PROJECT OF HIGH POWER STATIONARY NEUTRON TARGET OF CONICAL SHAPE

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Abstract

Presented is the proposal for the high intensity neutron target with the converter made of beryllium. The target comprises the stationary conical shape converter cooled by liquid. It is irradiated by the proton beam with energy 10 MeV and average power up to 300 kW. The target cooling is discussed for both water and liquid metal carriers. It is shown that in the case of water cooling the optimum target design is determined by the cooling channel wall temperature - it must not exceed water boiling temperature; in the case of liquid heat carrier target parameters are determined by the thermo-mechanical stress in it. Also problems of target design and materials selection are considered.

1 INTRODUCTION

In the framework of the European program to define a second generation Radioactive Ion Beam (RIB) facility, SPES (Study for Production of Exotic Species) facility is developing at LNL INFN for RIB originated by fission fragments produced by secondary neutrons. To obtain the intense (up to 10^{14} n/sec·cm^2) flux of neutrons, the high-intensity (up to 300 kW) proton beam with energy 10 MeV is directed to a neutron target with the converter made of material that provides the maximum neutron yield. Simulation performed with the use of MCNPx code [1] showed that beryllium converter gives the highest absolute yield [2] (see Fig. 1). To reduce the cubic density of heat power deposited in the target one needs to extend its operation surface. A good solution should be the target design of conical shape.

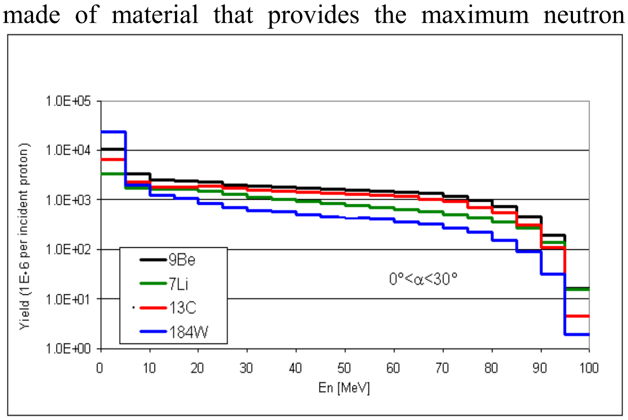

Figure 1: Comparison of neutron production yield in different converters, in the forward direction

2 TARGET DESIGN

The target layout is shown in Fig. 2. The target comprises a conical operation layer (converter material) made of beryllium (1). The converter, which has a suitable thickness to stop the primary proton beam, is clad with the small liquid layer of Na+K alloy (2). This allows to decrease the thermo-mechanical stress in the converter blanket. Spiral cooling channels are distributed along the converter blanket (3) and connected in parallel in order to decrease the thermal stress.

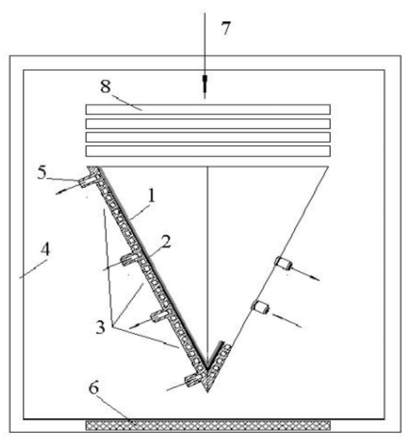

Figure 2: Layout of conical target with liquid agent cooling. 1 – operation layer, 2 – liquid metal layer, 3 – blanket with cooling channels, 4 – vacuum chamber, 5 – inlets and outlets of cooling channels, 6 – neutron beam output window, 7 – primary beam, 8 - collimator.

3 SELECTION OF TARGET MATERIALS

The materials composing the blanket were selected in order to satisfy specific criteria, which are:

- high resistance to the corrosion of cooling agent;
- high thermal conductivity;
- low radioactive activation and good resistance to neutron exposition.

Table 1 lists some thermal and corrosion characteristics of different materials taken into account for the converter assembly [3,4]. The corrosion to liquid agent is considered as "high" if the corrosion doesn't exceed 100 μm per year. Aluminum (if the temperature doesn't exceed 300^{0}C), low carbon steel and molybdenum were selected as best candidates for blanket material since they have shown the required characteristics.

Following analogous criteria, different cooling agents were analyzed (see Table 2). Again, the main characteristics are: high thermal conductivity, high specific heat value, low melting-point and high boiling temperature, as low as possible neutron activation cross-section.

Water is the most common liquid used to remove heat in many situations. Pure water has the advantages to be only slightly activated by neutrons [4], doesn't need special pumping devices in the cooling system, is not expensive and, in spite of its low thermal conductivity, has very high specific heat. A relevant disadvantage of water is the low boiling temperature.

