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Title of Paper : **DETERMINATION OF EFFECTIVE THERMAL NEUTRON MACROSCOPIC CROSS-SECTION OF BORON CARBIDE SAMPLES WITH THE HELP OF DENSITOMETRY READINGS USING FILM-BASED NEUTRON RADIOGRAPHY**

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ABSTRACT

Boron carbide (B_4C) is quite a unique material with respect to neutron imaging in the sense that its boron part is much better thermal neutron absorber whereas carbide offers greater scattering probability to thermal neutrons as compared to other structural materials of a nuclear reactor. Using film-based neutron radiographic technique, it is thus possible to obtain high contrast images of the subject material from where the effective thermal-neutron macroscopic cross-section (Σ_{eff}) can be determined with the help of densitometry readings. The transmitted part of thermal neutron flux can be estimated by the densitometry readings acquired from relatively whiter portion on an emulsion film which was occupied by the investigated sample during thermal neutron exposure whereas the incident flux is represented by the surrounding dark regions. In this paper a method is presented that can determine the value of Σ_{eff} of investigated B_4C samples having density around 1.95 gm/cm^3. In all the samples natural boron was used (i.e. ~ 20 % ^{10}B and ~ 80 % ^{11}B) along with 07 % (by weight) poly-urethane as binder. The average value of the effective thermal neutron macroscopic cross-section is found to be 0.41 cm^{-1}. In future, similar procedure is planned to be exercised on digital neutron images of the same material. *(End of abstract)*

This write-up describes on how to quantify neutron attenuation (i.e. I / I_o) and macroscopic cross-section Σ (in mm^{-1} or cm^{-1}) of a given neutron radiographed material by the help of densitometry readings.

The theme is that we pick up densitometry readings from over the area covered by the investigated material on radiographic film as well as from its surrounding regions and then note down any change between the two readings.

Start:
Equation of densitometer from literature [Ref.: Page 6.48, Chap. 6, "Handbook of NDE" by Charles Hellier, 2003 ed., McGraw-Hill]

$$D = \log\left(\frac{I_o}{I_t}\right) \qquad (1)$$

where

- D = film density value as picked up (or read) from densitometer
- I_o = intensity of ordinary light emerging from the bulb of the densitometer and incident on the film
- I_t = light intensity transmitted through the film

We slightly modify the symbols as under (the reason for this modification will soon become evident since another set of the same symbols I_o & I_t are also going to appear in this write-up which pertain to neutron exposure at the time of performing neutron radiography exposure) :-

$$D = \log \left(\frac{I_o^{from\ Densito's\ bulb}}{I_t^{Densito\ at\ a\ given\ position\ on\ film}} \right)$$

Taking anti-log on both sides

$$10^D = \frac{I_o^{from\ Densito's\ bulb}}{I_t^{Densito\ at\ a\ given\ position\ on\ film}}$$

If we take two (02) densitometer readings, where one of the readings is picked from the area covered by the investigated material on radiographic film (e.g. Boron Carbide B_4C specimen) and the other reading from its surroundings

$$10^{D^{on\,B_4C\,area}} = \frac{I_o^{from\,Densito's\,bulb}}{I_t^{Densito\,at\,B_4C}} \quad (2)$$

and

$$10^{D^{surroundings}} = \frac{I_o^{from\,Densito's\,bulb}}{I_t^{Densito\,surroundings}} \quad (3)$$

Note that in *Equations (2)* & *(3)*, we only know the values of LHSs (since these are the values displayed on densitometer at the time of measurements) whereas all 4 parameters on RHSs are unknown.

From *Equations (2)* & *(3)*

$$\Rightarrow \quad \frac{10^{D^{on\,B_4C\,area}}}{10^{D^{surroundings}}} = \frac{I_t^{Densito\,surroundings}}{I_t^{Densito\,at\,B_4C}} \quad (4)$$

Now we want to relate densitometry measurements back to neutron attenuation when the investigated specimen was exposed to neutron beam.

