The Abdus Salam International Centre for Theoretical Physics

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School on Physics, Technology and Applications of Accelerator Driven Systems (ADS)

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Thermal Hydraulics of Heavy Liquid Metal Target for ADS. Part I

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Thermal-hydraulics of Heavy Density liquid Metal Target for ADS

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ADS Target Development Section

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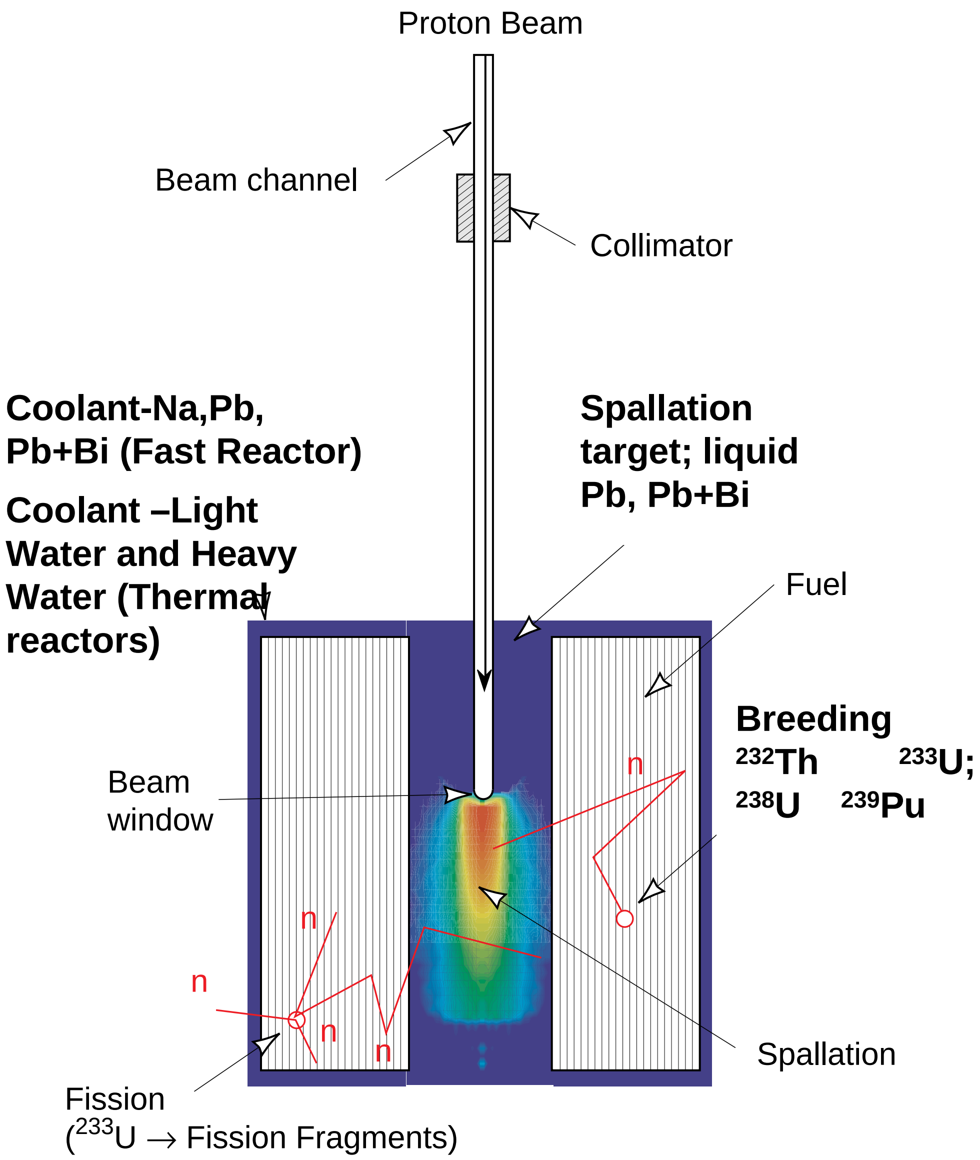
Typical ADS Target Location



Requirement of neutrons for a typical ADS

- **It depends on power of the Reactor**
- **It depends on k_{eff} of the reactor**

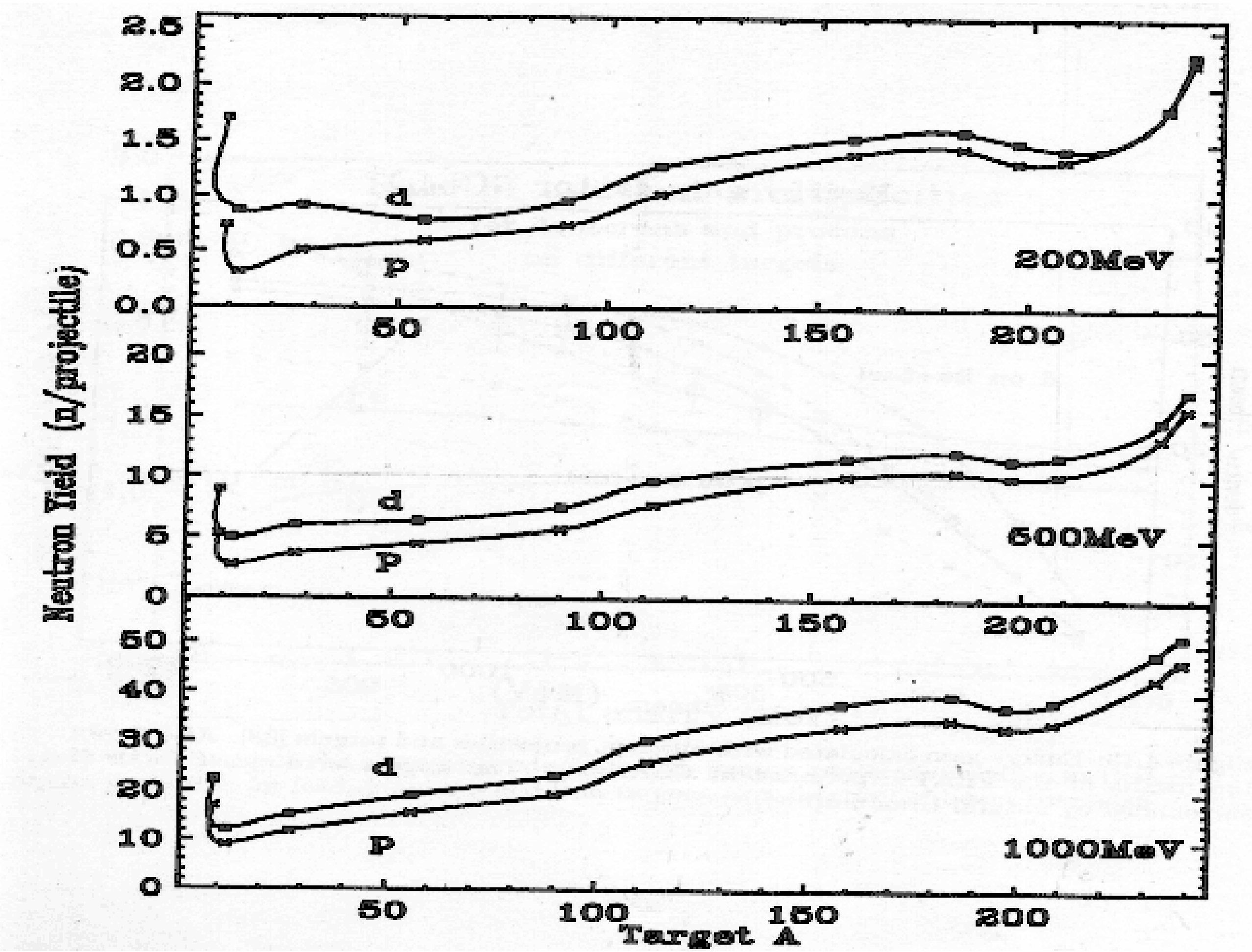
  $k_{eff} \sim 0.95$ to 0.98

Typically requirement ~ 10^{18} - 10^{19} per second

Thermal-hydraulics of ADS target - Lecture-1

Contents:

Suitable Spallation Target Material



NEUTRON YIELD Vs TARGET ATOMIC MASSES

Hybrid Nuclear Reactor-Nifenecker Etal

Neutron Yield for Different Proton Beam Energies – LBE target

Proton Energy (MeV)	~Neutrons Produced per proton
100	0.26
350	4.52
500	8.86
1000	25.3
1500	38.73
2000	50.1

