HIGHER ACTINIDE TRANSMUTATION IN THE ALMR

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ABSTRACT

The Advanced Liquid Metal Reactor (ALMR) is a US Department of Energy (DOE) sponsored fast reactor design based on the Power Reactor, Innovative Small Module (PRISM) concept originated by General Electric and fueled with ternary metal fuel (under development by Argonne National Laboratory in the IFR Program). Higher actinide transmutation may be accomplished in the ALMR by using either a breeding or burning configuration. This paper discusses actinide transmutation core designs that fit the safety and design envelope of the ALMR and utilize spent LWR fuel as startup material and makeup. Different core sizes are considered with different burner configurations. Impacts on system operational and safety performance are evaluated. Lifetime actinide mass consumption are calculated as well as changes in consumption behavior throughout the lifetime of the reactor.

I. INTRODUCTION

The objective of the Advanced Liquid Metal Reactor (ALMR) Actinide Recycle Program, under the sponsorship of the U.S. Department of Energy, is to develop a competitive fast reactor system aimed at improving safety, enhancing plant licensability, simplifying plant operations, and capable of adding waste management flexibility. This activity, led by GE in reactor design [1] and Argonne National Laboratory (ANL) in fuel and fuel cycle design[2], is a national program involving wide participation by U.S. industries, the U.S. national laboratories, universities, and international contributors. One of the goals of the program is to develop a standardized design that can be licensed and certified. The core designs utilize ternary metal fuel. This paper discusses actinide transmutation in core designs that fit the design and safety envelope of the ALMR and utilize spent LWR fuel as startup material and for makeup.

Higher actinide transmutation has long been an intriguing concept associated with closing the nuclear fuel cycle and improving waste management. The concept involves transmutation or fissioning of the longer-lived transuranic [TRU] isotopes to shorter-lived fission products. The primary incentives for transmutation of these TRU isotopes are to eliminate them from the ultimate waste stream via processing spent fuel and to recycle the TRU as an ALMR fuel source. LWR irradiated fuel contains about 1% transuranics in total heaw metal. This transuranic mass consists of 6% minor actinides (MA-neptunium.

americium, and curium) at discharge,; the minor actinide fraction increases with time (i.e., 11 % after 10 years) as fissile 241 Pu (half-life of 14.4 years) decays into fertile ^{241}Am.

There are two basic processing concepts, aqueous and pyroprocess, to achieve actinide recovery from spent LWR fuel for recycle to the ALMR. Aqueous processes and pyroprocesses may be used for recovery of actinides from both LWR and ALMR spent fuel and recycle to the ALMR. The pyroprocesses for processing LWR and ALMR spent fuel are the reference processes in the ALMR program and are under development by ANL. Unlike the aqueous process, the pyroprocess does not separate Pu from other TRU; thus, the minor actinide content of the metal fuel is dictated by its relative concentration in the LWR spent fuel. The lack of a pure plutonium stream in the pyroprocess enhances the proliferation resistance of the fuel cycle.

The conceptual limit of transuranic burning is a 'pure' burner core where only transuranics are utilized as fuel material (i.e., no U-238 is present in the reactor). For a pure burner, the transuranic consumption rate is simply the product of the reactor power level and a fission energy conversion factor (1.07 grams per MWt-day assuming 200 MeV/fission). Thus, an 840 MWt ALMR pure burner design operating at an 85% capacity factor would consume 280 kg/yr of transuranics. In practice, a variety of design constraints limit the net transuranic consumption rate to much lower levels. The ALMR is a reactor system that uses passive safety features (including metal fuel), and the actinide burning cores studied in this paper should not have a significant impact on these features. The reported study was done in the context of this system and an evaluation was made of the impacts on the cores' safety features.

