Activation and Waste Stream Analysis for RTL of Z-Pinch Power Plant

L. El-Guebaly, P. Wilson, M. Sawan

November 2006

UWFDM-1308

Presented at the 17th ANS Topical Meeting on Fusion Energy, 13-15 November 2006, Albuquerque NM.

Activation and Waste Stream Analysis for RTL of Z-Pinch Power Plant

L. El-Guebaly, P. Wilson, M. Sawan

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

http://fti.neep.wisc.edu

November 2006

UWFDM-1308

Presented at the 17th ANS Topical Meeting on Fusion Energy, 13-15 November 2006, Albuquerque NM.

ACTIVATION AND WASTE STREAM ANALYSIS FOR RTL OF Z-PINCH POWER PLANT

L. El-Guebaly, P. Wilson, and M. Sawan

Fusion Technology Institute, University of Wisconsin, Madison, WI, elguebaly@engr.wisc.edu

The main goal of this assessment is to classify the radwaste stream of the recyclable transmission lines (RTL) at the end of the Z-Pinch plant operation. With the emergence of the new clearance standards, we included both the national and international standards in our analysis and assessed the implications for the RTL waste stream. The 3-D spectral flux was coupled to the ALARA pulsed activation code to estimate the activation responses. Our results indicate that for the first time an internal component close to the target, such as the RTL, can be cleared from regulatory control following a storage period of 50 y after plant decommissioning. As a design requirement, the recycling process must be economically feasible, accomplished within 1.1 day with no hands-on manufacturing and in the absence of personnel access to the fabrication facility. Advanced remote handling equipment must be developed to handle a dose rate of 3000 Sv/h.

I. INTRODUCTION

The Z-pinch IFE concept is relatively new and has become an essential part of the inertial fusion energy (IFE) community over the past five years.[1,2] Initiated by Sandia National Laboratories (SNL), the project investigates the scientific principle of a power generation system using the Z accelerator in a 1000 MW$_e$ power plant application. Furthermore, it integrates the liquid-protected chamber, RTL recycling and manufacturing, and cartridge replacement mechanism. The present strategy is to use high yield (3 GJ per shot), a low rep rate per chamber (0.1 Hz), and a replaceable cartridge that is manufactured on-site. The magnetically insulated RTL connects the driver to the target as shown in Fig. 1. It should be made of a steel that is easy to fabricate and separate from the chamber coolant/breeder. The RTL assembly enters the 10 m wide chamber through a 1 m radius single hole at the top. Since the inception of the Z study, recycling of the RTLs has been recognized as a "must" requirement to control its radwaste stream. As Fig. 2 indicates, recycling helps limit the RTL life-cycle inventory to 5000 tons, representing only 1% of the total machine radwaste. Every 10 seconds, the RTL/target assembly is inserted into the chamber, the shot is fired, portions of the RTL evaporate and mix with the chamber coolant/breeder, the upper remnant of the RTL is removed by a robot, and the cycle is repeated. An online separation of the elements leaving the chamber would sort out the breeder and target debris from the RTL shrapnel. The RTL materials spend ~28 hr (~1.1 d) outside the chamber for remanufacturing, assembly, and inspection.

The transition to a more advanced Z-pinch design[2] in 2005 involved several changes to the 2004 chamber and RTL parameters[1] that warrant updating the previous activation and waste stream analyses.[3] The most notable changes that influence the activation level are the height of the RTL and its reprocessing time. Other design parameters and radiation limits that are essential for this assessment are presented in Table I. Figure 3 illustrates the basic sequence of the recycling process that is designed to operate in an automated fashion. An online separation of the elements leaving the chamber would sort out the breeding material and target debris from the RTL shrapnel. The latter could be stored, then recycled using low technology manufacturing techniques. Prior to manufacturing, a cooling period might be needed to control the activity of the RTL debris. It is likely that the RTL fabrication and inspection processes could consume ~2.5 h.[2] Parallel fabrication of the target capsules, foam, etc. is anticipated. Before insertion into the chamber, a one-day storage of the backup supply is required to account for any malfunctioning during reprocessing. The final assembly process must be fairly rapid and should not take more than 10 s in a cryogenic environment. On this basis, the RTL materials spend ~1.1 day outside the chamber. Even though the process is highly automated, personnel may still be required for some processes. Our analysis will determine the severity of the radiation environment in the RTL fabrication facility and the feasibility of personnel access.

