DRAFT
12/29/99

Task 4

"A compilation and assessment of the engineering and nuclear performance of the various concepts proposed for neutron-source applications including fusion, fission and accelerator systems."

Table of Contents

1. Introduction

For many years, neutron sources have been considered for the transmutation of materials. Some of the most prominent reactions include fission reactor waste burning, weapons plutonium destruction, tritium production, and medical isotope production. In this assessment, we considered neutron source applications at the high-end neutron strength – 10^{19} – 10^{21} n/s – and with "near-term" feasibility. Emphasis was placed on fission waste burning and weapons plutonium destruction because these two applications offer the possibility of customers with both a near-term need and a sufficient market to justify an R&D program as ambitious as fusion energy research.

Three system types have been considered for this assessment: pure fission, fusion-driven and accelerator-driven. In any of these systems, the presence of fissile materials results in a large neutron multiplication factor, such that the majority of the neutron flux comes from fission reactions. In addition, thermal power is an unavoidable byproduct, such that electric power can be generated to help offset the costs.

Until recently, fusion was not considered to fit the criterion of "near-term". However, steady progress in international fusion programs over the past decades has led to the belief that both magnetic and inertial fusion confinement concepts could provide a source of neutrons sufficient to offer an alternative to fission reactors and accelerators. The objective of this subtask is not to judge the feasibility, cost or development risks for fusion, but rather to determine whether or not a fusion device might offer **performance** advantages as a neutron source.

Surprisingly, little effort has been invested previously to establish common performance goals and to perform comparative assessments of critical and subcritical transmutation systems. A recent report on OECD studies of accelerator-driven systems (ADS) and fast reactors (FR) noted: *"The increasing interest in ADS has resulted in some studies focusing an overview of existing projects, but none has considered in detail the added value and role of such ADS in advanced nuclear fuel cycles and the comparison with better known systems as FR"* (fast reactors). [1] Such comparative studies are only now beginning. [2]

There are four predominant characteristics for any neutron source used for actinide transmutation: (1) the fuel cycle choices (including chemical processing and separation), (2) the blanket design and materials, (3) the degree of criticality – k_{eff}, and (4) the neutron flux and spectrum. For either LWR waste or Pu transmutation, most neutronic performance attributes relate to the blanket design and fuel cycle choices rather than the external source of neutrons. In general, any one of the neutron sources can be adapted to utilize any of the blanket options, although some combinations may provide a better fit. Here we have attempted to focus on the unique distinctions between neutron sources rather than differences that arise from the choice of materials.

The most noteworthy distinction between the neutronic performance of the various systems is the presence of an external neutron source for fusion and accelerators, as compared with pure fission reactors that require self-criticality. The ability to supply neutrons externally and to operate in a subcritical mode leads to several significant engineering advantages, including [3]:

- Power control is not linked to reactivity feedback, delayed neutrons, or control rods.

- The systems are more independent of fuel composition.
- The inventory is not tied to criticality.
- Neutronics and thermal-hydraulics are decoupled.

To a large extent, the dominant underlying trade-off is between the added expense of an external neutron source *vs*. the increased safety and operational flexibility. It is generally well-known that "the economic efficiency of an (externally) driven system roughly depends on $(1–k)^{-1}$, which is a clear indication that an asymptotic optimum would be achieved for k=1" [4].

Systems driven by an external neutron source have the ability (in principle) to achieve complete burnup in a single core loading without recycle. The desirability and importance of single-pass deep burnup is debatable; in this assessment, depth of burnup was considered as one of the few parameters that differentiates the various systems.

A second important factor is the neutron spectrum. Fusion neutron sources and accelerators can provide harder spectra than fission reactors. Nearly all actinides will fission in a sufficiently fast spectrum. This gives maximum flexibility in the blend of fuel and potentially allows for deeper and more rapid burnup (less production of higher actinides). Fission products such as iodine and technetium can be transmuted as well. The most promising fission options also strive for faster flux designs such that the distinction in spectrum is reduced to some extent, but still a significant factor. If the spectrum becomes "too hard", then material damage and fluence limits could become important issues.

