Design Considerations for Subcritical Multiplier of ATW

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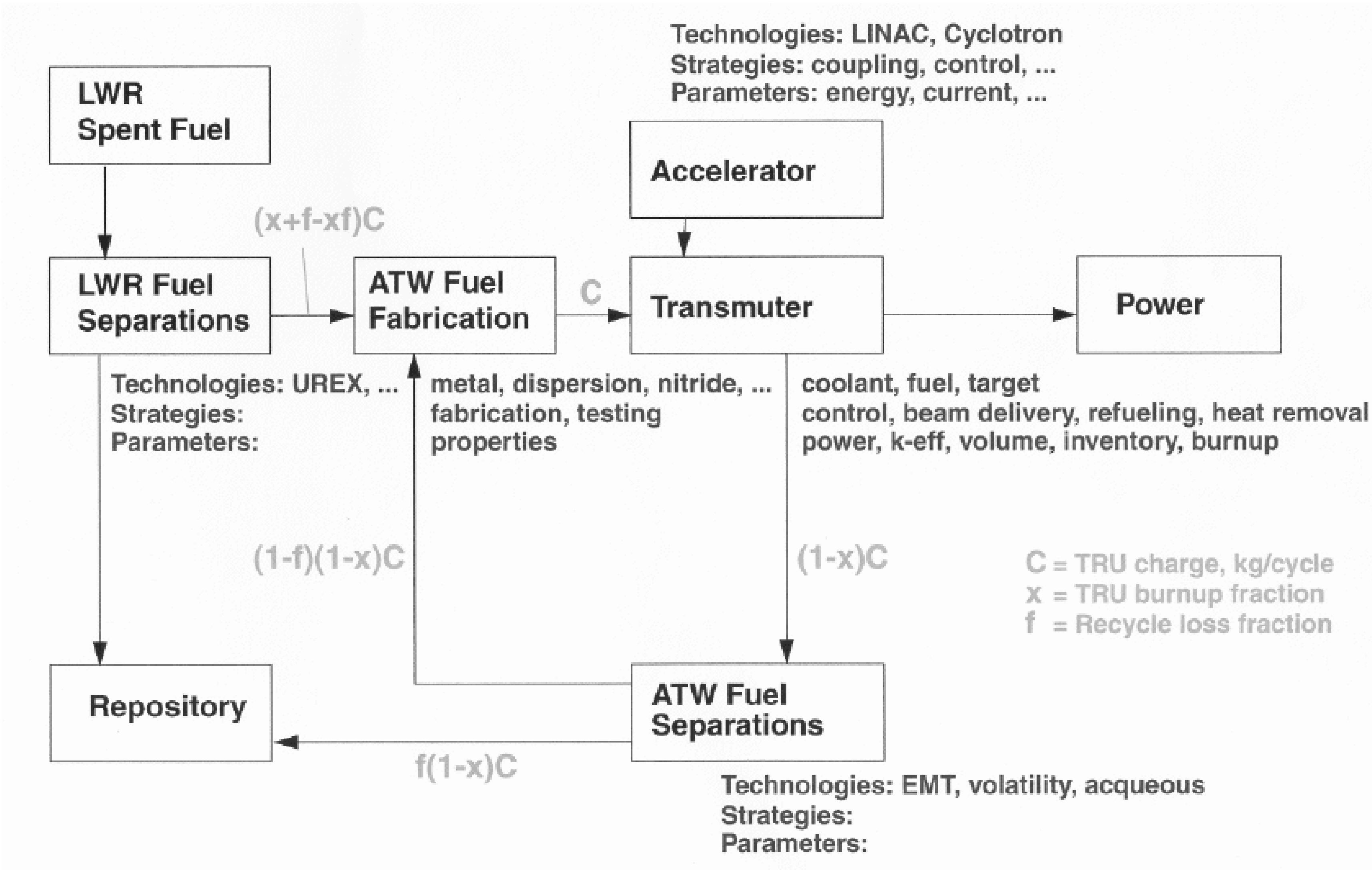
Main Design Objectives of Accelerator Transmutation of Waste (ATW) System

