Analysis of Engineering Issues Facing the In-Zinerator Z-Pinch Fusion Device Using MCNP

R. Grady, P. Phruksarojanakun, P.P.H. Wilson,
L.A. El-Guebaly, B. Cipiti

August 2007

UWFDM-1302

FUSION TECHNOLOGY INSTITUTE

UNIVERSITY OF WISCONSIN

MADISON WISCONSIN

Analysis of Engineering Issues Facing the In-Zinerator Z-Pinch Fusion Device Using MCNP

R. Grady, P. Phruksarojanakun, P.P.H. Wilson,
L.A. El-Guebaly, B. Cipiti*

Fusion Technology Institute
University of Wisconsin
1500 Engineering Drive
Madison, WI 53706

http://fti.neep.wisc.edu

August 2007

UWFDM-1302

*Sandia National Laboratory, Albuquerque NM

Abstract

The major limitations on repository capacity are the heat load and radiotoxicity. Reducing the amount of transuranic (TRU) elements in spent nuclear fuel reduces the heat load and radiotoxicity of spent fuel. This would in turn increase the capacity of a repository. One promising method to reduce the TRU inventory is through transmutation. This work investigates the engineering issues that face a particular transmutation device, the In-Zinerator Z-Pinch fusion device. The Z-Pinch device is an attractive option because it is a source for high-energy neutrons, which are advantageous for the transmutation process. The fusion device is pulsed every 10 seconds creating the high-energy neutrons, which drive fission in the subcritical blanket of TRU fuel; this transmutes the elements while producing energy through fission. In this work the engineering issues that face such a device are examined, in particular the selection of a reflector material; time dependence of the energy deposition; ^{6}Li enrichment and its effect on tritium breeding, Keff and energy multiplication; and techniques to produce constant energy multiplication. This work found that lead was the best option for a reflector because of its ability to reflect fast neutrons. Analyzing the time dependence of energy deposition showed that 99.9% energy is deposited in the device within 10 ms, with 50% in the first 50 μs. This work showed that the tritium breeding actually decreased with increasing ^{6}Li concentration, contrary to most fusion based systems. This is due to ^{6}Li being a better absorber, decreasing the neutron population. It was found that if energy multiplication is kept constant this relationship changed and ^{6}Li enrichment increased TBR. Lastly, in trying to create a system with a constant energy multiplication, beryllium failed to multiply neutrons to increase the energy output. This is because most of the In-Zinerator neutron spectrum is below the threshold energy for the beryllium (n, 2n) reaction. Though beryllium failed, a different system, leakage rods, succeeded in maintaining constant energy multiplication.

1. Introduction

In the Advanced Fuel Cycle Initiative (AFCI) set forth by the Department of Energy, transmutation of nuclear waste is one key goal in increasing repository capacity. Transmutation of key elements, the transuranic (TRU) elements, can reduce the heat load and radiotoxicity of the nuclear waste placed in a geological repository. Transmutation of most TRU elements is most advantageous, regarding capture to fission ratio, with higher energy (>0.5 MeV) neutrons[1]. This work examines the In-Zinerator Z-Pinch fusion device as a possible transmutation reactor. The In-Zinerator utilizes the high-energy fusion neutrons to drive the fissioning of the TRU elements. This device is subcritical and the fusion target is pulsed, producing power while transmuting TRU elements. Specifically, this work explores four main engineering issues: the reflector material used, the time-dependence of energy deposition, the effect of ^{6}Li enrichment, and methods to obtain constant energy multiplication.

A more detailed description of the In-Zinerator model along with the code and methodology used is given in section 2. The reflector material analysis is presented in section 3. The time-dependence of energy release is discussed in section 4. The effect of ^{6}Li enrichment is explored in section 5. Specifically, this work explores the effect enrichment has on tritium breeding ratio (TBR) and energy multiplication. In section 6 radiation damage to the components in analyzed. Section 7 discusses reactor control methods to obtain a constant energy multiplication throughout the life of the reactor. Future research and analysis suggestions are made in section 8 and conclusions from this work are presented in section 9.

2. In-Zinerator Model and Methodology

This work utilized MCNP for analysis and used two different models, shown in Figure 1a and 1b. The initial (Figure 1a) In-Zinerator design uses a 250 MJ D-T target pulsed every 10 seconds. The reactor is a 4.1 m tall cylindrical design, 4.8 m in diameter, with the fusion source in the center. A central void surrounds the target. Fuel tubes in a Pb coolant and a Pb reflector surround this central void. The actinide fuel is in the form of a liquid eutectic, $(LiF)_2(ActinideF_3)$, flowing in fuel tubes. This fluid is flowing in three rows of fuel tubes containing 263 tubes and is submerged in a 50 cm thick Pb coolant layer. A 35 cm Pb reflector surrounds the fuel and coolant. The first wall is stainless steel, 5 cm thick, and 145 cm from the target. A 5 cm thick stainless steel back wall divides the coolant and the reflector. The first analysis used this model, specifically the time dependence of energy release, comparison of different reflector materials, and initial exploration into different methods to create a constant energy multiplication.

The final In-Zinerator model shown in Figure 1b replaced the initial model for final analysis. This reactor is larger with a height of 6 m and a diameter of 6.4 m. The first wall moved from 1.45 m to 2 m away from the source and the back wall does not divide the coolant and reflector. The reflector thickness changed to 50 cm and the number of tubes increased. The 1146 fuel tubes are set in an array surrounding the target. Argon fills the central cylinder. A steel plate, 50 cm thick, is placed on the top and bottom of the reactor to simulate the capture of neutrons and photons in the actual reactor. The analysis of tritium breeding, radiation damage and final methods of reactor control used the final model. The comparison of the time-dependence of energy release used both the initial and final models.

The initial and final designs were modeled in MCNP. This allowed a statistical analysis of the engineering issues of interest, following many particles using random numbers to determine their path, energy, and reactions. This generates a statistical answer with a corresponding uncertainty. The analysis

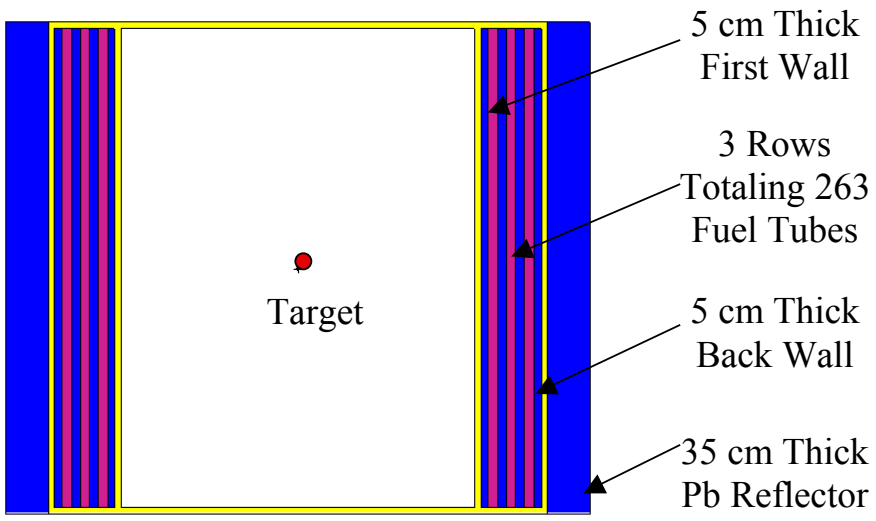

Figure 1a. Initial In-Zinerator MCNP model.

