22.251 Systems Analysis of the Nuclear Fuel Cycle
Fall 2005
Lab exercise #6 Investigation of potential uprate of a PWR core using VIPRE
Solution

<u>2) Overpower, conservative parameters and hot channel exit equilibrium quality</u>
For the given input:

Total number of rods = 50952 (from table 1)
$q'_{core\text{-}ave}$ = 6.5776kW/ft (from input file, line 74)
Fuel active height = 144 inch (from input file, line 12)

The actual core power is

6.5776kW/ft * 144 inch /12inch/ft *50952 /1000MW/kW = 4021.7MW

The overpower factor is thus

4021.7/3411 = 1.18, i.e., **18% overpower**.

Table 1 compares core flow rate and core inlet temperature from the input and reference PWR from Table 1.

Table 1 Core flow and inlet temperature data – comparison with reference case

	PWR input	Reference PWR	difference
Core flow rate (Mg/s)	16.81	17.7	-5%
Core inlet temperature (°C)	294.7	292.7	+2

The data from PWR input after converting to SI units are given in Table 1. Core flow rate can be obtained as follows:
From VIPRE input, line 72, core-average mass flux G=2.613Mlbm/hr-ft^2=3543kg/m^2-s. From Table 1, assembly effective flow area is 0.02458, thus for 50952 fuel assemblies, total core flow effective area is 0.02458 * 50952 = 4.74m^2. Finally, core flow rate is 4.74 m^2 * 3543kg/m^2-s = 16,810 kg/s = 16.81 Mg/s – value shown in Table 1.
Note that since 1/8th core is modeled in VIPRE, so the flow rates obtained by VIPRE have to be multiplied by 8 to obtain total flow rate. It can be observed that the core flow rate in the VIPRE input was reduced by 5% and core inlet temperature was increased by 2°C. This is to account for uncertainties in the core bypass flow and uncertainty in temperature distribution at the core inlet since mixing in the lower plenum may not be perfect. These changes are made in the direction of the smaller MDNBR, i.e., higher core inlet temperature and smaller core flow rate produce smaller MDNBR, or more conservative results.

Studying the results we find that MDNBR = 1.480 occurs in channel 2 in contact with rod 4. Hence, the hot channel is channel 2. **The exit equilibrium quality from channel 2 is**

0.1038. Note that boiling occurs at overpower conditions. During normal operation, only subcooled boiling exists in the hot channel.

3) Power uprate by reducing core inlet temperature

Since lower core inlet temperature results in a larger MDNBR, core power can be increased if core inlet temperature is reduced. We want to keep the same MDNBR margin as for the reference core, i.e. MDNBR=1.480. Power increase can be accomplished by reducing core inlet temperature in the input (line 72) and at the same time increasing rod linear power on the same line. This is trial and run approach until we achieve MNDBR~1.480.

The results are summarized in Table 2. The first line shows reference case. It can be observed that reduction of core inlet temperature from 294.7°C to 271.11°C, i.e., by 23.6°C allows power uprate by 824MWt, i.e, by 20%. Figure 1, which plots power versus core inlet temperature, shows that the dependence is approximately linear, so the results for lower temperatures than 271.1°C can be easily extrapolated. It is also noted that core outlet temperature is reduced and that fuel centerline temperature in the hot rod (Tfmax) is increasing, but remains below melting point – see also Figure 2.

Table 2 Power uprate potential for reduced core inlet temperature

Tin(F)	Tin (°C)	q' (kW/ft)	Q(MWt)	Tfmax(F)	Tfmax(°C)	Tout (F)	Tout(°C)	MDNBR
562.46	**294.70**	**6.5776**	**4022**	**3968.6**	**2187.0**	**633.72**	**334.29**	**1.480**
556.46	291.37	6.78	4145	4074.8	2246.0	630.94	332.74	1.476
545	285.00	7.13	4359	4253.8	2345.4	625.32	329.62	1.482
535	279.44	7.45	4555	4411.5	2433.1	620.63	327.02	1.481
520	271.11	7.925	4846	4605.9	2541.1	613.64	323.13	1.483

One can reduce core inlet temperature even more – down to 480°C and at the same time increase power up to 5630MWt, about 40% uprate. At this point, MDNBR is still 1.480 and peak fuel centerline temperature just reaches melting point of 2800°C. However, stored energy in the fuel becomes too high, which would lead to unacceptable LCOA performance. Also, fission gas release at such high operating fuel temperatures would be unacceptable, hence the data beyond 20% uprate were not included in Table 2.

