

# **REPORT ON THE ARIES FUSION NEUTRON-SOURCE STUDY**

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## **BACKGROUND AND APPROACH**

- **The purpose of this study was 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 which consisted of the following four tasks:**

## **BACKGROUND AND APPROACH *(CONTINUED)***

- (1) A market 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**
- (3) System studies to assess the economic characteristics of MFE-based fusion neutron-source applications**

## **BACKGROUND AND APPROACH *(CONTINUED)***

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

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

## **OBSERVATIONS**

- (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
- (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 neutron source

## **OBSERVATIONS** (continued)

- (4) The most fundamental distinction among the neutron-source options is associated with 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 are comparable to those of an accelerator-based transmuter. Economic parameters for the fission-based options considered could not be found.

## **OBSERVATIONS** (continued)

- (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

## **OBSERVATIONS** (continued)

- (9) The impact of these potential safety advantages in terms of economic implications and public perception is yet to be determined
  
- (10) 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 OFES should decide on a followup to the NS study,  
the following activities would be proposed

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- Identify a reference set of objectives, metrics & goals
- Select a fusion configuration & blanket option consistent with the above
- Develop a design to a level comparable with previous ARIES designs
- Develop a roadmap for implementation based on the ATW roadmap

**TECHNICAL**

**DETAILS**

# 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

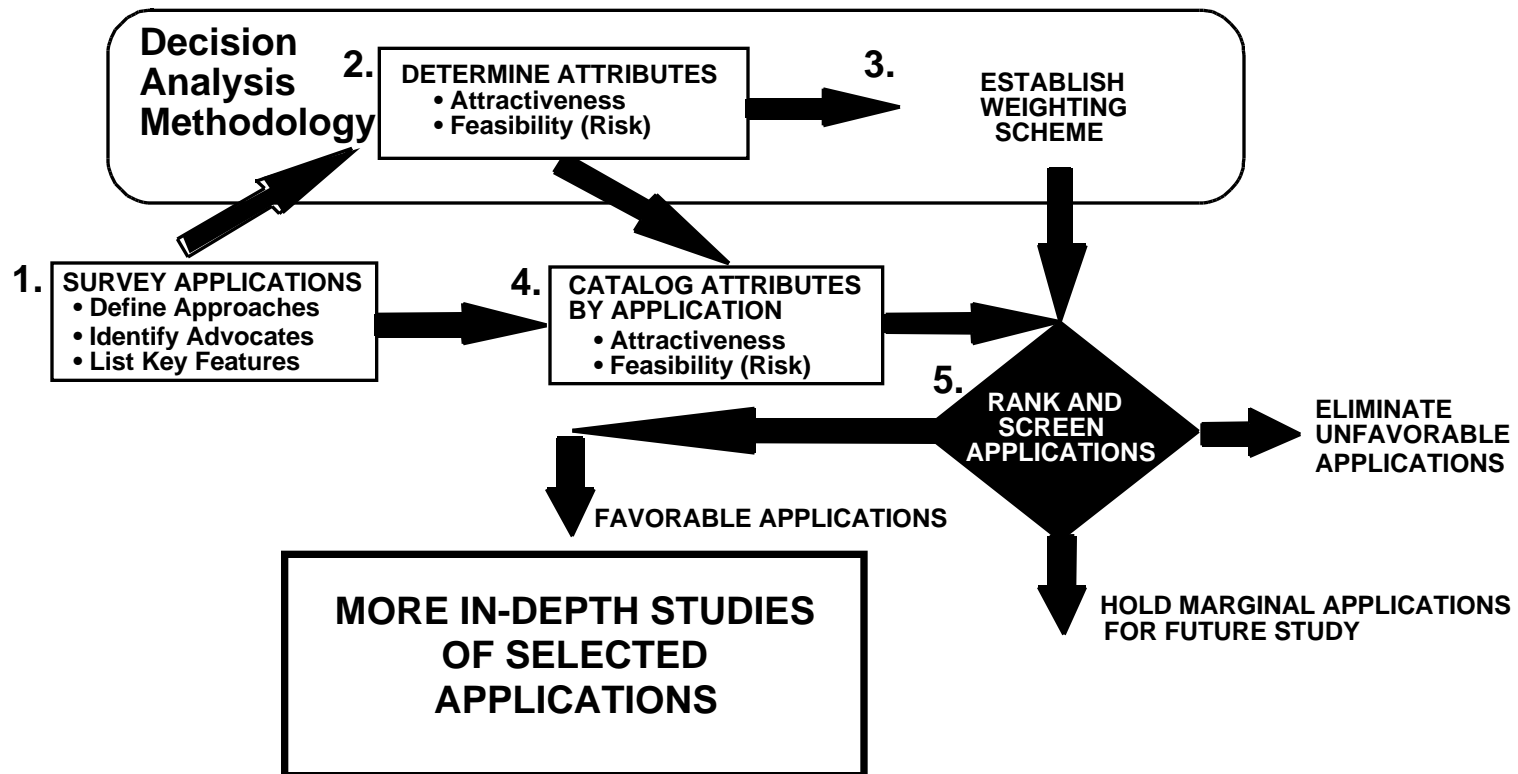
## Direct usage

- 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

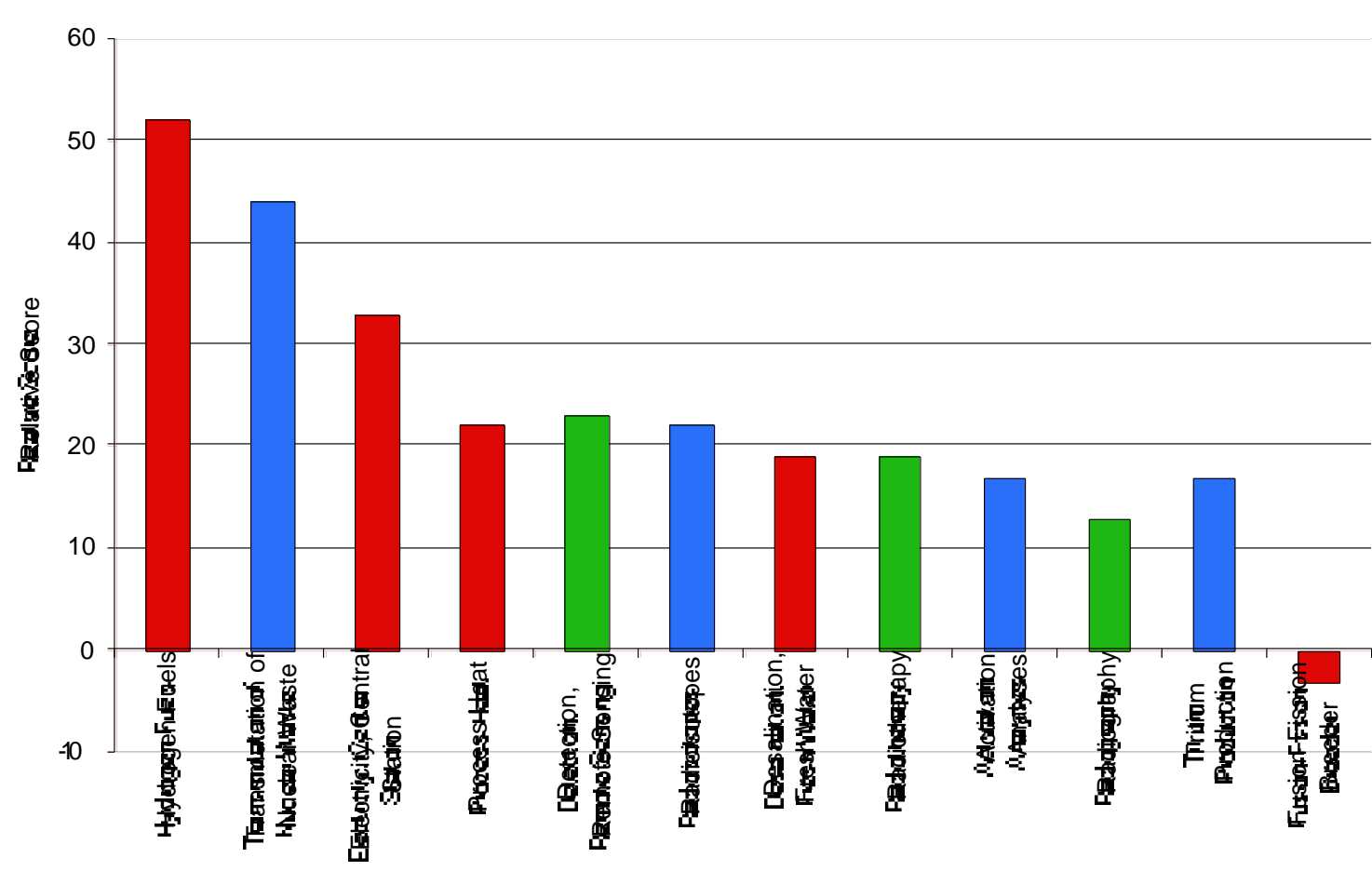
# ASSESSMENT OF NEUTRON SOURCE APPLICATIONS