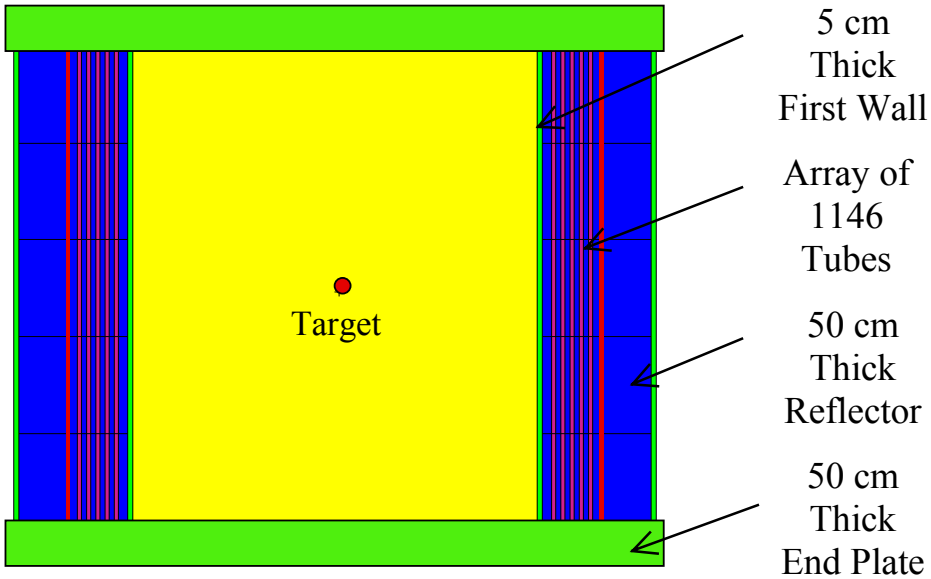

Figure 1b. Final In-Zinerator MCNP model.

of the device used two different modes. One mode was an eigenvalue problem to determine Keff. 1500 particles were used in 130 sequential runs to determine the number of neutrons in the next generation. For the other mode, used for the analysis of all other aspects of the In-Zinerator, the source of neutrons was the fusion target in the center of the device. This target was modeled as a fusion source of 14.1 MeV neutrons with layers of hydrogen, carbon and gold to slow the neutrons as in the real system. From this source, particles were born and followed to find what reactions would take place using random numbers and probability. With MCNP, using a NONU card, the system could be analyzed with all fissions treated as captures. This stopped fission neutrons from contributing to the results, finding the contribution from only the fusion neutrons. The contribution of fusion neutrons could be subtracted from the total, resulting in the contribution from only the fission neutrons. In the In-Zinerator model, the materials used are important to note. The steel in the final design is Hastelloy with materials described in Table 1. Table 2 describes the flowing actinide solution. The argon was modeled as natural argon and the lead composition is described in Table 3.

Element	Isotope	Percent
C	Natural	0.4
Si	Natural	2.12
Ti	Natural	0.44
Cr	50	0.35
Cr	52	6.73
Cr	53	0.76
Cr	54	0.19
Mn	55	0.87
Fe	54	0.31
Fe	56	4.9
Fe	57	0.11
Fe	58	0.01495
Co	59	0.2
Ni	58	49.13
Ni	60	18.92
Ni	61	0.82
Ni	62	2.62
Ni	64	0.67
Cu	63	0.23
Cu	65	0.13
Mo	Natural	9.95
W	182	0.0424
W	183	0.0229
W	184	0.04903
W	186	0.04548

Table 1. Isotopic composition for Hasteloy steel.

Element	Isotope	Percent
Li	6	1.25014
Li	7	23.75267
F	19	62.50702
Np	236	9E-07
Np	237	0.907602
Pu	238	0.331287
Pu	239	5.663136
Pu	240	3.287869
Pu	241	0.115763
Pu	242	0.723831
Pu	243	0.000141
Am	241	1.15763
Am	242	0.002063
Am	243	0.260029
Cm	242	4.98E-06
Cm	243	0.00035
Cm	244	0.026878
Cm	245	0.011051
Cm	246	0.002488
Cm	247	4.8E-05
Cm	248	5.54E-06
Bk	249	1.25E-08
Cf	249	1.25E-08
Cf	250	1.25E-08

Table 2. Isotopic composition of actinide solution.

3. Reflector Material

The reflector material used in the In-Zinerator device ideally would not soften the spectrum and would be able to reflect a fast neutron spectrum. A hard (fast) neutron spectrum is desired for the In-Zinerator device because many transuranics have a fission to capture ratio that is most advantageous at high neutron energies.[1] A reflector that has the ability to reflect fast neutrons is desired because this would offer a simple pathway to obtain a constant energy multiplication through manipulation of the reflector. Three reflector materials were investigated: beryllium, lead and graphite. These materials are investigated because they are common reflector materials. To compare the materials, tests were run with each reflector material having a 35 cm thickness and a 45 cm thickness. By changing the reflector material thickness, the ability of the material to affect energy multiplication can be tested. These results are compared to a reference case with the reflector removed. A second set of tests was run to compare the neutron flux spectrum that resulted from the different reflector materials and thickness, again with a reference case of no reflector. A 63 energy group neutron spectrum was found and normalized to the reference case for analysis.

In Figure 2, there is a clear division of the different reflector material's ability to affect energy multiplication with increased reflector thickness. Changing the thickness of the beryllium reflector had no significant effect on energy multiplication and graphite had only a small effect. Comparing the energy released with a 45 cm reflector thickness to the reference case of no reflector, both beryllium and graphite caused the energy released to increase only by a factor of two. In contrast, the lead increased the energy release by more than an order of magnitude with the 45 cm reflector. In addition to the effect on energy deposition, a fast spectrum was desirable because of the increased effectiveness of transmutation at higher energies.

Figure 3 illustrates the softening effect is minimal. After normalizing the flux to the reference case, the fast flux is not significantly affected. For beryllium and graphite there is an increase in the neutron flux between 10^{-8} and 10^{-6} MeV but this in not significant because the flux is comparatively small, three to five orders of magnitude less than the fast flux. The softening of the spectrum does exist but is not significant enough to eliminate any reflector material based on the spectrum softening alone. This leads to the selection of lead for the reflector because of its ability to affect the energy multiplication.

Element	Isotope	Percent
Pb	206	24.1
Pb	207	22.1
Pb	208	53.7
Cu	63	0.4
Cu	65	0.2
Bi	209	0.05

Table 3. Isotopic composition of lead coolant.

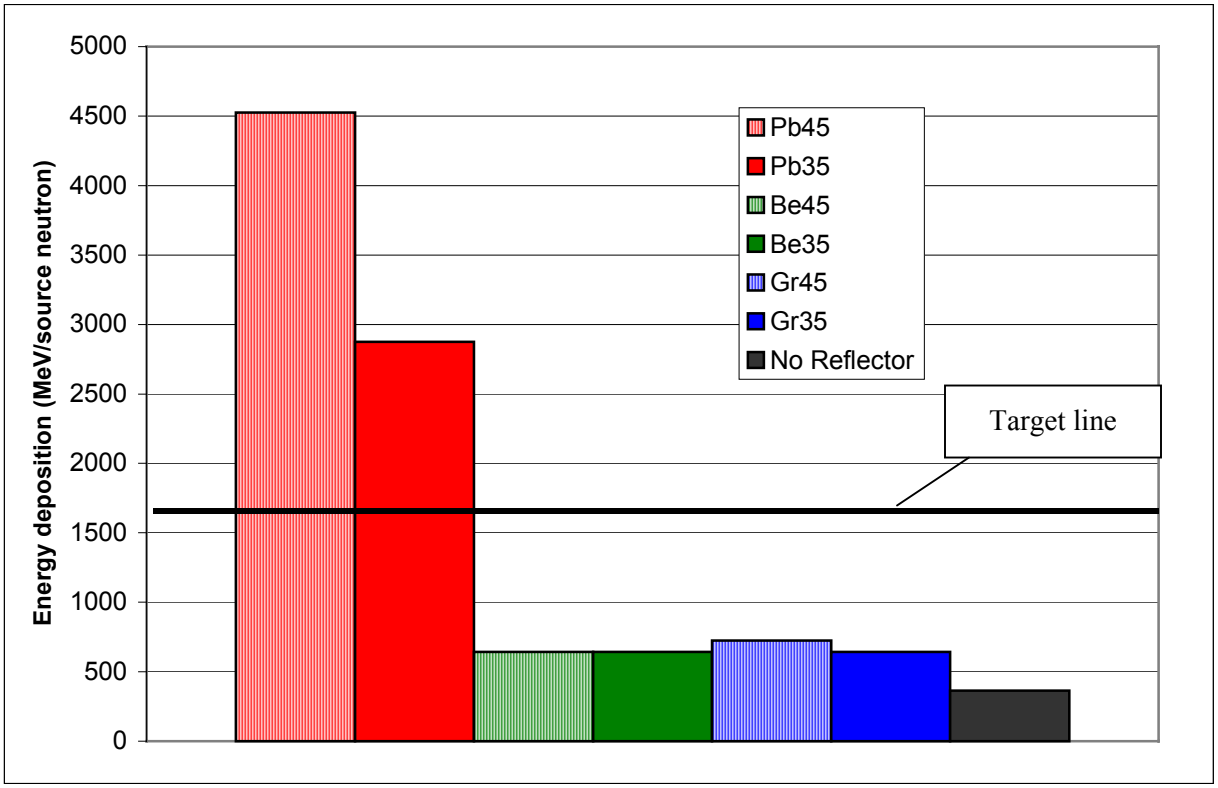

Figure 2. The effect of reflector material and thickness on energy multiplication compared to the case with no reflector.