II. PLANT DESCRIPTION

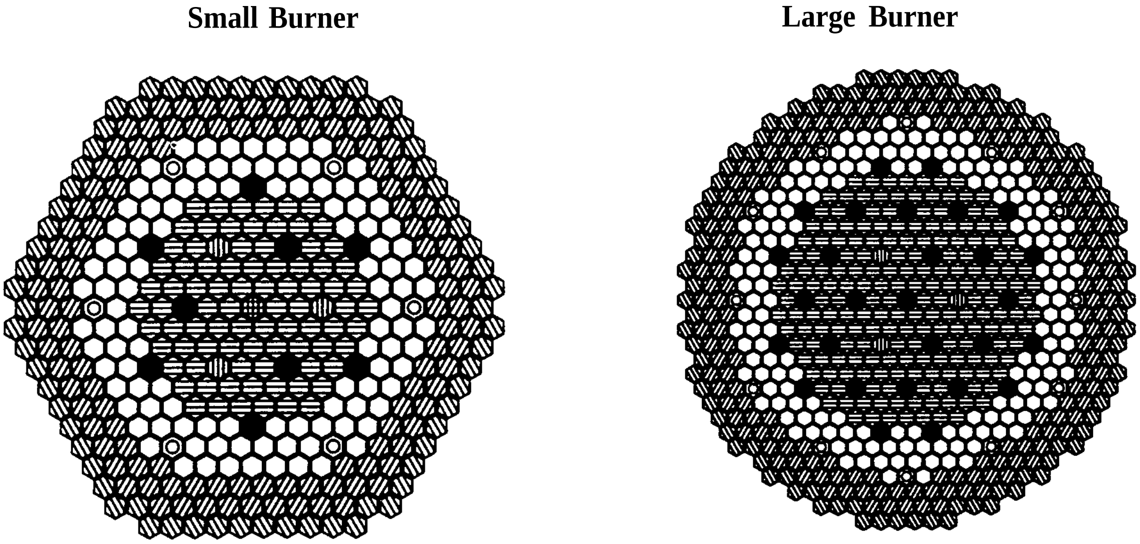
The ALMR plant utilizes six reactor modules in three identical 606 MWe power blocks. Each power block consists of two identical reactor modules, each with its own helical coil steam generator, that jointly supply steam to a single turbine generator. The thermal rating of each module is 840 MWt. A sodium-filled intermediate heat transport system provides normal heat removal for the reactor through an intermediate heat exchanger (II-IX) and transports the energy to the steam generator in a superheat steam cycle. The reactor facility is seismically isolated to provide high margins in seismic performance.

The pool-type reactor contains the core, two IHXs, four primary electromagnetic pumps, and interim spent fuel storage. Containment is provided by a low leakage, pressure-retaining boundary, which completely encloses the reactor coolant boundary. The containment boundary consists of a lower containment vessel surrounding the reactor vessel and an upper dome over the reactor closure.

III. CORE DESCRIPTION

The core system is designed to generate 840 MWt of power. Conventional ALMR core designs utilize a radially heterogeneous configuration; the inclusion of internal blanket zones allows fuel cycle operation in a 'breakeven' mode where the fissile material (transuranics, primarily Pu-239 and Pu-241) is consumed and destroyed at roughly equal rates. The 840 MWt breakeven core has an active fuel height of 42 inches, with a diameter of 141 inches, and a total of 192 fueled assemblies (108 drivers and 84 blankets). The fuel form is ternary (U-TRU-10%Zr) metal fuel alloy in the drivers and binary (U-10%Zr) metal fuel alloy in the blankets. The geometric envelope of this core system does not preclude the substitution of oxide fuel. Minor actinides are included in the recycled transuranic feed in the proportions present in the source LWR spent fuel (10.7% MA/TRU). HT9 is used as the core structural material.

Two burner configurations are analyzed in this paper. A primary goal in developing the burner core configurations is to maintain compatibility with the breakeven reactor design; design changes to the conventional reactor are to be minimized. Net consumption of transuranics in the burner designs is achieved by removing fertile material from the breakeven configuration; all blanket assemblies are replaced with drivers, thus reducing the uranium inventory. The conversion ratio is further reduced by pancaking the core shape (decreasing the core height), This design technique removes additional fertile material and increases the neutron leakage probability. Allowable height decreases are constrained by


Small Burner

Large Burner

	Small Burner
▤ **Low Enrichment Fuel**	84
⬡ **High Enrichment** Fuel	108
⬢ Control	**9**
▥ **Ultimate** Shutdown	3
⊞ **Source**	1
◎ . . . **Expansion Module**	6
▨ Reflector	114
▧ **Shield**	**66**
Total	391

	Large Burner
▤ **Low Enrichment Fuel**	192
⬡ **High Enrichment** Fuel	**162**
⬢ Control	28
▥ **Ultimate Shutdown**	3
◎ **Gas Expansion Module**	12
▨ Reflector	162
▧ Shield	**90**
Total	649

Figure 1. CORE LAYOUTS

several nuclear performance limits which are applied to each of the core designs: the burnup reactivity swing is limited to $10, the peak fuel burnup is limited to 150 MWd/kg, the peak neutron fast fluence is limited to 4.0x 1023 n/cm^2, and the transuranic enrichment is limited to 30 wt.% of the ternary alloy (the range of the current metallic fuels database).