- **ATW system is designed to reduce the mass, toxicity and longevity of the high-level waste to be disposed in the repository**
  - Achieved by separating transuranic (TRU) elements from the spent fuel and transmuting them in the ATW blanket (multiplier)
- **Radiotoxicity reduction is primarily achieved by reducing the fraction of the initial TRU inventory that is not transmuted and lost to the waste stream**
- **Minimization of fractional loss requires**
  - Maximizing the discharge burnup
  - Minimizing the reprocessing and fuel fabrication losses
- **Additional key objective: low reactivity loss per cycle**
  - Minimize the resulting needs for increasing accelerator power and/or introducing an excess reactivity and active reactivity control

System Configuration and Parameters



Sub-criticality and Source Importance

- **Subcriticality is an important system performance parameter**
  - Determines beam current to generate a desired system power
  - Defines margin to critical reactor performance regime
- **The subcriticality level can be defined in different ways**
  - Effective multiplication factor (used for critical reactors)
    - Direct property of transmuter
    - Independent of source distribution
    - But, flux distribution differs from source-driven state
  - Source multiplication factor
    - Based on source-driven flux distribution
    - Varies with source distribution (space and energy)
- **A source importance factor can be defined as the probability of an external source neutron to cause a fission reaction relative to a fission neutron**
  - Can be measured for known source distributions and be calibrated for different source distributions using the calculated flux distributions
  - The proton current required to produce a desired fission power can be determined using this source importance factor and the effective multiplication factor

