

# 1. MATERIAL SCIENCES

## 1.1. Target foils

**Chairmen: V. Bechthold ( Karlsruhe ) and R.J. Nickles ( Madison )**

V. Bechthold discussed the general criteria for evaluating foil materials, seals, cooling and maintenance. The ideal material should

- be available in a 1–200  $\mu\text{m}$  range of thicknesses, pin–hole free
- have a high mechanical strength
- have a high melting point
- have a good thermal conductivity
- have chemical resistance to oxidation.

The foil is secured to the supporting flange, sealed either by an O–ring or welding. The temperature limits of O–rings were discussed; Perbunan ( 100°C ), Viton ( 150°C ), silicone ( 160°C ), Kalrez ( 260°C ) and metals ( In, Cu, Au and Al ). The radiation effects on the bulk properties of these materials were also considered. Welded foils have definite advantages in strength and heat conduction, but pose additional constraints on the foil and support materials.

To assist foil cooling, helium–cooling of a double–foil sandwich is preferred over simple indirect cooling of a single foil from the support flange. Foil lifetimes should exceed 100  $\mu\text{Ah}$ . Replacement should be done through remote handling facilities dedicated to routine production of radioisotopes.

R.J. Nickles followed with particular emphasis on maximizing yield when beam current is limited.  $X(p,n)Y$  reactions on enriched targets offer the needed hundred  $\text{mCi}/\mu\text{A}$  saturation yields of  $^{13}\text{N}$ ,  $^{15}\text{O}$  and  $^{18}\text{F}$  at 11 MeV, with concomitant need for

- minimal target inventories and recycling
- rigorous monitoring of foil integrity
- neutron counting to assure target thickness.

Early warning of foil failures is given by a residual gas analyzer (RGA) set on the target mass ( e.g.  $^{18}\text{O}_2$ : 36 amu ), sampling the system vacuum immediately in front of the foil. This distinctive partial pressure shown below ( Figure 1. ) is several decades more sensitive than the total pressure in detecting pre–pinholes, allowing a solenoid fast valve ( msec ) to close before substantial gas loss has occurred. The issue of density reduction is simply put to rest by observing the thick target pressure, above which the neutron counting rate is unchanged. Finally, the need for extreme care in excluding "hard cations" in aqueous  $^{18}\text{F}^-$  has led to the use of platinum, and now rhodium as the entrance foil in  $\text{H}_2^{18}\text{O}$  targets. The one  $\text{cm}^3$  target inventory is rapidly pumped in a closed loop ( recirculation time = few sec ) to free the target of bubbles to measure the conductivity during irradiation and to assist cooling.

