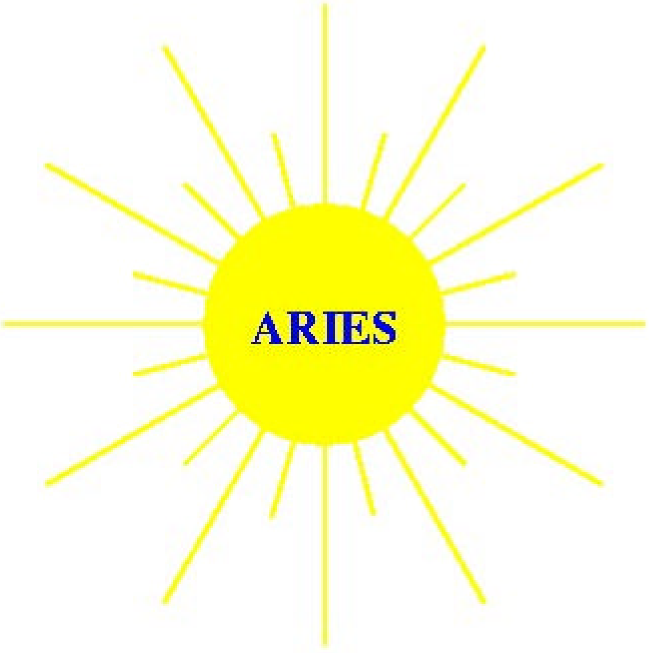
UCSD-ENG-0083

THE ARIES FUSION NEUTRON-SOURCE STUDY

D. Steiner, E. Cheng, R. Miller, D. Petti, M. Tillack,
L. Waganer and the ARIES Team



August 2000

1. Introduction

Last year the ARIES team initiated the study of fusion-neutron source applications. The purpose of this study is to assess the potential and competitiveness of a fusion neutron source as an intermediate-term application of fusion energy research, on the path to fusion power systems.

The study began with a concept definition phase that consisted of the following four tasks:

(1) An assessment to identify the most useful application and product.

(2) A compilation and assessment of the engineering and nuclear performance characteristics of the various options proposed for neutron-source applications including fusion, fission and accelerator systems.

(3) System studies to assess the economic characteristics of MFE-based fusion neutron-source applications. These studies would include assessments of both D-T and catalyzed D-D-T fuel cycles.

(4) An assessment of the environmental, safety and licensing implications of fusion neutron-source applications.

The intent of the concept definition phase is to determine if any of the fusion neutron-source applications offer sufficient promise to warrant detailed design and development path consideration.

The purpose of this document is to report on the results of the concept definition phase. Results in each of the four tasks described above are summarized in Sections 2.0 through 5.0, respectively. Section 6.0 summarizes the major observations of the study and recommends activities for future investigation.

2. Assessment of neutron source applications

2.1. Introduction

Intense, high-energy neutrons may be used in a multitude of applications to create or modify a wide range of useful, and perhaps unique, commercial and consumer products. The assessment of these potential applications is challenging because of the disparate attributes for the potential applications and customers. An assessment is necessary to help guide the development of the neutron sources and the processes to create the product or products.

2.2. Potential Fusion Neutron Source Applications

There are several different approaches to generating high-energy neutrons including fission reactors, accelerators and fusion systems. This assessment will focus on the high-energy neutrons generated with a fusion plasma, ~14.1 MeV produced in the D-T reaction.

The most common potential utilization of fusion neutrons is the thermalization of the neutrons to create high-grade heat in the coolant/heat transfer media for a power core. In turn, the heat transfer media would directly or indirectly turn a turbine to generate electricity. In principle, this approach would be ideally suited to a large tokamak fusion power plant, providing baseload electrical power generation for a large utility or independent power producer.

In addition to electrical power generation, there are many other applications that may effectively use fusion neutrons to create products or modify existing products. Table 2-1 presents a list of possible neutron source applications for consideration and evaluation in this study.

Table 2-1 List of Neutron Applications

Transmutation
Breed fissile fuels (energy-suppressed mode) for use in complementary fission plants
Produce energy in a subcritical fissionable blanket
Transmute fission nuclear wastes to stable elements or short-lived isotopes
- Plutonium
- Minor actinides (Elements 89-103)
Create tritium
Create radioisotopes
Direct usage
Conduct neutron activation testing
Alter material properties
Use for detection and remote sensing
Conduct radiotherapy
Conduct neutron radiography or tomography
Thermal Conversion
Generate electricity
Generate process heat
Dissociate water into hydrogen and oxygen
Electrolysis or high temperature electrolysis of water to create hydrogen and oxygen
Desalination

2.3. Assessment Methodology

The goal of this task is to assess the ability of a fusion neutron source to provide a useful product to the customer at a reasonable cost. The customer might be a consumer, company, university, laboratory, or government agency. To address the technical capability and competitiveness of a particular neutron source application, several questions must be addressed in a documented process:

1. What is the market potential for the application?
2. What is the cost of the product and is the cost competitive with other existing and proposed applications?
3. Is the time to market consistent with the market demand?
4. Are there critical, difficult, or costly developments required?
5. Are there any significant environmental, safety, and licensing issues?

To address these general questions, a decision analysis methodology was formulated to assess and prioritize the market potential of the fusion products identified earlier. The major elements of this decision analysis methodology are show in Figure 2-1. The initial step is to identify the critical attributes for a successful product that meets the perceived expectations of the customer and/or decision-maker (performance, schedule, cost, or safety). These attributes were selected to characterize the candidate application and help guide the decision-maker as to the benefits and risks in deciding to undertake (support) the project.

Some of the attributes could be measured directly, such as product economics and schedule, while others are indirect or subjective values, such as good will, strategic advantage, and environmental impact. Table 2-2 lists the general categories as determined from the examination of past large, high technology projects and the attributes adopted for this assessment. Weighting values were assigned to each of the attributes according to the perceived importance to the decision-makers. Some of the long-term market trends suggested in the December 1997 Kyoto Climate Change Conference were incorporated into the weighting scheme. These weighting values are adjustable to allow sensitivity studies and examination of changing priorities.

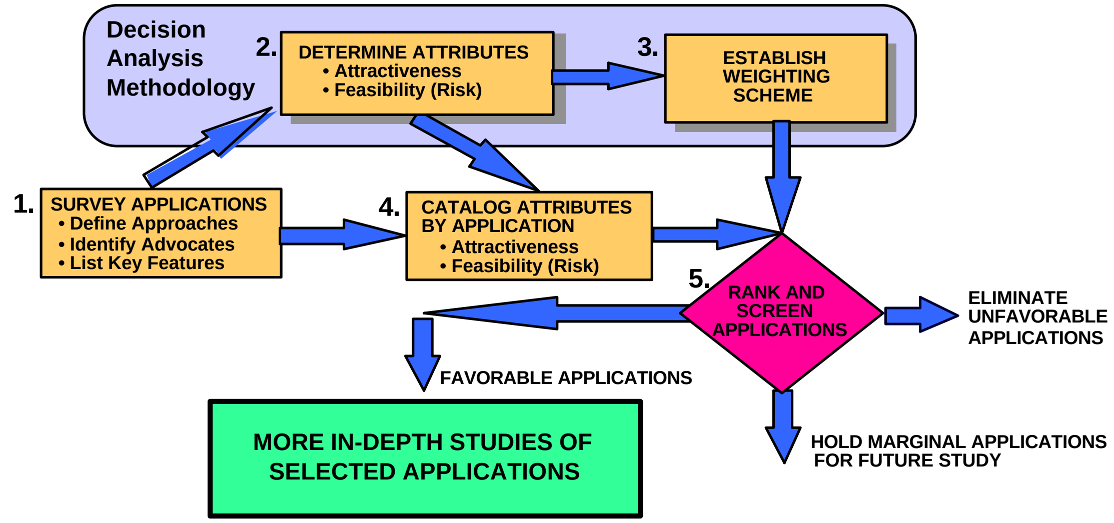


Figure 2-1. Assessment of Neutron Source Applications

Table 2-2. Decision Criteria Attributes

Market Factors	**Relative Value**
Necessity	High (3)
Uniqueness	High (3)
Market Potential	High (3)
Environmental Factors	**Relative Value**
Depletion of Valued Resources	High (3)
Environmental Impact	High (3)
Economic Factors	**Relative Value**
Competitive Product	Moderate (2)
Improvement in GNP	Low (1)
Risk Factors	**Relative Value**
Investment for Return of Capital	Moderate (2)
Maturity of Technology	Moderate (2)
Time to Market	Moderate (2)
Public Perception Factors	**Relative Value**
National/Company Prestige	High (3)
Public/Governmental Support	High (3)

The attributes are grouped into similar factors. Market factors help determine how well the product can penetrate the proposed market (necessity for the product and the market potential) and the uniqueness of the product. Environmental factors examine how well the product will help preserve or restore the natural resources and the level of environmental impact (positive or negative). Economically, can the new product compete on a competitive basis and will it significantly improve the US Gross National Product? Risk is assessed with regard to return on capital, maturity of the technology, and time to market. The public perception is measured in terms of perceived prestige arising from the product and public or governmental support.

