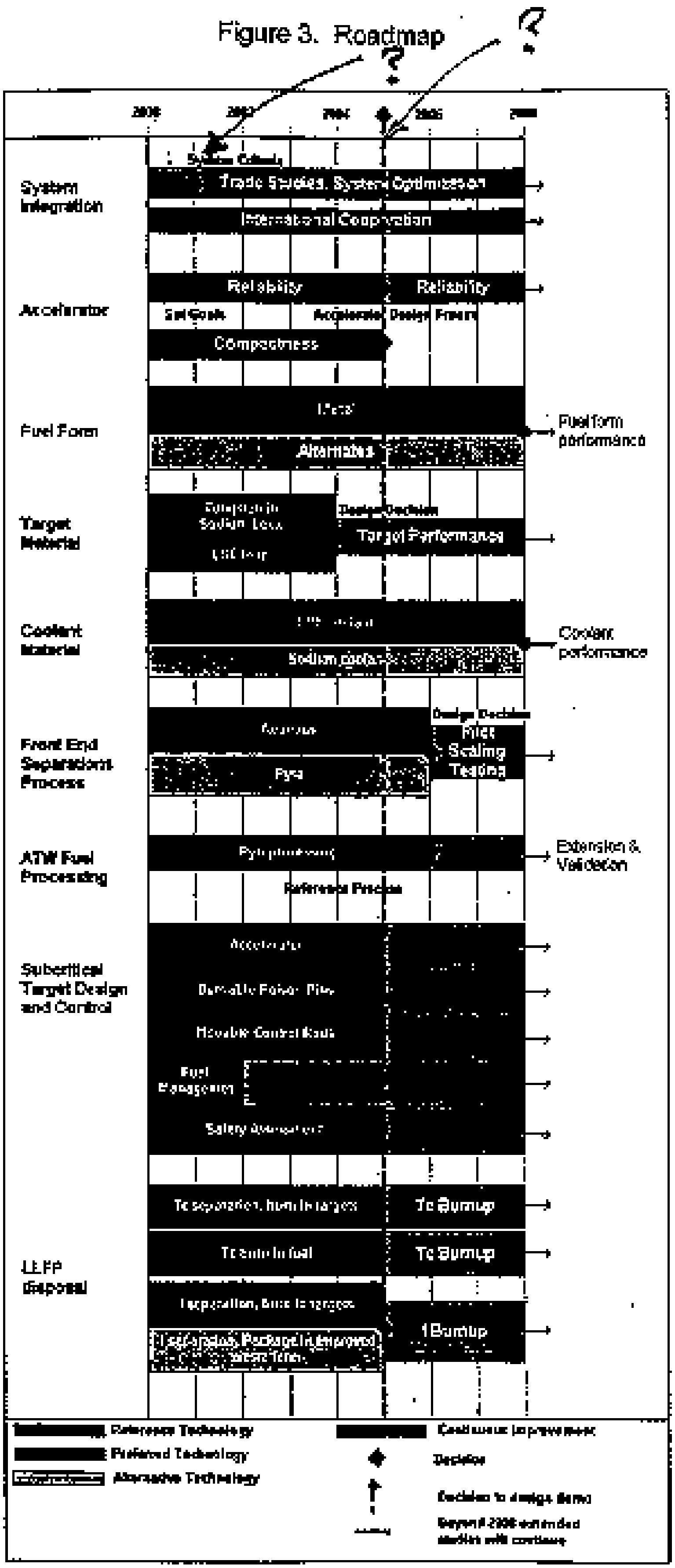
Fuel issues :

- If irradiation facility is abroad, is it realistic to envisage fuel fabrication in another coutry ? PIE ? (transport issues)
- High Zr content : compatibility with LBE ? Production of Zr-93 : is it an issue ?
- Is it possible to focus on one fuel, if choice of coolant is open ? Same fuel for LBE or Na ?
- Also : how to dimension a fuel S/A ?

Separations :

- At front end : separation of Lanthanides is it an issue ?
- Waste forms : what are the objectives ?
- Recovery factors : what impact on scenarios performance ? How realistic recovery factors of 0.01% at industrial level ?

Figure 3. Roadmap



Appendix C. ATW Reference Plant Parameters

The following table details the plant parameters used to predict the performance of the reference ATW plant.

Table C-1. Assumed and Computed Reference ATW Plant Parameters

Separations Facility

Parameter	Assumed or Input	Computed	Units
TRU loss fraction per pass	0.0010		
Fractional burnup per pass	0.3000		
Total processing loss	0.0033		
Tc & I processing loss	0.05		
Throughput- kgs of TRU/year		1765.8	kgs/yr
Throughput-kgs of Tc-99/yr		135.6	kgs/yr
Throughput-kgs of I/yr		37.9	kgs/yr
Throughput-Spent Fuel		169.2	tonnes/yr
Approximate Capital Cost	820.0*		$M
Annual Operating Costs	10.4%	85.3	$M

*1/9th of a $1500 M aqueous plant plus $100 M for pyro reprocessing

Accelerator

Parameter	Assumed or input	Computed	Units
Proton Energy	1		GeV
Proton Current	90		mA
Number of beamlines	2		
Targets Supported	8		
Beam Power		90.0	MW
Power Required-Accelerator		304.0	MWe
Accelerator net efficiency		29.6	%
Power Required-Plant		378.6	MWe
Approx. Capital Cost per beamline	860		$M
Approx. Capital Cost for Accelerators		1720	$M
Annual Operating costs	2.5%	43	$M

LLFP : Tc and I

- What target forms for I?
  The transmutation rates of 15% (50%) per year seem to be overestimated -
  If lower : how much Tc, I in the ATW fuel cycle?
  Inventories can be very high!

System

- What rationale for $K \simeq 0.97$? What safety approach? Defence in depth?
- High fuel burn-up : $\Delta\rho$ / cycle? (6% $\Delta K/K$?)
- Evolution of Pu/MA composition/isotopic vectors :
  How different equilibrium from start-up?
  Need of different control strategies?
- What shielding design strategy? Need for experimental validation? Activation of accelerator structures?
- Why 2 accel / 8 units? - Any trade studies with, e.g. 1 accel / 1 unit (lower beam power)?

Coolant

- See previous remarks

Potential Areas for collaboration

- Accelerator development
  - Somewhat already under way
  - However : state goals in common
  - Share of R and D efforts ?
  - Reliability issue and interface with system : Benchmarks

- Target Technology
  - There is LBE effort in Europe (Also, the MEGAPIE exp at PSI) (ISTC-559 still alive ?)
  - Strong interest in solid targets (W, Pb)
  - What about Hg ? (Links with SNS ?)

  First series of significant experiments → 2004/5 ; share of efforts ?
  - Benchmarks : the "Efimov" benchmarks and their analysis.

- Neutronics experiments
  - The MUSE experiments at Cadarache : large scale, can simulate relevant fuels, coolants, source environments. Wide range of experiments ⇒ 2004/2005

- Basic nuclear data (experiment and evaluation)
  - Improve coordination via NEA-NSC working groups
  - Intermediate energy data libraries
  - Spallation residues
  - Data related to neutron damage (H, He production)
- Common code validation
  - Benchmarks (NEA-NSC)
- "Motivation" studies:
  via NEA-NDC study (phase 2)
- Collaboration on alternate options:
  - gas coolant ?

⇒ Fuel development:
  - what frame
  - what objectives
    e.g. have metal/cercer/cermet/nitride studies and basic properties assessment
  - Irradiation ?
- Pyroprocessing
  - Any collaboration envisageable ?