Neutron Source Analyses

- **Analyses have been performed to maximize the neutron source strength to enhance the neutron flux and the sub-critical assembly power:**

$$\text{Neutron mutiplication } \alpha \ \frac{S}{1-K_s}$$

S **Neutron source strength**
K_s **System mutiplication factor**

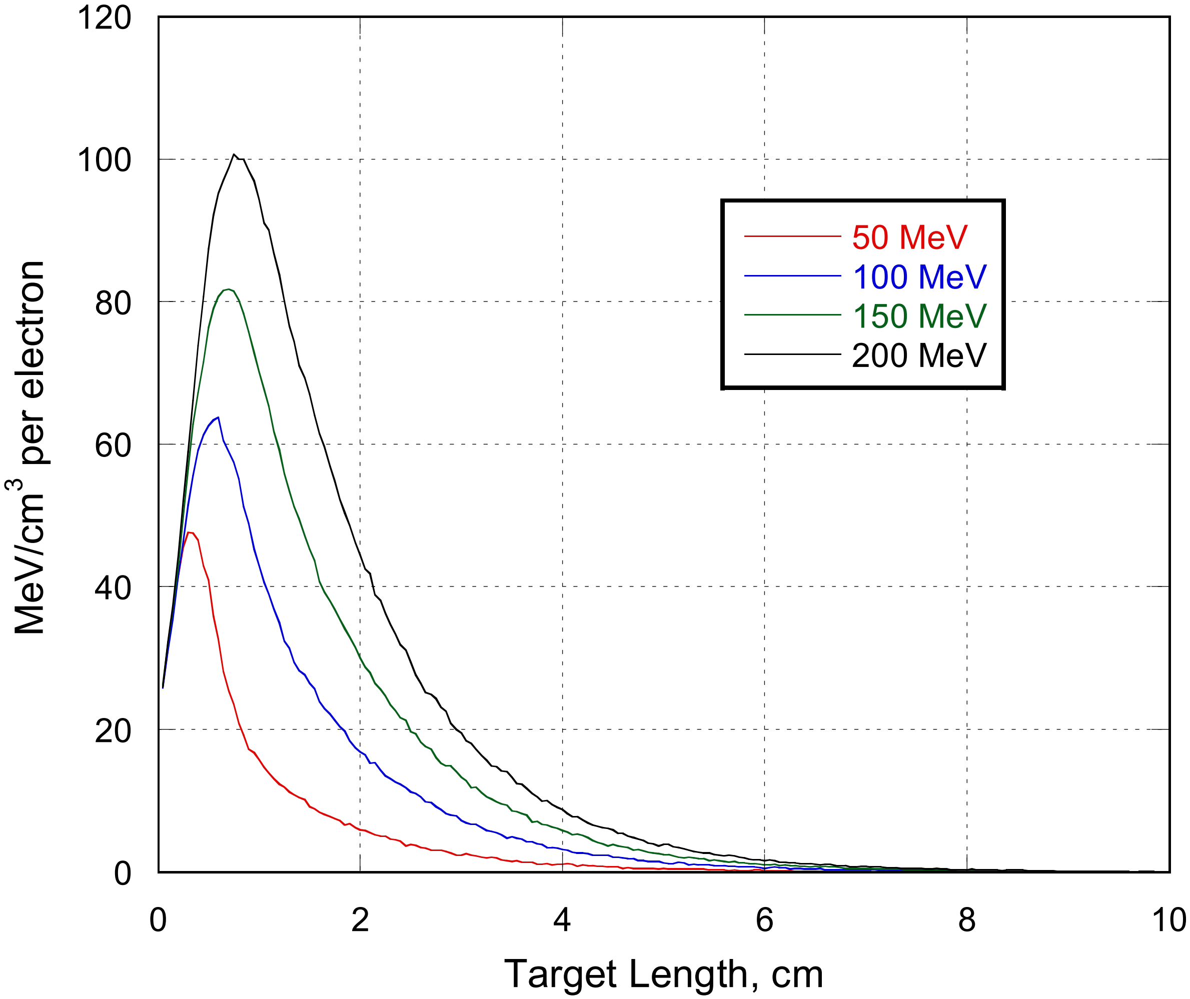
$$\text{Subcritial assembly power } \alpha \ \frac{S \cdot K_s \cdot Q}{\nu^* \cdot (1 - K_s)}$$

ν^* **Number of neutronper fission including (n,xn)**
Q **Energy release per fission**

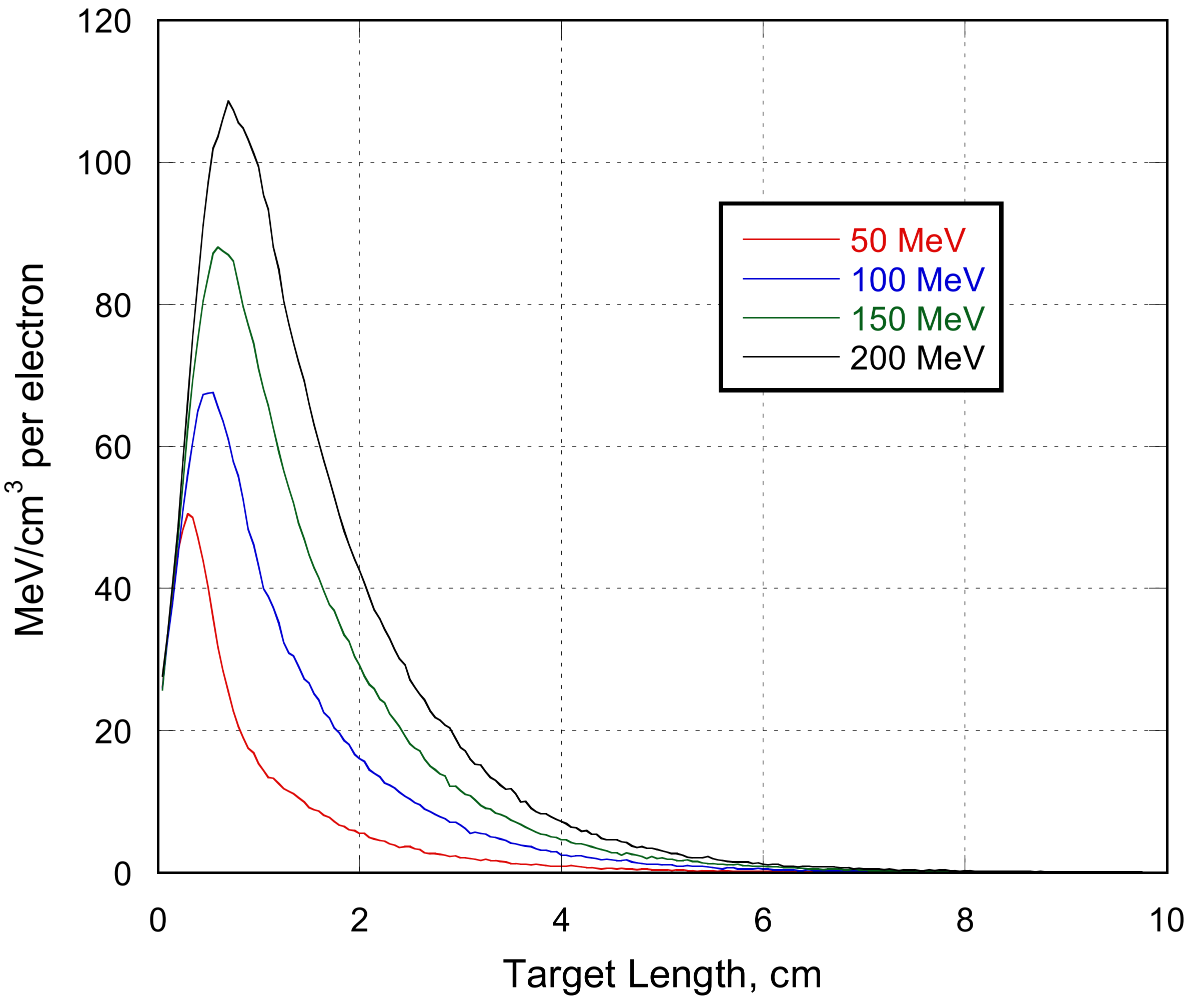
- **The analyses studied the impact of the beam and target parameters on the neutron source performance including:**
  - Electron and deuteron beams
  - Target materials
  - Beam parameters
  - Target geometry and dimensions

- **The neutron source performance parameters included:**
  - Neutron yield
  - Neutron spectrum
  - Peak and spatial energy deposition
  - Target dimensions and design

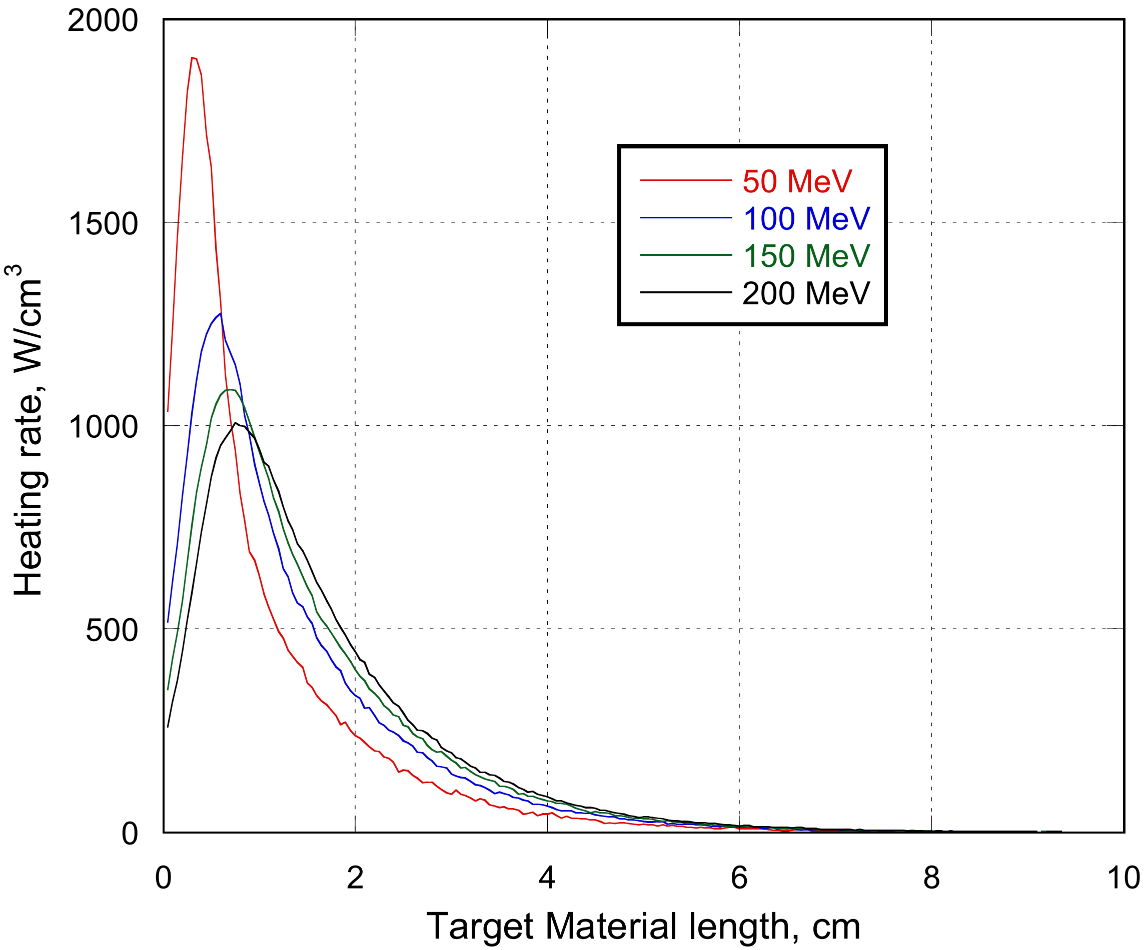
Spatial Energy Deposition per Electron in Pure Tungsten Target Material for Different Electron Energies



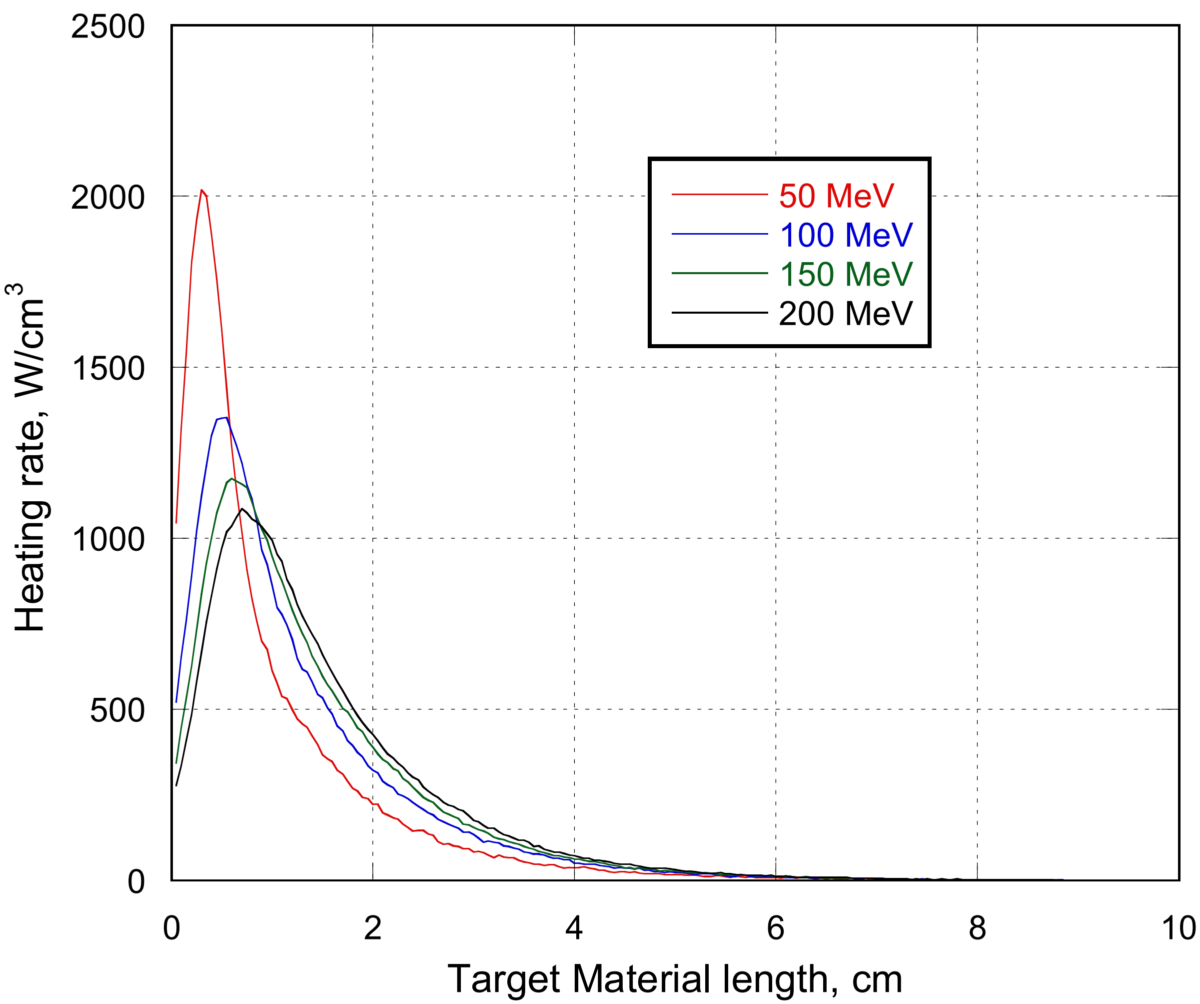
Spatial Energy Deposition per Electron in Pure Uranium Target Material for Different Electron Energies



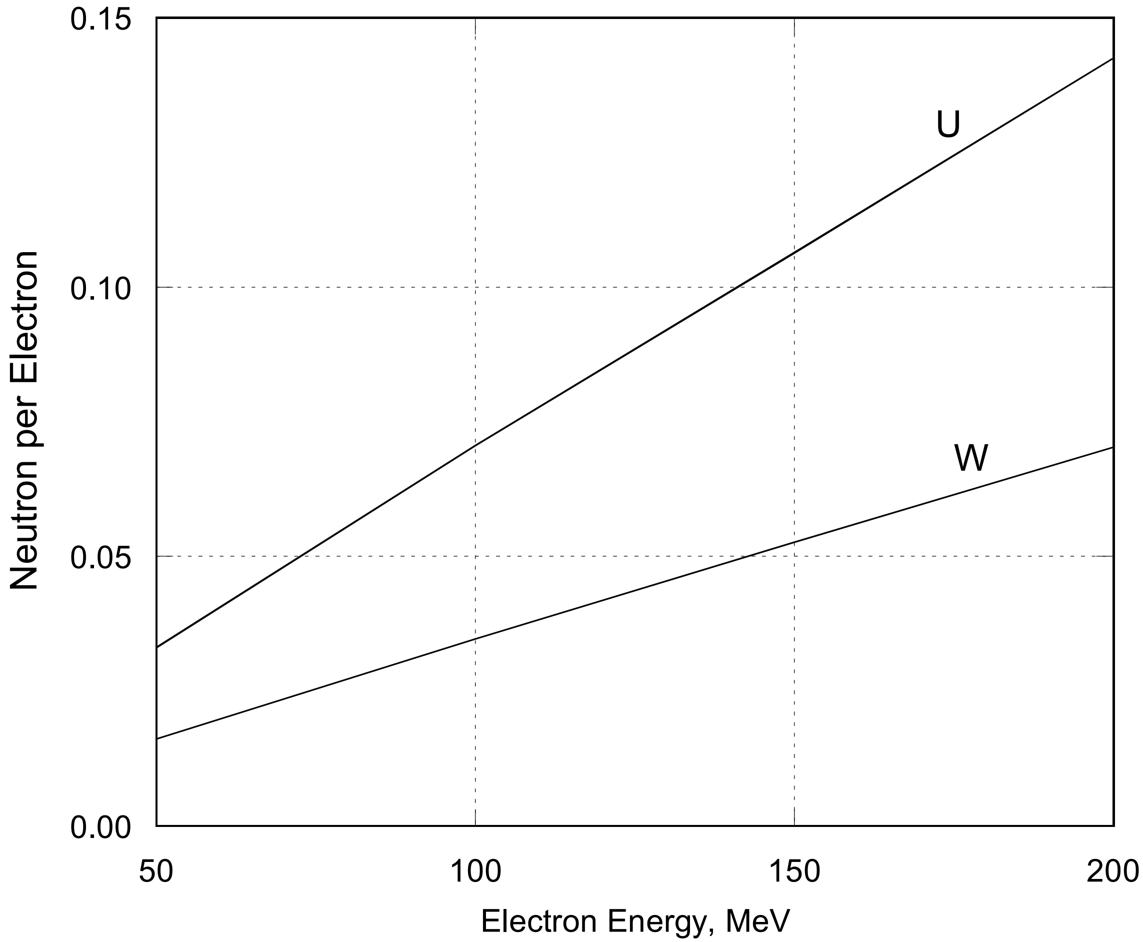
Spatial Energy Deposition Normalized to Beam Power of 2 KW/cm^2 in Pure Tungsten Target Material for Different Electron Energies



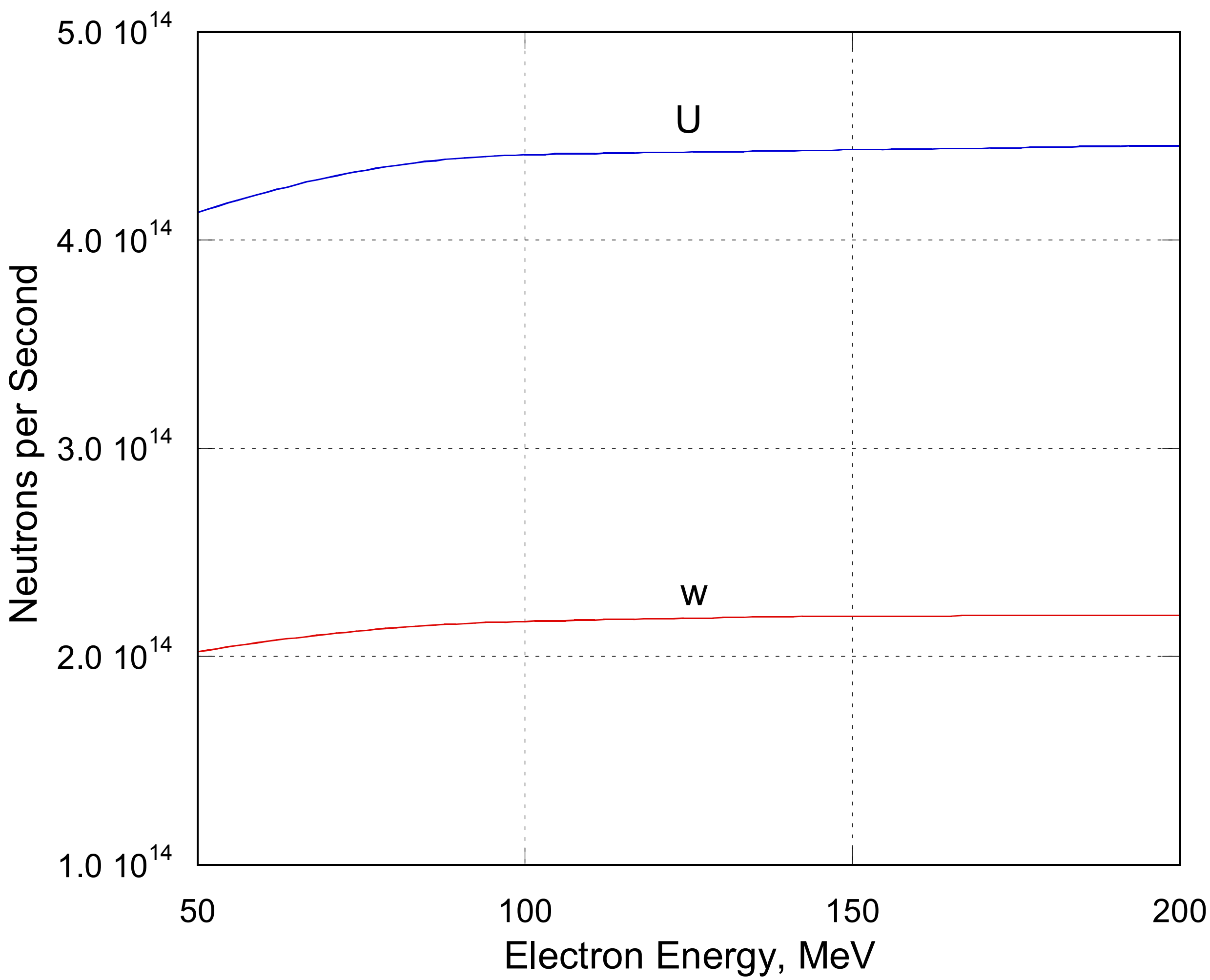
Spatial Energy Deposition Normalized to Beam Power of 2 KW/cm^2 in Pure Uranium Target Material for Different Electron Energies



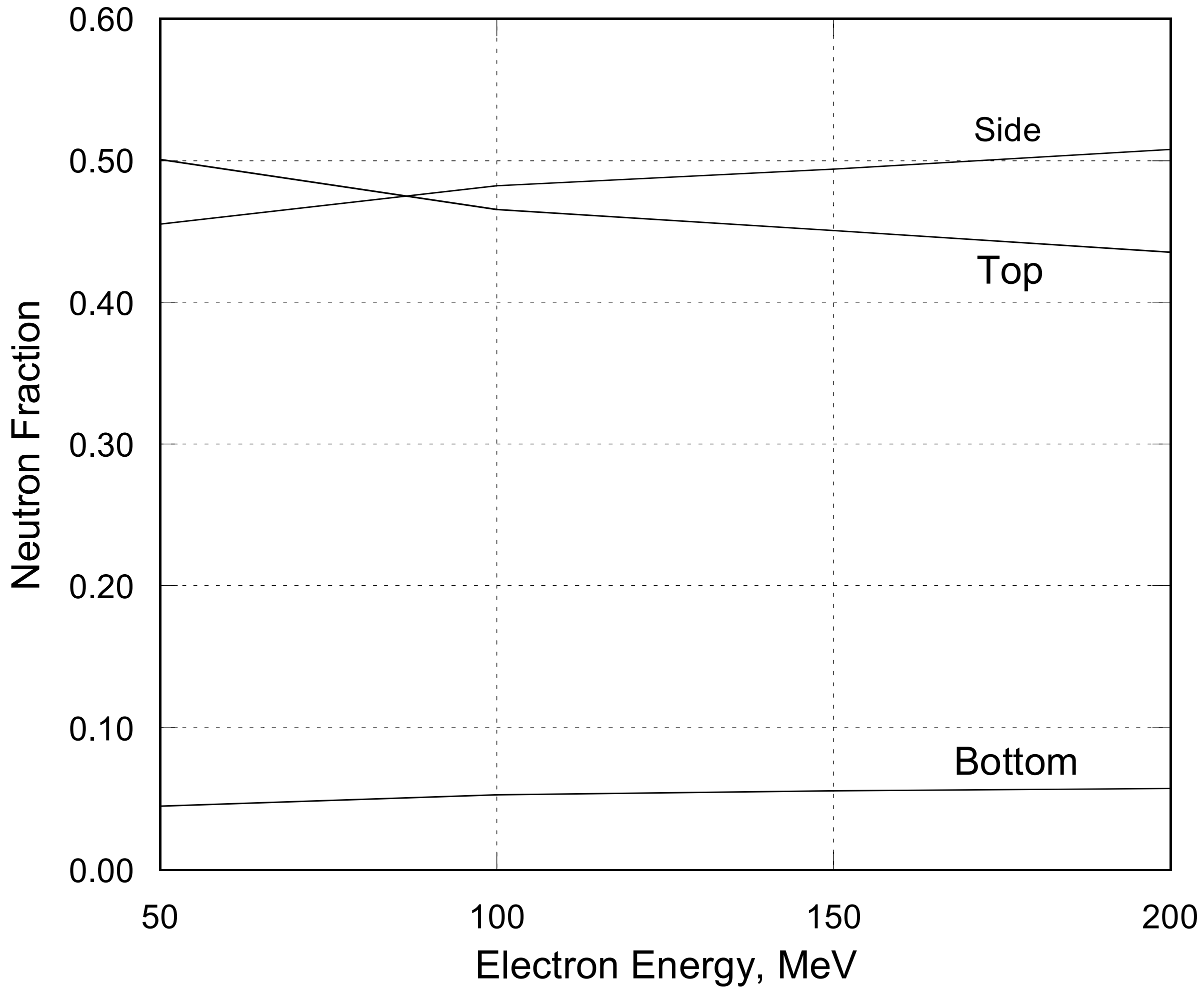
Neutron Yield per Electron as a function of the Electron Energy for Pure Uranium and Tungsten Target Materials



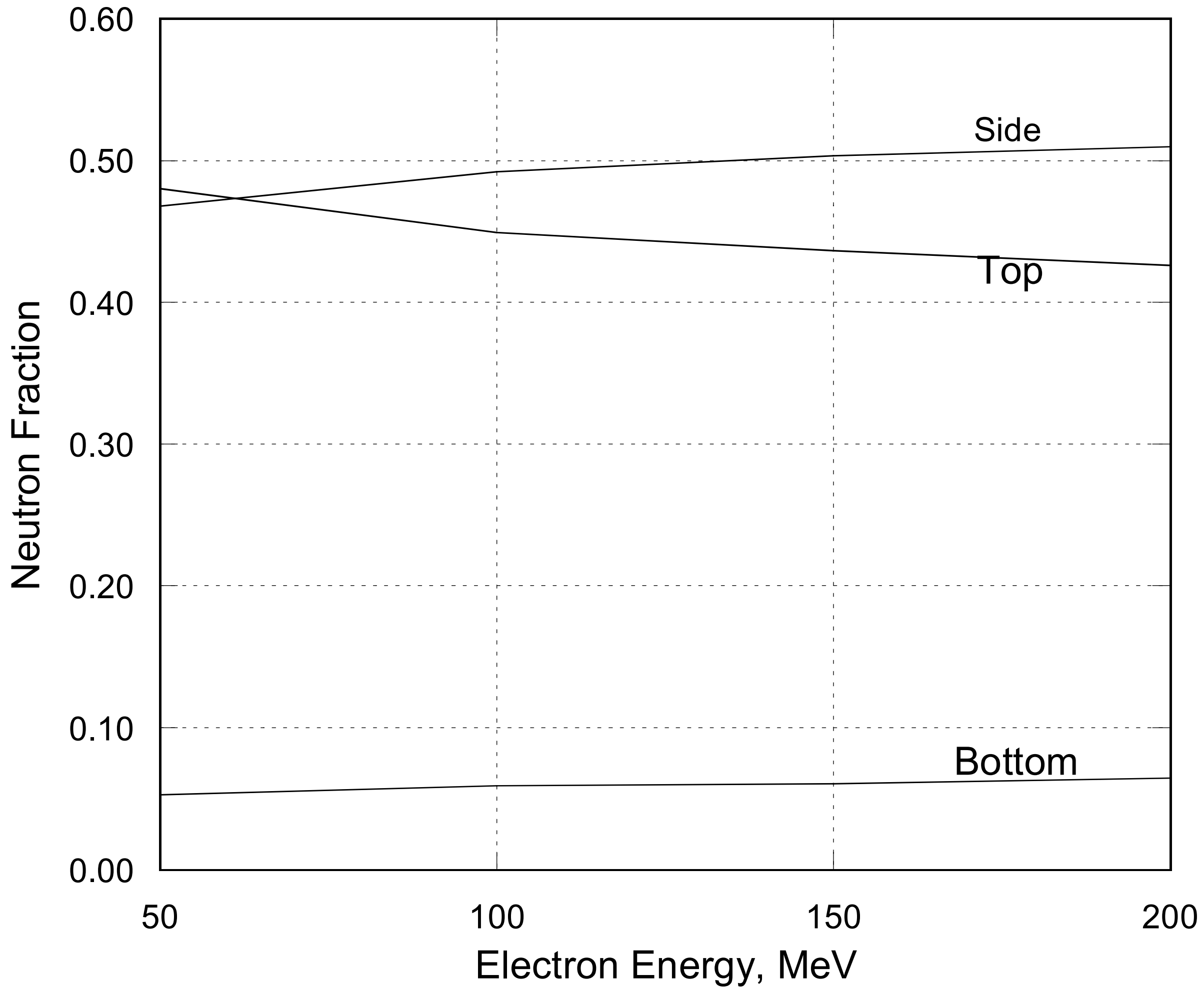
Neutron Source Strength as a function of the Electron Energy for 100 KW Beam Energy Pure from Uranium and Tungsten Target Materials



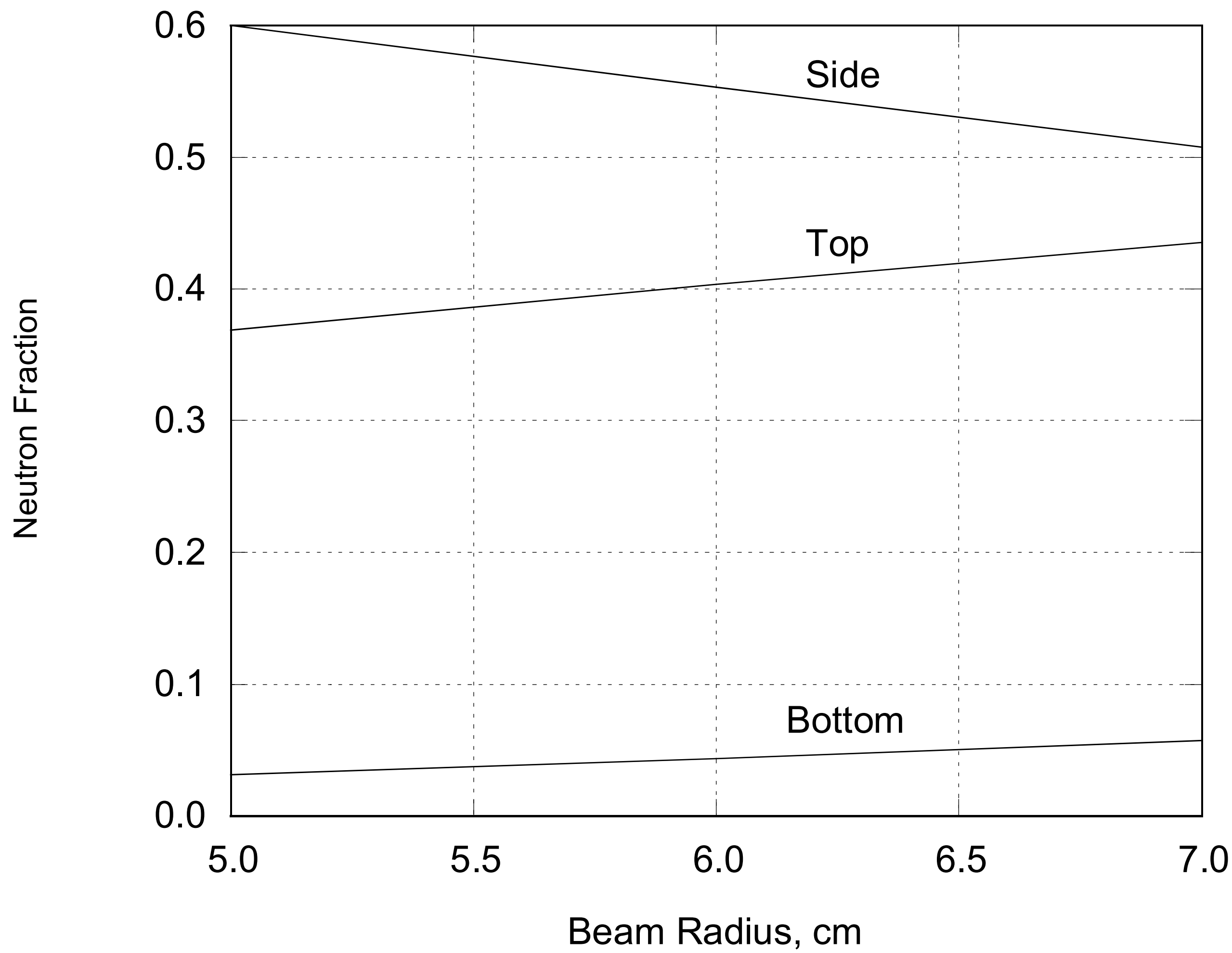
Neutron Fraction Distribution from the Pure Tungsten Target as a function of the Electron Energy for 7-cm Beam Radius and 10-cm Target Length