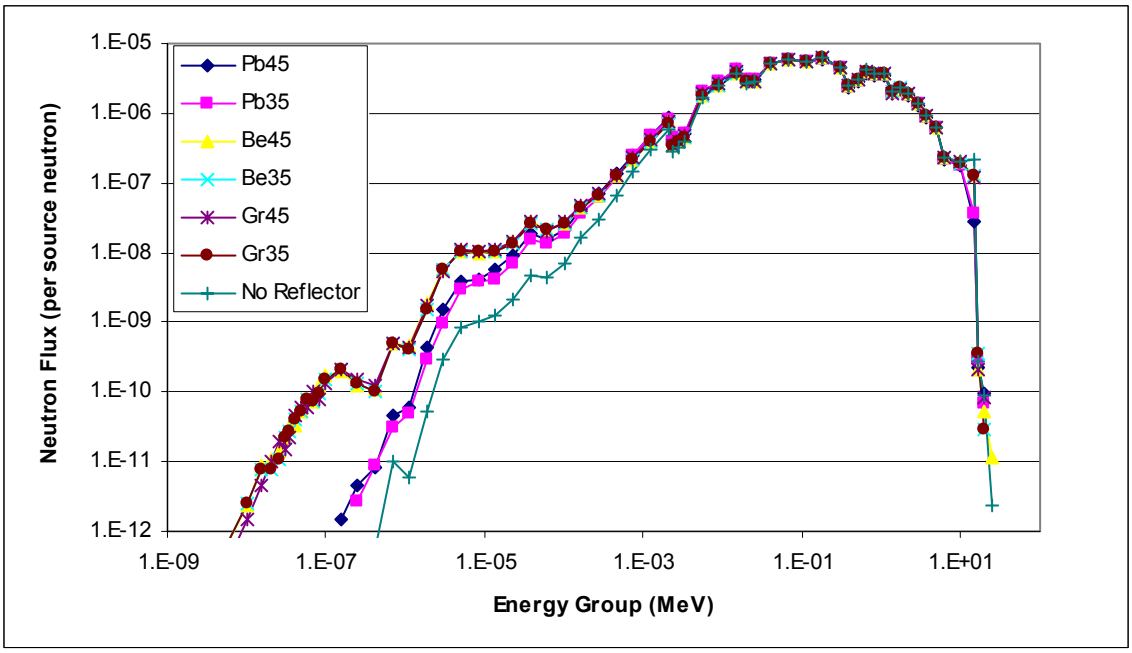

Figure 3. Comparison of different reflectors and the effect on the normalized neutron flux spectrum.

4. Time Dependence of Energy Release

With the Z-Pinch design, deposition of energy is rapid. This is because the subcritical blanket produces a high initial pulse of energy and decays away at a rate related to the difference between 1 and Keff through the inhour equation. The greater the margin between Keff and 1, the faster the rate of energy deposition decays away. Since one of the important features of the In-Zinerator design is to avoid a critical design, the difference between Keff and 1 has to include a margin of safety. The final design has a Keff of ~0.97. This design feature creates the high initial pulse of energy deposition with the deposition rate quickly decaying to zero.

In Figure 4, for both the initial and final design, the high pulse of energy deposition is illustrated. For the initial design, the initial pulse is as high as 1.75E14 watts in the first 50 ns. For the final design, the pulse magnitude decreased but remained high; the pulse height decreased to 1.55E14 watts in the first 100 ns. The final design, along with decreasing the pulse magnitude, prolonged the energy deposition. In the initial design, all energy was deposited in the first 0.2 ms. In the final design all energy was deposited in the first 0.1 s. This is illustrated in Figure 5.

Figure 5 shows the cumulative energy deposition for each model over time. The final design releases the energy slower but remains high. The energy deposition rate is an engineering issue that must receive more attention in the future but is beyond the scope of this work. This quick deposition of energy will produce high pressures and large temperature gradients. The effect that this pressure, temperature, and heat transfer has on the materials on such small time scales has not been tested. Material testing may be needed to find the feasibility of such a design.

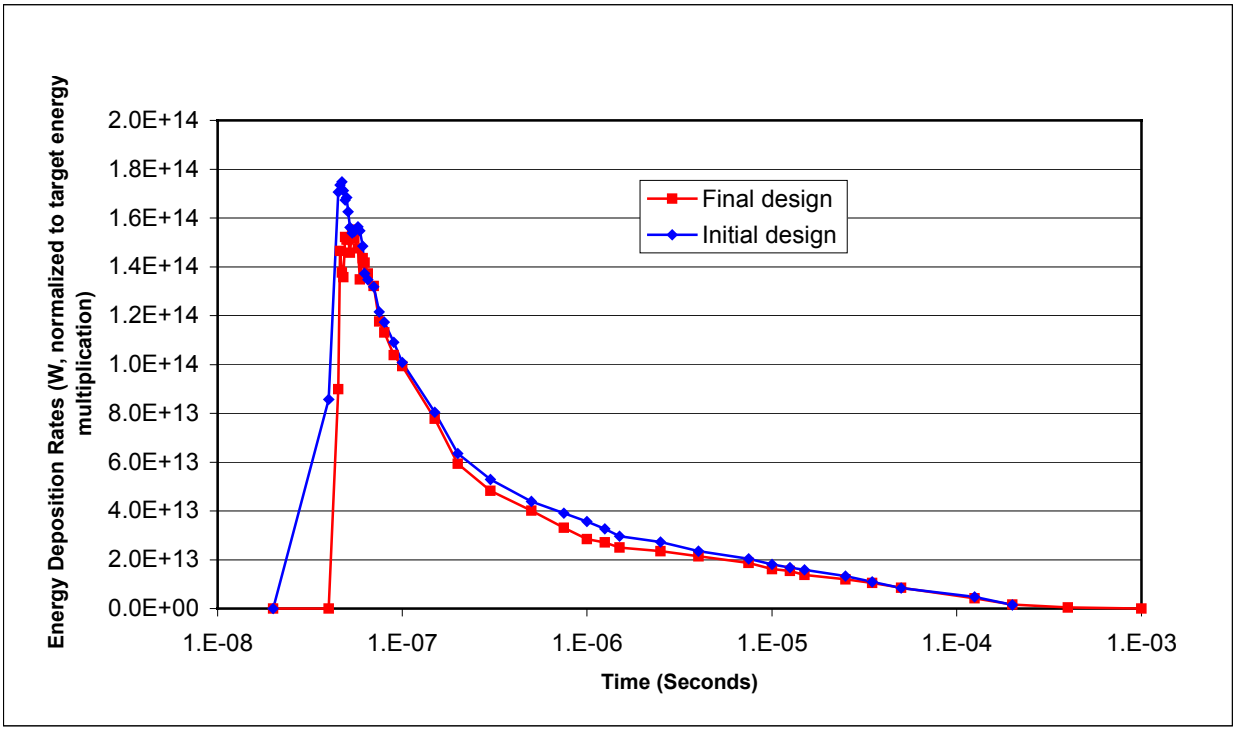

Figure 4. Time dependence of energy release for the initial and final design.

