

Monte Carlo Studies in Accelerator Driven Systems for Transmutation of High Level Nuclear Waste

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1. Introduction

- For the last fifty years, the nuclear systems have been producing increasing amounts of highly radioactive waste. The spent fuel consists of a wide variety of elements and isotopes.
- The majority of the long-lived isotopes comes from transuranic wastes and minor actinides.

- **The aim is to transmute the minor actinides and fission products which are created from the operation of nuclear power reactors for the production of electricity.**

- Transmutation of minor actinides and long-lived fission products is a promising concept to reduce the radioactive waste and its long-term radiotoxicity.
- The transmutation technology to incinerate the long-lived radioactive isotopes using an accelerator driven subcritical reactor is one of the best solutions.

2.The system

The transmutation system (Fig. 1.) is composed of

- linear accelerator
- natural lead target,
- beam window,
- subcritical core,
- reflector,
- structural material.

- **Neutrons are produced by the spallation reaction of protons from a high intensity linear accelerator in the spallation target and the fission reaction in the core.**

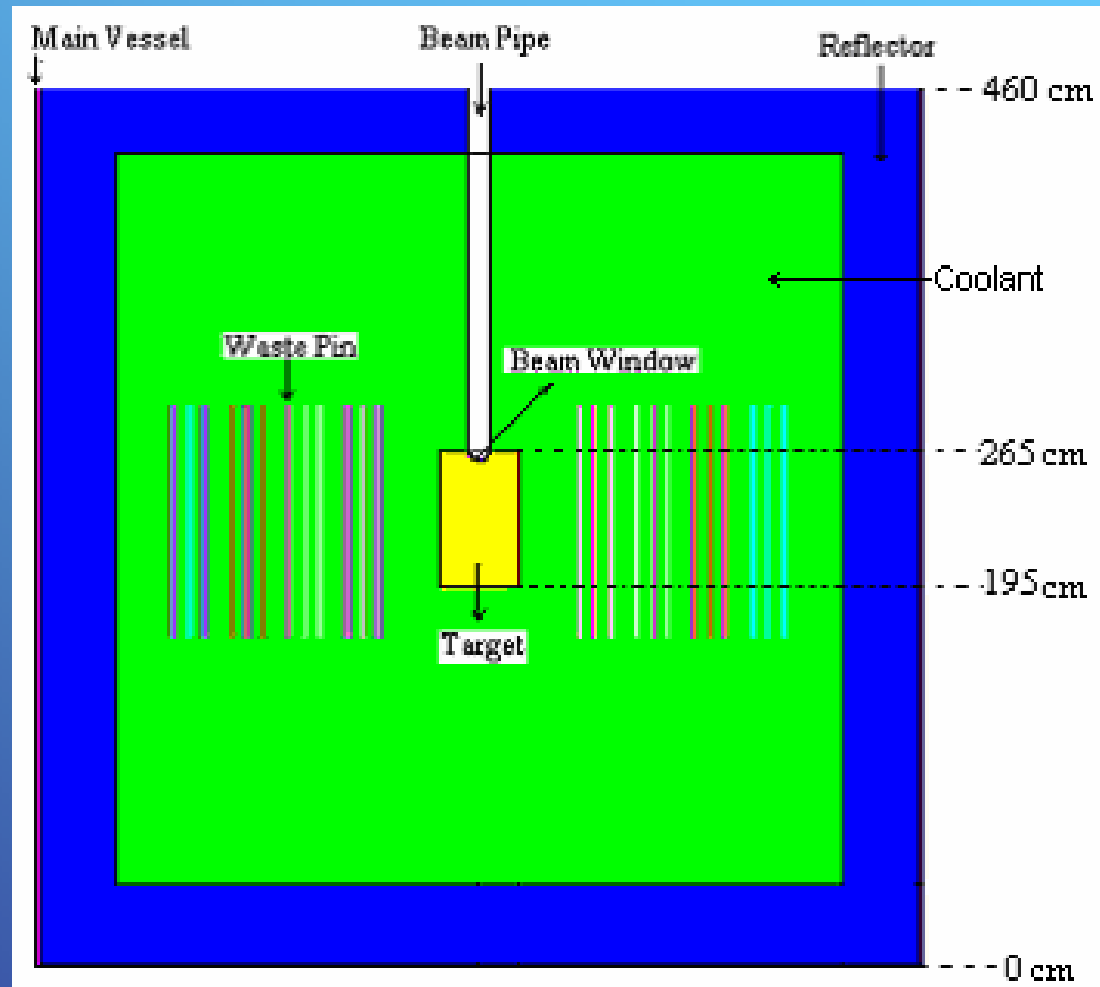


Figure 1. Horizontal sectional views of the present ADS design

- The system is driven by a 1 GeV, 10 mA proton beam incident on a natural lead cylindrical target, 20 cm radius, 70 cm height entering the target through a 5.3 cm radius hole.
- The protons were uniformly distributed across the beam of radius 2 cm. The core is cylindrical assembly, 2.3 m radius, 4.6 m high.
- The wall thickness of the main vessel is 2 cm. The main vessel is surrounded by a reflector made of graphite, 40 cm thick. The axes of proton beam and the target are concentric with the main vessel axis. The structural walls and beam window are made of the same material, stainless steel, HT9.

3. Neutronic analysis

- In the calculations, Monte Carlo code MCNPX, which is a combination of LAHET and MCNP, was used.