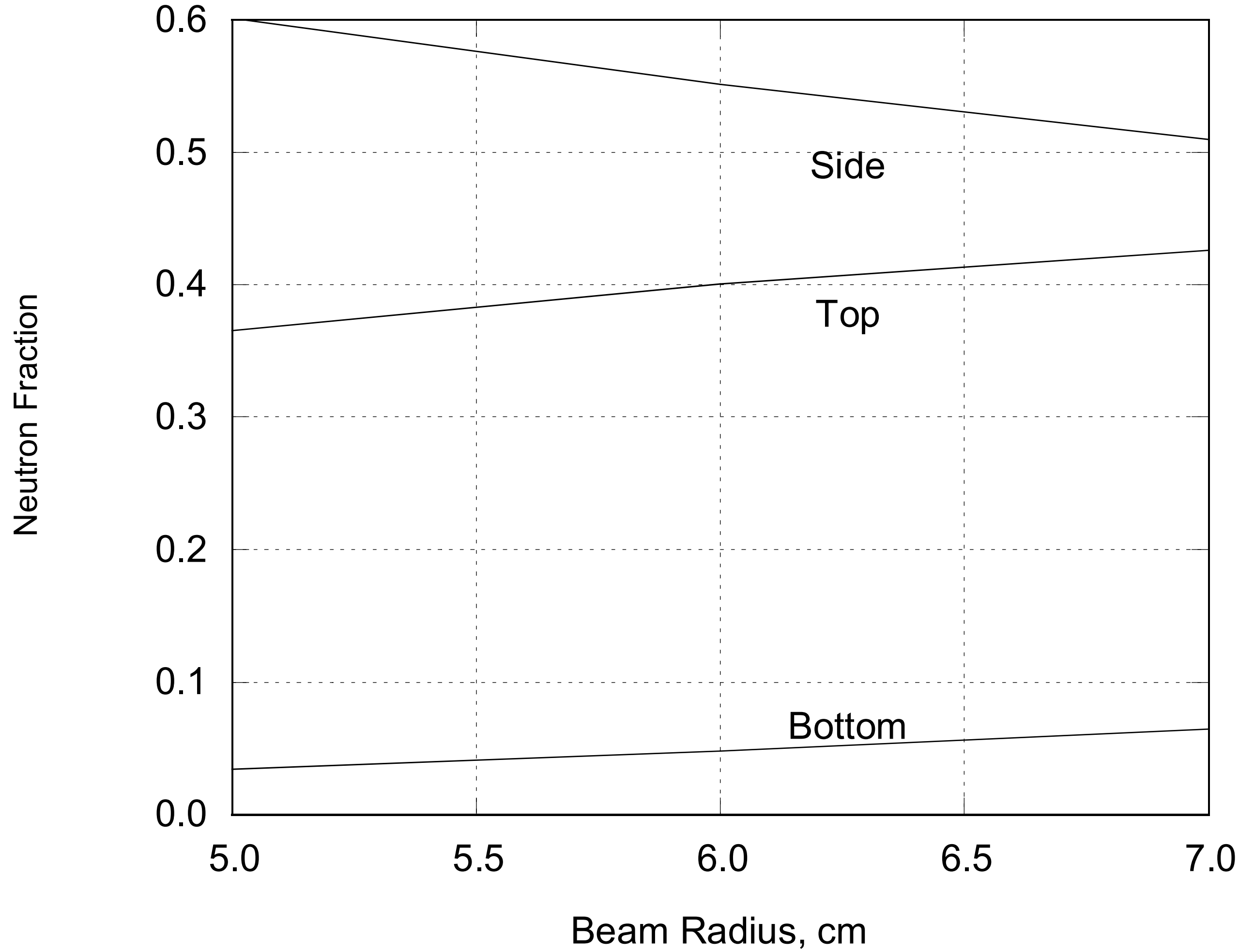
Neutron Fraction Distribution from the Pure Uranium Target as a function of the Electron Energy for 7-cm Beam Radius and 10-cm Target Length



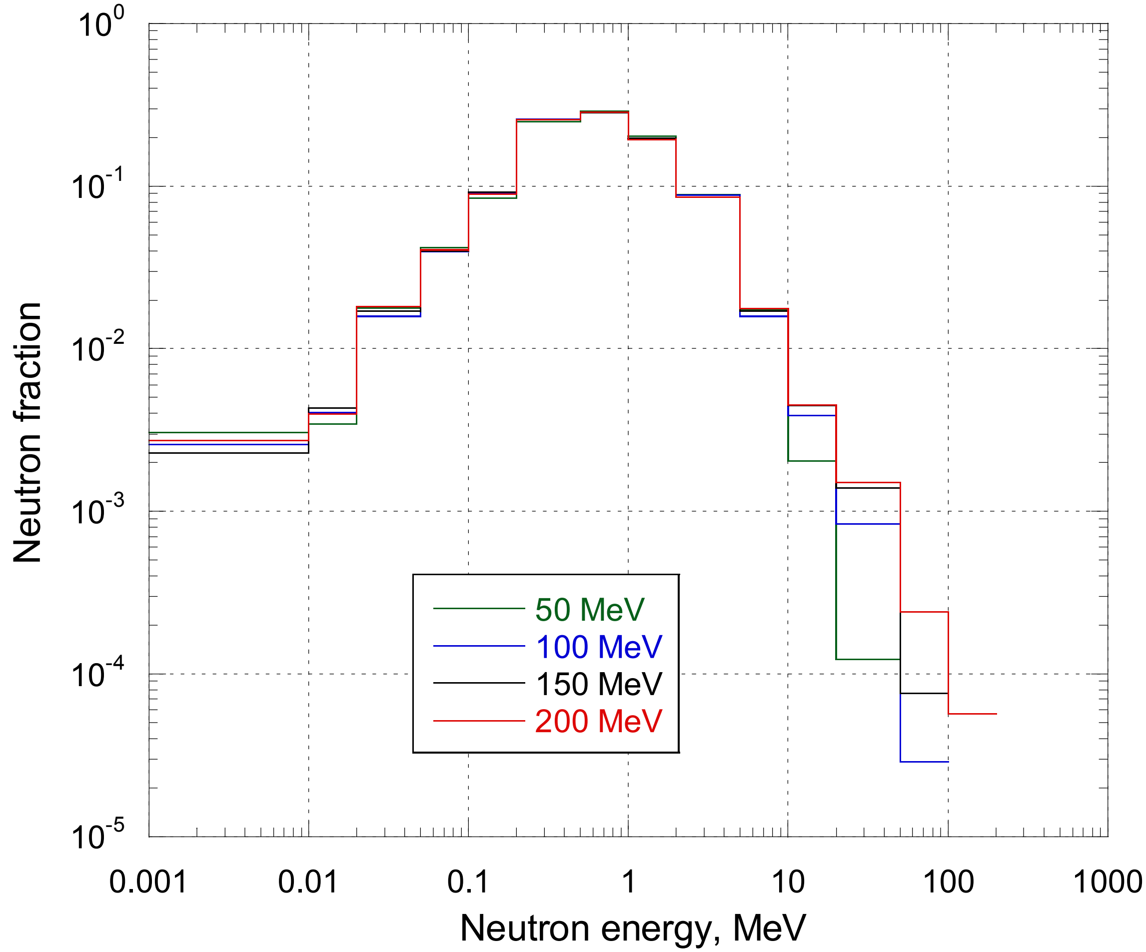
Neutron Fraction Distribution from the Pure Tungsten Target as a function of the Beam Radius for 200-MeV Electron Energy and 10-cm Target Length



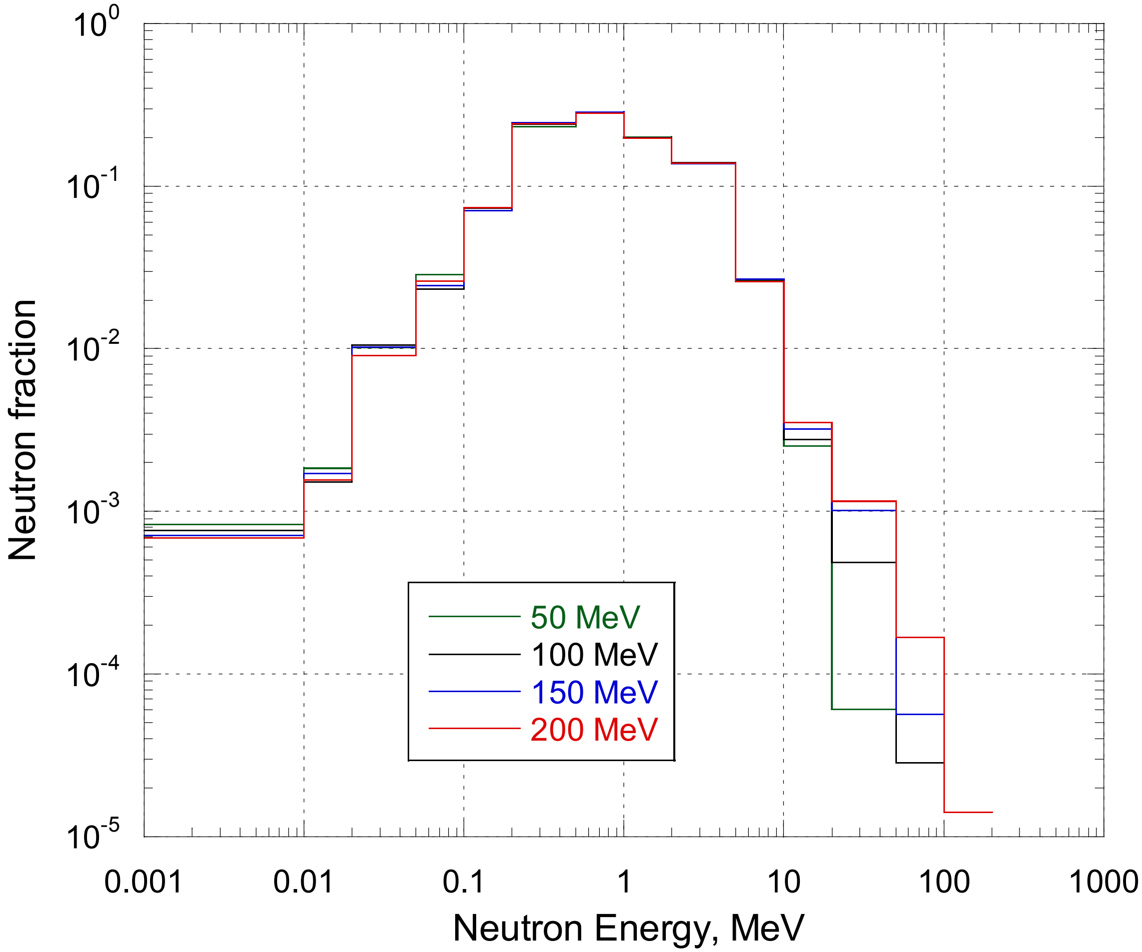
Neutron Fraction Distribution from the Pure Uranium Target as a function of the Beam Radius for 200-MeV Electron Energy and 10-cm Target Length



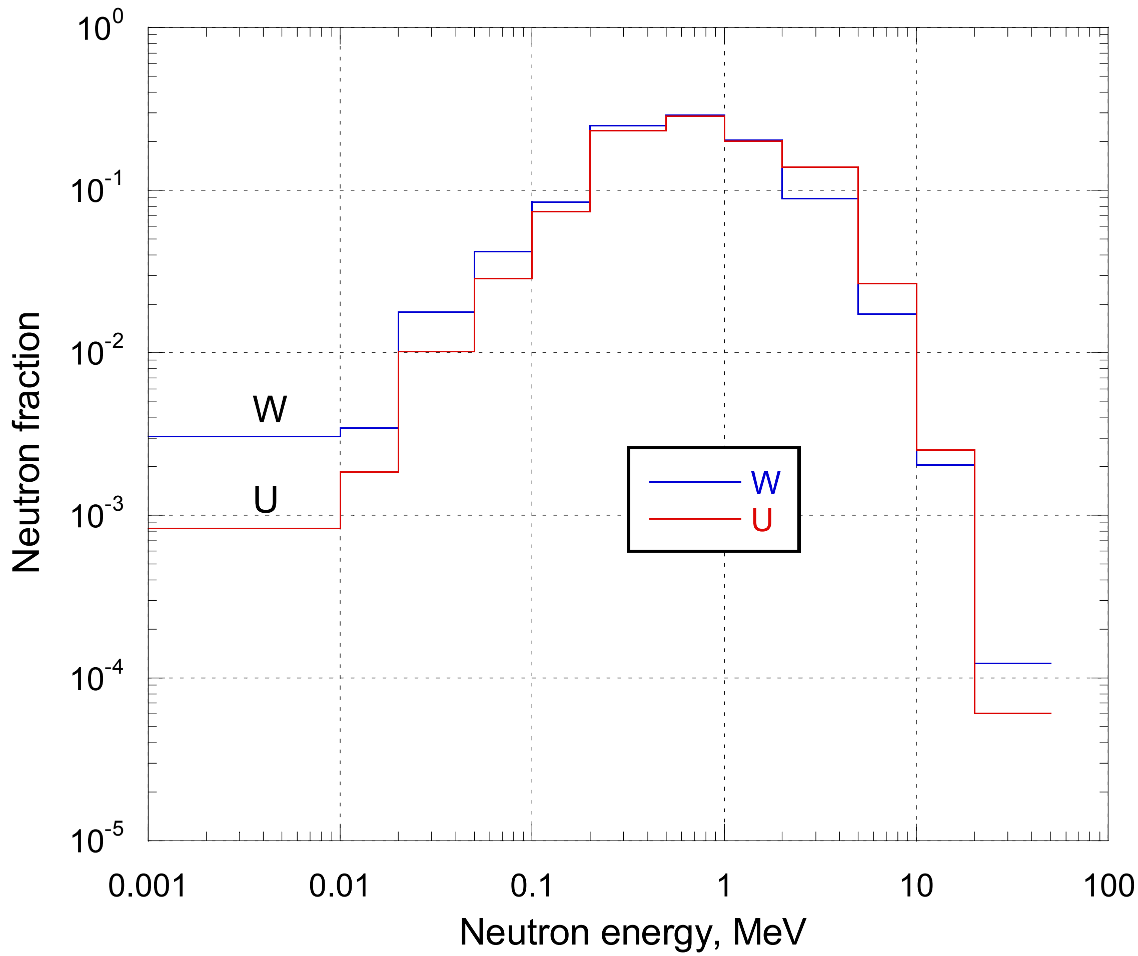
Normalized Neutron Spectra from Pure Tungsten Target as a Function of the Electron Energy



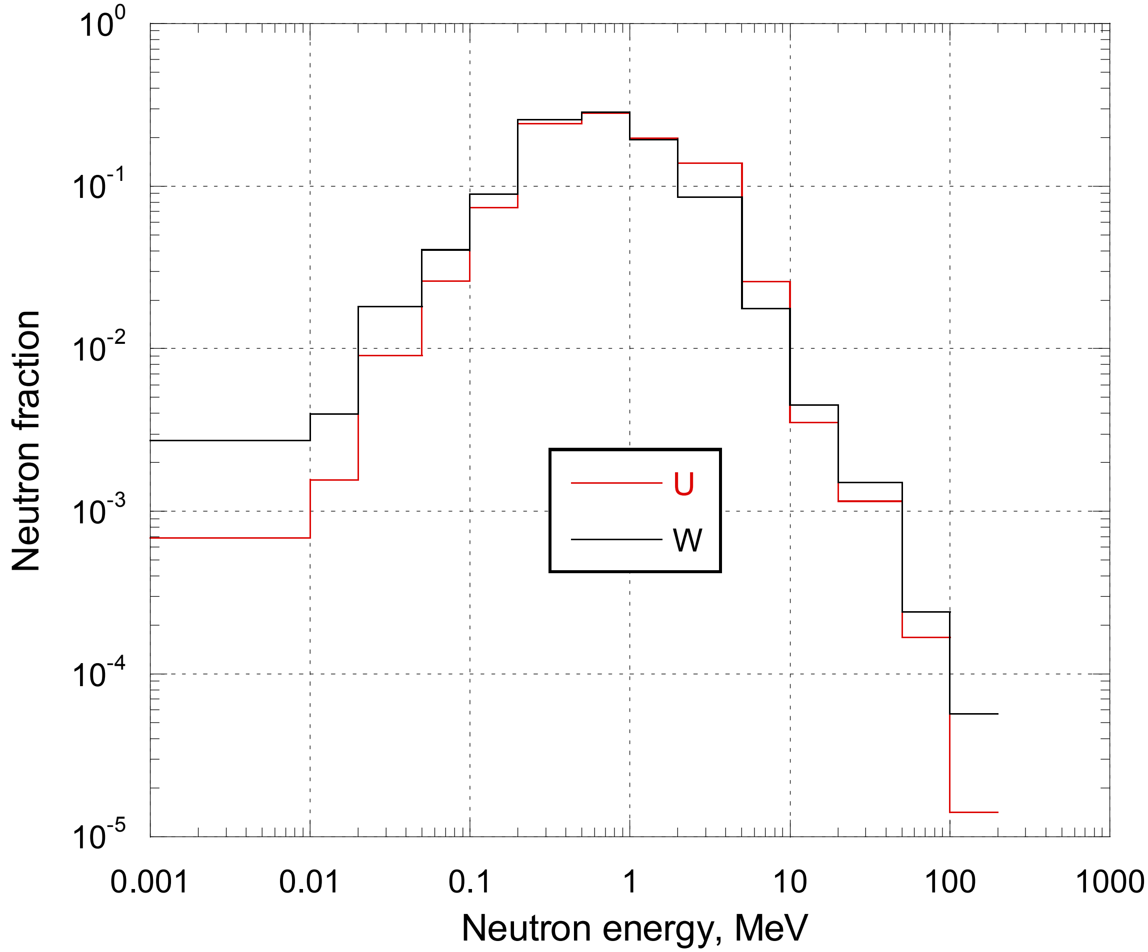
Normalized Neutron Spectra from Pure Uranium Target as a Function of the Electron Energy



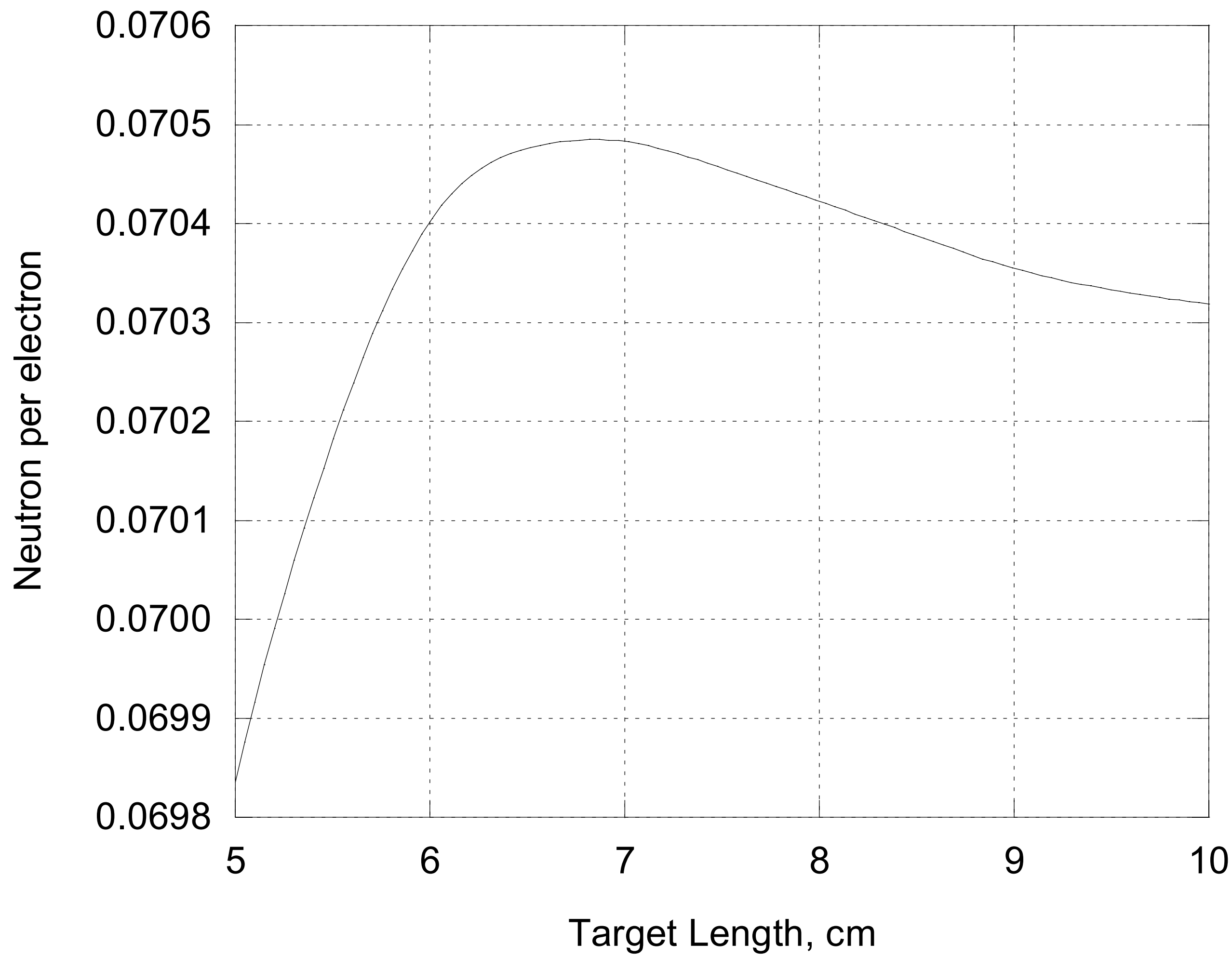
Normalized Neutron Spectra of Pure Uranium and Tungsten Targets for 50 MeV Electrons



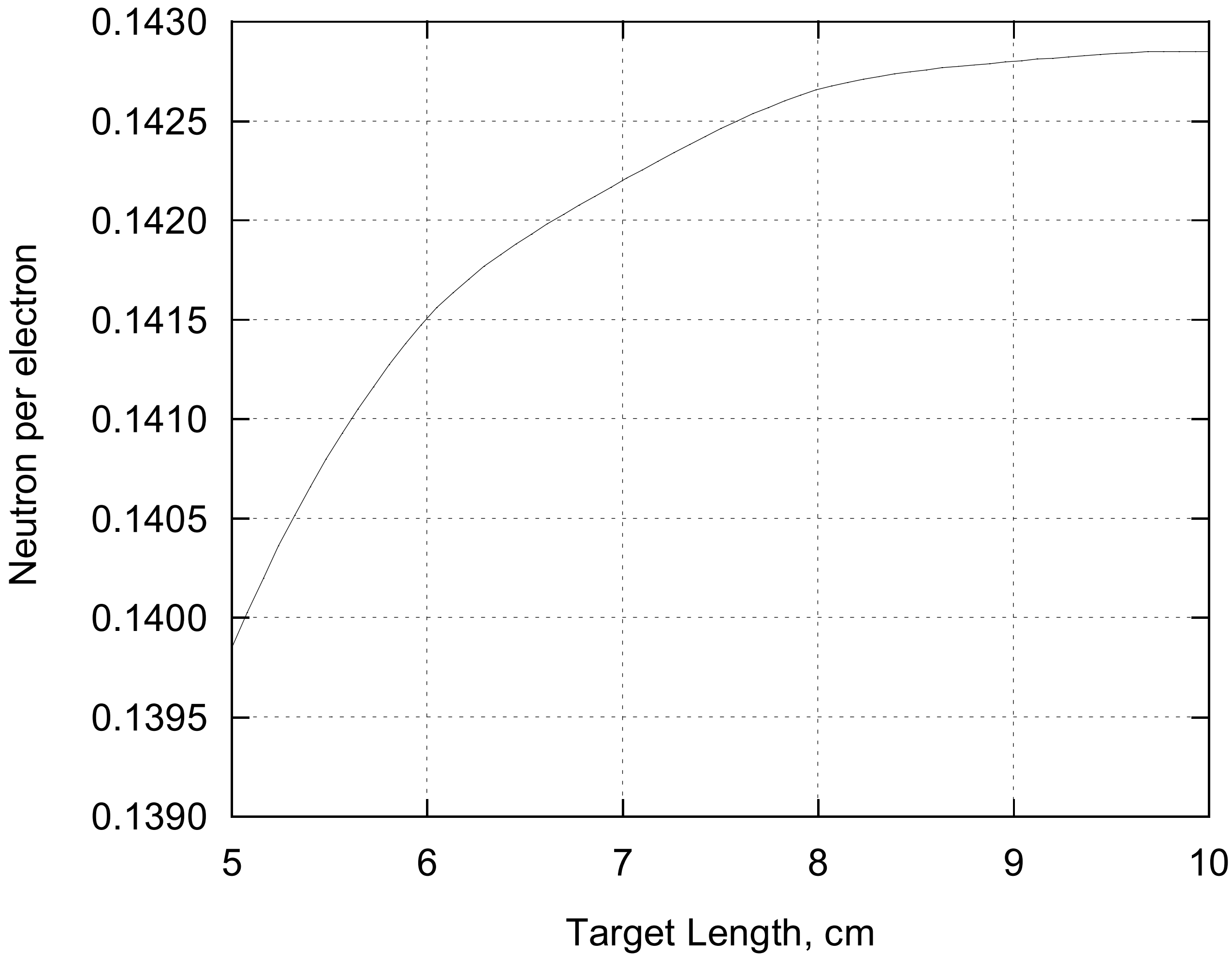
Normalized Neutron Spectra of Pure Uranium and Tungsten Targets for 200 MeV Electrons



Number of Neutrons from Pure Tungsten Material per Electron as a Function of the Target Length



Number of Neutrons from Pure Uranium Material per Electron as a Function of the Target Length

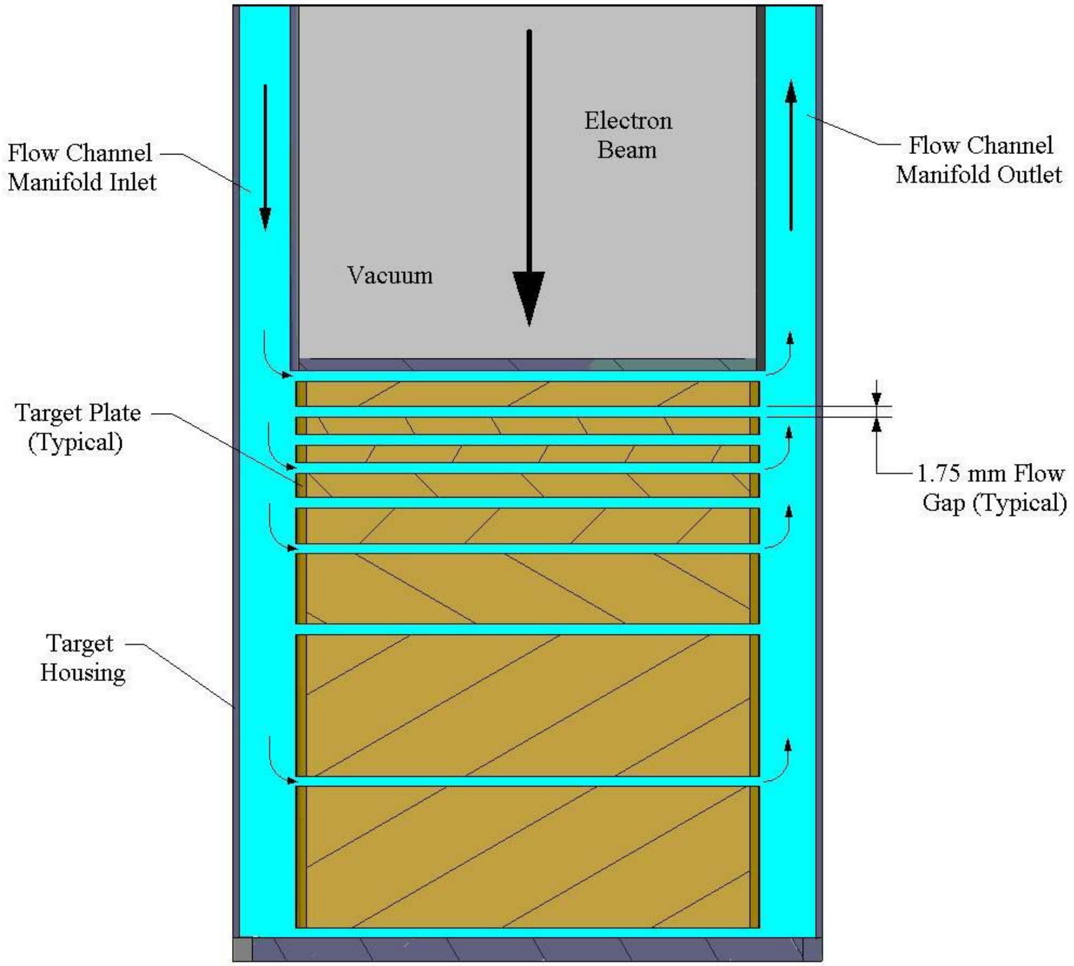


Thermal-Hydraulics Design of the Tungsten and Uranium Targets

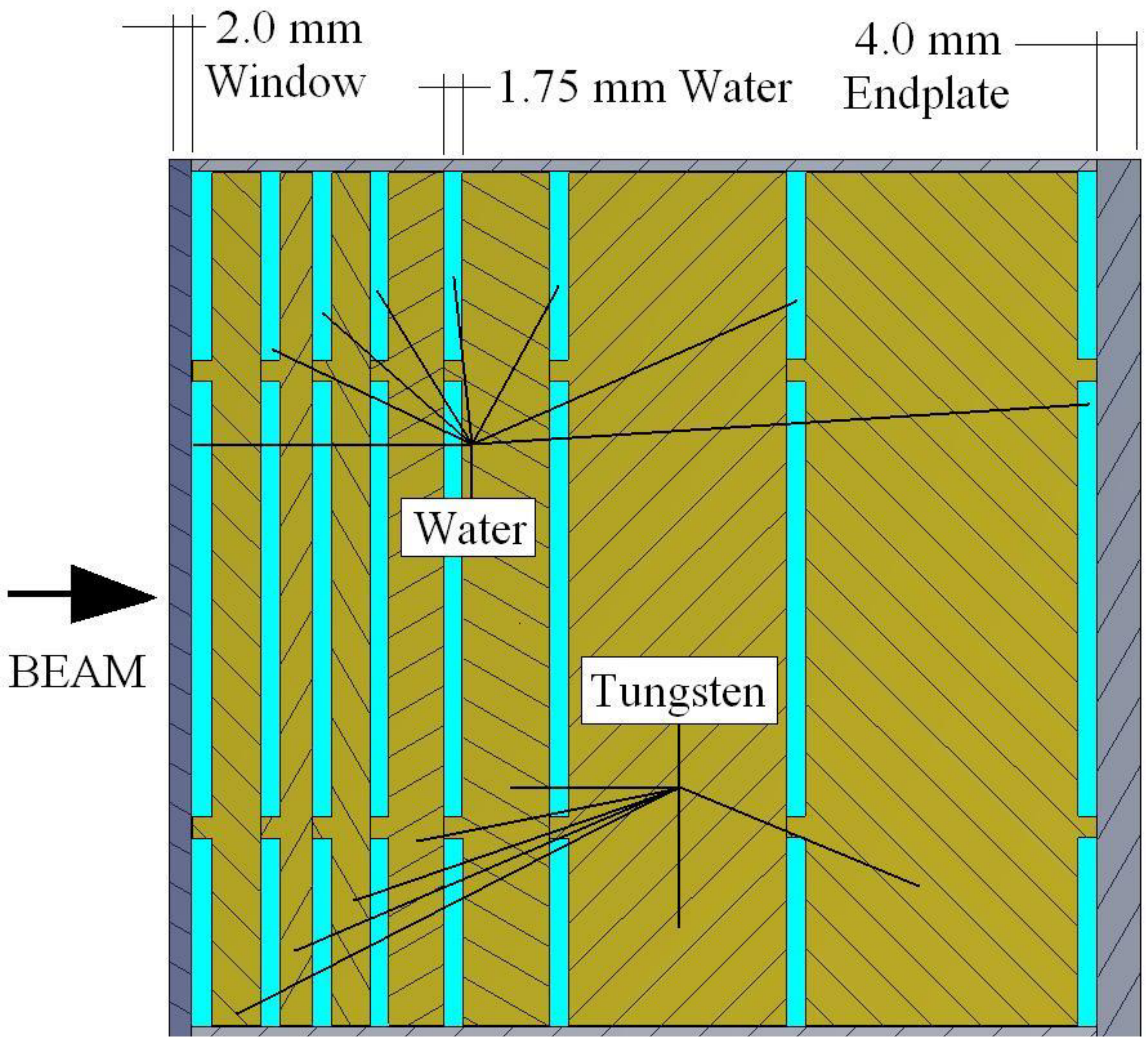
- The following parameters are used for developing the target configurations:
  - Inlet water temperature 20 °C
  - Outlet water temperature <25 °C
  - Inlet water pressure 4 atm
  - Target water velocity 7 m/s
  - Maximum target surface temperature 80 °C
  - Water coolant channel thickness 1.75 mm

- Aluminum alloy is used for the beam window and the target structure.
- Target materials are in the form of disks perpendicular to the beam direction.
- Each target disk is cooled from both sides to reduce thermal stresses and maximize the disk thickness.
- Uranium disks used aluminum clad to avoid coolant contamination with fission products.
- The target disks are cooled in parallel with coolant velocity perpendicular to the beam direction.