After the attributes and weights are established, an additive utility theory methodology is used to qualitatively evaluate the proposed applications in terms of their market potential, environmental considerations, economic impact, risk, and public perception. Both multiplicative and additive utility functions were considered for the decision methodology. The multiplicative utility function was considered to be inappropriate in this assessment because a score of zero in any single attribute would disqualify the product from further consideration. This might be appropriate when all the concepts under consideration are well developed. In that case, a concept should be disqualified if it has a fatal flaw or cannot achieve a mandatory threshold value. But at this stage in the definition of the fusion products, a score of zero should not eliminate a product from consideration, as it might be capable of improving that particular attribute in the future. The adopted additive utility function will penalize the product with a zero score for that evaluation factor, but not eliminate it from further consideration. The formulation of the decision analysis methodology is:

$$\text{Score} = \Sigma\ (\text{Attribute Weight}) \times (\text{Attribute Value})$$

$$\text{Attribute Weights} = 1 \text{ to } 3$$

$$\text{Attribute Values} = -5 \text{ (least attractive) to } +5 \text{ (most attractive)}$$

The weighting scale is simple: 1 for less important factors and up to 3 for factors deemed to very important. The attribute values for each product were established on a scale of -5 (for a very negative attribute) to +5 (for a very attractive attribute). The use of positive and negative attribute values is arbitrary in this assessment, but this positive and negative value approach helps an evaluator more easily judge positive and negative attributes. Each of the attributes was assigned a qualitative description of the least attractive, neutrally attractive, and most attractive attributes to help reduce the bias of the evaluator. This methodology was tested with prior projects and produced results that correlated well with historical data.

2.4. Application of Decision Analysis Methodology

Most of the candidate fusion products in Table 2-1 were selected for assessment. The intent was to evaluate a complete range of viable fusion products. The processes to alter material properties and the dissociation of water were not selected because they are not presently well developed and the market potential is judged to be insufficient to justify inclusion in the study.

The choice of a fusion confinement concept is immaterial in assessing many of the attributes of the product, especially the market factors, the public perception factors, and many of the environmental factors. But when the risk factors of investment, technology maturity, and time to market are considered, a confinement concept must be mated with the product to complete the assessment.

Table 2-3 illustrates the selected fusion neutron products (identified in the first row) and the assumptions and descriptions used to describe and evaluate those products. The second row lists the key assumptions for each product, such as confinement concept and processes assumed. The left-hand column lists the attributes that are addressed for each product. The associated attribute weighting factors are shown in the second column. The individual attribute values for each product are shown in the corresponding spreadsheet cells.

The author first completed this evaluation process. Next, it was reviewed by a small assessment group from the ARIES team and then by the entire ARIES project team and some fusion experts from the University of Wisconsin Fusion Technology Institute. Meanwhile, several product advocates critiqued the methodology and assessment. Comments from all these sources were integrated into the preliminary assessment data shown in Table 2-3. The weighted sum scores for each product are shown on the bottom row of the table. A rank-ordered graph of these scores is shown in Figure 2-2 and discussed in the next section.

Table 2-3 Preliminary Fusion Neutron Product Evaluation Data

	Fusion Applications		Hydrogen Fuels	Transmutation of Nuclear Waste	Electricity, Central Station	Process Heat	Detection, Remote Sensing	Radioisotopes	Desalination, Fresh Water	Radiotherapy	Activation Analyses	Radiography	Tritium Production	Fusion-Fission Breeder
Attribute	Weight	Assumptions	Use HTE + electricity generation	Transmutation and power generation, no fuel recycle	Central station power plant	Heat only, no cogeneration	Land mines, remote surveying		Desalinate with electrodialysis + fusion-generated electricity	Neutron and proton	Neutron and proton	Neutron and proton	For other fusion plants + defense programs	Breeder + transmutation fuel recycle
Necessity	3		**3**	2	2	1	2	2	2	1	2	1	1	-2
Uniqueness	3		**4**	**4**	2	1	3	2	0	3	**4**	3	**4**	3
Market Potential	3		**4**	**4**	3	1	3	2	3	2	2	1	2	2
Resources	3		**4**	1	3	2	0	1	**4**	0	0	0	3	3
Environment	3		**5**	4	4	4	0	0	2	0	0	0	0	1
Competitive	2		-2	0	-2	-1	**1**	-2	-2	-2	**1**	-2	2	-1
Helps GNP	1		**4**	2	3	3	1	1	1	1	0	1	1	2
Investment	2		-4	-2	-4	-3	**-1**	**-1**	-2	**-1**	-2	**-1**	-2	-3
Technical Maturity	2		-4	-2	-3	-2	**-1**	**-1**	-3	**-1**	-2	**-1**	-3	-4
Time to Market	2		-4	-2	-3	-2	-2	**-1**	-3	**-1**	**-1**	**-1**	-2	-4
Prestige	1		**4**	3	3	2	1	1	2	1	1	1	-1	1
Public Support	3		**4**	2	3	2	1	3	1	3	0	2	-1	-1
Weighted Sum	± 140		52	44	33	22	23	22	19	19	17	13	17	-3

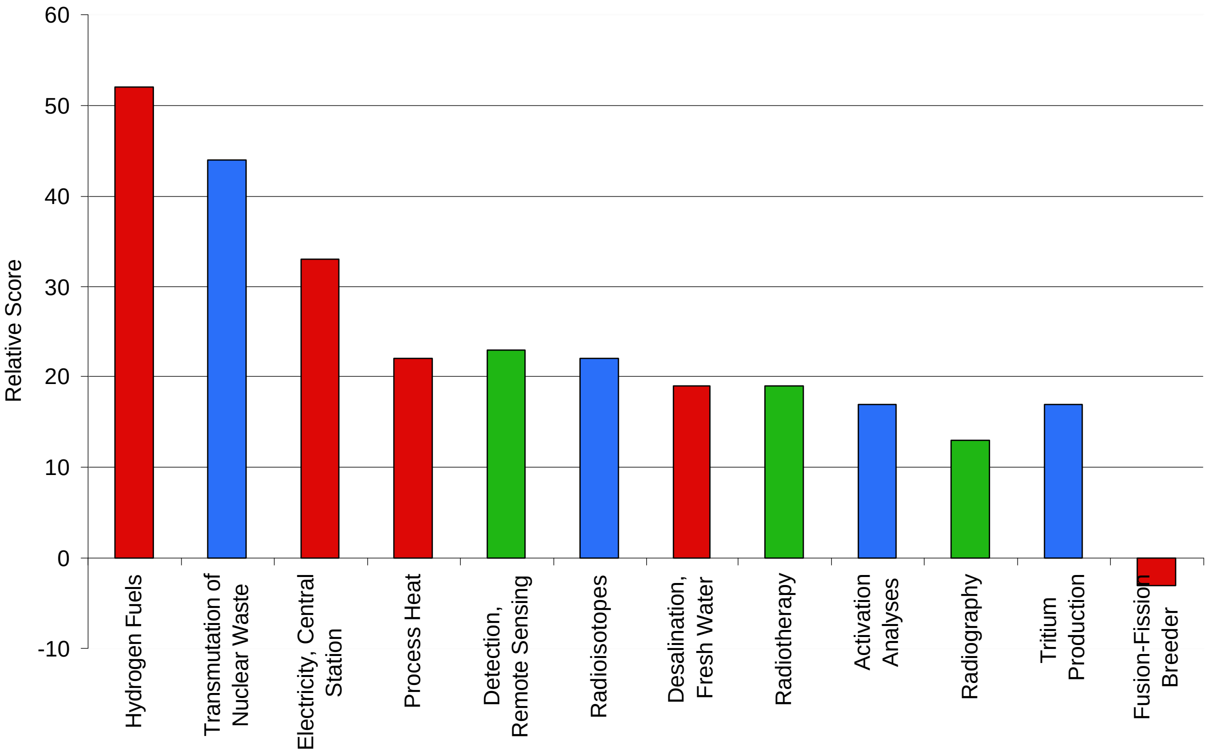


Figure 2-2. Ranked Weighted Values Of Fusion Products

2.5. Discussion of the Results

Using the adopted decision analysis methodology and the weighting scheme of the criteria attributes, the weighted sum of each product in Table 2-3 indicates the relative attractiveness of the product in regard to the current US market. This data is pictorially presented in Figure 2-2.

