CALCULATION OF THE MAXIMUM TEMPERATURE ON THE CARBON STRIPPING FOIL OF THE SPALLATION NEUTRON SOURCE

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Abstract

The maximum temperatures expected on both 220 μg/cm^2 and 400 μg/cm^2 carbon foils, used to strip the 1 GeV H^- beam at injection into the accumulator ring of the Spallation Neutron Source (SNS), were determined by finite-element analysis. This beam will have a pulse length of 1 ms with a repetition rate of 60 Hz and an average current over a single beam pulse of 18.2 mA. The foil size will be 10 mm x 30 mm and will be mounted in a 20 cm diameter stainless steel beam pipe in the injection area of SNS. In the model, the heat generated in the foil was radiated to the wall of the beam pipe, which was exposed to ambient temperatures. The results showed that the maximum temperatures were 1728 K for the 400 μg/cm^2 case and 1574 K for the 220 μg/cm^2 case. A 225 μg/cm^2 thick commercial carbon foil was tested to verify the analysis. The experiment used the 750 keV H^- beam at the AGS Linac, which has a pulse length of 0.5 ms and a repetition rate of 7.5 Hz. By using the same mathematical model as described above, the maximum temperatures on the foil corresponding to various energy depositions were calculated and were compared against the carbon melting temperature (3973 K). The results showed that: 1. When the predicted maximum temperature was above the carbon melting temperature, the foil failed within 1 minute of running time. 2. When the predicted maximum temperature was below the carbon melting temperature, the performance of the foil was not affected up to the end of our 10 minutes tests.

1 INTRODUCTION

Injection into the accumulator ring of the Spallation Neutron Source (SNS) will be done by stripping H^- beam provided by the Linac. A carbon foil [1,2] will be used to fully strip the electrons at one location. The foil will be located in the gap of a dipole magnet which is part of the injection orbit bump. The 1 GeV H^- beam from Linac has a pulse length of 1 ms with repetition rate of 60 Hz and an average current over a single beam pulse of 18.2 mA. The energy lost on the carbon foil will heat the foil and could destroy it. The lifetime of the stripping foil will depend on the maximum temperature of the carbon foil, the repetition rate of the beam, and the fabrication method of the carbon foil. The performance of the foils fabricated by various methods has been reported previously [3,4,5]. This paper focuses on determining the maximum temperatures that the carbon stripping foil can operate at before failure. Analysis was done for 220 μg/cm^2 and 400 μg/cm^2 foils. A 225 μg/cm^2 thick carbon foil was tested to verify the analysis result. More testing to determine foil lifetime is planned.

2 THERMAL ANALYSIS OF THE CARBON STRIPPING FOIL

The carbon foil (10 mm x 30 mm) will be mounted in a 20 cm diameter stainless steel beam pipe in the injection area of SNS. Fig. 1 shows the layout of SNS injection foil and the model that was used for the thermal analysis.

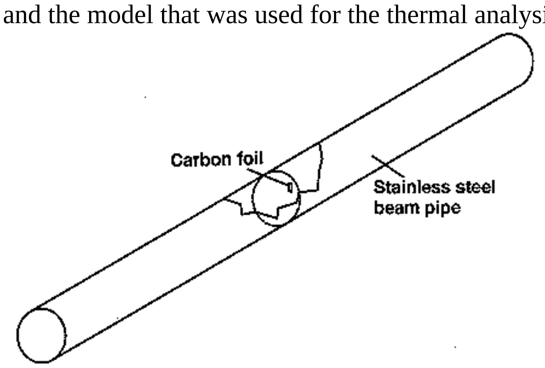

Fig.1: A carbon foil inside a stainless steel beam pipe

2.1 Assumptions

The assumptions for the analysis are as follows:

1. SNS injected beam properties [1,2]:

Kinetic energy	1 GeV
Beam pulse length	1 ms
Repetition rate	60 Hz
Ave. beam current (1 MW)	18.2 mA
RMS emittance (x &y dir.)	0.14 π mm-mr
Beta function	17.4 m (x dir.) 4.56 m (y dir.)
Beam current density distribution on the foil	2-D Gaussian distribution
Beam size @ 1- σ	3.1 mm (x.dir.) 1.6 mm (y.dir.)

2. The power density, P, on the carbon foil could be derived using the following equation [6]: (for the case of stripping a 1 GeV H^- beam)

$$P = 6837551 \times t \times I \quad (W/m^2) \quad (1)$$

where t is the foil thickness in g/cm^2 and I is the current density in A/m^2.