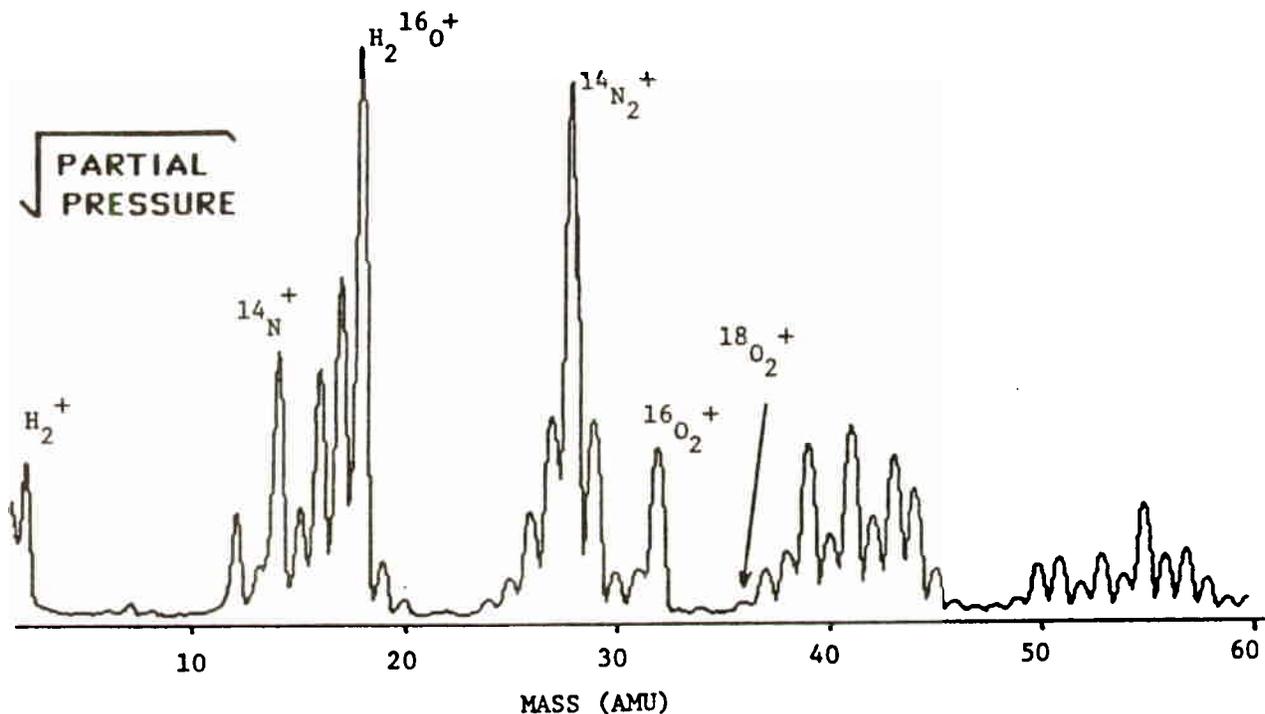


Figure 1.

Several special purpose targets were discussed, including

- a two-shot, passivated nickel target to produce  $^{18}\text{F}_2$  from  $^{18}\text{O}_2$
- a  $2\text{ cm}^3$   $^{80}\text{Kr}$  target with hair-triggered fast valves
- a  $^{15}\text{N}_2$  target with an internal carbon filament for the production of  $\text{C}^{15}\text{O}_2$  during bombardment.

The targets destined for use on the CTI 11 MeV cyclotron at Wisconsin are built from VCR fittings, with the nickel gasket modified to become a helium-cooled double foil module. The foils (  $10\ \mu\text{m}$  Havar;  $25\ \mu\text{m}$  rhodium ) are silver-brazed ( BT; mp =  $780^\circ\text{C}$  ) to the gasket, which is then indium-tinned to minimize the closing torque required. The result is an all-metal seal with an extended range in operating temperature and pressure.

In the discussion that followed, considerable time was spent in a comparison of the various foil materials with regard to their mechanical, thermal and chemical properties. The table below lists fourteen candidates, with an indication of their welding and activation properties. Foil suppliers were discussed, with Havar available from Hamilton Watch, Goodfellows and a Swiss source. TRIUMF/AECL volunteered to handle small requests, resolving the minimum-order dilemma faced by single buyers.

A discussion of thermal properties of foils followed, recognizing that conduction is a minor heat sink when compared to forced convection between a double-foil window. The radial equation describing heat transfer by conduction alone

$$\frac{dQ}{dt} = Kt 2\pi r \frac{dT}{dr}$$

is solved inside  $T = \left(\frac{P}{2Kt}\right) \left(r^2 + \ln \frac{A}{R} + \frac{1}{2}\right) + T(0) \quad r \geq R$

and outside  $T = P \left(\ln \frac{A}{r}\right) + T(0) \quad A > r > R$

the beam strike of radius  $R$  on a foil supported at radius  $A$ , temperature  $T_0$ , shown below for  $P = 1 \text{ W} = 1 \mu\text{A} \cdot 1 \text{ MeV}$ ,  $t = 25 \mu\text{m}$  and  $K = 0.4 \text{ W/cm} \cdot \text{°C}$ . The addition of a radiant  $\sigma T^4$  term is a second order correction. The essential data needed for a rational approach to foil selection is the detailed information on tensile strength at elevated temperature.