If all the fueled assemblies of the breakeven core are converted to drivers, the resulting homogeneous core design is shown in Fig. 1; this core design will be called the small burner throughout this paper. The minimal core height is 26 inches with a diameter of141 inches and a total of 192 fueled assemblies.

Alternatively, further geometric spoiling (more pancaked core configurations) may be achieved by increasing the diameter of the core; enough empty space exists within the core barrel to allow roughly 3 feet of radial expansion. A core configuration utilizing this extra space is shown in Fig. 1; this core design will be called the large burner throughout this paper. The minimal core height is 18 inches with a diameter of 175 inches, and a total of 354 fueled assemblies. The resulting total fueled volume is 25°/0 larger than the small burner. In addition, extra control assemblies are required because of the reduced active fuel height and increased radial dimensions.

The large burner design requires some modifications to the reactor system. Provisions

Table 1 Neutronics Results

	Breakeven	Small Burner	Large Burner
Core Height (in.)	42	26	18
Core Diameter (in)	141	141	175
# of Fuel Assy	108	192	354
# of Blanket Assy	84		
Conversion Ratio	1.06	0.72	0.59
Cycle Length (months)	23	12	12
Burnup Reactivity Swing ($)	0.57	8.99	8.45
Peak Linear Power	9.5	10.4	8.2
Sodium Void Worth	6.2	-2.50	< 0
TRU Em. (wt% in U-TRU-Zr)	21	19123	24129
TRU Inventory (kg/core)	2681	2554	3890
TRU Consumption Rate			
kg/year /core	-28.2	83.2	121.0
% inventory/year	-1.1	3.3	3.1

must be made on the head to accommodate additional control rods; this necessitates a larger diameter Upper Internals Structure (increases by two feet) and enlarged plug diameter (by one foot) as well as art extension of the In-Vessel Transfer Machine pantograph reach. These modifications can readily be accommodated in the closure and in the space above the enclosure where the driveshafts and motors are located. In addition, the reactor vessel length is increased by 5 inches to accommodate the inlet plenum diameter increase required by the larger diameter core.

Table 2 Summary **of Reactivity Data at BOEC**

	Breakeven Core	Small Burner	Large Burner
Uniform Axial Expansion (Hdk/dH)			
Net Effect	-0.16430	-0.13400	-0.10053
Geometry Effect	0.15792	0.27700	0.34592
Uniform Radial Expansion (Rdk/dR)			
Net Effect	-0.48418	-0.69253	-0.79745
Geometry Effect	0.16026	0.12947	0.09545
Doppler Coefficients (Tdk/dT)			
Driver Fuel	-0.00190	-0.00280	-0.00240
Blankets	-0.00251		
Total	-0.00441	-0.00280	-0.00240
Fuel Density Coefficients			
Driver Fuel	0.41989	0.42090	0.44800
Blankets	-0.03111		
Total	0.38878	0.42090	0.44800
Sodium Density Coefficients			
Driver Fuel	-0.01383	-0.00925	-0,00188
Blankets	-0.00671		
Others	0.00197	0.00368	0.00353
Total	-0,01857	-0.00557	0.00165
Total Beta-effective	0.00337	0.00321	0.00303

The core and its restraint and reactivity control systems are designed such that operation of the shutdown system (i.e., scram) is not necessary to protect the public for the following events: loss of normal heat sink; loss of all primary system cooling by the intermediate heat transport system, without forced primary flow; and transient overpower due to withdrawal of all control rods to rod stops.

IV. NEUTRONICS RESULTS

Neutronic results are given in Table 1. The large burner has a lower conversion ratio, slightly lower burnup reactivity swing, and lower peak linear power than the small burner. The extreme pancaking (and thus higher leakage) of the large burner also gives a negative sodium void worth. Core parameters such as burnup and peak fast fluence are well within design limits for all cores.

Calculations of reactivity coefficients and neutron kinetics parameters were carried out utilizing DIF3D/VARI3D with 22 neutron groups in a fine-meshed triangular-z geometry model. The results of these calculations are summarized in Table 2.

The uniform axial expansion coefficient provides significant negative feedback during transient events as fuel expands axially with rising temperature. This coefficient becomes smaller with shorter height and greater pancaking of the core.