- To transport a wide variety of particles, The Los Alamos High Energy Transport Code, LAHET, was used.
- These include charged particles such as protons and charged pions as well as neutrons with high energies. MCNPX offers options based on three physics packages; the BERTINI and ISABEL models taken from the LAHET Code System, and the CEM package .

The calculations were carried out for three steps:

- **Only the spallation target+
proton beam pipe+
beam window**
- **The system for absence of the fissile materials
and wastes.**
- **The full system.**

**In the calculations, we did not take time
evaluation of the neutron spectrum and other
quantities into account.**

- One of the fundamental parameters of the spallation target is the number of neutrons produced per beam particle incident on target.
- Calculation of number of neutrons produced in the target is done by summing up the absorption and leakage. Because of small neutron absorption of lead, the leakage is considered to be equal to the neutron production.
- Spallation neutron and proton yields per one incident proton are
27.4 and 1.2E-02,
respectively.
- Other particle yields such as, pion and muon per one incident proton have been neglected due to their low particle fluxes.

- The target was designed to maximize the neutron yield. The target optimization means finding the maximum of neutron production inside the target and the maximum of neutron leakage to the core at given proton energy and target shape and material.

- The neutron leakage on the whole surface of the target for all three steps mentioned above is shown in Table 1. Some of the spallation neutrons produced by protons in the target can escape through the beam pipe, therefore it is desired to minimize the neutron escape through the beam pipe.
- The neutron leakage through the beam pipe for target-beam pipe system (Fig. 2.) isolated from the core is shown in Table 2. The ratio of the neutron leakage into the proton beam vacuum to the total neutron leakage from the target top face is 1.54%.