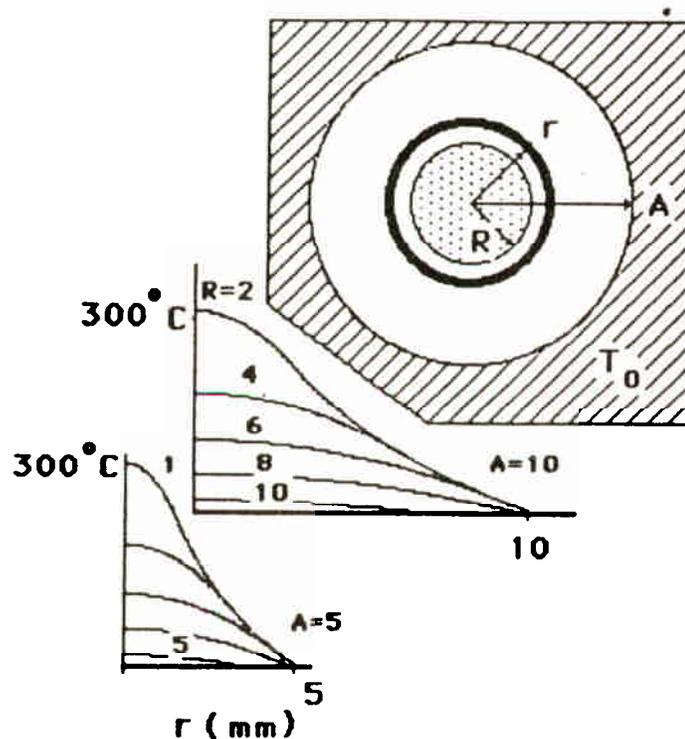


Figure 2

The Louvain group observed that beam wobbling was effective only in the case when the beam strike was swept at a frequency (kHz) far greater than the reciprocal of the thermal rise time.

Beam sweeping at mains frequency ( 50–60 Hz ) is analogous to slowly moving a concentrated blowtorch over a thin plate.

The effect of flexing and fatigue were discussed by J.R. Dahl. Particular attention is needed

- to avoid sharp edges on the support flange
- to avoid unnecessarily cycling the curved foil by reversing the pressure gradient
- to pre-shape the curvature under pressure loading prior to filling

The need for chemical inertness of the entrance foil is widely appreciated for  $^{18}\text{F}$  targets, but C. Crouzel pointed out that sputtering of cold carbon from steel foils can compromise the specific activity in the production of  $^{11}\text{CO}_2$  during the workup of labeled neuroleptics.

A questionnaire polling the foil material preference revealed a rich diversity of opinions and prejudices.

**Table 2**  
**Target foil material**

Material	Weldability	Activation Problems
Be	V	high flux of neutrons during irradiation
C*	–	none
Al and Ti	acid flux soldering bonding in H <sub>2</sub> atmosphere	slight – <sup>24</sup> Na, <sup>48</sup> V
SS	V,T	<sup>56</sup> Co, <sup>57</sup> Co, <sup>58</sup> Co
Havar	V	moderate to high (energy dependent)
Ni	V,T	<sup>61</sup> Cu
Cu	V,T	<sup>65</sup> Zn
Nb	–	moderate
Mo	–	moderate
Rh	V	<sup>103</sup> Pd
Ta	–	slight
W	–	slight
Pt	V,T	slight

\* highly anisotropic

Silver brazing

V – vacuum brazing  
T – torch brazing

Table 1  
**Properties of entrance foil materials**

Material	Atomic Number	Density [g/cm <sup>3</sup> ]	Melting point [°C]	Tensile strength [kpsi]	Thermal conductivity [cal/cm-°C]	dE/dx (10 MeV protons) [keV/μm]
Be	4	1.85	1283	80	0.44	6.9
C	6	2.2	>3000	0.6*	13.6*	9.1
Al	13	2.7	660	30	0.50	9.2
Ti	22	4.5	1668	120	0.14	13.5
SS	26	8.02	1427	120	0.08	22.9
Havar	27	8.3	1493	250	0.03	24.2
Ni	28	8.9	1453	120	0.20	25.4
Cu	29	8.9	1082	30	0.94	24.2
Nb	41	8.6	2468	50	0.12	21.2
Mo	42	10.2	2610	80	0.32	24.4
Rh	45	12.4	1966	110	0.32	29.4
Ta	73	16.6	2996	35-70	0.13	30.8
W	74	19.3	3387	500	0.40	36.3
Pt	78	21.4	1769	20	0.17	38.6