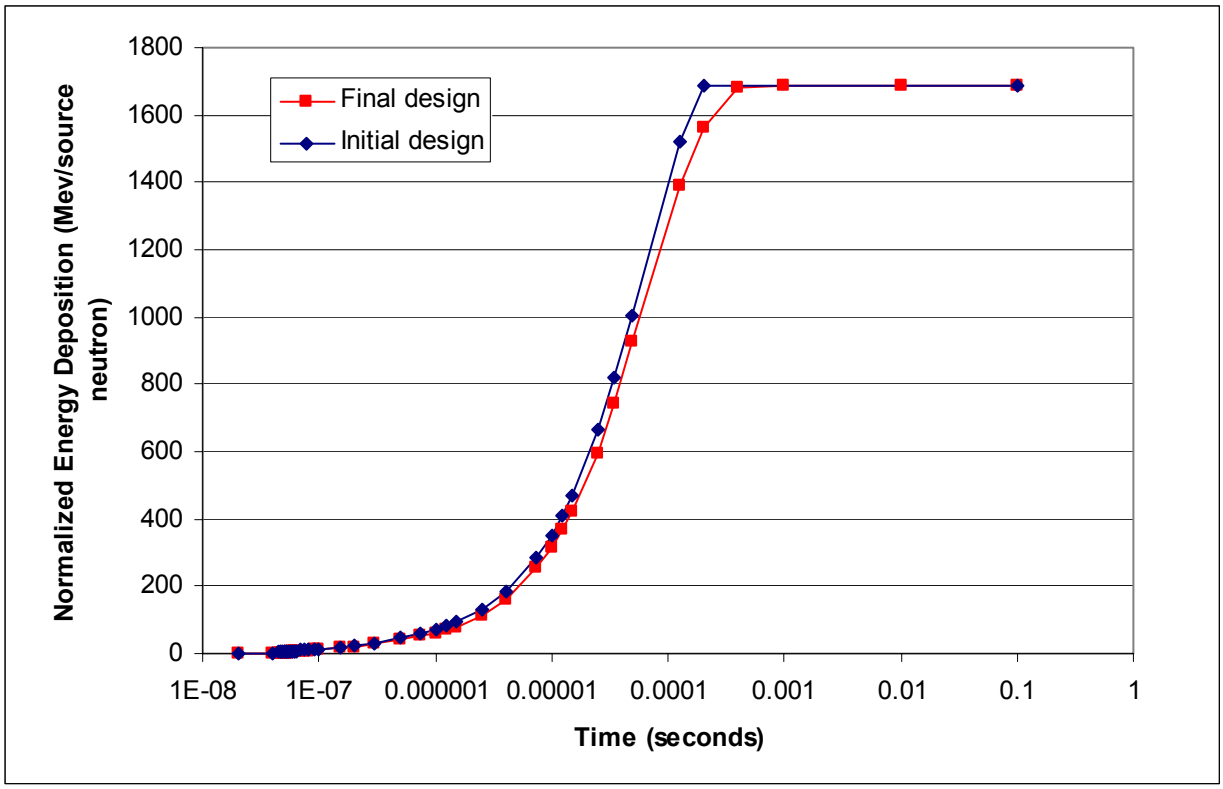

Figure 5. Total energy deposition normalized to 1689.06 MeV/source neutron (the target energy deposition), comparing the final model to the initial model.

5. ^{6}Li Enrichment

Since the In-Zinerator utilizes the D-T reaction and tritium is not very abundant, the tritium breeding ratio (TBR) is an important aspect of the reactor design. The device would ideally breed all of its tritium needs. The target TBR for operation is 1.1, which will allow the device to sustain the required tritium inventory without obtaining tritium elsewhere. In a fusion system, tritium breeding increases by increasing ^{6}Li enrichment, which produces tritium through a neutron capture event. The In-Zinerator is mostly a fission system and the effect of ^{6}Li enrichment is unknown and needs exploration.

5.1 TBR

Since the In-Zinerator is dominated by fission and ^{6}Li produces tritium through neutron capture, which decreases the neutron population, it is unknown if these two effects will combine for a net increase or decrease in TBR when the ^{6}Li is enriched to a higher percent. The In-Zinerator model was tested with a range of ^{6}Li enrichments to find the effect on TBR.

Figure 6 shows that the TBR decreases with ^{6}Li enrichment. Using the NONU card the contribution of the fusion neutrons and fission neutrons could be differentiated. This analysis showed that increasing the ^{6}Li enrichment increased the TBR from the fusion neutrons as expected but the TBR contribution from the fission neutrons was significantly reduced. This was further explored by finding the effect ^{6}Li enrichment had on Keff and energy deposition.

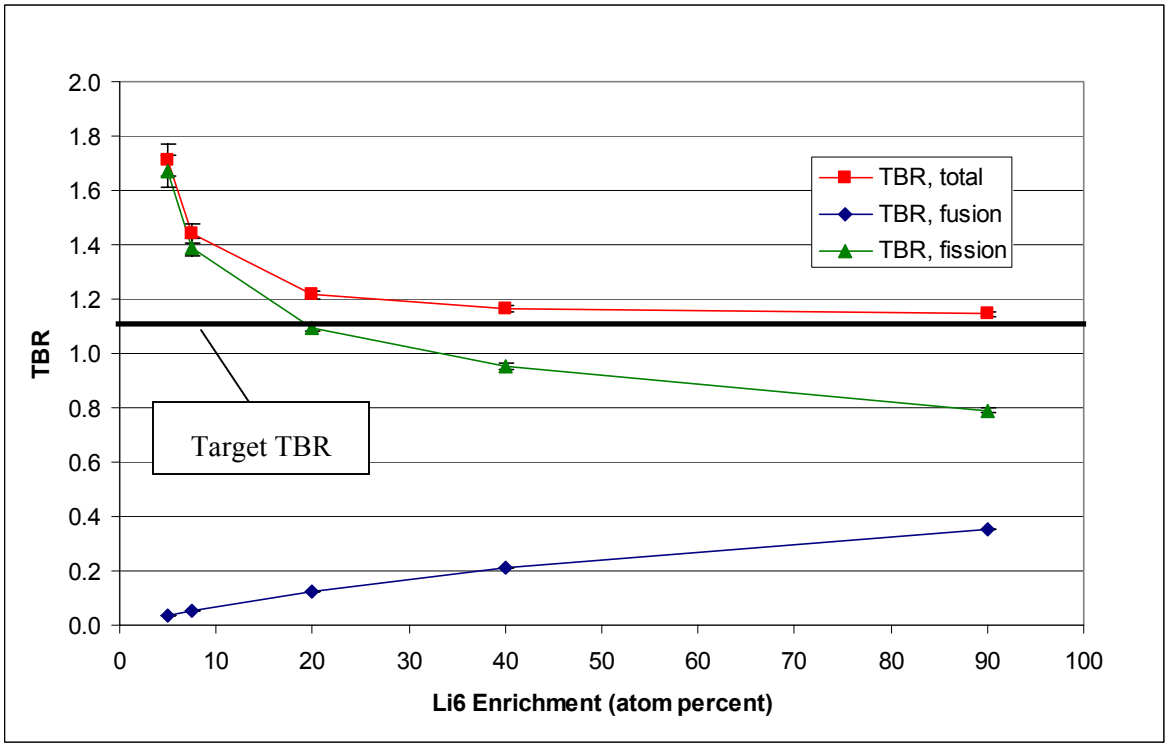

Figure 6. The contribution of the fusion, fission and total neutron population to the TBR vs. ^{6}Li enrichment.

5.2 Keff and Energy Deposition

Figure 7 shows that the energy multiplication for the system decreases with increasing ^{6}Li enrichment. This is most likely due to the effect that ^{6}Li has on absorbing neutrons available for fission. Since ^{6}Li is a better absorber of neutrons than ^{7}Li, increasing the ^{6}Li concentration will decrease the neutron population available to cause more fission events, decreasing total energy deposition. This result makes it necessary for further analysis of the relationship between ^{6}Li enrichment and tritium breeding. Since the energy multiplication will be held constant in the real system, the relationship with ^{6}Li enrichment will need to be examined with the energy multiplication held constant.