Cross Section View of the Target Assembly Showing the Coolant Flow Direction

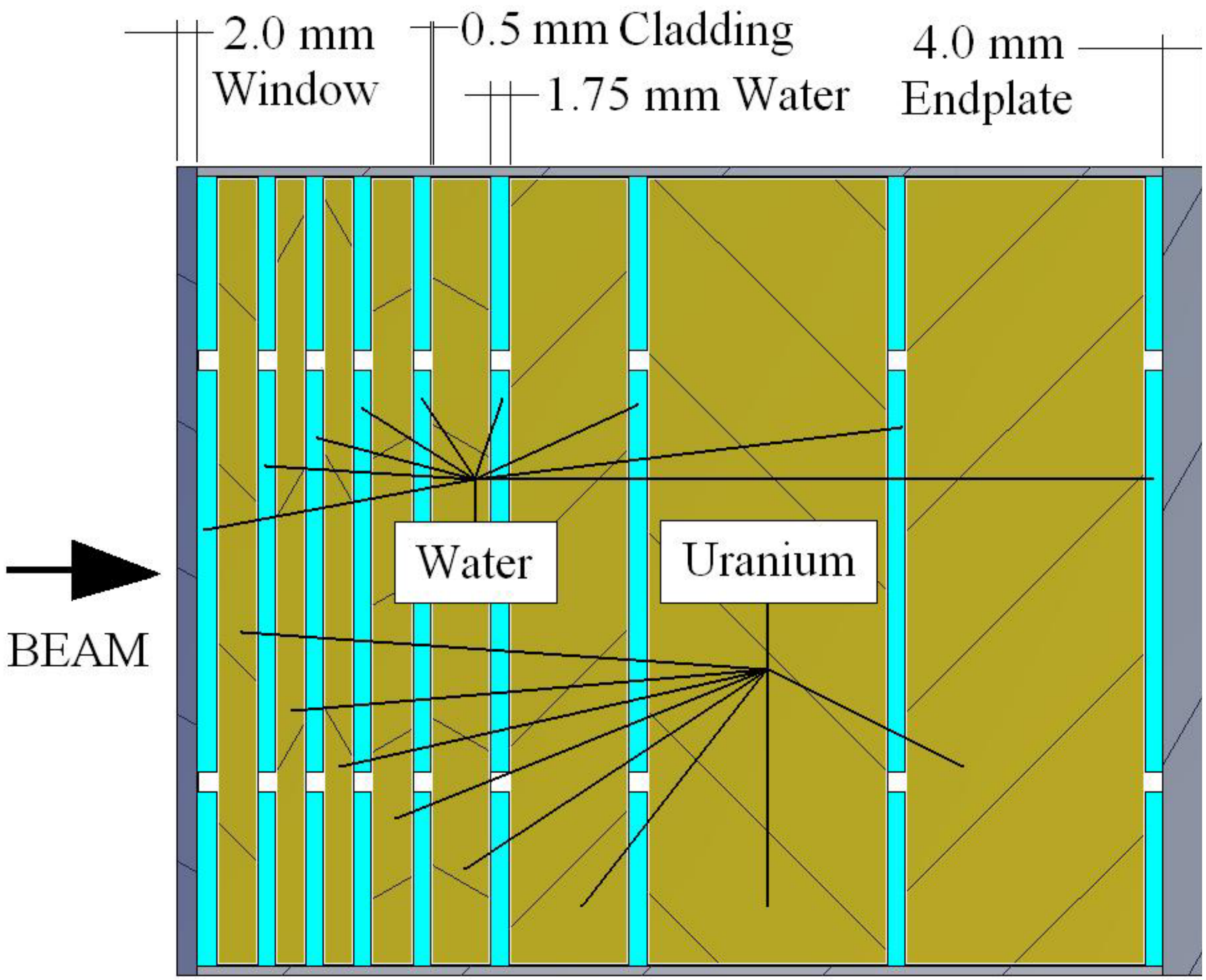


Tungsten Target Configuration Based on Physics, Thermal Hydraulics, and Stress Analyses



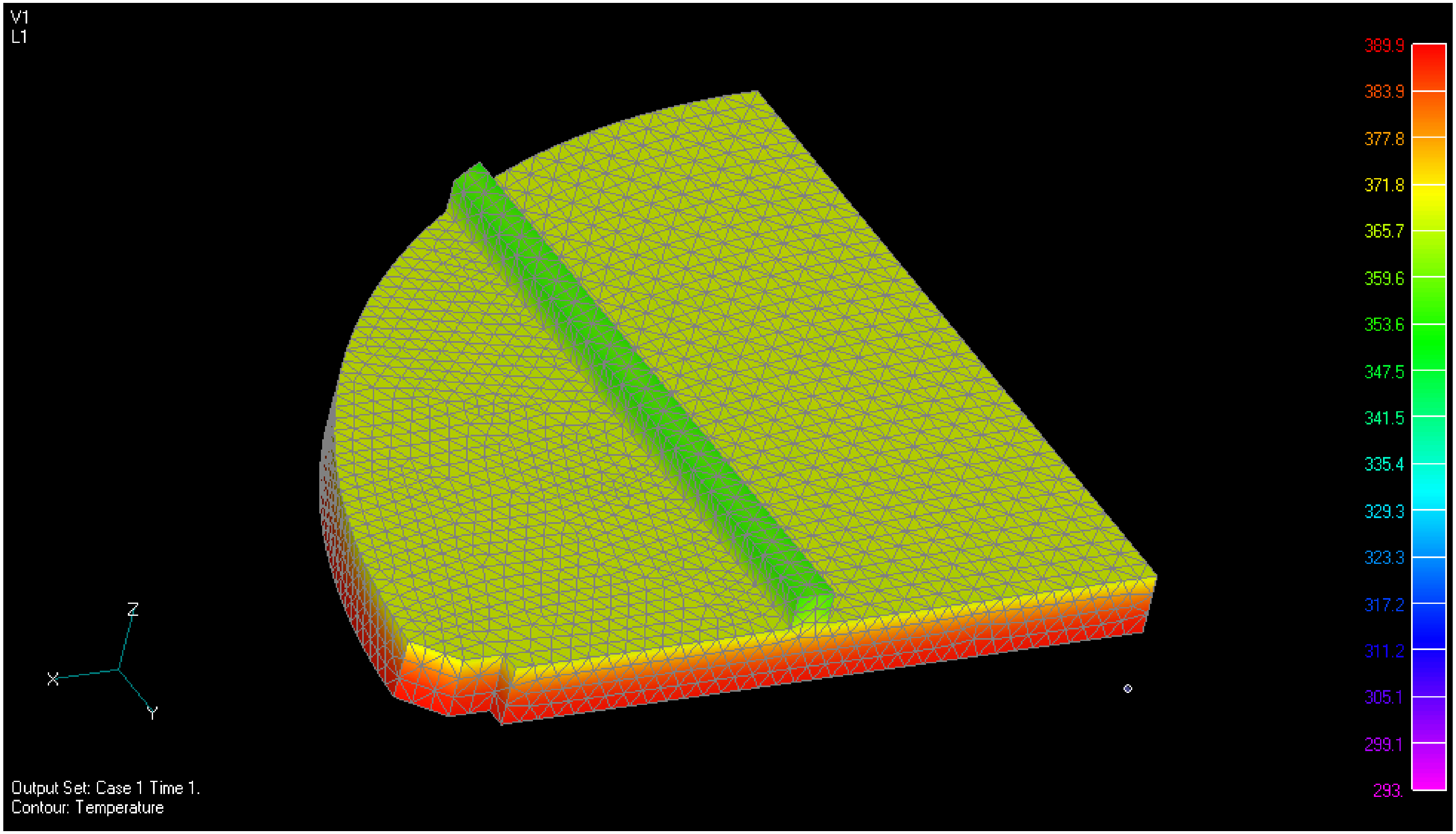
Disk Number	Disk thickness, mm
1	4.5
2	3.0
3	3.5
4	5.0
5	8.0
6	20.0
7	25.0

Uranium Target Configuration Based on Physics, Thermal Hydraulics, and Stress Analyses

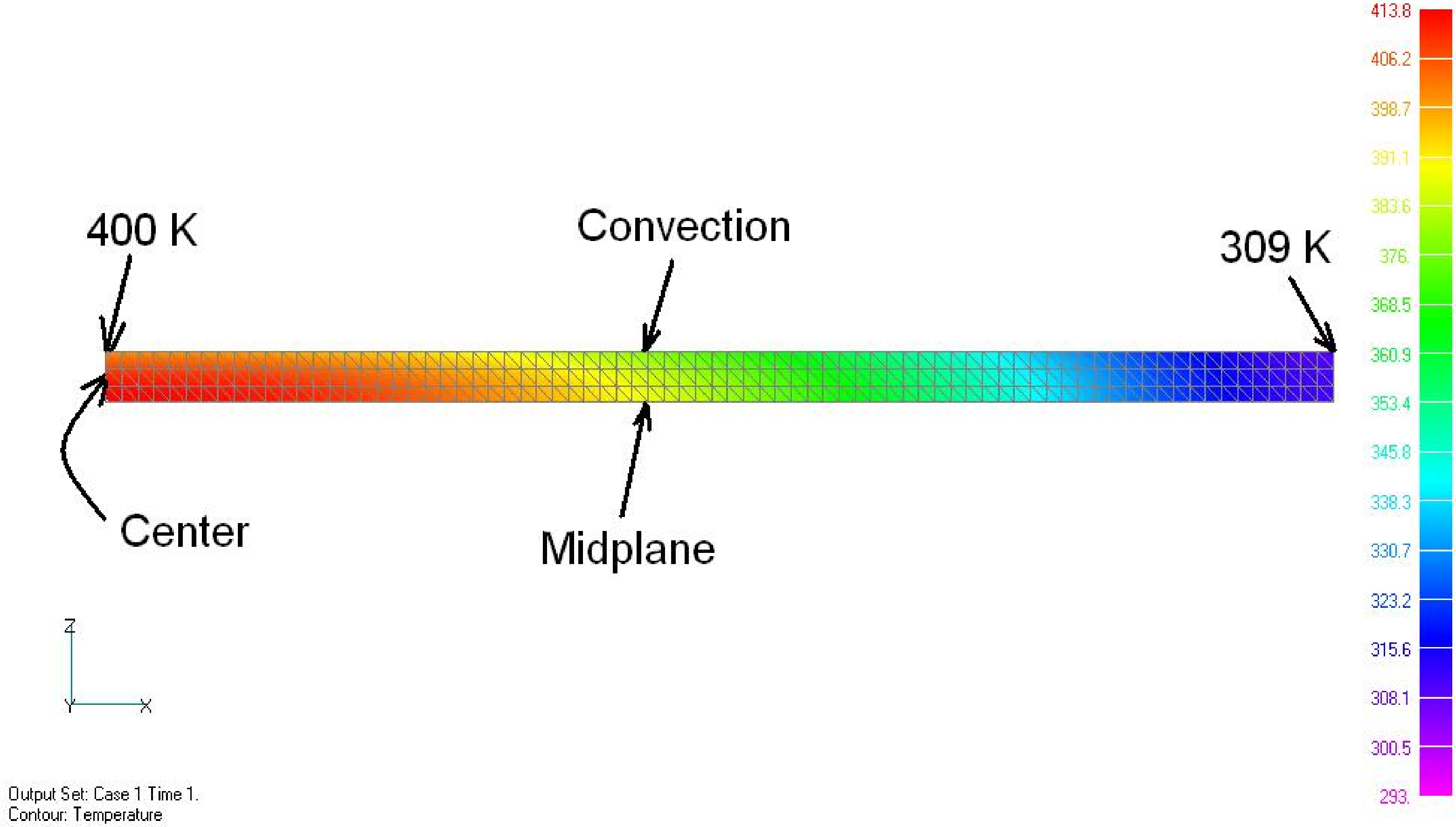


Disk Number	Disk thickness, mm
1	4.2
2	3.0
3	3.0
4	4.2
5	6.0
6	12.0
7	24.0
8	24

Tungsten Disk Temperature Distribution with the Peak Energy Deposition Including the Engineering Details

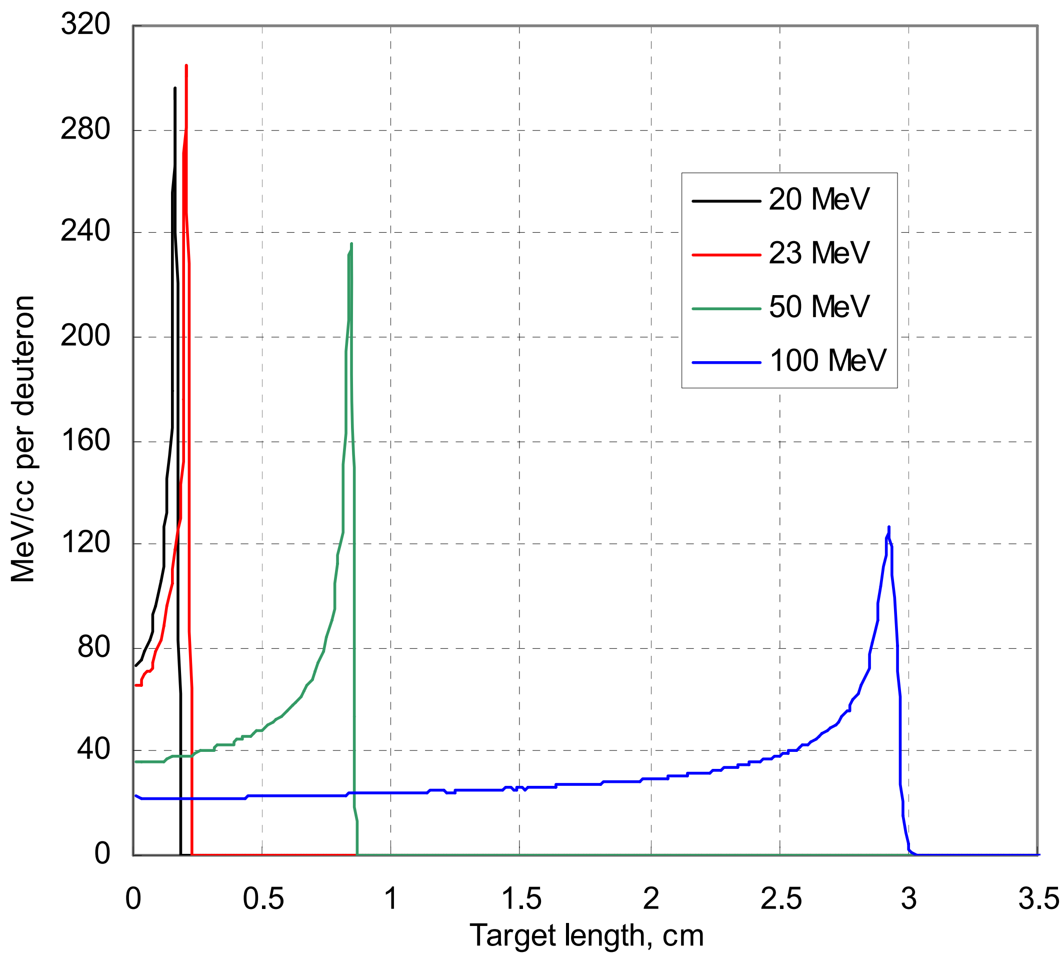


Tungsten Disk Temperature Distribution with the Peak Energy Deposition with Cosine Power Distribution

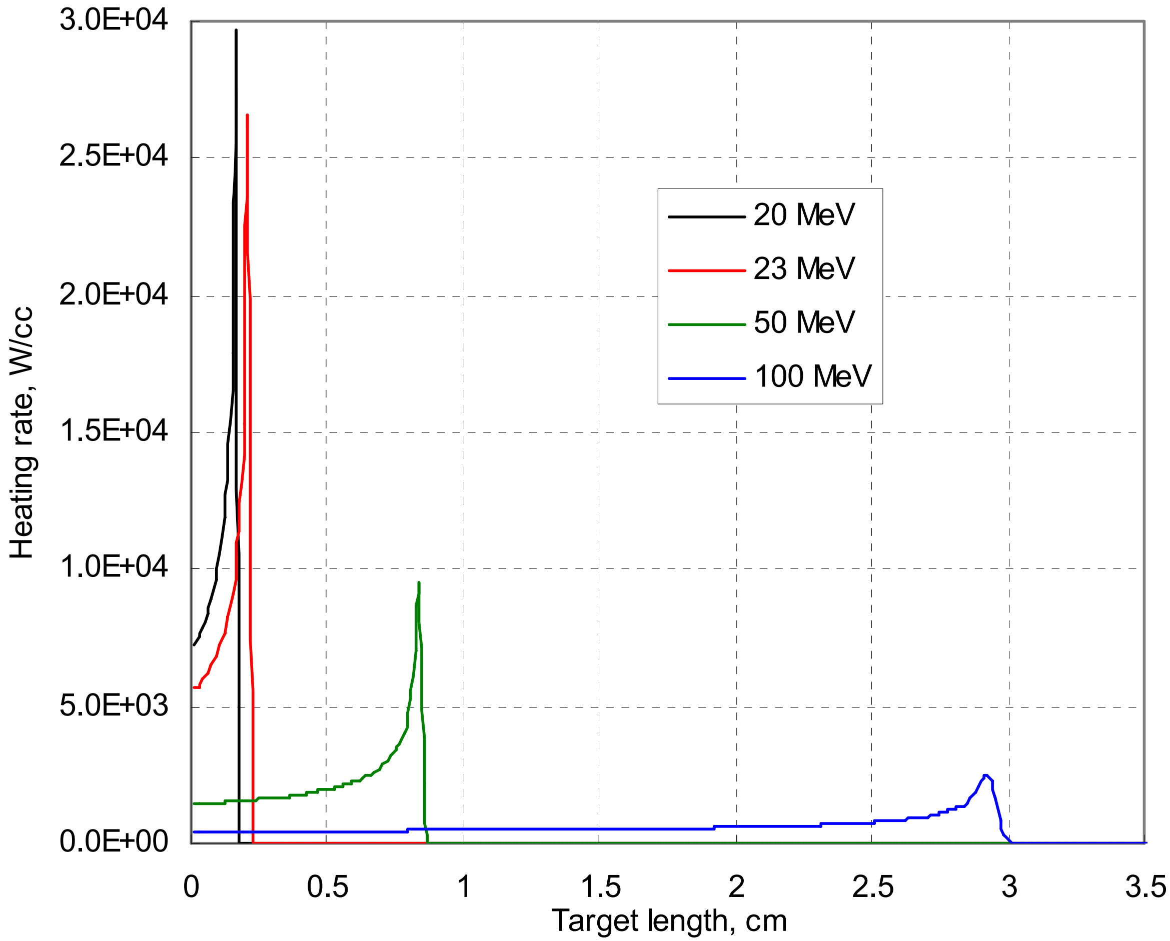


Uniform power distribution results in 344 K peak temperature.

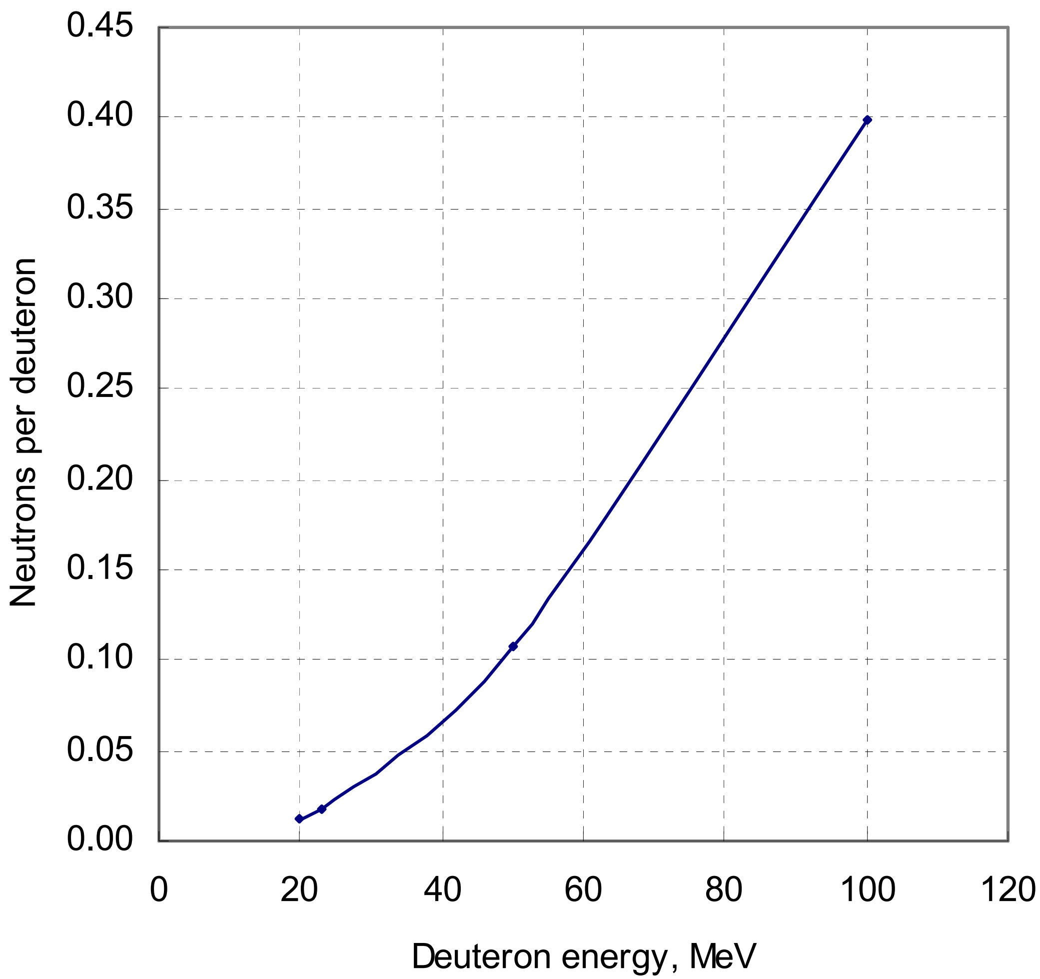
Spatial Energy Deposition per Deuteron in Pure Beryllium Target Material for Different Deuteron Energies



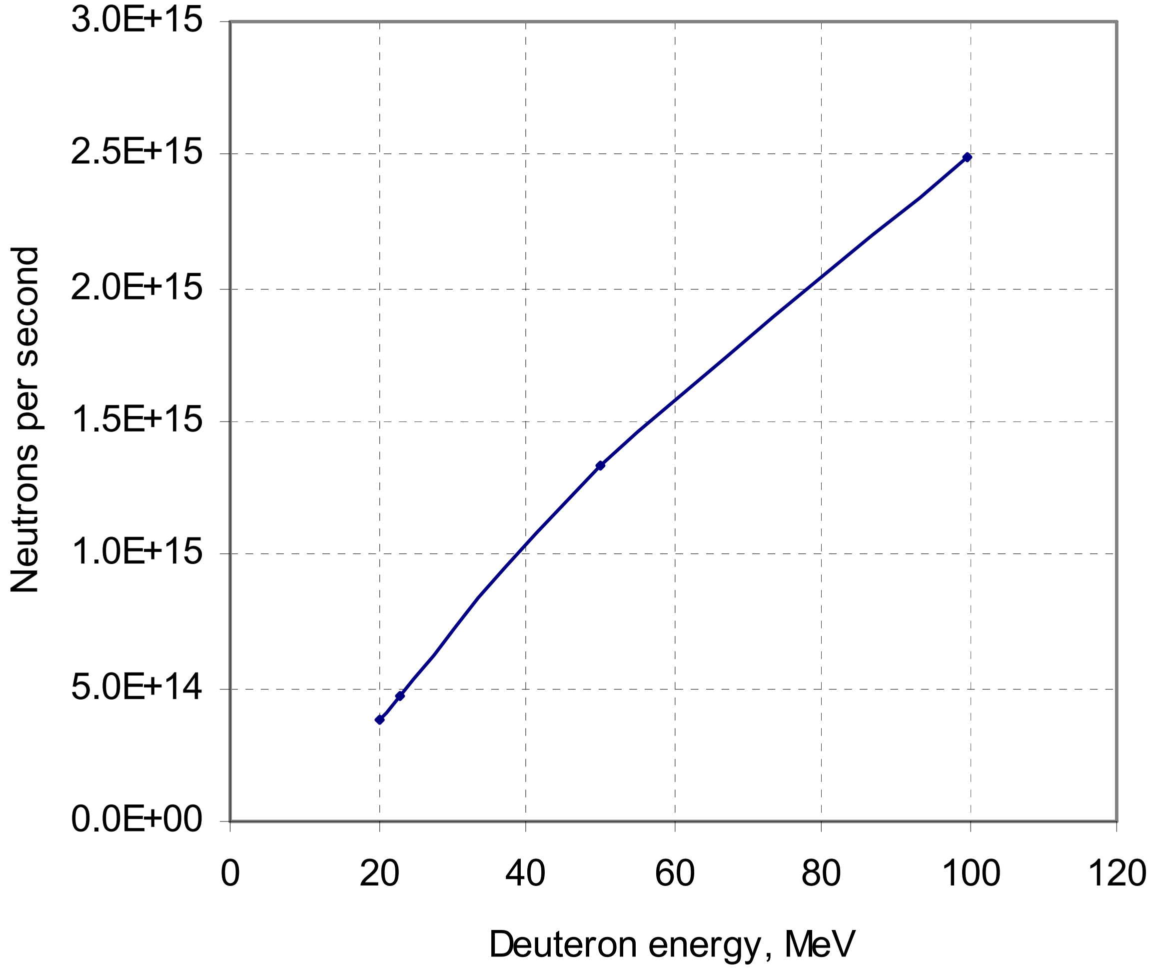
Spatial Energy Deposition in Pure Beryllium Target Material for Different Deuteron Energies Normalized to Beam Power of 2 KW/cm^2



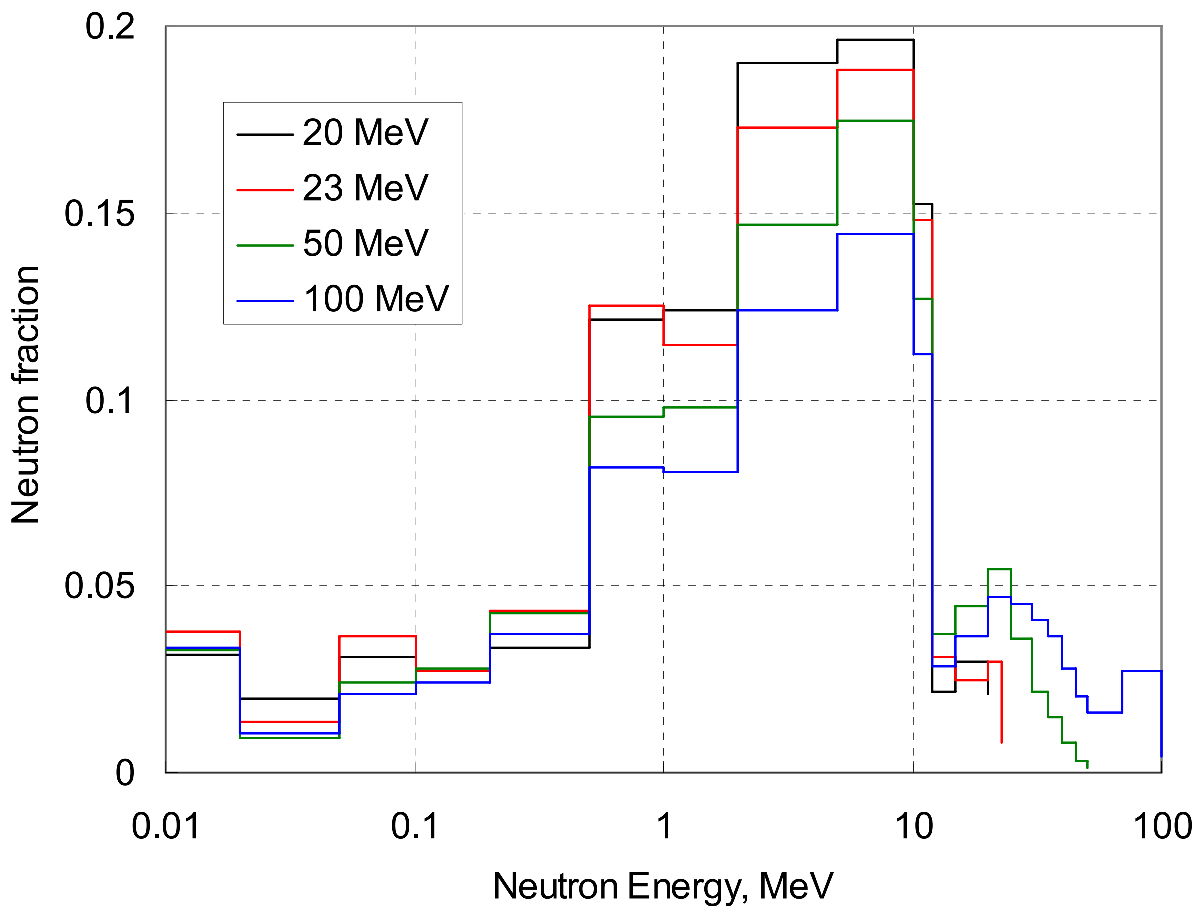
Neutron Yield per Deuteron for Pure Beryllium Target as Function of Electron Energy



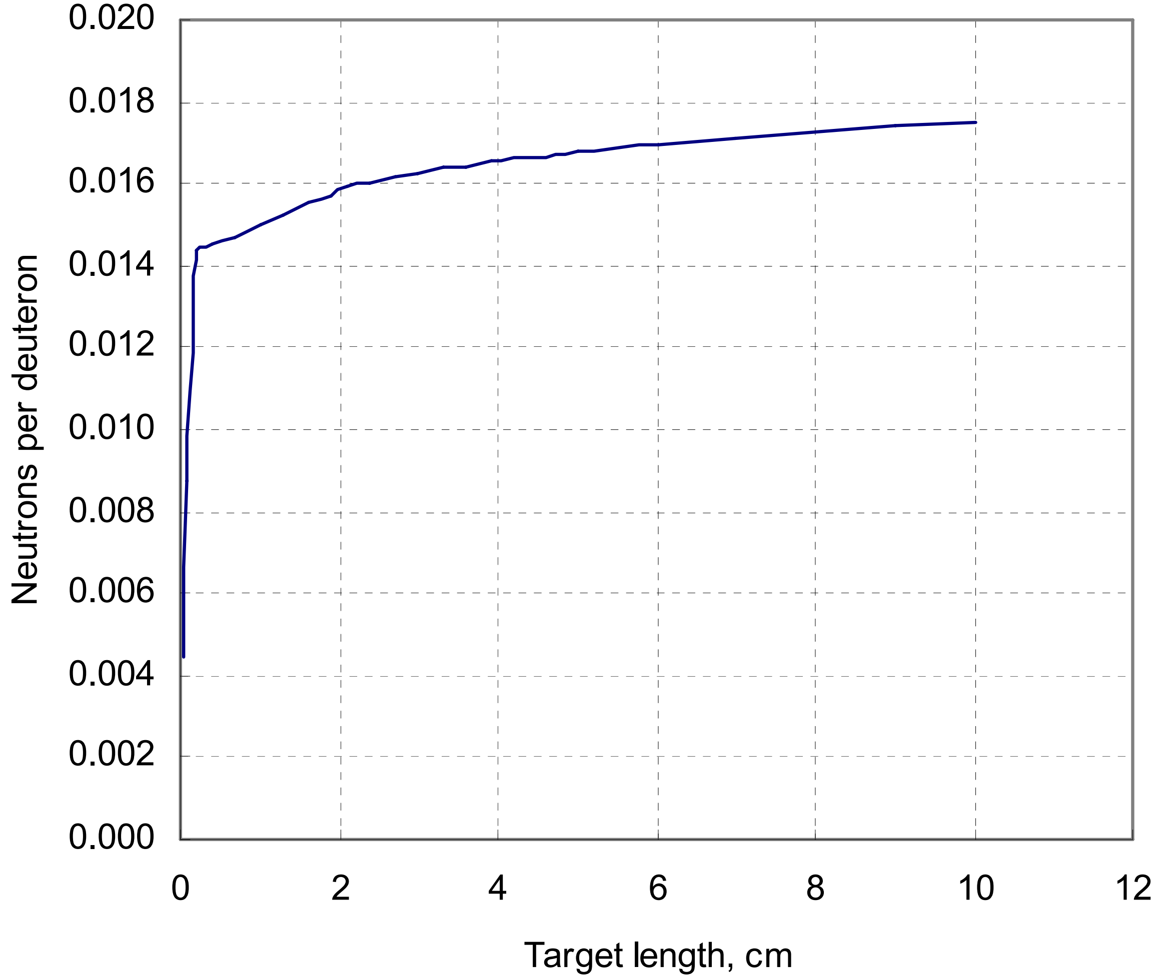
Neutron Source Strength for Pure Beryllium Target as Function of Electron Energy with 100 KW Beam



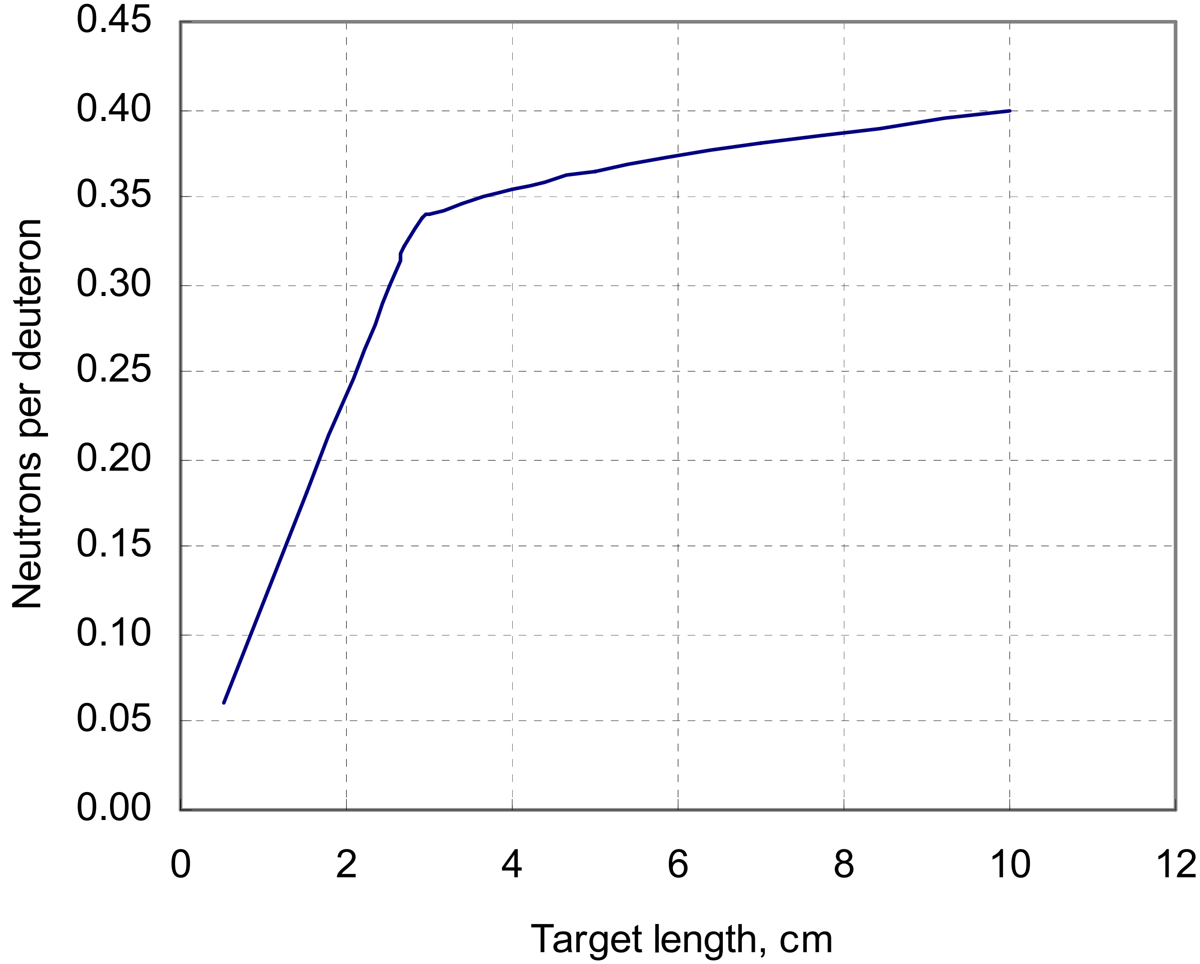
Normalized Neutron Spectra in Beryllium Target for Different Deuteron Energies



Neutron Yield as Function of Pure Beryllium Target Length for 23 MeV Deuteron Beam



Neutron Yield as Function of Pure Beryllium Target Length for 100 MeV Deuteron Beam