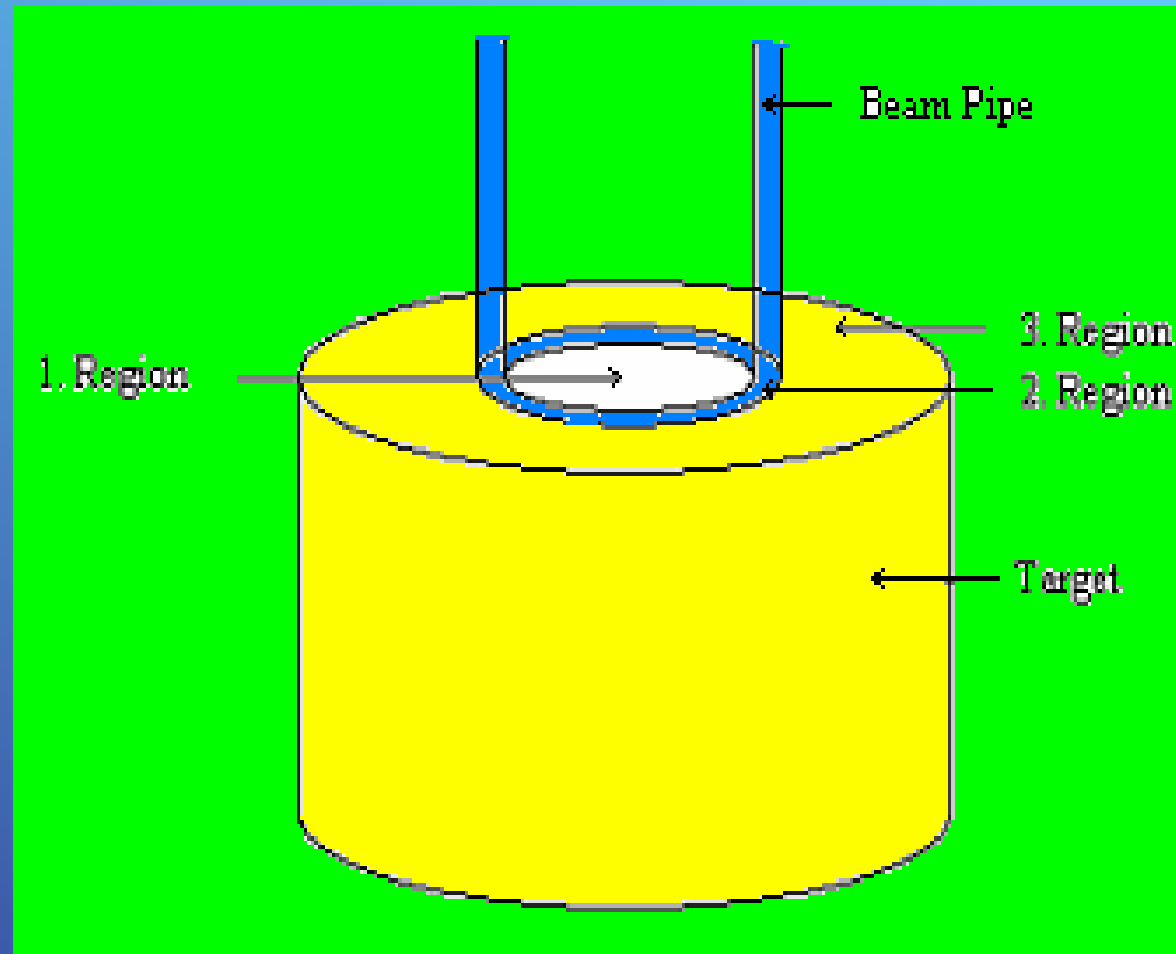


Figure 2. Scheme of the target-beam system

Table 1. The neutron leakage on the whole surface of the target and main vessel wall.

Neutron Leakage (n/s)	Beam pipe + target	Beam pipe + target + coolant	Full System
Target			
top face	3.25E+17	5.68E+17	1.44E+18
side face	1.34E+18	2.78E+18	9.43E+18
bottom face	4.02E+16	1.63E+17	1.03E+18
Main vessel			
top face	1.12E+14	8.60E+15	8.73E+16
side face	-	4.12E+16	3.42E+17
bottom Face	-	6.92E+15	8.15E+16

Table 2. The neutron leakage on the target top face for full system.

Target Top Face	1. Region (n/s)	2. Region (n/s)	3. Region (n/s)	Total (n/s)
	1.43E+17	1.54E+16	1.28E+18	1.44E+18

3.1 Energy and spatial distribution

- The transmutation performance of a nuclear system mainly depends on flux level and neutron spectrum.
- The energy distributions of the spallation neutron and proton fluxes, the radial and axial variations of the neutron flux in target and energy distributions of the spallation neutron and proton fluxes in the beam window are shown in Fig. 3-5.

