4.6 RECONSTRUCTION OF CORE INLET TEMPERATURE DISTRIBUTION BY COLD LEG TEMPERATURE MEASUREMENTS

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ABSTRACT

The reduced core of Loviisa NPP contains 33 thermocouple measurements measuring the core inlet temperature. Currently, these thermocouple measurements are not used in determining the inlet temperature distribution. The average of cold leg temperature measurements is used as inlet temperature for each fuel assembly. In practice, the inlet temperature distribution is not constant. Thus, using a constant inlet temperature distribution induces asymmetries in the measured core power distribution. Using a more realistic inlet temperature distribution would help us to reduce virtual asymmetries of the core power distribution and increase the thermal margins of the core.

The thermocouples at the inlet cannot be used directly to measure the inlet temperature accurately because the calibration of the thermocouples that is done at hot zero power conditions is no longer valid at full power, when there is temperature change across the core region. This is due to the effect of neutron irradiation on the Seebeck coefficient of the thermocouple wires. Therefore, we investigate in this paper a method to determine the inlet temperature distribution based on the cold leg temperature measurements. With this method we rely on the assumption that although the core inlet thermocouple measurements do not measure the absolute temperature accurately they do measure temperature changes with sufficient accuracy particularly in big disturbances.

During the yearly testing of steam generator safety valves we observe a large temperature increase up to 12 degrees in the cold leg temperature. The change in the temperature of one of the cold legs causes a local disturbance in the core inlet temperature distribution. Using the temperature changes observed in the inlet thermocouple measurements we are able to fit six core inlet temperature response functions, one for each cold leg. The value of a function at an assembly inlet is determined only by the corresponding cold leg temperature disturbance. The linear combination of the six response functions gives the inlet temperature distribution. In this paper the reconstruction method is described and the effect of inlet temperature distribution on core power distribution is studied.

1. INTRODUCTION

In Loviisa NPP core reload design is done using HEXBU-3D code, [1]. Reloads are designed using 60 degree symmetry for burnup distribution and constant inlet flow and temperature distributions. In reality, inlet flow and temperature distributions are not constant. The difference between maximum and minimum cold leg temperature and mass flow rate can be even 2 °C and 20 %, respectively. Asymmetric flow and temperature distributions also induce asymmetries in the measured power and burnup distributions. The asymmetries are automatically taken into account in the online core monitoring system RESU, [2], that is based on HEXBU-3D.

However, using a constant i.e. average inlet temperature distribution in the online core monitoring system increases, unnecessarily, the asymmetries. The reactor power distribution is obtained from the theoretical assembly powers by fitting them to the measured assembly powers. The measured assembly power is calculated from the outlet and inlet temperature difference. If the actual inlet temperature at the inlet of an assembly is larger than the constant temperature used the measured temperature increase of the assembly becomes larger than it actually is and, thus, also the power is interpreted larger than it actually is. Vice versa if the actual inlet temperature at the inlet of an assembly is smaller than the constant temperature used the power is interpreted smaller than it actually is. Thus, the asymmetry in the fitted power distribution is larger than it would be with the actual inlet temperature distribution.

Currently, the thermal margins of Loviisa NPP are barely sufficient but larger margins would help the core reload design. Reducing the asymmetries in the power distribution by using a non-constant inlet temperature distribution would increase also thermal margins of the core. In this paper a method to obtain a more realistic inlet temperature distribution is investigated. The method is based on the data obtained at the yearly testing of the safety valves of the steam generators.

2. MEASUREMENTS DURING THE STEAM GENERATOR SAFETY VALVE TESTING

In steam generator safety valve tests the pressure of the steam generator is changed to test the functioning of the safety valves. The change in the steam generator pressure can be more than 10 bars, Fig. 1. Increase in the steam generator pressure induces also a large increase in the corresponding cold leg temperature, Fig 2. The test is carried for each steam generator individually i.e. the pressure of the other five steam generators remains the same while the safety valves of one steam generator are under testing. This means that the temperature change also happens in only one cold leg at a time. The temperature at the cold leg can temporarily increase up to 12 °C during the test. Due to the large temperature increase the test is carried out at roughly 80 % power level in order not to exceed the maximum allowed subchannel outlet temperature limit.