The uniform radial expansion coefficient provides two important inherent reactivity feedback mechanisms: the radial thermal expansion of the grid plate which is controlled by coolant inlet temperature, and the radial thermal expansion of assembly duct load pads (located axially above the active core). Both mechanisms are expected to provide negative feedback with rising core temperatures. The short core height results in large density coefficient because of high axial leakage, leading to a relatively large radial expansion coefficient.

The Doppler coefficient (Tdk/dT) is smaller for shorter cores due to higher TRU enrichments. Approximately 2/3 of the core Doppler is contributed by the inner low enriched fuel assemblies in the burner cores.

The sodium density coefficient is expressed as fractional change in core reactivity per fractional change in sodium density. The positivity of these coefficients in the large burner, as opposed to normally negative coefficients in a taller core, e.g., the ALMR breakeven core, is a direct result of pronounced axial leakage that overshadows the spectral effect in a short core.

The sodium void reactivity for all fuel assemblies is $6.30 for the breakeven core, $2.5 for the small burner, and -0.50 for the large burner at BOEC, assuming total assembly voiding. These values are predicted with the continuous energy Monte Carlo method. The reduced sodium void worth for the burner designs comes at the expense of large increases in the burnup reactivity loss.

V. TRANSIENT SAFETY ANALYSES

Transient results were calculated for the large burner core configuration. The following results were computed for a design utilizing different TRU isotopics than presented earlier in the paper. However, the results are expected to be similar to the core designs presented in the previous section.

The performance analysis of the basic RVACS event (loss of non-safety grade decay heat removal paths, with scram) conservatively assumes that the normal and auxiliary heat removal systems, as well as the Intermediate Heat Transport System (IHTS) sodium, are lost immediately following reactor and primary pump trips. The passive RVACS only is available to remove reactor decay heat.

The maximum average core outlet temperature reached for the LWR spent fuel "startup" core, which has the highest level of decay heat, is 1152°F on a nominal basis, and with 2-sigma uncertainties added, 1230^{o}F. These temperatures are below the 1250°F ASME Level C limit set for reactor structures. It should be noted that sodium and structural temperatures in the other regions of the reactor are lower, most considerably lower than the average core outlet temperature.

The ALMR safety design goal is to accommodate selected ATWS events, specifically unprotected transient overpower (uTOP), unprotected loss of flow (ULOF), and unprotected loss of heat sink (ULOHS), so that reactor (core and structures) damage leading to a safety challenge does not occur. The corresponding conservative criteria are the following:

- ASME code limits maintained for all reactor structures
- Cladding attack by fuel/clad eutectic less than 10% cladding wall thickness (2 roils)
- No local sodium boiling
- Limited extent of centerline fuel melting
- Limited number of unrelated pin cladding failures; no pin failure propagation

Analyses of ATWS events are performed with the events being initiated while the reactor is at nominal, full power conditions, with a core inlet temperature of 680”F and a mixed mean outlet temperature of 930°F. The analyses are performed at both beginning and end of equilibrium cycle conditions. A summary of ATWS results for the breakeven and large burner cores are given in Table 3.

Temperatures for the large burner core during a 0.3$ UTOP transient are shown in Figure 2 for the beginning of cycle of the large burner core. At BOC, the power rises as the control rods are withdrawn during the UTOP event and reaches a peak of 138°/0 of rated soon after the rods reach the rod stops, The power then drops rapidly from the negative feedbacks that develop as the core is heated. A significant difference with this core compared to the breakeven core design is the negative feedback due to sodium expansion in the early part of the transient. Sodium expansion feedback as the core heats up results in a positive feedback in the breakeven ALMR design, but it provides a negative feedback in this core because of its pancake configuration. The power reaches an equilibrium level of about 11 3°/0 of rated in about 300 seconds after the start of the event.

The core temperatures during a ULOF/LOHS transient are shown in Figure 3 for the beginning of cycle. The major difference in the ULOF/LOHS event between this core and the breakeven core design is in the pump coastdown performance. The large burner core has much less heat generation in each assembly than the breakeven core design, with a comparable reduction in the assembly flow. The lower flow results in much lower core pressure drop, so less kinetic energy is expended by the synchronous machine during the same coastdown interval. In the breakeven core design, the pumps have stopped pumping within 250 seconds after a pump trip. With the large burner core, the pumps continue for over 700 seconds after a pump trip. The sustained coastdown flow results in much lower peak temperatures during the early phases of the event,

Table 3
ATWS Performance for the Large Burner Compared to the Standard ALMR Mod B Design