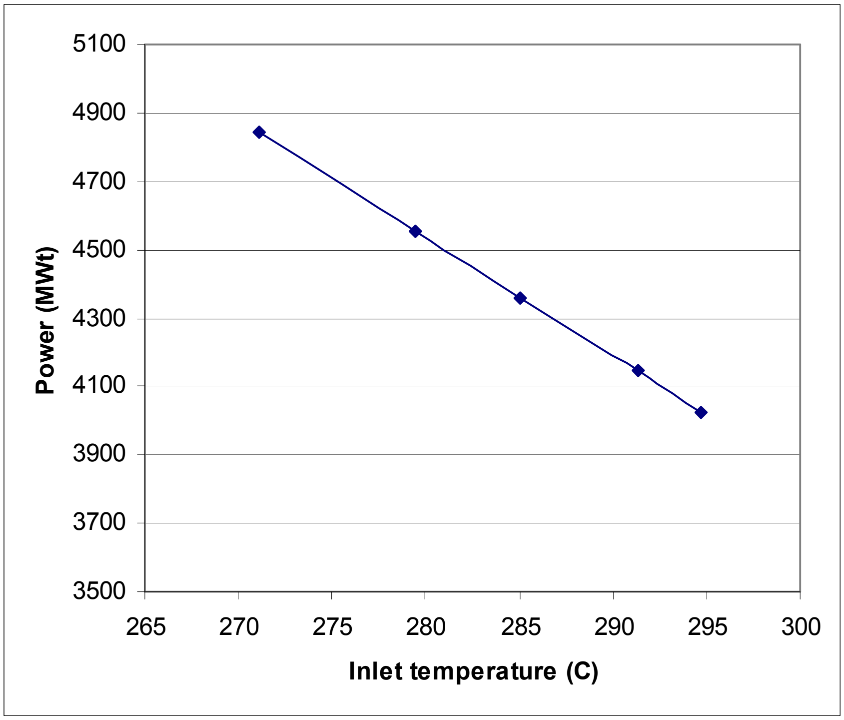

Figure 1 Core power versus core inlet temperature

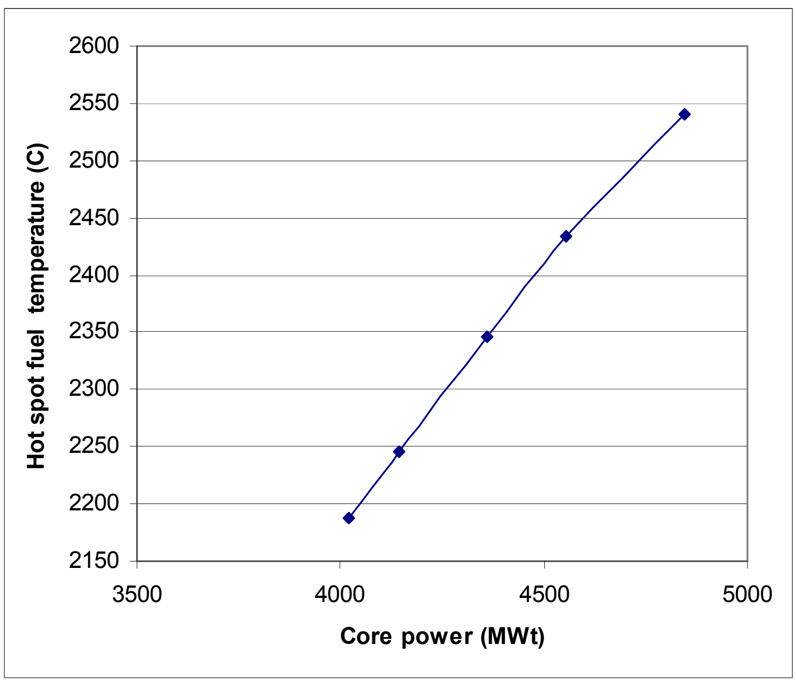

Figure 2 Fuel centerline temperature versus power

It is important to note that while core thermal power can be increased, the reduced core inlet temperature will lead to lower steam generator temperature on the shell side and thus to reduced efficiency. The effect of smaller efficiency on generated electrical power output is very important and needs to be considered. The reference PWR has efficiency of 33.5% at steam generator pressure of 5.7MPa , which corresponds to saturation temperature of 272.2°C. If we assume that the size of the steam generator will not be increased beyond power uprate ratio, i.e., not more than 20% (this is reasonable assumption since current SGs were optimized with economic considerations), about the same temperature difference between the primary and secondary should be maintained. Hence, the reduction of core inlet temperature by 23°C will lead to reduction of steam temperature by about 23°C, or to 249.2°C. Such temperature reduction will lead to Carnot efficiency reduction (assuming condenser temperature of 20°C) from

$$\eta_c = \left(1 - \frac{20 + 273.15}{272.2 + 273.15}\right)100\% = 46\%$$

to

$$\eta_c = \left(1 - \frac{20 + 273.15}{249.2 + 273.15}\right)100\% = 43.9\% .$$

If no changes to Rankine cycle layout are made, on can estimate that the net cycle efficiency of the uprated reactor, which is proportional to the Carnot efficiency, will be roughly

33.5% *43.9/46 = 31.9%.