\* highly anisotropic

A simplistic figure of merit for conductive heat transfer ( CHT ) away from the beam strike can be formed from the product

$$CHT = \frac{\text{melting point} \times \text{conductivity} \times \text{tensile strength}}{\text{energy loss suffered by the beam.}}$$

### Physical Properties of Target Foil Materials

Material	Density kg/dm <sup>3</sup>	Melting Point °C	Thermal Cond. $\frac{\text{cal}}{\text{cm sec } ^\circ\text{C}}$	Tensile Strength kg/mm <sup>2</sup>
Al	2.7	660	0.53	10 - 30
Ti	4.5	1668	0.041	30 - 80
Ni	8.9	1453	0.22	35 - 100
Cu	8.96	1083	0.94	15 - 60
Mo	10.2	2620	0.35	30 - 250
Ag	10.5	960	1.00	10 - 40
Ta	16.6	2996	0.13	35 - 100
W	19.3	3385	0.48	15 - 400
Pt	21.5	1773	0.17	20 - 40
Au	19.32	1063	0.71	10 - 30
Monel 400	8.85	~1375	0.062	50 - 85
Inconel 600	8.43	~1300	0.043	60 - 80
Hastelloy C	8.94	~1300	0.02	60 - 130
HAVAR	8.3	~1350	~0.04	180 - 250
SS 1.4571	7.8	~1300	0.04	50 - 75
Cu Be 2	~8.5	~800	0.3	40 - 150
Monel 400: 65% Ni / 31% Cu / Si / Fe / Mn / C				
Inconel 600: 76% Ni / 16% Cr / 7% Fe / Mn / Si / Cu				
Hastelloy C: 57% Ni / 16% Mo / 16% Cr / 6% Fe / 4% W / Co / Mn				
HAVAR: 42.5% Co / 20% Cr / 13% Ni / 3% W / Fe / Mo / Mn				
SS 1.4571: 17% Cr / 11% Ni / 2% Mn / 2% Mo / Si / Ti / Fe				
Cu Be 2: 97% Cu / 2% Be / Co / Ni				

Table I.4: ELASTOMERS

POLYMER PROPERTIES (ASTM)	ACRYLICS (PURE GUM)	BUTYL (PURE GUM)	ETHYLENE PROPYLENE	FLUOROELASTOMERS			NYPALON (PURE GUM)	NATURAL RUBBER (PURE GUM)
				VINYLUDE FLUORIDE HEXAFLUORO- PROPYLENE	FLUOROSILICONE	POLYCHLORO- TRIFLUORO- ETHYLENE		
SPECIFIC GRAVITY (g/cm <sup>3</sup> ) (D 792)	1.09	0.90	0.86	-	1.40	1.85	1.10	0.93
DIELECTRIC STRENGTH (kv/mm) (D 149)	5	6 - 20	16 - 30	12 - 24	12 - 24	12 - 24	16 - 30	8
VOLUME RESISTIVITY ( $\Omega$ , cm) (D 257)	10 <sup>10</sup> - 10 <sup>12</sup>	10 <sup>12</sup> - 10 <sup>14</sup>	10 <sup>12</sup> - 10 <sup>14</sup>	> 10 <sup>14</sup>	10 <sup>12</sup> - 10 <sup>14</sup>	> 10 <sup>14</sup>	10 <sup>11</sup> - 10 <sup>14</sup>	> 10 <sup>14</sup>
DIELECTRIC CONSTANT (D 150) 60 cycl/s 1000 cycl/s	3 - 3.5 7 - 10	3 - 3.5 7 - 10	3 - 3.5 7 - 10	3 - 3.5 7 - 10	3 - 3.5 7 - 10			
TENSILE STRENGTH (kg/cm <sup>2</sup> ) (D 412)	16 - 28	175 - 210	140 - 238	140	70	25 - 42	250 - 280	175 - 245
ELONGATION %	450 - 750	750 - 950	400 - 600	> 350	200	500 - 800	600	750 - 850
HARDNESS	A 40 - A 90	A 40 - A 90	A 30 - A 90	A 60 - A 90	A 50 - A 60	A 45	A 45 - A 90	A 30 - A 90
COMPRESSION SET (%)	5	7.2	1.5 - 3	< 2	< 2	< 2	3 - 5	13
STRAIN AT 28 kg/cm <sup>2</sup> (%)	36	31	-	-	-	-	-	30
ABRASION RESISTANCE	Good	Good	Good	-	Poor	-	Excellent	Excellent
WATER RESISTANCE	Good	Excellent	Excellent	Excellent	Excellent	Excellent	Good	Excellent
OIL RESISTANCE	Excellent	Poor	Poor	Excellent	Excellent	Excellent	Good	Poor
OZONE RESISTANCE	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Poor
PERMEABILITY TO GAS	Low	Very Low	Low	Low	Low - Medium	Very Low	Low	Low
MINIMUM SERVICE TEMPERATURE (°C)	- 19	- 46	- 50	- 46	- 68	- 50	- 40	- 50
MAXIMUM SERVICE TEMPERATURE (°C)	175	150	160	232	200	200	160	60