Besides criticality and spectrum, one additional distinction between transmutation systems is the unique requirement on DT fusion to breed tritium in-situ for fuel self-sufficiency. This removes at least one neutron from the blanket for every neutron produced in the plasma. The neutron multiplication in the blanket is typically high enough such that breeding becomes an issue only after the transuranics are significantly depleted (by ~70% or more) [5]. However, in comparing accelerator and fusion sources of external neutrons, the cost per excess neutron is strongly impacted by the breeding requirement.

Engineering performance metrics also might be used to distinguish different neutron sources. Engineering metrics, interpreted in the broadest sense, could span a very wide range of system features including safety attributes, maintainability, reliability, operability, design margins, technology extrapolation, and others. A comparison based on all of these attributes would be intractable. We focused on a select set of attributes related to power and power density, thermal

conversion efficiency, neutron damage limits, and peaking factors. In general, engineering parameters depend on design choices and not the source of neutrons. Additional discussion of safety attributes is found in Subtask 5, whereas cost comparisons are found in Subtask 3.

Finally, one of the most challenging aspects of a comparison between technologies is the lack of a common set of goals. This has several direct effects: (1) while it is possible to evaluate the absolute performance of any individual system, it is not possible to determine how well it performs relative to an established set of objectives; (2) different technologies naturally highlight their better attributes, which are often different from concept to concept, making cross comparisons difficult; and (3) conclusions based on one set of assumed goals are not necessarily generic – any concept could be re-optimized to a different set of goals. These difficulties highlight the need for an activity to establish clear customer-based goals and apply them evenly to all candidate transmutation systems.

2. Design options

Two of the key design decisions for an actinide burner are the choice of fuel cycle and the choice of blanket design and materials. A brief review is provided here to highlight the primary options.

2.1 Fuel cycle options

Table 1 summarizes several possible operating scenarios for a transmutation reactor. Destruction of weapons Pu and/or fission waste actually represents a continuum of fuel cycle options. A variety of initial feedstocks can be used, and various make-up fuels can be added either in batch or continuous modes. Multiple fuel recycling is often utilized, such that chemical separation processes become important. Changes in core performance can occur over time unless fresh fuel is either added or bred in-situ from fertile isotopes, or a burnable poison is included to offset the change in reactivity.

Table 1. Fuel cycle options

Feedstock

- Weapons material (^{239}Pu) as sole source
- Fission waste as sole source
- Weapons material as makeup feed
- Minor actinides only (no Pu or U in feedstock)

Disposition scenario

- Power producing mode (high conversion ratio)
- Moderate destruction mode (conversion ratio of 0.5-1)
- Maximum destruction mode (non-uranium fuel, high burnup reactivity loss)
- Pu denaturing (*i.e.*, producing radioactive byproducts that contaminate the Pu)

Processing mode

- batch *vs*. continuous processing
- once-through *vs*. multiple recycle

2.2 Blanket design and material options

Many engineering concepts have been explored previously, as summarized in Table 2. Virtually any reactor design concept that has been considered for energy applications also has been considered as an actinide burner. Coolants include He, water, molten salt and molten metal. Metallic, ceramic and molten salt fuels have been considered in a variety of forms. Only selected concepts are assessed here, depending on the availability of data and the current level of interest of the approach.

Table 2. Some Engineering Concepts Considered in Previous Studies

Type	Coolant/ moderator	Fuel	Breeder/ target	Reference
Fission				
IFR	Na	metallic		[6]
HTGR	He	coated oxide		[7]
Heavy metal	PbBi	metallic		[8]
Fusion				
Molten salt	self-cooled	PuF	Flibe	[9]
HTGR	He	oxide	Li oxide	[5]
Accelerator				
Na-cooled	Na	metallic	W	[10]
PbBi-cooled	PbBi	metallic	PbBi	[10]
Aqueous	D_2O	oxide suspension	W/Pb	[11]
Non-aqueous	He/graphite	molten salt	Pb	[11]
HTGR	He/graphite	coated oxide		[12]

3. Performance metrics

3.1 Neutronic performance metrics

Neutronic performance metrics quantify the extent to which the device objectives are met; *i.e.*, the transmutation and final disposition of actinides. While spectrum is an obvious metric, the effects of spectrum are too complex and design-related to allow for a straightforward comparison of the neutron flux alone. Table 3 lists some of the key neutronic performance parameters that derive from the materials and spectrum, and are often used to distinguish different systems. These generally relate to the rate and depth of burnup, including the relative mix of materials that are produced or destroyed.