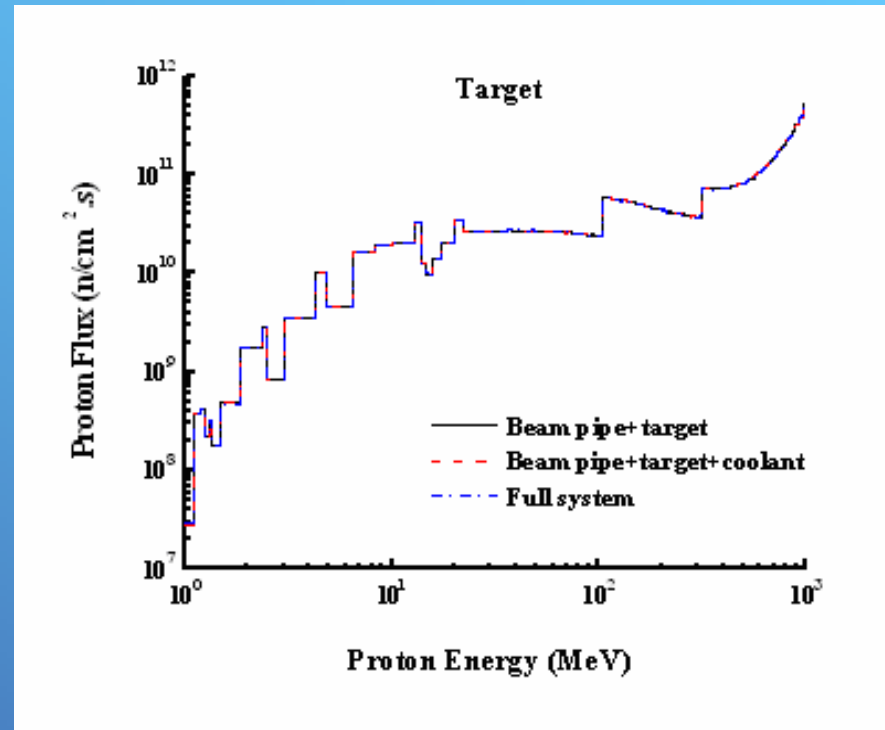
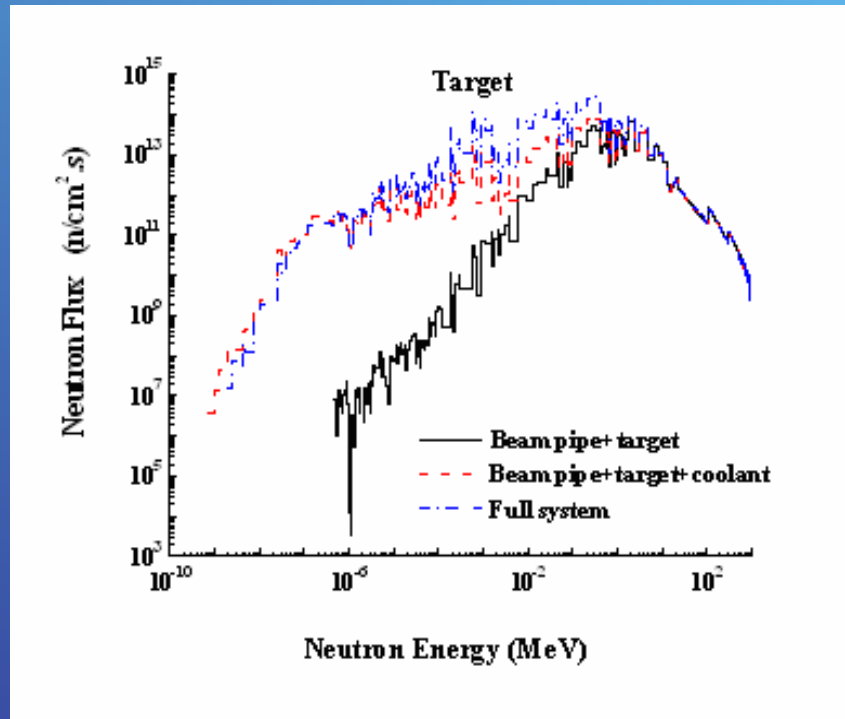


Figure 3. Energy distribution of the spallation neutrons