Modeling a Global View on Nuclear Fuel Leasing, Recycling, and Proliferation

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Abstract

The model was used to study fuel leasing possibilities after a system dynamics model was built to simulate fuel cycle interactions between two different nuclear organisations. The model was also used to assess the proliferation and economic consequences of a global leasing policy. An open fuel cycle results in large spent-fuel buildup in a nuclear expansion scenario. The leased fuel cycle, when combined with enhanced security and safety technologies, has the ability to alleviate proliferation concerns in a closed fuel cycle.

Keywords: *fuel, dynamics, proliferation, nuclear*

1. Introduction

1.1 The Multinuke Model

For each individual nation-state or confederation of nations Multinuke assumes that nuclear power market fragmentation is a manifestation of government strategy. The hybrid fuel cycle stock-and-flow diagram depicted in Figure 1 represents each entity in whole or in part. Multinuke contains both thermal and fast reactors, each having the capacity to operate with both open and closed fuel cycles, as well as the use of surplus nuclear weapons material as a fuel stock for both thermal and fast reactors. It monitors the movement of uranium, plutonium, and fission products through the nuclear fuel cycle. Specific fuel cycles may be represented by turning on or off certain sections of the flow diagram inside the software, and Multinuke is designed to compute the impacts of leasing fuel services from a fuel cycle state to a reactor state by allowing material transfers from one entity to another. The simulation produces chronological histories of material flows, expenses, and concerns about proliferation.

For the sake of this analysis, we've assumed that the primary goal of recycling is to manage wasted fuel, and Multinuke has been set up appropriately. If spent fuel storage is unrestricted, there is no recycling, and each nuclear power plant continues to run on an open fuel cycle. If spent fuel storage is limited (assumed to be the total of interim storage and permanent disposition), recycling is assumed to begin at a time and with a capacity (tonnes/year) such that the spent fuel storage limit is not exceeded throughout the simulation duration.

Multinuke may be used to explore potential interactions between any two organisations, such as Russia and Iran, or between multiple public or private consortia, or to investigate the worldwide repercussions of an international leasing system, as we will do in this work.