Conceptually, more neutron attenuation ← implies → *Whiter* region on film-based radiograph

$$\text{And conversely, if} \quad I_t^{Neutron} \uparrow, \quad \text{then} \quad D \uparrow \tag{5}$$

That is, if the transmitted neutron intensity emerged after passing through an investigated sample ($I_t^{Neutron}$) is high, it means that the densitometry reading (D) at that position will be a high number

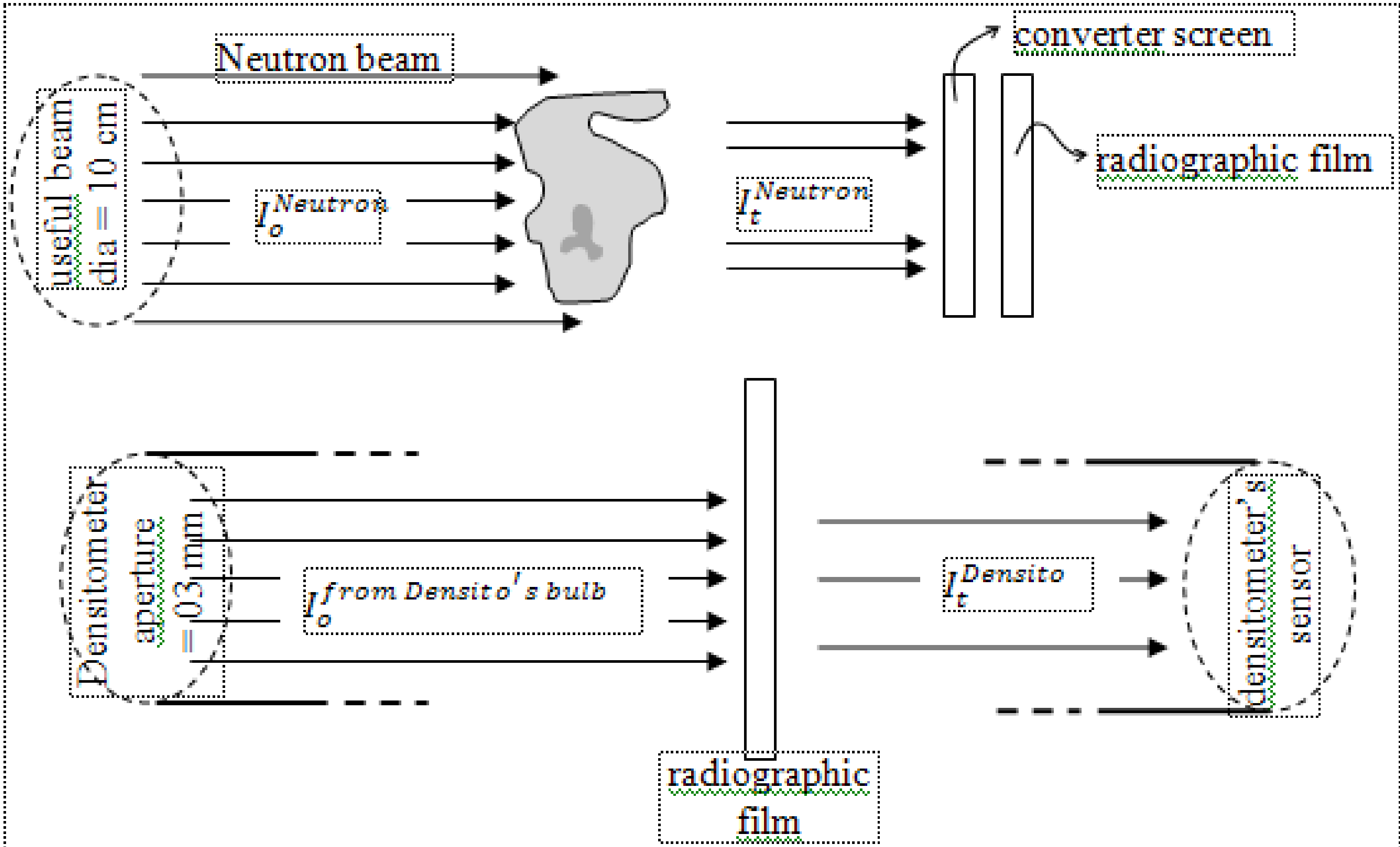


Figure Caption: Please note that the radiographic film has moved from the end position (in case of neutron exposure) to the centre position (in case of densitometer).