Most of these applications are perceived as favorable and valuable. The production of hydrogen fuels, transmutation of nuclear wastes, and generation of electricity score slightly higher than the other applications. The remainders, with the exception of the fusion-fission breeder, have very similar scores.

To understand why these products are evaluated as such, one has to examine the attributes of the chosen products and weighting methodology used. Only one of the products was rated at the maximum positive value of +5 for a single attribute, and none were scored at the maximum negative value. Most individual scores were in the middle of the range. The maximum weighting sum for any product was only 40% of the highest possible score.

The products that scored well in the weighted sums had several individual attributes that scored relatively high. These products were generally perceived to have shorter development times, more mature technologies, and good public support. They also required less investment capital to reach the market. Conversely, the breeder application was rated as the least attractive and was not viewed as being currently needed in the US marketplace—a large investment would be required, a long time to market is foreseen, and an immature technology is assumed.

To help understand the process, the high score for each attribute is shaded in Table 2-3. The production of hydrogen scored well because it captured the highest scores in 7 of the 12 attributes. It is judged a highly necessary product, with significant market potential. It helps to prolong critical petroleum resources while greatly improving the environment by not releasing any CO_2 when used. Since it will likely become a major industry, it will improve the US Gross National Product. Since it substantially helps conserve resources and improve the environment, it will generate a lot of public support and prestige. On the negative side, it is not viewed as being overly competitive at present, will require a lot of investment capital, needs to be technically developed, and has significant time to market. Nevertheless, the larger positives outweigh the negatives, making hydrogen (or synfuel) production the highest scoring fusion product. The production of hydrogen with fusion has been proposed using several different processes.

The transmutation of nuclear wastes rated closely as the second choice. Transmutation of nuclear wastes would likely be accomplished in a compact device with excellent confinement. The nuclear wastes would be in containers, housed in the reactor, exposed to the neutrons for long periods of time. This is a rather fusion-unique product with significant market potential, especially with appeal to cleaning up the nuclear waste and not despoiling the environment. The neutral attributes are helping with resources, competitive nuclear disposal costs compared with other disposal options, helping the GNP, prestige, and public support. The scores of some of these attributes could be increased, but it might entail a risk to highly publicize those attributes. The negative aspects are only slightly negative because it is viewed as a compact device, it does not require a huge capital investment, it has a reasonable technical maturity, and it will require a nominal time to market. The high marks for this product coupled with moderate negative scores yield a highly rated product.

The large, central station, electric generating plant also scored quite well. Interestingly, it did not have any of the highest rated attributes, but it did score well in many categories and only had a few negative scores. As such, it has a very good overall, weighted score.

The remaining fusion products had few high attribute scores to elevate their position. Because they are generally related to smaller fusion devices, they did not have many large negative scores like large capital investment or financial risk. They all scored well above the neutral or zero score. Thus, they all should be retained for further examination and concept improvement.

The fusion-fission breeder has many negative attributes. The market for fission fuel is depressed at this time; hence, the necessity for the product is not positive and the market potential is low. The concept would be a large plant, requiring significant capital investment, with a long time to market. The few small benefits for this concept presently do not outweigh the larger, negative aspects of the fusion-fission breeder concept.

2.6. Recommendations for Neutron Source Applications

The decision analysis methodology recommends those applications that scored highly in the assessment. Indeed, the hydrogen production facility and the central station electrical generation facilities are currently being studied by researchers for development as main line fusion applications. The process heat and desalination applications employ similar fusion power plant designs.

The development of the other applications should also be assessed to determine their suitability. In particular, applications such as transmutation of nuclear wastes and the burning of plutonium should be examined. These applications are probably best suited to a low-Q device.

Based on the results of this task, the remaining tasks focused on the transmutation of nuclear wastes, including the burning of plutonium from dismantled weapons.

3. A Comparative Assessment of the Various Concepts for Neutron-Source Applications to Waste Transmutation

3.1 Introduction

For many years, neutron sources have been considered for the transmutation of materials. Some of the most prominent applications include fission reactor waste burning, weapons plutonium destruction, tritium production, and medical isotope production. In this assessment, we focus on fission waste burning and weapons plutonium destruction because these two applications offer the possibility of customers with both an established 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 source comes from fission reactions. In addition, thermal power is a byproduct, such that electric power can be generated to help offset the costs.

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 task is not to judge the feasibility, cost or development risks for fusion, but rather to compare the performance characteristics of a fusion neutron source with those of fission and accelerator based neutron sources applied to waste transmutation.

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 on 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 such as FR"* (fast reactors) [1]. Such comparative studies are only now beginning [2].

There are four predominant characteristics for any system used for actinide and fission product 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 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. Design options are surveyed in Section 3.2.

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 potential engineering advantages, including [3]:

(1) Power control is not necessarily linked to reactivity feedback, delayed neutrons, or control rods.

(2) The systems are more independent of fuel composition.

(3) Inventory is not controlled by criticality requirements.

(4) Neutronics and thermal-hydraulics are more decoupled.

To a large extent, the dominant underlying trade-off between critical and subcritical systems is 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 $(1–k)^{-1}$" [4].

A second important factor is the neutron spectrum. Nearly all actinides will fission in a sufficiently fast spectrum. Fusion neutron sources and accelerators might provide harder spectra in the transmutation blanket than fission reactors. 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. However, the most promising fission options also strive for faster flux designs, such that the distinction in spectrum is reduced to some extent. If the spectrum becomes “too hard”, then material damage and fluence limits could become more severe. These tradeoffs require detailed designs in order to establish the true costs and benefits.

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].

Systems driven by an external neutron source have the ability in principle to achieve deep burnup in a single core loading without recycle. Whether or not this is truly an advantage is difficult to ascertain, both because there are no established criteria and because the discharge depth of burn is so highly design-dependent. Deep burn significantly degrades the performance of even externally-driven systems (*i.e.*, ATW and fusion). Typical transmutation reactors for LWR waste seek to burn between 20–50% of the initial feedstock before reprocessing, although values as high as 90% have been quoted [6]. The ATW roadmap set as its goal the destruction of 99.9% of the transuranics (TRU’s), recovery of 99.9% uranium, and 95% transmutation of ^{99}Tc and ^{131}I through a combination of transmutation and reprocessing [7].

It is unlikely that any amount of waste transmutation will eliminate the need for a repository. In fact, Conclusion #1 of the ATW roadmap states: “A repository is an essential element of the nuclear fuel cycle with or without ATW deployment. It is required in the U.S. for disposal of defense high-level waste, DOE-owned spent fuel, and civilian spent fuel”[7]. The National Academy also concluded: “A geologic repository would still be required even if a partitioning/transmutation system were introduced” [8]. Given that deep burn will not eliminate the need for a repository, and the fact that all systems will tend to operate more efficiently in conjunction with reprocessing, it seems that the advantage of deep single-pass burnup that external neutron sources allows is not a fundamental discriminator.

The National Academy of Science also has established a metric termed the “spent fuel standard (SFS)” which is used to evaluate different disposition technologies for weapons Pu. [8] 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 then can 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.

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, power density, and neutron flux. In general, engineering parameters depend on design choices and not the source of neutrons. Additional discussion of safety attributes is found in Section 5, whereas cost comparisons are found in Section 4.

Finally, one of the most challenging aspects of a comparison between technologies is the lack of a common set of goals. This situation results in 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.

3.2. 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.

3.2.1 Fuel cycle options

Table 3.1 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. Ordinarily the uranium isotopes are extracted from spent fuel before fabricating the transmuter fuel, such that only "transuranics" are burned.