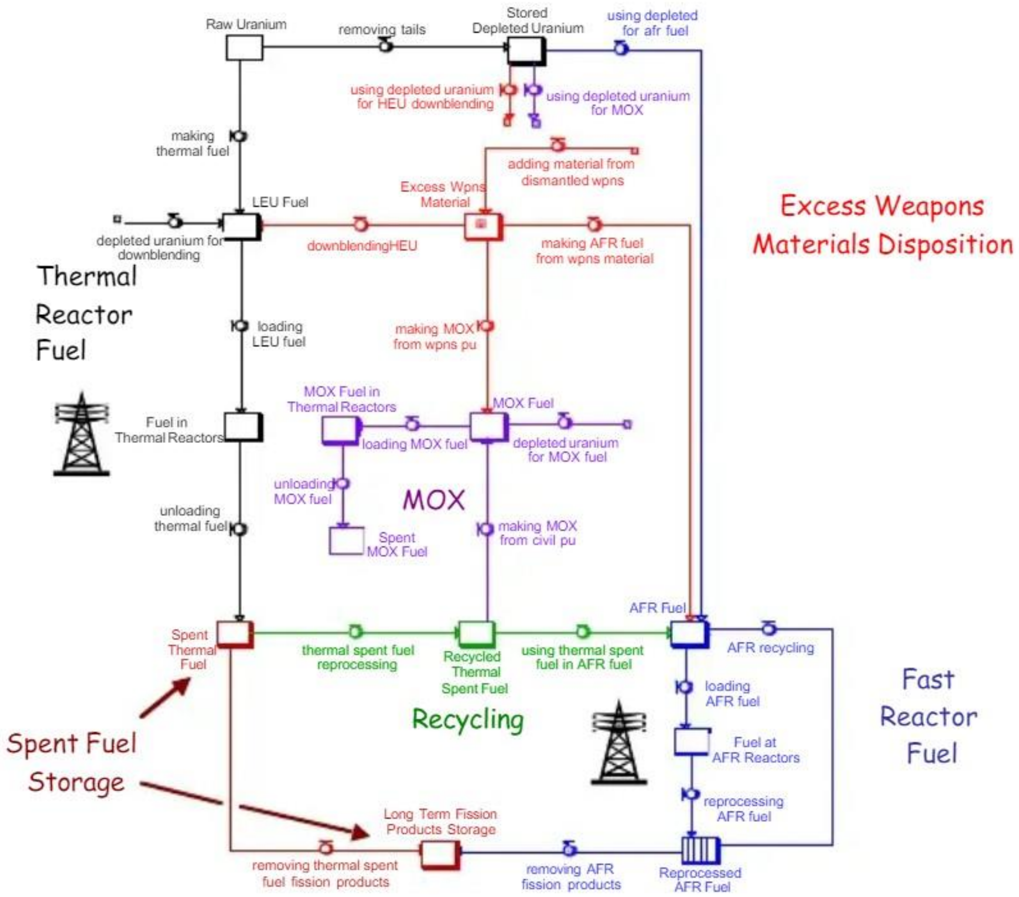

FIG 1. Stock and Flow Diagram of the Multinuke Fuel Cycle

Examples

We divide the world's nuclear power generating states into two categories to get a sense of the potential effects of nuclear fuel leasing: states with significant fuel cycle capacity – any or all of enrichment, recycling, or spent fuel storage – (Type 1), and states with little or no fuel cycle capability (Type 2). For the sake of this article, Type 1 nations include the present declared nuclear weapons states (the United States, the United Kingdom, France, Russia, and China), as well as Japan, while Type 2 states include everyone else. During an 80-year simulation period, suppose that electricity growth is 1% per year in Type 1 states and 2% per year in Type 2 states.Table 1 shows the initial figures for fossil power, nuclear power, and spent fuel based on Energy Information Administration compilations.

Table 1. Initial Values

	Type 1	**Type 2**
Nuclear Energy	220	100
Fossil Energy	560	700
Used Fuel	150,000	75,000

We suppose that from reprocessing activities in Type 1 states, there are 200 tonnes of civilian separated plutonium. For the sake of simplicity, we do not discuss how to dispose of extra nuclear weapons material (both HEU and plutonium) in this work. We also do not discuss the existing reprocessing and MOX fuel usage in thermal reactors for Type 1 states.

We analyse a scenario of aggressive nuclear power expansion to better understand the impact of nuclear fuel leasing and spent fuel recycling. (Such a scenario may be encouraged by a strategy that uses nuclear energy to cut carbon emissions from fossil fuel electric power plants.) We suppose both types of states increase their nuclear power production until it accounts for 50% of their total energy generation—in 30 years for Type 1 states and in 50 years for Type 2 states—and then keep it at that level. Figure 2 depicts the distribution of electricity; at the age of 30, a greater proportion of it is produced by Type 2 states.

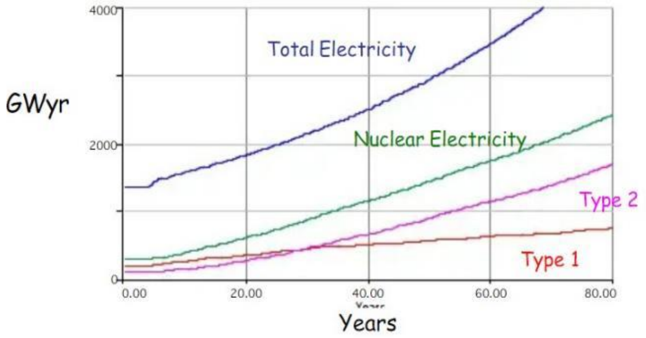

FIG2. Nuclear and Electricity Power Growth Assumed

We evaluate four instances to investigate the impacts of gasoline leasing and recycling on fuel management and proliferation:

1. Every state employs open-cycle thermal reactors and does not lease any. The amount of used nuclear fuel is unrestricted. Figure 3 illustrates this fuel cycle.