Table 1: Characteristics of some materials considered for the design of the converter blanket.

material	corrosion resistance to coolant (h - high, l - low, n - no)	thermal conductivity, W/(m·K)
aluminium	H_2O - h, Ga - n, Li - no data, Na+K - h (<300^{0}C)	237 (300 K) 240 (400 K) 230 (600 K)
titanium	H_2O - h, Ga - h, Li - l, Na+K - h	15.5 (293 K) 16.9 (573 K) 19.4 (973 K)
low-carbon steel	H_2O - h, Ga - n, Li - h, Na+K -h	88 (300 K) 58 (600 K)
copper	H_2O - l, Ga - n, Li - no data, Na+K - h	400 (293 K) 373 (573 K)
molybdenum	H_2O - h, Ga - h, Li - h, Na+K - h	162 (300 K) 158 (600 K)
tantalum	H_2O - h, Ga - h, Li - h, Na+K - h	63 (300 K) 68 (800 K)

Table 2: Characteristics of some liquid agents considered as possible coolant of the converter

material	specific heat, J/(kg·K)	thermal conductivity, W/(m·K)	melting-point / boiling temp. ^{0}C
H_2O (pure)	4170 (293 K) 4220 (373 K)	0.57 (293 K) 0.69 (373 K)	0 / 100
Ga	400 (400 - 600 K)	34.5 (400 K) 46.2 (500 K)	29.8 / 2204
Li	4400 (600 - 700 K)	42.8 (460 K) 52.9 (900 K)	180.5 / 1342
Na+K	900 - 1100 (300 - 600 K)	21 - 25 (300 -600 K)	-12.5 / 890

Among liquid metals, alloys of Na with K seem the most attractive. Compared to other liquid metals, its low corrosive effect makes Na+K compatible with many materials (see Table 1). Furthermore, this alloy (with 77.2% of K) has melting point down to -12.5^{0}C. Lithium has rather high melting-point that complicates its use in cooling channels and leads to degradation of thermal and mechanical characteristics of converter blanket materials. Liquid gallium may be a suitable coolant, but has the drawback to be much more corrosive than Na+K alloy.

Water and Na+K alloy were selected as the most suitable coolants and thermo-mechanical calculations were performed for them.

4 RESULTS OF THERMO-MECHANICAL CALCULATIONS

The temperature distribution in all parts of the converter was calculated following the known beam power distribution over the converter internal surface, taking into account the heat resistance of space between the cooling channel surface and operation layer. This thermal resistance can be calculated by the electrical engineering analogy [5]. The 300 kW primary proton beam was assumed to be Gaussian over radius with σ = 3 cm. A converter radius (cone basis) of 6 cm was taken. The heat transfer from the operation layer into cooling liquid was calculated as in Ref. 6. Rectangular cooling channels were grouped in sections (5 to 7 sections). Initial coolant temperature at the inlet of each section was 20^{0}C, while the pressure difference in each section was 5.5 at**.**

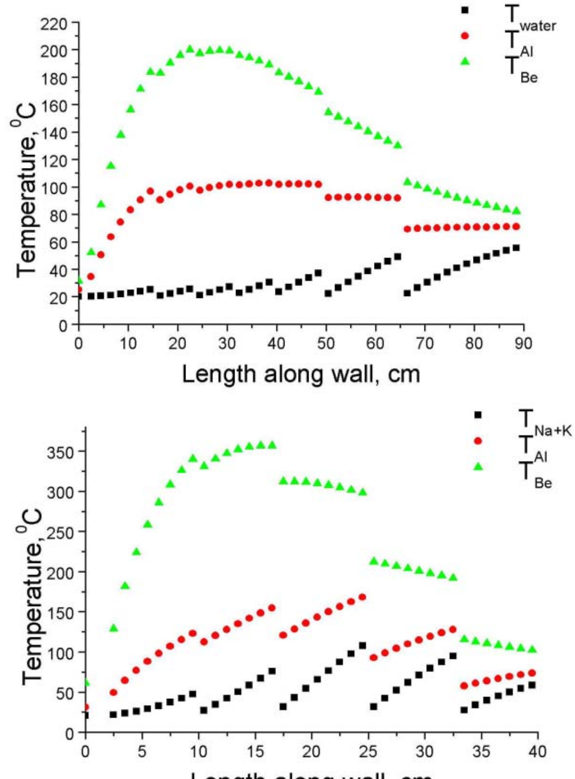

Figure 3: Operation layer, cooling channel wall and coolant temperature along cone wall. Above - water cooling, below - Na+K cooling.

