Target and Subcritical Developments to Dispose of US Spent Nuclear Fuel Inventory

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Accelerator Driven Design Concept for Disposing of Spent Nuclear Fuels

Argonne National Laboratory has started a research study to develop a design concept that can dispose of the US spent nuclear fuel inventory. This study assesses the needs, proposes a solution, identifies all components, and outstanding R&D needs.

Objective:

Develop a near term approach for disposing of US spent nuclear fuel inventory.

Guidelines:

- ***Utilize current technologies with minimum extrapolation,***
- ***Avoid multi-processing steps of the fuel materials,***
- ***Operate the systems at the peak power and produce energy to cover the system cost as much as possible, and***
- ***Minimize the number of the accelerator driven systems.***

US Spent Nuclear Fuels Inventory

- ***At present, ~60,000 MTof spent nuclear fuels are stored.***
- ***The current accumulation rate is ~2000 MT/y.***
- ***By the year 2015, the expected inventory is ~70,000 MT.***
- ***The 70,000 metric tons after 25 years of cooling time consists of:***
  - ***~96% enriched uranium – can be recycled for use in future nuclear power plants,***
  - ***~3% fission products – short lived isotopes can be stored for ~300 years to reduce their radiotoxicity by decay to that of the natural uranium ore, and***
  - ***~1% transuranics - ~700 MT (DOE/EIS-0250 Report).***
    - ***Plutonium is ~585 metric tons – a fraction can be used with the minor actinides in ADS and the balance as MOX fuel for thermal and fast power reactors***
    - ***Minor actinides (Np, AM, Cm) is ~115 MT and it can be used in ADS***

Accelerator Driven Design Concept Parameters for Disposing of Spent Nuclear Fuels

- The system power is ~3 GW_{th}, which can produce ~ 1 GW_e similar to a nuclear power plant.
- The effective neutron multiplication factor of the subcritical is 0.98.
- The required proton beam power for this system is ~25 MW.
- Lead bismuth eutectic or liquid lead is the fuel carrier (molten salt is backup option) with transuranics without uranium.
- Low plutonium concentration is mixed with the minor actinides to achieve the required effective neutron multiplication factor.
- The initial physics analyses show the required plutonium concentration in the transuranic is ~30%.
- For the 70,000 tons of spent nuclear fuels by 2015, the total minor actinides inventory is ~115 tons. Four to five accelerator driven systems can consume 150 tons (115 tons MA +35 tons Pu) for disposing of the US spent nuclear fuel inventory.