# ELONGATION IS STRONGLY DEPENDENT OF FILLER CONTENT.

Table I.4 (cont.): ELASTOMERS

POLYMER	NEOPRENE (PURE GUM)	NITRILE (PURE GUM)	POLYBUTADIENE (PURE GUM)	POLYISOPRENE- SYNTHETIC	POLYSULFIDE	POLYURETHANE	SBR	SILICONE
PROPERTIES (ASTM)								
SPECIFIC GRAVITY (g/cm <sup>3</sup> ) (D 792)	1.25	1.00	0.91	0.93	1.35	1.25	0.94	1.1 - 1.6
DIELECTRIC STRENGTH (kV/mm) (D 149)	12	6 - 22	6 - 22	6 - 22	6 - 22	> 10	6 - 22	12 - 24
VOLUME RESISTIVITY ( $\Omega$ .cm) (D 257)	$10^{10} - 5 \cdot 10^{12}$	$10^{10} - 10^{12}$	$\sim 10^{14}$	> $10^{14}$	$10^8 - 10^{10}$	$10^8 - 5 \cdot 10^{10}$	> $10^{14}$	$10^{12} - 10^{18}$
DIELECTRIC CONSTANT (D 150) 60 cycl/s	3 - 3.5	3 - 3.5	3 - 3.5	3 - 3.5	3 - 3.5	3 - 3.5	3 - 3.5	3 - 3.5
1000 cycl/s	7 - 10	7 - 10	7 - 10	7 - 10	7 - 10	7 - 10	7 - 10	7 - 10
TENSILE STRENGTH (kg/cm <sup>2</sup> ) (D 412)	210 - 280	35 - 63	14 - 70	70 - 140	> 70	> 350	14 - 21	42 - 91
ELONGATION (%)	800 - 900	450 - 700	400 - 1000	-	450 - 650	540 - 760	400 - 600	100 - 500
HARDNESS	A 40 - A 95	A 40 - A 95	A 40 - A 90	A 40 - A 80	A 40 - A 85	A 35 - A 100	A 40 - A 90	A 30 - A 90
COMPRESSION SET (%)	5 - 9	6 - 9	4 - 6	6	8 - 11	1.5 - 3	2 - 5	$\sim 1.5$
STRAIN AT 28 kg/cm <sup>2</sup> (%)	31	25	-	-	28	-	28	3.4
ABRASION RESISTANCE	Good	Good	Excellent	Excellent	Poor	Excellent	Good	Poor
WATER RESISTANCE	Good	Excellent	Excellent	Excellent	Good	Good	Excellent	Good
OIL RESISTANCE	Good	Excellent	Poor	Poor	Excellent	Excellent	Poor	Poor
OZONE RESISTANCE	Excellent	Poor	Poor	Poor	Excellent	Excellent	Poor	Excellent
PERMEABILITY TO GAS	Low	Low	Low	Very Low	Very Low	Very Low	Low	High
MINIMUM SERVICE TEMPERATURE (°C)	- 40	- 50	- 100	- 45	- 50	- 54	- 50	- 117
MAXIMUM SERVICE TEMPERATURE (°C)	115	120	95	80	120	115	80	240