The theory of thin conical shells in the approach of the long cone wall [7] was used for calculation of thermo-mechanical stress. Fig. 3 shows the temperature along the cone wall for operation layer, channel wall, and cooling agent for the converter with operation layer made of beryllium and blanket made of aluminum. Tables 3 and ,4 present maximum absolute values of meridian σ_m (along the cone wall) and azimuth σ_θ thermo-mechanical stress as well as ultimate strength σ_{ult} and flow limit σ_{fl} values for each material.

If water is used as a coolant, the maximum temperature of a channel wall is limited by the water boiling temperature, though thermo-mechanical stress in materials is far from ultimate value. This explains the large size of the converter (the length of cone wall reaches 90 cm). One can reduce essentially the converter size using Na+K alloy as a cooling agent. In this case the target size is lower limited by the thermo-mechanical stress in the blanket. The major drawback is the large coolant consumption (up to 300 lpm) and high coolant speed (over 20 m/s for pressure difference 5.5 at).

Fig. 4 shows the typical distribution of thermo-mechanical stress over the conical shell length and width. Due to the boundary conditions (free cone basis at z = 40 cm, Fig. 4, below) meridian stress is equal to 0 on the basis. Maximum stress is observed in the region with maximum temperature gradient.

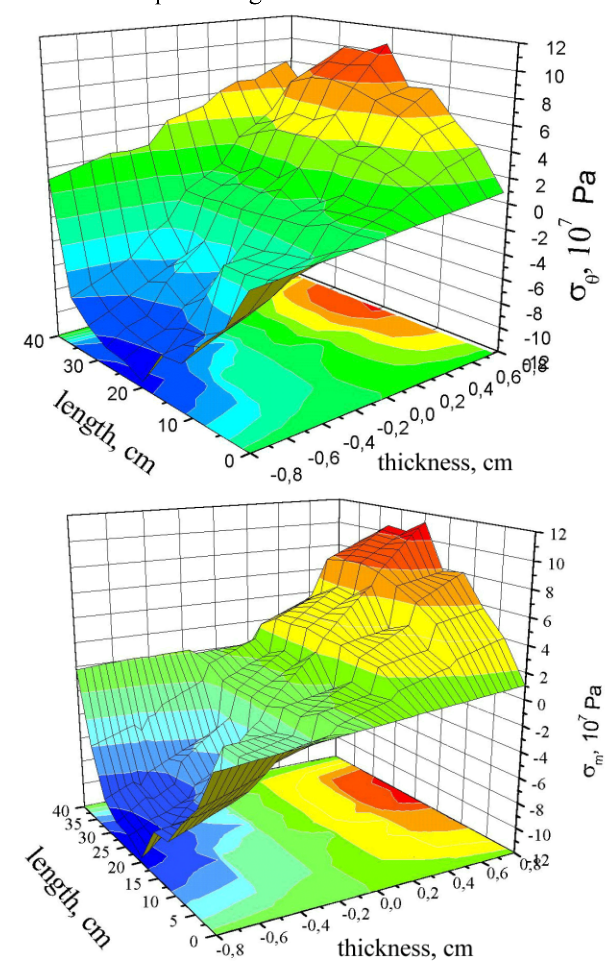

Figure 4: Azimuth (above) and meridian (below) thermo-mechanical stress distribution (10^7 Pa) over the cone length and thickness. Operation layer - Be, blanket - Al, coolant - Na+K

5 CONCLUSION

Neutron target with solid converter cooled by liquid agent can be used where high neutron flux density is not required, but high neutron production efficiency is desirable. As calculation showed, targets of this type can dissipate high heat power of a primary proton beam. In the case of water cooling the channel wall temperature is limited by water boiling temperature, so the use of liquid metal as a coolant seems more attractive and allows to reduce essentially the target size. Such problems as operation layer and blanket joint assembly design, and target radiation damage require experimental study. Final optimization of target parameters has to be done.

Table 3. Maximum thermo-mechanical stress (10^7 Pa) in the materials of a converter cooled by water

σ_m Be	σ_θ Be	σ_{ult} Be / σ_{fl} Be
8.62	10.79	27 - 37 / 25.5
σ_m Al	σ_θ Al	σ_{ult} Al / σ_{fl} Al
7.67	9.59	15.8 / 13.7

Table 4. Maximum thermo-mechanical stress (10^7 Pa) in the materials of a converter cooled by Na+K alloy

σ_m Be	σ_θ Be	σ_{ult} Be / σ_{fl} Be
20.29	25.37	27 - 37 / 25.5
σ_m Al	σ_θ Al	σ_{ult} Al / σ_{fl} Al
10.66	13.35	15.8 / 13.7

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