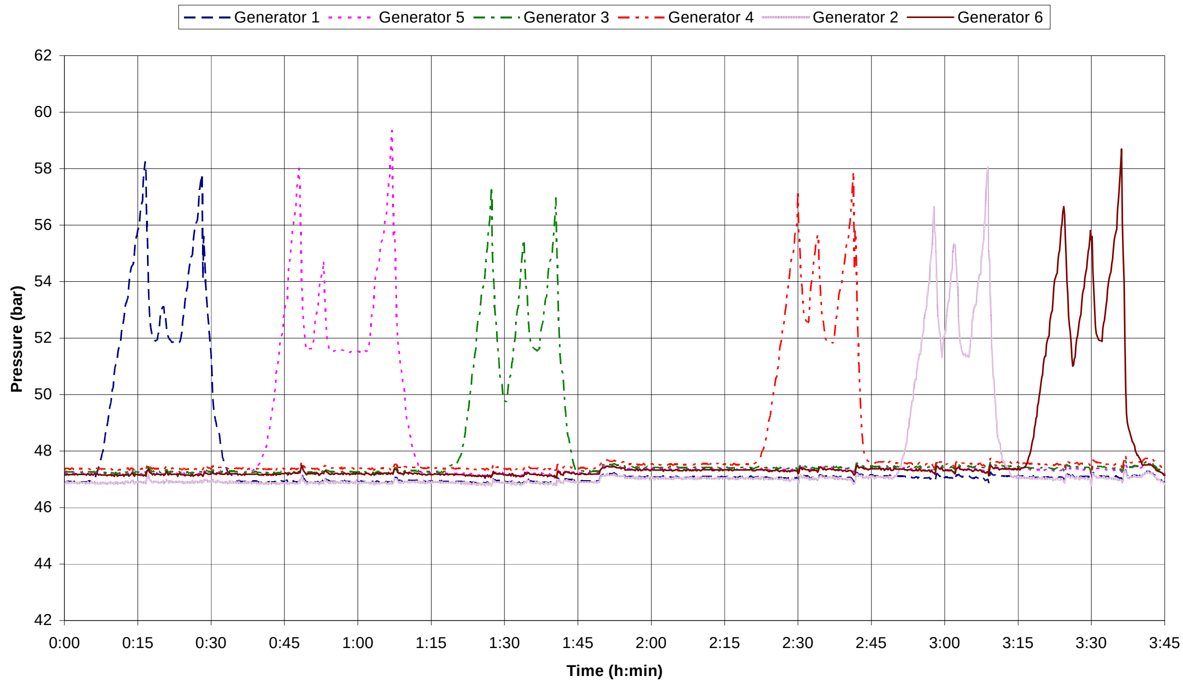

Figure 1. Steam generator pressure during safety valve tests.