Since energy multiplication is closely related to Keff, a similar relationship between ^{6}Li enrichment and Keff would be expected. Figure 8 shows that ^{6}Li enrichment decreases Keff. As stated previously this is due to ^{6}Li absorbing more neutrons than ^{7}Li, decreasing the neutron population in subsequent generations.

5.3 TBR and Energy Multiplication Design Window

From the results in section 5.2 and 5.1 it can be concluded that further study is needed to determine the relationship between ^{6}Li enrichment and TBR. This further study needs to determine how TBR is affected with increases in ^{6}Li enrichment while maintaining a constant energy multiplication. Another conclusion that can be taken from this section is that there may be a design window that needs to be determined. Given that TBR changes with ^{6}Li enrichment, a target TBR and target energy multiplication will need to

be found by changing ^{6}Li enrichment and reflector configuration. This analysis is summarized in section 7.4.1 where methods of reactor control are examined.

6. Radiation Damage

Another engineering issue of importance is the radiation damage to the components. The radiation damage will determine the lifetime of the internal components of the In-Zinerator. The analysis was conducted with the reference case of 5% ^{6}Li enrichment and 200 dpa was used for the lifetime limit of radiation damage for the Hastelloy steel components.

Figure 9 shows the variation of dpa along the axial direction. This figure shows fission neutrons have the most influence on dpa. In a fusion-based system, the FW is of most importance concerning dpa but with the addition of actinides, the neutron population within the device changed. This resulted in the 3rd and 4th row of fuel tubes having the highest dpa instead of the FW. Figure 10 shows the radial dependence on peak dpa. Again the fission neutrons are the dominant contributor to the dpa and become increasingly dominant in the fuel tube walls. In the 3rd and 4th row of fuel tube walls, the fission neutrons contributed over 98% of the total dpa. With the limit of 200 dpa, the only lifetime component would be the BW. The FW would have to be replaced at 11, 22, and 33 FPY. The fuel tube walls have a shorter lifetime ranging between 4.5 FPY to 5.5 FPY.

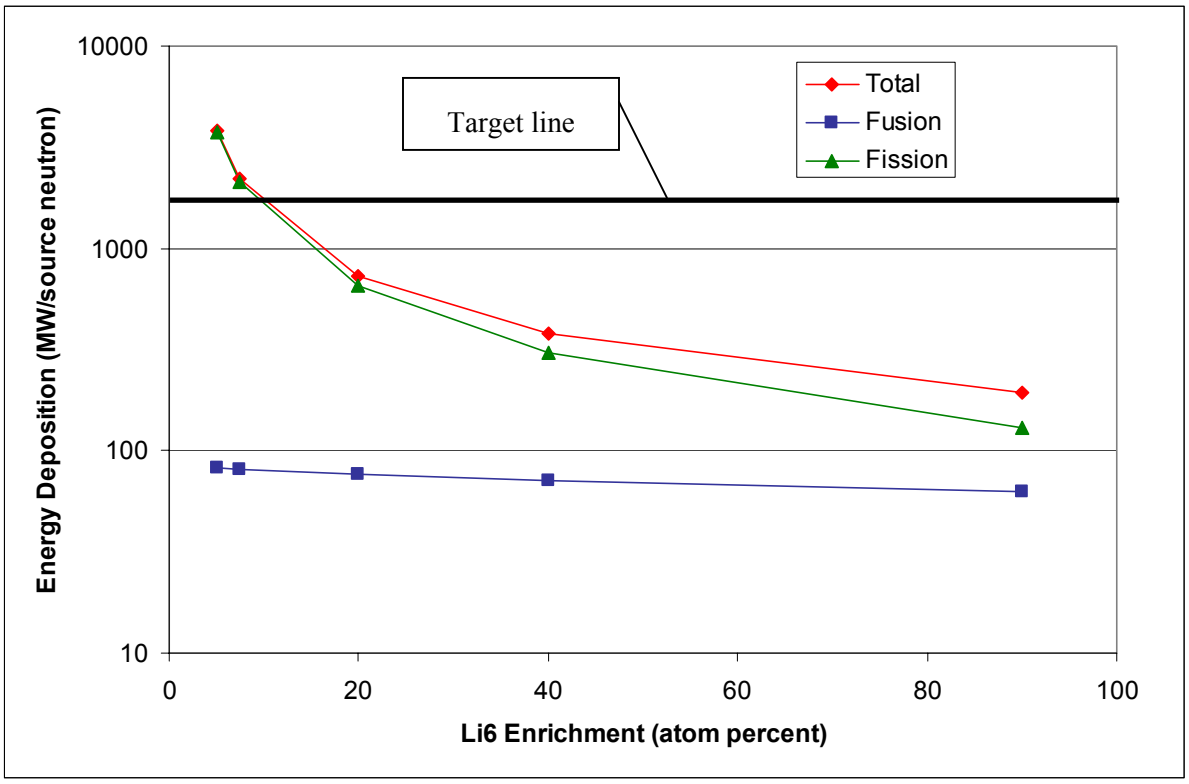

Figure 7. The effect of ^{6}Li enrichment on the energy multiplication from fusion, fission and the total neutron population.

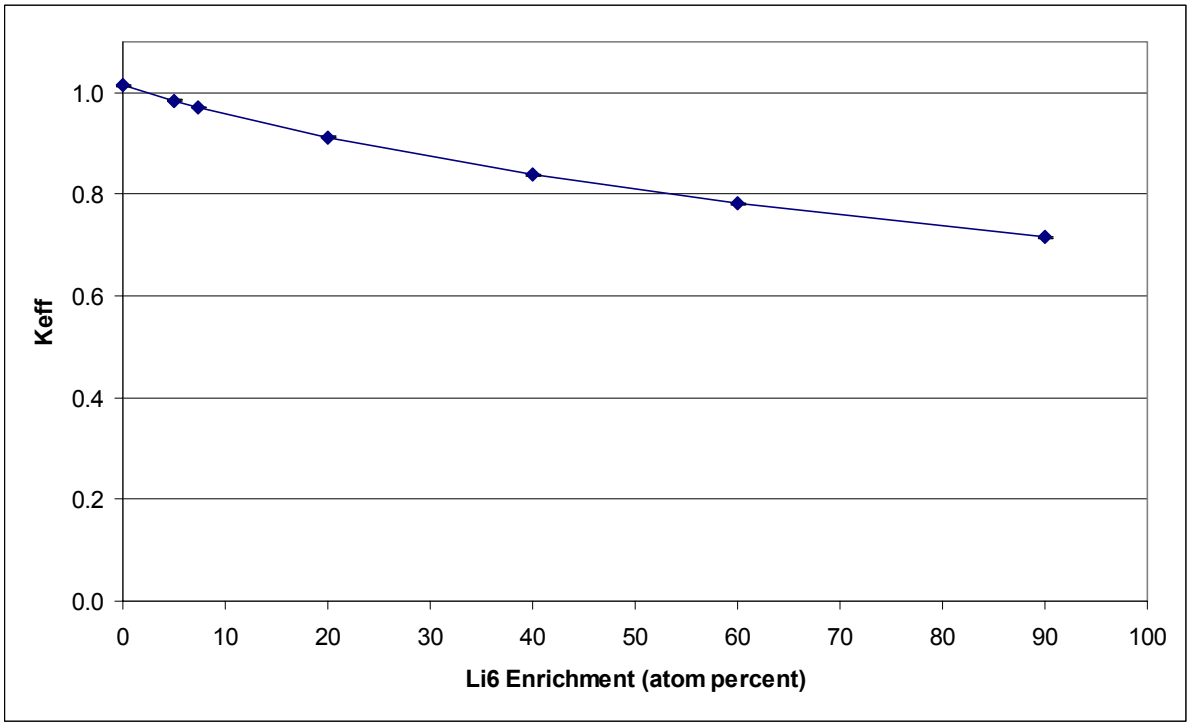

Figure 8. The effect of ^{6}Li enrichment on the Keff of the In-Zinerator.