II. RATIONALE FOR RTL MATERIALS SELECTION

The choice of the RTL materials plays an essential role in the activation analysis and affects other aspects of the design. The materials must satisfy several design requirements, having a direct impact on:

- Economics
- Refabrication and machinability
- Structural integrity
- Joule losses
- Post-shot shrapnel formation
- Disruption to breeder jets
- Separability from liquid breeder
- Vacuum and electrical connections to power feed
- Activation level and waste stream.

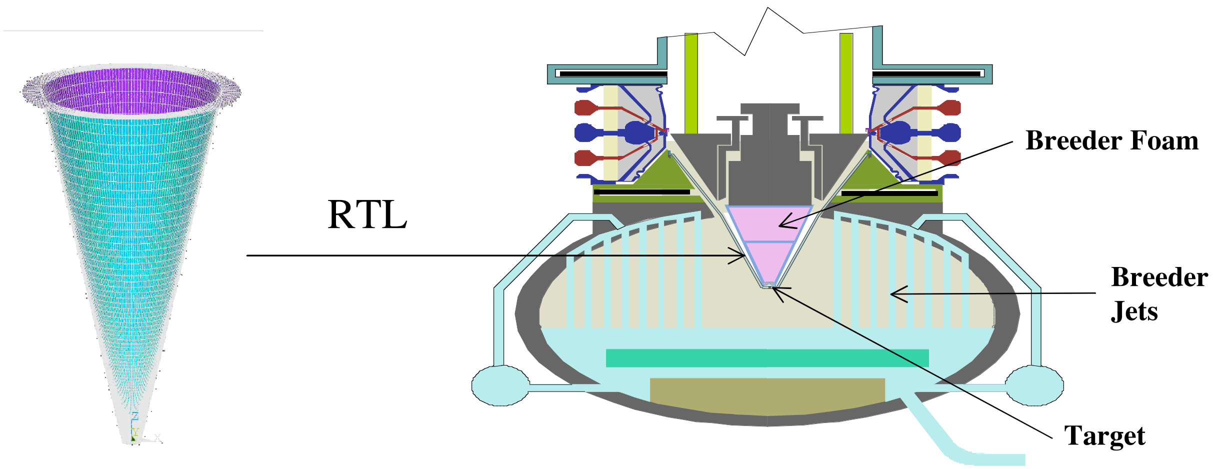

Fig. 1. Z-pinch IFE chamber concept.

TABLE I. Key Design Parameters for Z-pinch Activation Analysis

Design Parameters:	
Target Yield	3000 MJ
Rep Rate	0.1 Hz
# of Units per Plant	10
RTL Thickness	0.142 cm
Compacted Volume / RTL	0.006 m^3
Mass / RTL	50 kg
Plant Lifetime	40 FPY (47 y)
Projected Plant Availability	85%
Radiation Limits:	
Waste Disposal Rating	1
Clearance Index	1
Remote Recycling Dose Rate	3000 Sv/h

Carbon steel, mild steel, low activation ferritic steel, and pure iron have been proposed for the RTLs. Frozen Flibe and LiPb have also been considered but we are using the baseline material (carbon steel) to examine the recycling issues. Carbon steel (99.51% Fe, 0.08% C, 0.32% Mn, 0.04% P, and 0.05% S) is the preferred material as it offers the lowest cost per unit mass of all forms of steel. Unlike Flibe, steel has a high electrical conductivity for a thin low-mass RTL, a property of great importance for Z-Pinch. Also, steel precipitates as solids and can be easily recovered through filtering from the liquid that protects the chamber vessel. The present RTL weighs 50 kg and operates in a 10-20 torr background chamber pressure. For a yield of 3 GJ per shot and 1000 MW electric power plant, the RTL must be manufactured at a high rate. A plant containing 10 units, each operating at 6 pulses per minute, requires 60 RTLs per minute, calling for a state-of-the-art RTL manufacturing facility.[2]