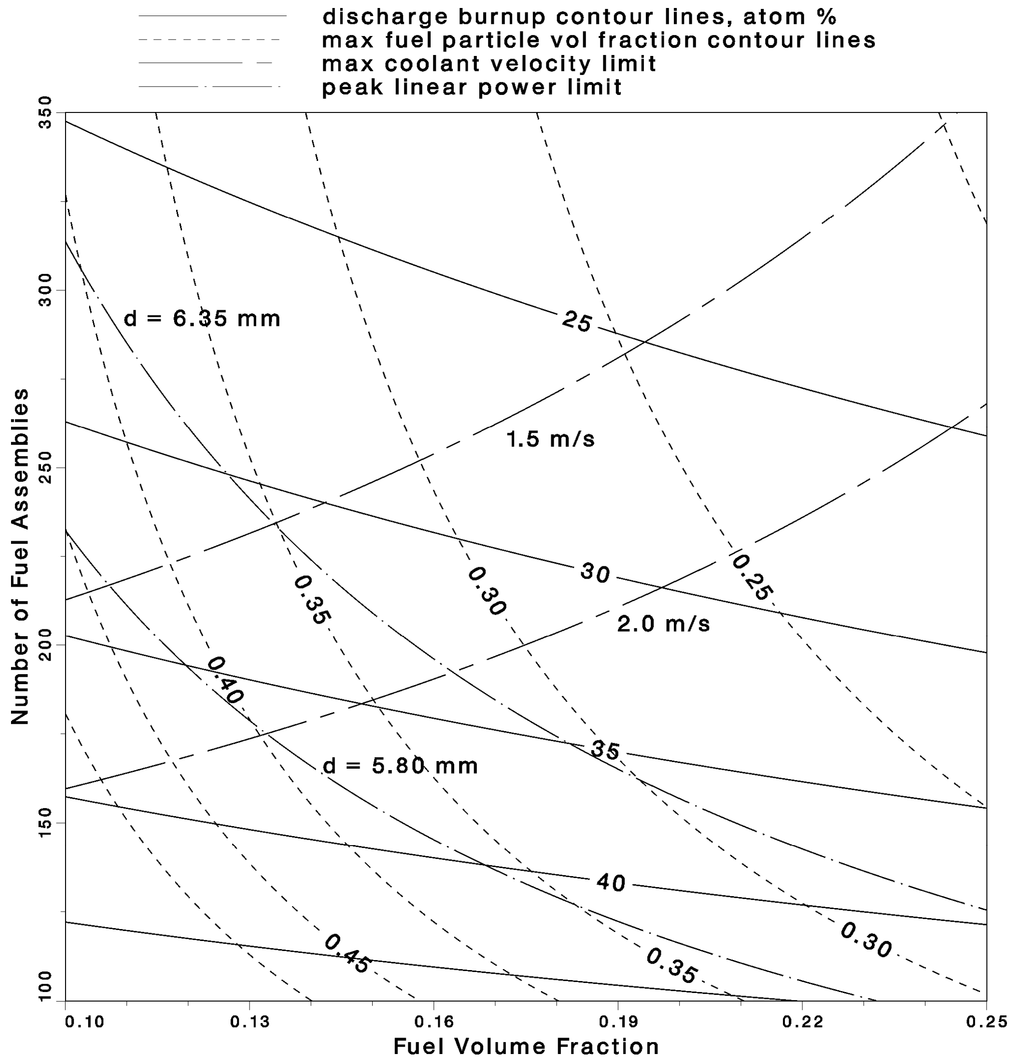
Fuel Discharge Burnup

- **Discharge burnup is proportional to the average power density and the fuel residence time, and inversely proportional to the fuel volume fraction and the TRU fraction in fuel**
  - This relation suggests that the discharge burnup can be maximized by designing for the maximum power density and fuel residence time and the minimum fuel volume fraction. However, these quantities are interrelated and limited by various design constraints
- **TRU fraction in fuel is determined such that the desired sub-criticality level is achieved for the selected blanket configuration and fuel management scheme**
  - Maximum TRU fraction is constrained by the irradiation performance of selected fuel form
- **Fuel residence time is typically constrained by the peak fast fluence limit for the structural material to ensure the fuel pin integrity**
- **Peak linear power is constrained by the need to limit peak fuel and/or cladding temperatures**
  - Minimum fuel volume fraction required to satisfy the specified constraint on peak linear power increases as the power density increases
- **Power density and coolant volume fraction are interrelated for adequate cooling**
  - For a specified coolant velocity, the minimum coolant volume fraction increases as the power density increases