3. Material properties [7,8]:

	Carbon	S. Steel
Density, ρ, kg/m^3	1900	8044
Thermal cond., k, W/m-K	(See Fig. 2)	16.2
Heat Capacity, c, J/kg-K	(See Fig. 2)	502
Rad. View factor, f	1	1
Rad. Emissivity, ε	0.8	0.05

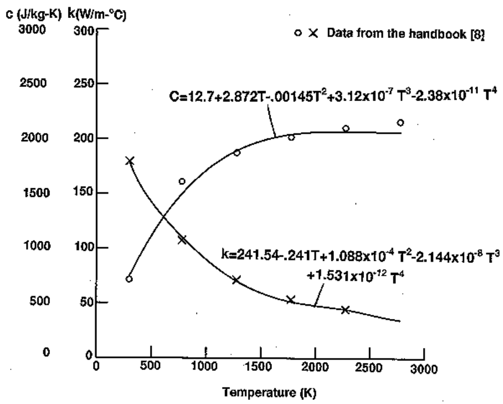

Fig. 2: Variation of carbon properties with temperatures

4. The convection coefficient at the outer surface of the pipe, h =8.17 W/m^2-K
5. Stefan-Boltzmann constant, σ = 5.67 x 10^{-8} W/m^2-K^4
6. Neglect the heat conduction from the foil to the foil holder.
7. Ambient temperature, T_o =297 K.
8. Initial condition: all components @ 297 K.

2.2 Mathematical models

1. The ANSYS model

The governing equations for the heat transfer analysis can be expressed as follows [9]:

On the carbon foil:

$$\nabla^2 T_c + 1/(k_c t_c)[P - 2\sigma f \varepsilon_c (T_c^4 - T_b^4)] = 1/\alpha_c \, \partial T_c/\partial \tau \qquad (2)$$

and on the beam pipe:

$$\nabla^2 T_b + 1/(k_b t_b)[\, 2\sigma f \varepsilon_b (T_c^4 - T_b^4) - h(T_b - T_c)] = 1/\alpha_b \, \partial T_b/\partial \tau \qquad (3)$$

where $\nabla^2 = \partial^2/x^2 + \partial^2/y^2 + \partial^2/z^2$, $\alpha_c = k_c/\rho_c c_c$, T_c = temperature on the foil, $\alpha_b = k_b/\rho_b c_b$, T_b = temperature on the beam pipe, t_c = thickness of the foil, τ = time, and all other parameters are defined in Section 2.1. Subscript, b and c, are for the beam pipe and for the carbon foil respectively.

An ANSYS model of the system was developed to solve Eq. (2) and Eq. (3) simultaneously. The beam properties, material properties, heat loads and the other assumptions are shown in Section 2.1. Due to the significant property changes of the carbon material over a wide temperature range [8], the heat capacity (c) and the heat conduction coefficient (k) of the carbon foil were modeled as functions of the temperature. For the convenience of the calculations, the best fitted polynomials were used. (See Fig. 2.) This model included the radiation heat transfer between the carbon foil and the stainless steel beam pipe, heat conduction through the foil to its base, a natural convection condition on the outer surface of the beam pipe, and a Gaussian distribution for the power density from the beam (in the x and y directions) on the foil. Two thicknesses, 220 μg/cm^2 and 400 μg/cm^2, were analyzed. After a few lengthy transient and non-linear numerical analyses, the maximum temperatures on the foil verse time are plotted in Fig. 3 and Fig. 4 (the continuous lines). The plots show the initial four cycles when beam first starts hitting the foil.

2.The simplified model

For comparison, a simplified model was developed to verify the correctness of the finite element analysis. This model neglected the heat conduction across the carbon foil and assumed a constant temperature for the inner wall of the beam pipe. Therefore, Eq.(2) (for the carbon foil) could be decoupled from Eq. (3), which resulted in the following ordinary differential equation:

$$\rho_c V_c c_c \, dT_c/d\tau = -2\sigma f \varepsilon_c A_c (T_c^4 - T_0^4) + PA_c \qquad (4)$$

where V_c = volume of the carbon foil, T_c = temperature on the carbon foil, τ = time, A_c = area on the foil surface, and all other parameters are given in Section 2.1. The integrated results of Eq. (4) for the initial four cycles are also shown in Fig. 3 and Fig. 4. (See the phantom lines.)

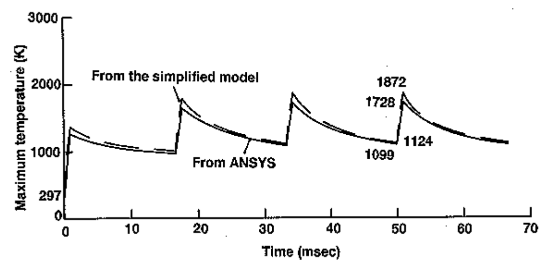

Fig. 3: The maximum temperatures on the carbon foil verse time in SNS (area density: 400 μg/cm^2)

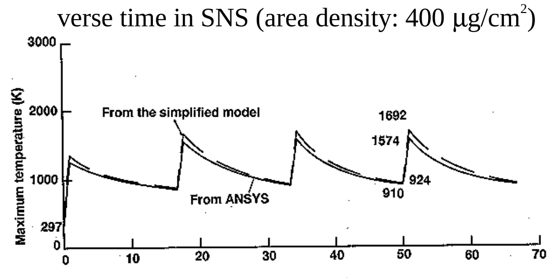

Fig. 4: The maximum temperatures on the foils verse time (area density: 220 μg/cm^2)