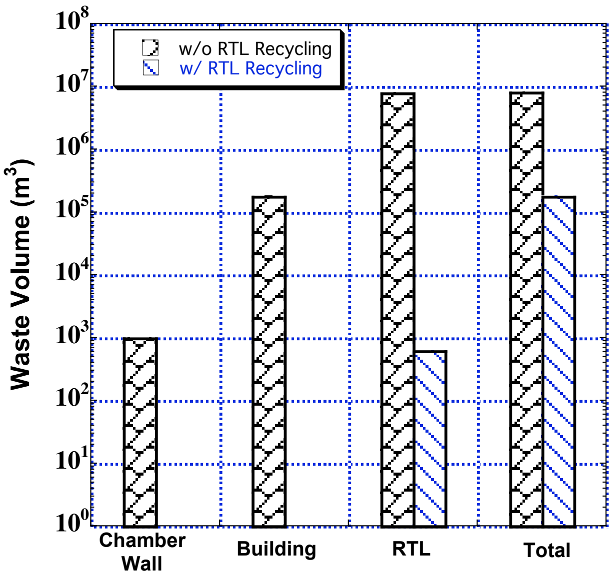

Fig. 2. RTL inventory and radwaste volume comparison.

III. CLASSIFICATION OF RTL ACTIVATED MATERIALS

The main goal of the activation and waste management study is to classify the RTL materials into high-level waste (HLW) and low-level waste (LLW). For the latter, we further distinguished between radioactive waste and slightly activated materials. As the 2000s began, many countries have successfully issued clearance guidelines that allow solids containing traces of radioisotopes (such as the RTLs) to be cleared from regulatory control and unconditionally released to the nuclear industry (or commercial market) for reuse after a specific storage period (≤ 100 y). With the emergence of the new clearance standards in the U.S. and abroad, we included both the proposed national[4] and international[5] standards in our analysis and assessed the implications for the Z-pinch power plant. Reference 6 addresses the social and political aspects of the clearance issue.

The 3-D Monte Carlo MCNP code[7] has been used to compute the average neutron flux over the 2 m high RTL. The flux amounts to 7 x 10^{15} n/cm^{2}s and 1 x 10^{16} n/cm^{2}s for the Flibe and LiPb chambers, respectively. The spectral flux, displayed in Fig. 4, was then coupled to the pulsed activation code ALARA[8] to estimate the activation responses, such as the radioactive inventory, waste disposal rating (WDR), clearance index (CI), dose to recycling equipment, etc. The ALARA code modeled all pulses (~13,000) over 40 full power years (FPY) of operation with the projected 85% availability. Despite the differences in the magnitude and spectrum of the Flibe and LiPb fluxes at the 2 m high RTL, the impact on the activation responses is negligible.

We applied the geological disposal, clearance, and recycling criteria to the disposition of the RTL materials. The disposal and clearance limits are those recommended by the U.S. (NRC and Fetter) and IAEA. The results show that at the end of the plant life the RTLs generate a Class A very low-level waste (WDR=10^{-4}), the least hazardous type based on the U.S. federal classification. The main contributors to the WDR are T and ^{14}C. The WDR meets the LLW limit within a wide margin. This means the RTLs contain traces of radionuclides, representing no risk to the public health and safety. Potentially, it could be cleared from regulatory control if the CI reaches unity after a certain storage period (< 100 y), and then released to the nuclear industry or commercial market for reuse. The clearance offers an economic advantage as it saves a substantial disposal cost for such a large quantity (5000 tons, 630 m^3) and frees ample space in the repositories for other radioactive waste.