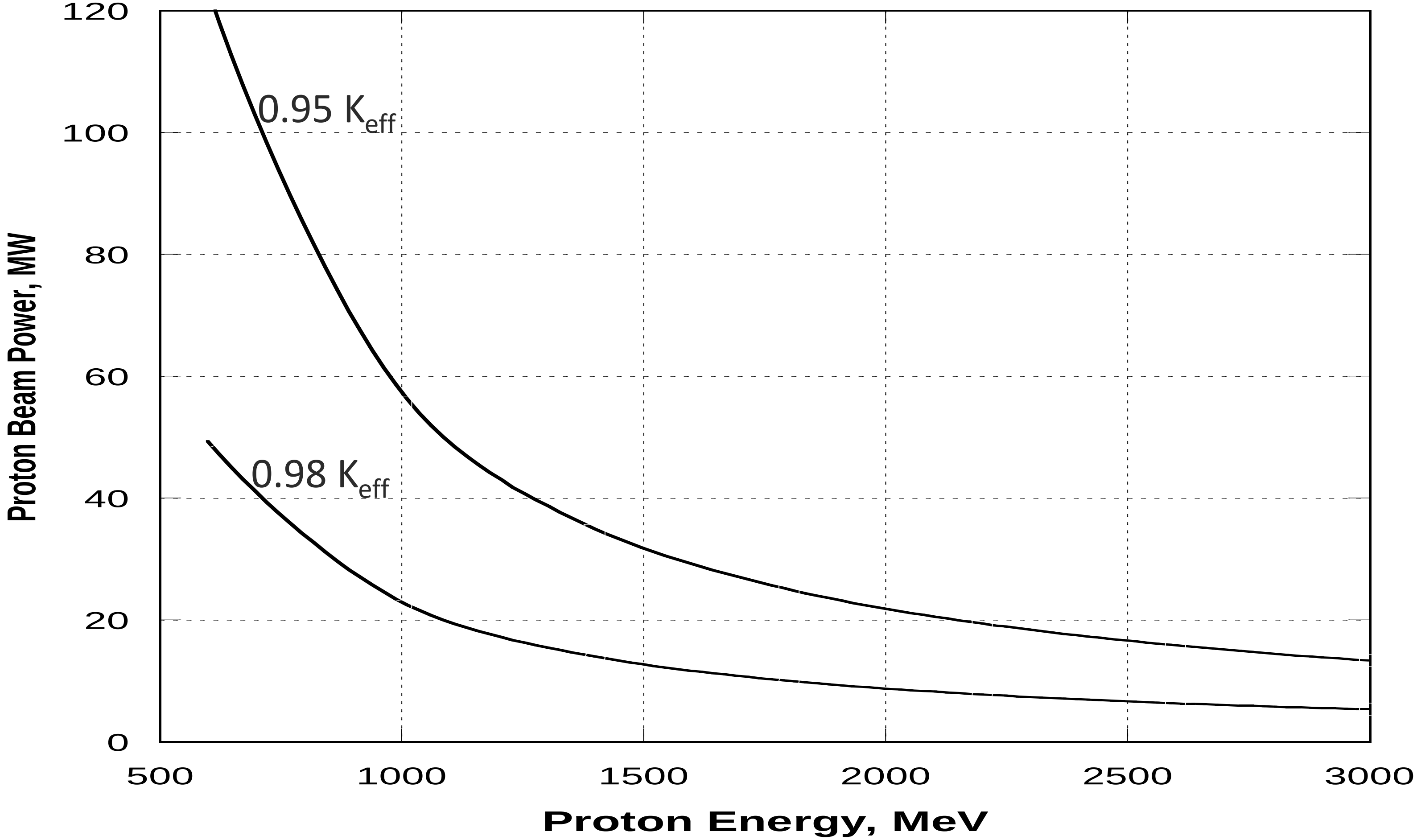
System Characteristics

- *Liquid metal targets are selected to simplify the target design, to enhance the target performance including its lifetime, and to relax some of the design requirements for the accelerator.*
- *Lead-bismuth eutectic and liquid lead are the main target candidates for this application.*
- *Subcritical assemblies with solid fuel materials are considered to utilize the gained experience from the fission power reactors. Such choice requires the development of new fuel designs, multi reprocessing steps, and additional fuel reprocessing plants. These characteristics require more R&D, time&cost, and time to dispose of the spent nuclear fuels.*
- *Mobile fuel forms with transuranic materials and without uranium are considered to avoid the issues of the solid fuel forms and to achieve the objective of eliminating the transuranics and most of the long-lived fission products of the spent nuclear fuels.*

System Characteristics
(continued)

- The mobile fuel form has a closed material cycle, which is proliferation resistance. The liquid carrier has the fission products mixed with the transuranics all the time.
- A significant fraction of the long-lived fission products are transmuted during the power generation process.
- The continuous feed of the transuranics during the operation reduces significantly the produced radioactive waste and the needed capacity for a long-term geological storage.
- The successful operation of fission reactors with lead bismuth eutectic coolant, spallation targets, and different lead-bismuth eutectic and liquid lead loops in Russia, Europe, India, Japan, Korea, and USA provides the technical experiences to proceed with such material.

Beam Power Requirements as a Function of the Proton Energy with Lead Bismuth Target for 3 GW_{th} System



Subcritical Assembly Concept Characteristics

- Mobile fuel forms:
  - Eliminate the minor actinides without the need for extra fuel processing steps.
  - Relax some of the reliability requirements for the accelerators,
  - Remove fission gases during operation,
  - Reduce the required R&D, the deployment time, and the total cost.
  - Fast system, which provides neutronics advantages relative to thermal systems:
    - Efficient neutron utilization,
    - Good neutron economy in the presence of fission products,
    - Lower probabilities for generating higher actinides.
  - Achieve the proposed objective and permit controlling the output power without changing the proton beam power

Subcritical Configuration with Mobile Fuel

Target

Proton beam power	25 MW
Proton energy	1 GeV
Target material	Lead Bismuth Eutectic
Proton beam radius	19.5 cm
Target length	70 cm
Target radius including I/O manifolds	35 cm

Subcritical

Outer radius	~150 cm
Height	~300 cm
Fuel carrier/coolant	Lead Bismuth Eutectic
Actinides oxide concentration	5.0, 7.0, or 10.0%
Plutonium concentration in the actinides for the above three actinides concentrations	35.7, 27.2, or 20.0%

Spallation Target Design Requirements

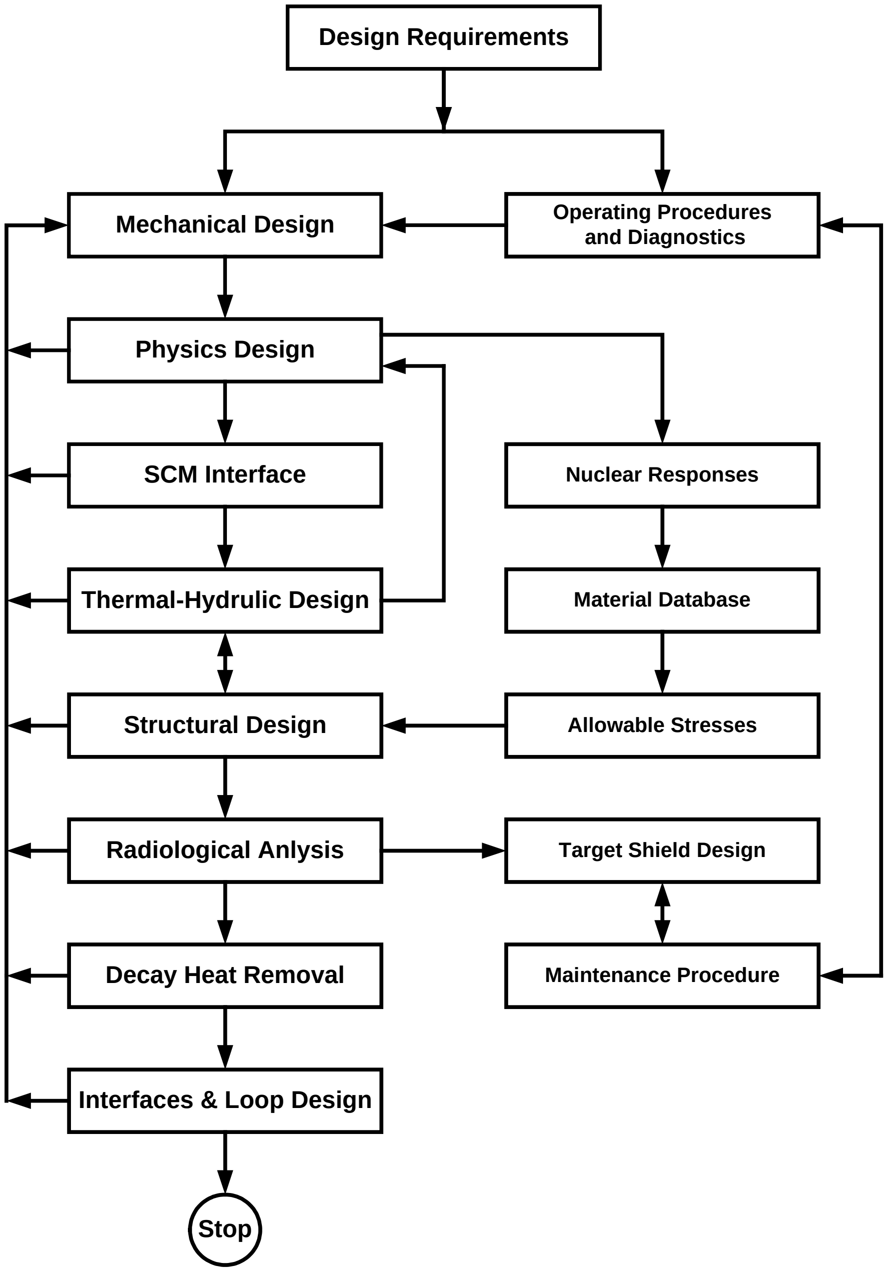
- Produce the required neutron source with the appropriate spatial distribution to drive the subcritical multiplier.
- Protect the subcritical multiplier from the high-energy protons.
- Contain the spallation products during normal and off-normal conditions.
- Achieve a lifetime that satisfies the plant availability goal.
- Utilize a fast & simple replacement procedure for normal and off-normal conditions.
- Operate and fail safely to achieve the required plant performance.
- Communicate with the accelerator and subcritical and interface with the plant design.