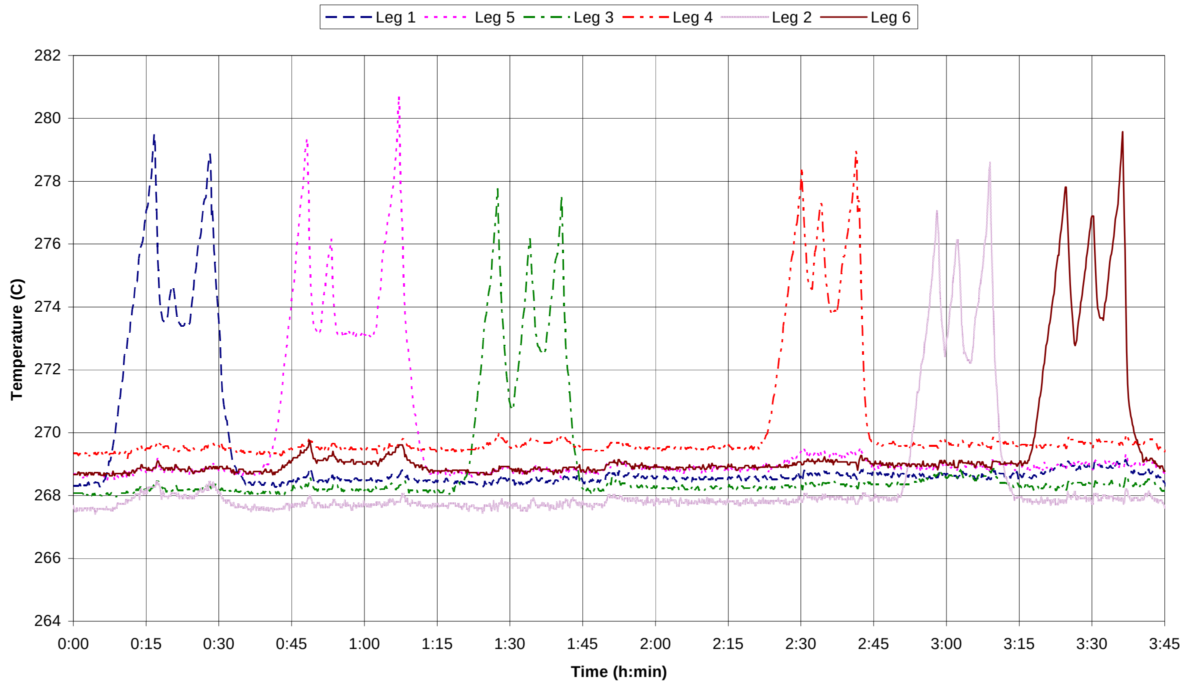

Figure 2. Temperature at cold legs during steam generator safety valve tests.

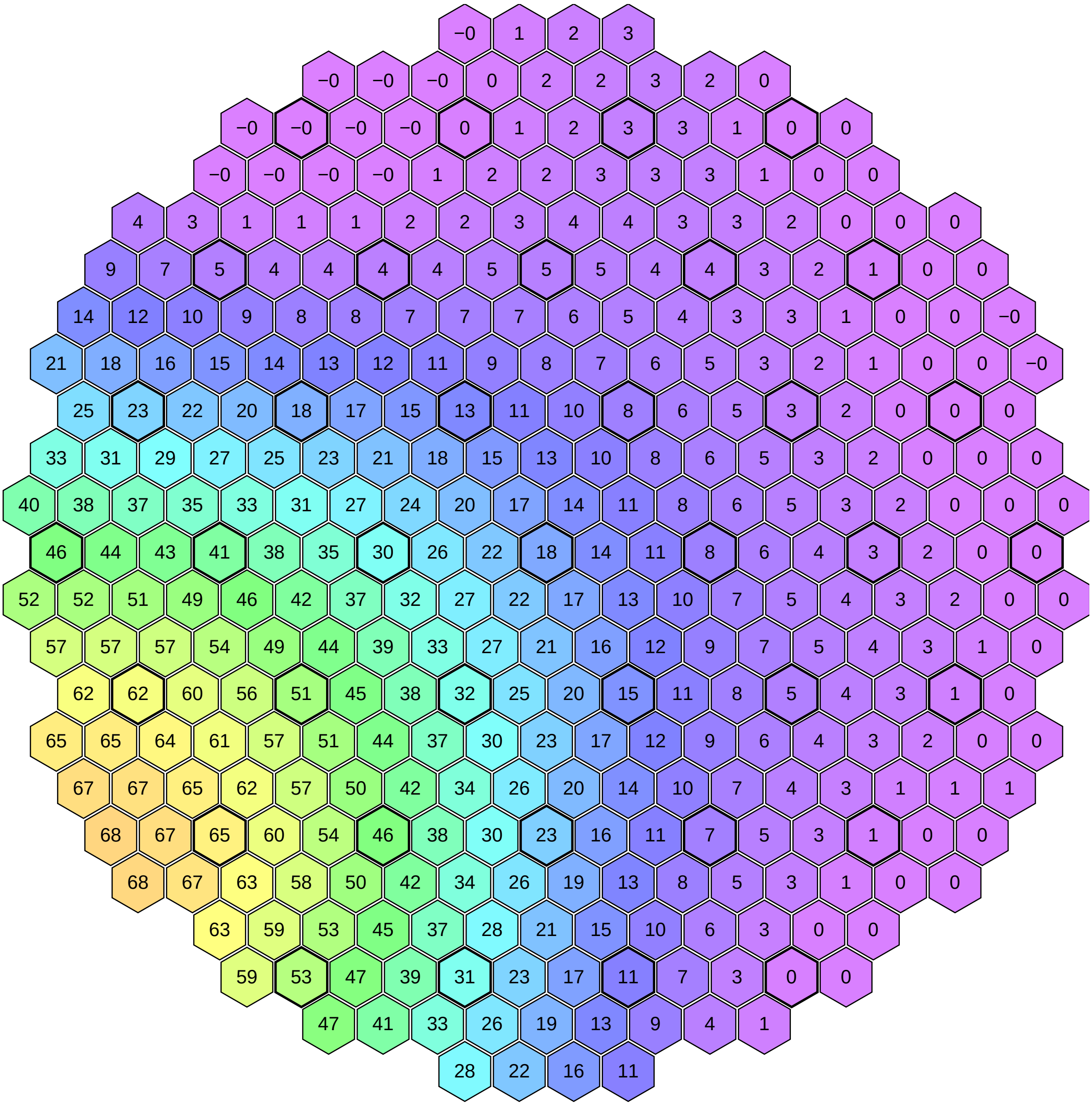
−0 1 2 3
−0 −0 −0 0 2 2 3 2 0
−0 −0 −0 −0 0 1 2 3 3 1 0 0
−0 −0 −0 −0 1 2 2 3 3 3 1 0 0
4 3 1 1 1 2 2 3 4 4 3 3 2 0 0 0
9 7 5 4 4 4 4 5 5 5 4 4 3 2 1 0 0
14 12 10 9 8 8 7 7 7 6 5 4 3 3 1 0 0 −0
21 18 16 15 14 13 12 11 9 8 7 6 5 3 2 1 0 0 −0
25 23 22 20 18 17 15 13 11 10 8 6 5 3 2 0 0 0
33 31 29 27 25 23 21 18 15 13 10 8 6 5 3 2 0 0 0
40 38 37 35 33 31 27 24 20 17 14 11 8 6 5 3 2 0 0 0
46 44 43 41 38 35 30 26 22 18 14 11 8 6 4 3 2 0 0
52 52 51 49 46 42 37 32 27 22 17 13 10 7 5 4 3 2 0 0
57 57 57 54 49 44 39 33 27 21 16 12 9 7 5 4 3 1 0
62 62 60 56 51 45 38 32 25 20 15 11 8 5 4 3 1 0
65 65 64 61 57 51 44 37 30 23 17 12 9 6 4 3 2 0 0
67 67 65 62 57 50 42 34 26 20 14 10 7 4 3 1 1 1
68 67 65 60 54 46 38 30 23 16 11 7 5 3 1 0 0
68 67 63 58 50 42 34 26 19 13 8 5 3 1 0 0
63 59 53 45 37 28 21 15 10 6 3 0 0
59 53 47 39 31 23 17 11 7 3 0 0
47 41 33 26 19 13 9 4 1
28 22 16 11