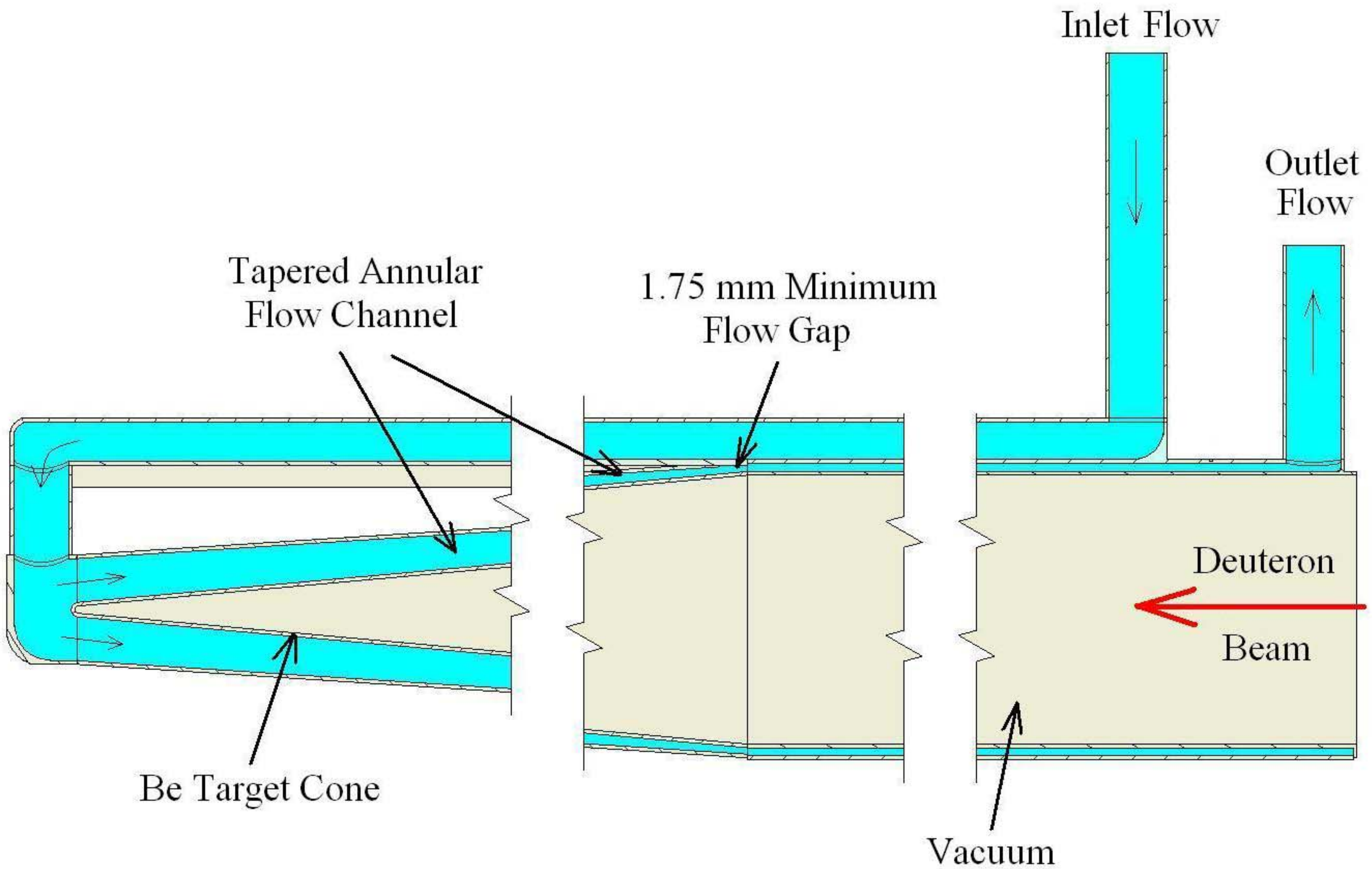


Thermal-Hydraulics design of the Beryllium Target

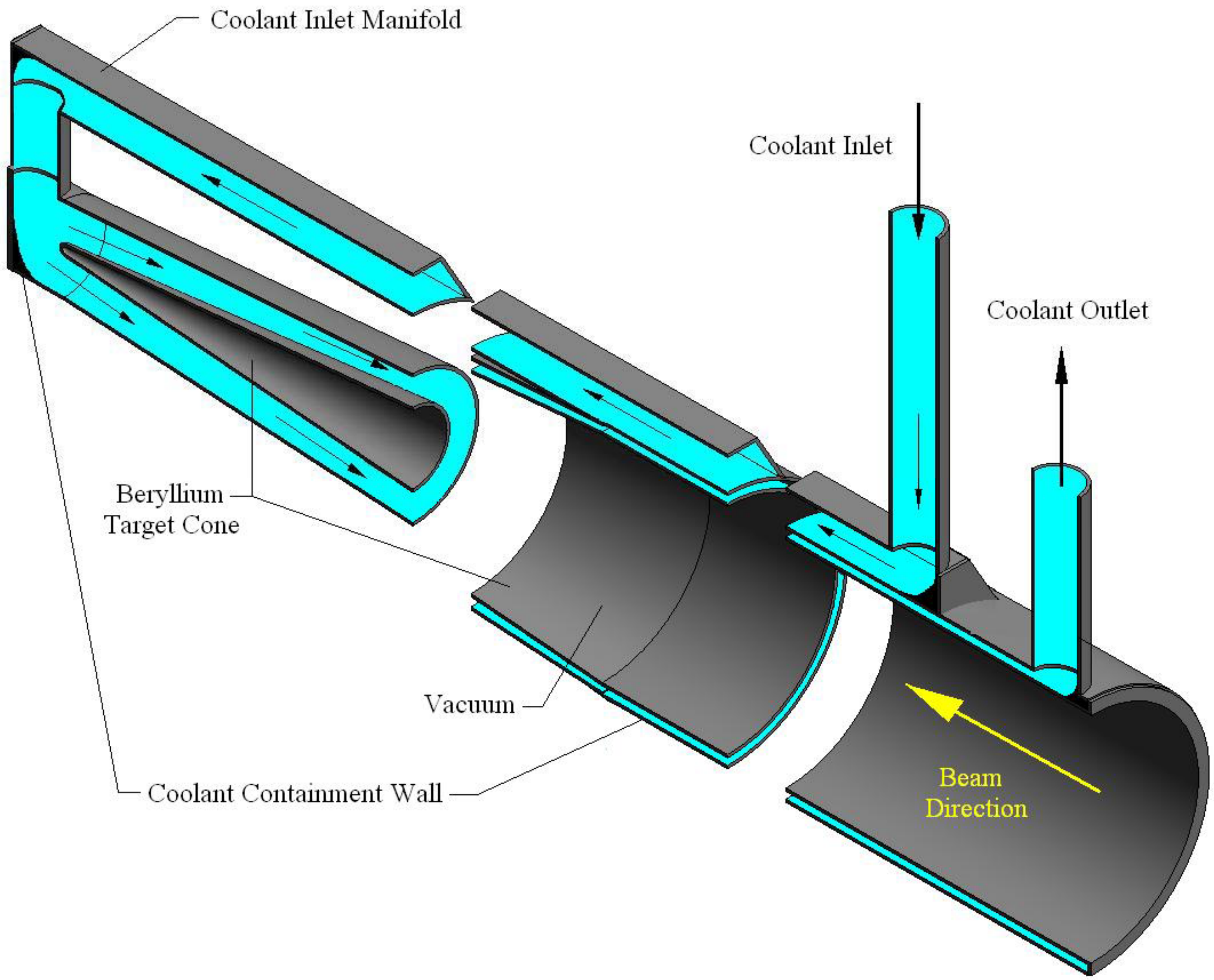
- The beryllium target can not utilize the disk design configuration because of the high power density, ~30 KW/cm^3.
- Also, the use of beryllium target material perpendicular to the beam direction results in localized neutron source, which is not desirable. A line source along the axis of the sub-critical assembly is preferred from the physics and operational considerations.
- A simple beryllium cone configuration is developed to avoid these difficulties. Beryllium material is used as a beam window material and target material.
- The following parameters are used for developing the target configurations:

– Inlet water temperature	20	°C
– Outlet water temperature	<25	°C
– Inlet water pressure	4	atm
– Target water velocity	7	m/s
– Maximum target surface temperature	100	°C
– Minimum water coolant channel thickness	1.75	mm

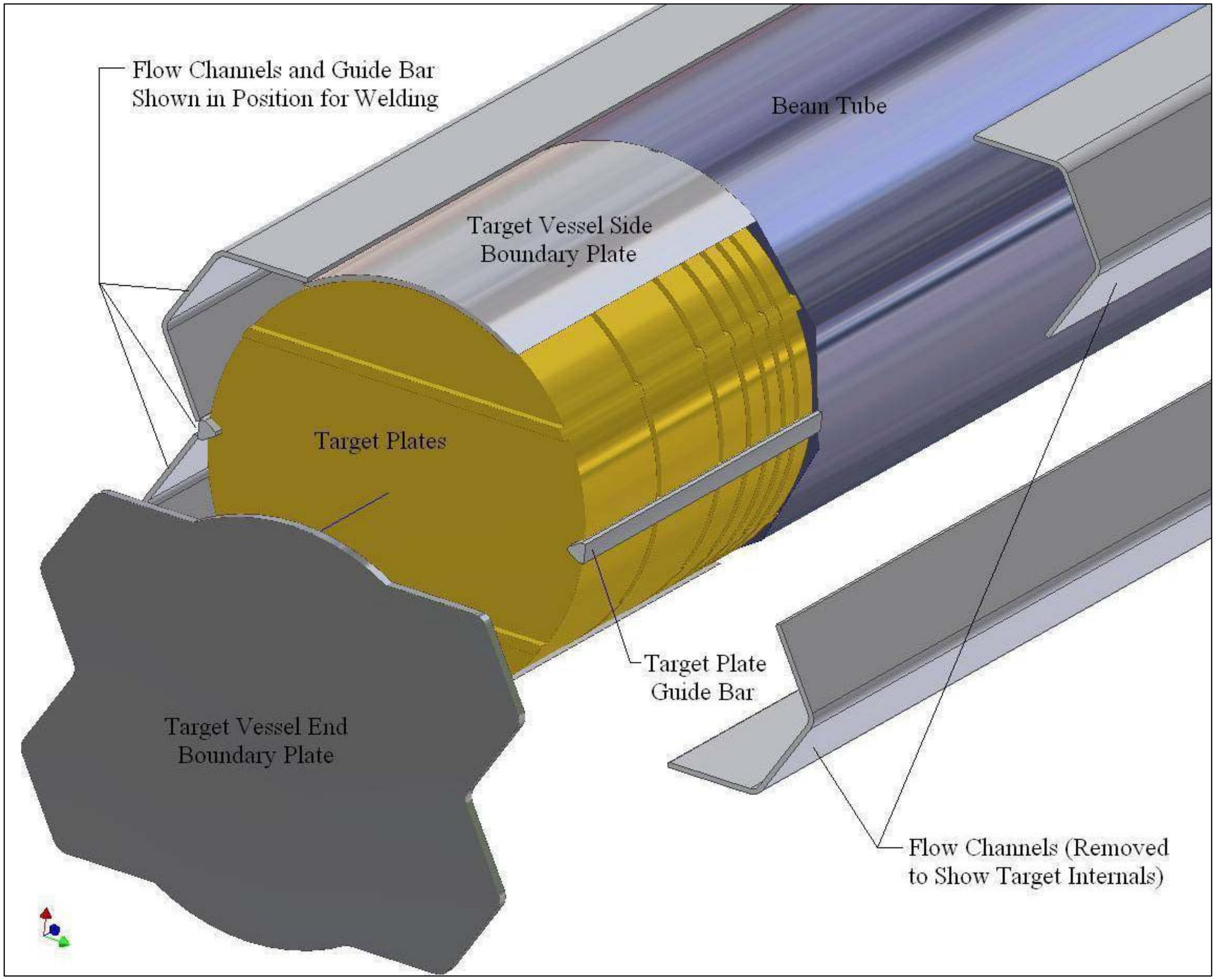
Beryllium Target Configuration Based on Physics, Thermal, Hydraulics, and Stress Analyses



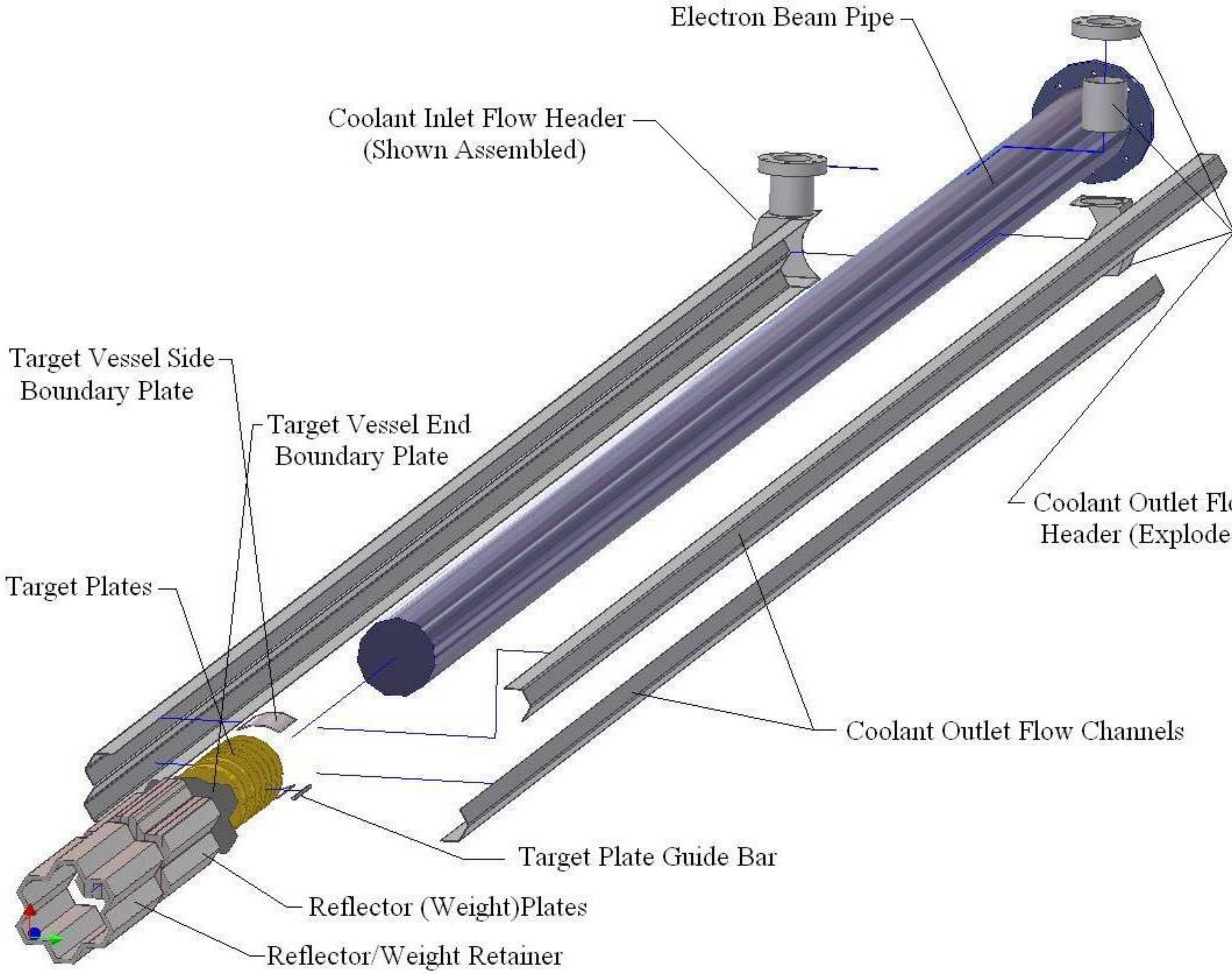
Expanded View of the Beryllium Target Conceptual Design



Expanded View of the Tungsten Target Conceptual Design



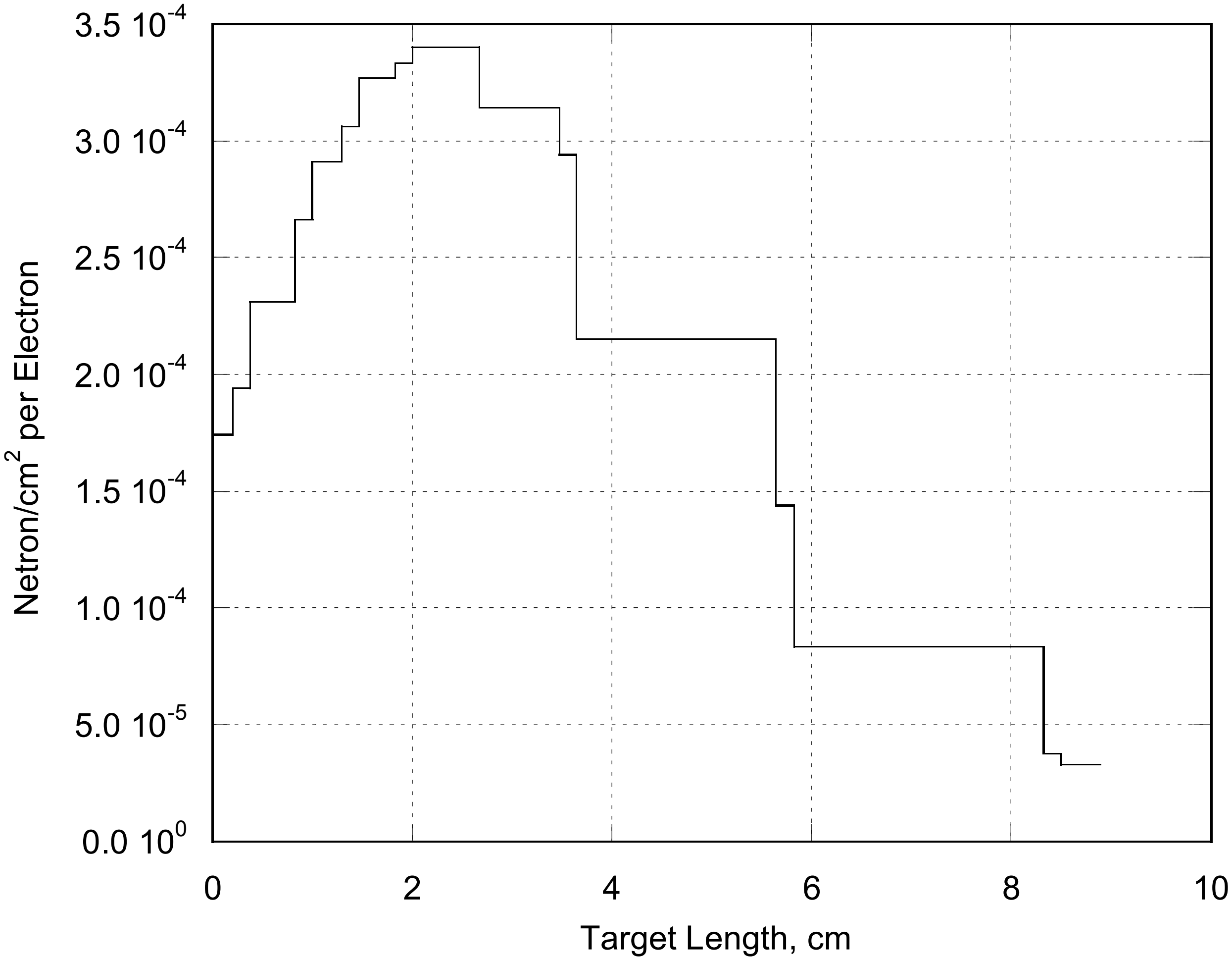
Expanded View of the Tungsten Target Assembly Conceptual Design



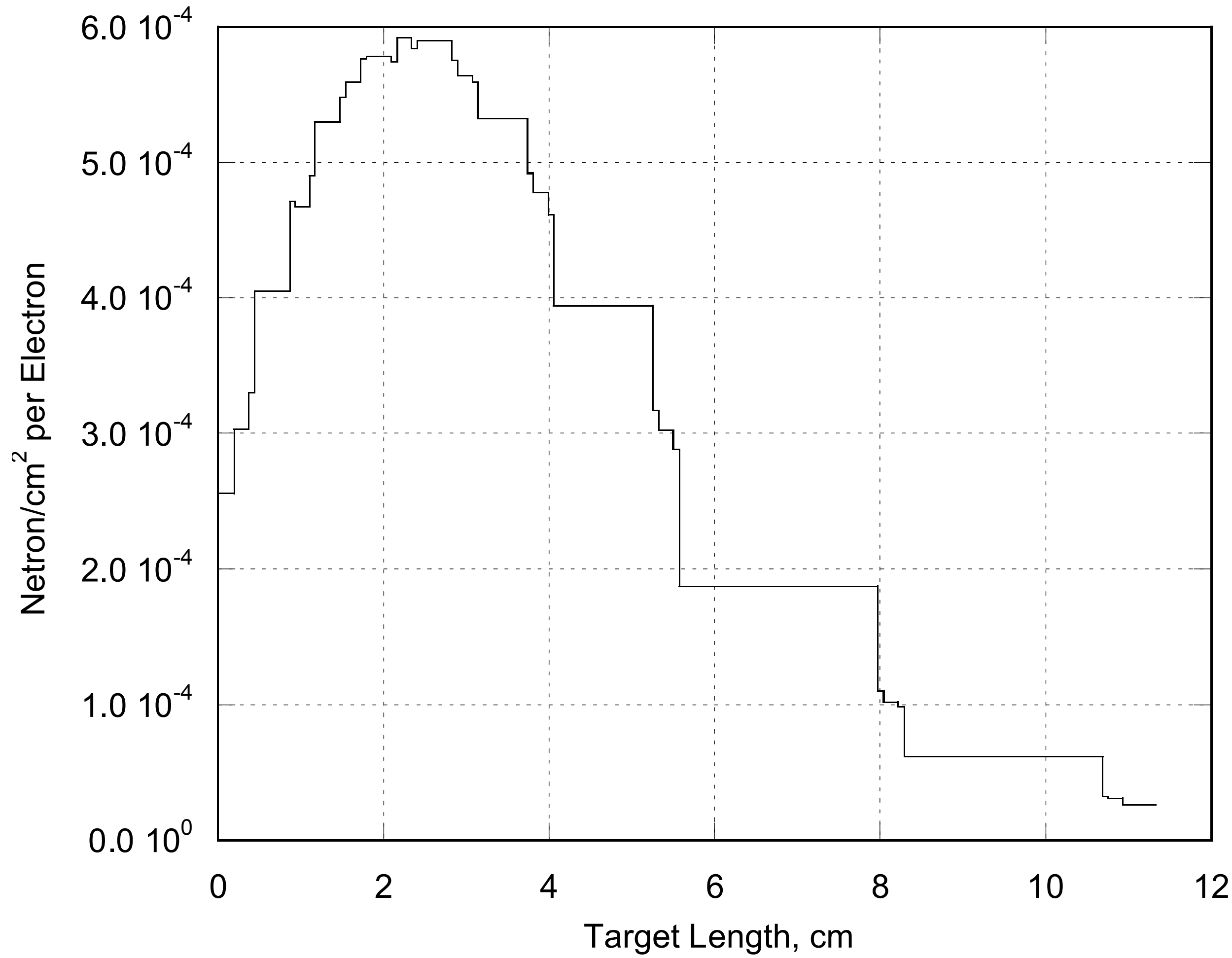
Neutron Leakage Percentage through Each Target Surface of the Target Conceptual Design

Target	W	U
Side	72.24	76.35
Bottom	4.22	2.47
Top	23.54	21.18

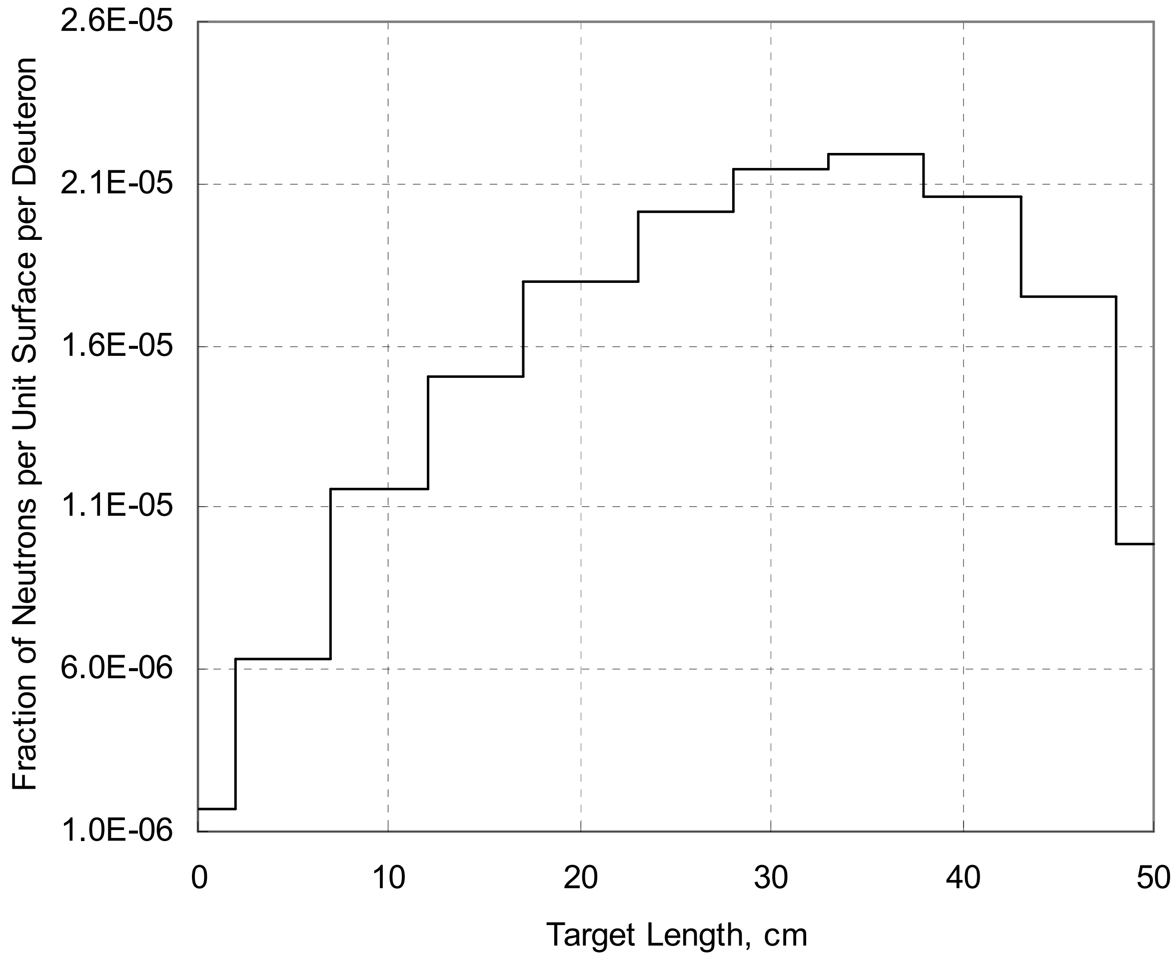
Neutron Source Distribution along the Side Surface of the Tungsten Target Conceptual Design



Neutron Source Distribution along the Side Surface of the Uranium Target Conceptual Design



Neutron Source Distribution along the Side Surface of the Beryllium Target Conceptual Design



Performance Comparison of the Different Target Designs

Target Concept	Beam Power, KW	Particle Energy, MeV	Beam Current, mA	Neutron Source Strength, n/s
Uranium with Electrons	100	200	0.5	3.273×10^{14}
Tungsten with Electrons	100	200	0.5	1.865×10^{14}
Beryllium with Deuterons	100 100 11.5	100 23 23	1.0 4.35 0.5	1.896×10^{15} 4.030×10^{14} 4.634×10^{13}

The selection process of the beam type needs to consider the following issues:

- Deuteron accelerators are expensive and difficult to operate in steady state mode relative to electron accelerators.
- A 100-KW beam power is much easier to obtain with electrons than deuterons.
- Target designs with disks are operating successfully around the world. The target cone design concept is new and needs development and testing to insure successful operation.

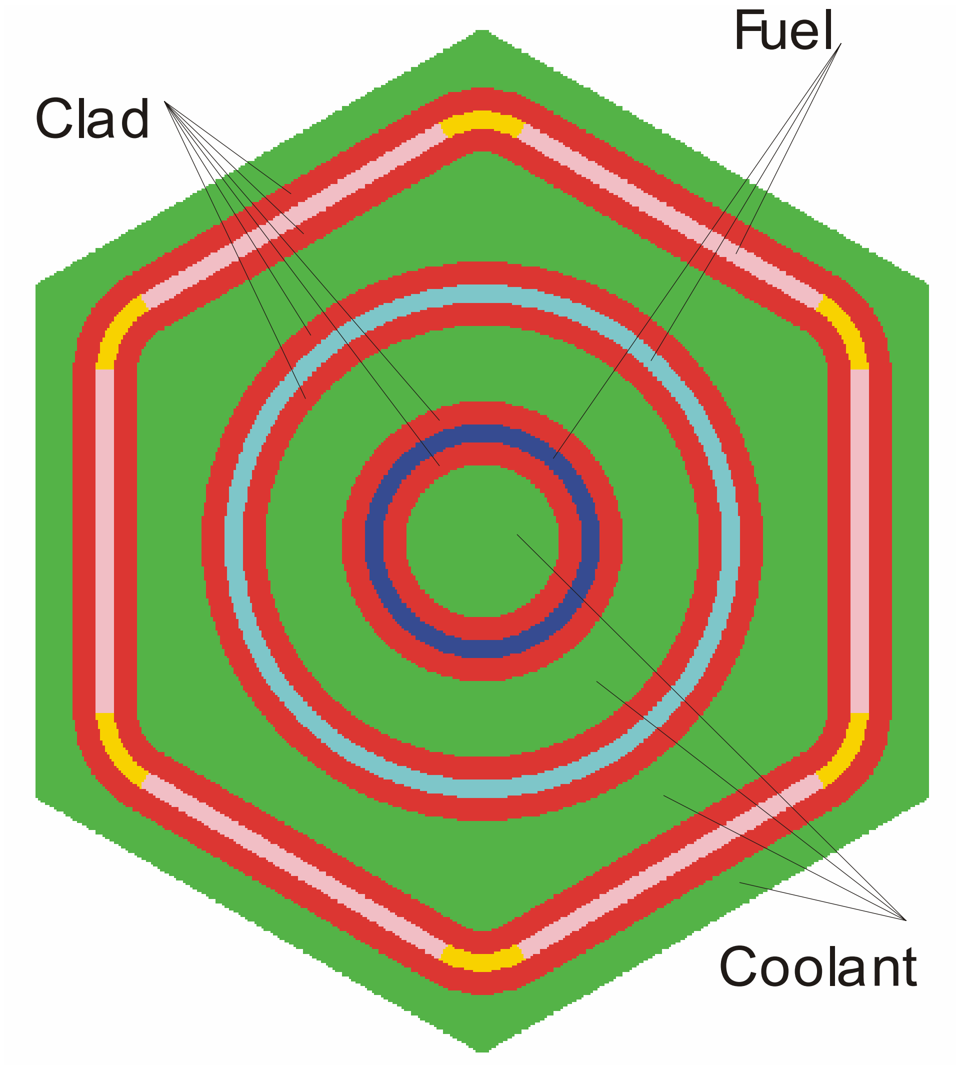
Sub-critical assembly Analyses

- The neutron flux and the total power were maximized.
- Neutron flux and power deposition distributions were analyzed.
- The total fuel requirements were defined for different target designs and reflector materials.
- The axial target location was examined to define the impact on the sub-critical assembly performance.