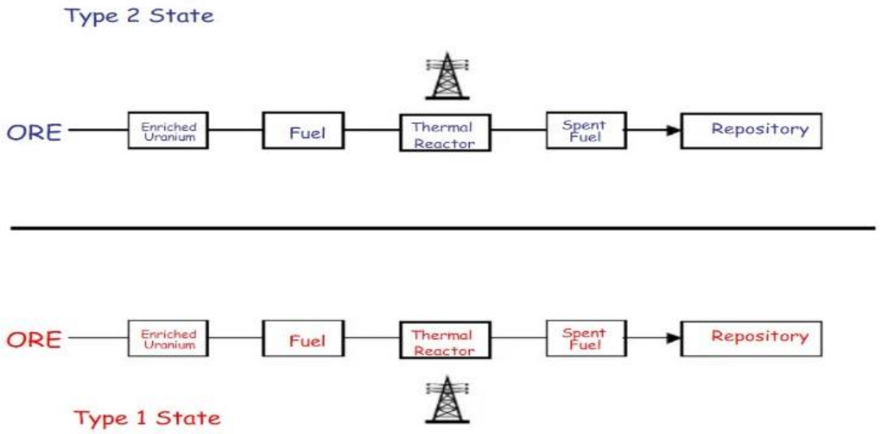

FIG 3. Diagram of the Fuel Cycle, Open Cycle, No Lease

2. Type 1 states have open-cycle thermal reactors and rent fuel to Type 2 states, which only have reactors, as shown in Figure 4. The quantity of used nuclear fuel is unrestricted. In a recent MIT research, this strategy was recommended.

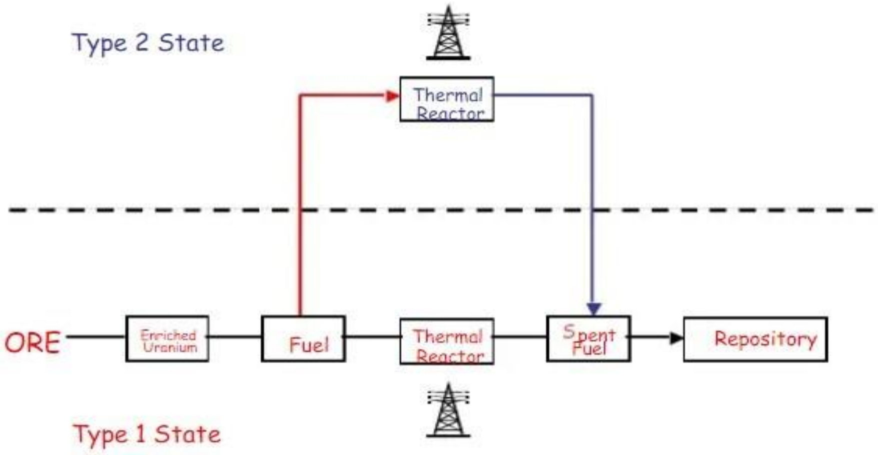

FIG 4. Diagram of the Fuel Cycle, Open Cycle, No Lease

3. Both feature closed fuel cycles and reprocessing to prevent exceeding an anticipated storage limit for used fuel, as shown in Figure 5. Four Yucca Mountain Equivalents (YME = 70,000 tonne) of permanent storage and four YME of interim storage are the maximums for Type 1 states, whereas four YME of permanent storage and six YME of interim storage are the maximums for Type 2 states.

Thermal MOX reactors are used by Type 2 states to complete their fuel cycle. We expect that 20% of the fuel for Type 2 new reactors will be MOX once reprocessing begins. Fast spectrum reactors are used by Type 1 nations to complete their fuel cycle. Fast spectrum reactors that operate in "burner" mode use the processed fuel as starter fuel. It is presumable that the features of rapid spectrum reactors and integrated fast reactors using liquid metal are comparable. The Advanced Fuel Cycle Initiative and Generation IV reactor initiatives of the US Department of Energy may lead to the creation of such a fuel cycle.

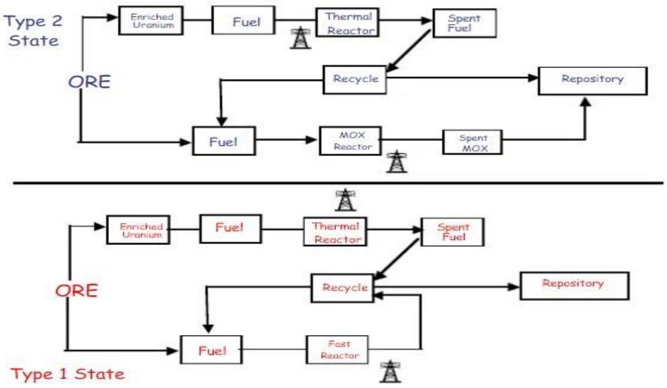

FIG 5. Diagram of the Fuel Cycle, Open Cycle, No Lease

4. Fast reactors are used to burn the reprocessed thermal reactor fuel from both Type 1 and Type 2 states in Type 2 states, which operate in the closed-cycle mode (Figure 6). Overall, the process turns uranium ore into power and fission products while preserving the storage of spent fuel.