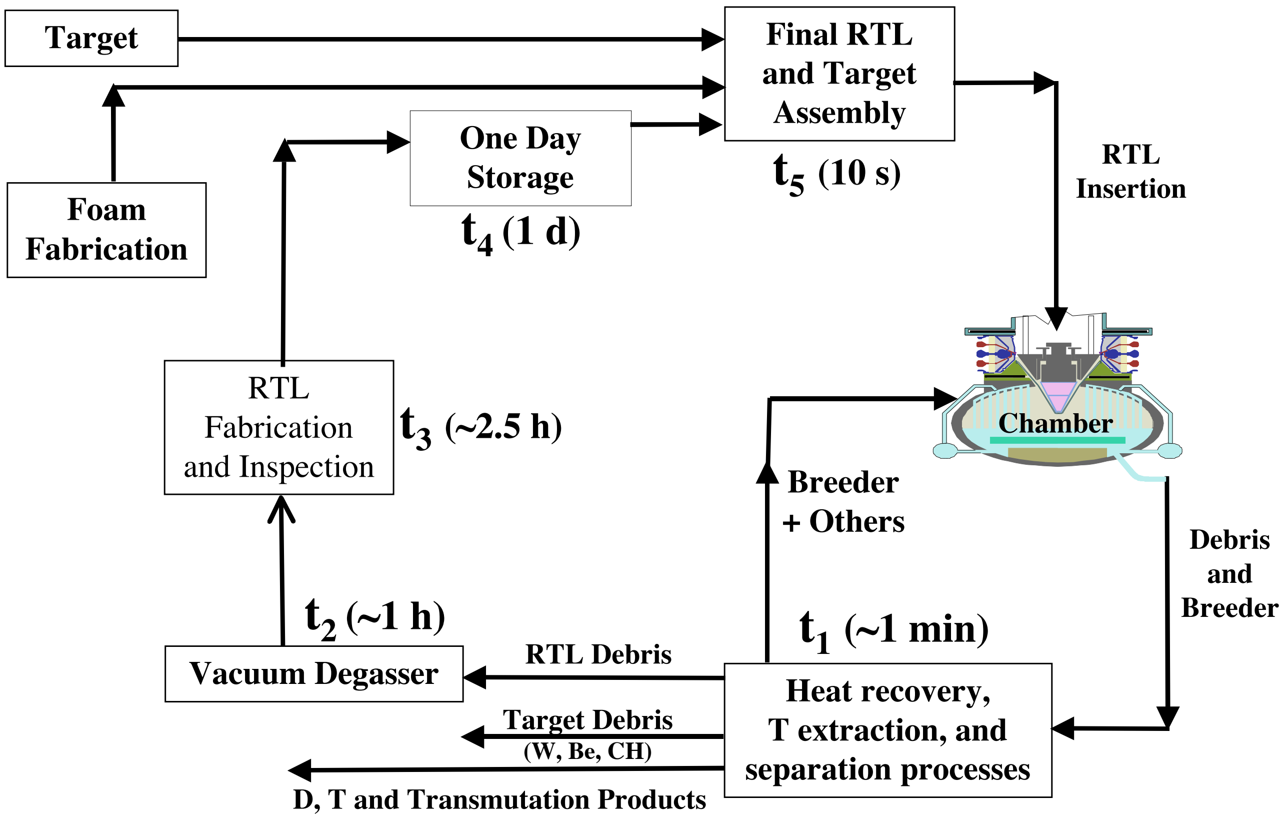

Fig. 3. Timeline of RTL recycling process.

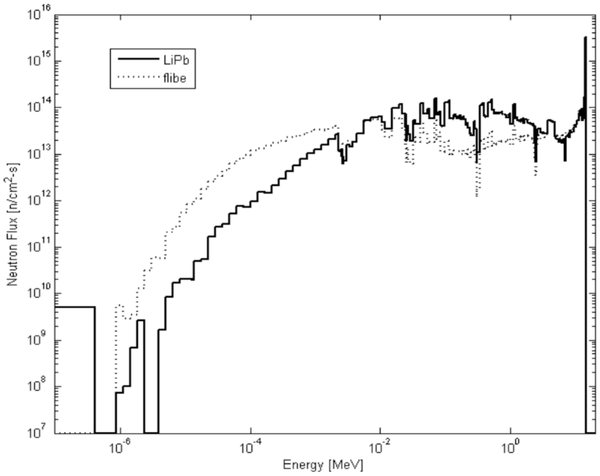

Fig. 4. MCNP calculated neutron flux at RTL for Flibe and LiPb breeder options.