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 3.1. Fuel cycle options

Feedstock

- Weapons material (^{239}Pu) as sole source
- Fission waste as the sole source (usually with uranium isotopes extracted)
- 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

3.2.2. Blanket design and material options

Many engineering concepts have been explored previously, as summarized in Table 3.2. 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 3.2 purposely excludes the fission option of using mixed-oxide (MOX) fuel in existing light water reactors (LWR) for the disposition of weapons-grade plutonium. This option is viewed as near-term while the options listed in Table 3.2 are regarded as intermediate-term.

Table 3.2. Some Engineering Concepts Considered in Previous Studies

Type	Coolant/ moderator	Fuel	Breeder/ target	Reference
Fission				
IFR	Na	metallic		[9]
HTGR	He	coated Pu oxide		[6]
Heavy metal	PbBi	metallic		[10]
Fusion				
Molten salt	self-cooled	PuF	He/$LiAlO_2$	[11,12]
LBE	PbBi	metallic	PbLi	[13]
HTGR	He	oxide	Li oxide	[5]
Accelerator				
Na-cooled	Na	metallic	W	[14]
PbBi-cooled	PbBi	metallic	PbBi	[14]
Aqueous	D_2O	oxide suspension	W/Pb	[15]
Non-aqueous	He/graphite	molten salt	Pb	[15]
HTGR	He/graphite	coated oxide		[16]

3.3. Performance metrics

3.3.1. 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 neutron spectrum and materials are important considerations, their effects are too complex and design-related to allow for straightforward comparisons on the basis of spectrum and materials alone. Table 3.3 lists some of the key neutronic performance parameters that derive from the materials and spectrum, and are often used to distinguish different systems. These parameters generally relate to the rate and depth of burnup, including the relative mix of materials that are produced or destroyed.

Table 3.3. Key Neutronic Performance Parameters

- Conversion ratio (ratio of production to destruction of actinides)
- Fission-to-capture ratio (including parasitic captures)
- 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
- 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) and fluence (n/cm^2)

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 and extent of depletion are 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. The discharge burnup will be limited by criticality requirements, radiation damage effects and safety considerations.

Any reactor consumes Pu at the same rate – about 0.95 MWd per gram of Pu fissioned, about 1.05 g/MWd. 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 actinides produced to actinides destroyed. If the conversion ratio is greater than zero, then higher actinides are produced and the *net* consumption is less than 1.05 g/MWd. 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 nature of the depleted material is described 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. The use of discharge composition as a comparison metric is difficult due to the importance of the separation chemistry processes and goals for final waste disposition.

3.3.2. 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 3.4. These relate to power, power density, thermal conversion efficiency, fluence limits, and peaking factors. Additional discussion of safety attributes is found in Section 5, whereas cost comparisons are found in Section 4.

Power density and peaking factors relate to both the cost and reliability of the system. Higher power densities tend to push the material limits and create more challenging design problems. High peaking factors make inefficient use of the fuel, such that larger inventories are needed to achieve the same rate of TRU destruction. Large time-dependent changes can result in several problems. Shorter cycle times may result from large time-dependent changes in reactivity, resulting in decreased capacity factor. The addition of burnable poison may be necessary in order to control the reactivity. For externally-driven systems, time-dependent core behavior places additional requirements on the size of the external neutron generator, with likely cost penalties. Finally, fluence limits on the fuel can affect both the cycle length and reprocessing requirements.

The achievable thermal conversion efficiency is related to the choice of blanket materials and coolant, and to the operating conditions in the blanket. Higher conversion efficiency will help increase the electric energy production, thereby helping to offset the capital cost of the facility.

Table 3.4. 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

3.4. Fission options

3.4.1. Integral fast reactor

Detailed studies of Na-cooled fast reactors have been performed at ANL [9]. The IFR (Integral Fast Reactor) 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:

(1) Multiple recycling of the fuel is used to allow complete actinide destruction.

(2) Burnup of ~10% per pass is achieved.

(3) The minimum ^{239}Pu fraction achieved is ~50%.

(4) 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 3.5 [9].

Table 3.5. Na-cooled IFR Parameters

	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
** 231 kg/yr = maximum achievable at 75% capacity factor

3.4.2. HTGR

A prime example of a high-temperature gas-cooled Pu transmutation reactor is the PC-MHR proposed by GA [6] (see Table 3.6). 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 3.6. HTGR Parameters ("deep burn" option) [6]

Thermal power	600 MW per module
Processing mode	once-through, no recycle
Fuel cycle length (months)	36 (1/3 replaced per year)
TRU inventory (kg)	634
TRU consumption rate (kg/yr)	230*
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 in fuel	4.2×10^{21} n/cm^2

*This number has been adjusted to be consistent with about 0.95 MWd/g fissioned.

3.4.3. 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 [10]. To further maximize the actinide transmutation, the fertile isotopes ^{238}U or ^{232}Th are removed. Table 3.7 gives some parameters for a PbBi-based transmuter [10].

Table 3.7. PbBi Reactor Parameters [10]

Processing mode	batch mode with recycling
Fuel cycle length (months)	20
Thermal power (MWth)	1800
TRU consumption rate (kg/FPY)	657*
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%

*This number has been adjusted to be consistent with about 0.95 MWd/g fissioned.

3.5. Fusion options

Three blanket types recently were analyzed for subcritical actinide burners using a fusion plasma for the external source of neutrons. These are: a self-cooled molten salt LWR waste transmutation blanket with a He-cooled Li ceramic tritium breeding blanket [11, 12]; a lead bismuth eutectic (LBE) cooled, IFR type Pu/MA containing Zr matrix blanket [13]; and a HTGR Pu transmutation blanket, also combined with a He-cooled Li ceramic tritium breeding blanket [5].

3.5.1. Molten salt blanket

Analysis was performed on a molten salt blanket to determine its performance as a LWR spent fuel actinide burner (90% plutonium and 10% MA as extracted from the spent fuel), a minor actinide (MA) burner (*i.e.*, absent any Pu isotopes), as well as a Pu-assisted waste burner (65% plutonium and 35% MA). The use of a molten fuel allows continuous feeding of fresh material as well as continuous extraction of fission products. In these blankets, the heavy metal (Pu and MA), in the form of fluoride, is dissolved in flibe. The concentration of the heavy metal is fixed at 0.5 molar percent. Table 3.8 summarizes some of the key parameters for these concepts.

Table 3.8. Fusion-Driven Molten Salt Blanket Parameters

	Actinide Burner [12]	**MA burner** [11]	**Pu-assisted** [11]
Processing mode	continuous	continuous	continuous
Thermal fission power, MW	3000	3000	3000
Fusion power, MW	250	210	75
Pu destruction rate (kg/yr)	760	0	760
Actinide destruction rate (kg/yr)	1170	1170	1170
Equilibrium Pu fraction (%)	82	48	66
Equilibrium ^{239}Pu fraction (%)	44	20	26
Actinide inventory* (tonnes)	4.5	2	5
Equilibrium k_{eff}	0.74	0.77	0.918
Average power density (W/cc)	50	80	80

* molten salt inventory is ~100 tonnes

3.5.2. LBE cooled IFR blanket [13]

A LBE (Lead-Bismuth-Eutectic)cooled IFR type fuel blanket similar to the one described in Section 3.4.3 was investigated in a fusion device with a D-T plasma. Two cases were analyzed (see Table 3.9). One is a high performance case, “Case H”, where the initial effective reactivity is set at 0.965. The other is a medium performance case, “Case M”, where the initial k_{eff} is set at 0.877. The effective reactivity will drop when the installed heavy metal inventory, which is the actinides including plutonium and minor actinide isotopes extracted from the LWR spent fuel, is depleted and fission products are generated. The performances of these two cases were calculated for the first cycle assuming a 20% average burnup in the heavy metal.

The calculation results are shown in Table 3.9 for the two cases when the fuel is fresh and at 20% burnup. A reactivity drop of 0.0075 for each percent of burnup in both cases is observed. For the high performance case, the initial energy multiplication (M) due to fission reaction is high, about 180. However, the reduction of M is significant, about 0.28% per percent burnup, averaged over the 20% burnup range. For the medium performance case, however, it is only 0.13% per percent burnup, although the initial M is lower (about 50). The resulting fusion power to maintain a constant thermal power output will have to increase due to reduction in energy multiplication. Over the 20% burnup cysle, the fusion power swing for Case H will be about 6, while it is only 2.5 for Case M.