Spallation Target Design Constraints

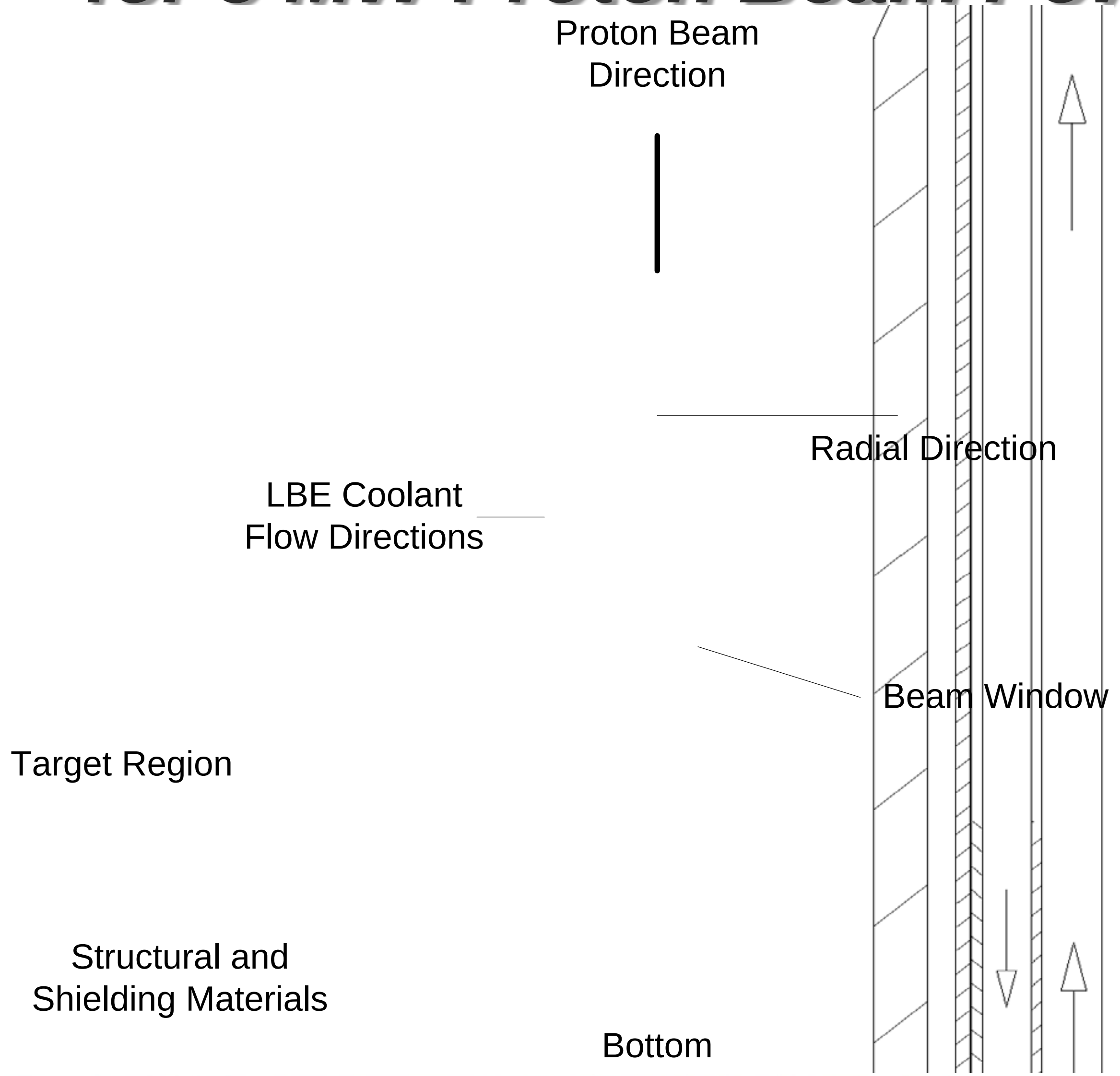
- The structural material properties limit the maximum power density in the target structure and the target lifetime.
- The coolant operating conditions are constrained to satisfy different engineering requirements.
- The coolant chemistry is closely controlled to reduce corrosion concerns.
- The structure temperature is constrained to insure satisfactory mechanical properties.
- The target diameter is minimized to maximize the utilization of the spallation neutrons, to simplify the target replacement procedures, to reduce the neutron losses in the beam direction, to decrease the shield volume, and to reduce the required fuel inventory.
- The target decay heat is removed by conduction, natural convection, and/or radiation to the surrounding materials.

Target Design Steps

- Design Tools are available to develop the target design.
- The current worldwide engineering experience and data base for designing and operating ADS targets are very limited.
- Irradiated structure design criteria need standardization, some effort is underway.
- The engineering material data base for the expected irradiation conditions of ADS is very limited and incomplete.
- The current state of the art are adequate to perform the design process but design validation is required.