The variation of the RTL CI with time after decommissioning is shown in Fig. 5. The CI reaches unity after 85 y according to the U.S. guidelines. The dominant radionuclides (in descending order) are the T (91%, $T_{1/2}$=12.3 y), ^{53}Mn (7%, $T_{1/2}$=3.7 My), and ^{60}Co (1%, $T_{1/2}$=5.3 y) for the U.S. CI=1 at 85 y and ^{53}Mn (87%), T (12%), and ^{14}C (0.5%, $T_{1/2}$=5.7 ky) for the IAEA CI=11 at 100 y. The differences between the clearance limits are discussed in Ref. 6. During reprocessing, a considerable fraction of the tritium diffuses out of the carbon steel and thus the CI could reach unity at a shorter time (~ 50 y) as shown in Fig. 5. These results are conservative as no credit was given to the possible removal of the transmutation products during reprocessing. Continual removal of the slag (which contains some of the transmutation products) would shorten the storage period further, but accumulates a limited amount of undesirable radioactive waste that may raise radiological concerns. This issue needs further investigation.

IV. FEASIBILITY OF REMOTE RECYCLING

Previous U.S. and European power plant studies have employed recycling criteria based solely on the contact gamma dose rate, intended to reflect the ability to recycle the materials by remote handling (RH) means, if necessary. Reviews of the RH criterion suggest that the present 0.01 Sv/h limit is unduly conservative. A more realistic dose limit would be 3000 Sv/h for advanced RH equipment based on current industrial practices.[6] The impact of the revised RH criterion is illustrated in Fig. 6, showing the reduction of recycling dose with time following the removal of the RTL debris from the chamber. The main contributors to the dose at 1 day are ^{54}Mn (90%, $T_{1/2}$=312.2 d) and ^{56}Mn (9.6%, $T_{1/2}$=2.58 h).

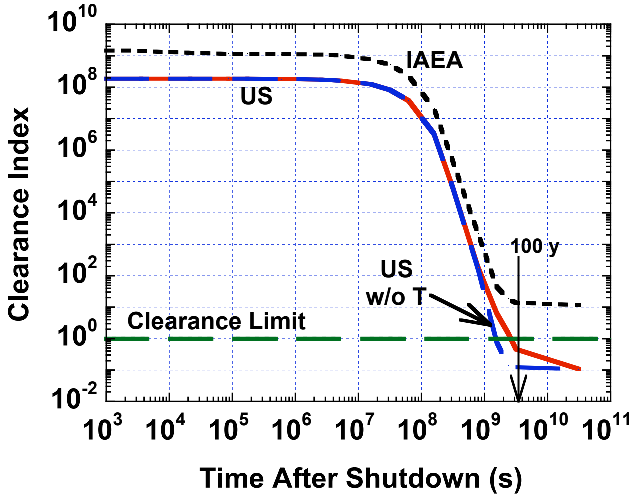

Fig. 5. Variation of RTL clearance index with time after plant decommissioning (no cooling period between shots and no removal of transmutation products).

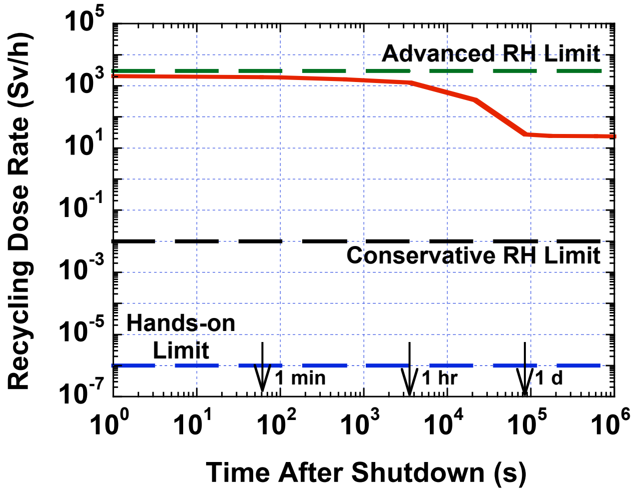

Fig. 6. Reduction of dose with time after RTL debris exits the chamber (no cooling period between shots and no removal of transmutation products).

Several observations can be made:

- Hands-on recycling is not allowed
- No personnel access is permitted to the RTL fabrication facility
- RH with advanced equipment is feasible
- The dose remains below the 3000 Sv/h advanced RH limit at all times during the recycling process
- Removal of the slag and the continual addition of supplemental fresh material during reprocessing are expected to lower the dose rate considerably.