Table 3.9. Performance of LBE/IFR Based Fusion Transmutation Systems (Actinide from LWR Spent Fuel)

	Case H		**Case M**	
Burnup	0%	20%	0%	20%
k_{eff}	0.965	0.816	0.877	0.729
TBR	9.3	2.1	3.0	1.57
M	180	32	50	20
TRU capture/fission	0.40	0.46	0.42	0.48
Δk/%burnup	0.00745		0.0074	
14 MeV neutron fluence/%burnup (MW-y/m^2)	0.050		0.082	
ΔM, %M/%burnup	0.280		0.125	
Average power density W/cc* W/gHM	300 350		300 406	
Neutron wall loading, MW/m^2	0.23	1.3	0.81	2.0
Thermal fission power, MW	3000		3000	
TRU inventory*, kg	8620		7430	
TRU consumption rate kg/full power year	1170		1170	
Fusion power, MW	21	120	75	190
20% burnup cycle fluence 14 MeV neutron, MW-y/m^2 Fast neutron, n/cm^2	1.0 1.27x10^{23}		1.64 1.26x10^{23}	

*In Zr-Pu-MA fuel only.

3.5.3. HTGR blanket

An HTGR blanket similar to the one described in Section 3.4.2 was used in combination with a DT fusion neutron source [5]. 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 3.10 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 3.10. Fusion-Driven HTGR Blanket Parameters [5]

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		

3.6. Accelerator options

Numerous designs have been developed for accelerator-driven subcritical assemblies for the transmutation of waste and weapons Pu. For simplicity, we have chosen three concepts to review: an HTGR blanket [16]; Na or LBE-cooled blankets with metallic fuel [14]; and an aqueous blanket [15]. For most systems, either W or PbBi are used as the accelerator target.

3.6.1. HTGR core

The HTGR core described in Section 3.4.2 was examined in a subcritical accelerator-driven mode for W-Pu destruction [15]. 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 3.11).

Table 3.11. GA Accelerator-Driven HTGR System Parameters [16]

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

3.6.1. 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 3.12 summarizes parameters for the LBE option.

3.6.2. Aqueous blanket

An aqueous transmuter concept also was explored as an option for ATW [15]. 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 3.13 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.

Table 3.12. Accelerator-Driven Liquid Metal Blanket Parameters [7,14]

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 all 8 modules)
TRU consumption rate (kg/yr)	226
TRU loading rate (kg/yr)	1038
Capacity factor	70%
Discharge burnup % (LWR feed)	22%
Average power density (W/cc)	350
Transuranic inventory (kg)	1483 (equilibrium feed, beginning of cycle)
k_{eff}	0.97 (assumed)

Table 3.13. Accelerator-Driven Aqueous Blanket Parameters

Thermal power (MW)	2088 MW
k_{eff}	0.96
Beam power on target	100 MW
Thermal conversion efficiency	30%
Ave. power density	700 MW/m^3
Neutron multiplication	12.7
Actinide capture-to-fission ration	1.6
Blanket actinide inventory	1300 kg
Actinide burnup rate	800 kg/yr
Cycle time	260 days

3.7. Summary

Key metrics have been examined in order to compare the engineering and neutronic performance of several actinide transmutation systems both with and without an external neutron source. There are many different transmutation fuel cycles and many different blankets proposed, each having its own unique characteristics. Table 3.14 summarizes some of the key performance parameters extracted from the previous tables. In all cases, it was assumed that the fertile uranium isotopes have been extracted in order to reduce the in-situ breeding and minimize the time for transmutation.

Even though quantitative metrics have been identified, a definitive comparison is difficult due to the absence of an established set of requirements for transmutation reactors. Therefore, point-design comparisons are necessarily tied to authors' individual assumptions. Most concepts could be re-optimized under a different set of assumptions. An activity to better coordinate studies on the various transmutation reactor concepts would be useful in order to enable more productive comparisons and to help focus future work.

Table 3.14 compares several blanket types, including molten salt, aqueous slurry, sodium IFR, PbBi fast reactor, and a gas-cooled HTGR blanket. One of the important conclusions of this assessment is the fact that most performance parameters are dependent more on blanket choices than on the source of neutrons. For the externally driven systems the energy multiplication in all cases is over 10, and in some cases as high as 180. From a neutronics point of view, an accelerator or fusion plasma is a perturbation on the transmutation blanket, and not the dominant source of neutrons. Furthermore, the rate of actinide transmutation is approximately 1.05 gram of TRU consumed per MWd for **any** system, because fission accounts for the vast majority of power produced. Normalized to the power level, all systems burn actinides approximately ***at the same rate***.

Engineering performance metrics are especially sensitive to the blanket choice. Power densities range from very low values (50 W/cc) for the molten salt system to high values for the aqueous slurry (700 W/cc). Actinide inventories also vary considerably, with the aqueous ATW concept having the lowest (0.6 kg/MW) and the IFR having the highest (8.9 kg/MW). In addition, the choice of blanket materials has a direct impact on the thermal cycle conversion efficiency, and hence the ability to offset the capital cost with electric energy produced. In summary, many of the key economic and safety metrics are dominated by blanket choices that are independent of the presence or absence of an external neutron source.

Table 3.14. Comparison of Performance Parameters for Fission, Fusion and Accelerator Based Transmuation Systems

	Fusion Systems (LWR TRU Spent Fuel)			Fission Systems			ATW	
	Molten Salt Flibe/Pu-MA (Equilibrium)	LBE/Zr-Pu/MA Case H 0%/20% burnup	LBE/Zr-Pu/MA Case M 0%/20% burnup	IFR Pu Burner Weapons-Pu (ANL)	PbBi actinide burner (MIT)	Fission HTGR Pu burner (GA)	PbBi actinide burner (ATW) LWR feed	Aqueous burner (LANL) LWR feed
k_{eff} (initial, unless noted)	0.74	0.965/0.816	0.877/0.729		1.2	1.0686 (5)	0.97	0.96
Burnup reactivity loss	0.0	0.00745/ % (2)	0.0074/ % (2)	3.2%				
Thermal fission power, MW	1000	1000	1000	840	1800	600	840	2088
Average power density W/cc W/gHM	50 680	300 (3) 350	300 (3) 406	155 113	126 313	 946	350 566	700 160
HM inventory, kg	1487 (4)	2873 (4)	2477 (4)	7470	5742	634	1483	1300
HM inventory per Watt, kg/MW	1.49	2.87	2.48	8.9	3.19	1.05	1.76	0.62
TRU conversion ratio (1)	1.6	0.40/0.46	0.42/0.48	0	0.23	0.205		
TRU consumption rate (kg/FPY)	390	390	390	308	657	230	323	800
Discharge burnup (%) MWd/g	20%	20%	20%	 0.334	 0.190	 0.590	22%	
Cycle length for fuel (months)				12	20	36	24	8.7
Fast neutron cycle fluence, n/cm^2	1.48x10^{22}	1.27x10^{23}	1.26x10^{23}	3.8x10^{23}		4.2x10^{21}		
Fusion or beam power, MW	83.3	7/40	25/63.3	0	0	0	70	100
Energy multiplication (M)	15	180/32	50/20				96	83

(1) ratio of captures to fissions

(2) change in k_{eff} per %burnup, averaged over 20% burnup cycle

(3) in Zr-Pu-MA fuel only

(4) blanket inventory only

(5) cold, with control rods removed

While many performance metrics depend primarily on the blanket choices, important distinctions do exist between systems with or without an external neutron source. The most fundamental distinction between these systems is criticality – *i.e.*, critical *vs.* subcritical blanket operation – and the depth of subcriticality as characterized by k_{eff}. For example, with an external neutron source and no requirement for criticality, deeper single-pass burnup is possible, in principle, without fuel reprocessing. Operating even a subcritical assembly 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. However, given that deep burn will not eliminate the need for a waste repository, and the fact that all systems will tend to operate more efficiently in conjunction with reprocessing, it seems that the advantage of deeper single-pass burnup that external neutron sources might allow is not an important discriminator.

Subcritical assemblies with high-energy external sources of neutrons could provide a harder spectrum. Soft spectrum reactors tend to have more parasitic captures and higher capture-to-fission ratios, thus limiting their performance to some extent. However, pure fission reactors are capable of obtaining spectra that are sufficiently hard to take advantage of spectrum effects; spectrum-related performance differences are modest and probably do not justify the added expense of an external neutron source. In addition, a very hard spectrum will result in additional radiation damage problems for materials, thus reducing the fluence limit and complicating the engineering.

