LH_2-Absorber Development

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NuFACT'00
Monterey, CA
5/25/00

Outline:

1. New absorber dimensions
2. Energy absorption
3. Absorber cooling design approaches
   a. external cooling loop
   b. absorber as heat exchanger
4. Window requirements
5. Other options
6. Prototype & test plans

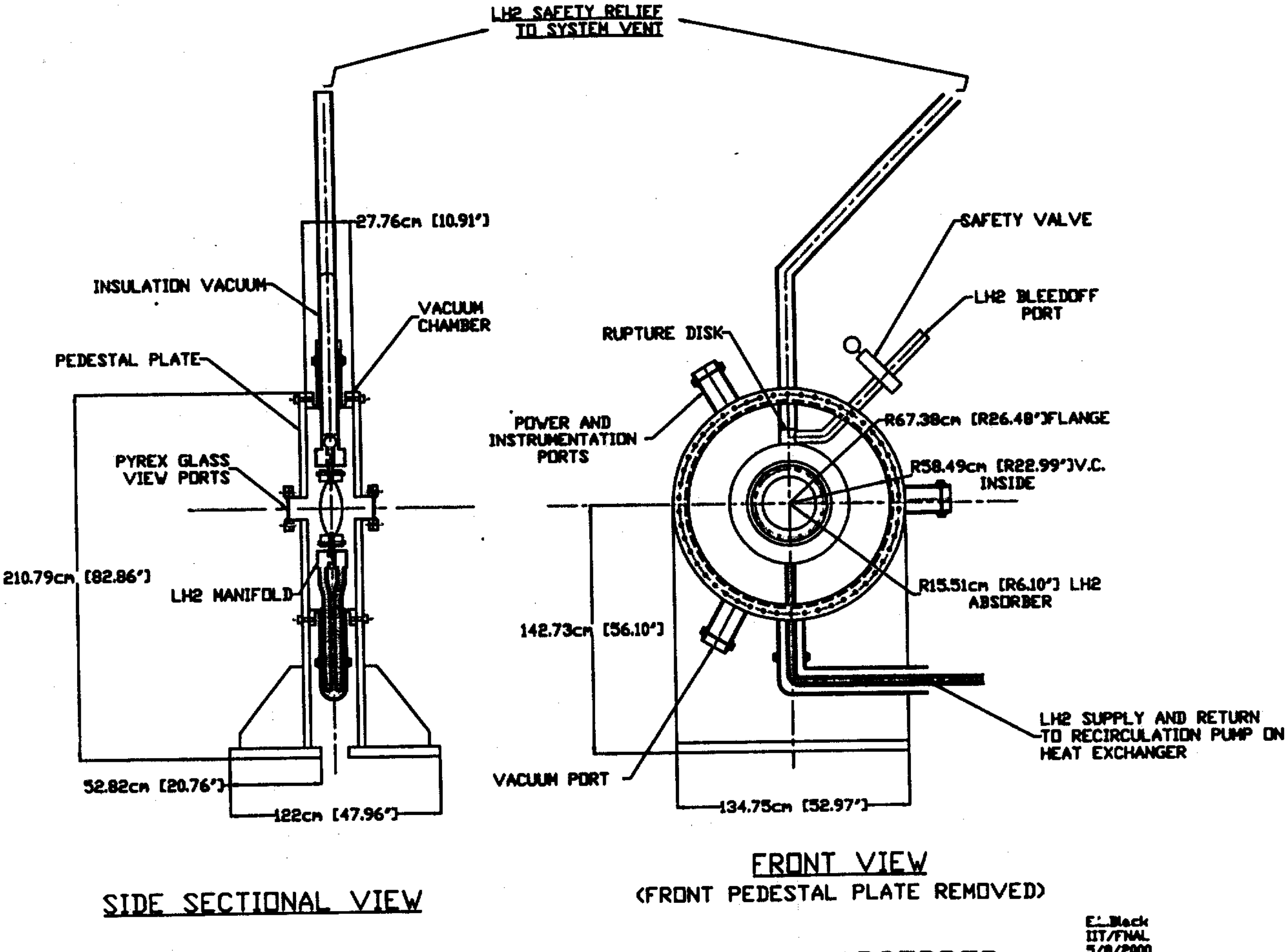
LH_2 Absorbers

Typical absorber specifications:

Config. / Param.	Single-Flip	FOFO1	FOFO2	unit
L	30	12.6	13.2	cm
ρ	0.0708	0.0708	0.0708	g/cm^3
areal mass density	2.1	0.89	0.93	g/cm^2
r	20	15	10	cm
V	38	9	4	*l*
T	20	20	20	K
P	2	2	2	atm
b.p.	22.8	22.8	22.8	K
f.p.	13.8	13.8	13.8	K

Energy absorption vs. muon momentum:

p_μ	$\langle dE/dx \rangle$	$\langle \Delta E \rangle$	$\langle P \rangle$(5.10[12]@15Hz)	
(MeV/c)	[MeV/(g/cm²)]	(MeV)	(W)	
106	6.0	13	230	30 cm
211	4.2	5.6	160	
317	4.1	5.5	157	
106	6.0	3.4	97	12.6 cm
211	4.2	2.4	68	
317	4.1	2.3	66	



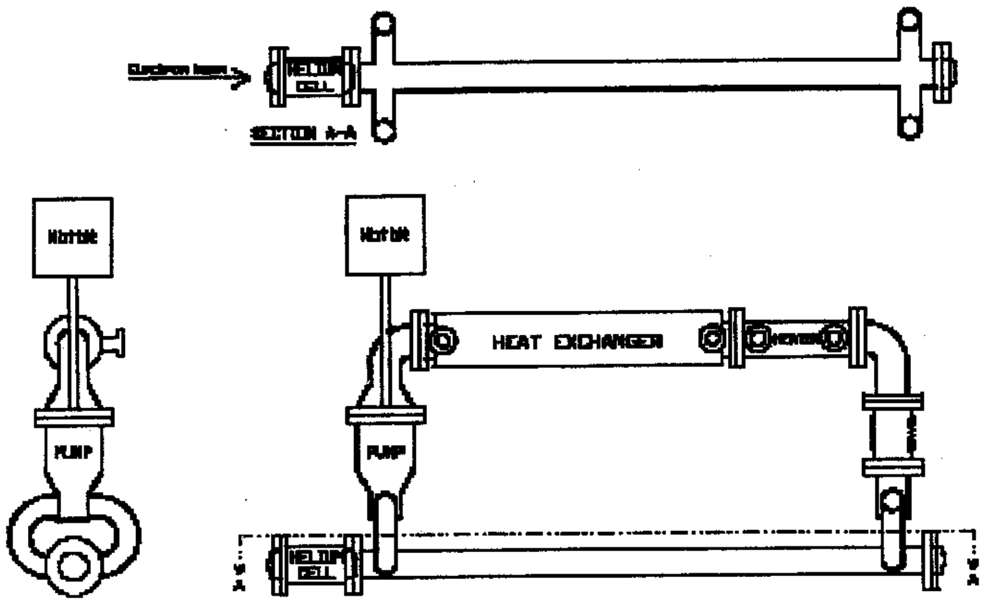
TEST STAND FOR THE FOFO ABSORBER

Key Problem:

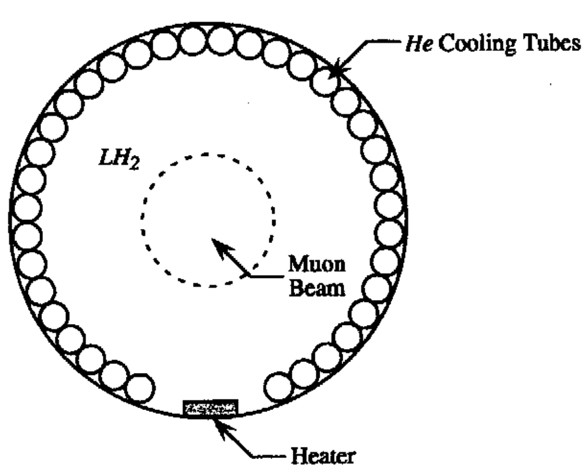
- How to get the heat out?