Using the *vertical arrow* conventions style as in *Relation (5)*

if Film Blackening $\uparrow$, then value of D $\uparrow$	*[This is an easy observation about densitometry readings]*	(6)
if Film Blackening $\uparrow$, then $I_t^{Densito} \downarrow$	*[Blacker color absorbs more light, also evident from* Equation (1)*]*	(7)

Combining *Relations (6)* & *(7)*

$$\text{if} \quad D \uparrow, \qquad \text{then} \quad I_t^{Densito} \downarrow \tag{8}$$

Now, combining *Relations (5)* & *(8)*

$$\text{if} \quad I_t^{Neutron} \uparrow, \qquad \text{then} \quad I_t^{Densito} \downarrow$$

That is, both these parameters behave inversely to each other. Of course, to a first (& close) approximation, these two parameters can safely be assumed to hold a **linear** relationship with each other.

$$\Rightarrow \qquad I_t^{Densito} \quad \propto \quad \frac{1}{I_t^{Neutron}}$$

Also note that the radiographic film moves from the end position (in case of neutron exposure) to the centre position (in case of densitometer) as can be seen in the diagram above.

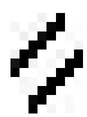
Another point to be noted here is that acc to general convention adapted for such relations / equations, the LHS consists of dependent parameters and RHS that of independent (as in the Charles's Law: V $\propto$ T, not T $\propto$ V). So, the above relationship becomes:-

$$\Rightarrow \qquad I_t^{Densito} \quad = \quad K \, . \, \frac{1}{I_t^{Neutron}} \qquad (9)$$

where “K” is a constant of proportionality and is an unknown (but unit less) number as yet.

Therefore, from *Equation (4)*, using *Equation (9)* we get

$$\frac{10^{D^{on\ B_4C\ area}}}{10^{D^{surroundings}}} = \frac{\dfrac{K}{I_t^{Neutron\ surroundings}}}{\dfrac{K}{I_t^{Neutron\ on\ B_4C\ area}}}$$

$\Rightarrow$  $= \dfrac{I_t^{Neutron\ on\ B_4C\ area}}{I_t^{Neutron\ surroundings}}$

Paying attention to the denominator of RHS, it is actually the original incoming neutron beam intensity (can also see from the figure above)

$$\Rightarrow \qquad \frac{10^{D^{on\,B_4C\,area}}}{10^{D^{surroundings}}} = \frac{I_t^{Neutron\,on\,B_4C\,area}}{I_o^{Neutron}} \qquad (10) \qquad \text{[Answer 1]}$$

Hence the fraction of neutron beam transmitted after passing through a given specimen can be determined by densitometry readings picked from radiographic film on the area occupied by the specimen and its surroundings.

For *[Answer 2]*, we want to determine macroscopic cross-section (Σ in mm^{-1} or cm^{-1}) of the given specimen / material.

Using the well known equation: $I = Io\ e^{-\Sigma\, t}$

where "t" is the thickness of the given material.

Since this is the neutron intensity equation (& NOT the densitometry one), so acc to our convention, we re-write it as:

$$I_t^{Neutron} = I_o^{Neutron}\ e^{-\Sigma\, t}$$

$$\Rightarrow \ \Sigma = -\frac{1}{t}\ln\left(\frac{I_t^{Neutron}}{I_o^{Neutron}}\right)$$

Using *Equation (10)*, we convert this into densitometry equation:

$$\Sigma = -\frac{1}{t}\ln\left(\frac{10^{D^{on\ B_4C\ area}}}{10^{D^{surroundings}}}\right) \qquad \text{[Answer 2]}$$

Hence the results [Answer 1] & [Answer 2]

Also, by taking multiple readings from densitometer we can take care for the (±) uncertainty values in [Answer 1] & [Answer 2] (using error propagation formula: G.F. Knoll, Chapter 4)