Note

-Beyond ~ 1GeV proton energy, the neutron yield per GeV energy remains constant

-The energy deposition ($\frac{dE_p}{dx}$) by the beam is minimum ~1.2 Gev

This has a bearing on selection of beam energy for ADS

Possible Spallation Targets

Element	Atomic Mass (A)	Atomic Number (Z)	A/Z	Melting Temperature (^0C)	Boiling Temperature (^0C)	Density at room Temp (g/cc)
Pb	207	82	2.524	327	1725	11.36
Bi	209	83	2.518	271	1560	9.80
LBE	~208	~82.5	~2.52	125	Similar to Pb/Bi	~10.0
Hg	200	79	2.532	-38.36	357	13.54
U	238	92	2.590	1132.3	3818	19.07
Ta	181	73	2.479	2996	5425	16.6
W	184	74	2.486	3410	5930	19.3

Heat deposition by High proton beam

Heat deposition of a 200 MeV Proton beam in Lead

(S. Buono, Y. Kadi, C. Rubbia)

	Energy (MeV)	Fraction of Proton Energy	Fraction of energy deposit as heat
Incident Energy	200	100	
Total energy deposited	183	91.5	100
Ionization losses	160	80	87.4
Charged evaporation products	1.9	0.95	1.0
Nuclei recoil (including fission products)	2.1	1.0	1.1
Slowed down charged particles	17.6	8.75	9.6
Neutral pion decay	-	-	-
Nuclei de-excitation	1.6	0.8	0.9

Heat deposition of a 1Gev Proton beam in Lead

(S. Buono, Y. Kadi, C. Rubbia)

	Energy (MeV)	Fraction of Proton Energy	Fraction of energy deposit as heat
Incident Energy	1000	100	
Total energy deposited	659	65.9	100
Ionization losses	450	45	68.3
Charged evaporation products	69	6.9	10.5
Nuclei recoil (including fission products)	41	4.1	6.2
Slowed down charged particles	38	3.8	5.8
Neutral pion decay	35	3.5	5.3
Nuclei de-excitation	26	2.6	3.9

Why Liquid Target?

-Very High Heat Deposition Density by proton beam ~ few kW/cm^3

-Very High Radiation Damage ~100 DPA or more/year

Embrittlement
Irradiation Creep
Void Swelling
Hydrogen Generation
Helium Generation
Transmutation

Solution for both these issues – Use circulating liquid target

Suitable Liquid Targets

Possible Liquid Targets

Element	Atomic Mass (A)	Atomic Number (Z)	A/Z	Melting Temperature (^0C)	Boiling Temperature (^0C)	Density at room Temp (g/cc)
Pb	207	82	2.524	327	1725	11.36
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Ta	181	73	2.479	2996	5425	16.6
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Hg is not suitable due to low boiling temp. for reactors

LBE has been identified as best target material

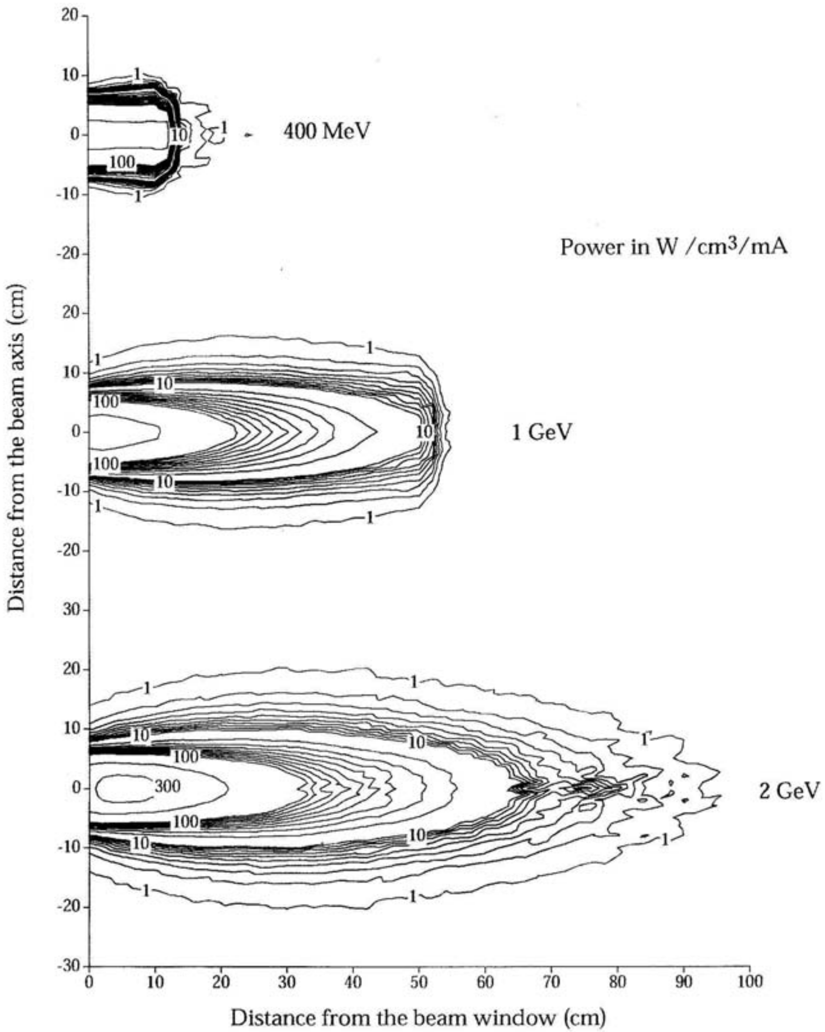


***Figure 3** - Power generated by a proton beam in a thick Lead target for different energies.*

The beam size was taken as a circular spot of $r_o = 7.5$ cm radius. In the Montecarlo calculations the beam distribution has been approximated with the parabola:

$$\frac{2I_o}{\pi r_o^2}\left(1-\frac{r^2}{r_o^2}\right).$$

Typical Heat deposition contours for different beam energies in lead target by FLUKA code–Ref: **S. Buono, Y. Kadi, C. rubbia**

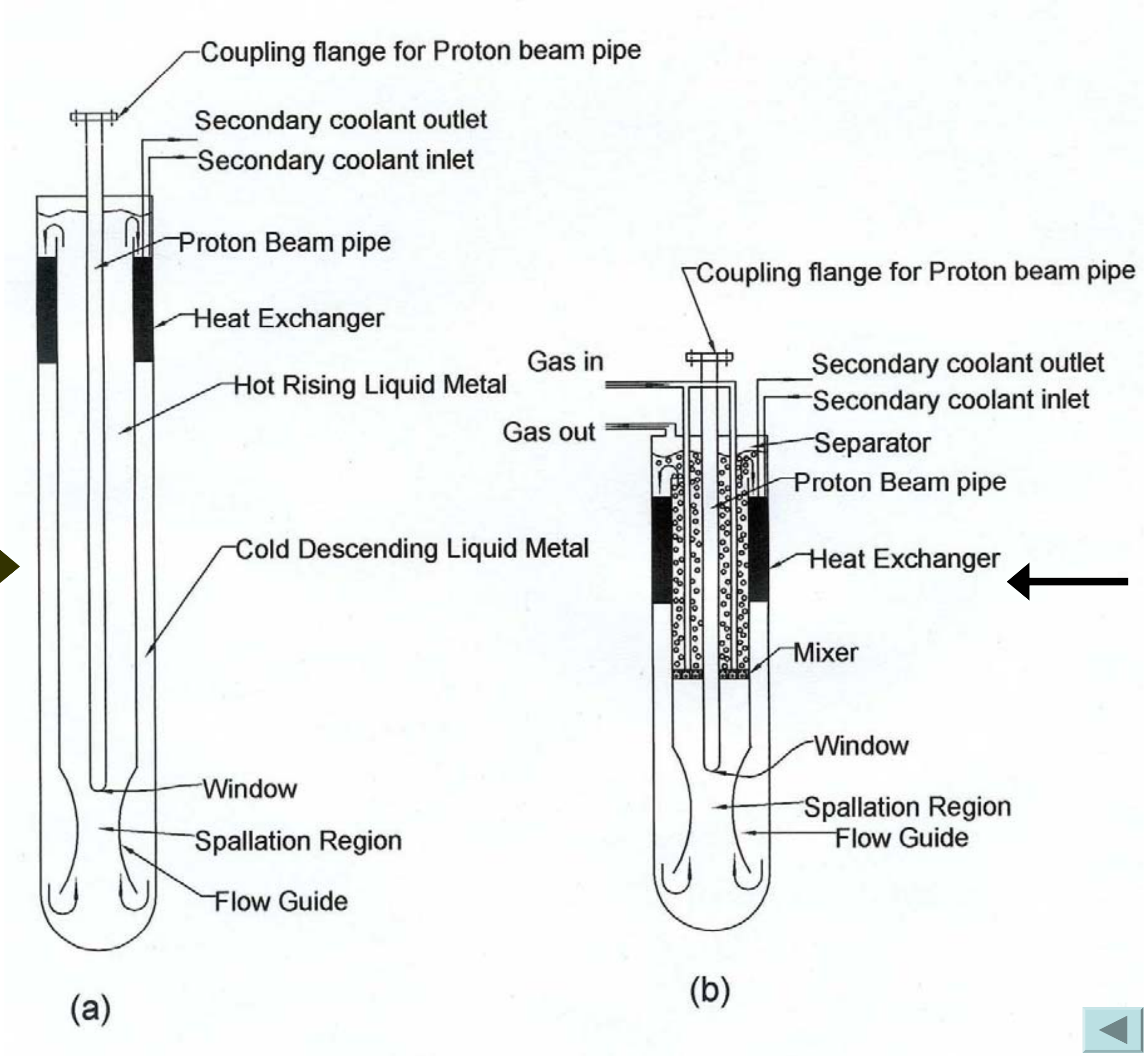
Methods of circulation for Target Module