Table 3. Key Neutronic Performance Parameters

- Conversion ratio (ratio of production to destruction of actinides)
- Peak and average ^{239}Pu discharge burnup (MWd/g)
- Consumption rate (kg/yr)
- Loading rate (kg/yr)
- Discharge fraction of ^{239}Pu
- Fraction of original Pu destroyed
- Fission-to-capture ratio
- External neutron source strength (MW)
- Inventory of ^{239}Pu and total actinides (within core and plant total)
- Total and fast neutron flux (n/cm^{2}s)

Maintaining a high transmutation rate with low inventory of actinides is an important overall goal. This implies high fluxes, high neutron multiplication (high actinide fission rate, low actinide capture-to-fission ratio, low parasitic capture) and low inventories both in the core and externally.

The *rate* of depletion is measured by several parameters, including the conversion ratio, discharge burnup, transmutation rate and loading rate. The consumption rate measures the amount of actinides actually consumed, whereas the loading rate measures the throughput. The throughput is higher than the consumption rate due to residual unburned actinides in the discharge stream and due to the presence of fertile isotopes.

Any reactor burns Pu at the same rate – 1 MWd per gram of Pu fissioned. However, depending on the feedstock, a reactor can be tailored to provide conversion ratios from zero to more than unity, where the conversion ratio is defined by the ratio of Pu produced to Pu destroyed. If the conversion ratio is greater than 0, then higher actinides are produced and the *net* burnup is less than 1 MWd/g. Normally the burnup is quoted relative to the loading and **not** the amount fissioned, such that care must be taken in interpreting these values. The "fission-to-capture ratio" and parasitic capture ratio are also sometimes used as measures of transmutation efficiency.

The *extent* of depletion is characterized by both the magnitude and mix of isotopes that are finally discharged (after one or many radiation cycles). Usually the dominant transuranics (other than uranium) are ^{239}Pu and ^{240}Pu, so that the most important metrics include the fraction of ^{239}Pu discharged as compared with the total Pu and the fraction of original inventory that is destroyed. However, in other cases, conversion of minor actinides is considered as an important metric.

The makeup of the discharge from a transmuter is important in part because of the impacts on further separation and reprocessing. This is a complex question related to the separation chemistry processes and programmatic goals for final waste disposition.

The National Academy of Science has established a metric termed the "spent fuel standard (SFS)" which is used to evaluate different disposition technologies for weapons Pu. [13] It states that destruction of weapons plutonium to the level of plutonium in spent fuel is adequate from a non-proliferation standpoint. The ultimate disposition of this material can then follow the route selected for spent fuel from current fission reactors. This standard is relatively easy to meet in any transmutation systems, and thus tends to reduce the importance of this metric.

3.2 Engineering performance metrics

Engineering performance metrics help to define aspects of overall system performance aside from the primary objective of actinide burning. Engineering metrics, interpreted in the broadest sense, could span a very wide range of system features including safety attributes, maintainability, reliability, operability, design margins, technology extrapolation, and others. A comprehensive comparison based on all of these attributes would be intractable. We focused on the select set of attributes summarized in Table 4. These relate to power and power density, thermal conversion efficiency, neutron damage limits, and peaking factors. Additional discussion of safety attributes is found in Subtask 5, whereas cost comparisons are found in Subtask 3.

Table 4. Engineering Performance Parameters

- Power density (linear power, surface heat flux, volumetric heating)
- Total thermal power
- Thermal conversion efficiency
- Fluence limits and materials lifetime
- Time dependence and spatial nonuniformity of blanket behavior

4. Fission options

4.1 Integral fast reactor

Detailed studies of Na-cooled fast reactors have been performed at ANL [2]. The IFR uses metal fuel with a hard spectrum to provide a high fission-to-capture ratio. Some of the important features of the IFR fuel cycle include:

- Multiple recycling of the fuel is used to allow complete actinide destruction.
- Burnup of ~10% per pass is achieved.
- The minimum ^{239}Pu fraction achieved is ~50%.
- All minor actinides are recycled.