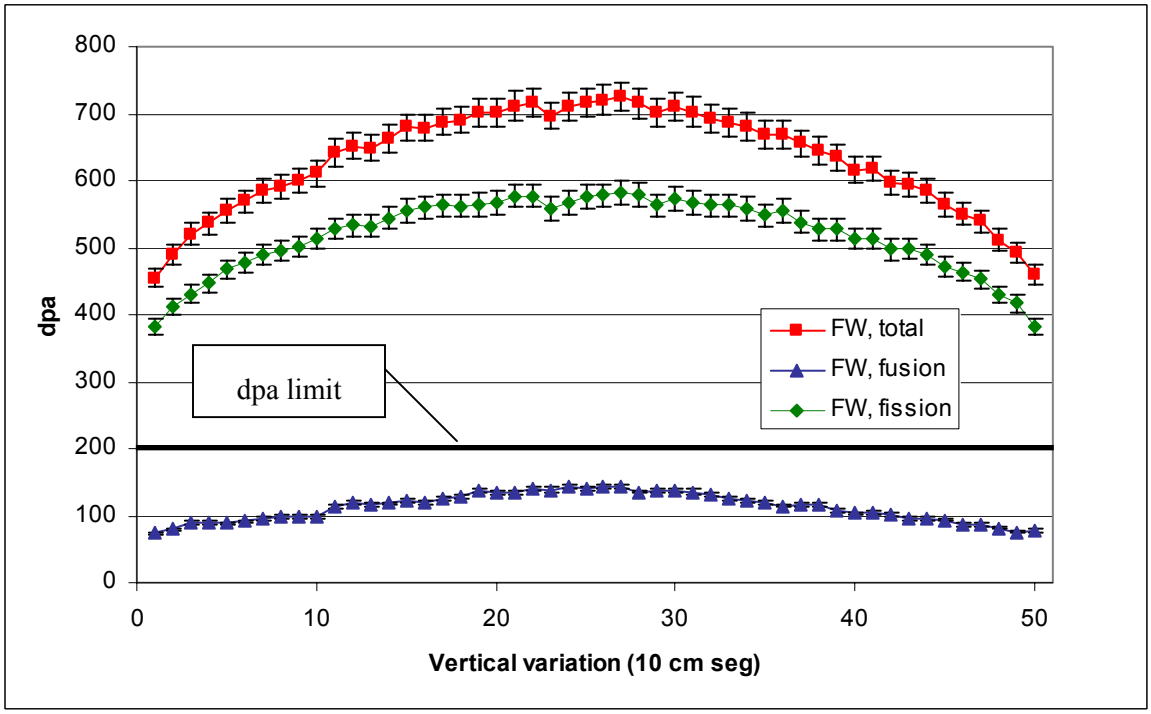

Figure 9. Vertical variation of dpa along FW for 40 FPY (20 segments, 10 cm each).

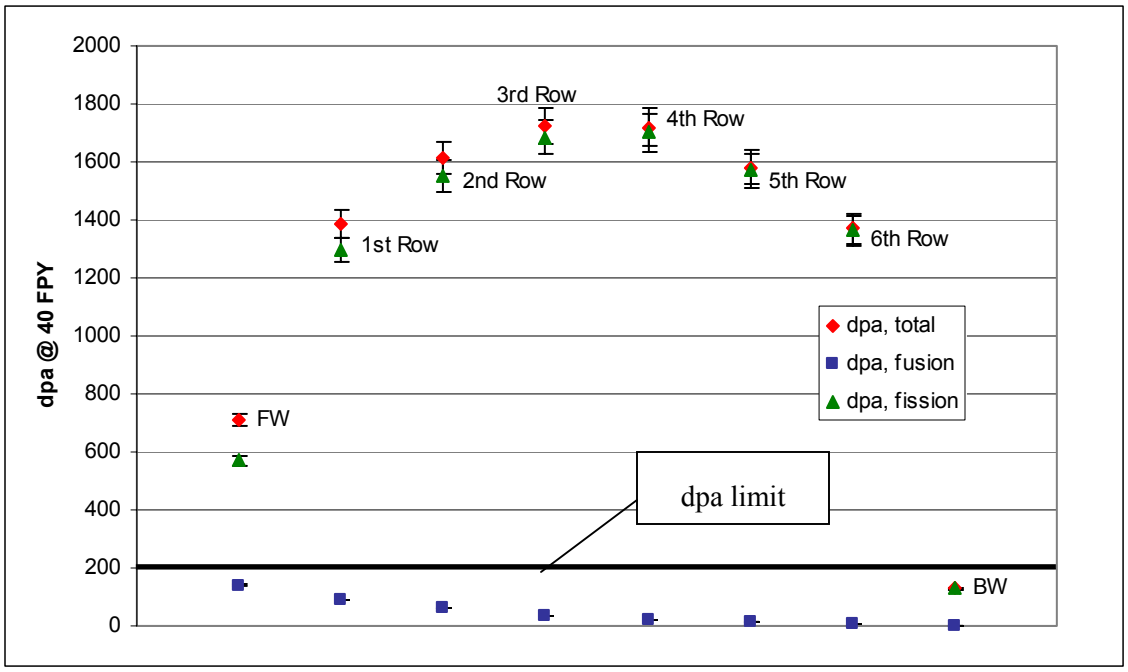

Figure 10. Peak dpa (middle 10 cm) for FW, BW and each row.

7. Reactor Control Strategies

In the current In-Zinerator design, the energy multiplication has a sharp decrease over the first 100 days. This is undesirable and the final design must include a method to maintain constant energy multiplication. In the attempt to scope feasible paths to maintain a constant energy multiplication, many different solutions were explored. These included the use of beryllium as a neutron multiplier to increase neutron population, changing the thickness of the reflector, using a separating reflector or an annular reflector, which would change the effective reflector thickness, and finally leakage rods that could be inserted into the device to increase neutron leakage.

7.1 Beryllium Neutron Multiplier

The idea behind using beryllium was that a neutron could be captured by the beryllium and the (n, 2n) reaction would result in a net increase in neutrons available for fission. The addition of beryllium in the coolant and in the fuel was tested. The theory did not hold true in this device and actually decreased the energy multiplication. This was due to two main factors. Firstly, the (n, 2n) reaction for beryllium is a threshold reaction with the threshold energy being around 1 MeV. In the In-Zinerator only 10% of the flux is above this threshold. Secondly, the (n, 2n) reaction produces neutrons in a range of energies in which most of the transuranic elements have their lowest fission cross-section. These two factors result in a decrease in energy multiplication.

7.2 Changing Reflector Thickness

Changing the reflector configuration was the next path explored to maintain the constant energy multiplication. The first analysis was to increase the reflector thickness to find the effect on energy

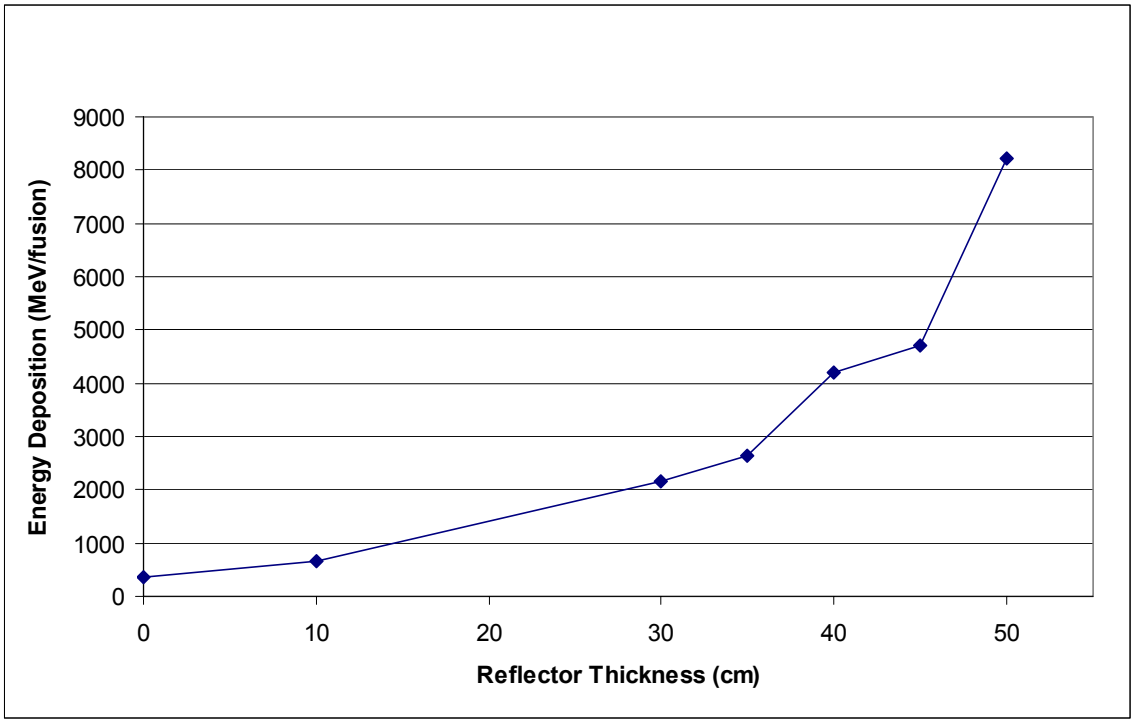

Figure 11. Energy multiplication dependence on the thickness of the lead reflector.

multiplication. This does not have physical significance since in a reactor the reflector thickness cannot be changed continuously. However, this would show the feasiblity of changing the effective reflector thickness, which could be achieved through a different method.