Burnup Reactivity Loss

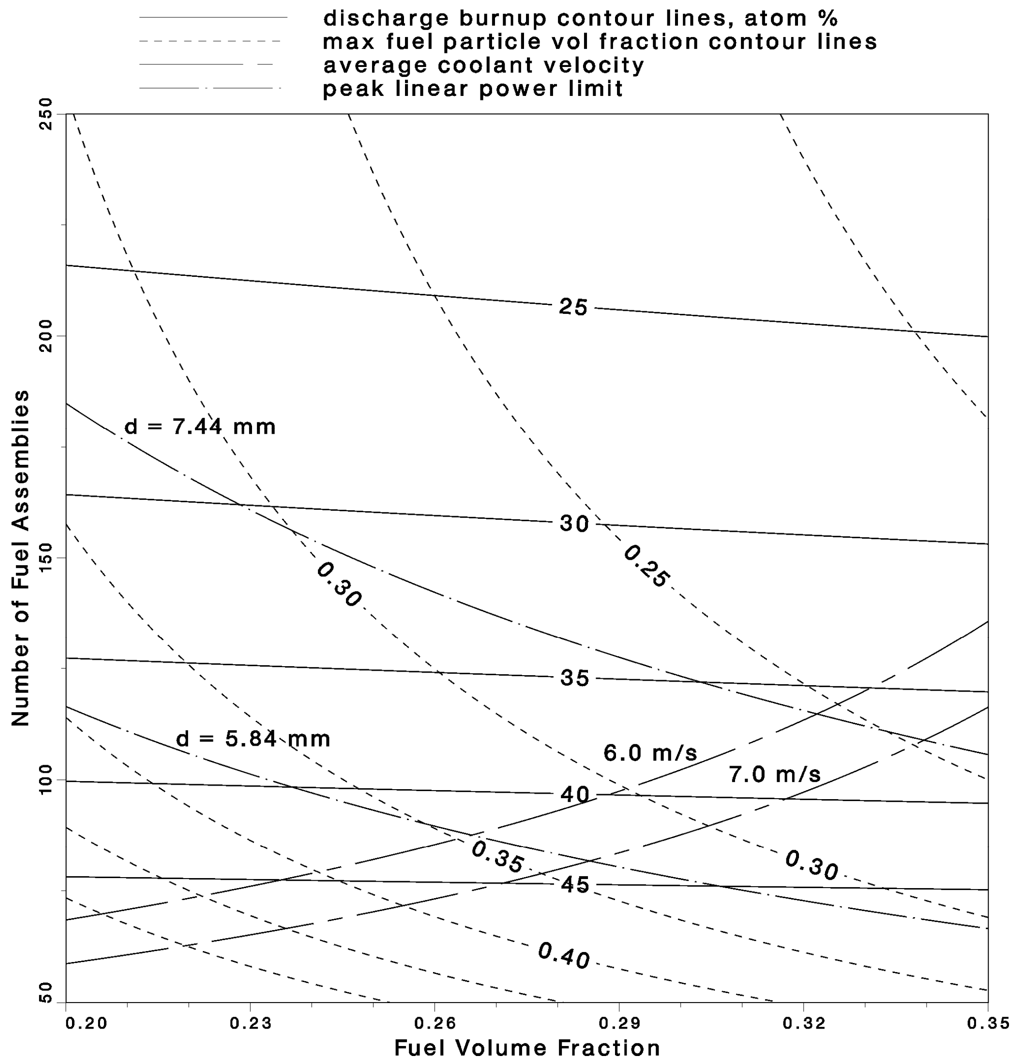
- **Without compensating measures, the fission power declines with fuel depletion**
  - Making it difficult to design an economic heat removal system
  - Reducing the generation of electric power whose sale is intended to reduce net system cost
- **Decline in blanket fission power over an irradiation cycle can be mitigated in three ways:**
  - Gradual addition of reactivity, e.g., by continuous replacement of depleted fuel with fresh fuel or by withdrawal of control rods
    - Adds to system complexity/cost and creates a potential accident initiator
  - Increase of the neutron source strength by gradually increasing beam power
    - Requires an accelerator that is "overdesigned" for the lower TRU depletion state early in the irradiation cycle and creates a potential for source increase accidents
  - Increase of the source importance factor, e.g., by reducing the fraction of source neutrons lost by leakage or through capture in the target
    - Would likely be similar in terms of cost/complexity as control rods and also introduces the possibility of accidental increases in source importance
- **Irrespective of the method used to compensate for the reactivity decline, there are strong economic and safety incentives to minimize the decline itself**