→ Two design approaches:

1. External cooling loop



2. Absorber as heat exchanger



LH_2 Cooling

1. External-loop design (á là SLAC, Bates...):

$c_p = 1.1 \times 10^4$ J/kg·K

$$\Delta T / s = \frac{\langle P \rangle}{c_p V \rho}$$

30-cm case

$$\leq \frac{180\text{W}}{1.1 \times 10^4\ \text{J/kg} \cdot \text{K} \times 38 l \times 0.0708 \text{kg}/l} = 0.006 \text{K/s}$$

→ Indep. of L since both $\langle P \rangle$, $V \propto L$

⇒ need < 0.05 volume change/s

= 1.9 l/s (Single-Flip)

(4x less for FOFO1)

→ should be no problem

LH_2 Cooling (cont'd)

2. **Convection approach** (K. Cassel, IIT):

Rate of heat transfer from LH_2 to He coolant:

$$\dot{q} = -\frac{A(T_o - T_i)}{\left(\frac{1}{h_{LH_2}} + \frac{\Delta x}{k_w} + \frac{1}{h_{He}}\right)\ln\left(\frac{T_{LH_2} - T_o}{T_{LH_2} - T_i}\right)}$$

where

A = surface area of cooling tubes
T_i = temp. of helium in
T_o = temp. of helium out
T_{LH_2} = avg. temp. of LH_2
h_{LH_2} = convective heat transfer coeff. for LH_2
h_{He} = convective heat transfer coeff. for He
Δx = thickness of cooling-tube walls
k_w = thermal conductivity of cooling-tube walls

Example (30-cm case, guestimate $h_{LH_2} \approx 130\ \mathrm{W/m^2 \cdot K}$):

$$\dot{q} = -\frac{0.25\,\mathrm{m}^2\ (15\mathrm{K} - 14\mathrm{K})}{\left(\frac{1}{130\mathrm{W/m^2\cdot K}} + \frac{1\mathrm{mm}}{170\mathrm{W/mK}} + \frac{1}{1580\mathrm{W/m^2\cdot K}}\right)\ln\left(\frac{20-15}{20-14}\right)}$$

$$= 180\ \mathrm{W}\ @\ \dot{m} = 0.0248\ \mathrm{kg/s} \Rightarrow \dot{m}/\rho = 3.5\ l/\mathrm{s}\ @\ 2\ \mathrm{atm},\ 14\ \mathrm{K}$$

BUT - need to understand $h_{LH_2} \Rightarrow$ CFD

Spatial distribution of heat load:

- **Energy deposition highly concentrated in the middle!**

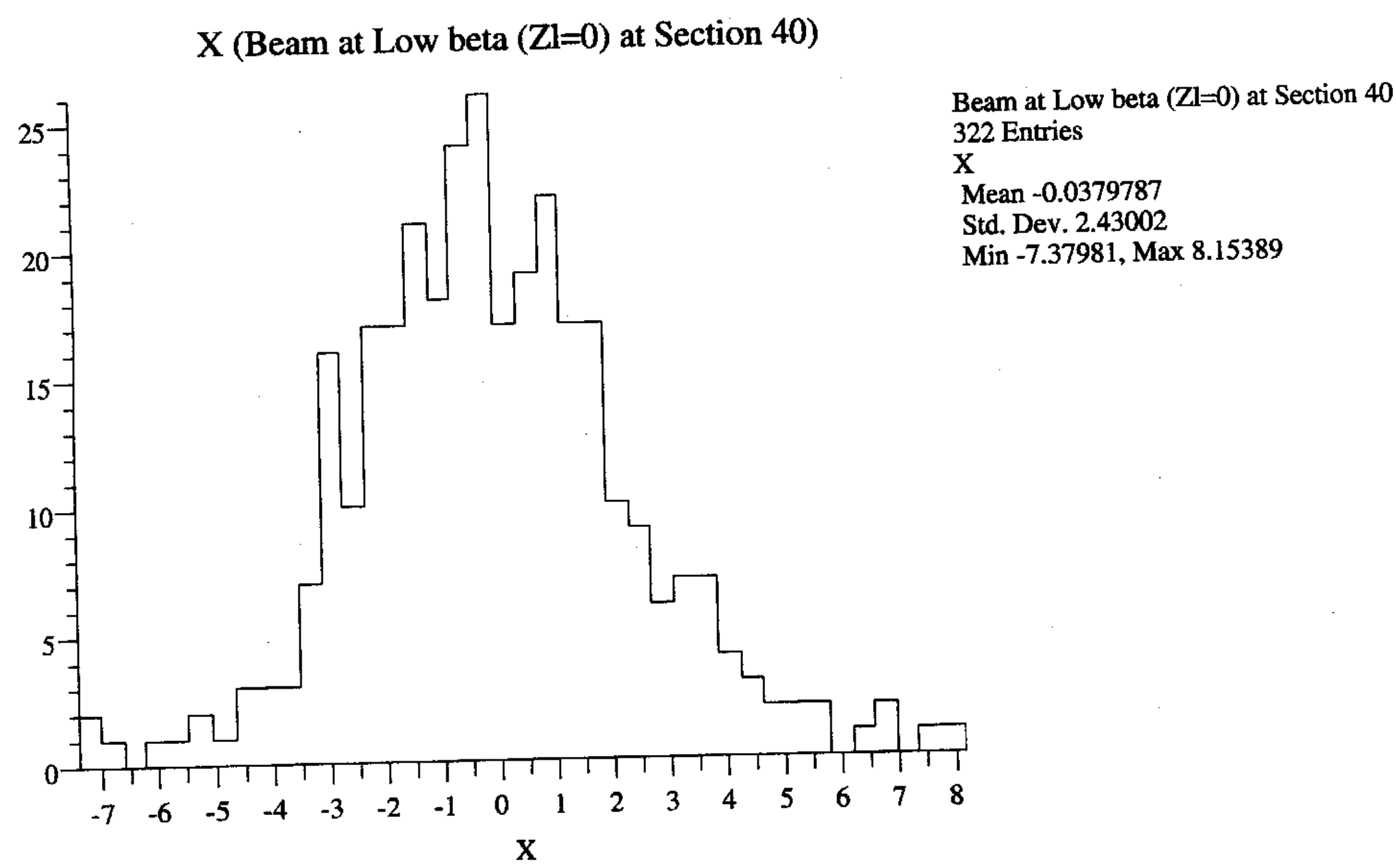
→ By end of cooling channel, areal power density along axis is ~$10^2\times$ average over face of absorber

⇒ need to ensure cross-flow near beam rather than longitudinal flow

  – occurs naturally in convective design

  – also possible in external-loop design,

- Parametrize spatial distribution by $s \equiv \sigma_x/r \gtrsim 0.25$:



CFD Study of Fluid Flow:

(K. Cassel & M. Boghosian, IIT)

- **What matters in convective design is h_{LH_2}**

→ depends on $\dot{q}$ in a manner to be determined by computational fluid dynamics (CFD):

On a 2D grid, iteratively solve Navier-Stokes and energy equations to calculate Nusselt number vs. Rayleigh number, where