Three disposition scenarios were examined. In the "conventional" power producing mode, a Pu conversion ratio near unity is obtained using a conventional IFR core with the weapons Pu added in special assemblies. The "moderate burner" case is achieved in a conventional core by reducing ^{238}U capture, for example by increasing the leakage fraction. Conversion ratios of ~0.5 have been demonstrated, although lower ratios are possible by further tailoring of the fuel composition. In the "pure burner" case, no uranium isotopes are used. Because a pure Pu core incurs excessive burnup losses, a substitute absorber may be needed (*e.g.*, Hf). Performance parameters for all three cases are summarized in Table 3 [2].

Table 3. Na-cooled IFR Parameters (Ref. 2)

	conventional	**moderate burner**	**pure burner**
Conversion ratio	1.15*	0.54	0
Net TRU** consumption rate (kg/yr)	–33*	110	231***
Peak discharge burnup (MWd/g)	0.151	0.160	0.450
Average discharge burnup (MWd/g)	0.107	0.118	0.334
Burnup reactivity loss (%Δk)	0.03	2.9	3.2
Fuel cycle length (months)	23	12	12
Equilibrium discharge $\%^{239}Pu$	63	58	52
^{239}Pu inventory (tonnes)	1.81	2.14	4.52
Heavy metal inventory (tonnes)	22.7	13.9	7.47
Peak linear power (W/cm)	320	280	155
Thermal power	840 MW per module		
Peak allowable fast fluence	3.8×10^{23} n/cm^2 (cladding limited)		

* could be tailored for TRU consumption =0

** TRU=transuranic

*** 231 kg/yr = maximum achievable

4.2 HTGR

A prime example of a high-temperature gas-cooled Pu transmutation reactor is the PC-MHR proposed by GA [3] (see Table 4). This design uses spheres of plutonium oxide coated by multiple layers of pyrolytic carbon and SiC. Very high burnup is possible as a result of the fuel composition and the use of a burnable poison (Er_2O_3). The neutron flux is relatively soft, with the peak of the neutron flux at ~0.1 eV.

Several operating modes were considered, depending on the length of irradiation. From shortest to longest, these are “Pu spiking”, “spent fuel” level of irradiation, and maximum “Pu destruction”

mode. Mixed fuels containing uranium isotopes were not considered, such that all of these scenarios fall under the category of “Pu burner”.

Table 4. HTGR Parameters (“deep burn” option) [3]

Processing mode	once-through, no recycle
Fuel cycle length (months)	36
Thermal power	450 MW per module
TRU consumption rate (kg/yr)	250
Peak discharge burnup (MWd/g)	0.785
Average discharge burnup (MWd/g)	0.590
^{239}Pu burnup	90-95%
Total Pu burnup	65-72%
Discharge ^{239}Pu fraction	<30%
Peak fast fluence (goal)	4.2×10^{25} n/cm^2

4.3 Pb and BiPb-cooled reactors

Heavy metal coolants, such as lead-bismuth eutectic (LBE) allow reactors to obtain relatively hard spectra. To effectively transmute plutonium and minor actinides from LWR spent fuel, it is desirable to minimize the loss of neutrons in order to attain a large surplus available for transmutation. Metallic fuels based on a zirconium matrix provide large excess reactivity due to the low parasitic absorption cross-section of zirconium and due to the hard spectrum achievable, because the fuel does not contain any moderating isotope. The larger weight fraction of zirconium relative to the heavy metals makes this fuel significantly different from the metallic fuel developed for the IFR [4]. To further maximize the actinide transmutation, the fertile isotopes ^{238}U or ^{232}Th are removed.

Table 5. PbBi Reactor Parameters [4]

Processing mode	batch mode with recycling
Fuel cycle length (months)	20
Thermal power (MWth)	1800
TRU consumption rate (kg/FPY)	767
Peak discharge burnup (MWd/g)	
Average discharge burnup (MWd/g)	0.190
Conversion ratio	0.23
Initial k_{eff}	1.2
Heavy metal inventory (kg)	5742
Volume averaged power density (MW/m^3)	126
Average linear power density (kW/m)	37
Peak linear power density (kW/m)	70
Thermal conversion efficiency	30%

5. Fusion options

Two blanket types recently were analyzed for subcritical actinide burners using a fusion plasma for the external source of neutrons. These are a molten salt LWR waste transmutation blanket with a He-cooled Li ceramic tritium breeding blanket [5] and a HTGR Pu transmutation blanket, also combined with a He-cooled Li ceramic tritium breeding blanket [6].