and protons in the energy range 0-1000 MeV in the target.

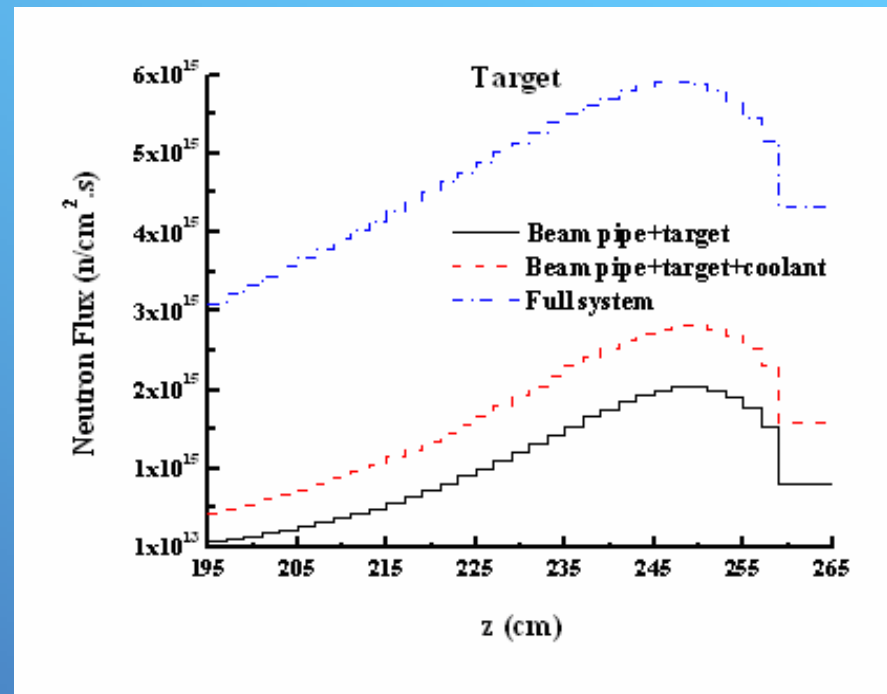
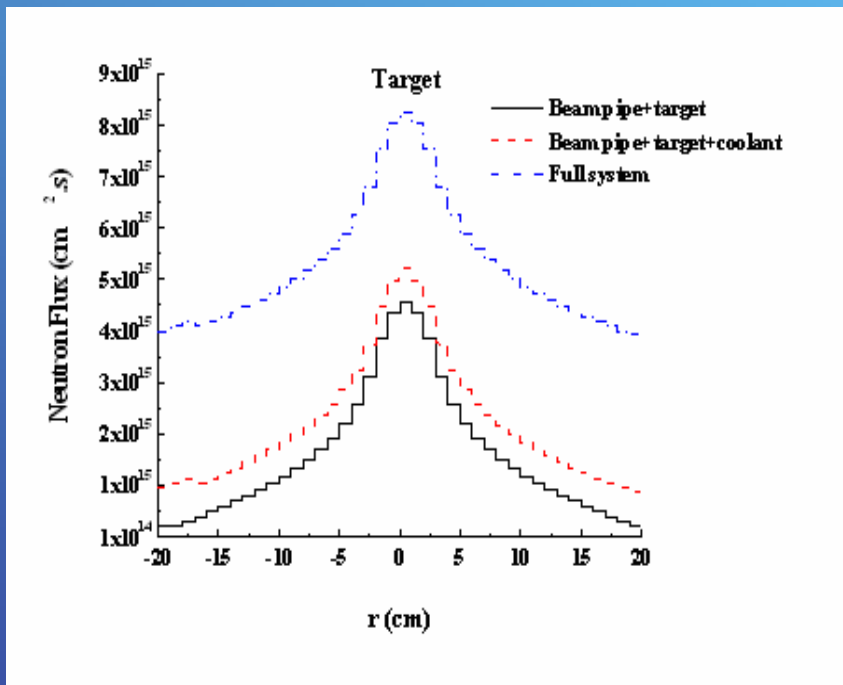