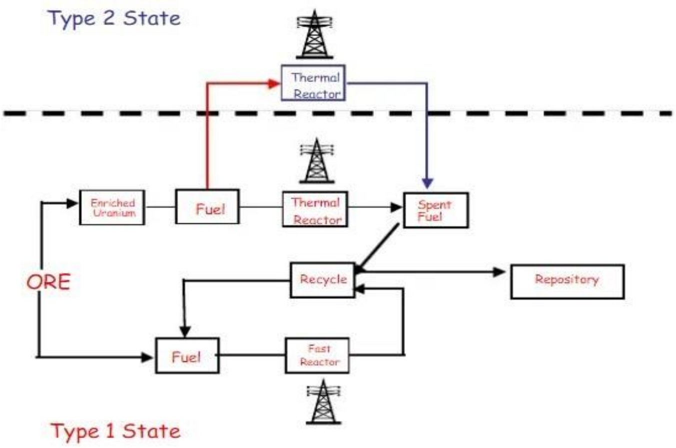

FIG 6. Diagram of the Fuel Cycle, Open Cycle, No Lease

Storage of spent nuclear fuel

For the aggressive growth scenario, using just open thermal cycles results in a significant increase in the amount of nuclear spent fuel that has to be stored. If the U.S. experience is any indicator, spent fuel storage might be a significant barrier to the expansion of nuclear power. Without recycling, the amount of wasted fuel stored globally increases to very high amounts, as seen in Figure 7.

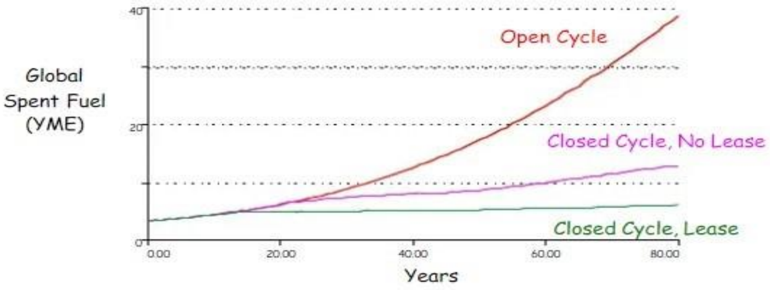

FIG 7. Accumulation of Used Fuel (Yucca Mountain Equivalents)

Given the anticipated expansion of nuclear power, keeping the spent fuel within the limitations set above would need enormous quantities of reprocessing (Figure 8). A significant amount of reprocessing is required, in particular, when fuel is leased from Type 2 states to Type 1 states in order to maintain the spent fuel within Type 1 storage restrictions. We point out that 7600 tonnes per year is the highest predicted worldwide reprocessing capacity for 2010.

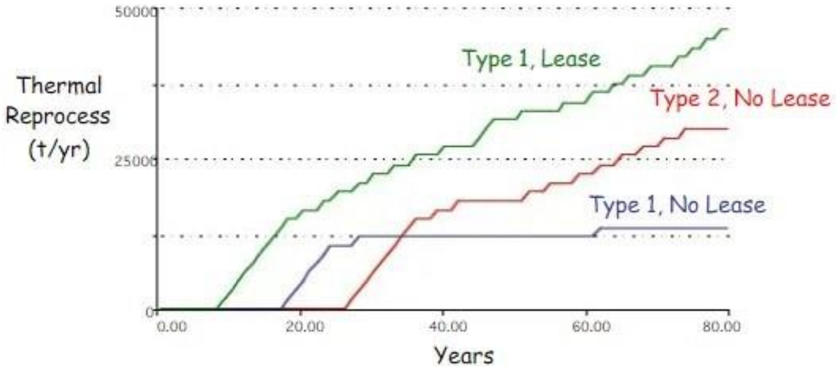

FIG 8. Minimum Recycling Capacity

Concern about Proliferation

Proliferation concern estimation is a particularly challenging issue that has been the focus of various studies and continuing assessments. Using an index that links the quantity of fissile material in the fuel cycle to its likelihood of being turned into a weapon, the quality of security and safeguards, and the state's covert desire to divert nuclear material into nuclear weapons is one strategy for addressing the proliferation concern. To begin, a "weapons potential" (W) is established for each component of the fuel cycle, i.e.:

A mass of material in form (i) is assumed to have the following weapons potential (W_i):

$$W_i = \Sigma M_{ij} C_{ij} T_{ij} / Q_j$$

M_{ij} =Fissile material mass in form(i) (kg)
C_{ij} =Compositional element (how easy is a material to handle - 0 to 1)
T_{ij} =Factor of technology (from 0 to 1): How simple is it to make a weapon
Q_j =Fissile material in a "Significant Quantity" (8 kg for Pu and 25 kg for U_{235}).