Lead-Bismuth Target Design Example for 5 MW Proton Beam Power



Main Parameters of the Target Design Example for the First Demonstration

Proton Beam

Power	5 MW
Current	8.33 mA
Proton Energy	600 MeV
Current Distribution	Uniform
Current Density	40 µA/cm^2

Engineering Parameters

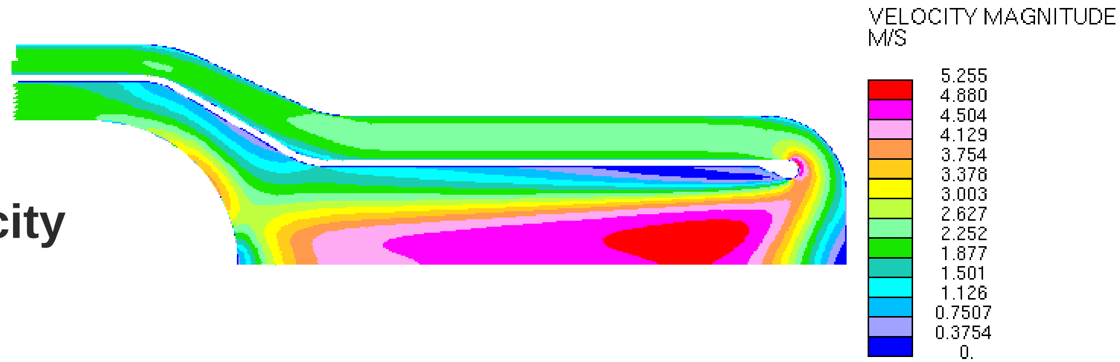
Steel Structural Material	HT9 or 316SS
Average Lead-Bismuth Velocity	2 m/s
Maximum Steel Surface Temperature	550 C
Maximum Steel Temperature	
HT9 Steel	550 C
Type 316 Stainless Steel	600 C
Leakage Detection Capability	
Passive Decay Heat Removal	

Beam Window Nuclear Responses of the Target Design Example

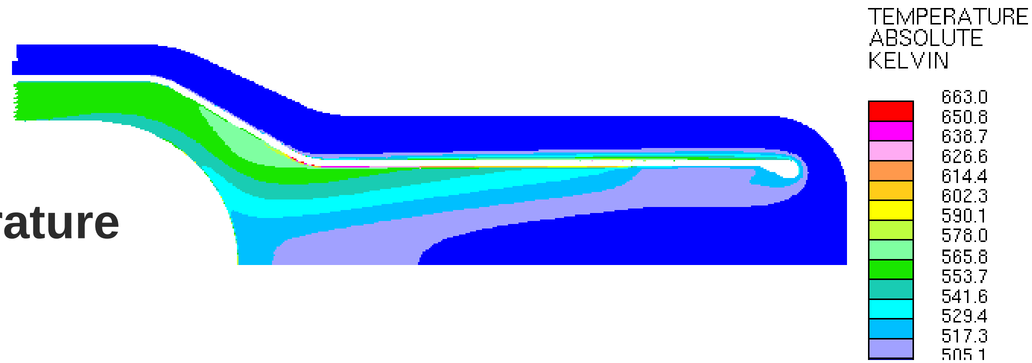
Energy deposition	766.5 W/cm3
Atomic Displacement	
Neutrons	46.2 dpa/fpy
Protons	21.1 dpa/fpy
Total	67.4 dpa/fpy
Helium Production	
Low energy neutrons < 20 MeV	6 appm/fpy
High energy neutrons > 20 MeV	50 appm/fpy
Protons	1437 appm/fpy
Total	1493 appm/fpy
Hydrogen production	
Low energy neutrons < 20 MeV	6 appm/fpy
High-energy neutrons > 20 MeV	1010 appm/fpy
Protons	26753 appm/fpy
Total	27769 appm/fpy