Figure 4. The spatial variation of the neutron fluxes in the target: (a) radial(left), (b) axial (right)

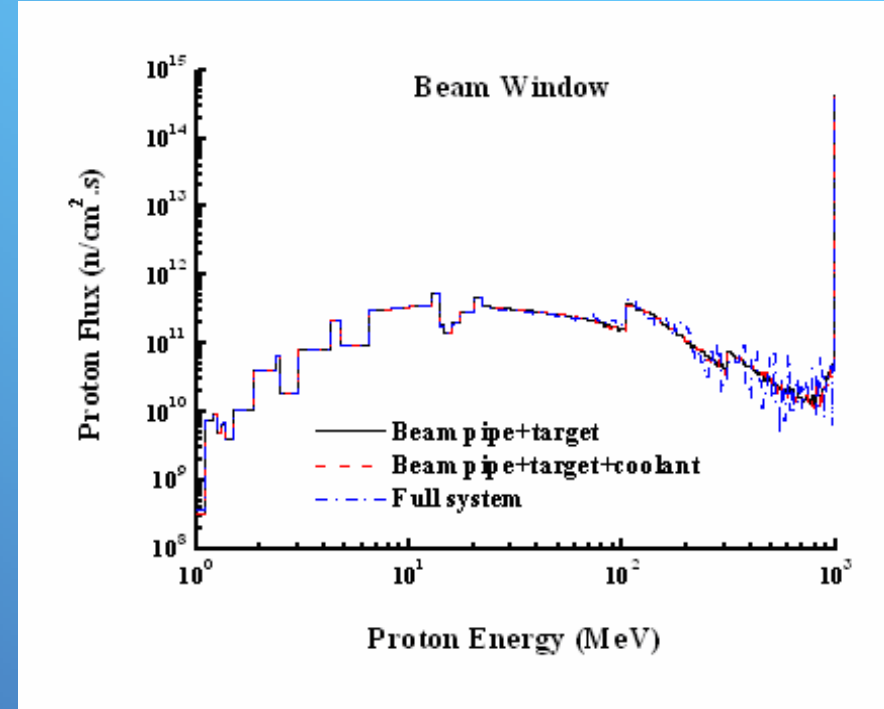
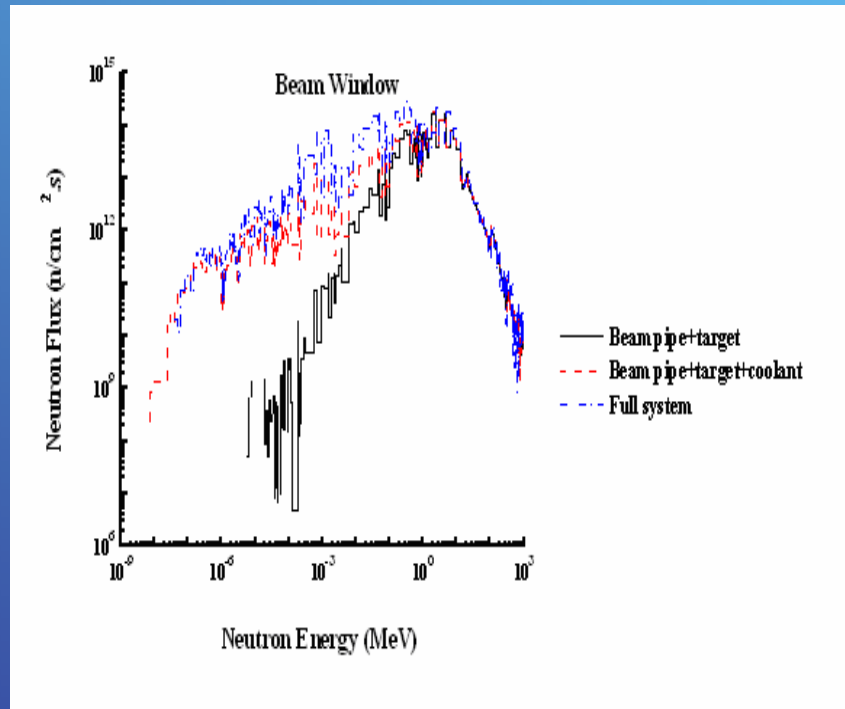