The term "equivalent nuclear weapons significant quantity" is used to describe the unit of weapons potential.

We distinguish between latent worry and security concern as two types of proliferation concern. The likelihood that a country may purposefully transform its civilian nuclear programme into a weapons programme, either publicly or secretly, is considered to be a "latent" worry.

$$\text{Latent Concern} = (\text{Breakout Concern})(1-S)(\Sigma_{i}(W_i))$$

Where S, a value between 0 and 1, represents the entire national level of safeguards. The breakout worry, which is likewise a number between 0 and 1, is essentially a political (and intelligence) assessment of a state's propensity to produce weapons from its civilian nuclear power programme at the moment. States that have formally admitted to having nuclear weapons would have a Breakout Concern of 0, as they already possess them. For instance, the United States would probably rate North Korea as having a Breakout Concern of 1, whereas China may give it a lower score.

The security problem, which is particularly relevant to terrorist threats, refers to a country's capacity to keep its nuclear material safe from theft or sabotage.

$$\text{Security Concern} = (\Sigma_{i}(W_i)(1-P_i))$$

P_i is the material's in-form protection level(i). We consider the sum of the latent and security risks to represent the overall proliferation concern.

We used the following assumptions for the weapons composition and technology elements in Table 2 and the breakout worry, safeguard and security factors in Table 3 to gain a feel of how the leasing concept influences the concern about nuclear material proliferation.

Table 2. Aspects of nuclear material proliferation

Material	Composition Factor	Technology Factor
MOX Fuel	0.8	0.9
Spent MOX Fuel	0.8	0.3
Seperated Civil Pu	0.8	1
Spent Thermal Fuel	0.8	0.3
Thermal Fuel(LEU)	0.3	0.3
Fast Reactor Fuel	0.8	0.9
Spent Fast Reactor Fuel	0.8	0.3

Table 3.Security Proliferation and Latent Factors

	Type 1	Type 2 No lease	Type 2 Lease
Breakout Concern	0	0.2	0.2
Safeguard	0.95	0.8	0.95
Security	0.9	0.9	0.9

The security values are related to the security customary at a weapons site, the composition values are all relative to pure weapons grade plutonium and uranium, and they represent educated judgement rather than in-depth investigation. With a Breakout Concern of 0, it signifies that 20% of all material Type 2 states are thought to be in states that might potentially transition into weapon states. Once more, this will depend on who is doing the calculations.

Figure 9 compares the worldwide weapons worry of the existing stockpile of fissile material to calculations of the global weapons concern in 50 years for the four distinct instances.

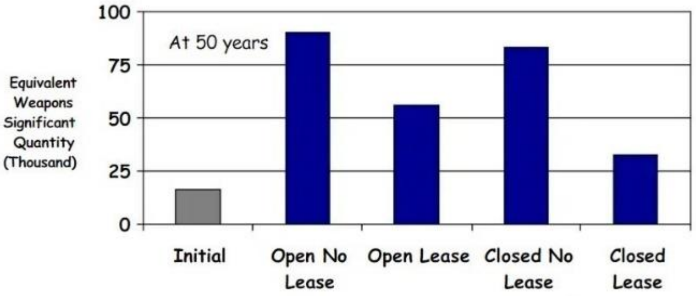

FIG 9. Concern about Global Proliferation

First, we should point out that the quantity of weapons in the world is quite huge and will only expand in growth scenarios. (Recall that the overall number of nuclear bombs at the height of the Cold War was reportedly approximately 80,000, with the majority being far more potent than those considered here). If nuclear power increases to the level anticipated here, there will be a lot more fissile material than there is at the current world level of production. However, leasing has the potential to greatly minimise proliferation worry for both open and closed cycles, and reprocessing strategies may be developed to do so rather than the opposite.This decrease in proliferation concerns is due to the transfer of nuclear material from Type 2 states to Type 1 nations (breakout worry of 0.2). (breakout concern 0). Recycling lowers the amount of stored spent fuel, which even in Type 1 states continues to be a security risk and results in a further reduction in the proliferation potential over time.