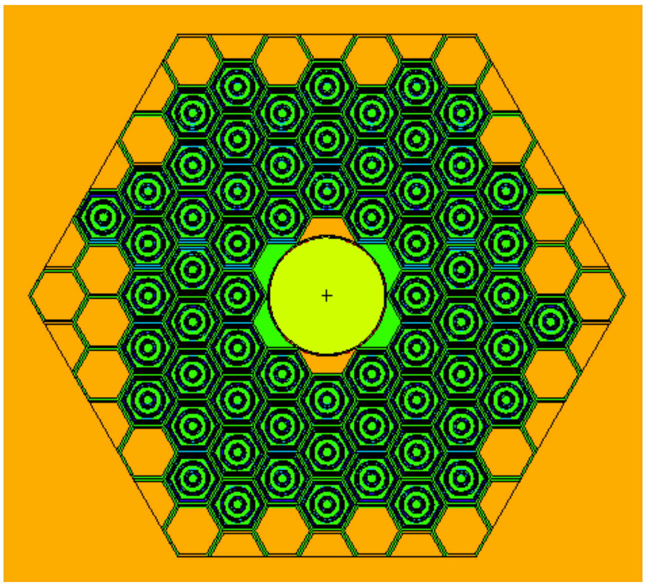
Performance and characteristics of LEU and HEU Sub-critical assemblies

- **Main Parameters:**
  - Fuel design is WWR-M2 type with LEU or HEU oxide in Aluminum matrix and clad.
  - Uranium density is 1 or 3 g/cm^3.
  - Fuel length is 50 cm.
  - Water is the coolant for the target, sub-critical assembly, and reflector.
  - Target assembly is located along the assembly vertical axis.
- **Configurations with different number of fuel assemblies were analyzed using different combinations of target designs (Tungsten, uranium, and beryllium) and reflector materials (beryllium and water).**
- **MCNPX computer code is used with continuous energy data libraries and S(α,β) data.**
- **The sub-critical analyses investigated the system multiplications factor, flux and energy distributions, and average flux in the irradiation channels.**

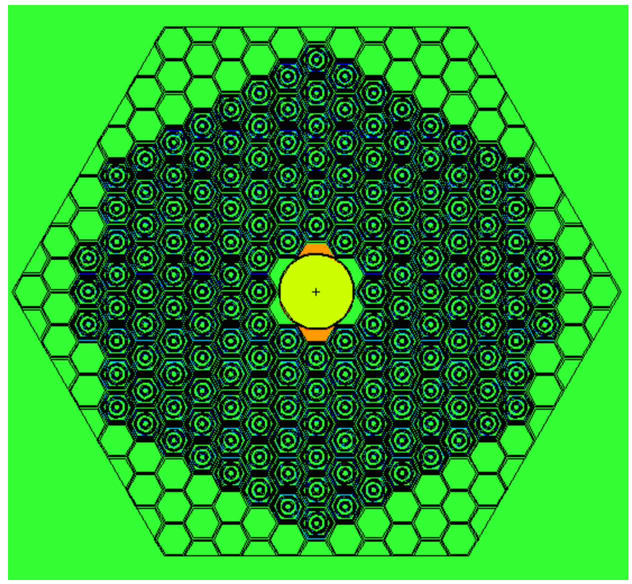
WWR-M2 Fuel Assembly Cross Section



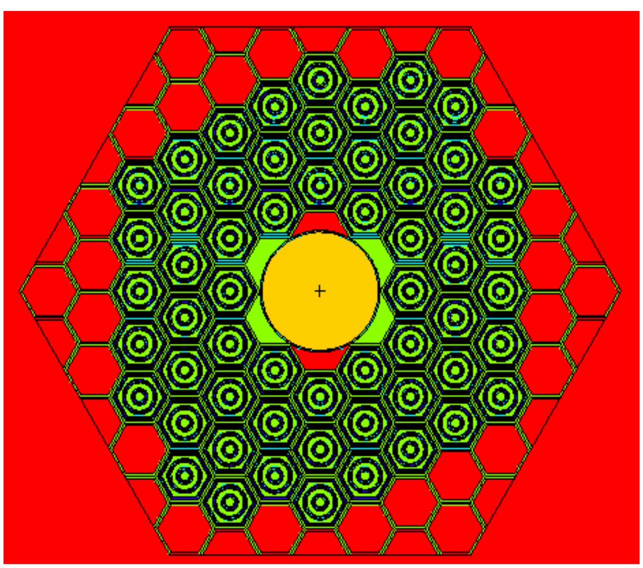
Obtained LEU Sub-critical Configurations with 1-g/cm^3 Uranium Density for Neutron Multiplication of ~0.98



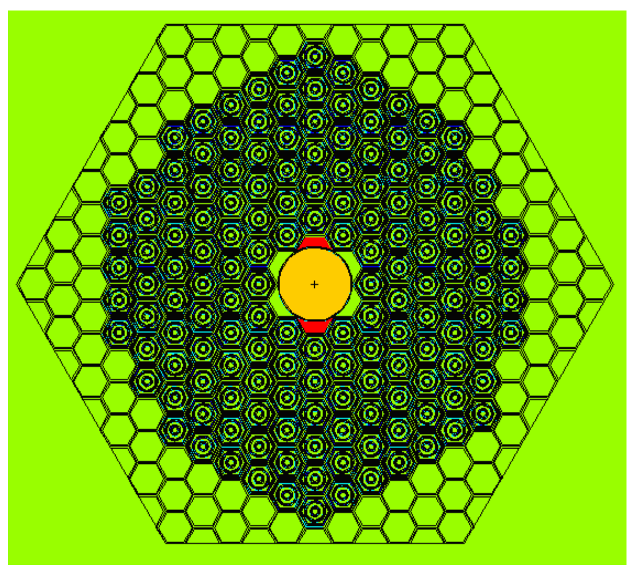
60 Fuel Assemblies for Tungsten Target and Beryllium Reflector



168 Fuel Assemblies for Tungsten Target and water Reflector

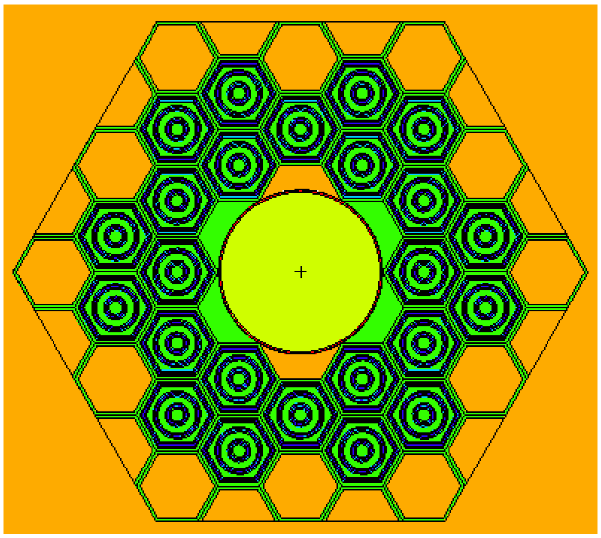


58 Fuel Assemblies for Uranium Target and Beryllium Reflector

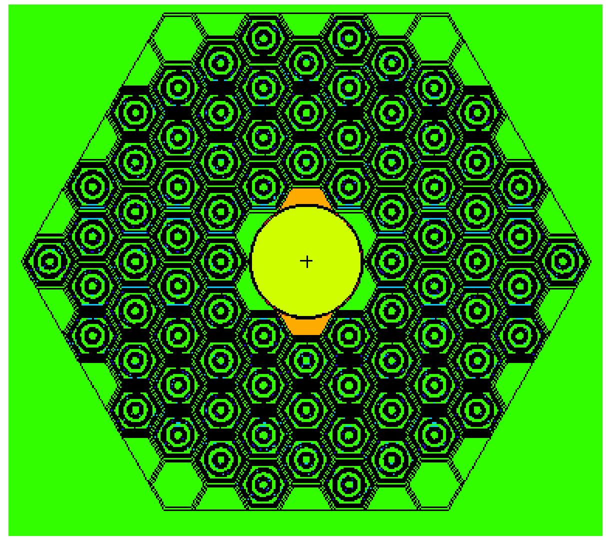


152 Fuel Assemblies for Uranium Target and water Reflector

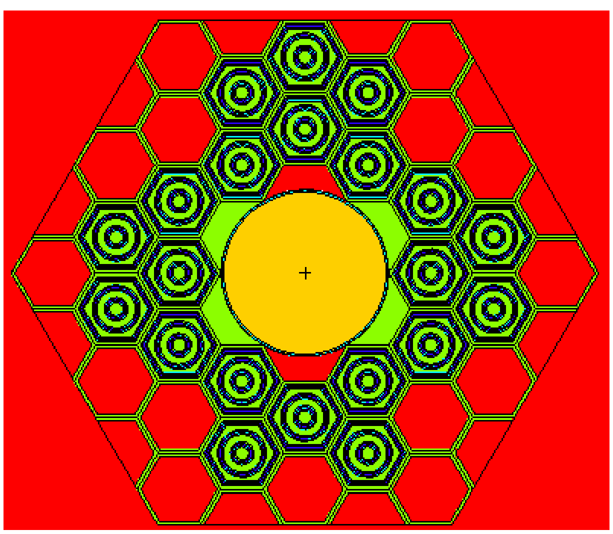
Obtained LEU Sub-critical Configurations with 3-g/cm^3 Uranium Density for Neutron Multiplication of ~0.98



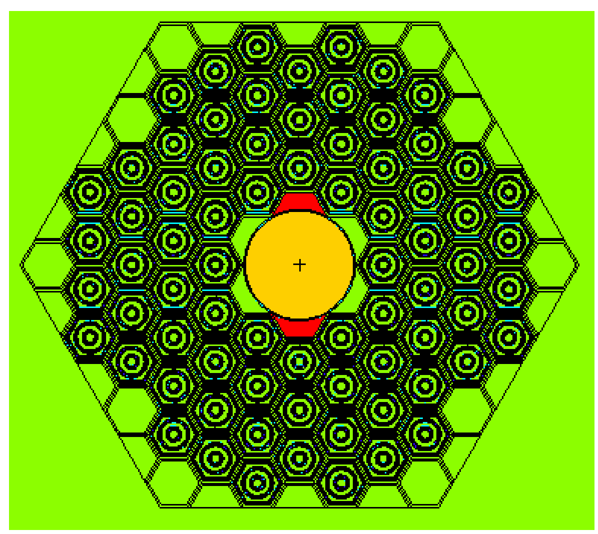
24 Fuel Assemblies for Tungsten Target and Beryllium Reflector



80 Fuel Assemblies for Tungsten Target and Water Reflector

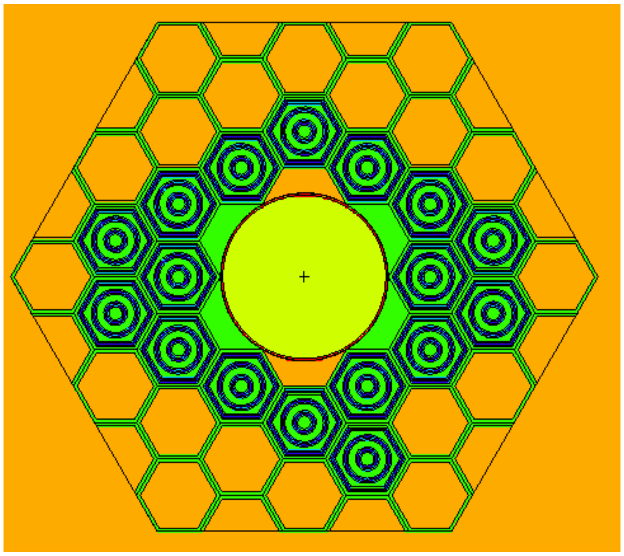


21 Fuel Assemblies for Uranium Target and Beryllium Reflector

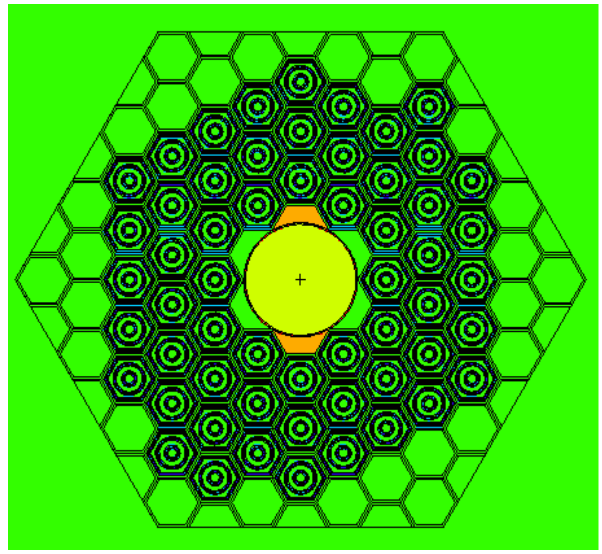


74 Fuel Assemblies for Uranium Target and Water Reflector

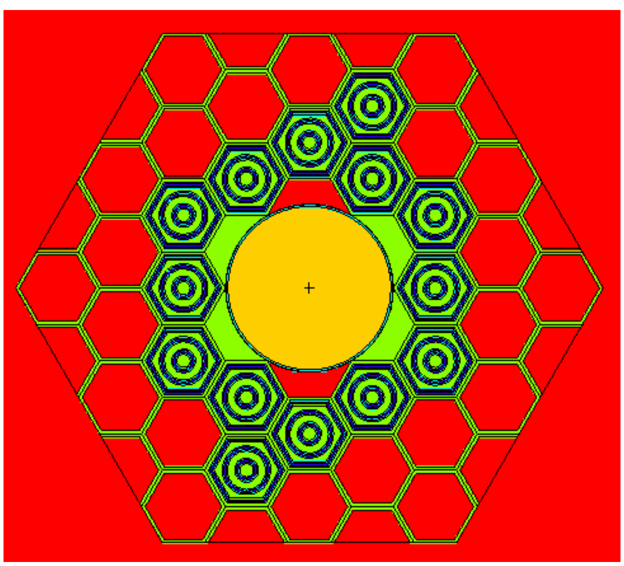
Obtained HEU Sub-critical Configurations with 1-g/cm^3 Uranium Density for Neutron Multiplication of ~0.98



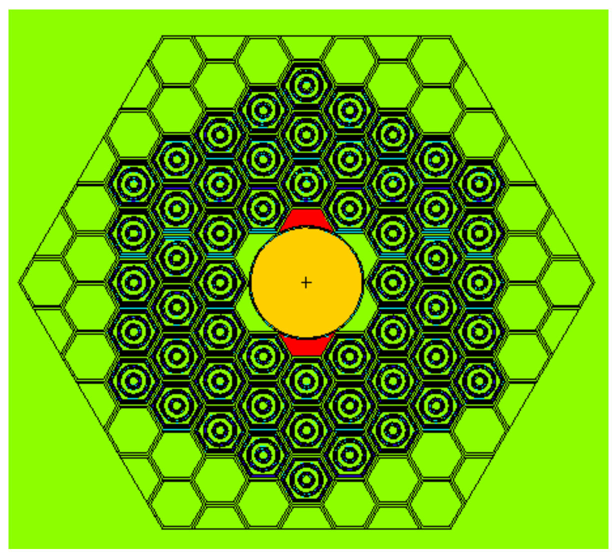
17 Fuel Assemblies for Tungsten Target and Beryllium Reflector



57 Fuel Assemblies for Tungsten Target and Water Reflector

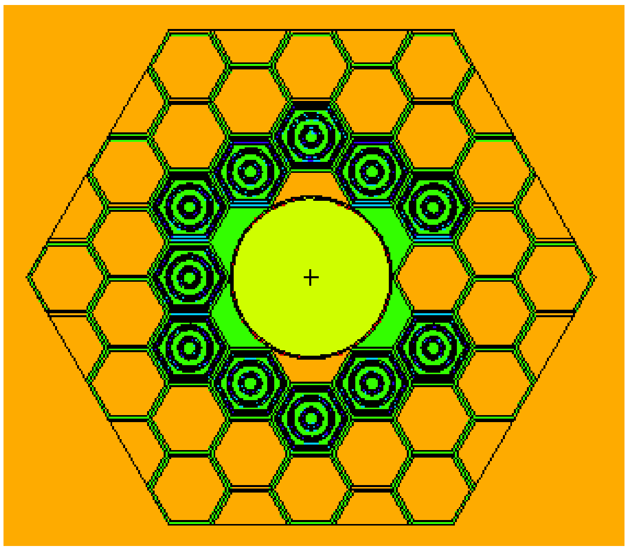


14 Fuel Assemblies for Uranium Target and Beryllium Reflector

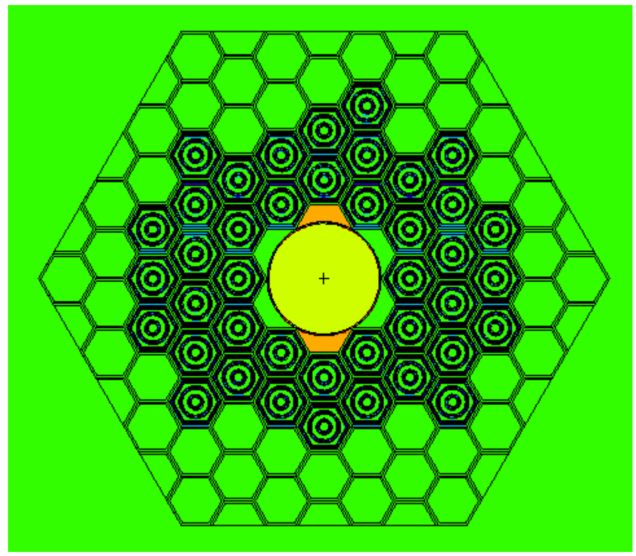


54 Fuel Assemblies for Uranium Target and Beryllium Reflector

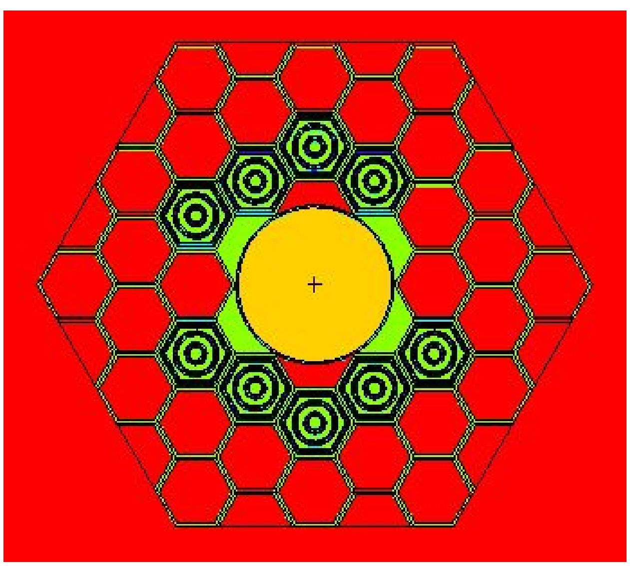
Obtained HEU Sub-critical Configurations with 3-g/cm^3 Uranium Density for Neutron Multiplication of ~0.98



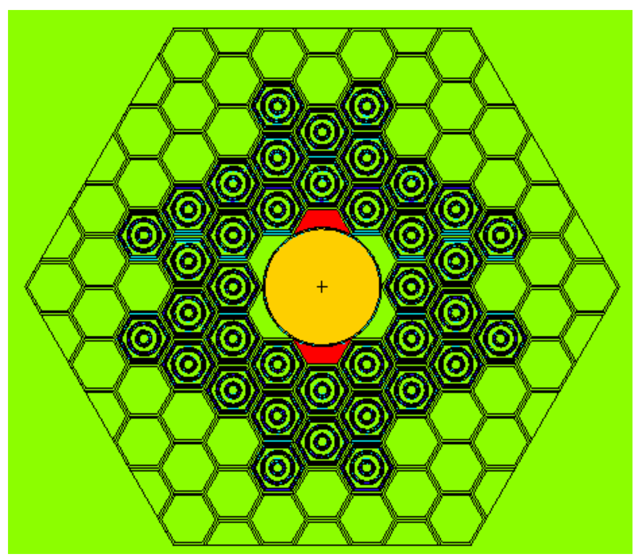
11 Fuel Assemblies for Tungsten Target and Beryllium Reflector



41 Fuel Assemblies Tungsten Target and Water Reflector



9 Fuel Assemblies for Uranium Target and Beryllium Reflector



38 Fuel Assemblies for Uranium Target and Water Reflector

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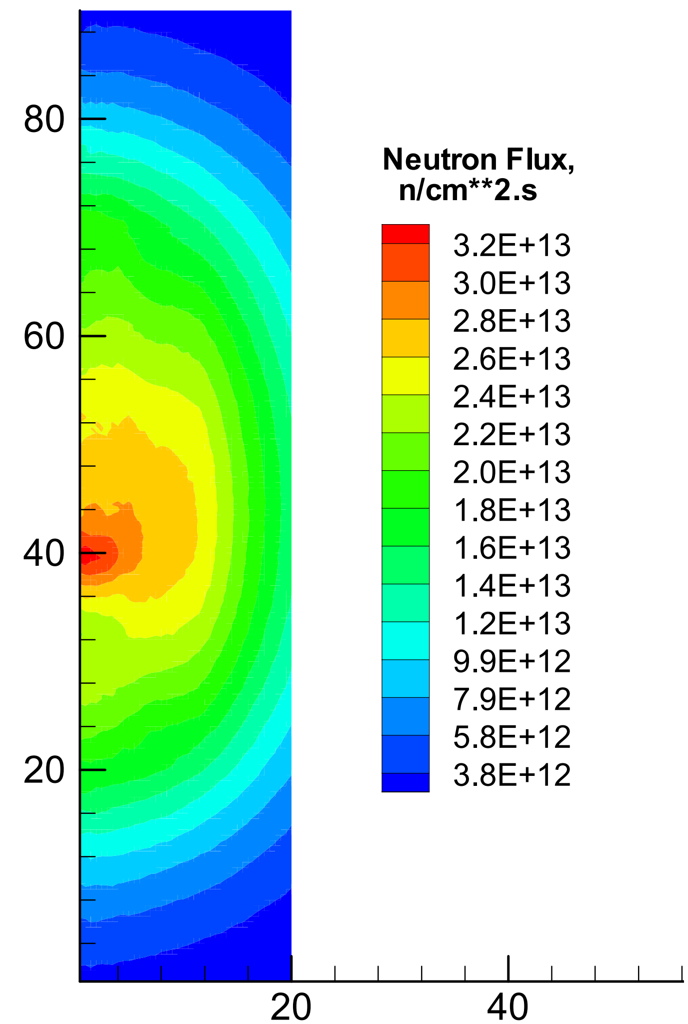
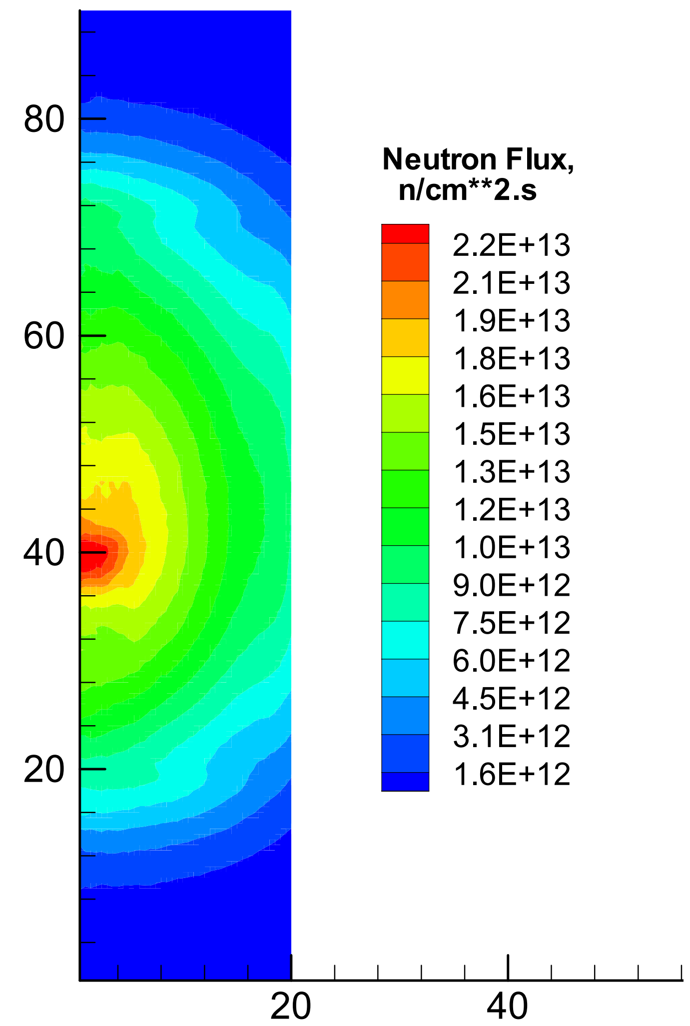
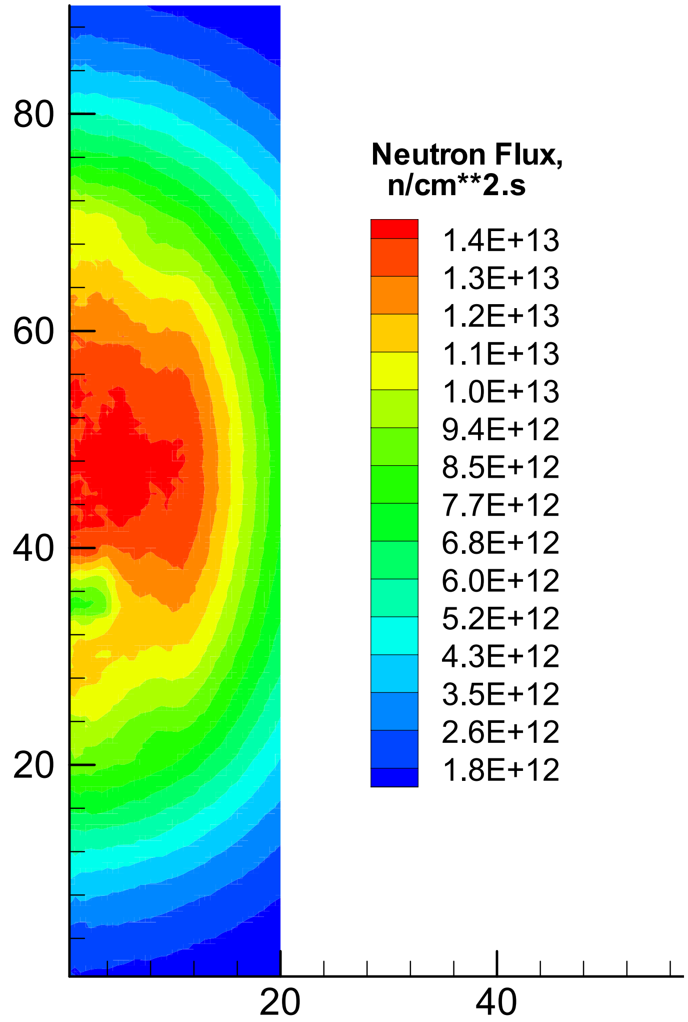
Axial Neutron Flux Distribution of the Sub-critical Assembly with Uranium Target, LEU Fuel (3-g/cm^3 Uranium Density), 21 Fuel assemblies, and Beryllium Reflector



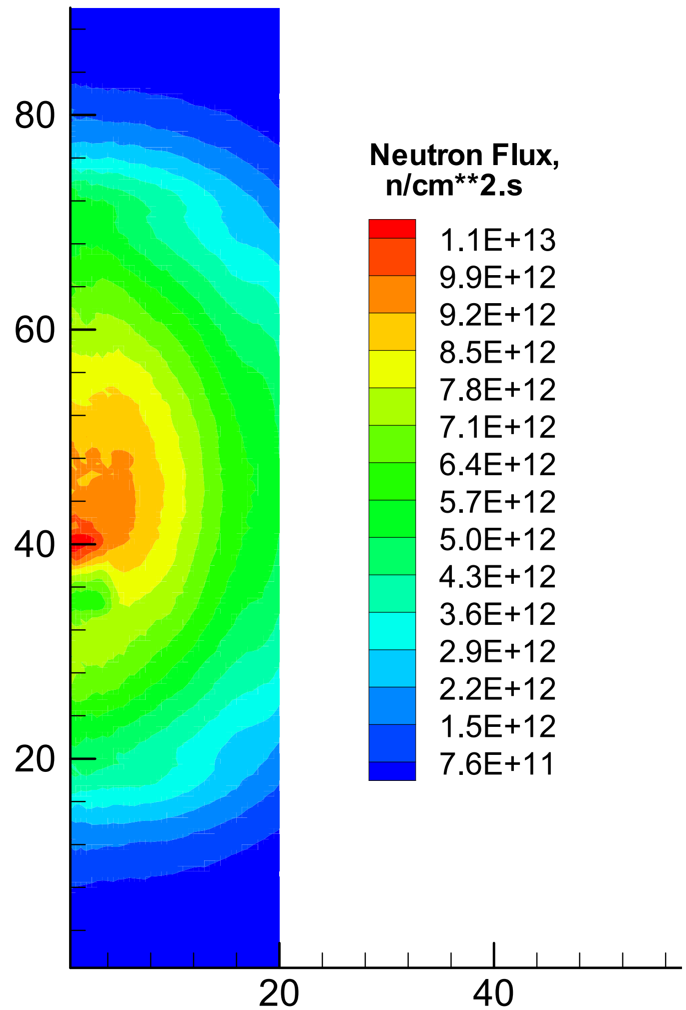
Axial Neutron Flux Distribution of the Sub-critical Assembly with Uranium Target, LEU Fuel (3-g/cm^3 Uranium Density), 74 Fuel assemblies, and Water Reflector



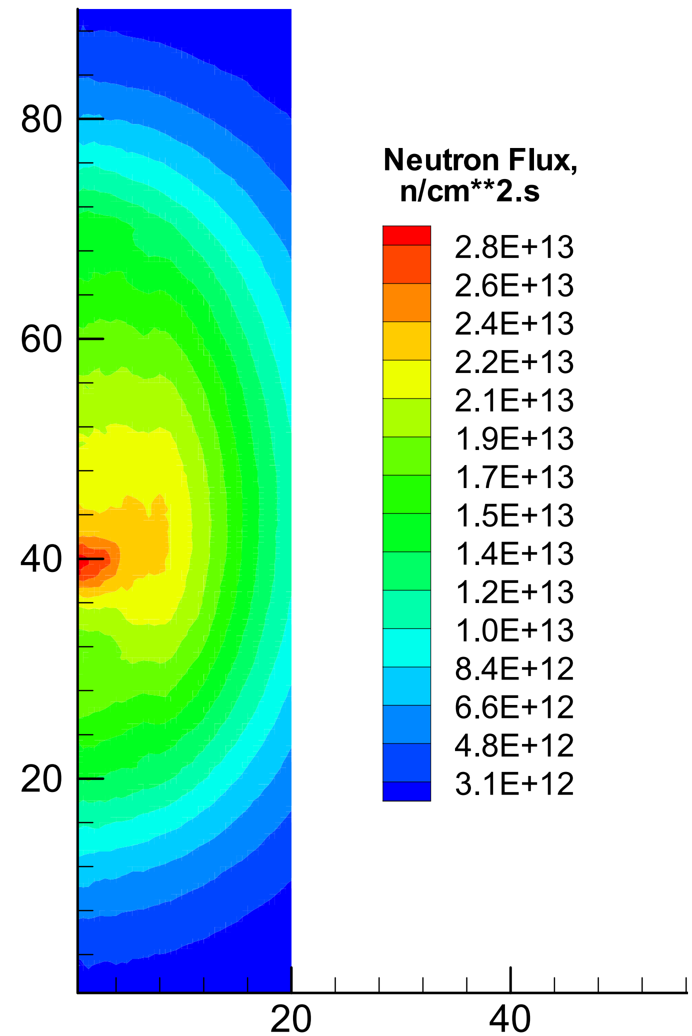
Axial Neutron Flux Distribution of the Sub-critical Assembly with Tungsten Target, LEU Fuel (3-g/cm^3 Uranium Density), 24 Fuel assemblies, and Beryllium Reflector



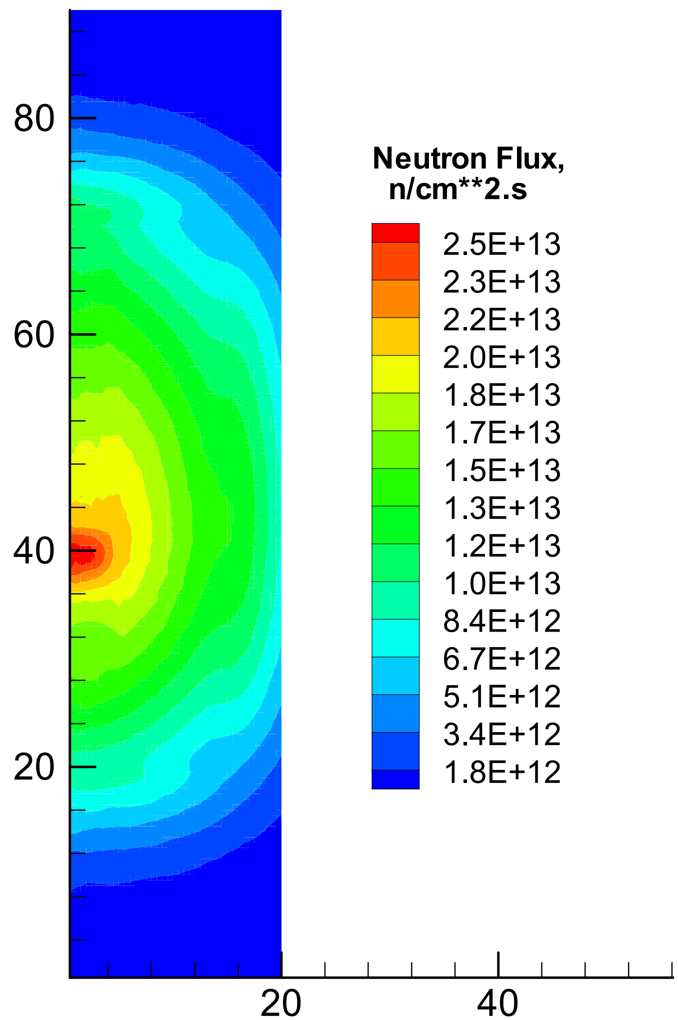
Axial Neutron Flux Distribution of the Sub-critical Assembly with Tungsten Target, LEU Fuel (3-g/cm^3 Uranium Density), 80 Fuel assemblies, and Water Reflector



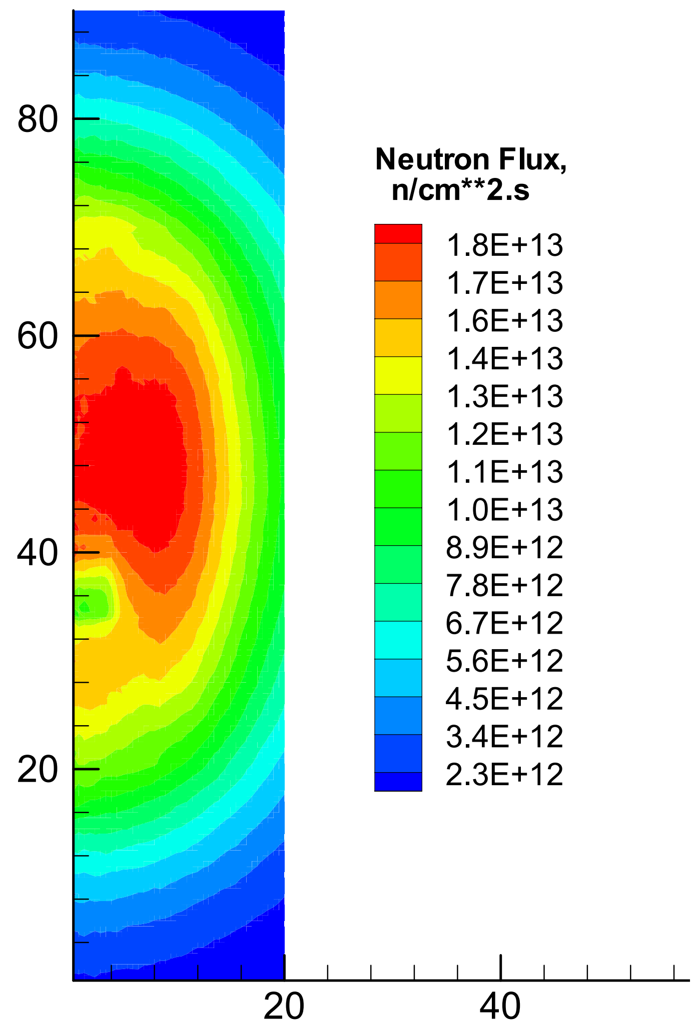
Axial Neutron Flux Distribution of the Sub-critical Assembly with Uranium Target, HEU Fuel (1-g/cm^3 Uranium Density), 14 Fuel assemblies, and Beryllium Reflector



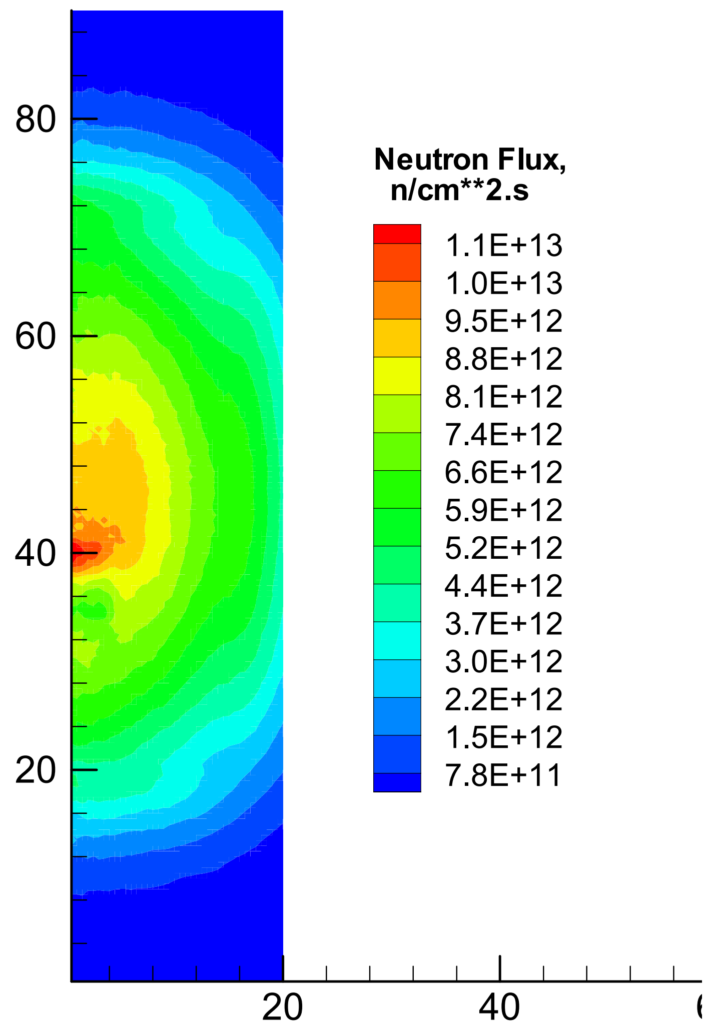
Axial Neutron Flux Distribution of the Sub-critical Assembly with Uranium Target, HEU Fuel (1-g/cm^3 Uranium Density), 54 Fuel assemblies, and Water Reflector