Methods of Circulation for Target Module

- Conventional Pump Driven loop
  - Mechanical Pump
  - Electromagnetic Pump (low efficiency: ~ 3% Due to low electrical conductivity ~10^6 mho/m)
- Buoyancy Driven Loop
- Gas driven Loop

Window Type Target loops-Various Circulating Methods

Buoyancy Driven



Gas-driven

Pressure head

1) Buoyancy Loop

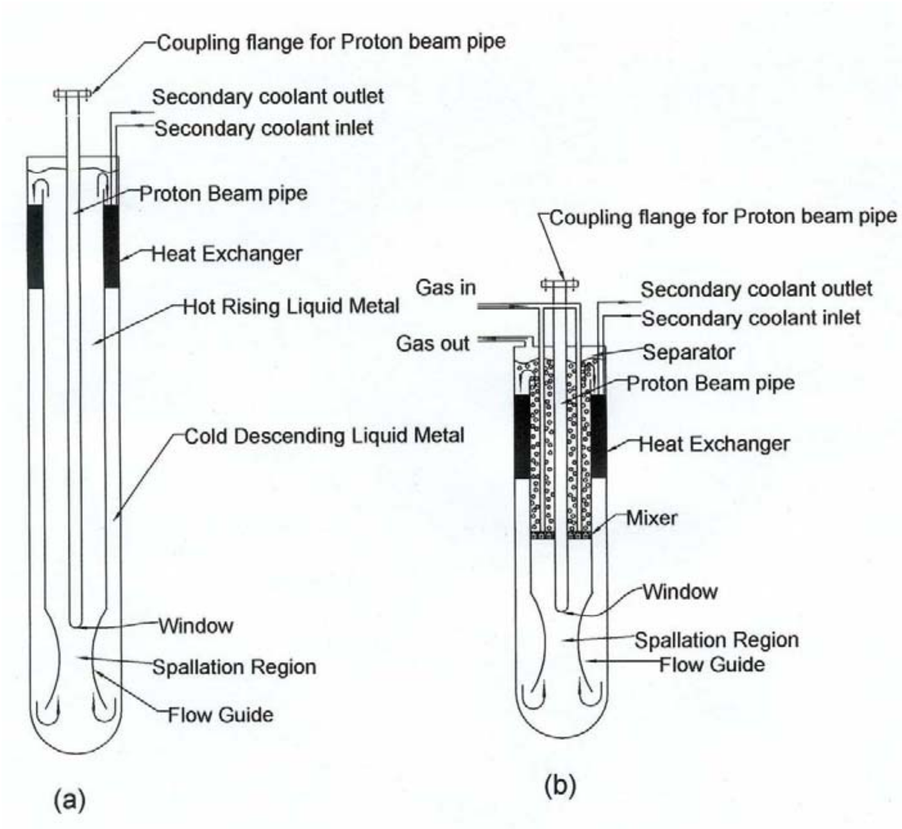
$$\Delta P_{Buoy} = \beta \rho_{cold} \Delta T g h$$

β =Volumetric Expansion coefficient (1/K) ~1.24×10^{-4} for LBE

2) Gas Driven Loop

$$\Delta P_{head} = \alpha_{ave} \rho_{cold} . g . h + \text{Buoyancy}$$

$\alpha_{ave} \sim 0.25$



Windowless Target Systems

What is Windowless target System?

- In this system window is eliminated and proton beam directly impinges on the Liquid metal free surface
- The free surface is exposed to vacuum environment (~10^{-6} torr) of the beam as required
- This is possible only if the Liquid Metal Vapour pressure is very small at the operating temperatures
- LBE and Pb are potential candidates

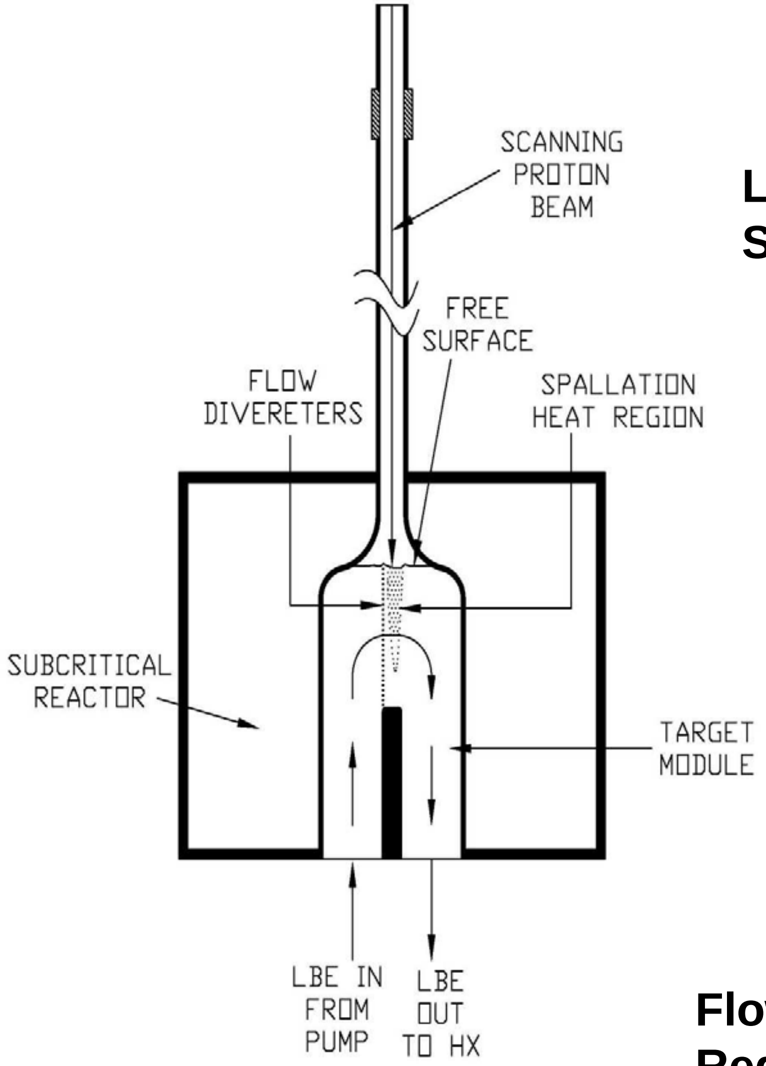
Saturated Vapour Pressure of LBE at Different temperatures