Optimum Blanket Composition and Size (LBE Cooled System)

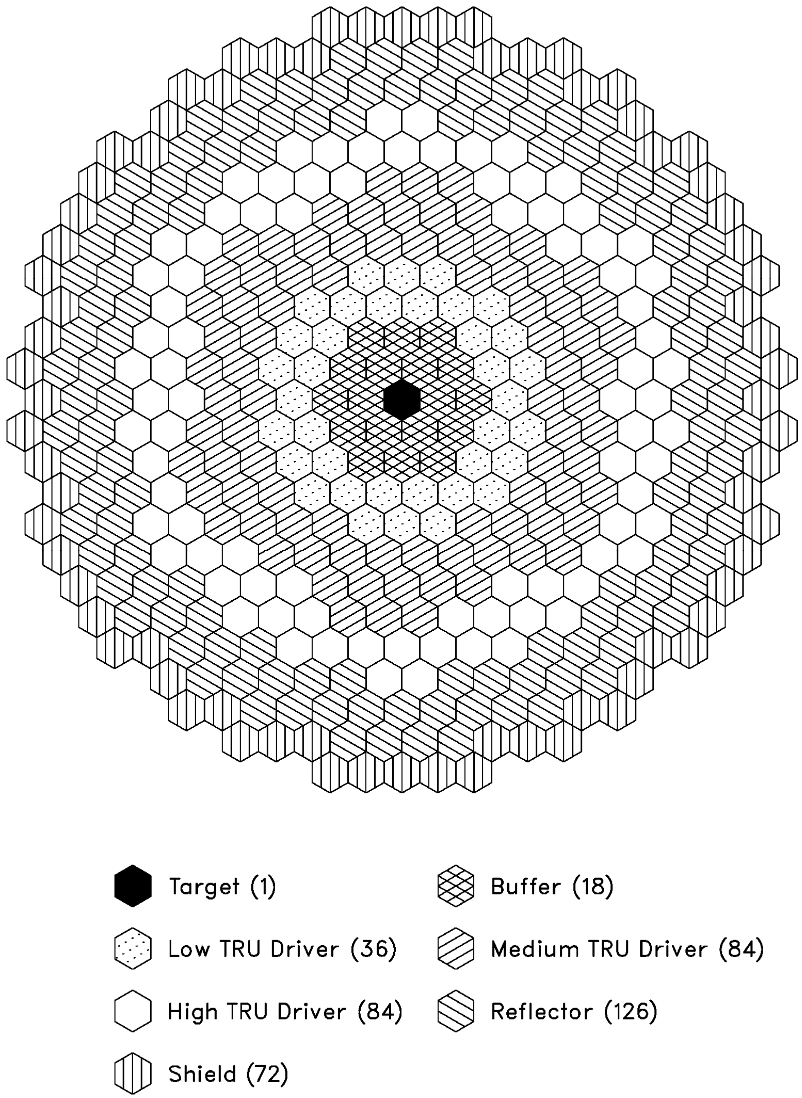


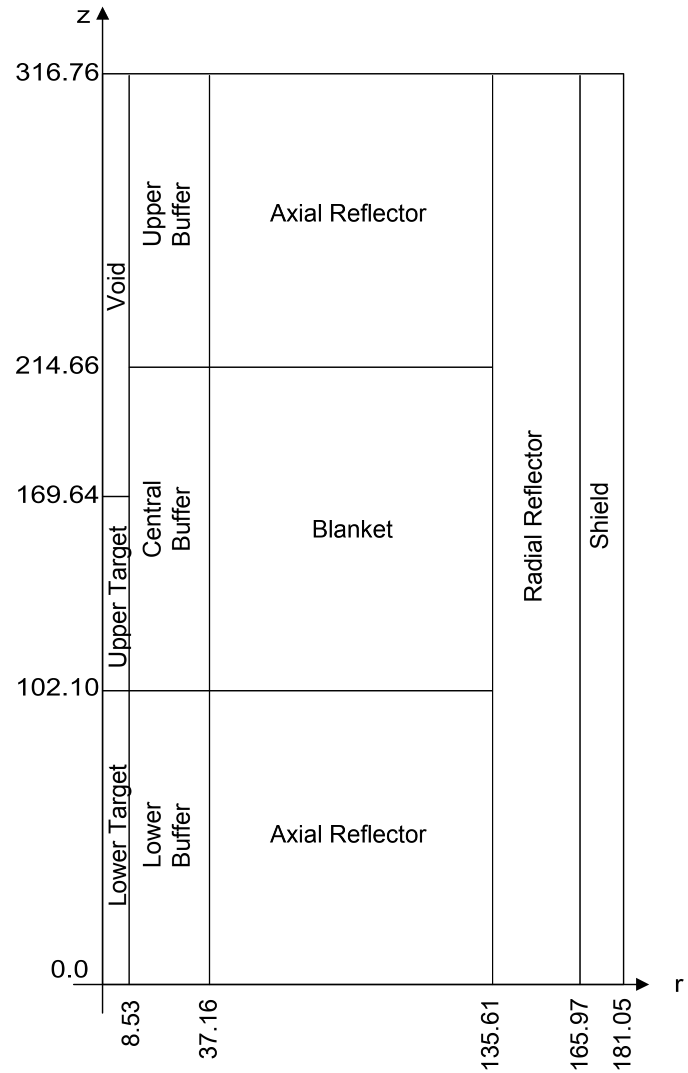
- Uranium-free dispersion fuel
- Variable blanket size and fuel volume fraction

Optimum Blanket Composition and Size (Na Cooled System)