Safety is a more compelling advantage of subcritical operation. Prompt criticality and positive reactivity coefficients are easier to avoid with a subcritical assembly. Economic penalties on safety systems and core size restrictions for critical assemblies may enable subcritical assemblies to compete with fission. The safety value of subcriticality and the desired depth of subcriticality must be addressed in order to perform this trade-off.

In comparing accelerator *vs.* fusion external sources of neutrons, the most compelling difference probably arises from the fact that the fusion system can operate with an energy gain greater than unity, whereas the accelerator by itself cannot (i.e., the fusion neutron source can be energy self-sufficient). This has several consequences:

(1) More neutrons can be produced by a fusion plasma per unit of input energy.

(2) Less recirculating power is extracted from the gross electric output per neutron.

(3) **The higher external neutron multiplication with a fusion source means that the fission blanket is relied upon less for neutron production.**

In essence, neutrons can be multiplied **externally** in a fusion plasma rather than **internally** in the transmutation blanket. This allows the blanket to operate more deeply subcritical (*i.e.*, lower k_{eff}) without the penalty on the energy balance that accelerators suffer. Note in Table 3.14 that the accelerator systems typically operate with k_{eff} close to unity. As with all of the performance metrics, in order to determine the importance of this distinction, a common set of criteria are needed to enable all designers to optimize their particular systems on a common basis.

References for Section 3:

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

7. A Roadmap for Developing Accelerator Transmutation of Waste (ATW) technology, A Report to Congress," DOE/RW-0519, October 1999.

8. 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

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

9. 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).

10. "Actinide Transmutation by Lead-Bismuth Cooled Reactors, MIT Annual Project Status Report," June 1999.
11. E. T. Cheng and R. J. Cerbone, "Prospect of Nuclear Waste Transmutation and Power Production in Fusion Reactors", ANS Fusion Topical Meeting, 1996.

12. E. T. Cheng, C. P. Wong, "Transmutation of Actinide in Fusion Reactors and Related Systems Analysis," to appear, Proc. ICENES 2000, September 2000.

13. E. T. Cheng, to appear, Proc. 14th ANS Topical Meeting on the Technology of Fusion Energy, October 2000.

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

15. C.A. Beard, J.W. Davidson, and R.A. Krakowski, "Parametric Systems Studies of the Aqueous-Based (Slurry) Blanket Concept for Accelerator Transmutation of Waste," Fusion Technology Vol. 110, June 1995, 321-356.

16. C.A. Beard, et al., "Neutronics and Engineering Design of the Aqueous-Slurry Accelerator Transmutation of Waste Blanket," Fusion Technology Vol. 111, July 1995, 122-132.

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

4. System Studies of Fusion

4.1. Introduction

In order to assess the economic characteristics of a fusion neutron source, the ARIES Systems Code (ASC) has been applied to preliminary studies of a magnetic fusion energy (MFE) neutron source employed for transmutation applications, including the transmutation of excess defense plutonium (Pu), and the destruction of other defense wastes or spent fission fuel from civilian power plants.

Although several MFE configurations may serve as suitable platforms for a fusion neutron source, this task has concentrated on the spherical tokamak (ST) as a representative system. Alternatives include an adaptation of the reduced-cost (RC) ITER, or perhaps a device based on the FIRE concept. Plasma-physics-based input files for the ASC are not currently available for these non-ST approaches. Several features of the ST suggest its attractiveness for the transmutation application. A resistive toroidal-field-coil (TFC) system operating at modest magnetic field, resulting from access to relatively high plasma beta, does not require a large development program, consistent with an intermediate-term application.

4.2. Figures of Merit

The facility under consideration is designated "ARIES-NS" for *N*eutron *S*ource. The ARIES-NS is anticipated primarily to provide a service, namely the destruction of Pu. Thus, a reasonable figure of merit is the unit cost of this service expressed in dollars per kilogram of destroyed material. Additionally, the ARIES-NS is expected to provide some electric power output, for which the appropriate figure of merit is the busbar cost of electricity [COE (mill/kWeh)]. It would be appropriate to assess a service charge for the transmutation activity that allows the electricity being produced to be sold at market prices.

4.3. Design Point Basis

The assumption of an intermediate-term ARIES-NS application suggests foregoing the highest plasma physics performance anticipated for the pure fusion central-station power plant, ARIES-ST, in Ref. [1]. Wall stabilization is not invoked and the plasma vertical elongation is kept near 3.1 at a representative plasma aspect ratio, $A \quad R_T / a_p = 1.6$. The bootstrap current fraction, $f_{bc,}$ exceeds 90%, but could be reduced at the expense of higher current-drive (CD) power input. The ST provides a modest source of fusion neutrons to drive the subcritical Pu-bearing outboard-only blanket. Manipulation of the plasma fuel composition and operating temperature can emphasize catalyzed D-D-T operation to reduce or eliminate the need to breed tritium.

Much of the thermal power of the system derives from the fissioning of Pu in the blanket. The ASC performs a steady-state power balance to meet the target net power output, *e.g.*,$P_E = 1.0$ GWe. The parameter that couples the fusion power to the blanket performance is the fusion neutron energy multiplication, M_n. The value of this parameter for a pure fusion system is typically, $M_n \simeq 1.1$. For the present study a value of $M_n = 60$, consistent with the early-life (high k_{eff}) result of Fig. 2 of Ref. [2] is used. Results for $M_n = 30$ are also reported, consistent with a time average over the changing performance of this proposed batch-burn scenario. Results for $M_n = 15$ are included to provide a broad range of k_{eff} options.

For the purposes of this study the plant capacity factor, p_f, is taken as 0.75. The fusion neutron wall load, I_w (MW/m^2) is so low in this fission-dominated device that a structural lifetime based on fusion neutron damage does not enter or contribute to a scheduled component replacement cost component to the COE. A suitable *fission* neutron fluence life should be considered in future assessments. The thermal conversion efficiency is assumed conservatively to be $\varsigma_{TH} = 0.35$, so that no development of an advanced power cycle, exotic materials, or high-temperature operation is required. The ASC cost database assumes tenth-of-a-kind unit costs. As a result of the presence of Pu and fission products the Level of Safety Assurance is taken to be $LSA = 4$, requiring active safety measures, high security, *etc*., and correspondingly higher direct and operating costs than a pure fusion application.

The selection of a Pu blanket concept has implications for an on-site chemical processing plant for preparation of the feed material as well as post-processing of the outflow. Using the simplified cost estimating relationship for the Chemical Plant Equipment (CPE) suggested in Table III of Ref. [3], and assuming that the Pu burnup fraction is 0.35, the incremental COE is projected, without detailed attention to the distinction between “front-end” preparation of Pu-bearing blanket sub-elements and “back-end” processing of the waste stream(s).

The parameters M_n and k_{eff} are related by $M_n = Fk_{eff} / (1 - k_{eff})$. The factor, F, which is the ratio of the average energy of the source neutrons to the average energy of fission neutrons (~2 MeV), is reported to be unity for the Accelerator Transmutation of Waste (ATW) concept considered in Ref. [3]; $F \simeq 7$ (*cf*. Ref. [4] for D-T fusion systems) is used here.

4.4. Design Point Alternatives

With fixed parameters described in the previous section and for the three values of M_n noted, the size of the ARIES-NS was varied with fixed plasma aspect ratio, $A = 1.6$, in order to identify near-minimum-COE design points. Key parameters of the three representative cases for the ARIES-NS (DT) are summarized in Table 4.1. For these cases, the plasma fusion gain, $Q_P = P_F / P_{CD} \simeq 2$ and the total capital cost (excluding the chemical plant) is about 5 billion dollars.

Neutron source and economic parameters for the three cases are summarized in Table 4.2. Note that Table 4.2 lists the COE excluding the chemical plant and also reports the incremental COE due to the chemical plant, calculated as noted above. The annual Pu destruction rate is over 1 tonne/year for all three cases. It is possible to consider the assessment of a Pu-processing charge to offset the projected COE values and allow the sale of electricity at market prices, e.g. 50 mill/kWeh. This charge can be expressed per unit of Pu mass destroyed, or as an annual payment (or subsidy) from the governmental customer. Both versions of the service charge are reported in Table 4.2.