## DECISION CRITERIA ATTRIBUTES

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

# RANKED WEIGHTED VALUES OF FUSION PRODUCTS



## SOME ENGINEERING CONCEPTS CONSIDERED IN PREVIOUS STUDIES

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Type	Coolant/ moderator	Fuel	Breeder/ target
<b>Fission</b>			
IFR	Na	metallic	
HTGR	He	coated Pu oxide	
Heavy metal	PbBi	metallic	
<b>Fusion</b>			
Molten salt	self-cooled	PuF	He/LiAlO <sub>2</sub>
LBE	PbBi	metallic	PbLi
HTGR	He	oxide	Li oxide
<b>Accelerator</b>			
Na-cooled	Na	metallic	W
PbBi-cooled	PbBi	metallic	PbBi
Aqueous	D <sub>2</sub> O	oxide suspension	W/Pb
Non-aqueous	He/graphite	molten salt	Pb
HTGR	He/graphite	coated oxide	

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# FUEL CYCLE OPTIONS

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## Feedstock

- Weapons material ( $^{239}\text{Pu}$ ) 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

# KEY NEUTRONIC PERFORMANCE PARAMETERS

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

## Na-COOLED IFR PARAMETERS

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	<b>Conventional</b>	<b>Moderate Burner</b>	<b>Pure Burner</b>
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 (% k)	0.03	2.9	3.2
Fuel cycle length (months)	23	12	12
Equilibrium discharge % <sup>239</sup> Pu	63	58	52
<sup>239</sup> 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

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\* could be tailored for TRU consumption =0

\*\* TRU=transuranic

\*\*\* 231 kg/yr = maximum achievable

## COMPARISON OF PERFORMANCE PARAMETERS FOR FISSION, FUSION AND ACCELERATOR BASED TRANSMUTATION 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
$k_{\text{eff}}$ (initial, unless noted)	0.74	0.965/0.816	0.877/0.729		1.2	1.0686 <sup>(5)</sup>	0.97	0.96
Burnup reactivity loss	0.0	0.00745/ % <sup>(2)</sup>	0.0074/ % <sup>(2)</sup>	3.2%				
Thermal fission power, MW	1000	1000	1000	840	1800	600	840	2088
Average power density W/cc	50	300 <sup>(3)</sup>	300 <sup>(3)</sup>	155	126		350	700
W/gHM	680	350	406	113	313	946	566	160
HM inventory, kg	1487 <sup>(4)</sup>	2873 <sup>(4)</sup>	2477 <sup>(4)</sup>	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 <sup>(1)</sup>	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 <sup>2</sup>	1.48x10 <sup>22</sup>	1.27x10 <sup>23</sup>	1.26x10 <sup>23</sup>	3.8x10 <sup>23</sup>		4.2x10 <sup>21</sup>		
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