		Temperatures					
Events	Power	Peak Fuel	Peak Clad	Peak Na	Mixed Na out	Clad @ 500s	Clad Attack
	%	“F	‘F	“F	“F	‘F	roils
LARGE BURNER							
0.30$ Unprotected Withdrawal of Rods							
BOC	138	1579	1219	1143	1020	1127	0.0
EOC	140	1570	1213	1138	1026	1139	0.0
0.60$ Unprotected Withdrawal of Rods							
At BOC	176	1784	1369	1273	1114	1176	0.02
Unprotected Loss of Flow and IHTS Cooling							
BOC	100	1389	1124	1123	1054	N/A	0.0
EOC	100	1363	1105	1070	1018	N/A	0.0
STANDARD ALMR BREAKEVEN DESIGN							
0.30$ Unprotected Withdrawal of Rods							
BOC	162	1861	1387	1321	1085	1261	0.05
EOC	170	1848	1392	1324	1104	1284	0.07
Unprotected Loss of Flow and IHTS Cooling							
BOC	100	1545	1327	1303	1074	N/A	0.00
EOC	100	1527	1337	1330	1112	N/A	0.02

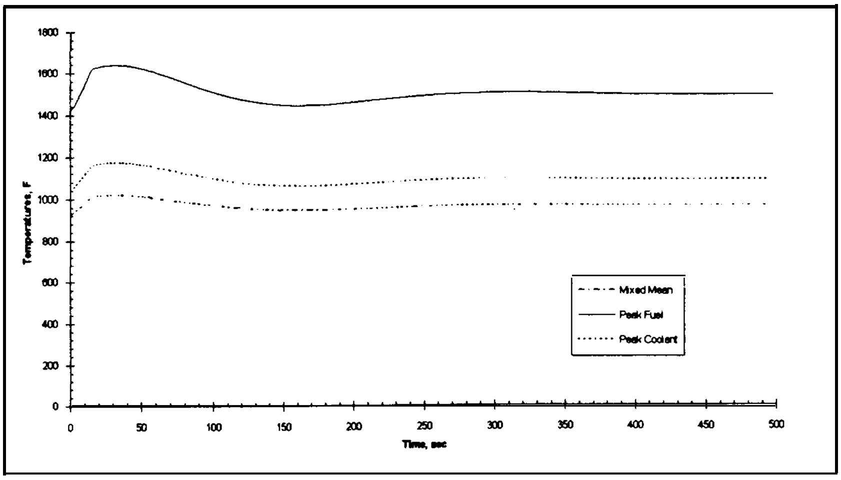


Figure 2 Temperatures During UTOP at BOC for Large Burner

The large burner has large margins in meeting the performance limits during the accommodated ATWS events, and it has greater margins than the breakeven core design for these events (See Table 3). However, some of the performance advantage may be difficult to obtain. The UTOP event was analyzed for the same amount and rate of positive reactivity insertion due to rod withdrawal to the rod stops. The rods can only move about 0.2 inches to limit the reactivity insertion to 0.30$ for the large burner at BOC. The rods can move almost 0.8 inches before 0.30$ is inserted in the standard ALMR design at BOC. This limitation will result in more frequent rod stop changes or the margin can be reduced by permitting higher reactivity insertions during the UTOP. If the rod stops are set for about the same amount of motion, the large burner would see about a 0.60$ UTOP. Table 3 also includes a summary of the large burner during a 0.60$ UTOP. The large burner has power peaking and peak fuel temperatures during the 0.60$ UTOP comparable to those of the 0.30$ UTOP in the standard ALMR design, and much lower peak coolant temperatures.