$$Ra_D = \frac{g\beta D^5}{\nu\alpha K}\frac{\dot{q}}{V},$$

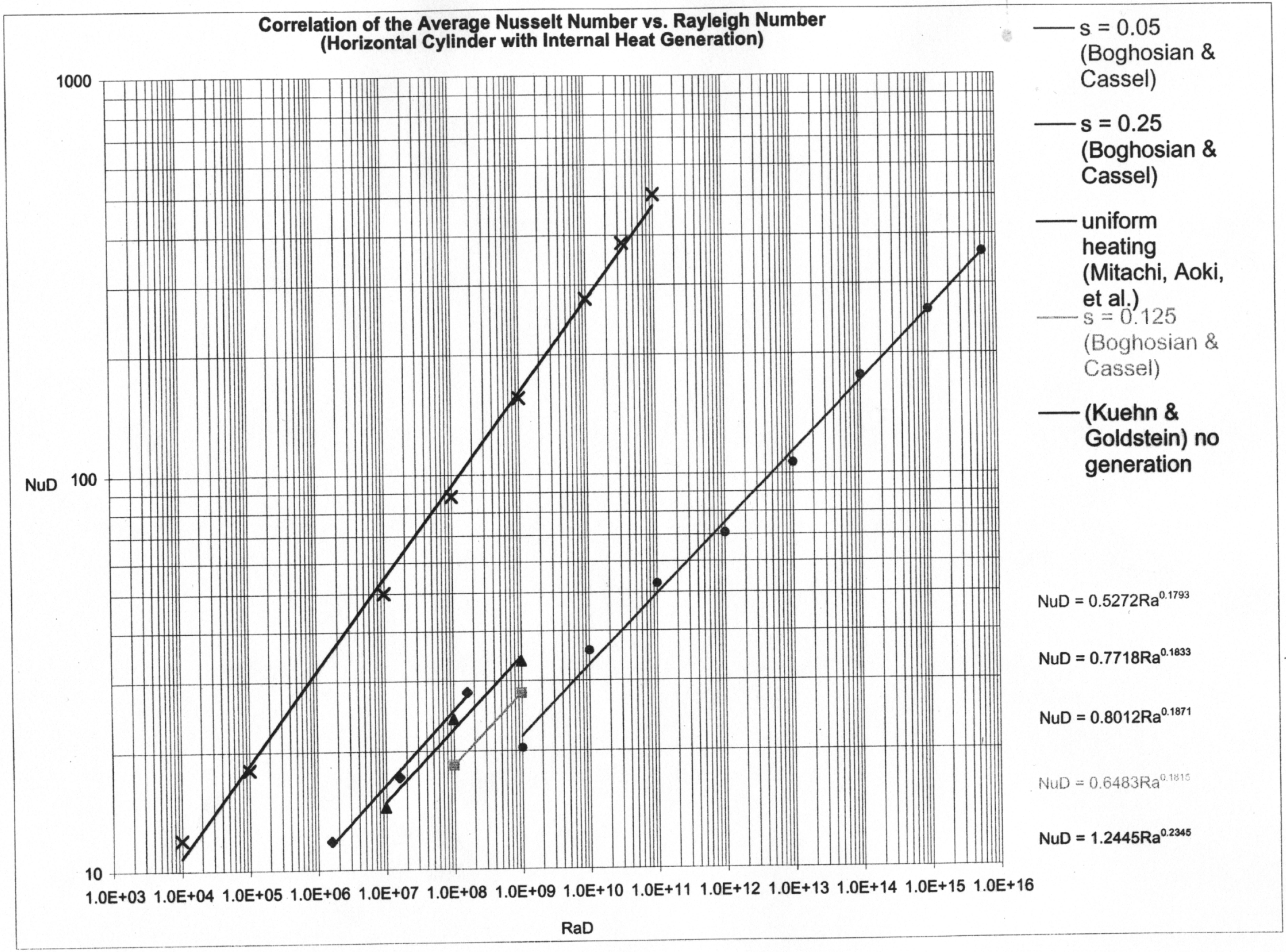
$$Nu_D = \frac{D}{K}\,h_{LH_2},$$

and

$g = 9.8$ m/s^2
$\beta = (1/V)\,dV/dT$ = volumetric coeff. of thermal expansion
D = diameter of absorber
ν = kinematic viscosity of LH_2
α = thermal diffusivity of LH_2
K = thermal conductivity of LH_2
V = volume of absorber

- Given $K = 0.0987$ W/m·K, $D = 0.4$ m, need $Nu_D \approx 400$ to give $h_{LH_2} \approx 130$ W/m^2·K

⇒ $Ra_D \sim 10^{15}$ for $s = \sigma_x/r \approx 0.25$


Correlation of the Average Nusselt Number vs. Rayleigh Number
(Horizontal Cylinder with Internal Heat Generation)
NuD
1000
100
10
1.0E+03 1.0E+04 1.0E+05 1.0E+06 1.0E+07 1.0E+08 1.0E+09 1.0E+10 1.0E+11 1.0E+12 1.0E+13 1.0E+14 1.0E+15 1.0E+16
RaD
s = 0.05 (Boghosian & Cassel)
s = 0.25 (Boghosian & Cassel)
uniform heating (Mitachi, Aoki, et al.)
s = 0.125 (Boghosian & Cassel)
(Kuehn & Goldstein) no generation
NuD = 0.5272Ra^0.1793
NuD = 0.7718Ra^0.1833
NuD = 0.8012Ra^0.1871
NuD = 0.6483Ra^0.1815
NuD = 1.2445Ra^0.2345