In reviewing the literature no economic assessments were found for the fission transmutation options reported in Section 3. However, reference 3 does provide an economic assessment of the ATW concept at a systems model level. Table V of reference 3 lists parameters for a “Base Case” producing about 1560 MWe at a thermal conversion efficiency of 35% and a plant factor of 75%. The COE for this case is about 77 mill/kWeh (including the chemical plant). When the results of reference 3 are normalized to the power levels of Tables 4.1 and 4.2, it is concluded that the economic performance of the ATW and the fusion system considered here are comparable.

Finally, it is noted that catalyzed D-D-T operation was also examined. However, for the cases studied the economic characteristics were deemed unattractive and this approach was not pursued.

4.5. Observations

The preliminary studies described here indicate that economic performance characteristics associated with a fusion neutron source used for transmutation applications are comparable to those associated with accelerator sources. A quasi-steady operating mode that maintains high values of M_n and k_{eff} in the Pu-fissioning blanket of the ARIES-NS is recommended as preferable to the batch, deep-burn option described in Fig. 2 of Ref. [2]. Such a quasi-steady mode avoids on the one hand a degrading of the net power output of the device over time as M_n drops under the simultaneous constraint that the fusion driver is operated to maintain 'steady' values of Q_p and P_F, implying an underutilization of the balance of plant late in the batch cycle. On the other hand, as depicted in Ref. [2], increasing the fusion driver performance late in the batch cycle to compensate by means of higher Q_p and/or P_F for lower fission power suggests underutilization of the fusion driver early in the batch cycle which would have to be designed to accommodate higher performance requirements late in the batch cycle. Both alternatives to the quasi-steady mode lead to higher COE projections and a greater service charge for the destruction of Pu.

References for Section 4:

1) R. L. Miller and the ARIES Team, "Design-Point Finalization for the ARIES-ST Power Plant" *Proceedings of the 18th IEEE/NPSS Symposium on Fusion Engineering*, (October 1999) 41.

2) E. T. Cheng, R. J. Cerbone, and C. P. Wong, "Disposition of Plutonium in a Fusion Driven Subcritical Assmebly," *Proceedings of the 18th IEEE/NPSS Symposium on Fusion Engineering*, (October 1999) 589.

3) R. A. Krakowski, "Accelerator Transmutation of Waste Economics," *Nuclear Technology*, 110 (June 1995) 295.

4) E. T. Cheng, personal communication (20 April 2000).

Table 4.1: DT ARIES-NS[(a)] Parameters

Parameter	Case 1	Case 2	Case 3
Net electrical power output, P_E(Mwe)	1,000	1,000	1,000
Major toroidal radius, R_T(m)	2.94	2.69	2.37
Minor plasma radius, a_p(m)	1.84	1.68	1.48
On-axis magnetic-field strength, B_o(T)	1.84	1.65	1.54
B-field strength at TFC-CP, B_c(T)	6.75	6.28	6.21
Plasma current, I_p(MA)(f_{bc} = 0.95)	17.9	14.6	12.0
Confinement factor, H_{98}	1.70	2.06	2.48
14.1-MeV neutron wall load, I_w(MW/m^2)	0.66	0.37	0.23
NBI current-drive power, P_{CD}(MW)	134	78	47
Plasma temperature, T_i/T_e(keV)	15/21	15/22	15/24
Neutron energy multiplication[(b)], M_n	15	30	60
Blanket neutron multiplication[(c)], k_{eff}	0.68	0.81	0.89
Fusion power, P_F(MW)	350	163	78
Total thermal power, P_{TH}(MW)	4,500	4,099	3,879
Fusion gain, $Q_P = P_F/P_{CD}$	2.62	2.09	1.66
Engineering gain, $Q_E = 1/\varepsilon$	2.74	3.30	3.80
1992-$ Total capital cost[(d)], (G$)	5.73	5.03	4.49

[(a)] ST w/o stabilizing wall, with disruption-avoidance beta margin (0.9), $A \equiv R_T/a_p = 1.6$, $\kappa = 3.1$, $\beta_N = 5.04$, $\beta = 0.266$, $\beta_p = 1.27$, $\eta_{TH} = 0.35$, $f_d/f_t = 0.487/0.487$

[(b)] Pu-burning outboard blanket

[(c)] $k_{eff} \simeq 1/[7/M_n) + 1]$

[(d)] not including chemical plant

Table 4.2: DT ARIES-NS(a) Parameters

Parameter	Case 1	Case 2	Case 3
Neutron energy multiplication(b), M_n	15	30	60
Blanket neutron multiplication(c), k_{eff}	0.68	0.81	0.89
14.1-MeV neutron wall load, I_w(MW/m^2)	0.66	0.37	0.23
Peak neutron wall load, $\hat{I}_W$(MW/m^2)	1.0	0.55	0.34
14.1-MeV-n source rate (n/s)	1.24×10^{20}	5.8×10^{19}	2.8×10^{19}
14.1-MeV-n source rate (mole/a)	4.86×10^{3}	2.25×10^{3}	1.05×10^{3}
Fusion power, P_F(MW)	350	163	78
Fission power, P_{Fis}(MW)	3,925	3,775	3,675
Total thermal power, P_{TH}(MW)	4,500	4,099	3,879
$n_{fission}/n_{fusion}$ (est.(d))	2.86	5.93	12.06
$(n_{fission} + n_{fusion})/\ n_{fusion}$	3.86	6.93	13.06
1992-$ Cost of electricity(e,f), COE (mill/kWeh) w/o LSA credits (LSA = 4)	96	86	78
Incremental COE due to chemical plant (mill/kWeh)	7.3	7.1	7.1
Annual Pu destruction rate(f), R_{Pu} (kg/a)	1,150	1,110	1,080
Pu service charge to meet COE target(g)(k$/kg)	306	258	216
Annual Pu service charge(g)(M$/a)	352	286	233

(a) ST *cf* Table 4.1

(b) Pu-burning outboard blanket

(c) $k_{eff} \simeq 1/[7/M_n) + 1]$

(d) assuming 200 MeV/fission and 2.9 fission neutrons per Pu fission

(e) not including chemical plant

(f) $p_f = 0.75$

(g) 50 mill/kWeh

5. Safety and Environmental Issues Associated with Transmutation

5.1. Introduction

The safety and environmental (S&E) issues associated with the different options for transmutation of fission waste or weapons plutonium destruction focus primarily on the source of the neutrons and the material choices used in the design. While there may be many similarities in the safety issues among these transmutation options, the focus here will be on the differences. In addition, the differences in the safety issues of a fusion power plant producing electricity and one burning plutonium will be discussed.

5.2. System Comparisons

There are differences in the configurations of the transmutation options (fission reactor, accelerator, and fusion reactor) that will lead to different safety issues that need to be addressed. The ability of the accelerator and fusion reactor to supply neutrons externally and operate in a subcritical mode leads to some safety advantages, namely the reduced risk from reactivity/criticality events and the separation of radioactive inventory from the neutron generator. By comparison, fission reactors require self-criticality for operation. The increase in safety afforded by these differences is open to debate. Proponents for the accelerator (see for example [1]) and fusion reactor options would argue that the decoupling of the neutrons offers increased assurance against reactivity/criticality events and allows much more operational flexibility than a fission reactor. Fission reactor proponents would claim that based on all recent fission reactor safety assessments (LWRs [2,3], MHTGRs [4], LMFBRs [5,6]), criticality/reactivity events have never been shown to be risk dominant. Inherent processes such as Doppler broadening, neutron leakage from the core and negative moderator temperature coefficients of reactivity, and the use of highly reliable reactivity and criticality control systems make the risk from such events quite small. This assumes that the plutonium is implemented in a mixed oxide fuel cycle in a conventional reactor embodiment where the goal is to burn to the spent fuel standard. In the case of burning the minor actinides and plutonium from spent fuel, some have argued that without any fertile material in the core, reactivity events become more important especially in fast reactors. However, some Doppler diluent is usually employed to replace the U-238 or Th-232 in the specific cycle. For example, the gas reactor has chosen erbium oxide in its plutonium burning design. In Pu-metal fueled fast reactors (e.g. sodium or lead bismuth) or over-moderated thermal reactors, care must be taken in the design to prevent large positive reactivity insertions that can occur in transient events such as voiding or loss of coolant. Design solutions such as pancake cores, axially layered cores and the use of neutron-streaming assemblies can help address the reactivity issues associated with Pu-metal fueled reactors. Additional design work is needed to prove the safety of such solutions because a reactor with an overall positive temperature coefficient would not be licensable in the US. Beyond these differences, the addition of the external source of neutrons (e.g. the plasma and associated ancillary systems for a fusion reactor or particle accelerator) and its impact as an accident initiator must also be considered in any overall S&E comparison of the different approaches.