Operating Conditions of the Target Design Example

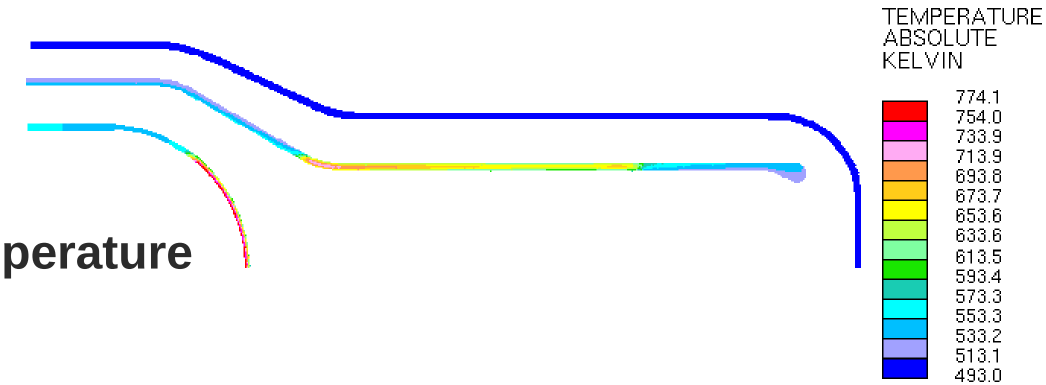
Fluid Velocity



Fluid Temperature



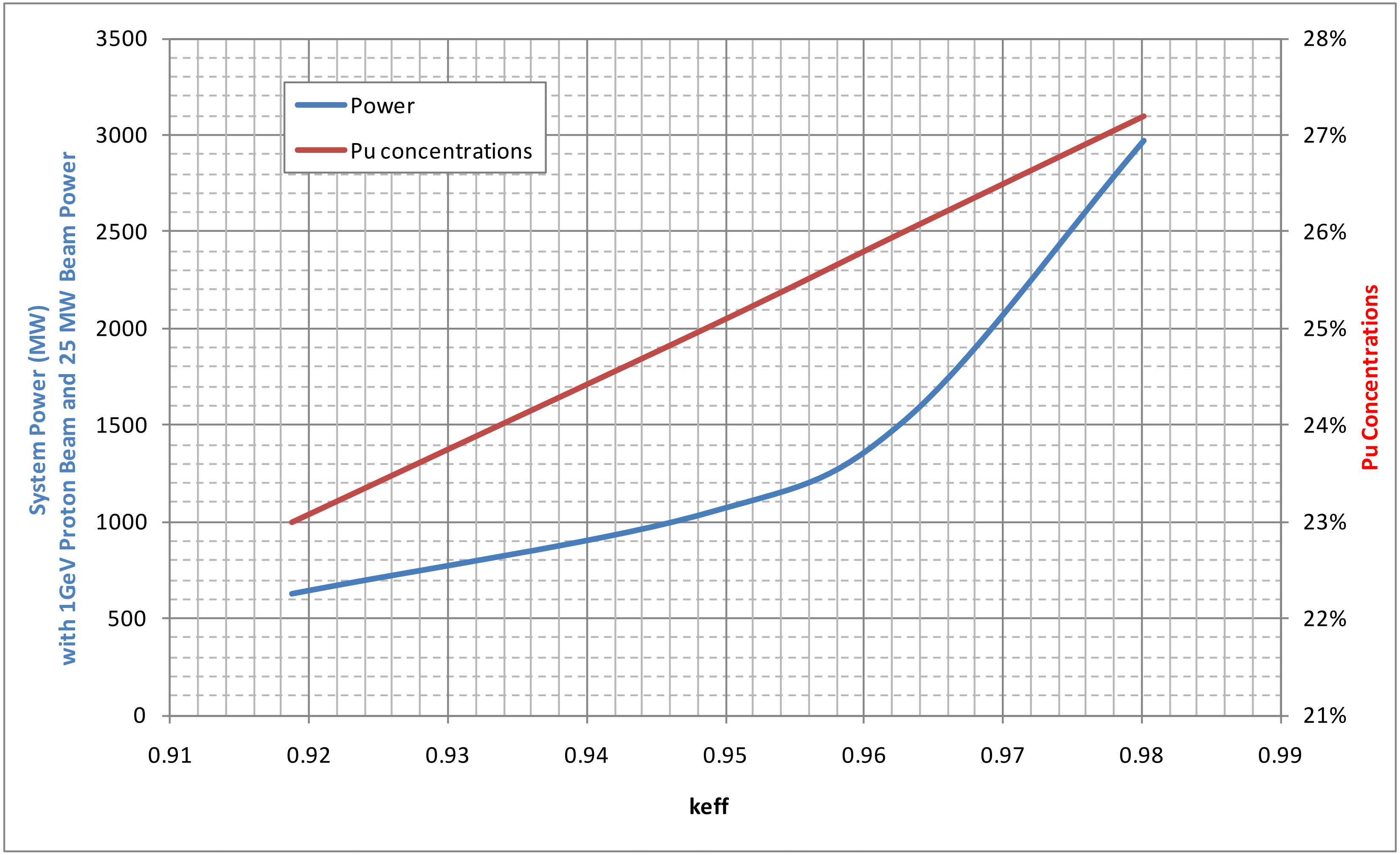
Structure Temperature



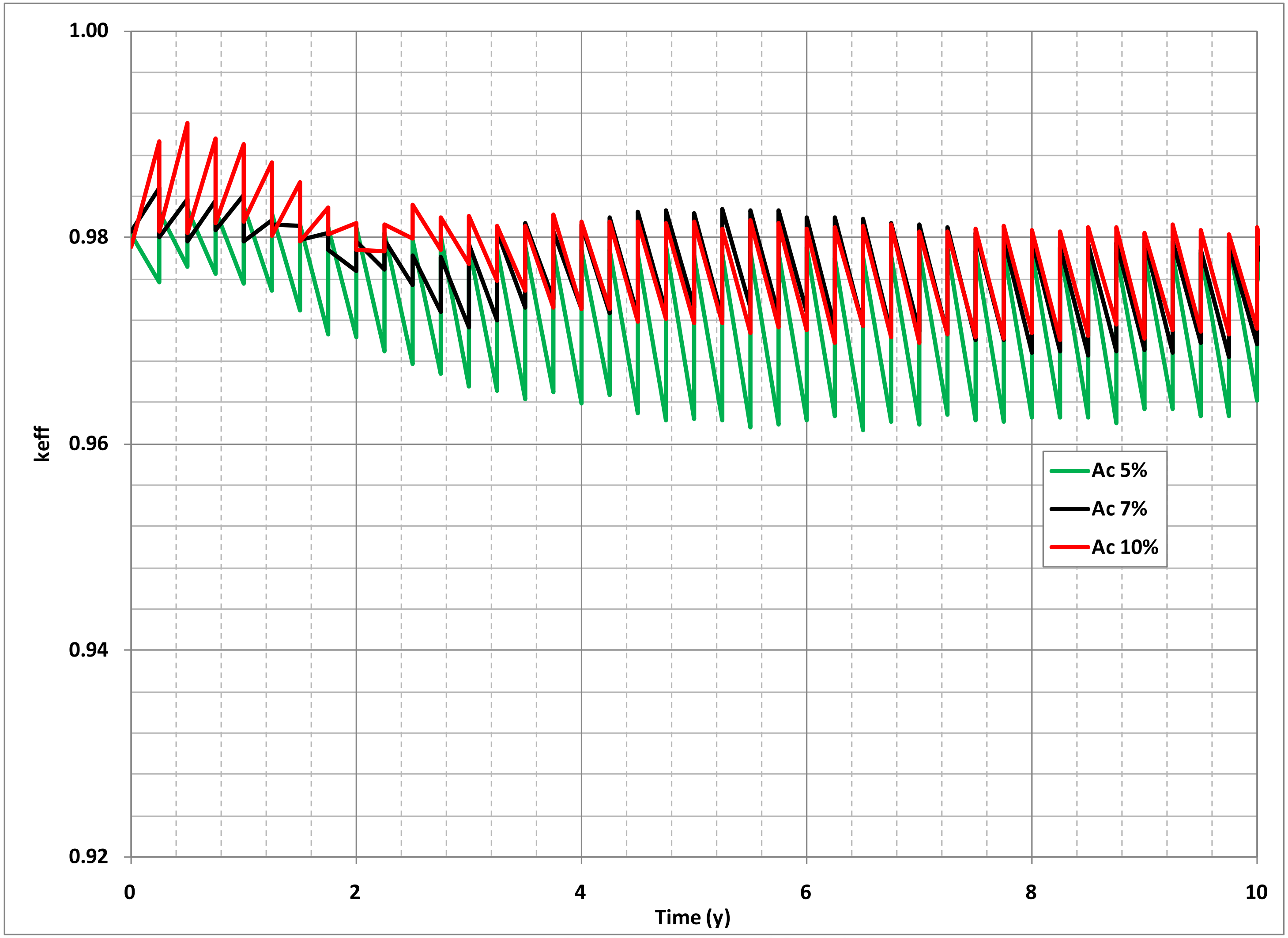
Beam Window Nuclear Structural Analyses of the Target Design Example