Window Thickness

- ASME UG-32, head thickness for pressure vessels:

hemispherical: $$t = \frac{0.5PL}{SE - 0.1P}, \quad s = L = 0.5D$$

ellipsoidal: $$t = \frac{0.5PD}{SE - 0.1P}, \quad s = 0.25D$$

torispherical: $$t = \frac{0.885PD}{SE - 0.1P}, \quad s = 0.169D$$

where
P = pressure differential
L = radius of curvature
D = length of major axis
S = max allowable stress
E = weld efficiency
s = sagitta

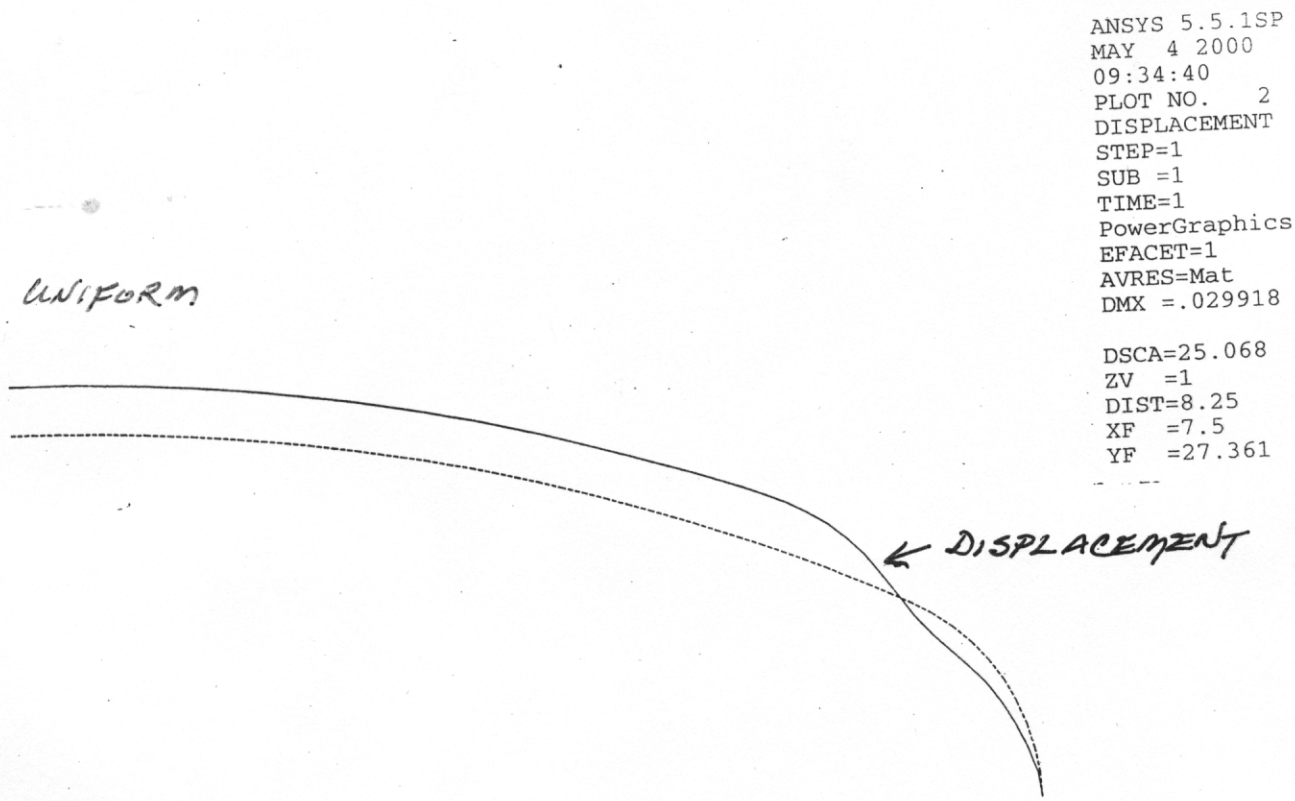
<u>Notes:</u> 1. ellipsoid has (major axis) = 2 × (minor axis)
2. "torisphere" has $r_2 = 6\%\ r_1$