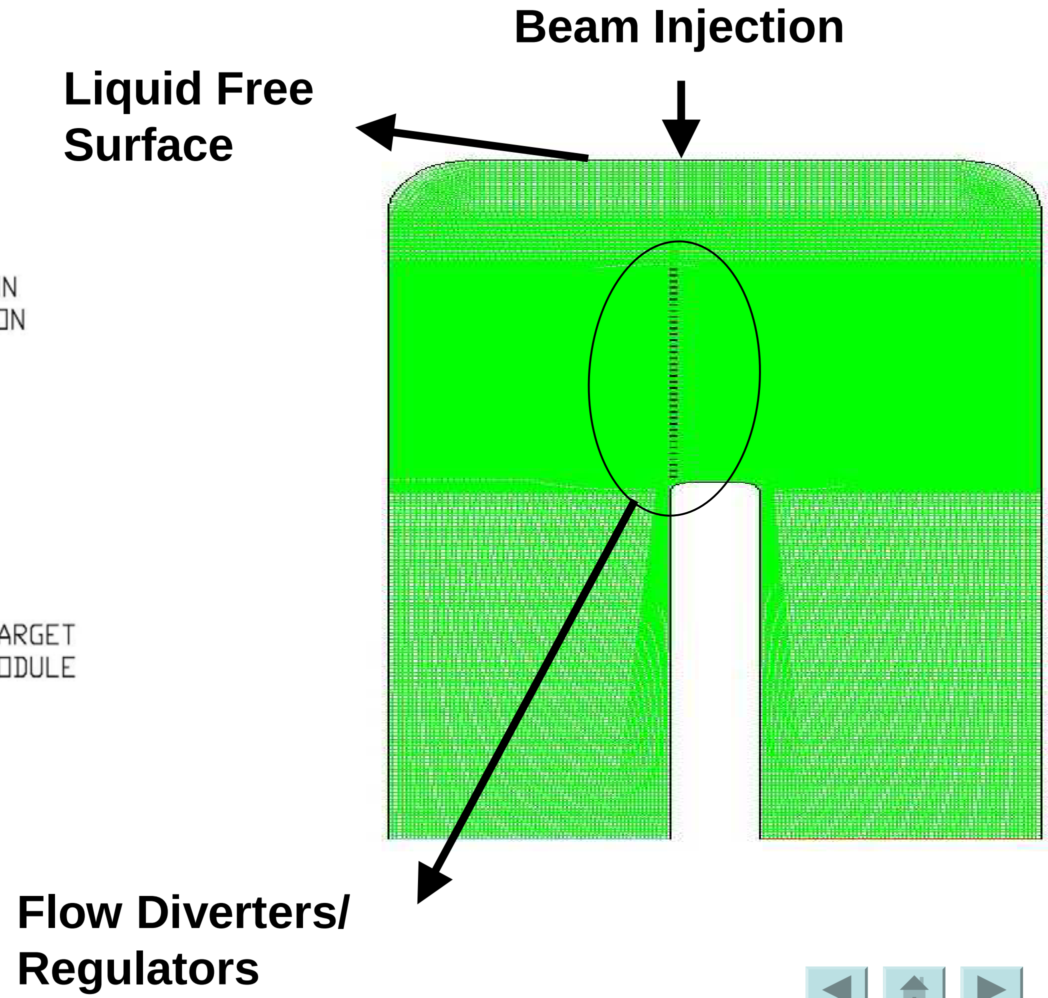
Ref: Hand book on LBE alloy and Lead properties, Material Compatibility, Thermal-hydraulics and technologies,

2007, NEA, Organisation for economic cooperation and development

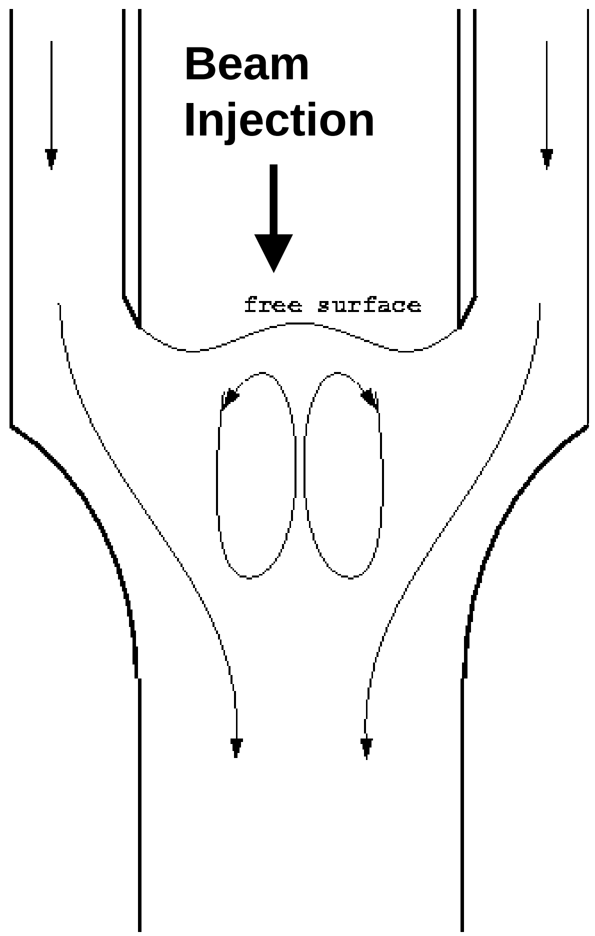
LBE	
Temperature K	Vapour pressure Pa
500	2.9×10^{-10}
600	5.3×10^{-7}
700	1.1×10^{-4}
800	6.3×10^{-3}
900	1.5×10^{-1}
1000	1.8

One of the Windowless target configuration currently under study





Alternative Windowless target configuration currently under study



Window vs Windowless

Window vs. Windowless

Issues	Solid Window	Windowless
Radiation damage and Thermal stresses and Corrosion effects	Yes	No
Life of Target module	Decided by Window (~6 months to 1 year)	Decided by rest of the components
Beam scanning area (Bearing on the target diameter and Activation of Structures above the reactor)	Large (~50 μA/cm^2)	Small (~120 μA/cm^2)
Flow Stability	Stable	Unstable free surface
Buoyancy driven flow	Possible	Not Possible

Typical Target Configuration Under Study in Various Institutions

MYRRHA -50 MW th - SCK.CEN
Windowless Target (*Aït Abderrahim Hamid*)

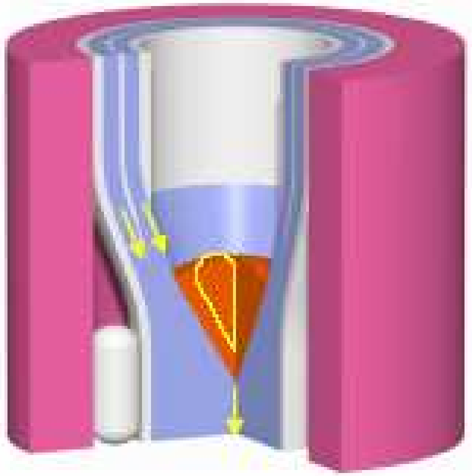
-Beam : 350 MeV , 5 mA

-Heat deposited : 80% of 1.75 MW

-Beam Penetration – 130 mm

-1.40 MW to be from – 500 cm^3

MYRRHA -50 MW th - SCK.CEN
Windowless Target -cont



- Windowless target
  - Space considerations : ϕ72 mm target
  - 5 mA current
    - ⇒ Beam density : 125-175 μA/cm²
- Vertical coaxial confluent LBE flow
  - Space consideration
  - Free surface formation
- Off axis LBE servicing
  - Leave top & bottom of subcritical core free
    - ⇒ Accessibility experimental radiation device
  - Main part of the spallation loop away from high radiation zone
    - ⇒ Lifetime

HYPER Reactor -1000 MW th
Beam – 20 MW (1GeV and 20 mA)

Korean Atomic Research Institute - KAERI

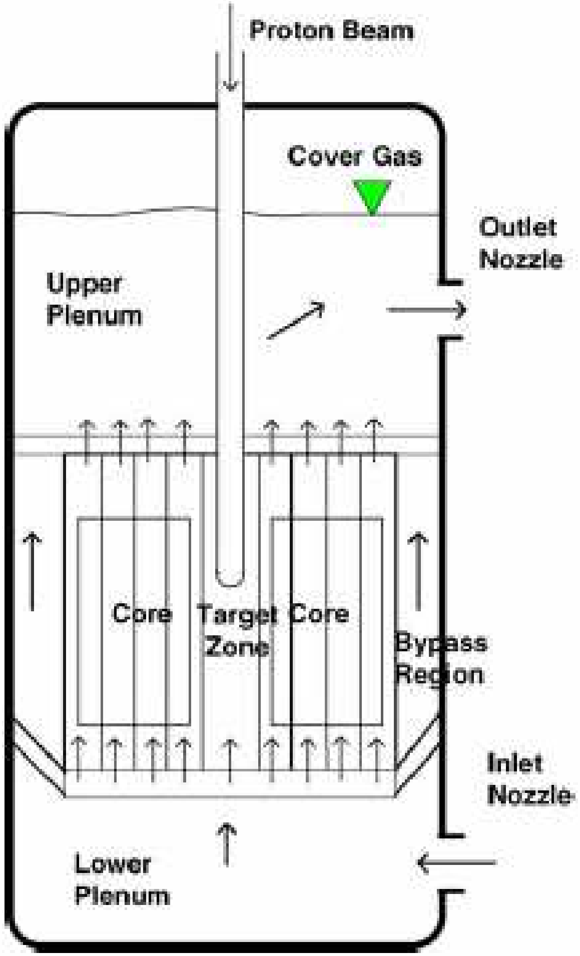


Fig. . The outline of HYPER.