Figure 5. Energy distribution of the spallation neutrons and protons in energy range 0-1000 MeV in the beam window.

3.2 Heat deposition

- The heat deposition by neutrons and protons in the some parts of the system for the three steps is given in Table 3.
- And radial variation of the heating in the target is shown in Fig. 6.
- There is a negligible energy deposition by neutrons in the other structural materials except beam window.

Table 3. Energy deposited by neutrons in the some parts of the system for three calculation steps

Heating (kW/cm³)	Beam pipe + target	Beam pipe + target + coolant	Full System
Target	28.66	29.12	31.93
Beam window	84.83	107.74	96.09
Beam pipe	0.0	3.00	4.86
Main vessel wall	0.0	2.65E-03	2.14E-03

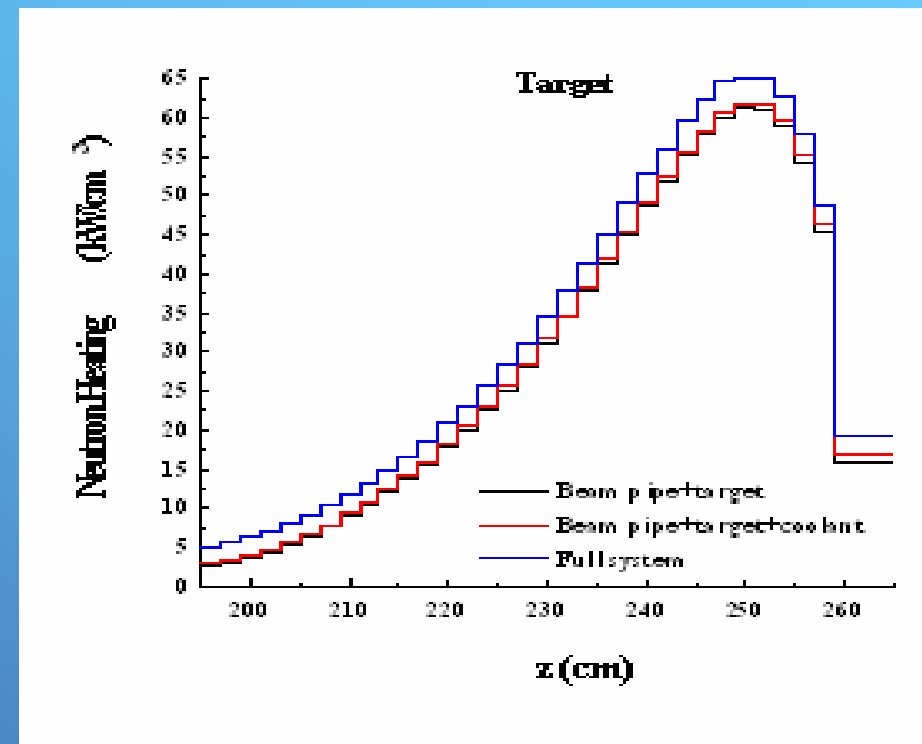
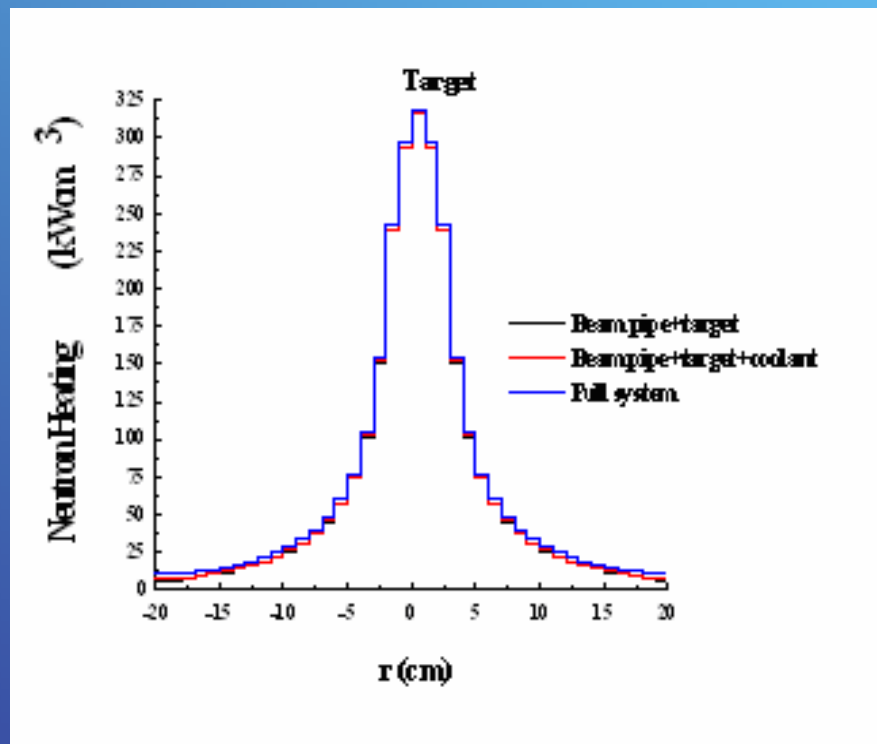


Figure 6. Radial and axial variation of the heating in the target.

3.3 H and He production rates

- The gas production rates in the target and beam window for full system are shown in Table 3.
- The results show that the gas production in the beam window is more intense than the target, as expected.

Gas Production (apmm / fpy)	Target	Beam Window
H	2798.21	33000
H-2	304.1	3770
H-3	181.67	810
Total H	3283.45	37200
He-3	11.12	565
He-4	514.69	3320
Total He	525.81	3880
Total H + He	3809.20	41100

Table 4. Gas production in the target and beam window

3.4 Transmutation

- The core of the system mainly consists of the spallation target region and fuel (and waste) assembly region.
- The fuel region consists of the pin-bundle type fuel assemblies and is cooled by liquid sodium.