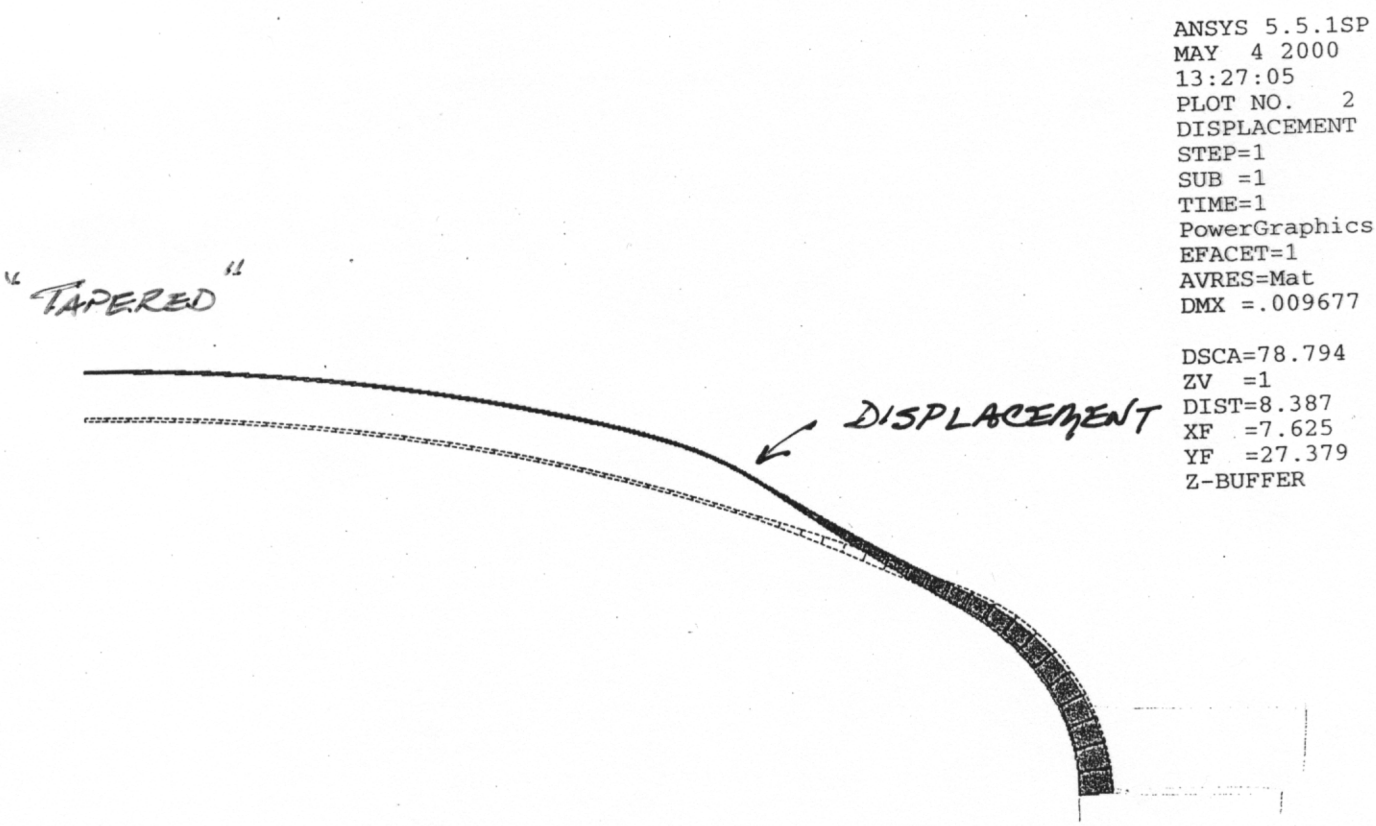
- Fermilab/ASME safety factors:
  S = smaller of $S_u/4$, $S_y/1.5$

- 6-month study:
  Take $E \approx 0.9$ (inspected full-penetration welds), Al alloy, 1 atm:

Case:	Single-Flip	FOFO1	FOFO2
Parameters:	r = 20 cm, ellipsoidal	r = 15 cm, torispherical	r = 10 cm, ellipsoidal
Thickness:	300 μm	400 μm	200 μm

TORISPHERICAL FEA STUDY





Recent window progress:

1. Safety may preclude operation at ≈1 atm:
   - J. Kilmer (Fermilab): risk of cryopumping air contamination into vent lines

   → recommends 2 atm

   ⇒ might R&D on safety design allow operation as low as 1.1 atm?