Figure 3. Response function for leg 4. Function values multiplied by 100.

Since the temperature change is happening only at one cold leg at a time we can study the individual effect of each cold leg's temperature to the inlet temperature distribution. The effect to inlet temperature distribution is studied by using the inlet thermocouple measurements. We assume that the inlet thermocouple measurements measure temperature changes with sufficient accuracy particularly in big disturbances. Disturbance in the cold leg temperature is only visible locally at the core inlet. A large temperature increase can be seen close to the leg whereas no temperature increase is observable at the other side of the reactor core inlet. Based on the observed temperature changes in the inlet thermocouple measurements response functions are fitted for each cold leg. Response function for leg 4 is shown in Fig. 3.

3. CALCULATION OF INLET TEMPERATURE DISTRIBUTION

After obtaining the response functions $f_i(x,y)$ for each cold leg from the steam generator safety valve test inlet temperature at each point (x,y) can be calculated as follows:

$$T(x,y) = T^{ave} + \sum_{1}^{6} dT_i \cdot f_i(x,y)$$

where dT_i = difference between the temperature of leg i, T_i, and average inlet temperature, T^{ave}. Temperature values are obtained straight from the cold leg temperature measurements. The response functions satisfy the requirement:

$$\sum_{1}^{6} f_i(x,y) = 1\,.$$

An alternative method for using the measured cold leg temperature is to calculate the cold leg temperature from the measured mass flow of the leg. The mass flow approach can be used to check the temperature measurement for possible errors. The inlet temperature distributions obtained using the two different methods for the cold leg temperatures should be quite similar.