- The ability of the target to withstand the mechanical and thermal loads is determined by comparing the calculated stresses to allowable stresses based on the irradiated material design criteria defined for the APT structural design, the international thermonuclear experimental reactor, and the ASME Code.
- The beam tube with the 3.5-mm hemi-spherical window and the 5-mm wall thickness satisfies the structural design rules for irradiated material.
- The structural analyses used allowable stresses for irradiated HT-9 with 72 dpa. The target has to operate more than full power year to get this dpa value.
- The irradiated material database need confirmation for the expected ADS radiation damage levels.
- At present, properties of irradiated structural materials are measured and alloys with higher irradiation resistance are being developed.

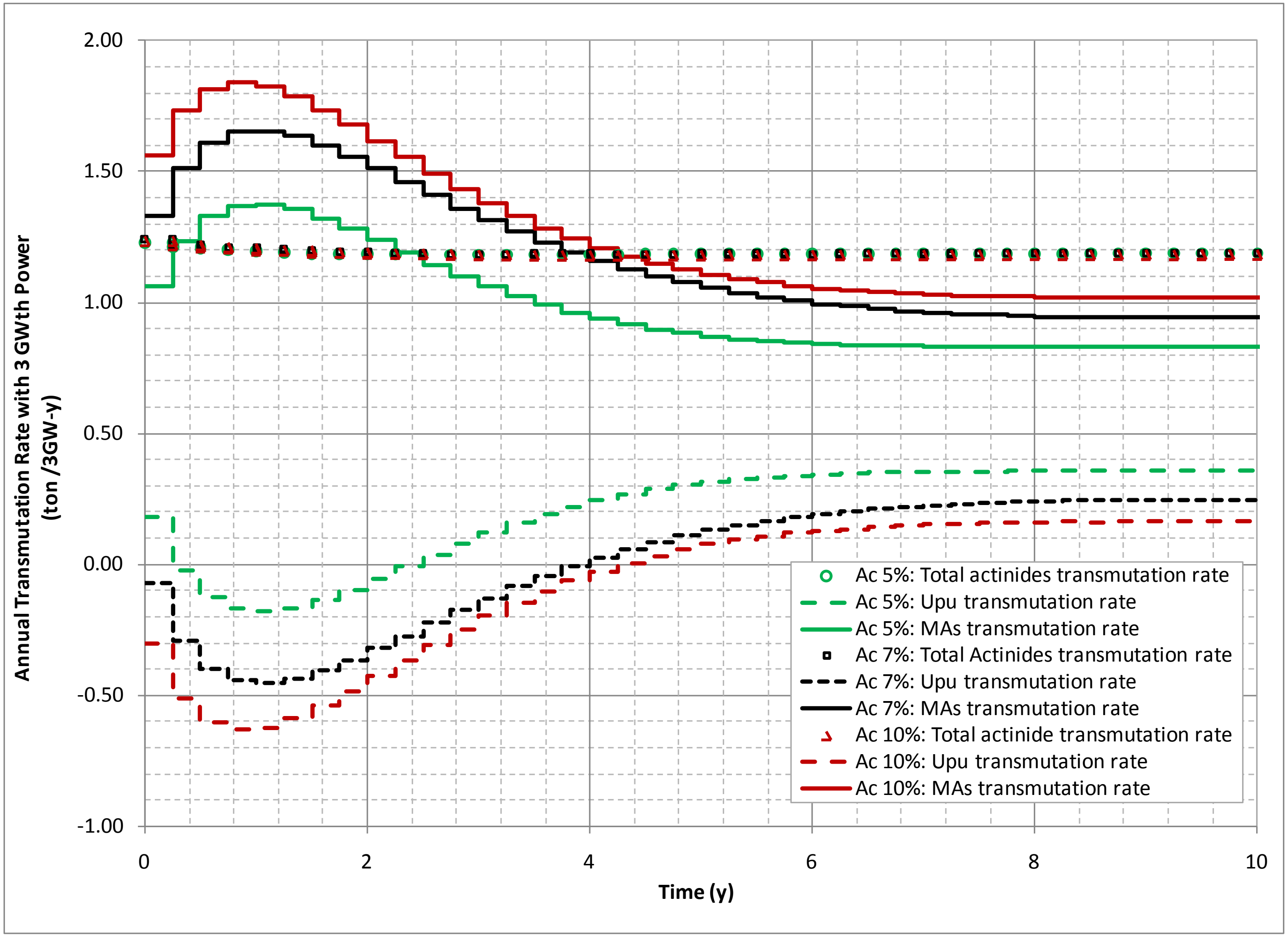
K_{eff} and ADS power from 25MW/1GeV proton beam and 7% actinides concentration in the lead bismuth eutectic as a function of the plutonium concentration