Furthermore, in comparing these options there is an underlying trade-off between safety, reliability and cost that must be considered in the overall evaluation. Although the external neutron source options offer the potential of improved safety, the fusion core (and to a lesser extent the accelerator) is very expensive and consists of a number of components whose availability is not yet proven at the scale needed for a transmutation system. By comparison, fission reactors have high availability and their criticality/reactivity control systems are proven high reliability components that have a modest cost impact on the overall facility.

In terms of the material choices that must be considered, there are differences in the S&E issues associated with each of the different material choices. None of the S&E issues are related to the source of neutrons in the given application. Furthermore, the safety issues associated with the plutonium, minor actinides and fission products tend to outweigh the coolant and structural material choices. With proper design, any of these options could probably meet current safety goals. The key issue is the cost to meet such goals. Detailed design data are needed to perform a useful comparison.

It is also important to note that the safety, environmental and licensing issues that must be addressed in a plutonium burning fusion reactor are quite different both in magnitude and in kind than the S&E issues associated with traditional magnetic fusion. In a traditional electricity producing fusion power system with reduced activation materials, the number of dedicated nuclear grade safety systems would be very small and the inherent safety and environmental advantages of fusion can be seen. However, the use of very hazardous materials like plutonium, actinides and fission products will require a stringent nuclear safety approach to the design of the fusion power system and the associated nuclear grade safety systems for many of the key safety functions such as confinement, decay heat removal, and plasma shutdown. The cost impact of such dedicated safety systems needs to be considered.

In this regard, plutonium, actinide and fission product containment is a key safety issue. Plutonium is a special nuclear material and as such, accountability issues need to be considered. Detailed design and safety analysis would be required to ensure that the design provides robust, reliable containment in the fusion environment under normal and off-normal conditions. The decay heat in such a system will also be substantial because of Pu and actinide isotopes. Whereas in traditional fusion reactor designs, decay heat can be removed passively with modest impact on the design, reliable and redundant decay heat removal will be necessary in the plutonium burning fusion reactor. The level of required redundancy and diversity in the decay heat removal system(s) would have to be addressed in the design. Robust plasma shutdown will be needed to ensure that ex-vessel transients ranging from pump trips to ex-vessel pipe breaks do not lead to overheating/failure of the first wall. While in conceptual fusion reactor studies such as ARIES [7], such events are of modest importance, when the blanket contains plutonium, actinides and fission product, blanket integrity becomes an even more important safety issue. Although the system will operate in a subcritical mode, criticality/nuclear reactivity accidents will have to be thoroughly assessed in the safety analysis. Analysis of different potential geometric configurations must be performed to present a complete safety case to the regulatory authorities. For example, is there a potential to reconfigure the system to be critical by improper loading of segments in the case of a solid blanket? Will special systems have to be employed to prevent accumulation of a spill of molten salt in the case of the Pu-Flibe option? With the Flibe option, the design will have to employ critically safe piping (~ 4-6 cm in diameter depending on the mix) What is the diversion risk associated with the molten salt blanket option? Is there any impact on the design from such issues?

5.3. Concluding Remarks

In summary, the safety advantages of externally driven neutron transmutation systems like an accelerator or fusion reactor are largely related to reduction in the risk of reactivity/criticality events and the physical separation of the neutron source and the radioactive inventory. The magnitude of this safety advantage is debatable when compared to the fission reactor option because public safety risk from fission reactors is not dominated by such events. Furthermore, this safety advantage must be weighed against the cost of the accelerator or fusion core and the associated availability at the large scale needed for transmutation. In comparison to a conventional fusion reactor, a plutonium burning fusion reactor poses more serious safety concerns. Special safety systems and nuclear-grade codes will be needed in the design of components that implement key safety functions such as containment and decay heat removal. These are important cost drivers that would have to be examined carefully to properly assess fusion's ability to compete as a viable alternative to burn plutonium.

References for Section 5

[1] J. M. Martinez-Val et al., "Critical vs. Subcritical Reactors for Nuclear Waste Transmutation,"

[2] Severe Accident Risks: An Assessment for Five U.S. Nuclear Power Plants, US Nuclear Regulatory Commission, NUREG-1150, December 1990.

[3] Simplified Passive Advanced Light Water Reactor Plant Program, AP-600 Standard Safety Analysis Report, Westinghouse Electric Corporatoin, Pittsburgh, PA, prepared for the US DOE San Francisco Operations Office under contract DE-AC03-90SF18495, revision 13, May 30,1997

[4] Probabilistic Risk Assessment of the Modular High-Temperature Gas-Cooled Reactor, GA Technologies, Inc., GAA-18930, July 1987.

[5] Preapplication Safety Evaluation Report (PSER) for the Power Reactor Innovative Small Module (PRISM) Liquid-Metal Reactor, US Nuclear Regulatory Commission, NUREG-1368, February 1994.

[6] "Safety Aspects of the US Advanced LMR (Liquid Metal Reactor) Design," Argonne National Laboratory, International Workshop on Safety of Nuclear Installations of the Next Generation and Beyond, Chicago, IL, August 28-31, 1989, CONF8908413.

[7] F. Najmabadi and the ARIES Team, "Overview of the ARIES-RS Reversed-Shear Tokamak Power Plant Study," Fusion Engineering and Design, Vol. 38, 1997.

6. Observations

The concept definition phase of this study consisted of four tasks:

(1) A market assessment to identify the most useful application and product.

(2) An assessment of the engineering and nuclear performance characteristics of the three options proposed for neutron-source applications, i.e., fission reactors, accelerators and fusion systems.

(3) System studies to assess the economic potential of MFE-based fusion neutron-source applications.

(4) An assessment of the environmental, safety and licensing implications of fusion neutron source applications.

In the context of the four tasks, the following key observations emerged from the study:

(1) The use of fusion neutrons for the transmutation of nuclear waste and the burning of plutonium scored very high in the market assessment and therefore, was chosen as the focus of the concept definition phase.

(2) There is no established set of objectives and metrics by which to compare the three options for transmutation of nuclear waste and burning of plutonium. Such a set of objectives and metrics is essential for definitive comparisons.

(3) The performance characteristics of the transmutation options are to a large extent dependent on blanket design and processing mode, and to a lesser extent dependent on the details of the neutron source.

(4) The most fundamental distinction among the neutron-source options is tied to the issue of criticality, i.e., fission systems operate in a critical mode, while fusion and accelerator systems provide external neutron sources, which drive subcritical blanket assemblies.

(5) Subcritical assemblies offer several operational advantages compared to critical assemblies, including deeper burnup of waste, and flexibility in engineering design and power control.

(6) The economic performance parameters of the fusion-based transmuter appear to be comparable to those of the accelerator-based transmuter. Economic performance parameters could not be found for the fission-based options considered.

(7) The estimated cost of electricity is higher for the fusion waste transmuter than for a pure fusion power system because of the more conservative physics assumptions, the requirement for a chemical processing plant and fewer safety credits. However, the primary goal of the transmuter is disposition of waste and any sale of electricity should be viewed as an offset to the capital and operational costs for the transmutation mission.

(8) The external neutron-source options offer the potential of improved safety compared to the fission option. These advantages relate to reduced risk of criticality events and the physical separation of the neutron source and the radioactive inventory. The impact of these potential safety advantages in terms of economic implications and public perception is yet to be determined.

In summary, it appears that a fusion-based system could provide a viable option for the transmutation of nuclear waste. The extent to which the fusion community should pursue and promote such an application of fusion is more a matter of policy than technical feasibility. If a follow-up to this study were recommended, the following activities would be proposed:

(1) Identify a reference set of objectives, metrics, and goals.

(2) Select a fusion configuration and blanket option consistent with the above.

(3) Develop a design to a level of detail comparable with previous ARIES designs.

(4) Develop a roadmap for implementation based on the ATW roadmap.

Acknowledgements:

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

Additional Bibliography

1) 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.

2) 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.

3) 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).

4) 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 French Section.

5) 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).

6) K.A. Williams, “Life Cycle Costs for the Domestic Reactor-Based Plutonium Disposition Option,” ORNL/TM-1999-257, October 1999.