Figure 11 shows that changing the reflector thickness is an effective method to change energy deposition. By adding a 45 cm thick reflector, the energy deposition increased by an order of magnitude compared to a reactor without a reflector. Though a continuous change in reflector thickness is not physically feasible, changing the effective reflector thickness by using a reflector section that could be separated from the In-Zinerator or leakage rods which could be inserted into the reflector could be feasible. The separating reflector was explored next.

7.3 Separating Reflector

The separating reflector would use a 45 cm thick reflector with eight sections that could move away from the device. Figure 12 illustrates the In-Zinerator with the separating reflector moved 10 cm from the device. These separating reflector sections could move closer or further away from the In-Zinerator to produce the desired energy multiplication.

This separation would decrease the effective reflector thickness. The analysis of such a system showed promise, with a separation of 10 cm decreasing the energy multiplication by more than a factor of two.

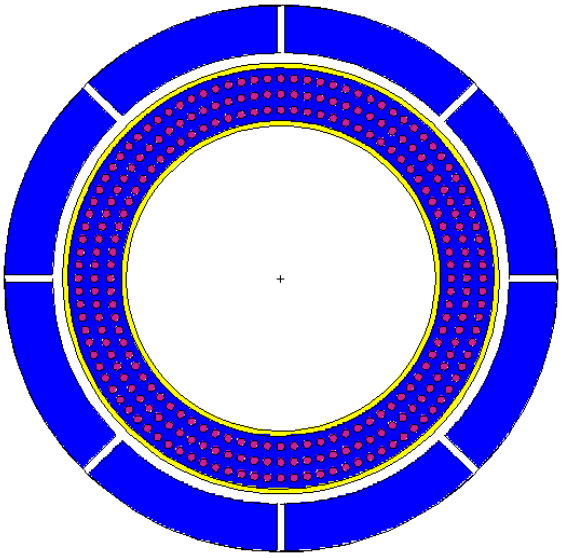

Figure 12. Top view of separating reflector at 10 cm.

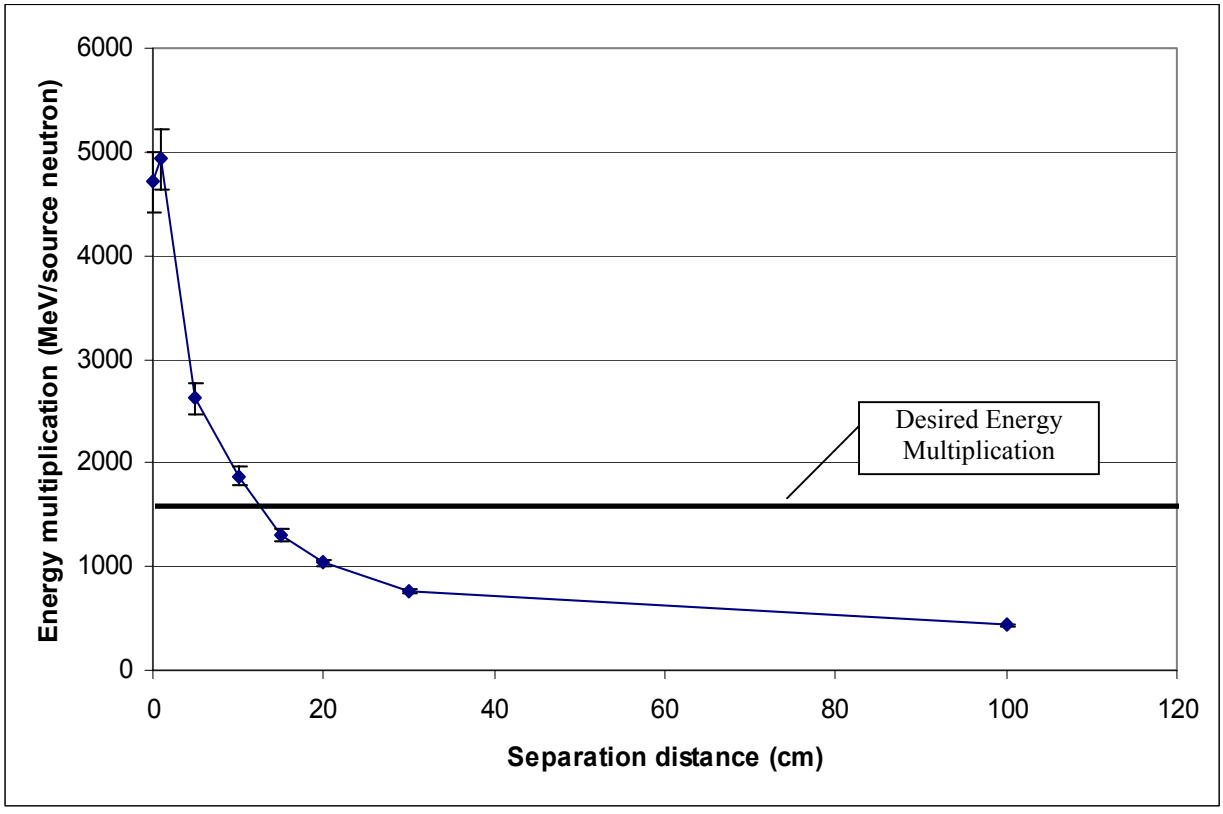

Figure 13. Energy multiplication as a function of the separation distance.

Figure 13 shows that small changes in separation distance will greatly affect the energy produced by the system. Since the initial drop in energy multiplication is less than a factor of two, this particular system would be able to maintain the desired energy multiplication with continuous motion of the reflectors over the initial drop in energy output.

7.4 Leakage Rods

The next method for reactor control was air filled leakage rods, which could be inserted into the Pb reflector. These leakage rods are not a criticality control but rather an energy deposition control. These rods would increase the leakage of neutrons from the system because the rods would displace reflector material. This particular reactor control mechanism is the most promising because it would be able to be continuously changed and would be a more feasible option, instead of moving very heavy reflector sections away from the reactor.