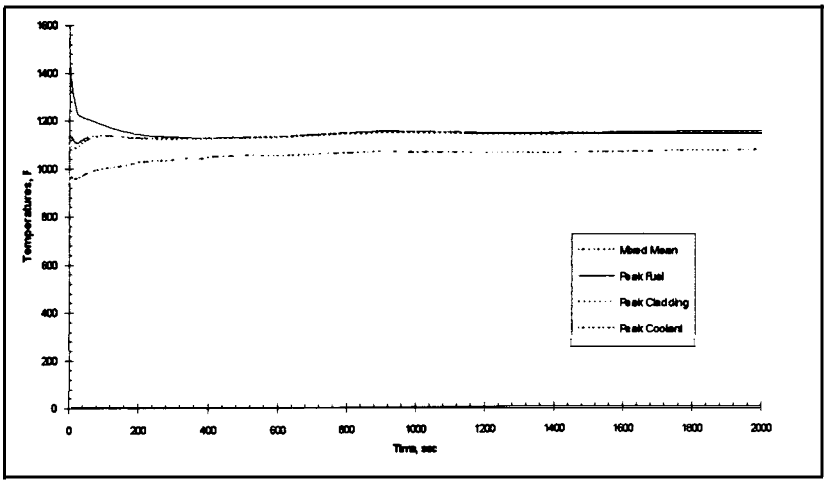


Figure 3 Temperatures During ULOF/LOHS at BOC for Large Burner

There is a possibility of **decreased seismic margin** due to the greatly increased rod worth per inch of the control rods in the shorter cores, but this was not pursued further in this study.

In summary, ATWS and RVACS performance of the burner design appears to be comparable to or better than the performance of the conventional (break-even) core design; however, evaluation of the overall safety of the system requires more detailed study.

VI. TRU MASS CALCULATIONS

To assess actinide consumption rates and total consumption amounts over time, ORIGEN2 calculations were completed for different cores. These results illustrate the effects of recycle and makeup in the ALMR actinide transmuting cores. Results indicate that the concentration of each minor actinide appears to approach an equilibrium value. The percentage of MA in total TRU becomes smaller during the core lifetime, despite the TRU makeup dominating the core composition. The reference breeder ALMR, not requiring LWR TRU makeup, would have a substantially lower equilibrium MA concentration (e.g. changing from 16% to 2.6%). The small burner drops to 6.4'% MA in TRU. The large burner changes to 8.2'% MA in TRU.

Results also indicate unique

characteristics for individual isotopes in both actinide burner designs. Np bums out steadily throughout the plant lifetime. Over 80% of all Np loaded into the ALMR cores over the plant lifetime is consumed. In a similar manner Am and Pu are steadily consumed. During the early cycles, Cm is produced and it is only late in the reactor lifetime (after 30 years) that any Cm isotope is consumed. The amount of Cm produced is small in terms of mass and large in terms of decay heat.

Comparisons of core designs with a parametric variation in core height indicate that shorter cores both load and consume more TRU than the taller cores over the plant lifetime (due to the larger required makeup in the shorter cores). However, the larger cores require larger inventory at startup. The crossover point where the additional makeup required by the shorter core is greater than the larger amount of TRU loaded into the taller core is at approximately 20 years. The lower conversion ratio of the shorter cores also leads to greater consumption amounts during the plant lifetime. However, in the case of the large burner (shorter core, larger diameter), the core both requires larger makeup as well as consumed more TRU per year.

The ORIGEN2 calculations gave different results than the diffusion calculations. The small burner destroyed approximately 315 kg of MA and 2400 kg of TRU per core over 60 years. The large burner destroyed 483 kg of MA over 60 years and 3300 kg of TRU per core over 60 years. These values are smaller than the diffusion calculations predict. The true consumption values are probably between these two values.

More than 60 percent of the total TRU introduced to the burner ALMR is consumed during the reactor lifetimes as well as more than 60 percent of the MA introduced. In addition to the net consumption of TRU in the burner ALMR design, an additional benefit is gained from the storage of the working TRU inventory in the metal fuel cycle for the system lifetime.

As the total core power rises, a larger amount of TRU is transmuted per core. In addition, the lower the conversion ratio, the greater the amount of TRU transmuted perMWt produced. Also, more pancaked cores transmute about the same percentage as less pancaked cores, but since their inventory is larger and the leakage is greater, flatter cores transmute a greater amount per given MWt produced.

Risk and cost associated with processing need to be evaluated and compared to direct disposal of LWR spent fuel. However, recycling waste will allow the incorporation of process changes which could modify the final waste composition to improve repository performance. With unprocessed spent fuel, packaging is the only part of the waste which can be improved or modified to enhance the repository performance.

VII. CONCLUSIONS

Overall, actinide recycle and consumption appear promising as a waste management approach as well as providing fuel for ALMR startup and deployment for power production. Processing spent fuel provides an opportunity for removal of the actinides and selected fission products from the waste streams as well as potentially improved waste forms. Burner core designs appear to have favorable passive safety responses similar to conventional breakeven core designs. The ALMR is very flexible and well positioned to provide actinide recycle in both breakeven and burner modes. The IFR fuel cycle has the potential to recover TRU element from spent fuel; this results in lower TRU levels in the ultimate waste stream and sustained power production from the recovered materials.

VIII. REFERENCES

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