2.3 Results

The analysis results are as follows: (1) The temperature cycles on both 400 μg/cm^2 and 220 μg/cm^2 thick foils become stable after the third heating cycle. (2) During the operation, the maximum temperature on the foil would fluctuate from 1099 K to 1728 K for the 400 $\mu g/cm^2$ case and from 910 K to 1574 K for the 220 $\mu g/cm^2$ case. (3) The maximum temperatures on the foil, which were calculated by the simplified model were slightly higher than those computed by the ANSYS model. This is because that the simplified model does not include the heat conduction effect on the foil.

3 CARBON FOIL TEST

Since there is no pyrometer fast enough to detect the maximum temperature on the carbon foil while stripping the H^- beam with a pulse length being shorter than 1 ms, the following test was used as an alternative method to verify the analysis results. This test was based on the assumption that the carbon foil would fail within a short period of time only if the temperature on the carbon foil is equal or higher than the melting point of the material. Using the equations from Section 2, the maximum temperatures on the foil verse energy depositions were calculated analytically. The melting point of carbon (3973 K) was obtained from a handbook [7]. By measuring the critical energy deposition above which the foils would fail immediately the analysis results could be verified.

3.1 Test setup

The test setup included a viewing box, an upstream collimator (a carbon rod with 1 mm dia. center hole), a 225 $\mu g/cm^2$ carbon foil (17 mm x 62 mm) mounted on an aluminum frame. The frame was mounted on a linear drive mechanism positioned by a stepping motor so multiple shots at various energies could be taken on the same foil. A Faraday cup downstream of the foil detected the beam current. The carbon foil was made by Arizona Carbon Foil Company. It was glued onto the mounting frame along one edge to prevent any restriction when the foil deforms. The foil was positioned 1.83 cm away from the collimator so that the beam size is very close to the aperture of the collimator. The 750 keV H^- ion beam, generated in Linac of BNL, was used in the test. The pulse length was 0.5 ms and the repetition rate was 7.5 Hz. Different energy depositions on the foil were achieved by varying the beam current. The test was performed with the foil under the vacuum. The beam size and current density at the foil location were carefully measured before the test, using the emittance heads.

3.2 Comparison between the analytical and the test results

The power densities deposited on the carbon foil were calculated based on the beam size given by the emittance measurements, the beam current, and the energy of the beam. The maximum temperatures on the foil verse the applied power densities were derived by integrating Eq. (4) with the material properties, given Section 2.1.

Eight tests were conducted at increasing current levels. (See Fig. 5.) The results showed that (1) The beam current densities that predicated a temperature above the carbon melting temperature (3973 K)[7] caused the foil to fail after < 1 minute of running time. (2) The beam current densities that predicted a temperature below the carbon melting temperature did not affect the performance of the foil after 10 minutes of testing. (3) Even at operating temperatures below the foil melting point there was permanent deformation of the foil. From the current readings this deformation did not affect the performance of the foil.

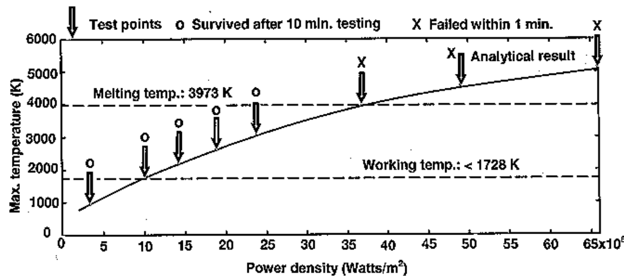

Fig. 5: Comparison of the test results with the analytical calculations

4 REFERENCES

[1] SNS Project Design Manual, 1998, Brookhaven National Laboratory.

[2] SNS Conceptual Design Report, 1997, Brookhaven National Laboratory.

[3] I Sugai, et al, "Development of thick, long-lived carbon stripper foils for PSR of LANL", Nucl. Instr. and Meth. A 362 (1995)70.

[4] M.J. Borden, "Long-life Carbon-fiber-supported carbon stripper foils", Nucl. Instr. and Meth. A 303 (1991)63.

[5] I Sugai, et al, " A new method for making long-lived carbon foils for heavy Ion beam strippers", Nucl. Instr. and Meth. A 236 (1985)576.

[6] Herbert L. Anderson " A Physicist's Desk Reference", 2nd Ed.of Physics Vade Mecum, AIP, New York.

[7] Brady, Clauser, & Vaccari, " Materials Handbook" 14th Ed., McGraw Hill Book Company.

[8] "Handbook of Materials Science", CRC Press, 2nd ed., Vol III.

[9] J.P. Holman, " Heat Transfer" 5th Ed., McGraw Hill Book Company.