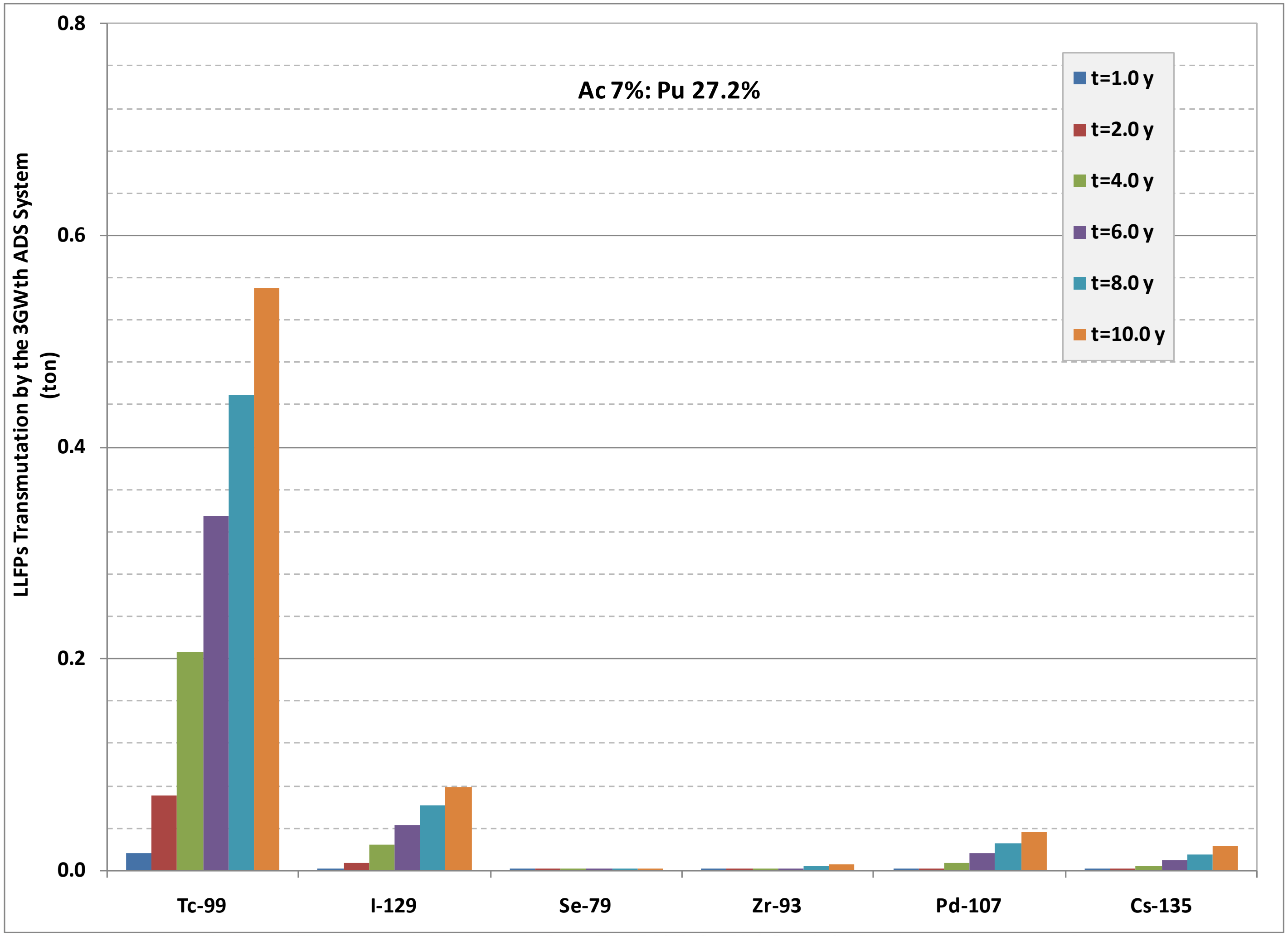
k_{eff} at each fuel burnup time step for the ADS system with 5%(35.7% Pu), 7%(27.2% Pu)or 10%(20% Pu) actinides concentration in the lead bismuth eutectic



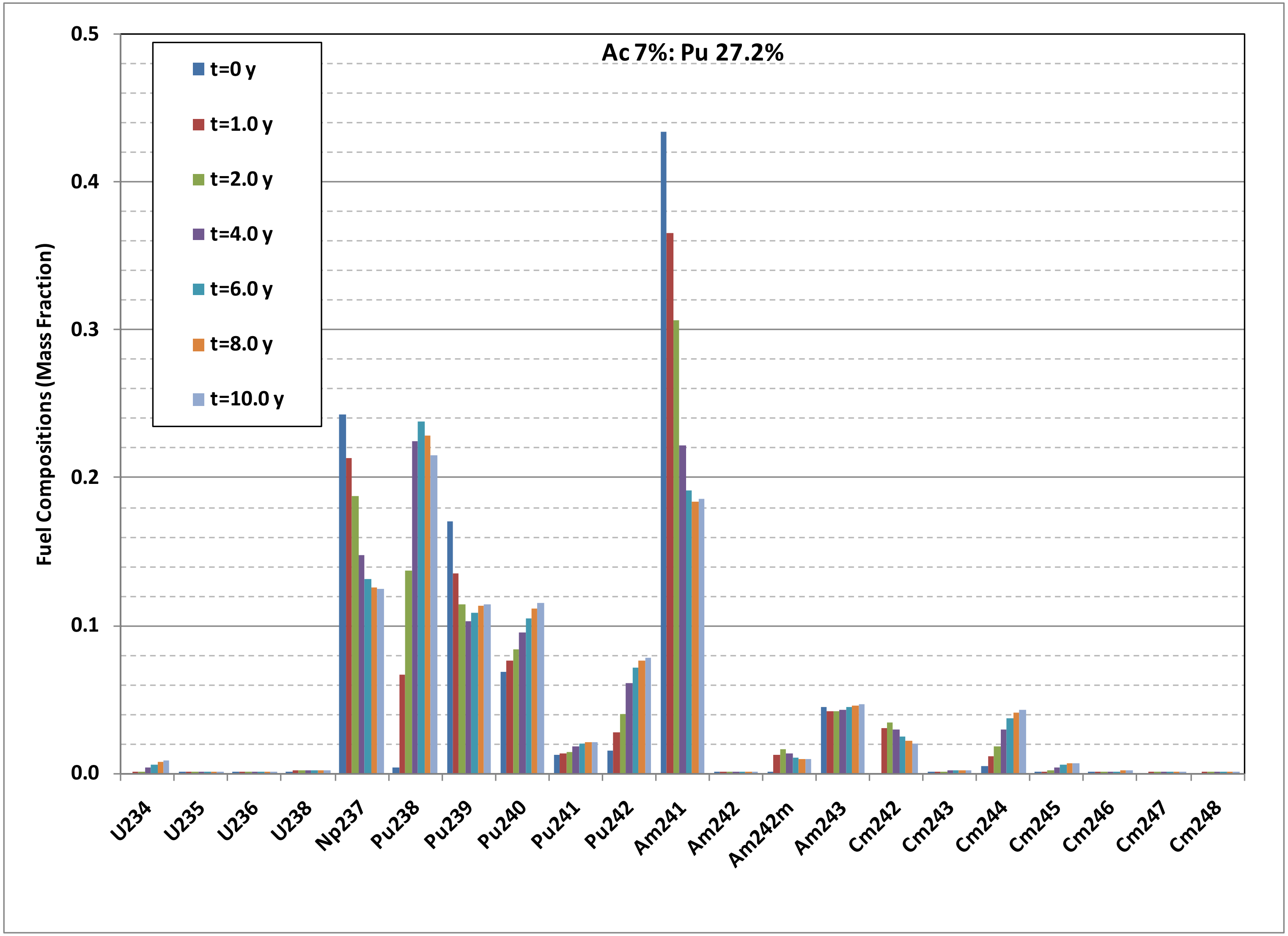
Actinides, plutonium, and minor actinides annual transmutation rates for the ADS system (3MW$_{th}$) with 5%(35.7% Pu), 7%(27.2 Pu)% or 10%(20% Pu) actinides concentration in the lead bismuth eutectic