2. ASME standard assumes uniform thickness
   - ANSYS FEA calculation (Z. Tang, Fermilab):

   → can be ≈30% thinner in middle if suitably thicker at edges

   - Integral flange (machined, not welded) ⇒ E = 1
   - Will continue to iterate → try to reduce thickness further

Case:	**Single-Flip**		**FOFO1**		**FOFO2**	
Params:	**r = 20 cm, 1 atm, ellipsoidal, E = 0.9**	**r = 20 cm, 1.1 atm, improved torispherical,* E = 1**	**r = 15 cm, 1 atm, torispherical, E = 0.9**	**r = 15 cm, 1.1 atm, improved torispherical, E = 1**	**r = 10 cm, 1 atm, ellipsoidal, E = 0.9**	**r = 10 cm, 1.1 atm, improved torispherical,* E = 1**
Thick:	300 μm	367 μm	400 μm	275 μm	150 μm	180 μm

*Note: torispherical shape ⇒ improved circulation near windows

Other Ideas:

1. Thinner windows

   AlBeMet? Beryllium? (compatible with LH_2?)

	ρ	S_y	S_u	X_0
Material	**(g/cm^3)**	**(MN/m^2)**	**(MN/m^2)**	**(cm)**
Al (6061-T6)	**2.7**	**241**	**289**	**8.9**
AlBeMet	**2.1**	**314**	**413**	**18.8**

2. LiH?

   Hazardous to handle since reacts with H_2O, releasing hydrogen and igniting!

   Not available commercially in large pieces

   On our list of things to think about...

3. "No" windows!

   Use high-pressure ($\approx$20 atm) cold gaseous hydrogen
   $\Rightarrow$ 1 thick window at each end

   - OK if $\beta \approx$ constant (e.g. single-flip, DFOFO)

   $\rightarrow$ would need R&D on operating RF cavities in high-pressure hydrogen atmosphere (freon/SF_6 admixture?)

Prototype Test Plans

(M. A. C. Cummings, NIU)

1. Destructive Al window test at $\geq 4P_W$
2. (Cryogenic) material tests of AlBeMet
3. Fluid-flow bench tests (certify CFD calcs)
   - LH_2 analogue (water?) at room temp.
   - heat fluid electrically?
   - monitor heat transfer in each heat-exchanger tube?
   - understand signatures of boiling
4. Cryo bench test
5. High-power beam test

Beam Tests

• Requirements:

1. Availability within next ≈year
2. Particle energy and flux sufficient to penetrate absorber and deposit ~10W/cm
3. Accommodate one or more LH_2 absorbers and possible solenoid
4. Desirable: near Fermilab

• Options:

Argonne: (poor solution – low flux or poor equipment access)

Beamline	Particle / Energy	flux (/s)	⟨P⟩ (W/ cm)
1. APS	e^+, e^- / 450 MeV	$5{\cdot}10^{13}$	2
2. IPNS	p / 450 MeV	$9{\cdot}10^{13}$	5
3. Atlas	heavy nuclei / 100–2000 MeV	low	low
4. LINAC	e^- / 20 MeV	$3{\cdot}10^{11}$	low

Bates

CEBAF

MSU

SLAC

TRIUMF

Summary & Outlook:

- Have conceptual solutions for main engineering problems
- Plan:
  1. complete finite-element analyses of stresses in graduated windows
  2. continue CFD studies of flow
  3. refine designs & iterate with simulators
  4. refine cost estimates
  5. FY00-01: build and test prototypes
     – including high-current beam test
  6. investigate LiH as option
  7. consider high-pressure gaseous hydrogen?