LBE-Cooled System Point Design



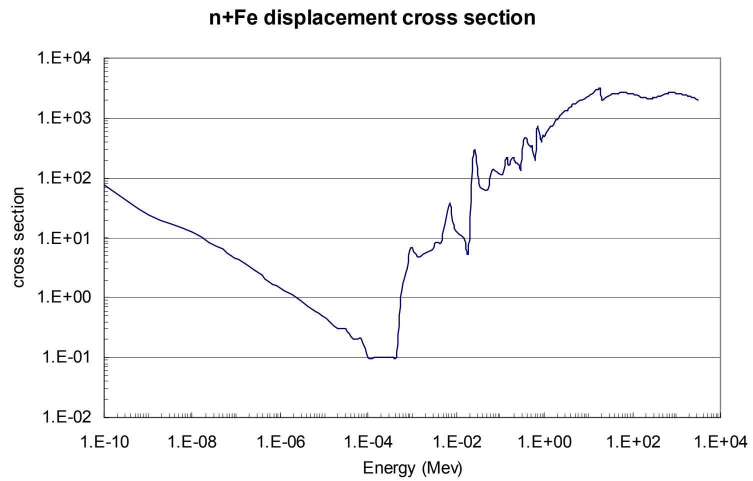


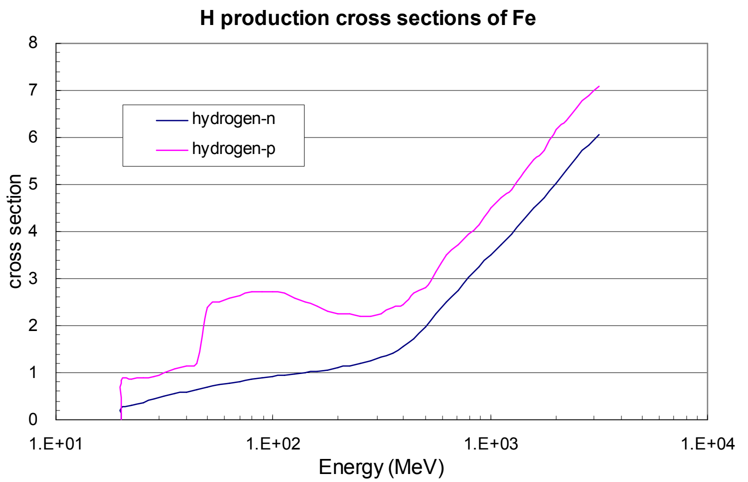
Buffer Design

- **Spallation neutron target and subcritical blanket are coupled through a buffer region**
  - Enhances the diffusion of spallation neutrons to the blanket
  - Reduces the damage to fuel by high-energy neutrons
- **The target and buffer designs needs to be optimized based on a compromise between two competing objectives**
  - Increasing the spallation source importance
    - Reduce the fuel inventory for a desired subcriticality level
    - Increase the discharge burnup for a fixed fuel residence time
  - Reducing the peak damage to fuel
    - Increase the fuel residence time
    - Increase the discharge burnup for a fixed fuel inventory
- **Principal design variables**
  - Buffer thickness
  - Axial position of target
  - LBE density in buffer

Irradiation Damage to Fuel Cladding

- **Atomic displacement rate of structural material**
  - Mainly induced by low-energy (< 20 MeV) neutrons
  - High-energy neutron and proton induced damages are negligible
- **H and He production rates**
  - High-energy (>20 MeV) neutron contribution to H production is significantly larger than low-energy neutron contribution
  - High-energy neutron contribution to He production is comparable to low-energy neutron contribution
  - Proton induced H and He production rates are generally much smaller than neutron induced ones, but become non-negligible for thin buffer