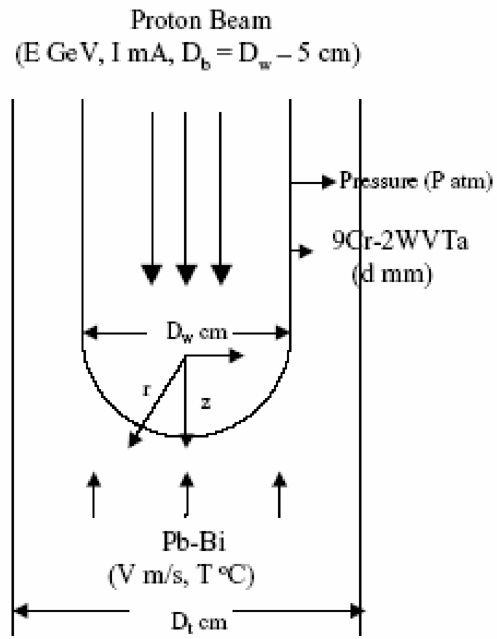


Fig. Outline of the target system design.

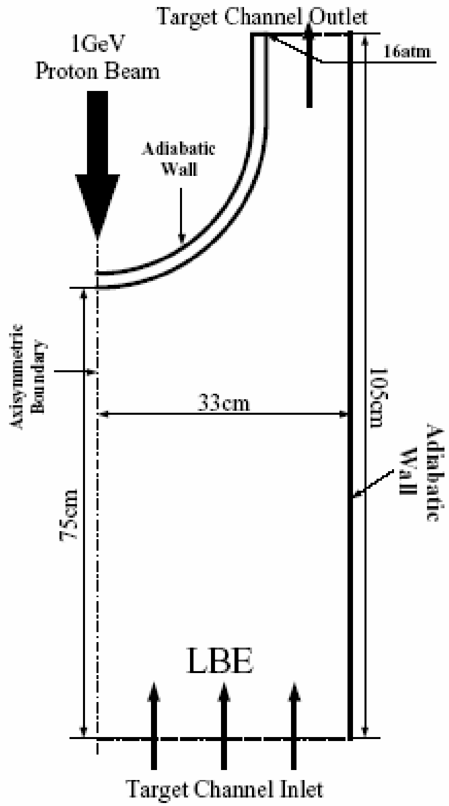


Fig. Computational domain and boundary conditions.

FZK – 1500 MWth (Germany)
3 Beams (Power 4 MW each – 1GeV & 4mA

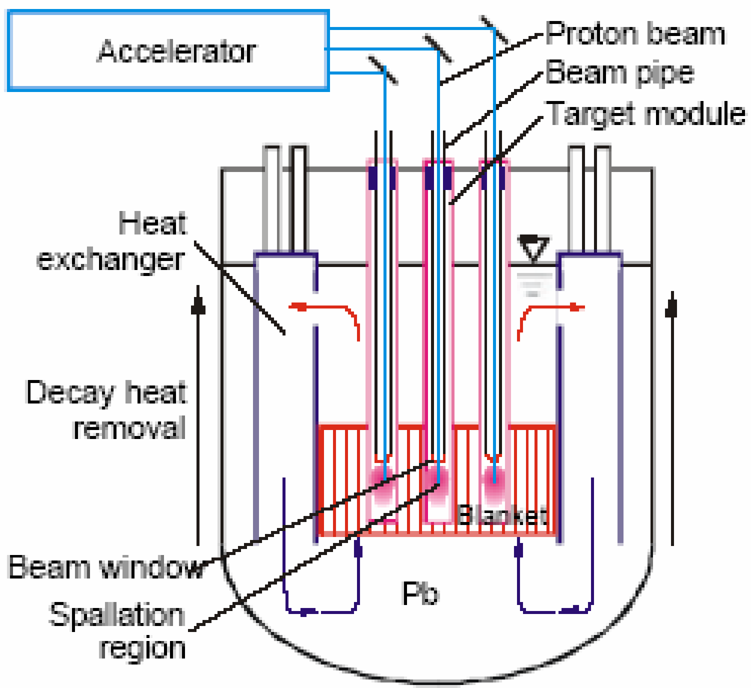


Figure . schema of the FZK proposal

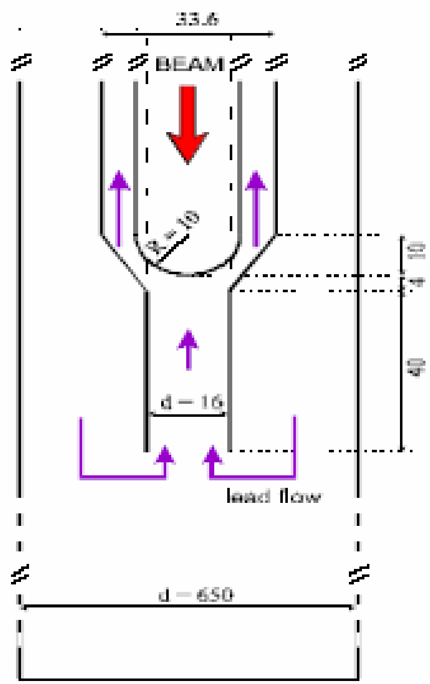


Figure : Spallation target: unit in cm

Pb coolant

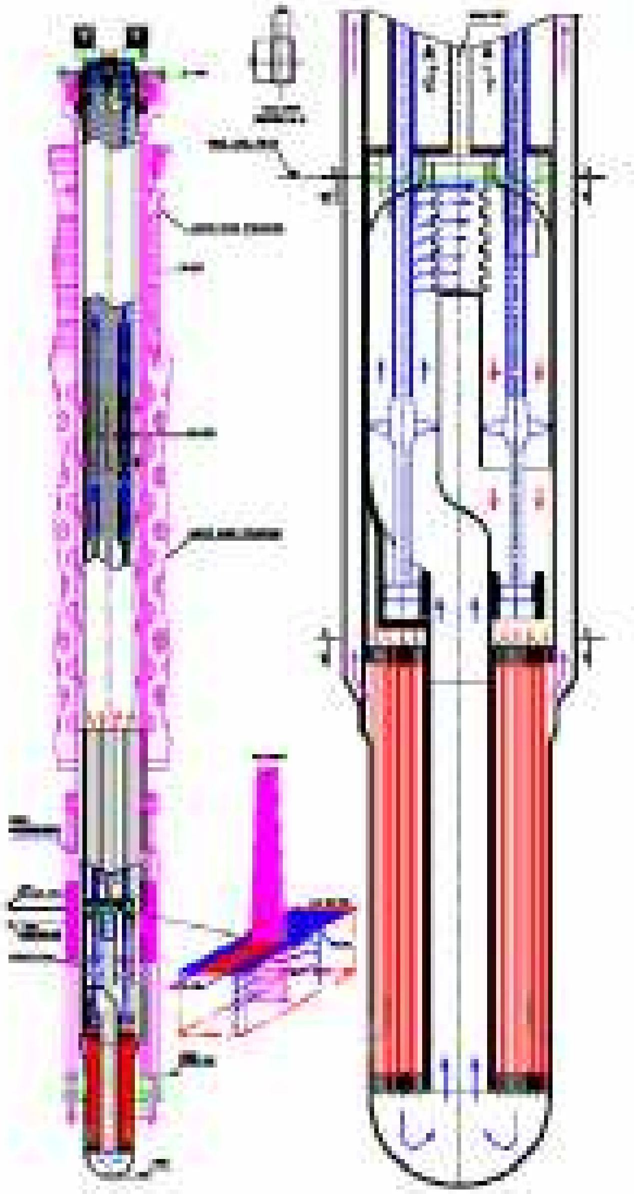


Figure Target unit sketch

ADS-80 MWth-EURATOM 5th Frame Work

L. Cinotti et al.

Proton energy	600 MeV
Current	6mA
Beam power	3.6 MW
Heat Deposited	2.6 MW
LBE Temp.: Inlet outlet	 335 ^{0}C ~440 ^{0}C
LBE Velocity: Flow Average Max. Surface Velocity	 0.5 m/s ≤ 2.0 m/s

JAERI- 800 MWth (Japan) Beam Power 30 MW (1.5 Gev and 20 mA)