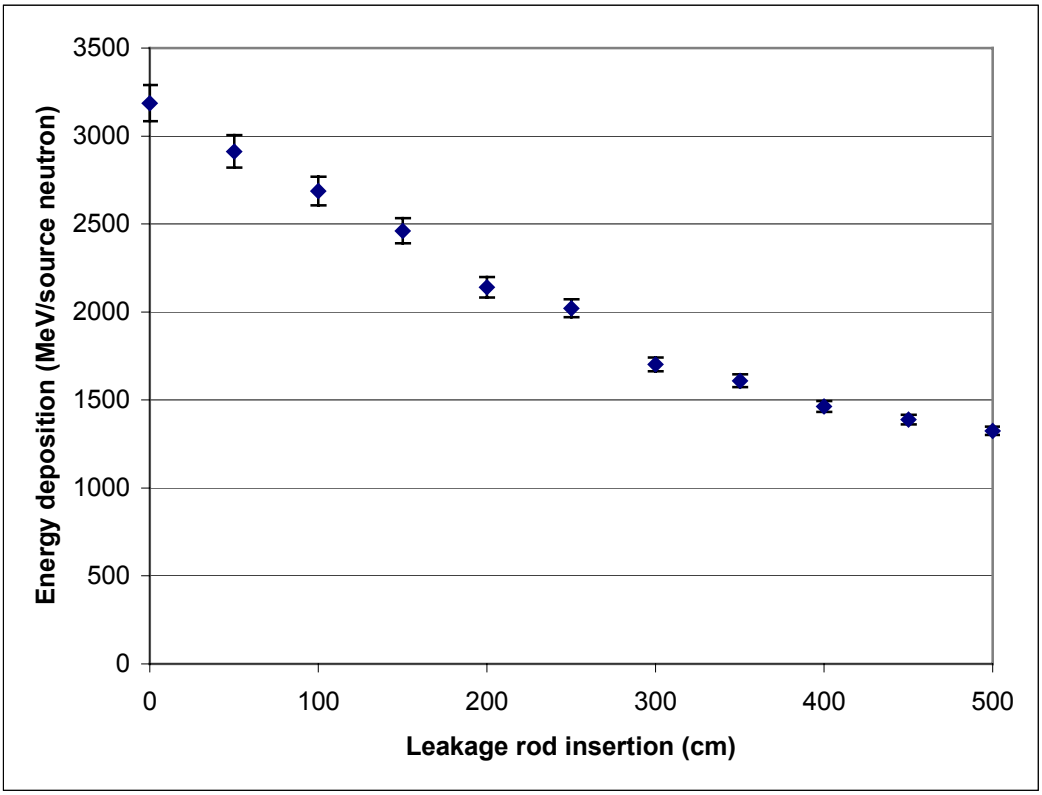

Figure 14. Energy deposited in the coolant, reflector and fuel vs. leakage rod insertion.

Figure 14 shows the effect of inserting the leakage rods into the reflector, starting from 0 cm insertion to full insertion at 500 cm. This is based on the nominal case of 5% ^{6}Li enrichment. The desired effect was seen in that leakage rod insertion reduced the energy deposited in the system. Most importantly the magnitude of this effect was adequate to control the initial energy drop in the In-Zinerator. The energy deposition with leakage rods inserted to 500 cm was 41.6% of the energy deposited with no leakage rod insertion.

7.4.1 TBR With Constant Energy Multiplication

As discussed in section 5, the TBR and energy multiplication both decrease with ^{6}Li enrichment and the effect of the enrichment had on TBR with a constant energy multiplication was unknown. Using leakage rods, an iterative process of changing ^{6}Li enrichment and changing leakage rod position can be now used to determine if ^{6}Li enrichment increases or decreases TBR while maintaining a constant energy multiplication.

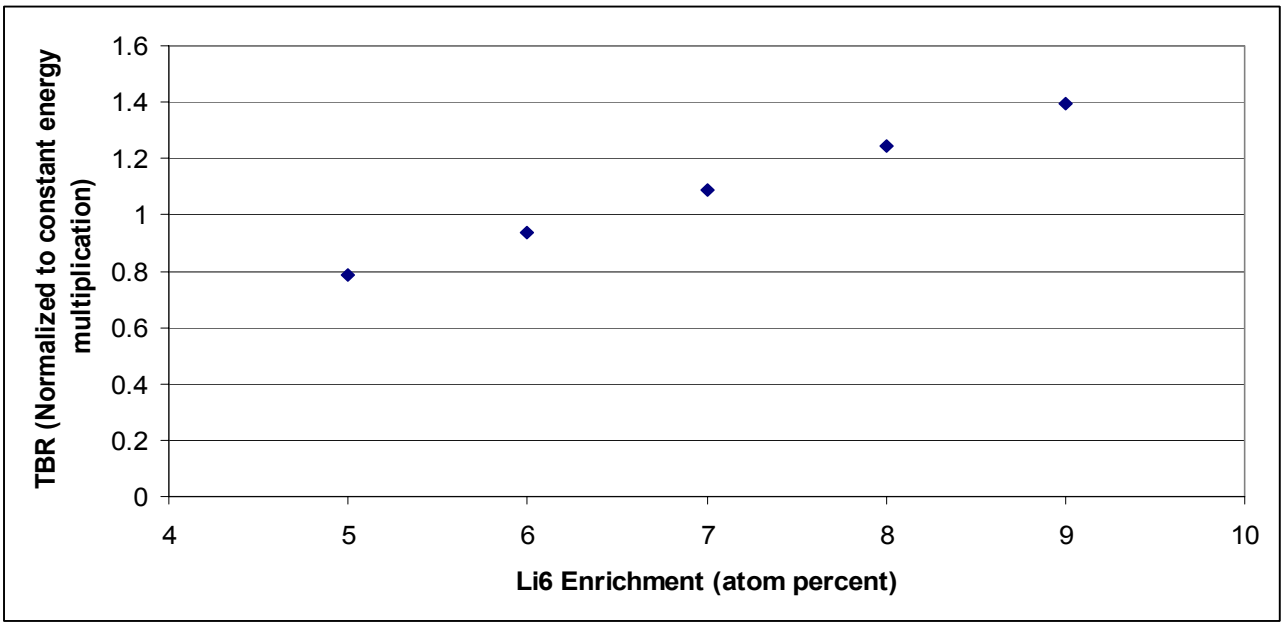

Figure 15. TBR as a function of ^{6}Li enrichment while maintaining a constant energy multiplication through the use of leakage rods.

Figure 15 shows the relationship between TBR and ^{6}Li enrichment is a positive correlation if the energy multiplication is kept constant with leakage rods. This is different than the relationship found without a constant energy multiplication. As discussed earlier, the relationship with a constant energy multiplication is of more consequence because the real system will follow this relationship.

8. Future Work

Further analysis will be in the areas of constant energy production over the life of the reactor and material testing for materials used in the In-Zinerator. Material testing will be needed to find the effect of the high rate of energy release on the materials used in this particular system. The In-Zinerator creates high pressure and temperature gradients that may cause too great of a stress for the materials used in the reactor. The analysis of constant energy production over the life of the reactor may need to be an iterative process in which the assumption that the specific isotopic composition does not have an effect on the parameters such as leakage rod worth and relationships with ^{6}Li enrichment will need to be tested. First isotopic composition will need to be determined for a later time in reactor life then these assumptions will need to be tested using the same tests completed in this work, which assumes an initial time and isotopics.

9. Conclusion

This preliminary work has identified key areas of further research and found some important results. For future study, the feasibility of the power output in the short pulse produced by the In-Zinerator and the issue of constant energy multiplication need to be addressed. Material testing may be needed to find the response of the materials to the high pulse of energy. To address the constant multiplication, iterations between running tests and changing the isotopic composition need to be run. This will serve the purpose of confirming the assumptions made in this work. One important result from this work is that leakage rods effectively control energy multiplication. Other important findings include the optimal reflector material, the effect of ^{6}Li enrichment on TBR, and the dominance of the fission neutrons contributing to the dpa and TBR. The optimal reflector material was found to be Pb. Other common reflecting materials, such as graphite and beryllium, were not feasible with the fast spectrum of the In-Zinerator. The ^{6}Li enrichment increases TBR if energy multiplication is held constant with leakage rods. Lastly, this work found that the fission neutrons are dominant in contributing to the dpa and TBR. This causes the internal fuel tube walls having the highest dpa. The fission neutron population is highest in the central tubes and therefore causes more radiation damage.

References

1. B.B. Cipiti, "Fusion Transmutation of Waste and the Role of the In-Zinerator in the Nuclear Fuel Cycle", Technical report, Nuclear and Risk Technologies, Sandia National Laboratories, June 2006.

2. L.A. El-Guebaly, "Engineering Issues Facing Transmutation of Actinides in Z-Pinch Fusion Power Plant," 17th ANS Topical Meeting on the Technology of Fusion Energy, Albuquerque NM, November 2006.

3. B.B. Cipiti, P.H.Wilson, P. Phruksarojanakun, and L.A. El-Guebaly, "Transmutation of TRU using Z-Pinch Fusion," 17th ANS Topical Meeting on the Technology of Fusion Energy, Albuquerque NM, November 2006.