Axial Neutron Flux Distribution of the Sub-critical Assembly with Tungsten Target, HEU Fuel (1-g/cm^3 Uranium Density), 17 Fuel assemblies, and Beryllium Reflector



Axial Neutron Flux Distribution of the Sub-critical Assembly with Tungsten Target, HEU Fuel (1-g/cm^3 Uranium Density), 57 Fuel assemblies, and Water Reflector



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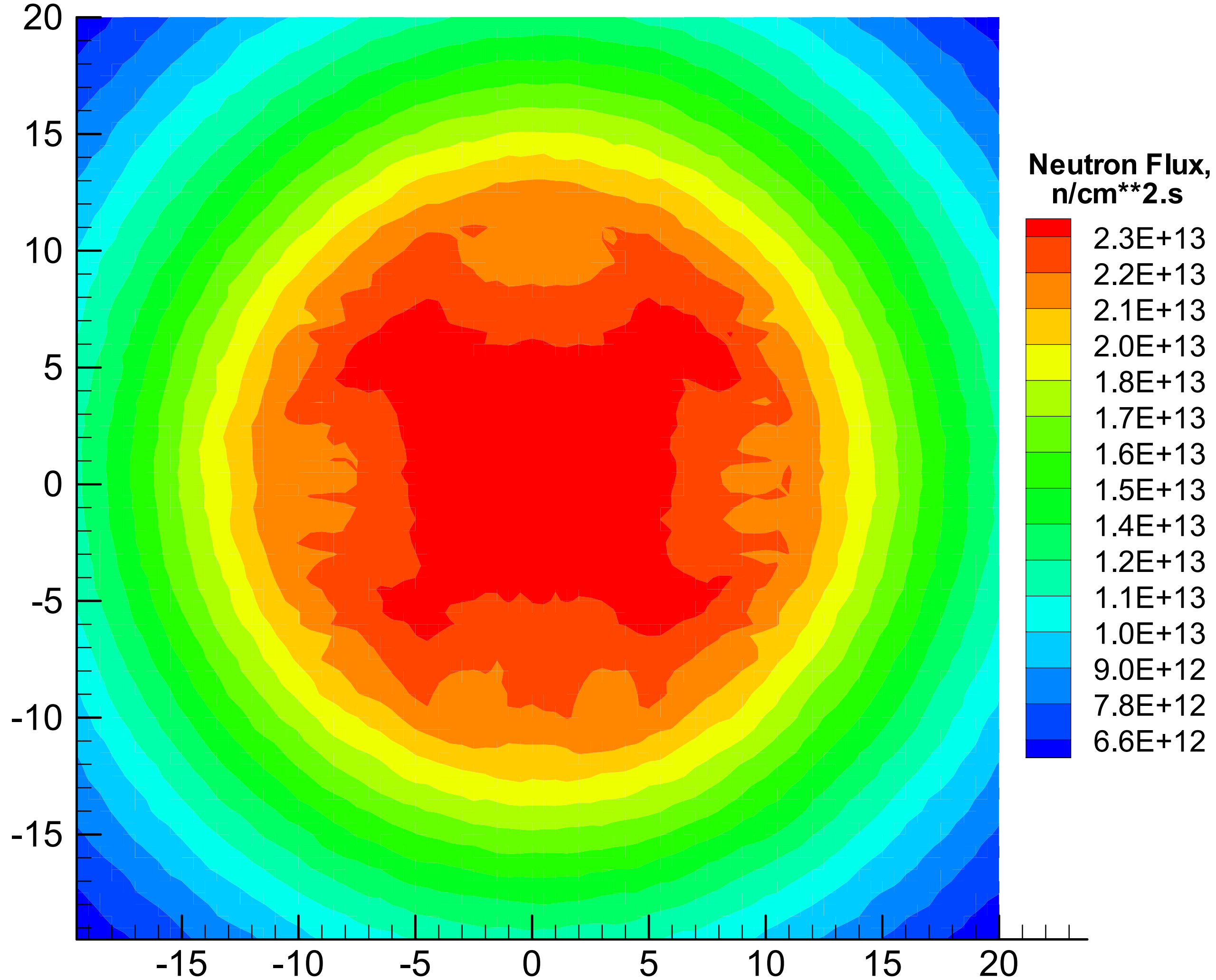

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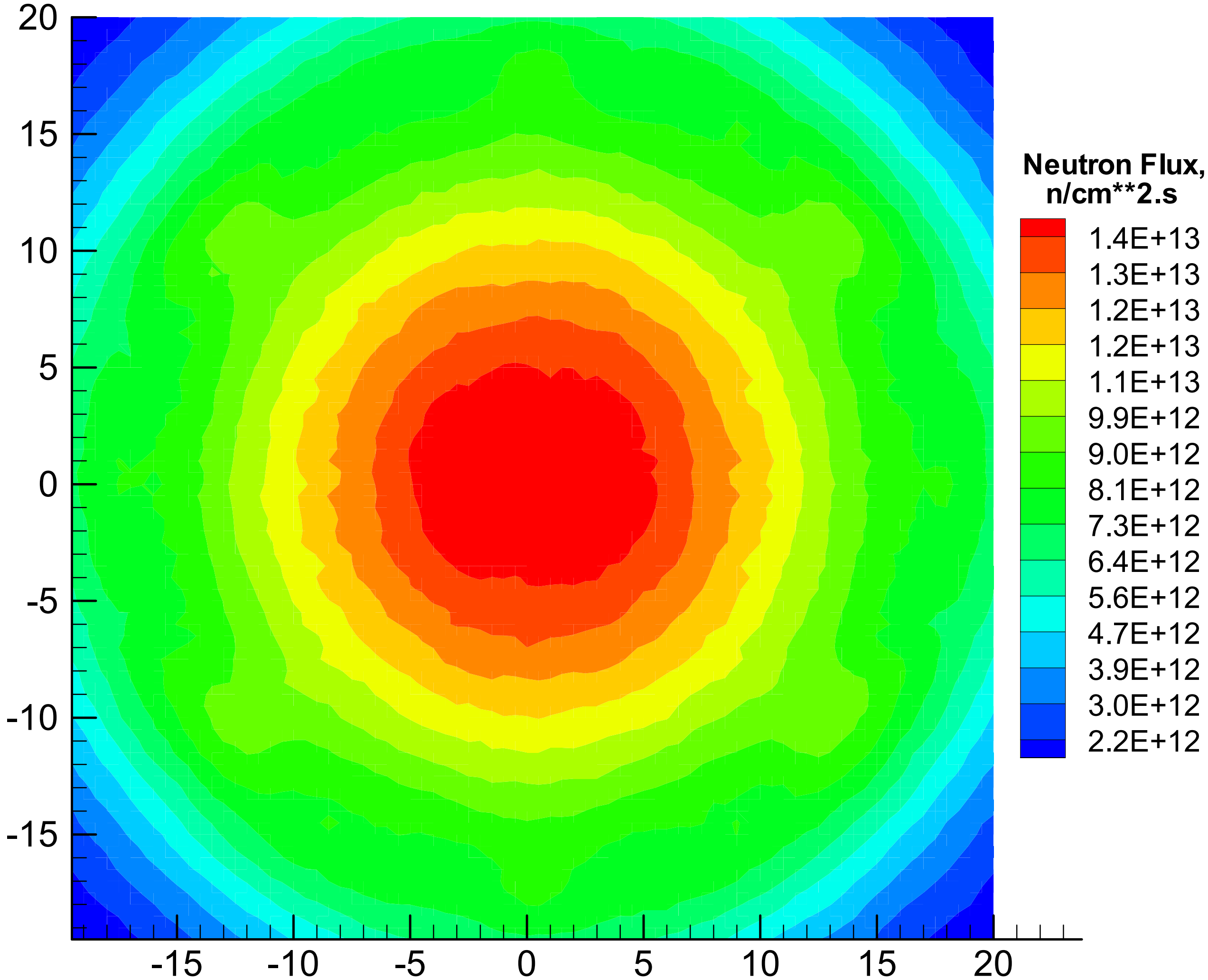
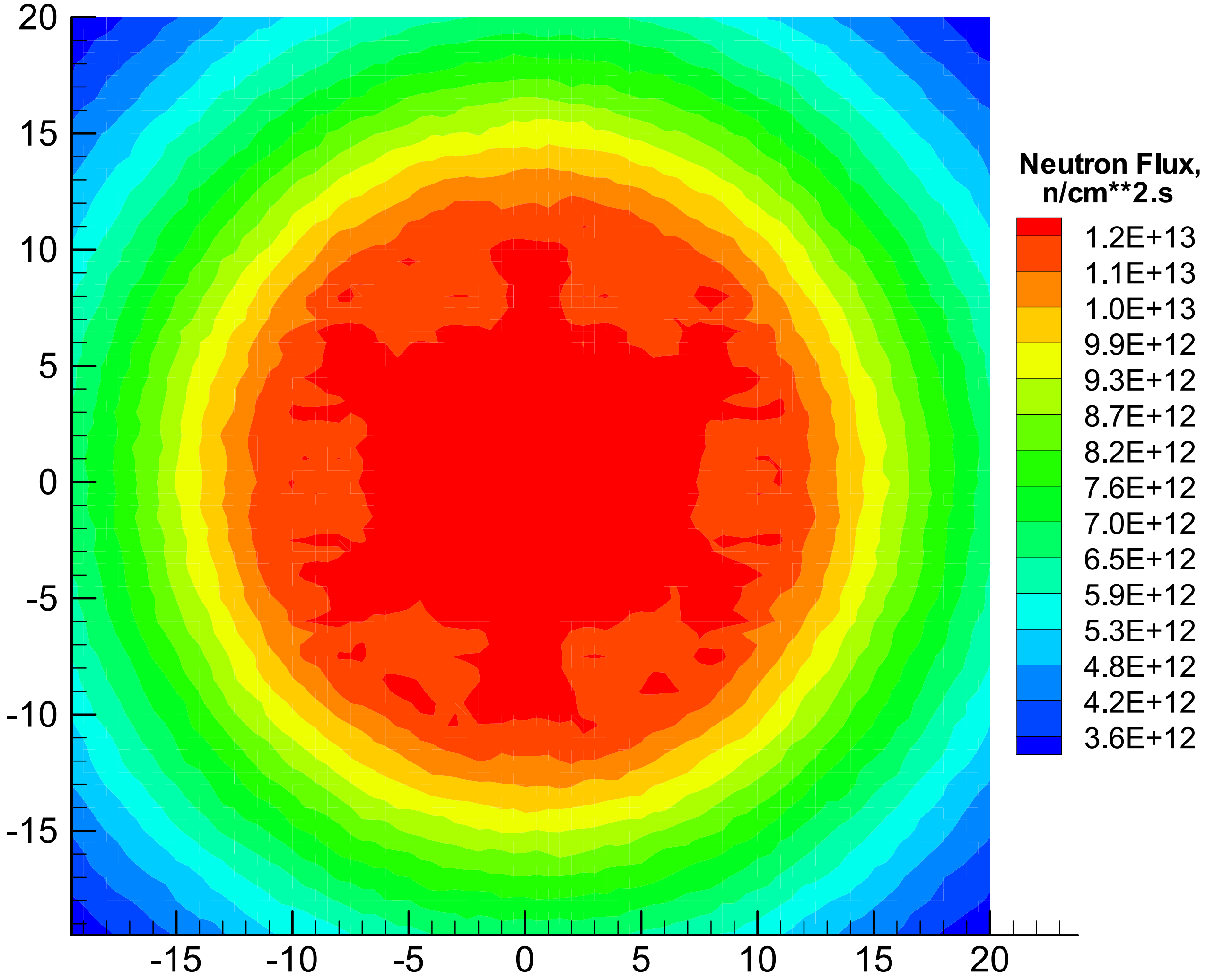


Radial Neutron Flux Distribution of the Sub-critical Assembly with Tungsten Target, LEU Fuel (3-g/cm^3 Uranium Density), 24 Fuel assemblies, and Beryllium Reflector



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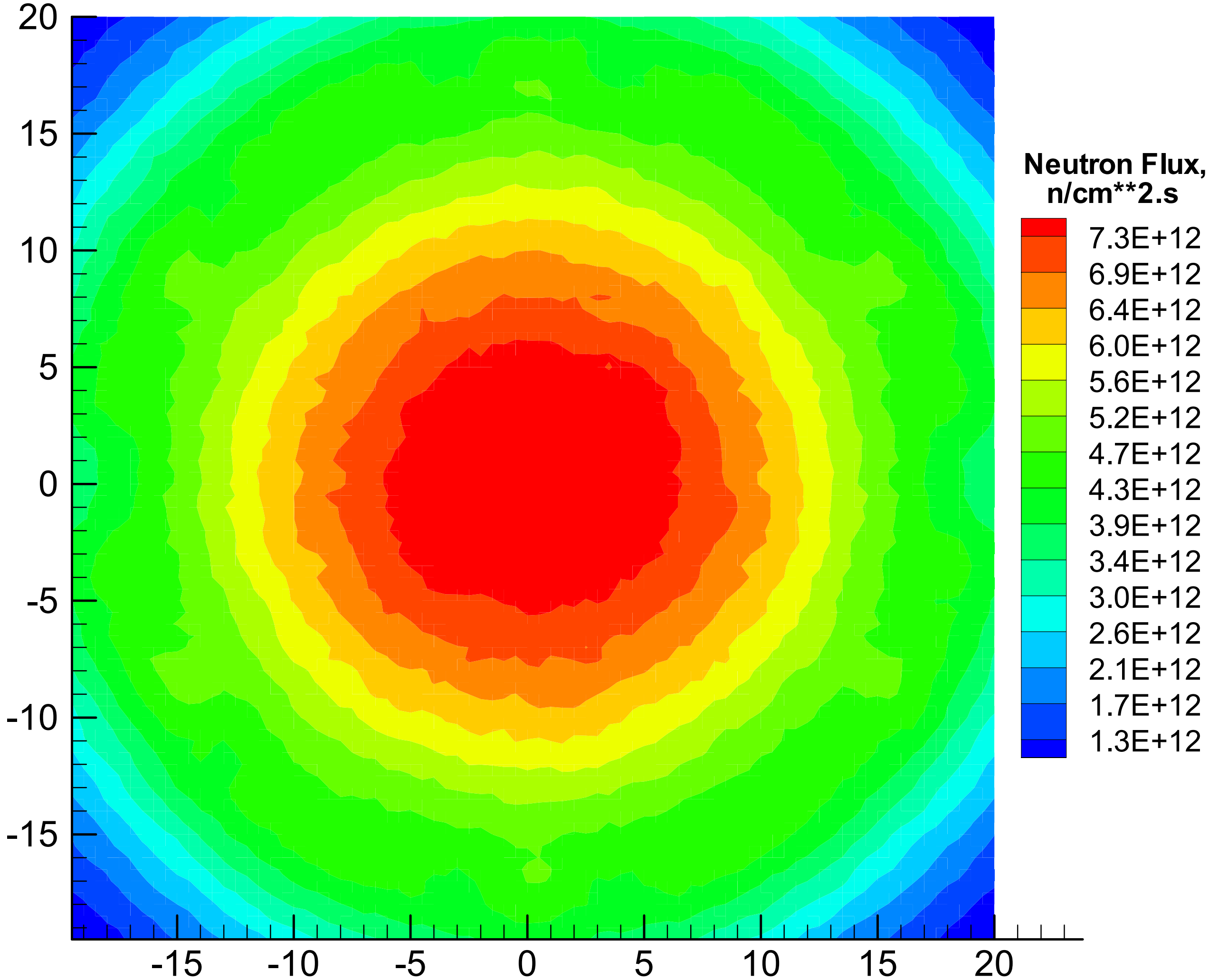

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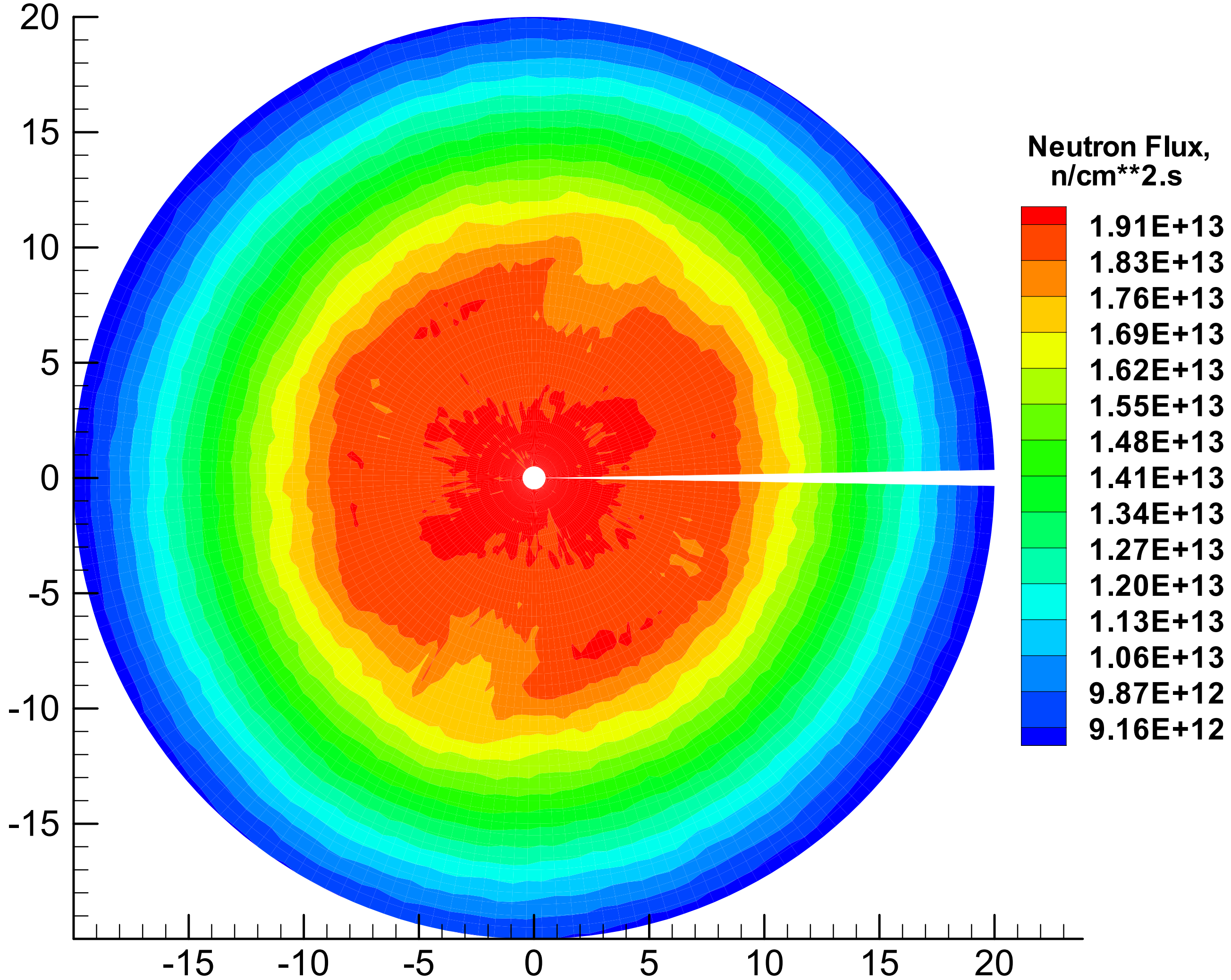

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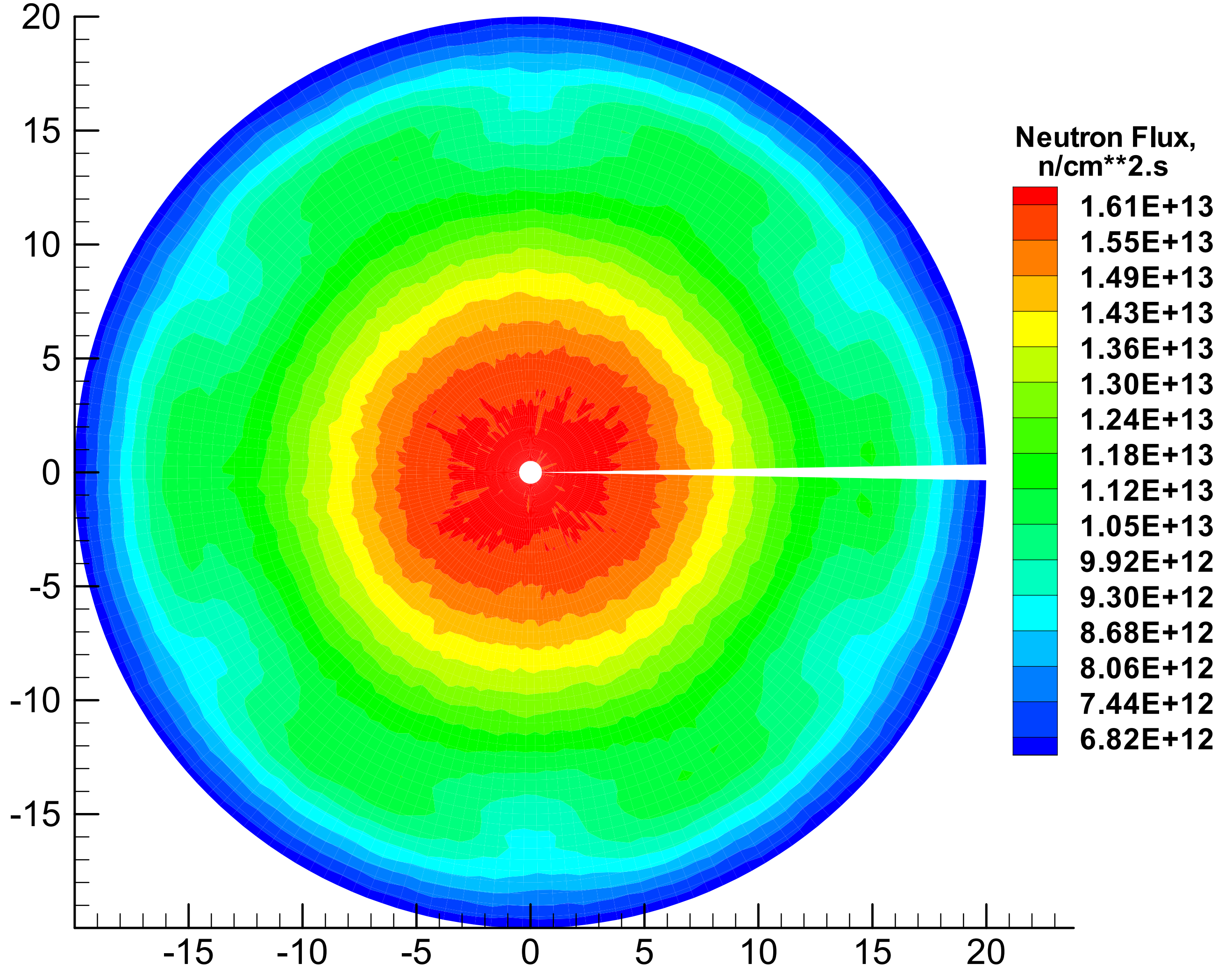
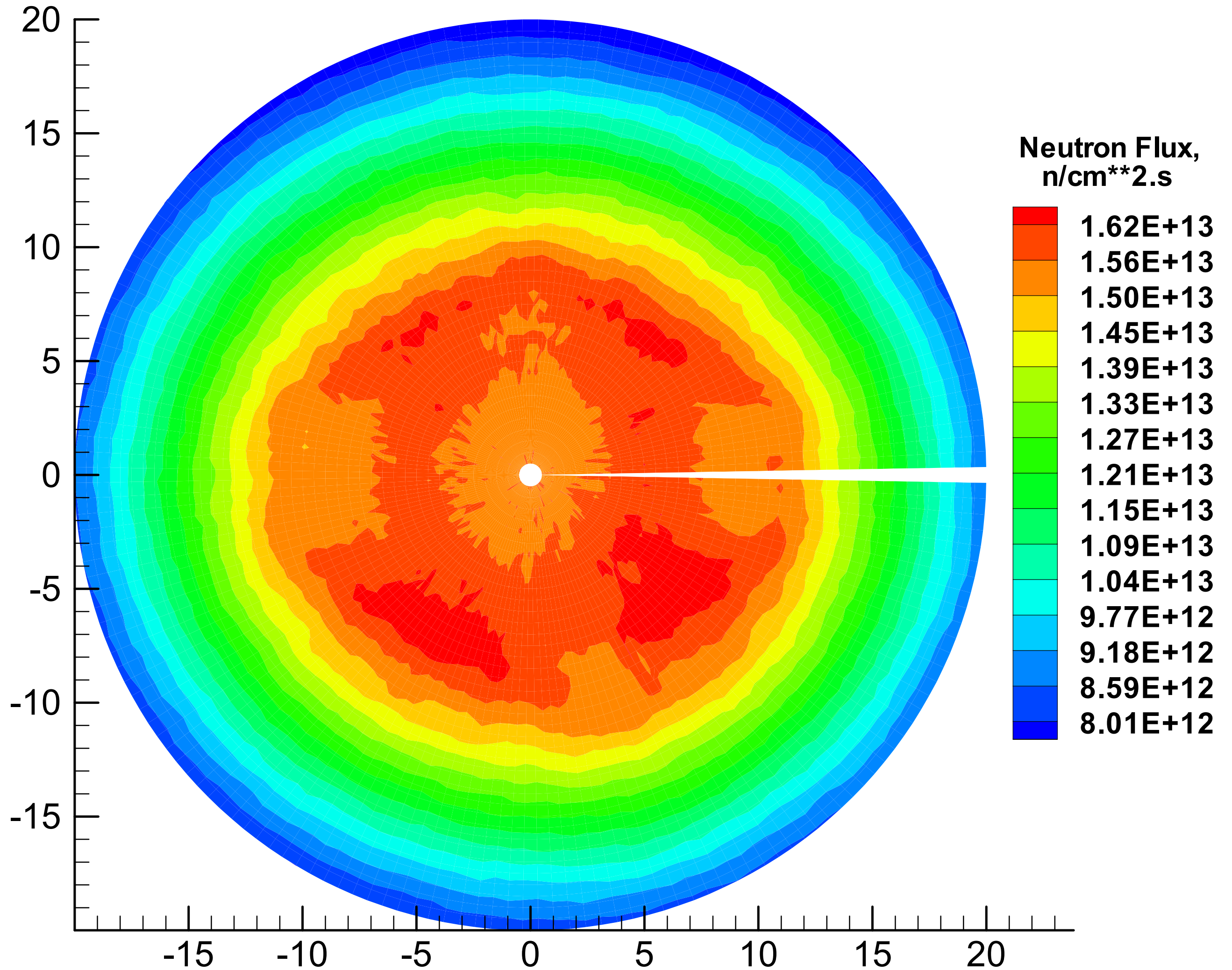


Radial Neutron Flux Distribution of the Sub-critical Assembly with Tungsten Target, HEU Fuel (1-g/cm^3 Uranium Density), 17 Fuel assemblies, and Beryllium Reflector



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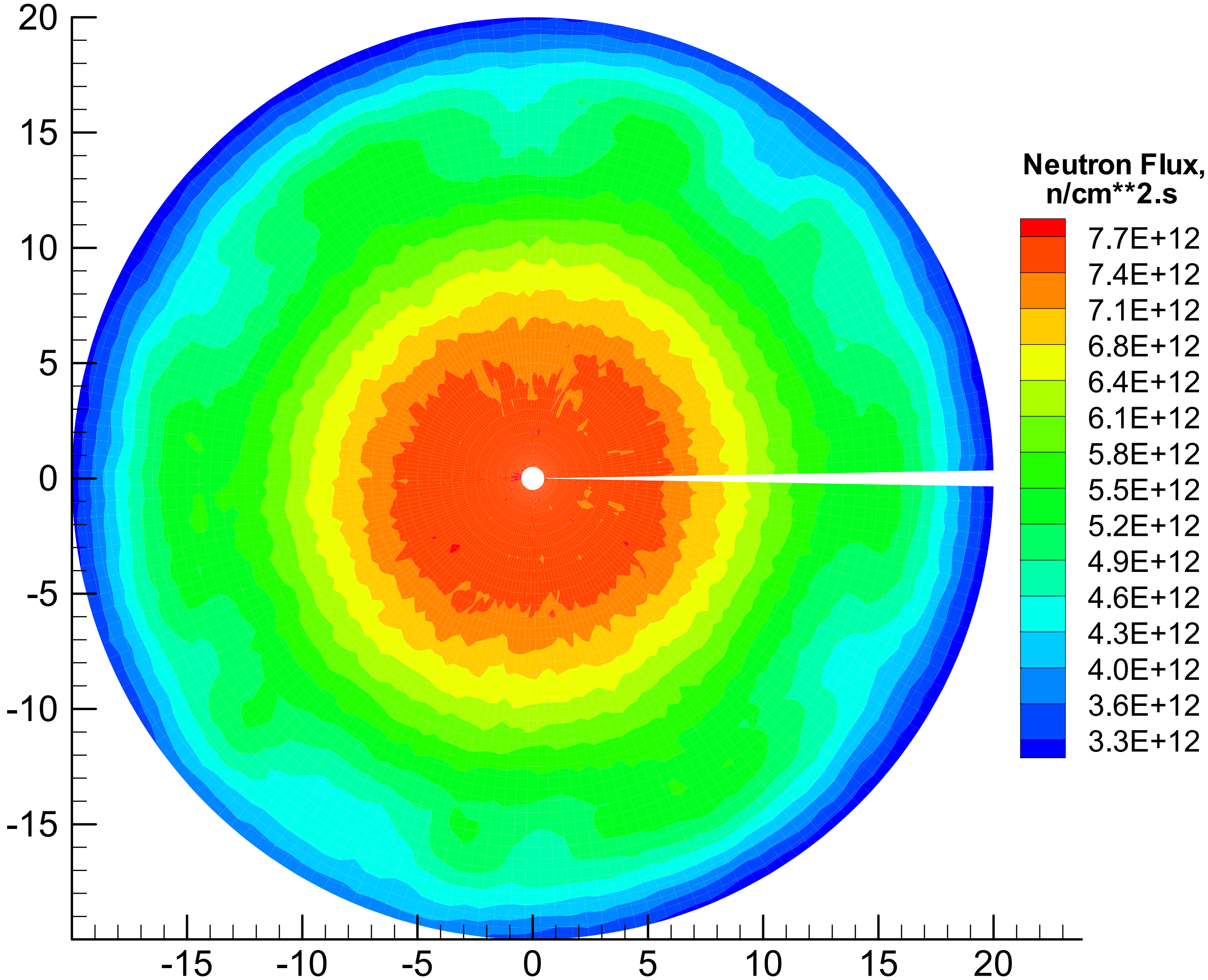
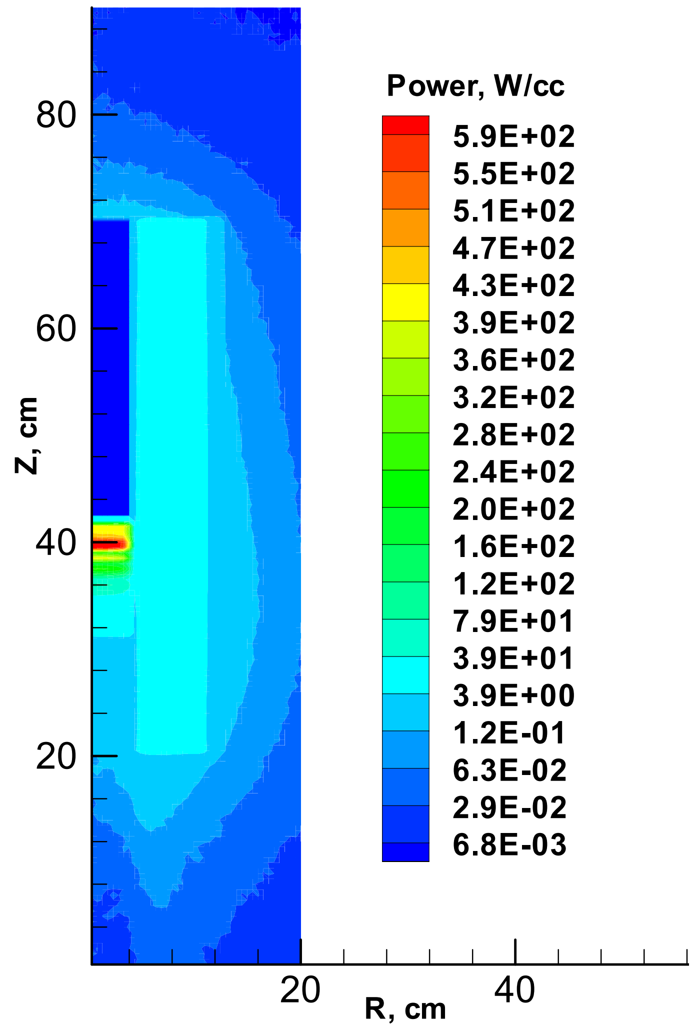


Power Density Distribution of the Sub-critical Assembly with Uranium Target, LEU Fuel (3-g/cm^3 Uranium Density), 21 Fuel assemblies, and Beryllium Reflector



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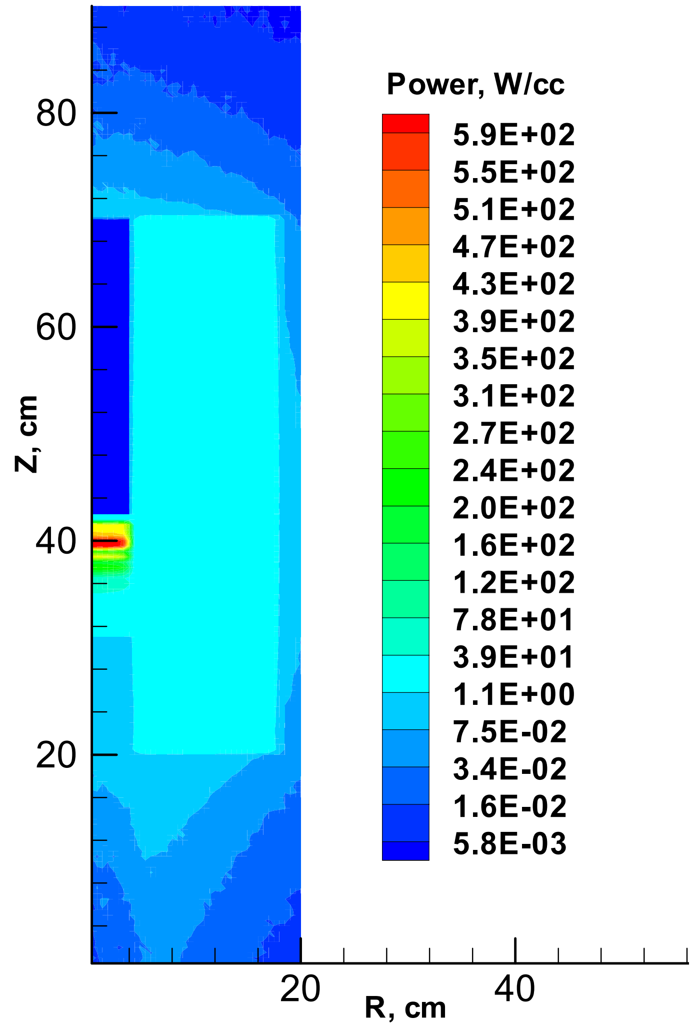