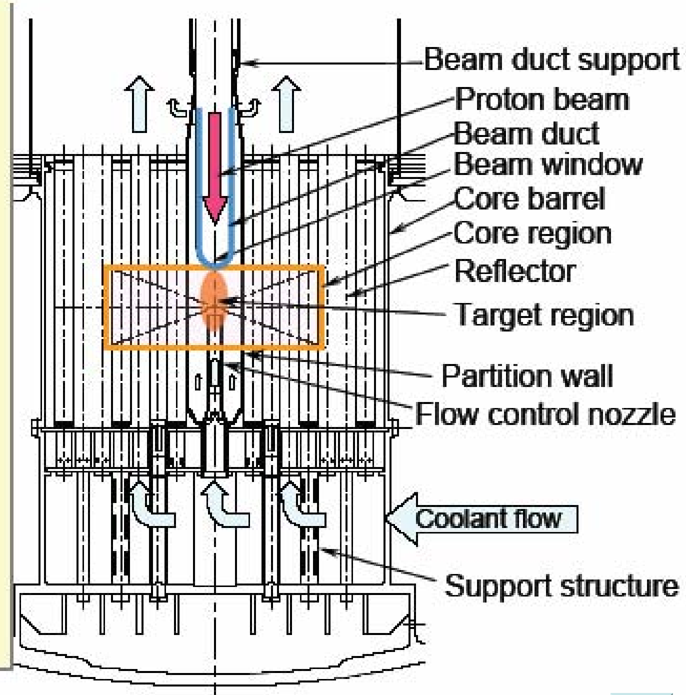
Engineering Feasibility: Spallation Target and Beam Window

- 30 MW proton beam with 1.5 GeV causes heat deposition of 15.7MW.

- Conditions and criteria for the beam window:
  - ✓ Inlet temp. : 300 ºC
  - ✓ LBE flow: < 2m/s
  - ✓ Temp. of outer surface: < 520ºC
  - ✓ Structural strength: Thermal stress, buckling, etc.

- The feasibility of the beam window was verified under the nominal operation conditions, but the effect of corrosion, irradiation and fabrication accuracy should be discussed.

- **We should accumulate experience on LBE spallation target.**



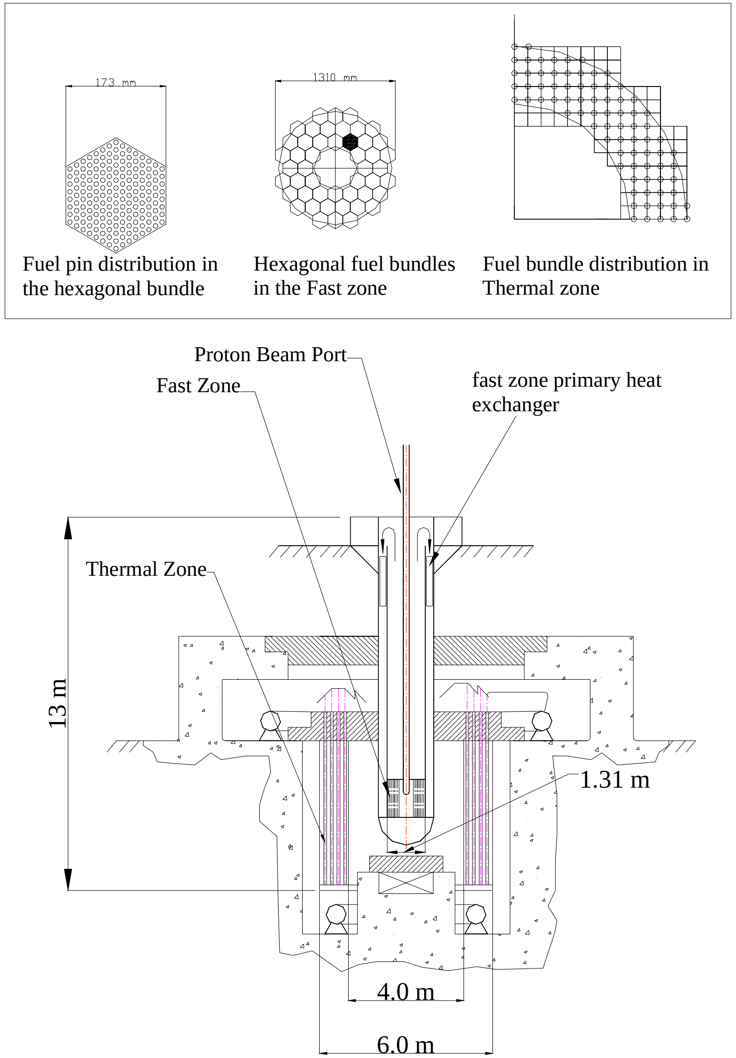


Fig. 1. Schematic of the 750 MW fast-thermal ADS

Indian One-way coupled Fast-Thermal Reactor -750 MW Thermal

-100 MW Fast Core – (Neutron Multiplier)

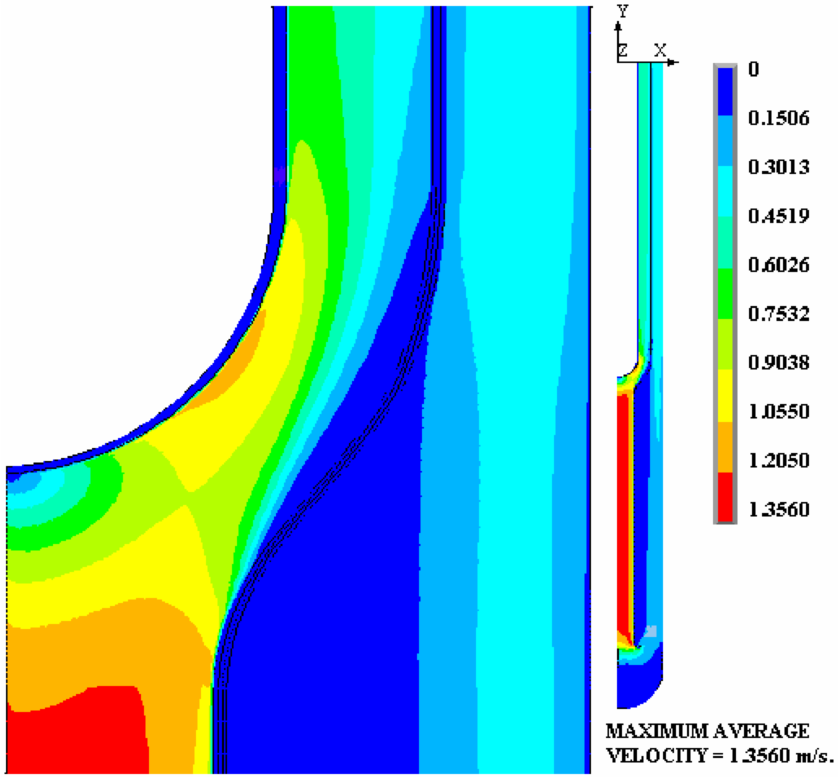
Proton Beam -1GeV,2mA

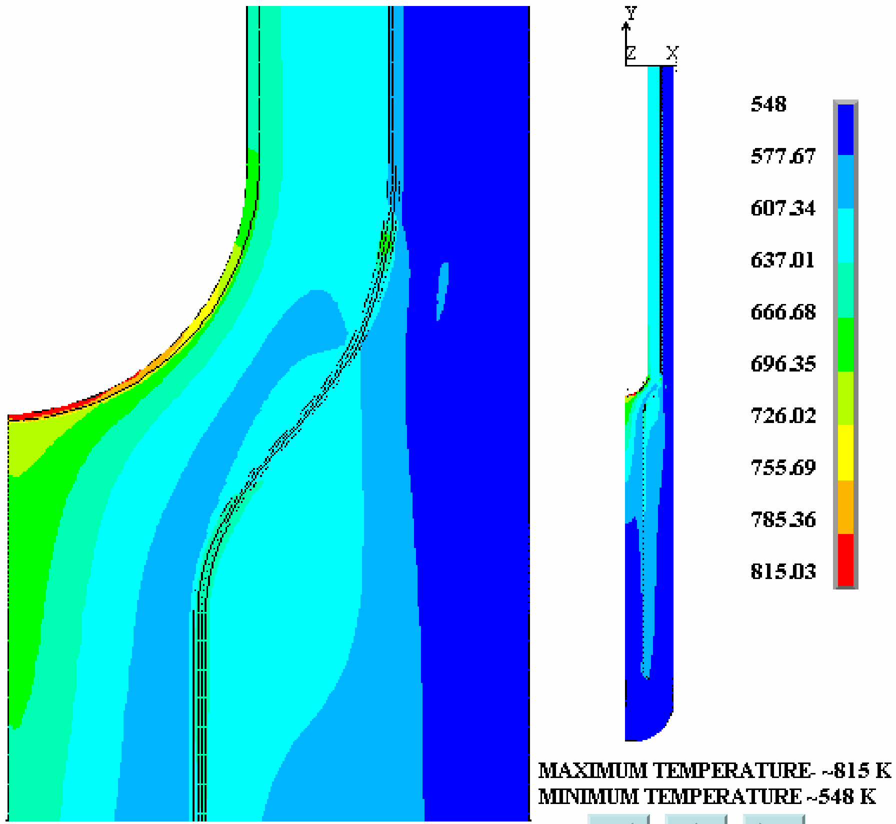
-Inner fast core -Pu /U233 – Th MOX fuel