V. CONCLUDING REMARKS

Unlike magnetic fusion concepts or other laser and heavy ion beam driven IFE concepts, the Z-pinch illustrates for the first time an internal component close to the target contains only traces of radioactivity primarily due to the limited irradiation history (one shot per 1.1 day). This means the slightly activated 630 m^3 carbon steel can be cleared from regulatory control following a storage period of 50 y after plant decommissioning. An efficient slag removal system could shorten the storage period considerably by removing the troublesome radionuclides (^{53}Mn and ^{60}Co). The recycling process must be economically feasible with no hands-on manufacturing and in the absence of personnel access to the fabrication facility. Advanced remote handling equipment must be developed to handle 3000 Sv/h or more and the recycling process should be accomplished remotely in a relatively short time of 1.1 day. The effect of the degradation of the RTL electrical conductivity due to neutron-induced transmutation products needs further investigation. Should the RTL physics and fabrication technique permit RTLs made of non-steel materials, we strongly support fabricating the RTL out of breeding materials (Flibe or LiPb) to eliminate the need for the RTL separation process and reduce the RTL energy demand below 200 MW_e.

The online removal of the slag and continual supplement of fresh material to the RTL stream may positively impact the end results. With adequate knowledge of the efficiency of the slag removal system, isotopic inventory simulation can be used in the future to determine the changes in inventories throughout the RTL flow stream. Both ALARA[7] and MCise[9] systems are capable of handling such a problem. The newly developed MCise (Monte Carlo Isotopic Simulation Engine) system could simulate the details of the isotopic inventory with a more detailed modeling of the RTL flow, online chemistry/separations of radioisotopes, and recirculation process. A variety of calculations and analyses will be necessary to address other secondary impacts such as the waste disposal rating of the slag and the feasibility of hands-on recycling.

ACKNOWLEDGMENTS

The work was performed under the auspices of Sandia National Laboratories (contract #297000). The authors wish to thank C. Olson, G. Rochau, and B. Cipiti (SNL) for helpful discussions and useful comments in preparing this manuscript.

REFERENCES

1. C. OLSON, G. ROCHAU, M. MATZEN et al., “Z-Pinch IFE Program – Final Report for FY04,” Sandia National Laboratories Report, SAND-2005-2742P (April 2005).

2. C.L. OLSON et al., “Z-Pinch IFE Program Final Report for FY05,” Sandia National Laboratories report, SAND–2006-7399P (2006).

3. L. EL-GUEBALY, P. WILSON, M. SAWAN, D. HENDERSON, and A. VARUTTAMASENI, “Recycling Issues Facing Target and RTL Materials of Inertial Fusion Designs,” *Nuclear Instruments & Methods in Physics Research,* Section A, **544,** 104-110 (2005).

4. Nuclear Regulatory Commission, “Radiological Assessments for Clearance of Materials from Nuclear Facilities,” Washington, D.C., Main Report NUREG-1640 (2003). Available at: http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1640/

5. International Atomic Energy Agency, “Application of the Concepts of Exclusion, Exemption and Clearance,” IAEA Safety Standards Series, No. RS-G-1.7 (2004). Available at: http://www-pub.iaea.org/MTCD/publications/PDF/Pub1202_web.pdf

6. M. ZUCCHETTI, L. EL-GUEBALY, R. FORREST, T. MARSHALL, N. TAYLOR, and K. TOBITA, “The Feasibility of Recycling and Clearance of Active Materials from a Fusion Power Plant,” Proceedings of ICFRM-12 Conference, Dec. 4-9, 2005, Santa Barbara, CA.

7. X-5 Monte Carlo Team, “MCNP - a General Monte Carlo n-Particle Transport Code,” Version 5-Volume II: Users Guide, LA-CP-03-0245, Los Alamos National Laboratory (2003).

8. P. WILSON and D. HENDERSON, “ALARA: Analytic and Laplacian Adaptive Radioactivity Analysis Code Technical Manual,” University of Wisconsin Fusion Technology Institute, UWFDM-1070 (1998).

9. P. PHRUKSAROJANAKUN and P.P.H. WILSON, “Monte Carlo Techniques for the Comprehensive Modeling of Isotopic Inventories in Future Nuclear Systems and Fuel Cycles,” University of Wisconsin Fusion Technology Institute Report, UWFDM-1282 (October 2005). Available at:

   http://fti.neep.wisc.edu/pdf/fdm1282.pdf