5.3 Core design: an illustrative LWR example

The results of the last few sections allow presentation of a simplistic but illustrative design methodology for the reactor core. In this section an illustrative LWR example is examined; the next section presents an LMFBR example.

For the sake of this simplified numerical evaluation of a LWR core, it is stipulated that the maximum temperature in the fuel must be well below the melting temperature of uranium dioxide, specifically much less than about $3000^\circ K$. Consequently the usual red-line design maximum is in the range $2000-2300^\circ K$. Since the maximum coolant temperature is about $500^\circ K$ and the maximum temperature difference between the center of the fuel rod and the coolant is therefore about $1500-1800^\circ K$, this effectively limits the heat flux from the fuel rod for a given radius, R_f, of that rod. From this perspective the smaller the rod the greater the potential power output but there are other considerations (such as the structural strength and the neutronics) that necessarily limit how small the fuel rod radius can be. These compromises led to fuel rod radii, R_f, of 0.53 cm and 0.71 cm respectively for the typical PWR and BWR.

Then equation 7, section 5.1.3, (or equation 2, section 5.1.3) determines the maximum heat flux allowable in the reactor. For a fuel thermal conductivity of $k_f = 0.03\ W/cm^\circ K$ these equations yield a maximum allowable value of $\mathcal{Q}$ of about 430 W/cm in the hottest part of the core. This, in turn, implies a red line value for the *average* heat flux of about 180 W/cm.

The next step is to stipulate the desired ratio of moderator volume to fuel volume, α_{mf}. This is primarily determined by nuclear considerations that dictate a moderator to fuel volume ratio of $\alpha_{mf} \approx 1$.

The objective in this example will be to find the size of the cylindrical reactor needed for a 1150 MW electric power plant with efficiency of 34% so that the thermal power generated by the core is $P = 3400\ MW$. The target is a cylindrical reactor of diameter, $2R$, and a height equal to that diameter. Then the fuel volume (neglecting the cladding volume) will be $2\pi R^3/(1+\alpha_{mf})$ and the required number of fuel rods, N_f, of the same height as the reactor will be

$$N_f = R^2/\left[R_f^2(1+\alpha_{mf})\right] \tag{1}$$

Moreover the thermal power of the reactor power, P, will clearly be given by the heat added to the coolant during its passage through the core or

$$P = 2R\mathcal{Q}_{av}N_f \tag{2}$$

where $\mathcal{Q}_{av}$ is the average heat flux per unit fuel rod length, averaged over the volume of the reactor. If the maximum value of that heat flux is set at 420 W/cm (see above) then a reasonable, illustrative value of this average would be $\mathcal{Q}_{av} = 180\ W/cm$. Substituting this value into equation 2 as well as the expression 1 for N_f and $P = 3400\ MW$ yields an expression for the dimension of the reactor, R. For the aforementioned values of α_{mf} and R_f this yields:

$$\textit{For PWR:}\quad R = 1.7\ m \quad ; \quad \textit{For BWR:}\quad R = 2.0\ m \tag{3}$$

values that are close to the actual volumetric-equivalent radii of $1.7\ m$ and $1.8\ m$ for the typical PWR and BWR respectively. Despite the crudeness of these calculations they come close to the dimensions of light water reactor cores.

In addition substitution back into equation 1 yields $N_f \approx 54,000$ and $N_f \approx 46,000$ for the PWR and the BWR respectively, values that are again close to the actual typical numbers of fuel rods, namely $56,000$ and $47,000$ respectively.