4. RESULTS

Loviisa-2 cycle 29 was calculated with offline calculation afterwards using the inlet temperature fit described above. In table 1 the asymmetries in the power distribution in each 60 degree sector after 20 FPD operation are given. The asymmetries after 202 FPD operation are given in table 2.

The asymmetries are given with and without the inlet temperature fit. The inlet temperature distribution is calculated based on both cold leg temperature measurements and cold leg mass flow measurements. In tables 1 and 2 also the cold leg temperature differences from the average inlet temperature are given. Each cold leg is paired with the sector to which the leg has the largest effect. However, as can be seen from Fig. 3 each cold leg has influence to a larger area than just one 60 degree sector.

Table 1. Asymmetries in the power distribution in each sector when using constant inlet temperature and fitted inlet temperature. Inlet temperature fit is done from leg temperature and leg mass flow measurements. The cold leg temperature difference from the average is also given. Loviisa-2 cycle 29 after 20 FPD operation.

Sector	Constant inlet temperature	Fitted inlet temperature		Leg	Cold leg temperature from average
		Leg temperature	Leg mass flow		
1	-2.3 %	-1.7 %	-1.4 %	1	-0.1 °C
2	-1.3 %	-1.8 %	-1.9 %	6	0.4 °C
3	0.2 %	-0.6 %	-0.7 %	5	0.2 °C
4	2.4 %	1.2 %	1.4 %	4	1.2 °C
5	1.6 %	1.9 %	1.9 %	3	-0.5 °C
6	-0.6 %	0.9 %	0.7 %	2	-1.1 °C
Stdev	1.77 %	1.57 %	1.56 %		0.8 °C
Max	2.4 %	1.9 %	1.9 %		1.2 °C
Min	-2.3 %	-1.8 %	-1.9 %		-1.1 °C

Table 2. Asymmetries in the power distribution in each sector when using constant inlet temperature and fitted inlet temperature. Inlet temperature fit is done from leg temperature and leg mass flow measurements. The cold leg temperature difference from the average is also given. Loviisa-2 cycle 29 after 202 FPD operation.

Sector	Constant inlet temperature	Fitted inlet temperature		Leg	Cold leg temperature from average
		Leg temperature	Leg mass flow		
1	-2.1 %	-1.5 %	-1.2 %	1	-0.1 °C
2	-0.8 %	-1.3 %	-1.4 %	6	0.4 °C
3	0.2 %	-0.6 %	-0.7 %	5	0.2 °C
4	2.2 %	1.1 %	1.3 %	4	1.1 °C
5	1.5 %	1.8 %	1.7 %	3	-0.5 °C
6	-1.0 %	0.6 %	0.3 %	2	-1.1 °C
stdev	1.62 %	1.35 %	1.31 %		0.8 °C
max	2.2 %	1.8 %	1.7 %		1.1 °C
min	-2.1 %	-1.5 %	-1.4 %		-1.1 °C

After 20 FPD operation the powers of the sectors range from -2.3 % to 2.4 % relative to the average sector power when constant inlet temperature distribution is used. If the inlet temperature fit is used the maximum and minimum of sector power deviation from the average decrease roughly 0.5 %. The behaviour is similar whether the fit is based on cold leg temperature measurements or cold leg mass flow measurements. After 202 FPD operation the behaviour is very similar to that of after 20 FPD operation i.e. the results do not change much during the cycle.

After 20 FPD operation maximum linear heat rate is 317.2 W/cm without the fit and 315.6 W/cm with the fit. Maximum subchannel outlet temperature is 324.2 C without the fit and 324.0 C with the fit. After 202 FPD operation there is no difference in the maximum linear heat rate and maximum subchannel outlet temperature.

5. SUMMARY AND CONCLUSIONS

In this paper a method for fitting the core inlet temperature distribution is described. The method is based on the temperatures of the cold legs and their response functions on the inlet temperature distribution. With this method we were able to reduce the sector asymmetries of power distribution by 0.5 %. However, in maximum linear heat rate and maximum subchannel outlet temperature the decrease was somewhat smaller than expected i.e. 1.6 W/cm and 0.2 °C, respectively. The effect becomes more pronounced with higher disturbances, for example during the steam generator safety valve test itself.

REFERENCES

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