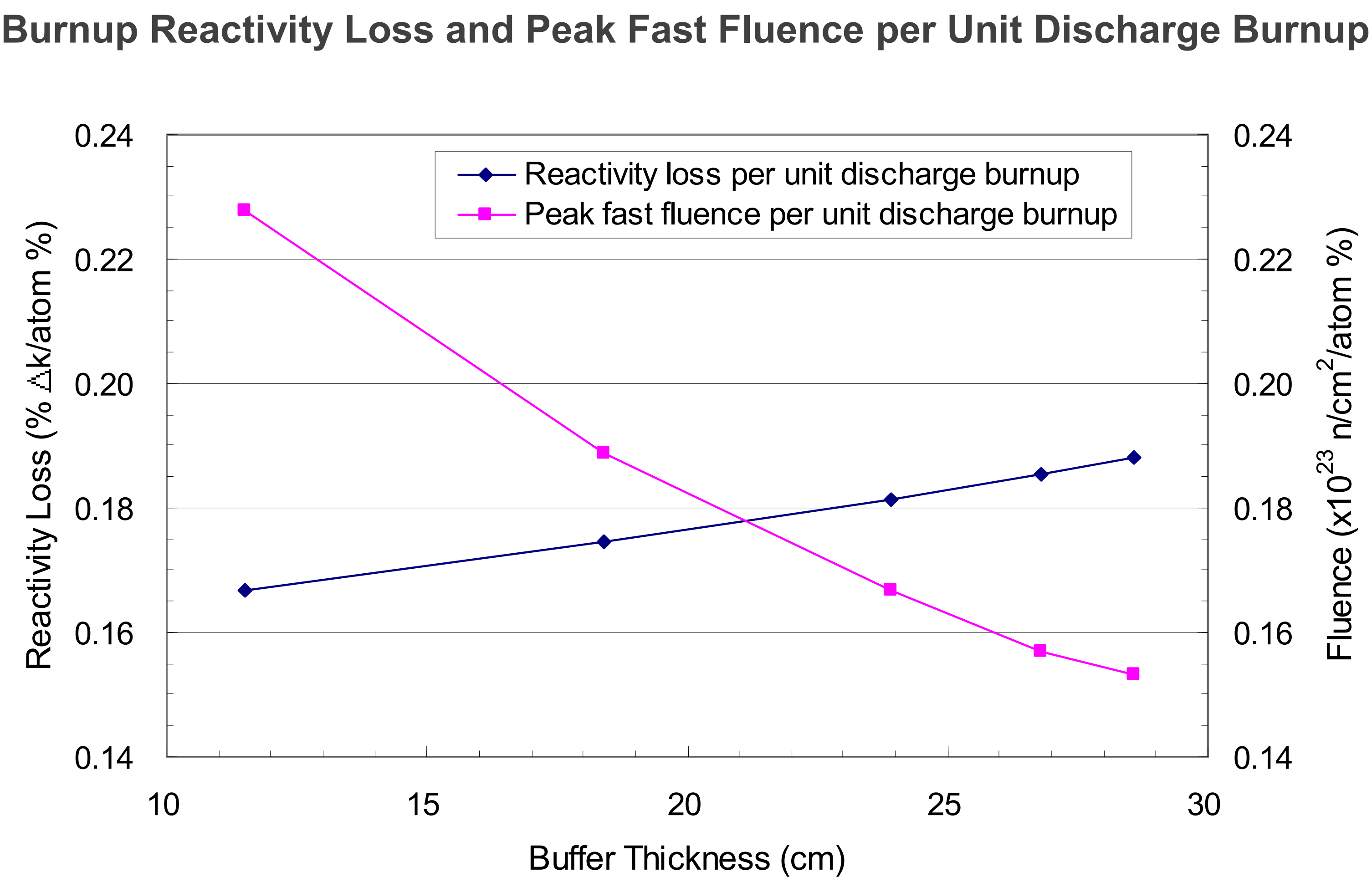


Equilibrium Cycle Performance

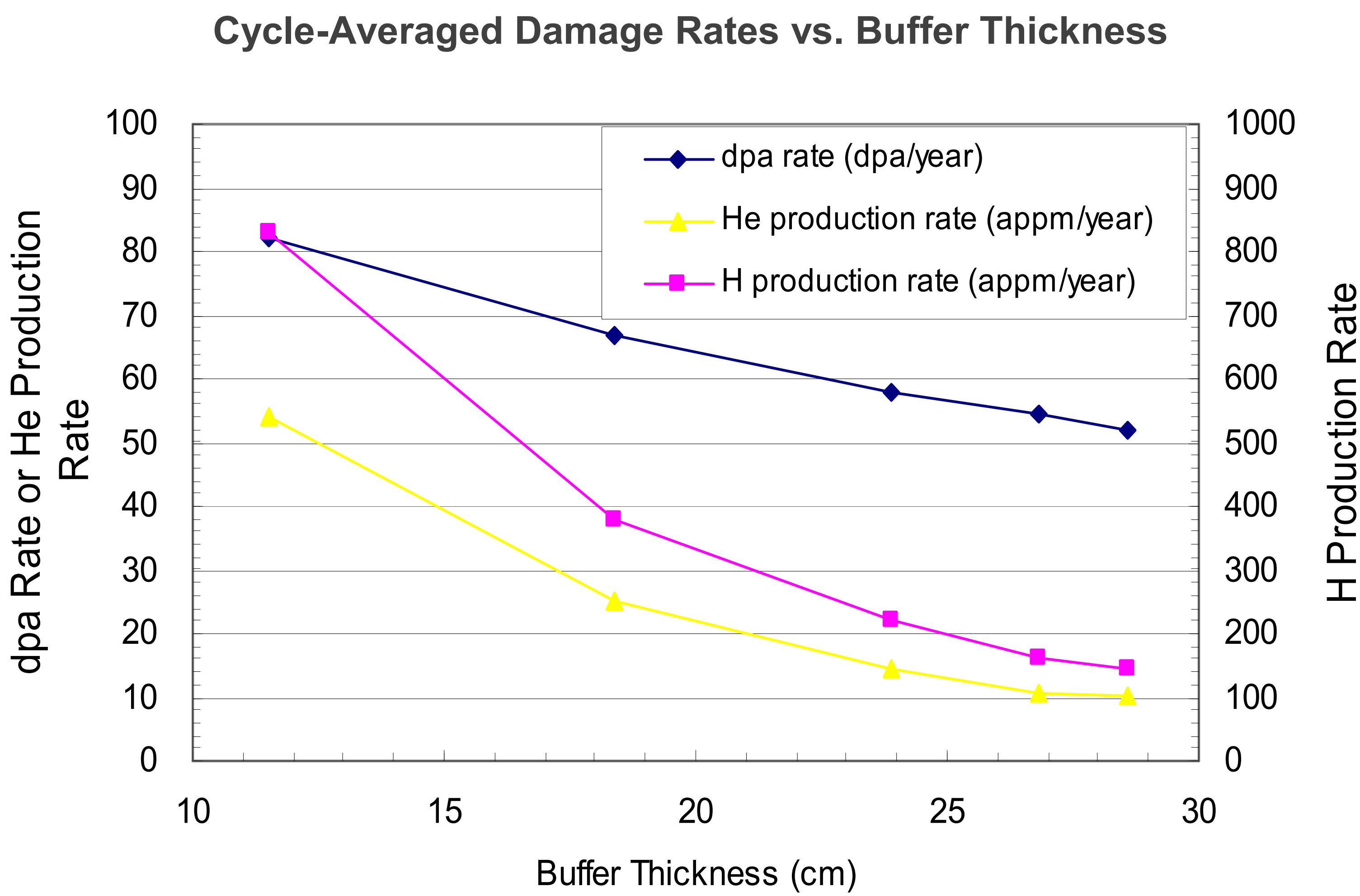
- **Effect of Buffer Thickness**

Buffer thickness (cm)	28.6	26.8	23.9	18.4	11.5
BOEC TRU inventory (kg)	3085	3074	3048	3004	2961
Burnup reactivity loss (%)	5.30	5.24	5.16	5.02	4.87
Discharge burnup (atom %)	28.2	28.3	28.5	28.8	29.2
Peak fast fluence ($x10^{23}$ n/cm^2)	4.31	4.44	4.74	5.44	6.64
Power peaking factor					
BOEC	1.358	1.361	1.370	1.386	1.402
EOEC	1.488	1.517	1.584	1.741	2.024
Source importance factor					
BOEC	0.801	0.817	0.843	0.891	0.952
EOEC	0.788	0.803	0.827	0.871	0.926

Equilibrium Cycle Performance



Irradiation Damages to Structural Material



Concluding Remarks

- **Physics of subcritical multiplier are not much different from those of critical reactors, and various subcritical multipliers can be designed, depending on the mission**
  - Actinide transmutation, power production, material irradiation test, etc.
- **To compete with alternative solutions,**
  - Economically competitive
  - Develop unique physical or technical advantages
- **In general, the optimum design is mainly determined by the imposed constraints, rather than the governing equations**
  - To eliminate unnecessarily conservative design margins, realistic design criteria based on experimental data need to be developed