<sup>(1)</sup> ratio of captures to fissions

<sup>(4)</sup> blanket inventory only

<sup>(2)</sup> change in  $k_{\text{eff}}$  per % burnup, averaged over 20% burnup cycle

<sup>(5)</sup> cold, with control rods removed

<sup>(3)</sup> in Zr-Pu-Ma fuel only

## DT ARIES-NS<sup>(a)</sup> 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 <sup>2</sup> )	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 <sup>(b)</sup> , $M_n$	15	30	60
Blanket neutron multiplication <sup>(c)</sup> , $k_{eff}$	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, $Q_E = 1/\epsilon$	2.74	3.30	3.80
1992-\$ Total capital cost <sup>(d)</sup> , (G\$)	5.73	5.03	4.49

## DT ARIES-NS<sup>(a)</sup> PARAMETERS

Parameter	Case 1	Case 2	Case 3
<b>Neutron energy multiplication<sup>(b)</sup>, <math>M_n</math></b>	<b>15</b>	<b>30</b>	<b>60</b>
<b>Blanket neutron multiplication<sup>(c)</sup>, <math>k_{eff}</math></b>	<b>0.68</b>	<b>0.81</b>	<b>0.89</b>
<b>14.1-MeV neutron wall load, <math>I_w</math>(MW/m<sup>2</sup>)</b>	<b>0.66</b>	<b>0.37</b>	<b>0.23</b>
<b>Peak neutron wall load, <math>\hat{I}_w</math>(MW/m<sup>2</sup>)</b>	<b>1.0</b>	<b>0.55</b>	<b>0.34</b>
<b>14.1-MeV-n source rate (n/s)</b>	<b>1.24x10<sup>20</sup></b>	<b>5.8x10<sup>19</sup></b>	<b>2.8x10<sup>19</sup></b>
<b>14.1-MeV-n source rate (mole/a)</b>	<b>4.86x10<sup>3</sup></b>	<b>2.25x10<sup>3</sup></b>	<b>1.05x10<sup>3</sup></b>
<b>Fusion power, <math>P_F</math>(MW)</b>	<b>350</b>	<b>163</b>	<b>78</b>
<b>Fission power, <math>P_{Fis}</math>(MW)</b>	<b>3,925</b>	<b>3,775</b>	<b>3,675</b>
<b>Total thermal power, <math>P_{TH}</math>(MW)</b>	<b>4,500</b>	<b>4,099</b>	<b>3,879</b>
<b><math>n_{fission}/n_{fusion}</math> (est.<sup>(d)</sup>)</b>	<b>2.86</b>	<b>5.93</b>	<b>12.06</b>
<b><math>(n_{fission} + n_{fusion})/n_{fusion}</math></b>	<b>3.86</b>	<b>6.93</b>	<b>13.06</b>
<b>1992-\$ Cost of electricity<sup>(e,f)</sup>, COE (mill/kWeh) w/o LSA credits (LSA = 4)</b>	<b>96</b>	<b>86</b>	<b>78</b>
<b>Incremental COE due to chemical plant (mill/kWeh)</b>	<b>7.3</b>	<b>7.1</b>	<b>7.1</b>
<b>Annual Pu destruction rate<sup>(f)</sup>, <math>R_{Pu}</math> (kg/a)</b>	<b>1,150</b>	<b>1,110</b>	<b>1,080</b>
<b>Pu service charge to meet COE target<sup>(g)</sup> (k\$/kg)</b>	<b>306</b>	<b>258</b>	<b>216</b>
<b>Annual Pu service charge<sup>(g)</sup> (M\$/a)</b>	<b>352</b>	<b>286</b>	<b>233</b>

<sup>(a)</sup> ST *cf* Table 4.1

<sup>(b)</sup> Pu-burning outboard blanket

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

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

<sup>(e)</sup> not including chemical plant

<sup>(f)</sup>  $p_f = 0.75$

<sup>(g)</sup> 50 mill/kWeh