Thus, at 271°C inlet temperature, DNBR-limited core thermal power of 4846MWt will yield 4864 *0.319 = 1551MWe, which is only 15% more than the reference power of 4022*0.335 =1347MWe (recall this is at 18% overpower). Although, power increase can be achieved with this approach, economical analysis would have to be made if this is attractive. Another possibility is to increase the size of SGs beyond 20% enlargement, which ahs also negative impact on the economy.

4) Power uprate by increasing core flow rate

In this case, we keep core inlet temperature constant and increase core flow rate (or mass flux) and core power (through pin average linear heat rate in VIPRE input) while striving for the same MDNBR margin (MDNBR=1.480). The results are summarized in Table 3 and in Figure 3.

Table 3 Results for increased core flow rate

G Mlbm/hr-ft2	m (kg/s)	q'(kW/ft)	Q(MWt)	Tfmax (F)	Tfmax (°C)	Tout (F)	Tout (°C)	MDNBR
2.613	16807.78	6.5776	4022	3968.6	2187.0	633.72	334.29	1.48
2.813	18094.26	6.9	4219	4137	2280.6	632.12	333.40	1.479
3.113	20023.97	7.38	4512	4377.9	2414.4	630.06	332.26	1.482
3.413	21953.68	7.88	4818	4588.4	2531.3	628.49	331.38	1.483
3.713	23883.39	8.4	5136	4788.4	2642.4	627.3	330.72	1.478

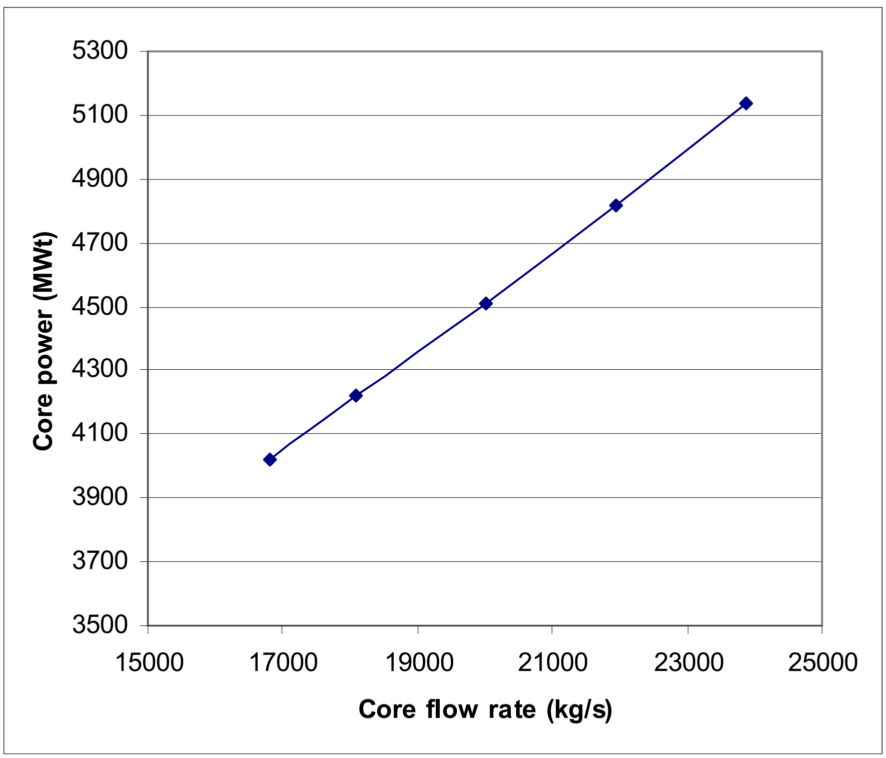

Figure 3 Core power versus core flow rate

It can be observed that increase in flow rate of 42% can accommodate power uprate by 27%. In this case, core outlet temperature is only slightly reduced and core inlet temperature is fixed, hence plant efficiency will be hardly affected. Similarly, as for power uprate through core inlet temperature reduction, one can further push power and flow rate to higher values until melting point is reached, but this would results in too high fuel temperatures wrt fission gas release and stored energy.

The other issues to be considered are:

- Large pressure drop, which will require new pumps (note that pressure drop increased from 17psi to 30psi (about doubled)
- Vibration – rods will be more susceptible to vibration at high velocities
- Potential overheating during LOCA. This is because of larger stored energy due to higher fuel temperature and potential problems to flood the core because of higher steam generation rate, which may prevent entrance of water