5.1 Molten salt blanket

Analysis was performed on a molten salt blanket to determine its performance both as a minor actinide (MA) burner (*i.e.*, absent any Pu isotopes) as well as a Pu-assisted waste burner. The use of a molten fuel allows continuous feeding of fresh material as well as continuous extraction of fission products. Table 6 summarizes some of the key parameters. At equilibrium, the discharge burnup is relatively high.

Table 6. Fusion-Driven Molten Salt Blanket Parameters [5]

	MA burner	**Pu-assisted**
Processing mode	continuous	
Thermal power	3000 MW	
Pu destruction rate (kg/yr)	0	760
Actinide destruction rate (kg/yr)	1170	1170
Equilibrium burnup (MWd/g)	0.94	0.94
Equilibrium Pu fraction (%)	47.8	65.9
Equilibrium ^{239}Pu fraction (%)	20	26
Actinide inventory* (tonnes)	2	5
Equilibrium k_{eff}	0.77	0.918
Peak power density (W/cc)	80	80

* molten salt inventory is ~100 tonnes

5.2 HTGR blanket

An HTGR blanket similar to the one described in Section 4.2 was used in combination with a DT fusion neutron source [6]. Deep burnup is possible within a single cycle. With no refueling and no burnable poison, relatively large changes in the core behavior occur over time. For example, the energy multiplication drops by about an order of magnitude and the required fusion power increases by an order of magnitude over a 10 year period.

Results are shown in Table 7 at several stages of burnup. The tritium breeding ratio is initially very high (>4) and drops below unity at a burnup of ~70%. Assuming that a large stockpile of tritium will not be acceptable, data are presented only up to this level of depletion.

Table 7. Fusion-Driven HTGR Blanket Parameters [6]

Heavy metal burnup %	30	50	70
Heavy metal burnup (MWd/g)	0.30	0.50	0.70
Pu fraction (%)	67	50	26
^{239}Pu fraction (%)	68	50	33
Processing mode	once-through, no recycle		
Thermal power	3000 MW		

6. Accelerator options

Numerous designs have been developed for accelerator-driven subcritical assemblies for transmutation of waste and weapons Pu. For simplicity, we have chosen three concepts to review: an HTGR blanket [9], a Na-cooled concept with metal fuel [7], and an aqueous blanket [8]. For most systems, either W or PbBi are used as the accelerator target.

6.1 HTGR core

The HTGR core described in Section 4.2 was examined in a subcritical accelerator-driven mode for W-Pu destruction [9]. The main difference between the critical and subcritical core is the addition of an accelerator beam tube through the central column of graphite blocks. The discharge from the HTGR fission core is used following a 3-year irradiation. In this condition, the fuel starts already with 90% of the ^{239}Pu and 65% of the total Pu destroyed. One year of irradiation with a 72 MW accelerator results in over 99% of the initial ^{239}Pu inventory and 83% of the total Pu inventory destroyed (see Table 8).

The ATW program also examined an HTGR core [7]. In that case, they considered a multiple irradiation scenario in which irradiation for 1 yr in fast spectrum assemblies was performed after prior irradiation in a thermal spectrum. Table 9 summarizes the depth of burnup that was achieved. Without pre-irradiation in a thermal spectrum, actinide burnup of ~33%/yr is achieved in fast spectrum assemblies.

Table 8. GA Accelerator-Driven HTGR System Parameters [9]

Processing mode	once-through, no recycle	
Cycle length (months)	12	
Thermal power	300 MW	
	Initial feed	**Final discharge**
Pu burnup %	65	83
^{239}Pu burnup %	90	> 99
^{239}Pu fraction (%)	< 30	< 4

Table 9. ATW HTGR Burnup Parameters (all units in kg) [7]

Thermal power		1000 MW	
	Initial charge	**Thermal irradiation discharge**	**Fast flux irradiation discharge**
^{239}Pu	940	3.6	1.4
^{240}Pu	60	41.5	28.3

6.2 Liquid metal core

One of the currently favored approaches for ATW is a system with metallic fuel and sodium coolant – similar to the IFR core, except that the fuel is composed of 80-90 atom-% Zr mixed with the actinides to allow for high burnup. This concept was developed in the late 1980's and early 1990's under the name PRISM, and was formally reviewed by the NRC. An alternate lead-bismuth eutectic (LBE) system also has been studied due to its harder neutron spectrum.