Although it offers a valuable viewpoint, looking at the proliferation issue from a global weighted nuclear material basis tends to obscure several crucial proliferation difficulties. The capability of enrichment, which would be required to provide fuel for Type 2 states if they choose not to lease fuel, and the potential production of separated, "cold," plutonium as an intermediate product in recycling are two such challenges.

Recently, North Korea has been the focus of considerable worry due of its enrichment capabilities. Separated civilian plutonium continues to raise concerns about proliferation due to how easily it may be turned into viable bombs. Clandestine enrichment plants in Iran, Iraq, Libya, and Libya have been identified (or confessed to having). Figure 10 depicts the theoretical capability for Type 2 governments to produce weapons provided they follow the projected civilian growth pathways and do not lease.

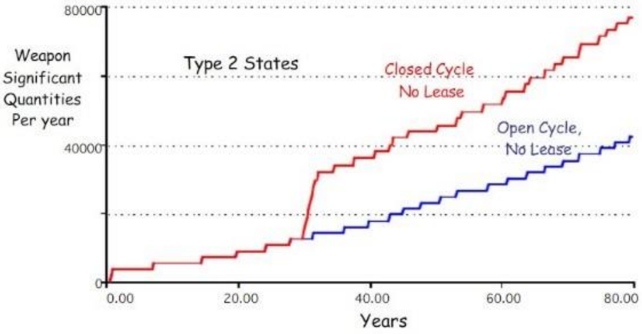

Fig 10. Potential Production Capacity of Type 2 State Weapons

From the standpoint of possible terrorist use, separated civilian plutonium is usually considered to be a specific proliferation threat. The substantial reprocessing capacity of the closed fuel cycles produce significant quantities of reprocessed plutonium for the simplified material flow model proposed here, as shown in Figure 11. Once the spent fuel limit is reached in Type 2 states without leasing, plutonium builds up quickly and can also reach high amounts in Type 1 states.One of the reasons for the development of the integral fast reactor was to address this issue. Pyroprocessing, the reprocessing method used in this reactor, does not separate plutonium from the other actinides, keeps it highly radioactive, and creates a product that is much harder to turn into a weapon. Given the quantity of material to be handled and the ongoing security concerns in Type 1 nations, this breakthrough would be especially significant if the leasing idea were to be implemented.

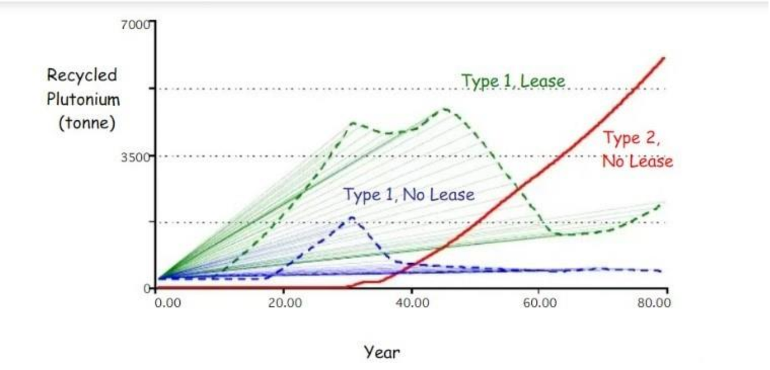

Fig 11. Examples of Recycled Plutonium for Closed Cycles

Monetary considerations

Finally, we must think about the circumstances in which the lease agreement makes financial sense for both Type 1 and Type 2 states. When will leasing be less expensive for the Type 2 state than building and operating its own fuel cycle? Each facility has a fixed cost and an operational cost dependent on material throughput under Multinuke's extremely straightforward cost model. For reactors, the fixed cost comprises "cost-of-money" components and nighttime construction, both of which are incurred when the plant is operational. We have presumptively set the loan term at 20 years, with an interest rate of 5% for Type 1 states and 8% for Type 2 states.