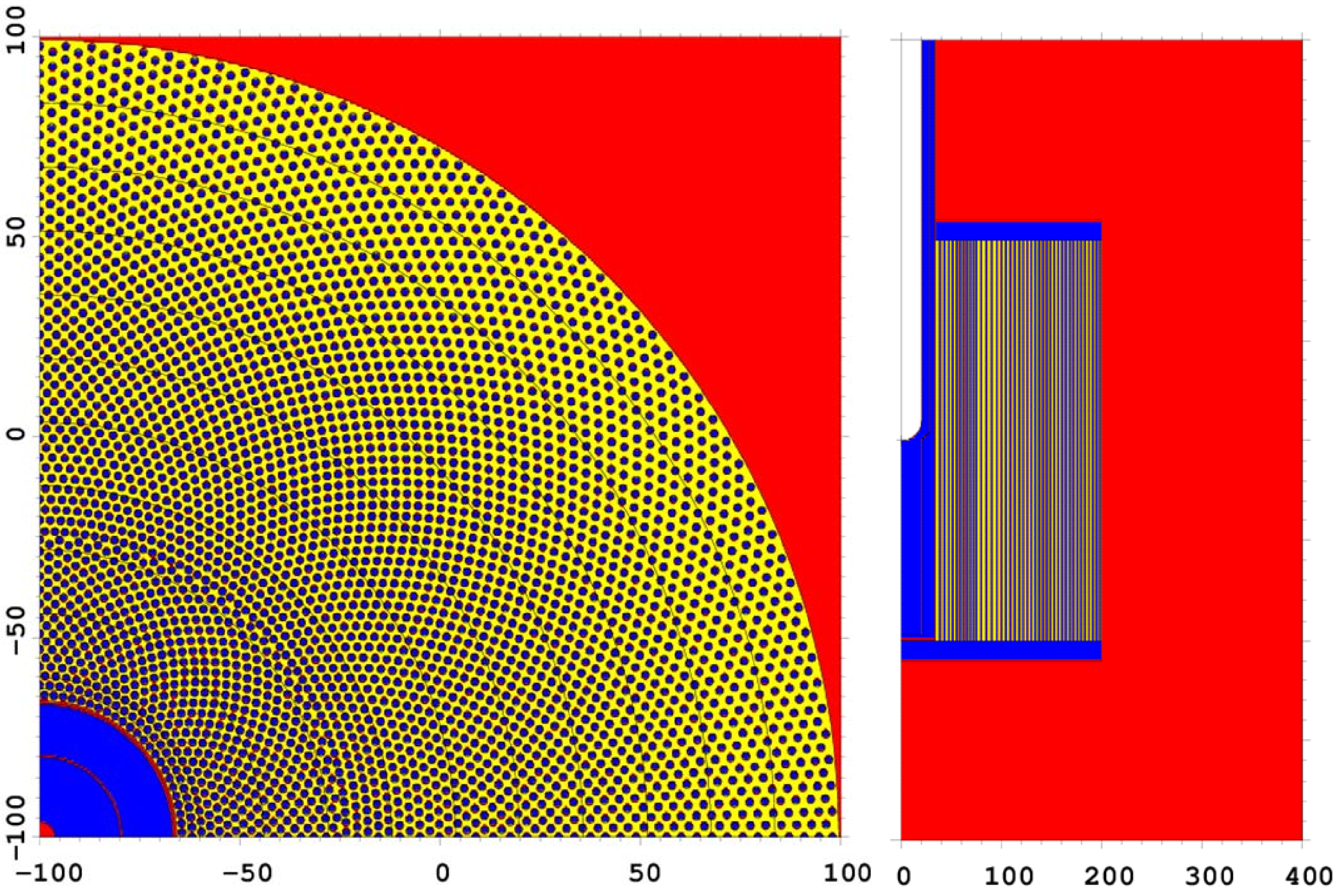
Long lived fission products transmutation during the first 10 years of ADS operation with 7% actinides (27.2% Pu) in the lead bismuth eutectic



Fuel compositions for 10 years of operation of the fission blanket with 7% actinides and 27.2% plutonium concentration



Subcritical Assembly Concept Example



Subcritical Assembly Concept Example Parameters

Fuel Carrier	**LBE**
Ac Concentration	**8%**
Pu concentration	**46.2%**
Coolant tube dia	**8.5/10 mm**
Number of tubes	**13632**
inner radius	**34.27 cm**
outer radius	**1995 cm**
Height	**400 cm**
Fuel volume	**29.65 m^3**
Coolant volume	**18.89 m^3**
Mas inventory	**12.35 ton**
Pu&U inventory	**10.59 ton**
Power	**2.54 GW**
Keff	**0.97965 ±0.00015**

Power Density Distribution, KW/cm³

Acknowledgements

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