A relatively short cycle time is employed to reduce the reactivity loss and minimize cost and safety penalties. Fresh fuel is loaded on the outside and rotated inward during successive cycles. The discharge burnup is about 35% for the Na-cooled system, rising to 45% in the LBE system. Table 10 summarizes parameters for the LBE option.

6.3 Aqueous blanket

An aqueous transmuter concept was explored as an option for ATW [8]. The technology was based on CANDU reactors having heavy water coolant./moderator, although in this case both actinides and fission products are transported through the core in either aqueous solution or slurries. In addition to actinides, fission products also are substantially transmuted.

Table 11 summarizes performance parameters for a single target/blanket module, where 4 modules are assumed to be attached to a single accelerator which treats waste from 8 fission reactors. One of the most notable characteristics of this concept is the low thermal conversion efficiency for either the baseline (20%) or advanced option (30%). The large recirculating power to run the accelerator implies little net electric to be sold on the grid.

Table 10. Accelerator-Driven Liquid Metal Blanket Parameters [7]

Irradiation length (days)	100
Cycle length (days)	122
Fuel residence time (# of cycles)	6
Thermal power	840 MW (each module)
Average power density	350 MW/m^3
Beam power	70 MW (for 8 modules)
TRU consumption rate (kg/yr)	516
TRU loading rate (kg/yr)	1158
Discharge burnup % (LWR feed)	45
Average power density (W/cc)	350
Transuranic inventory (kg)	1483 (equilibrium feed, beginning of cycle)
k_{eff} (assumed)	0.97

Table 11. Accelerator-Driven Aqueous Blanket Parameters (Ref. 8)

Processing mode	continuous
Thermal power (MW)	1542
Beam power	100 MW
Actinide burnup (kg/yr)	625 (4 units)
Tc burnup (kg/yr)	63 (12 internally generated)
I burnup (kg/yr)	20 (4 internally generated)
k_{eff}	1.00
Actinide inventory (kg)	390
Thermal flux (<2.6 eV) in slurry region	21.2 %
Average neutron flux (n/cm^2s)	$2.5x10^{15}$

7. Observations

1. There are many different transmutation fuel cycles and many different blankets proposed, each having its own unique characteristics.

2. There is no established set of criteria for transmutation reactors. Therefore, point-design comparisons are tied to authors' assumptions. Most concepts could be re-optimized under a different set of assumptions.

3. Most performance parameters are mostly or entirely dependent on blanket choices, and **not** the source of neutrons.

4. The most fundamental distinction between these systems is whether or not an external source of neutrons is provided – *i.e.*, critical *vs*. subcritical blanket operation. With an external neutron source and no requirement for criticality, deeper burnup is possible. Safety is the primary advantage of subcritical operation. Prompt criticality and positive reactivity coefficients are easier to avoid. Economic penalties on safety systems and core size restrictions for critical assemblies may enable subcritical assemblies to compete with fission.

5. Both fusion and accelerators provide external sources. If depth of burnup is the chief reason for using an external source, then accelerators are superior to DT fusion because the need to breed tritium restricts the depth of burnup for fusion systems. Catalyzed DD fusion has some unique advantages in this regard.

6. Subcritical assemblies offer some safety and operating advantages over critical assemblies, but spectrum-related performance differences are modest and probably do not justify the expense.

A very hard spectrum will result in severe radiation damage problems for materials, thus reducing the fluence limit and complicating the engineering.

7. Operating a subcritical assembly starting from an initial loading to complete burnup implies a very wide range of operating conditions. A combination approach, in which only the latter stages of burnup are achieved using an external neutron source, offers a sensible alternative.

Acknowledgments:

The authors wish to thank Jacopo Buongiorno (MIT), Steve Herring (INEEL), and Ken Schultz (General Atomics) for valuable discussions and pointers to the extensive literature on transmutation of actinides.

References:

1. L. Van Den Durpel, *et al*., "OECD/NEA Comparative Study on ADS and FR in Advanced Fuel Cycles," Proc. 3rd Int. Conf. on Accelerator Driven Transmutation of Waste, Prague, June 1999.