- -Target and coolant for Fast Core- LBE
- -Outer thermal (PHWR/AHWR) core - low enrichment / insitu produced U233 in Th MOX
- -Separated by gap and thermal liner
- -Keff of each core <~ 0.95
- -Combined Keff <~ 0.98

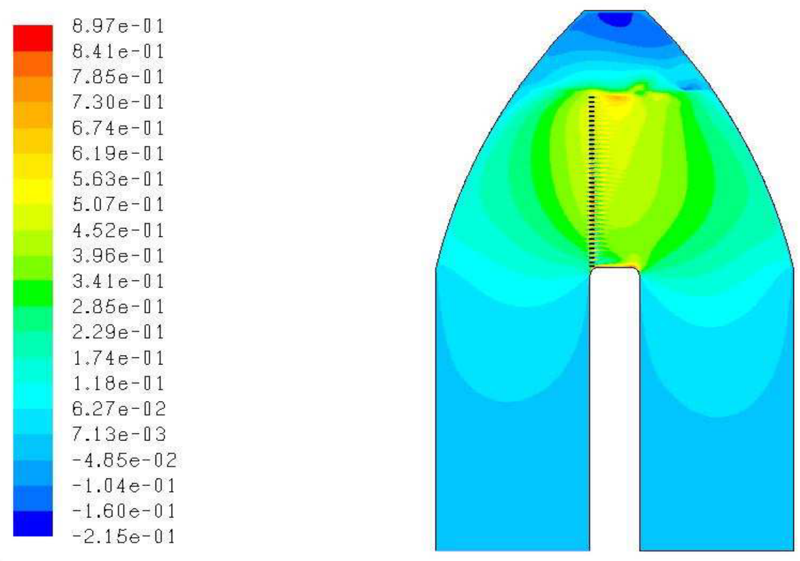
Thermal Analysis of Target for One-way coupled Fast-Thermal Reactor

(1GeV, 2mA Proton Beam)
LBE (91 kg/s, T_{in} = 275 C)
Window (T91, T_{max} = 540 C
Heat Deposition by FLUKA)



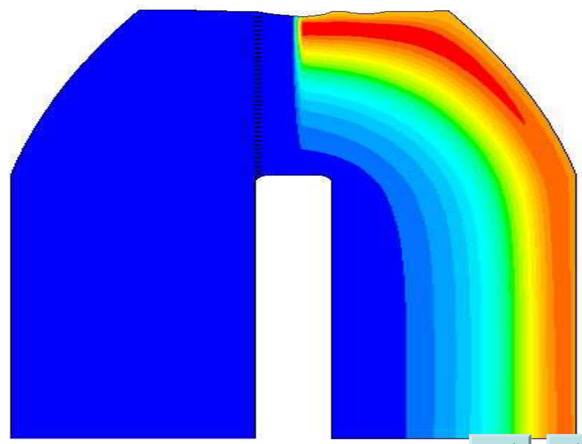


Thermal Analysis of Windowless Target for One-way coupled Fast-Thermal Reactor (1GeV, 2mA Proton Beam)



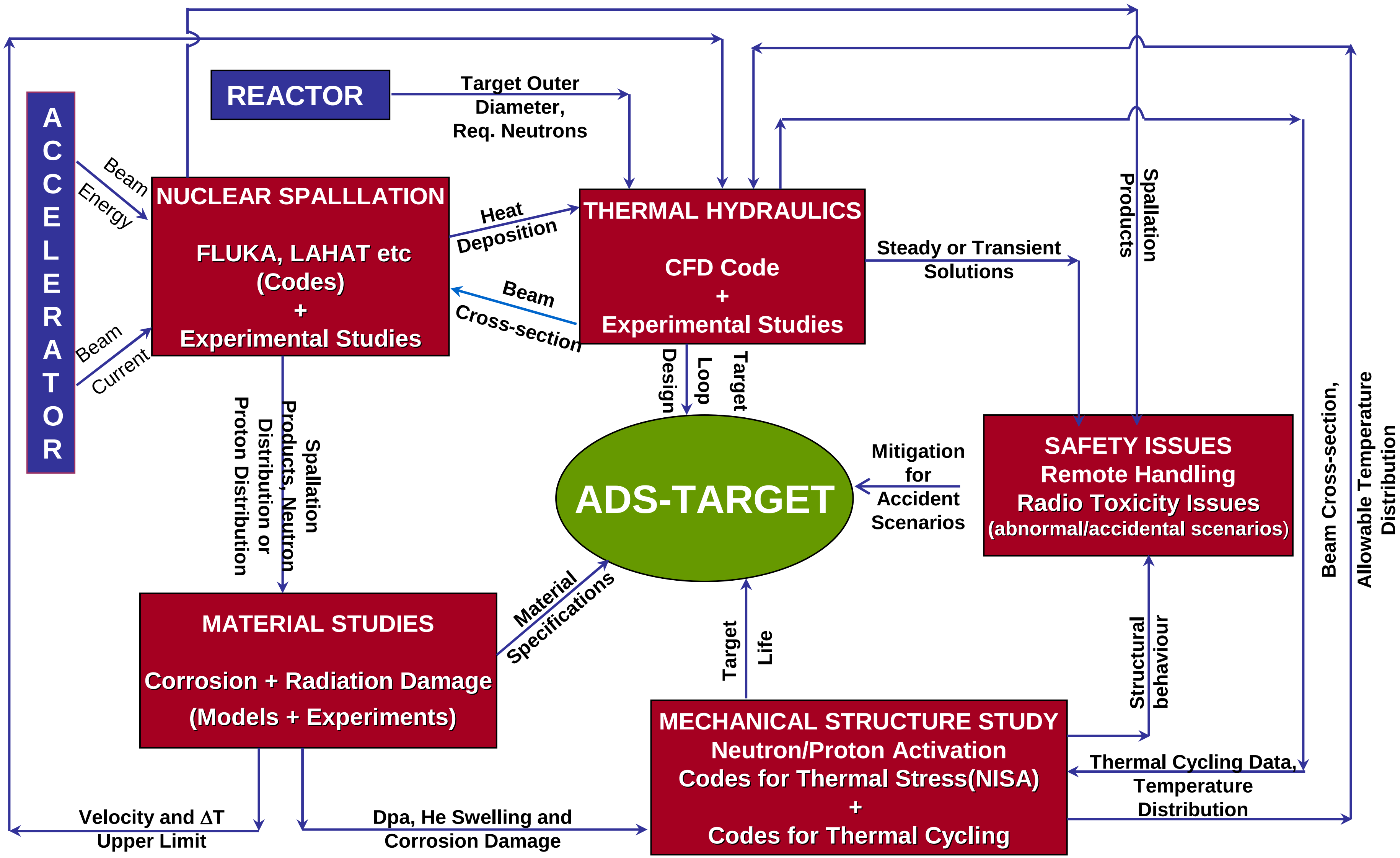
Contours of horizontal-velocity (m/s)

Mass Flow Rate	120 kg/s
Riser Width	0.5 m
Downcomer Width	0.5 m
Inlet Temp	493 K
Flow Diverters	36 blocks 3mm thick 14.5 mm gap
Free surface length	0.64 m