Table 4.Cost Related Factors

Facility	**Fixed Cost**	**Operating Cost**
Thermal Reactor	$1400/kW(overnight)	1.4¢ /kWhr
Fast Reactor	$1400/kW(overnight)	0.7¢ /kWhr
Enrichment & Fuel Manufacture	$4B/10M kg-SWU	$100/kg-SWU $600/kg fuel fab
Reprocessing & Pu Fuel Manufacture	$6B/2500t spent fuel/yr	$0.5M/t spent fuel
Interim Storage		$400/kg spent fuel
Permanent Storage	$48B/ YME	

By integrating the entire cost of the power generated, divided by the total electricity generated, we can get the average cost of electricity during the course of the simulation. In terms of the levelizedconst measure, which is frequently used to examine financial decisions, this is practically similar to a "going-forward levelized cost." According to Figure 12, the break-even cost for both the Type 1 "fuel cycle" state and the Type 2 "reactor" state is roughly $2000 per kilogram of fuel services leasing.

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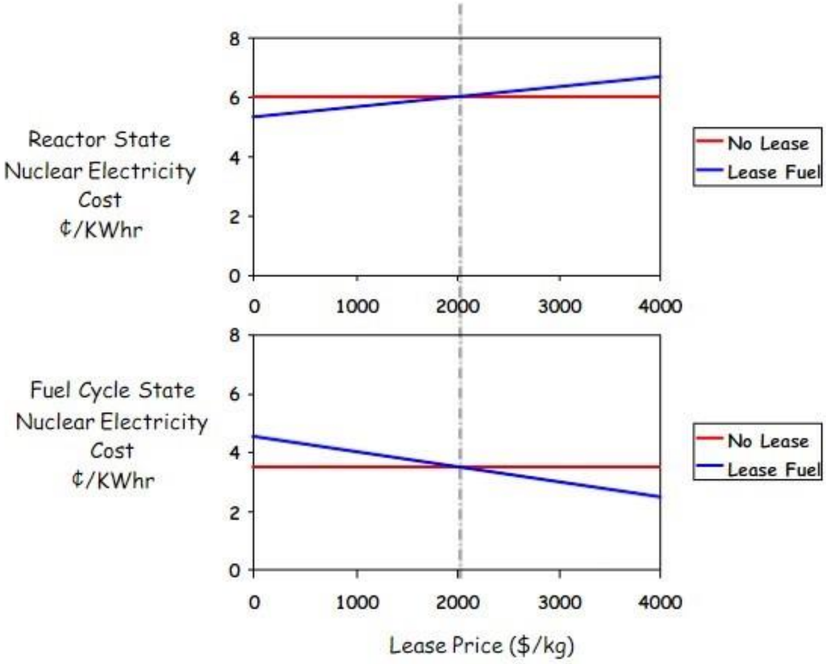

Fig 12. Comparison between leasing costs and levelized electricity costs

Discussion

This paper's goal was to show how a very straightforward system dynamic model may be used to study a novel multi-state fuel cycle idea, elucidating how and why various policy perspectives affect prospective outcomes. The instances addressed here only cover a small portion of potential nuclear technological improvements, and the values assumed for a number of crucial variables are at best approximations. Additionally, several of the problems mentioned, such as energy production, nuclear fuel storage, and proliferation, may be best handled at the national or corporate level as opposed to a global one. However, the findings highlight some significant links with regard to the potential for nuclear fuel leasing. Beginning from the top:

- A substantial portion of electricity must be produced by nuclear power plants for nuclear energy to have a meaningful influence on reducing carbon emissions from electricity generation. This will call for a worldwide nuclear business that is many times bigger than what is already in place.

- An enormous amount of spent fuel will be produced if thermal reactors using modern technology are used to supply this nuclear electricity. This fuel's disposal is a persistent political and technological problem.

- Reprocessing thermal used fuel into start-up fuel for new fast reactors is one way to lessen the amount of spent fuel. Reprocessing need to be carried out without increasing separated plutonium stockpiles, as this poses a persistent security and proliferation risk.

- Nuclear security and proliferation concerns will rise along with a significant increase in nuclear power output. When combined with increased security and safeguards, fuel leasing from governments with low latent proliferation risk to those with high latent proliferation concern may assist to lessen overall proliferation concern.

- Fuel leasing will look less discriminatory or coercive and will be more likely to be adopted as part of an international system if it can be made economically feasible for both parties to the agreement.

In conclusion, it appears that the fuel-leasing idea would be a viable way to pursue a major expansion of nuclear power while limiting the increase of proliferation concerns. In spite of the obvious technical, political, and economic difficulties, establishing such a new nuclear regime poses a significant challenge to the international community. However, if the findings of this analysis are any indication, it also offers a significant opportunity to carry President Eisenhower's "Atoms for Peace" vision into the twenty-first century.

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