2. OECD/NEA, "First Phase P&T Systems Study Status and Assesement Report of Actinide and Fission Product Partitioning and Transmutation," (May 1999) http://www.oecdnea.org/html/trw/docs/neastatus99/

3. F. Venneri, N. Li, M. Williamson, M. Houts, G. Lawrence, "Disposition of Nuclear Waste Using Subcritical Accelerator-Driven Systems: Technology Choices and Implementation Scenario," 6th Int. Conf. on Nuclear Eng., ICONE-6, May 10-15, 1998.

4. J. M. Martinez-Val, J. M. Perlado, E. Minguez and M. Piera, "Critical vs. Sub-critical Reactors for Nuclear Waste Transmutation," Proc. 3rd Int. Conf. on Accelerator Driven Transmutation of Waste, Prague, June 1999.

5. E. T. Cheng, R. J. Cerbone and C. P. C. Wong, "Disposition of Plutonium in a Fusion Driven Subcritical Assembly", 18th Symposium on Fusion Engineering, 1999.

6. R. N. Hill, D. C. Wade, J. R. Liaw, and E. Fujita, "Physics Studies of Weapons Plutonium Disposition in the Integral Fast Reactor Closed Fuel Cycle," Nuclear Science and Engineering **121**, 17–31 (1995).

7. MHTGR Plutonium Consumption Study, Phase II Final Report, GA/DOE-051-94, April 29, 1994.

8. "Actinide Transmutation by Lead-Bismuth Cooled Reactors, MIT Annual Project Status Report," June 1999.

9. E. T. Cheng and R. J. Cerbone, "Prospect of Nuclear Waste Transmutation and Power Production in Fusion Reactors", ANS Fusion Topical Meeting, 1996.

10. "Roadmap for the Development of Accelerator Transmutation of Waste," Draft report of the ATW Roadmap Target and Blanket Technical Working Group, June 1999.

11. "The Los Alamos Accelerator Transmutation of Nuclear Waste (ATW) Concept," Los Alamos Report #LA-UR-92-2020, April 1992.

12. General Atomics White Paper, "Fuel Development Status of the Plutonium Consumption Modular Helium Reactor (PC-MHR)," February 28, 1995.

13. Management and Disposition of Excess Weapons Plutonium: Reactor-Related Options," National Research Council Panel on Reactor-Related Options for the Disposition of Excess Weapons Plutonium, National Academy Press (1995), http://books.nap.edu/books/0309051452/html/index.html

    see also: "Management and Disposition of Excess Weapons Plutonium," National Academy Press (1994), http://www.nap.edu/books/0309050421/html/index.html

    "Nuclear Wastes: Technologies for Separations and Transmutation," National Research Council Committee on Separations Technology and Transmutation Systems (1996)

Additional Bibliography

K. A. Williams, J. W. Miller and R. L. Reid, "A Comparative Assessment of the Economics of Plutonium Disposition" Proceedings of the International Topical Meeting on Advanced Reactors Safety - Volume 1, Orlando Florida, June 1-5, 1997, pages 411 to 420.

R. N. Hill, "LMR Design Concepts for Transuranic Management in Low Sodium Void Worth Cores," *Proc. Int. Conf. Fast Reactors and Related Fuel Cycles*, Kyoto Japan, Oct. 28-Nov. 1, 1991, p. 19.1-1, Atomic Energy Society of Japan.

C. L. Cockney, T. Wu, A. J. Lipps, and R. N. Hill, "Higher Actinide Transmutation in the ALMR," *Proc. Int. Conf. and Technology Exposition Future Nuclear Systems: Emerging Fuel Cycles and Waste Disposal Options Global '93*, Seattle Washington, Sept. 12-17, 1993, p. 123, American Nuclear Society (1993).

R. N. Hill, D. C. Wade, E. K. Fujita and H. Khalil, "Physics Studies of Higher Actinide Consumption in an LMR," *Proc. Int. Conf. Physics of Reactors*, Marseille France, April 23-27, 1990, p. I-83, American Nuclear Society Frenc Section.

C. J. Hamilton et al., "The Modular Helium Reactor as a Plutonium Burner," *Proc. Int. Conf. and Technology Exposition Future Nuclear Systems: Emerging Fuel Cycles and Waste Disposal Options Global '93*, Seattle Washington, Sept. 12-17, 1993, p. 123, American Nuclear Society (1993).