Contours of Temperature (K)
T (maximum surface) ~ 718 K

Thermal-hydraulics and Related Technology Issues of LBE Target System



ADS TARGET DEVELOPMENT

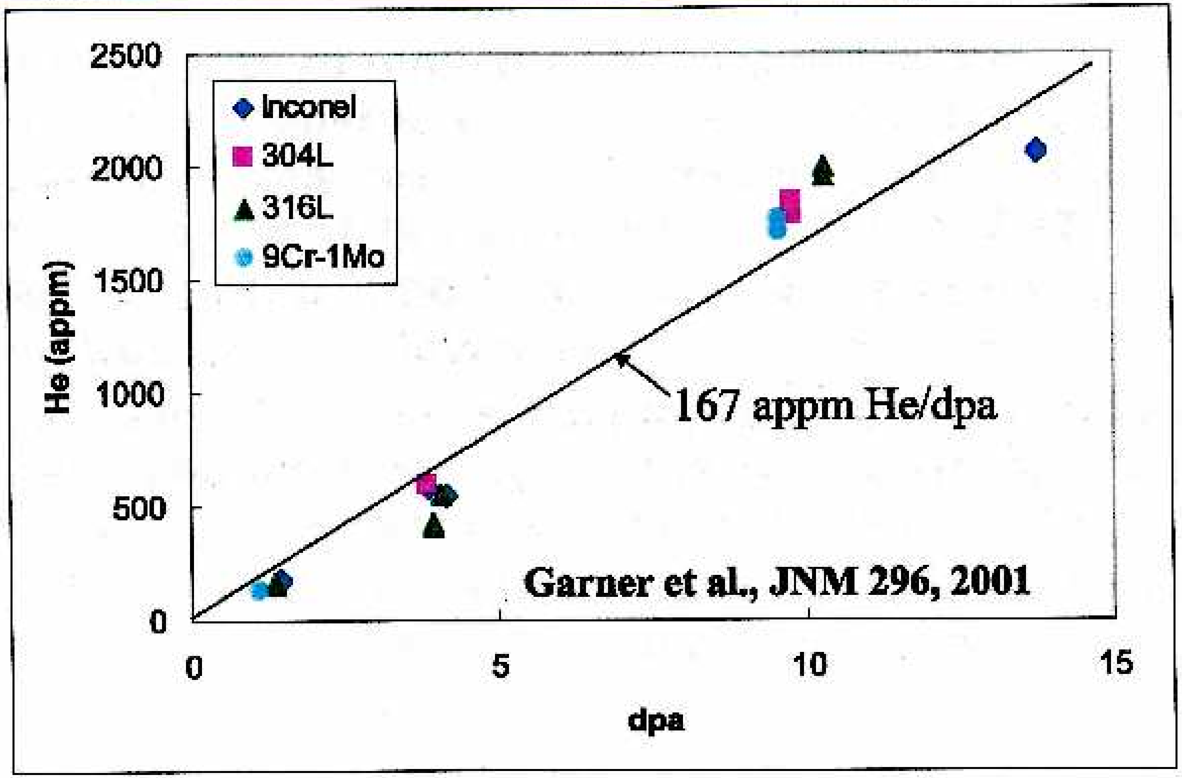
INTER-LINKED TECHNOLOGY ISSUES

Radiation Damage Effects on Target Window

Expected DPA Per Annum: ~100

- Embrittlement
- Irradiation Creep
- Void Swelling
- Hydrogen Generation
- Helium Generation
- Transmutation

Helium measured in various alloys following irradiation in LANSCE with 500-800 MeV protons and spallation neutrons



MEGAPIE Target-T91 Window

Proton beam:570 MeV & 1.4 mA

(European Union)

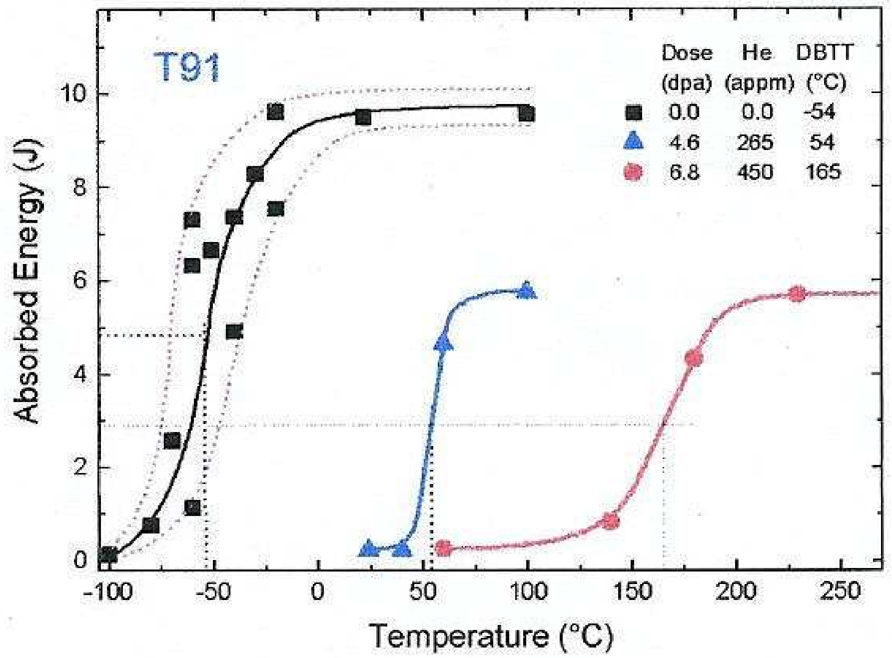


Figure 1: Charpy impact properties of T91 steel in the as-received condition and after irradiation to 4.6 and 6.8 dpa.

Candidate Materials for Target Window

T-91 / F91 (Steel)
(Ni:0.13,Cr:8.26,Mn:0.38,Mo:0.95,Si:0.43,Ti:0.014, V:0.2,C:0.105,P:0.009,S:0.003,Nb:0.08,N:0.055, Al:0.024,Cu:0.08,As:0.02,Sn:0.008,Fe:balance)

HT-9 (Steel)
(Ni:0.5,Cr:12.0,Mn:0.2,Mo:1.0,Si:0.25,W:0.5,V:0.5, C:0.2, Fe:balance)

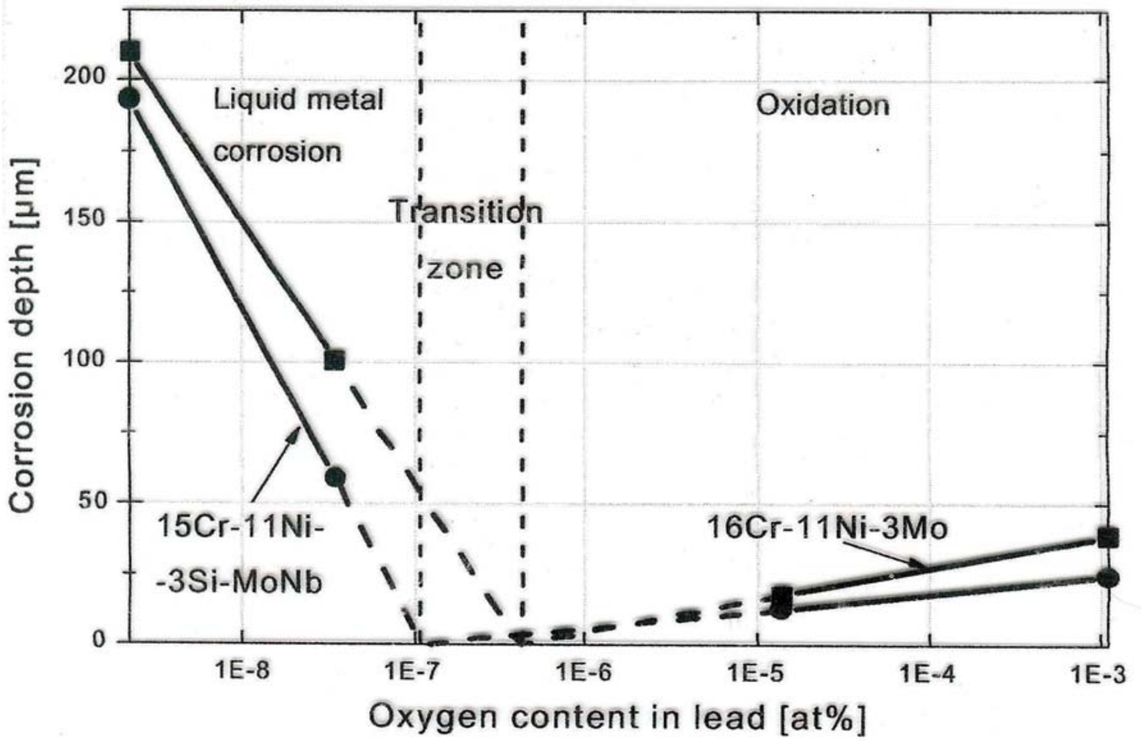
EP-823 (Steel)-Russian Steel
(Ni:0.8,Cr:12.0,Mn:0.6,Mo:1.0,Si:1.3,W:0.8,V:0.4, C:0.2, Fe:balance)

Oxygen for Corrosion Control in lead/LBE

CORROSION OF STEELS

IN FLOWING LEAD after 3000 h at 550°C

From: V. Markov, Prometey, St. Petersburg



End of Lecture -1

Thank You for Your Attention