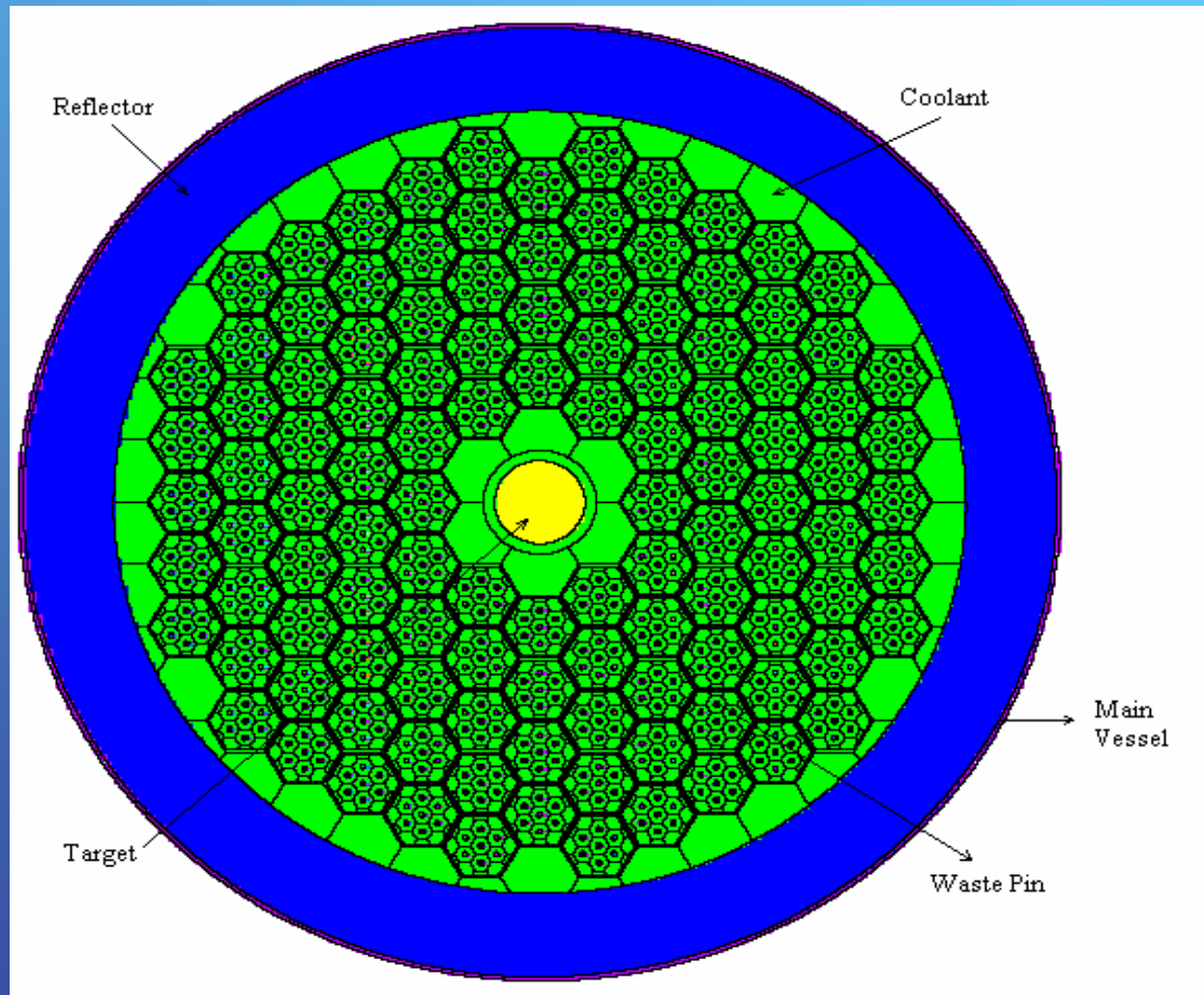


Figure 7. Vertical sectional views of the present ADS design

- **The fuel elements consist of a stainless steel cladding, 0.35 cm thick, characterized by an external radius of 1.35 cm and a total height of 120 cm, end cap included.**
- **The fuel is a cylinder, 119.30 cm height. As mentioned above, we used a hexagonal lattice for fuel assemblies.**

- The fuel subassemblies, bundles, are arranged in an annular array of five rings, each fuel subassembly contains 7 fuel rods. There are 114 bundles in the system.

The core configuration for the calculations is characterized by:

- 10 bundles in ring 1 (^{239}Pu)**
- 20 bundles in ring 2 (^{237}Np)**
- 24 bundles in ring 3 (^{129}I)**
- 30 bundles in ring 4 (^{99}Tc)**
- 30 bundles in ring 5 (^{241}Am)**

All calculations are based on pure ^{99}Tc , ^{129}I , ^{237}Np , ^{239}Pu and ^{241}Am isotopes.

- The neutron multiplication factor, k_{eff} , with its standard deviation was calculated by “kcode” card of the MCNP code and was found as, after running a large number of histories, 0.966460 for the core without the proton beam.

- The capture reactions rates of LLFP increases in the thermal energy region of ADS is hard, so it is necessary to establish.
- The region with softer spectrum for transmutation of LLFP. However, the effect on the MA transmutation properties of ADS is significant. Results of transmutation calculation are given in Table 5.

Table 5. Transmutation calculation results

	^{99}Tc	^{129}I	^{237}Np	^{239}Pu	^{241}Am
Initial mass (kg)	910.434	182.509	1068.769	522.932	1082.229
Total transmutation (kg/fpy)	1.455	0.806	36.434	47.254	4.212

4. Conclusions

- Accelerator driven transmutation system was investigated. The system consists of 1 GeV, 10 mA proton accelerator and a subcritical core with an effective neutron multiplication factor of 0.96.
- For the neutronic analysis, we used the MCNPX code system. In the neutronic calculations, time evaluations have not been taken into account.

- The transmutation rates of minor actinides and long-lived fission products vary in the range 0.806-47.254 kg/fpy. The ADS proposed in this study produces energy from nuclear waste material, while a considerable amount of this spent fuel is incinerated.

Thank You

References

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