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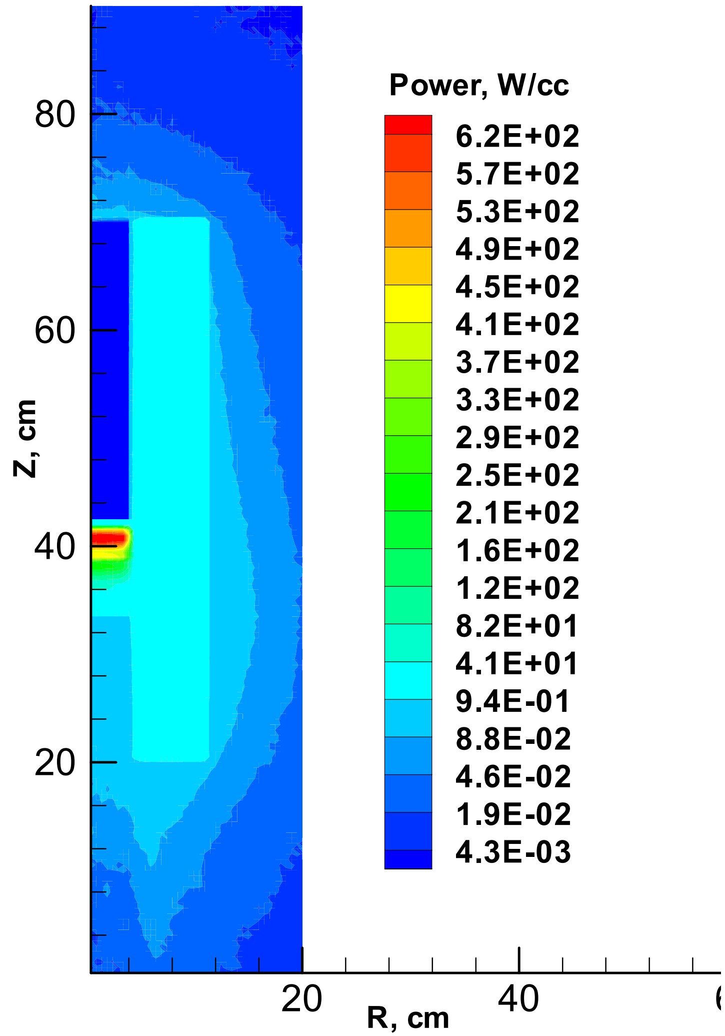

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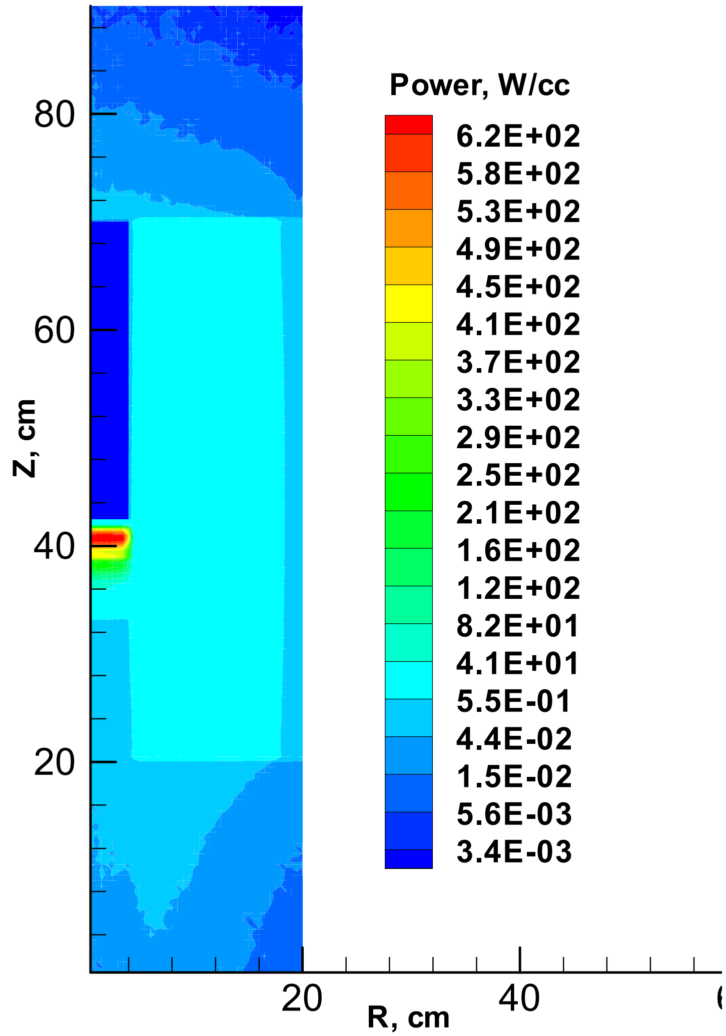

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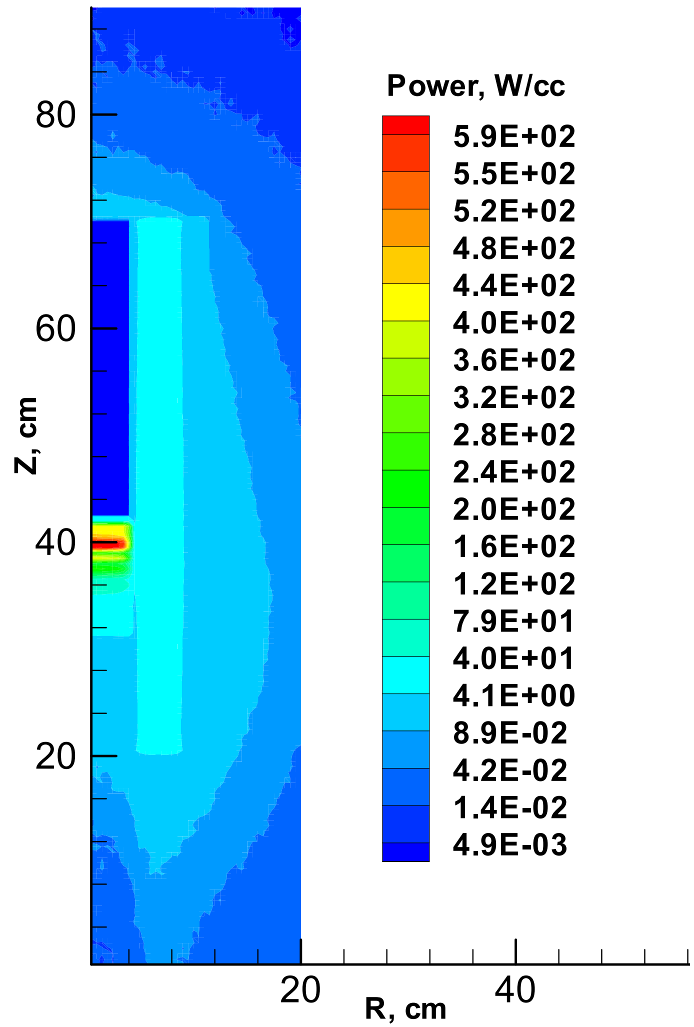

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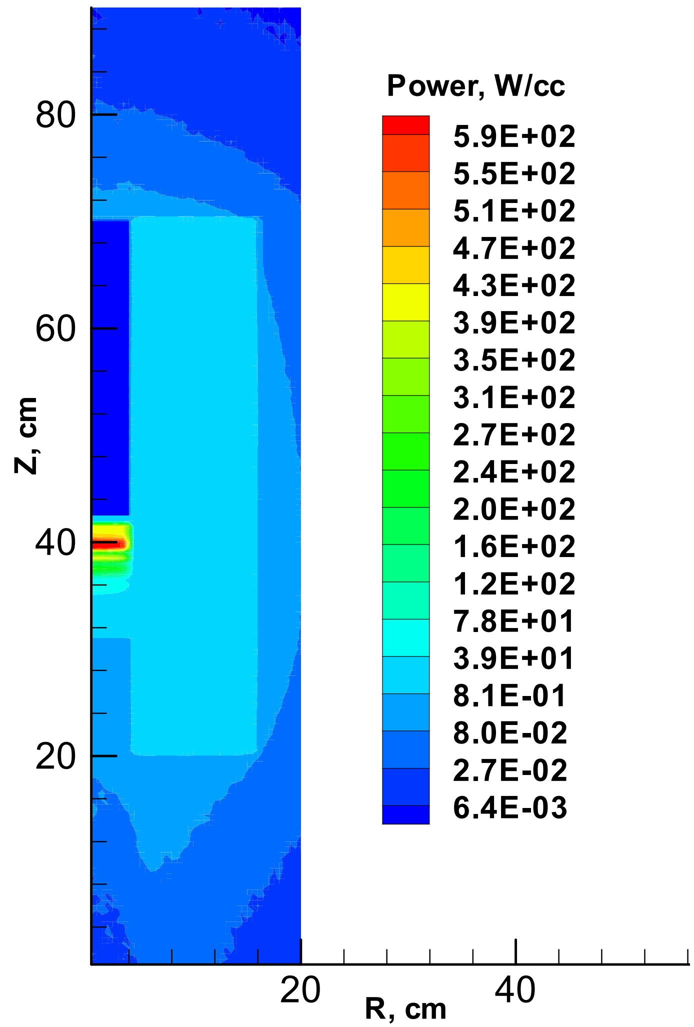

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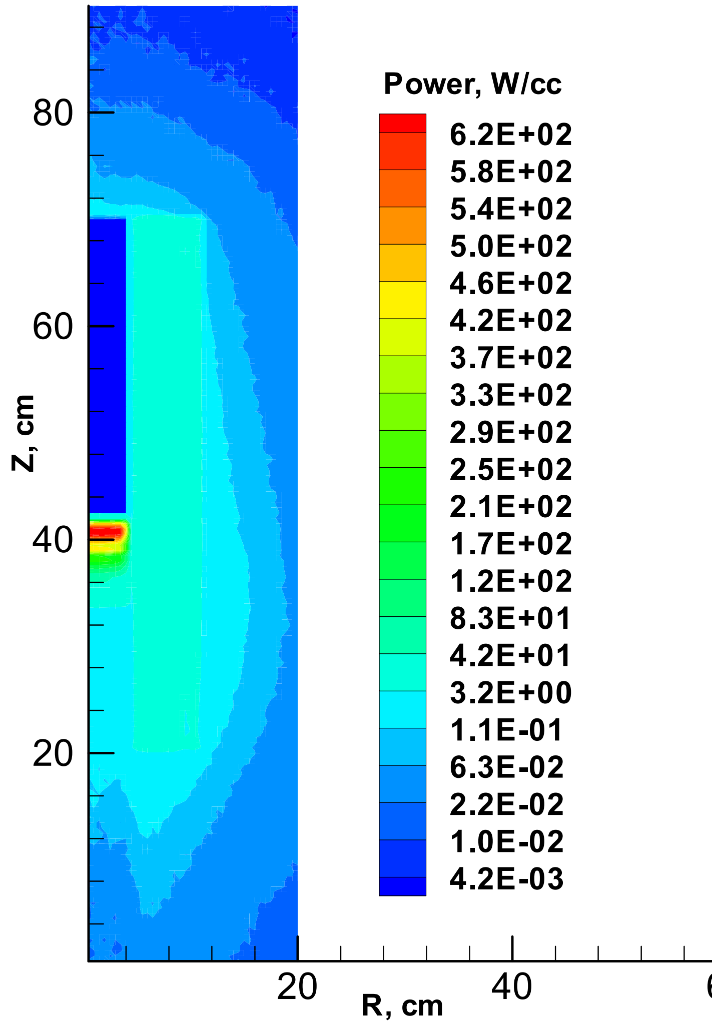

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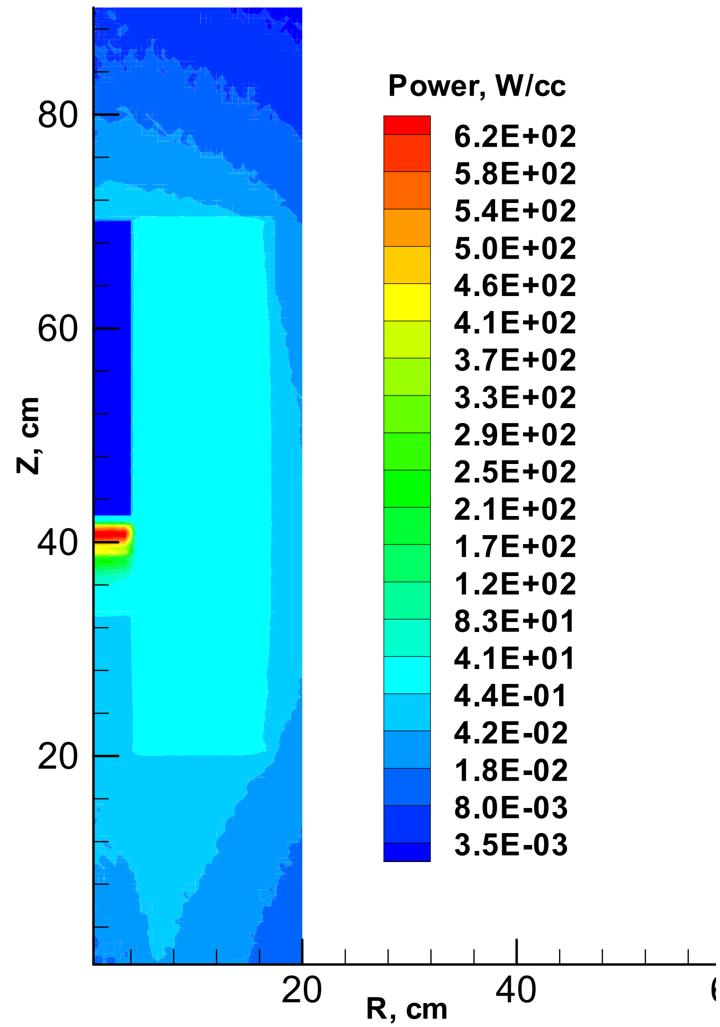

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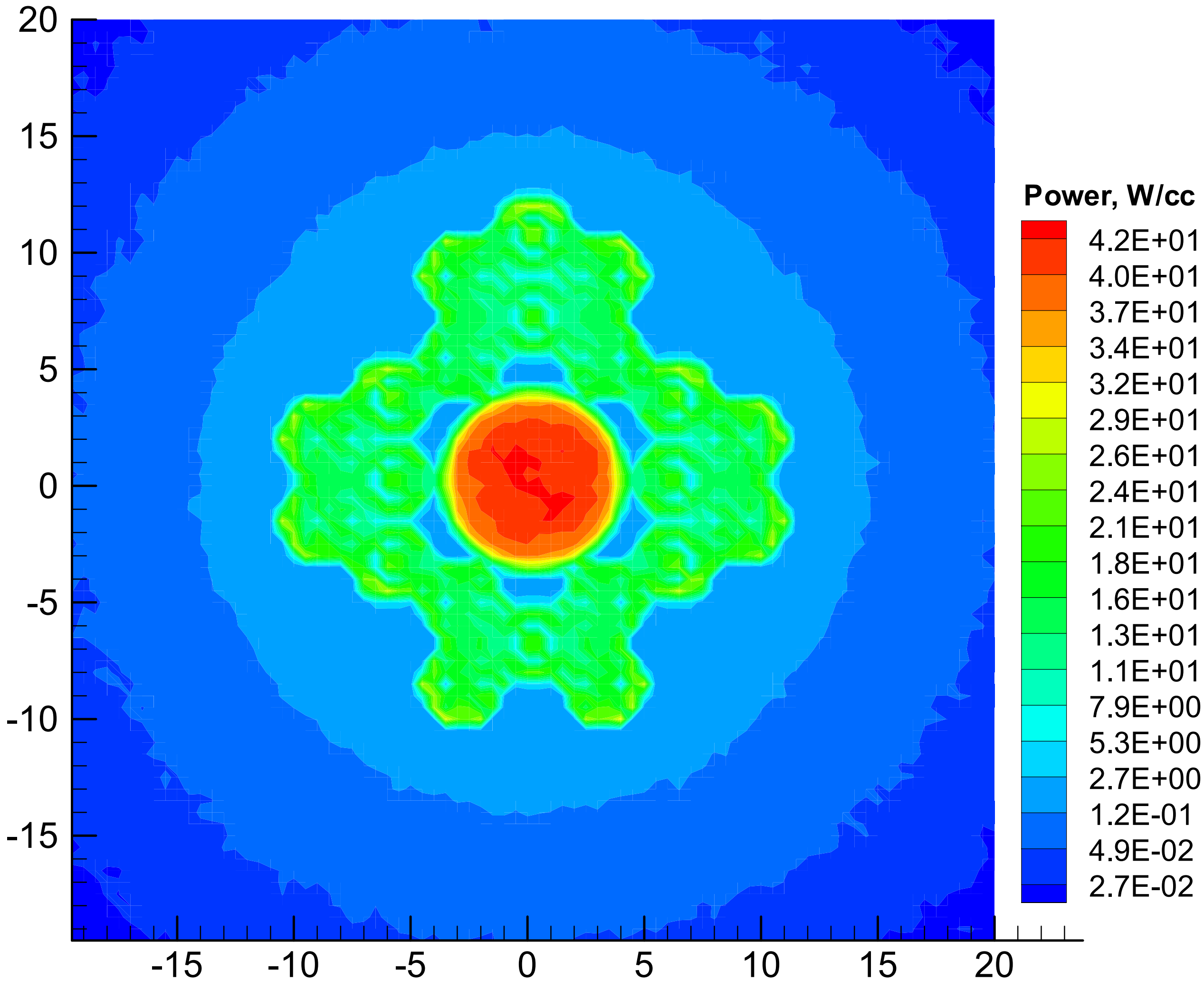

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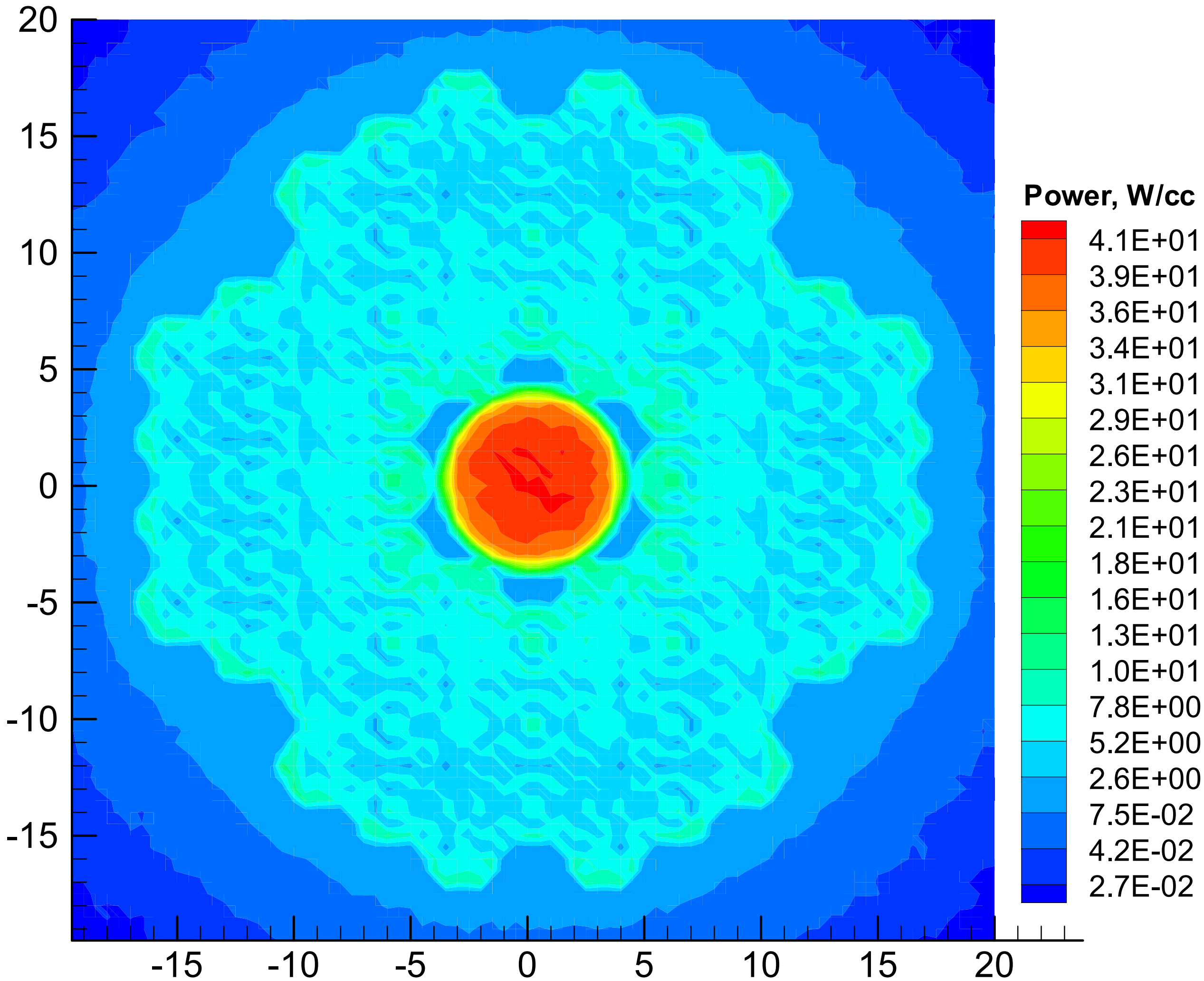

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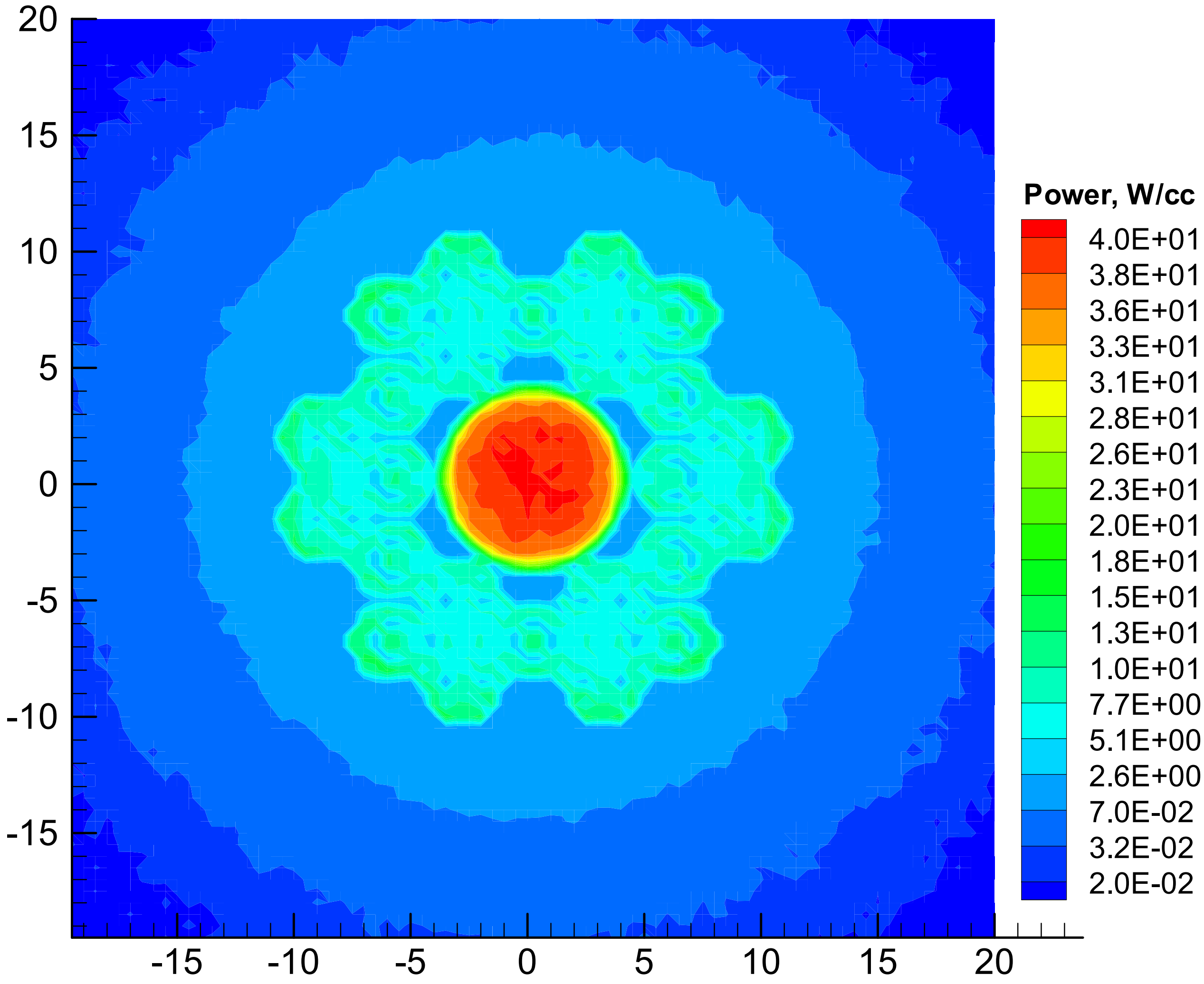

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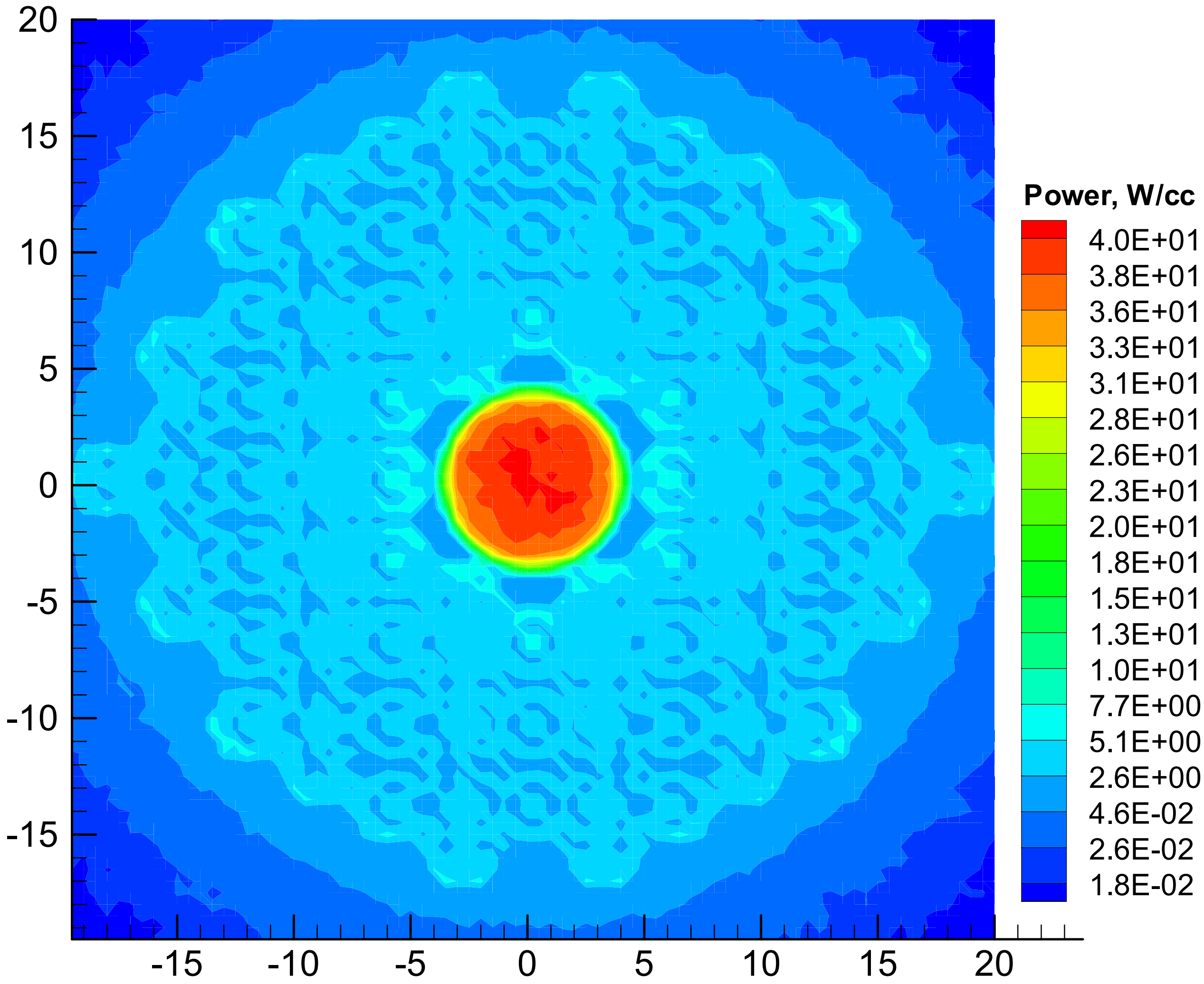
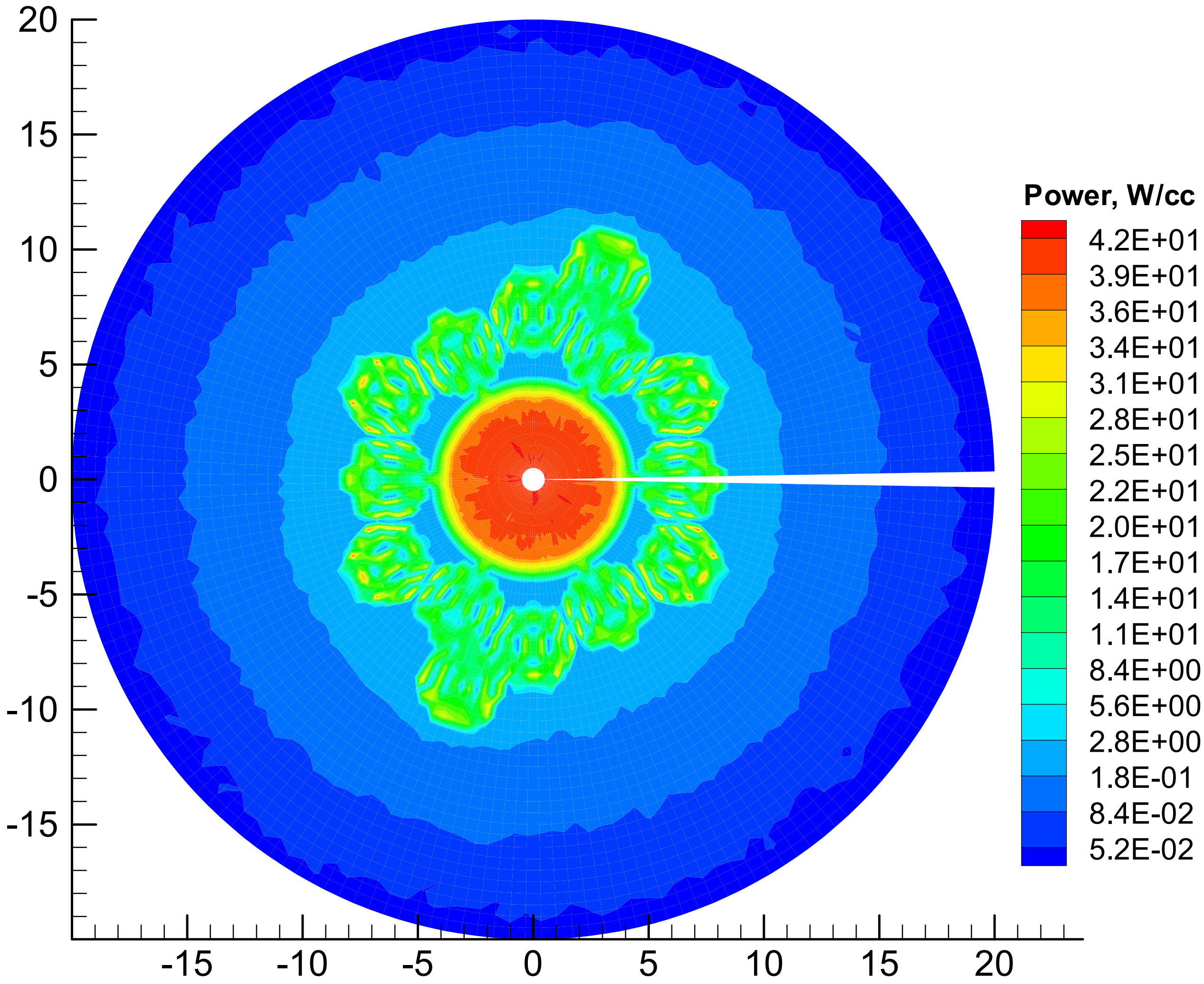


Radial Power Density Distribution of the Sub-critical Assembly with Uranium Target, HEU Fuel (1-g/cm^3 Uranium Density), 14 Fuel assemblies, and Beryllium Reflector



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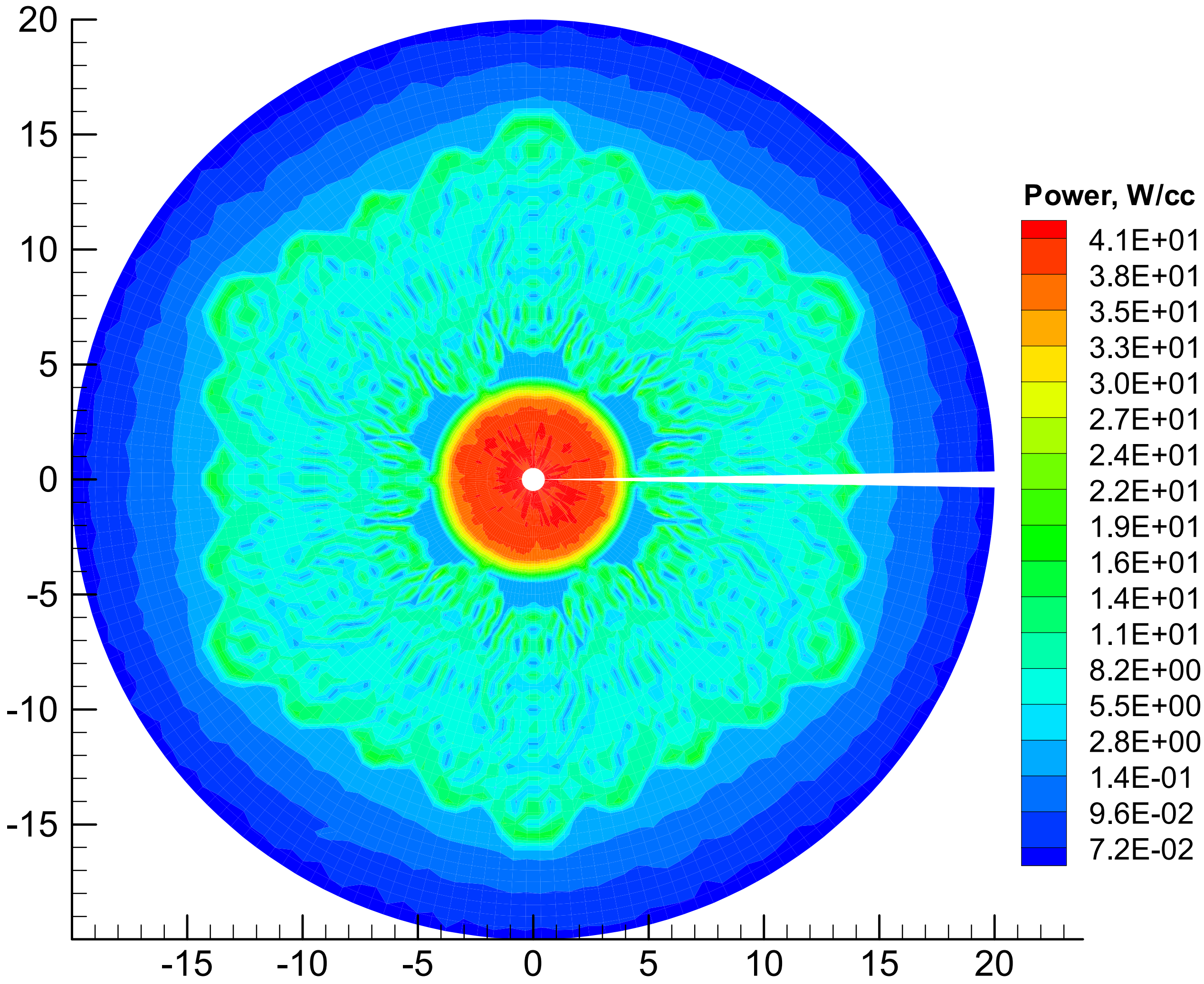

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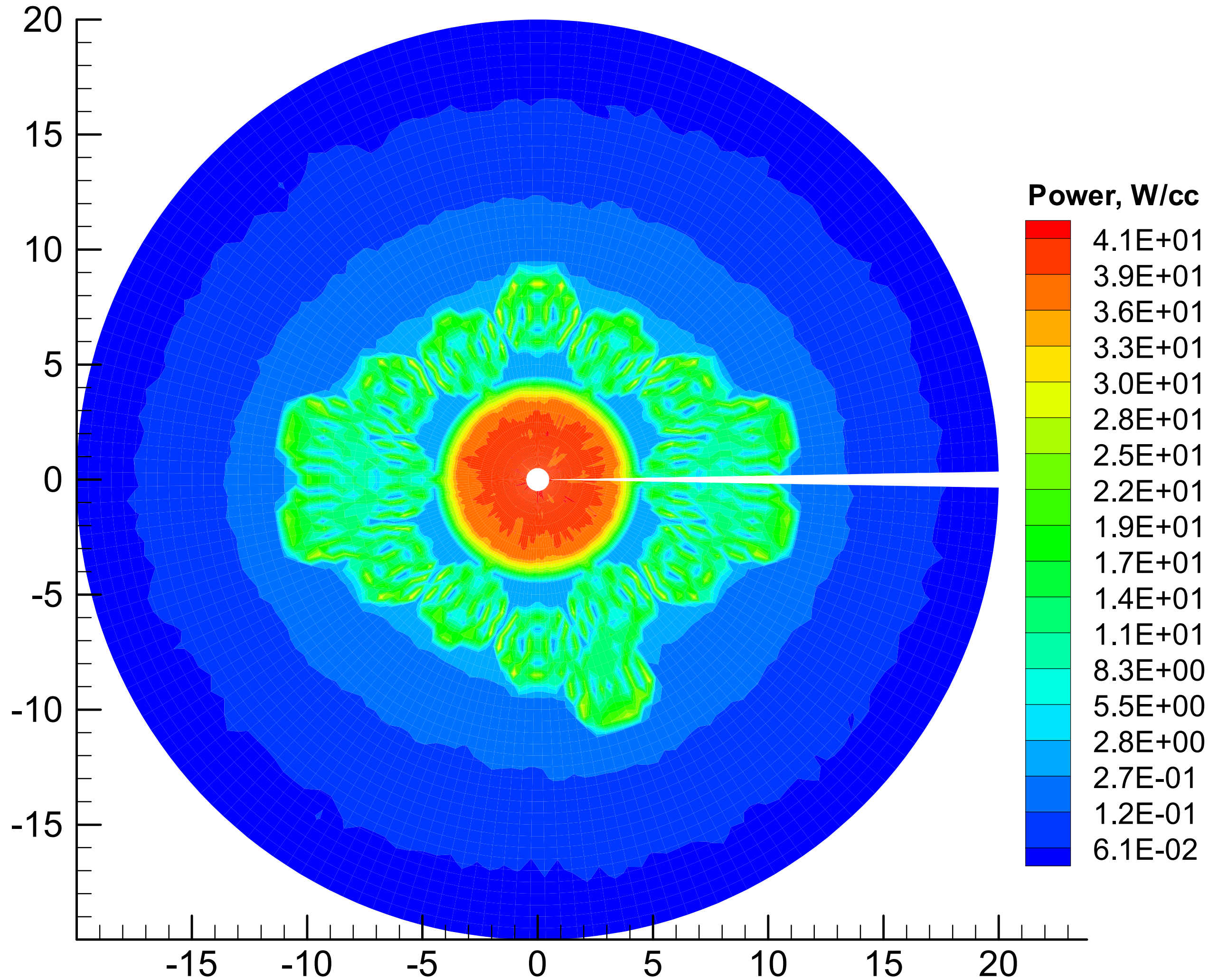
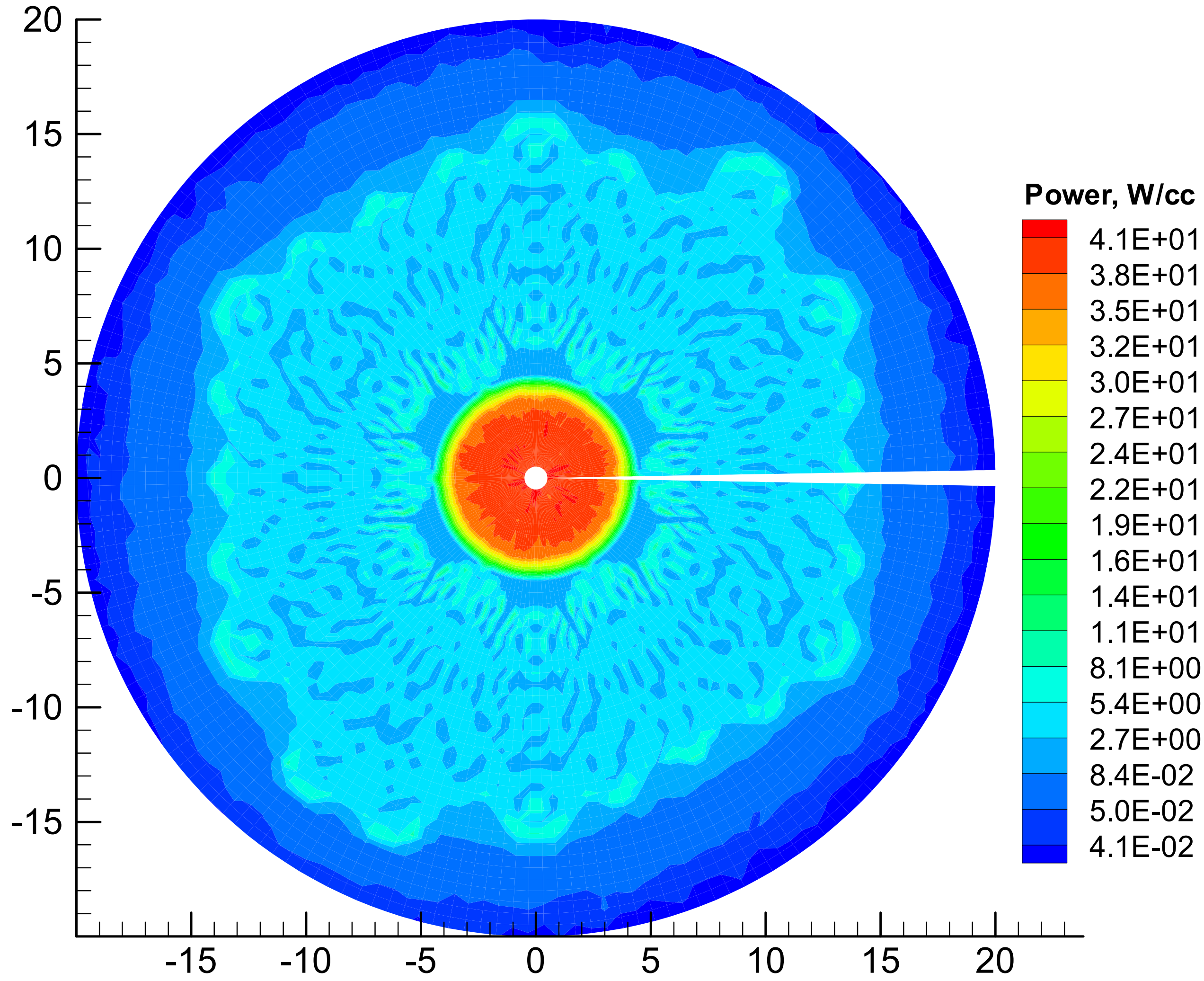


Radial Power Density Distribution of the Sub-critical Assembly with Tungsten Target, HEU Fuel (1-g/cm^3 Uranium Density), 57 Fuel assemblies, and Water Reflector



Required Fuel Loading for Different Combinations of Target and Reflector Materials

Fuel Enrichment		LEU				HEU			
Uranium Density		1.0		3.0		1.0		3.0	
Target	reflector	N	k_{eff}	N	k_{eff}	N	k_{eff}	N	k_{eff}
Tungsten	Beryllium	59	0.976	23	0.968	16	0.963	10	0.962
		60	0.980	24	0.978	17	0.983	11	0.983
		61	0.984	25	0.989	18	1.002	12	1.002
	Water	167	0.979	79	0.978	56	0.973	40	0.969
		168	0.981	80	0.981	57	0.979	41	0.978
		169	0.981	81	0.985	58	0.983	42	0.983
Uranium	Beryllium	56	0.974	20	0.971	13	0.948	9	0.962
		57	0.977	21	0.980	14	0.973	10	0.997
		58	0.982	22	0.991	15	0.989	11	1.015
	Water	151	0.978	73	0.979	53	0.979	37	0.972
		152	0.980	74	0.980	54	0.983	38	0.981
		153	0.981	75	0.983	55	0.990	39	0.983

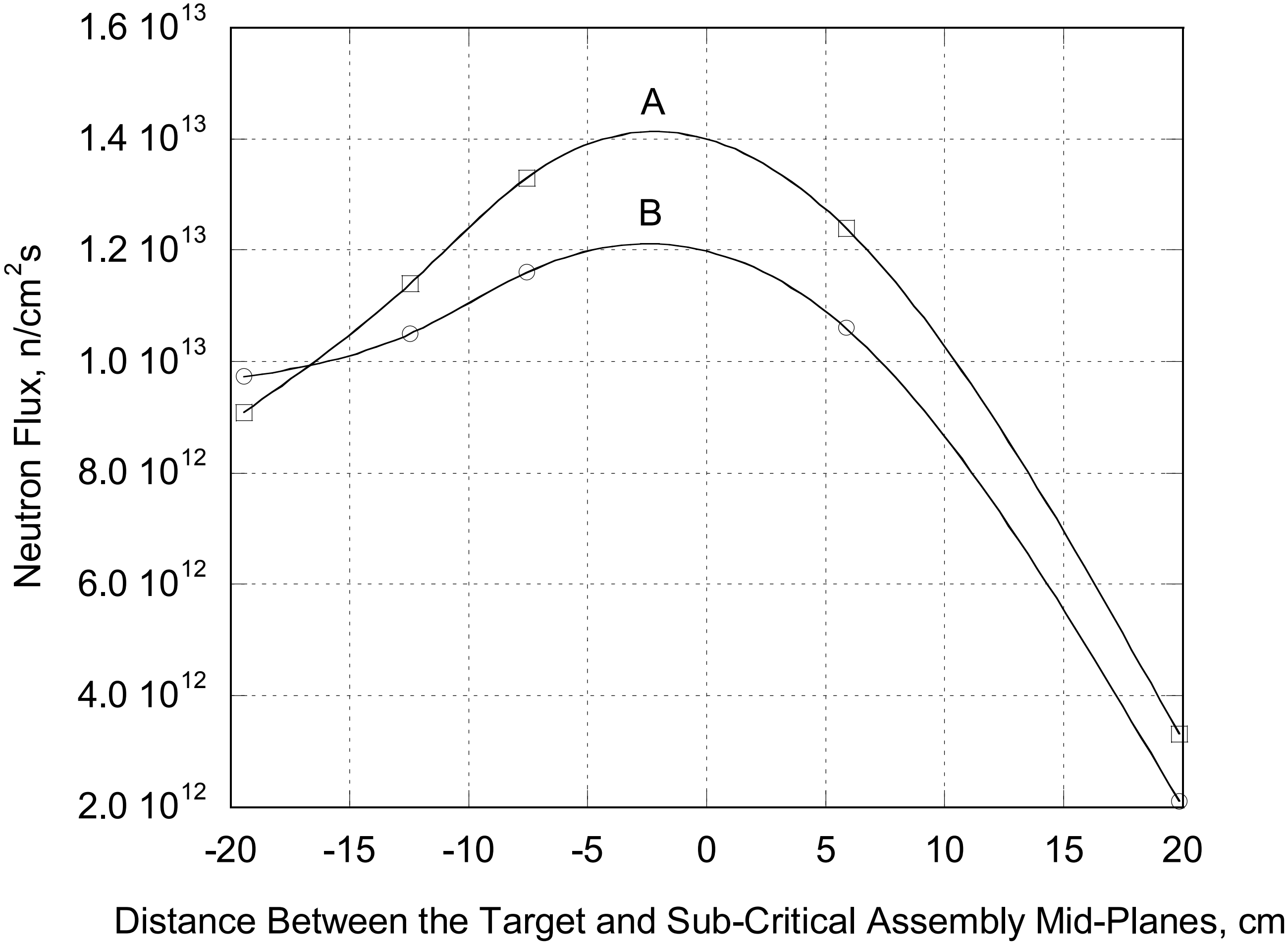
Neutron Flux in the Irradiations Channels between the Target and the Sub-Critical Assembly Fuel Averaged over the Fuel Length for Different Combinations of Target and Reflector Materials

Uranium Density, g/cm^3			1.0			3.0		
Fuel Enrichment	Target Design	Reflector Material	N	k_{eff}	Flux	N	k_{eff}	Flux
LEU	Tungsten	Beryllium	60	0.9804	8.65E+12	24	0.9783	1.09E+13
		Water	168	0.9807	6.57E+12	80	0.9810	7.62E+12
	Uranium	Beryllium	58	0.9815	1.81E+13	21	0.9800	2.26E+13
		Water	152	0.9796	1.25E+13	74	0.9803	1.44E+13
HEU	Tungsten	Beryllium	17	0.9828	1.42E+13	11	0.9831	1.42E+13
		Water	57	0.9791	7.51E+12	41	0.9775	6.41E+12
	Uranium	Beryllium	14	0.9729	1.83E+13	9	0.9620	1.52E+13
		Water	54	0.9834	1.63E+13	38	0.9811	1.31E+13

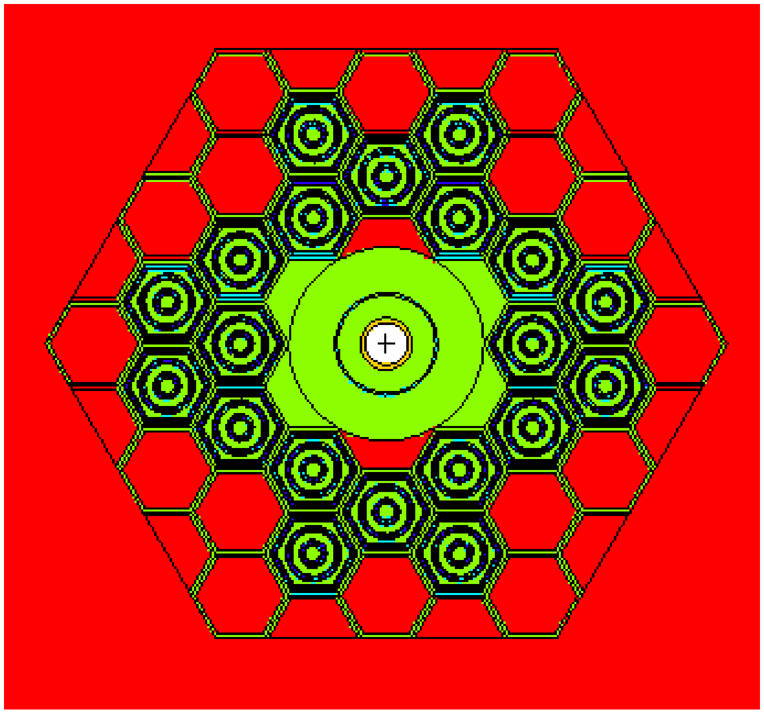
Neutron Flux in the Irradiation Channels between the Target and the Sub-Critical Assembly Fuel Averaged over the Target Length for Different Combinations of Target and Reflector Materials

Uranium Density, g/cm^3			1.0			3.0		
Fuel Enrichment	Target Design	Reflector Material	N	k_{eff}	Flux	N	k_{eff}	Flux
LEU	Tungsten	Beryllium	60	0.9804	9.74E+12	24	0.9783	1.26E+13
		Water	168	0.9807	8.20E+12	80	0.9810	9.85E+12
	Uranium	Beryllium	58	0.9815	2.90E+13	21	0.9800	3.68E+13
		Water	152	0.9796	2.18E+13	74	0.9803	2.54E+13
HEU	Tungsten	Beryllium	17	0.9828	1.62E+13	11	0.9831	1.68E+13
		Water	57	0.9791	9.81E+12	41	0.9775	8.93E+12
	Uranium	Beryllium	14	0.9729	3.05E+13	9	0.9620	2.62E+13
		Water	54	0.9834	2.85E+13	38	0.9811	2.41E+13

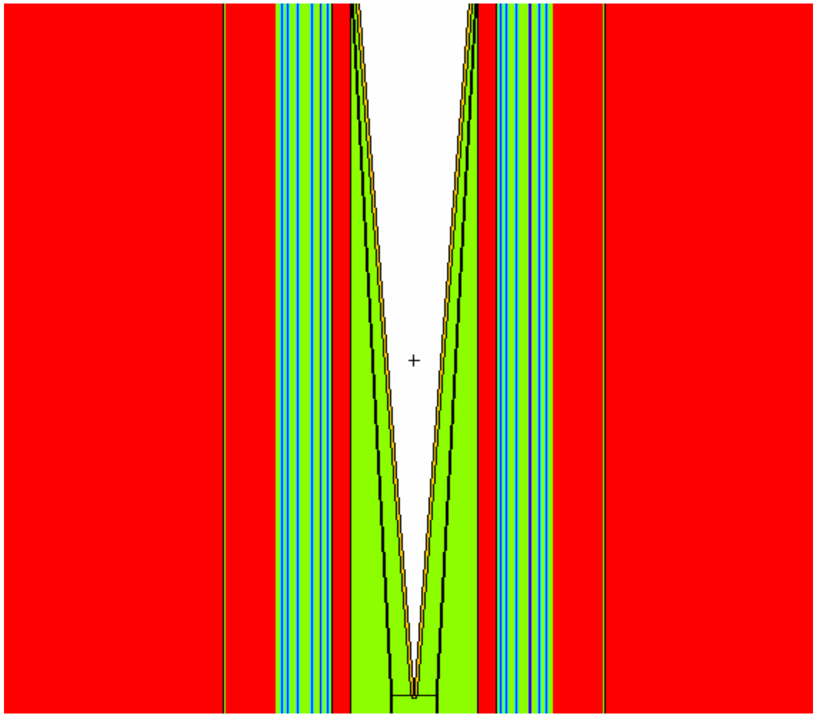
Average Neutron Flux in the Irradiation Channels between the Target and the Fuel over the Target Length (A) and the Fuel Length (B)



LEU Sub-critical Configurations with 3-g/cm^3 Uranium Density and Beryllium Target



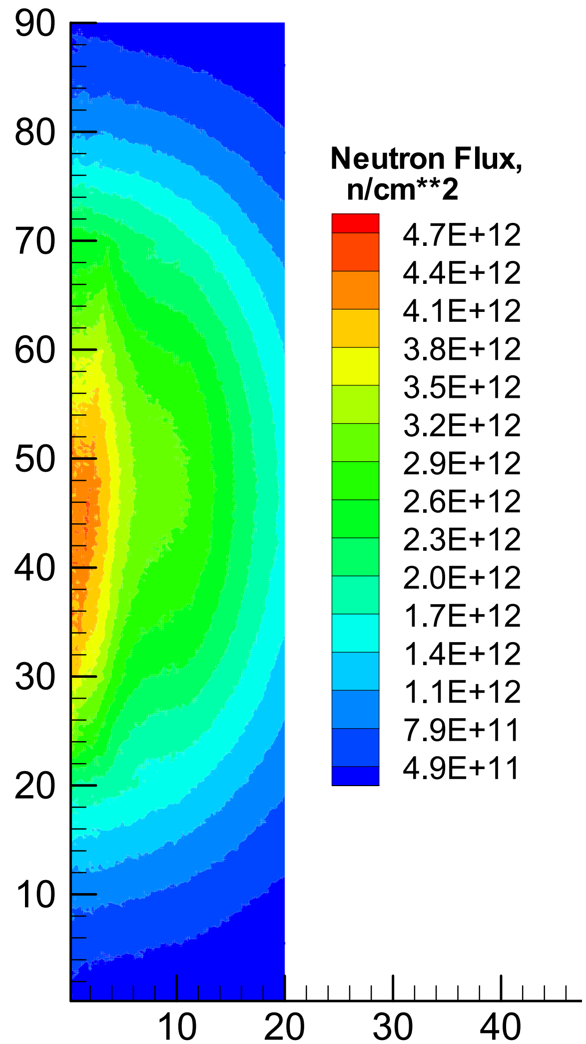
Mid Plane Cross Section of 20 Fuel Assemblies with Beryllium Reflector



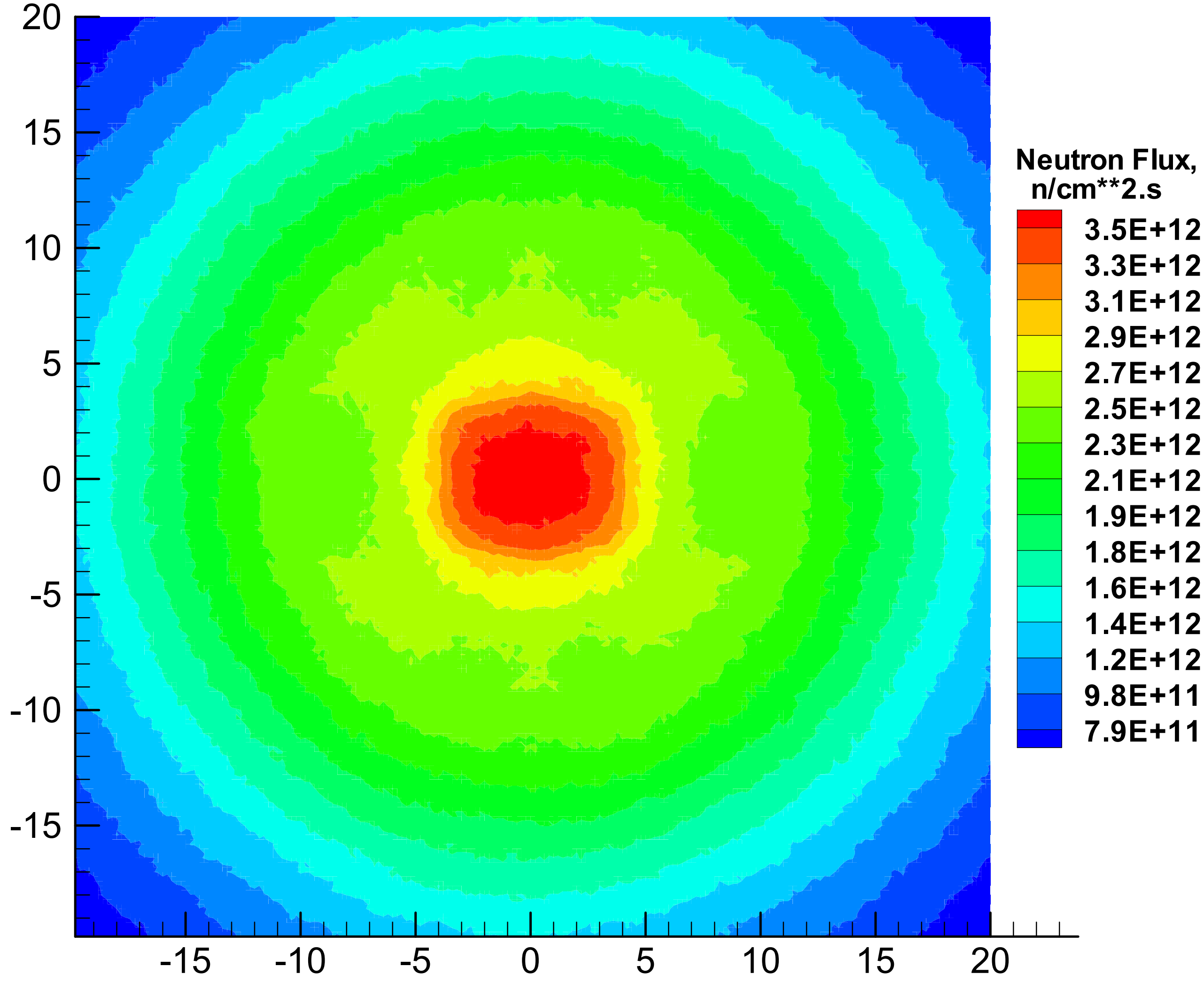
Vertical Cross Section of 20 Fuel Assemblies with Beryllium Reflector

- **K_{eff} is 0.9809.**
- **Average neutron flux in the irradiation channels between the target and the fuel assemblies is 2.89E+12 for the 11.5-KW Deuteron beam power.**

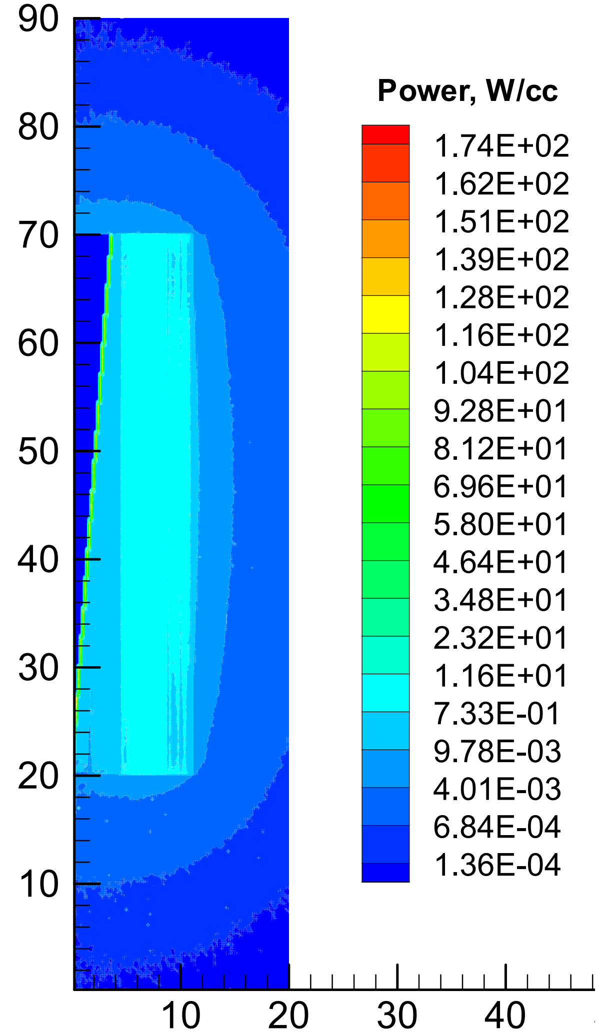
Axial Neutron Flux Distribution of the Sub-critical Assembly with Beryllium Target, LEU Fuel (3-g/cm^3 Uranium Density), 20 Fuel assemblies, and Beryllium Reflector



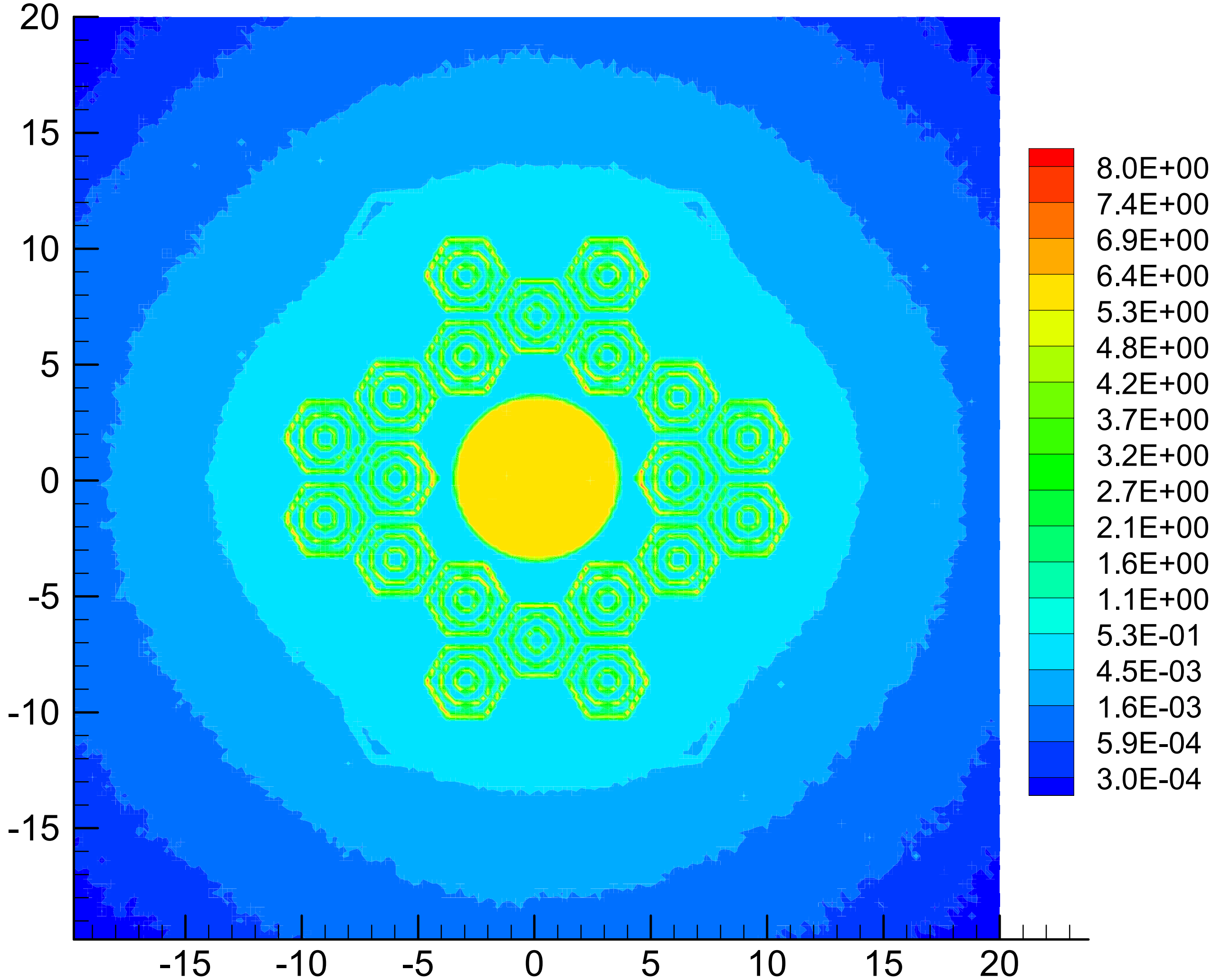
Radial Neutron Flux Distribution of the Sub-critical Assembly with Beryllium Target, LEU Fuel (3-g/cm^3 Uranium Density), 20 Fuel assemblies, and Beryllium Reflector



Axial Power Distribution of the Sub-critical Assembly with Beryllium Target, LEU Fuel (3-g/cm^3 Uranium Density), 20 Fuel assemblies, and Beryllium Reflector



Radial Power Distribution of the Sub-critical Assembly with Beryllium Target, LEU Fuel (3-g/cm^3 Uranium Density), 20 Fuel assemblies, and Beryllium Reflector



Target and the Sub-Critical Assembly Power for Different Combinations of Target and Reflector Materials, Uranium Enrichment, and Uranium Density

Uranium Enrichment		LEU					HEU				
Uranium Density, g/cm^3		3.0					1.0				
Target Design	Reflector Material	Fuel Assembly Number	k_{eff}	Target Power, KW	Sub. Power, KW	Total Power, KW	Fuel Assembly Number	k_{eff}	Target Power, KW	Sub. Power, KW	Total Power, KW
Tungsten	Beryllium	24	0.9783	89.2	71.1	160.3	17	0.9828	89.3	80.5	169.8
	Water	80	0.9810	89.1	88.0	177.1	57	0.9791	89.1	75.4	164.5
Uranium	Beryllium	21	0.9800	90.9	112.6	203.5	14	0.9729	90.0	78.3	168.3
	Water	74	0.9803	89.5	132.4	221.9	54	0.9834	89.6	135.7	225.3

Selection of Uranium Enrichment, Uranium Density, and Reflector Material for the Sub-Critical Assembly for an Optimum Performance

- Beryllium reflector generates higher uniform flux field, which is useful for experimental studies and neutron irradiation relative to the water reflector.
- The use of beryllium reflector reduces significantly the required fuel inventory for the same K_{eff} relative to the water reflector.
- The number of HEU fuel assemblies required for 0.98 K_{eff} is very small, which causes a difficulty for performing experimental studies.
- The reactivity worth of the HEU fuel assembly is large, which results in safety concerns and difficult operating procedures.
- The obtained neutron flux levels from the use of LEU and HEU fuel and uranium target are the highest.

Uranium Enrichment	Uranium Density, g/cm^3	Number of fuel assemblies	K_{eff}	Flux, n/cm^2s
LEU	1	58	0.9815	$2.90x10^{13}$
LEU	3	21	0.9800	$3.68x10^{13}$
HEU	1	14	0.9729	$3.05x10^{13}$
HEU	3	9	0.9620	$2.62x10^{13}$

- Subcriticality measurement and calibration are difficult for small asymmetrical assemblies, which reduces the utilization and use of the facility.
- LUE and density of less than 3 gm/cm^3 result in the best performance for the sub-critical assembly.

Conclusions

- The analyses show that the following parameters/choices provide the best possible performance from the sub-critical assembly for the project under consideration:
  - Electron beam for neutron generation
  - About 100 KW beam power
  - Electron energy in the range of 150 to 200 MeV, preferable 200 MeV
  - Uranium target material, tungsten for lower performance operation
  - Low enrichment uranium for the fuel material
  - Uranium density in the range of 1 to 3 gm/cm^3
  - Research reactor fuel design
  - Low pressure and temperature water coolant
  - Aluminum structure for the sub-critical assembly

- The sub-critical assembly has a total flux of 3.7×10^{13} n/cm^{2}s and a total facility power of 204 KW, which can be utilized for experimental studies, medical isotope production, and material characterization.