Power Calibration in a TRIGA Reactor

The GSTR Reactor

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A report submitted for the Nuclear Reactor Laboratory class
at the Colorado School of Mines.

SEPTEMBER 14, 2016

Abstract

Licensed reactors have to respect a power limit in terms of thermal output, specified in the licensing documents. The thermal power output is correlated to the measured neutron leakage. Hence, the power instruments must be adjusted so that the indicated thermal power output equals the actual thermal power output. In order to do so, the actual power output needs to be measured and used to calibrate the instruments. This was performed on September 7th, 2016, at the GSTR facility.

Several methods can be applied to measure the actual thermal power output. The method mostly used in nuclear power plants is the calorimetric power calibration. The GSTR does not have a primary water flow instrument, so the mass flow rate usually measured to compute the heat transferred cannot be used. Instead, we use the heat capacity to determine the change in heat in a given amount of water, the temperature varying.

To measure the temperature in the tank water, two sensors are used. This will allow us to compute an average. A water mixer is also installed in the tank, to compensate for the absence of cooling and support natural thermal convection. This allows us to get better temperature reading by avoiding stagnant water around the sensors. The calibration needs the system to be isolated, thus the cooling system is turned off and the discharge valves are closed. The temperature will be scrutinized and the reactor will shut down if it reaches 60°C.

After the reactor reaches a given thermal power output, according to the different detectors to be calibrated, the temperature measurements are taken every two minutes. This allows us to obtain the slope for each temperature sensors and using the net constant of the GSTR, corrected for the water level in the tank, one can compute the actual power output. We see in this report that at an aimed 850 kW of thermal power, the actual thermal power output measured is 910 kW.

All three detectors in the reactor (NM1000, NPP1000 and NP1000) display a lower than measured thermal power output (respectively 840, 870 and 850 kW versus 910 kW, or approximately -7%). This discrepancy can be caused by badly calibrated instruments. In that case, the three detectors will need to be re-calibrated soon in order to give the operators the correct thermal power output, and not be in violation of the GSTR license. Other causes could be thought of to explain this difference. One of them is a quite new 8 inches beam tube, which might have been isolating some water and thus lower the actual amount of water in the tank. However, a quick calculation shows that this is unlikely to be the cause, at least by itself. Another potential cause to explain at least part of the difference could be the measurement uncertainties in the system.

The instruments have not been adjusted following this experiment, because of time-constraints and because an official calibration was already scheduled. This second calibration was performed on September 8th, 2016 [1]. It showed similar results, all power instruments reading lower than the actual measured power. The power channels were thus adjusted and they are now all correctly calibrated.

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Chapter 1

Theory

Licensed reactors have to respect a power limit in terms of thermal output, specified in the licensing documents. The thermal power output is correlated to the measured neutron leakage. Hence, the power instruments must be adjusted so that the indicated thermal power output equals the actual thermal power output. In order to do so, the actual power output needs to be measured and used to calibrate the instruments.

In the GSTR, three detectors are able to give the thermal power output of the reactor based on the neutron flux, the NM1000, NP1000 and NPP1000. These are the instruments we aim at calibrating in this experiment, displayed in appendix C.

The theory and procedure is issued from handouts from the USGS-Reactor Lab course at the Colorado School of Mines [2].

1.1 Power calibration

Several methods can be applied to measure the actual thermal power output. The method mostly used in nuclear power plants is the calorimetric power calibration. This consists of measuring the heat transferred to the tank water:

$$Q' = m'\Delta h \tag{1.1}$$

The mass flow rate can be easily measured by flow sensors, and the enthalpy can be determined from pressure, temperature and steam quality (two phases).

1.2 Application to the GSTR

Unfortunately, the GSTR does not have a primary water flow sensor, hence the water flow rate cannot be used. Instead, heat capacity is used to determine the change in heat in a known amount of water as the temperature changes:

$$Q = \sum(m_i c_i)\Delta T \tag{1.2}$$

In order to use this method, one has to assume that the reactor tank is thermally insulated from its surrounding during the time of the measurement, approximately 45 minutes. The water flow in and out of the reactor has to be stopped, the cooling and purification systems are thus turned off. The lights inside the tank are also turned off. While of low energy, only 60W, they can still have an impact on the temperature sensors. To avoid stagnant water around the temperature sensors and support natural convection, a water mixer is installed. Since we are going to run the reactor with no cooling system for the calibration, it is important to start at a low water temperature.

Due to an issue with the original tank, the GSTR has the particularity of having a newer second tank inside the designed one, with an air gap in between the two. This, even though it was not the objective, allows for a better insulation of the water in the tank.

The GSTR has an approved net heat constant of 28.1°C per MWh. This heat constant varies slightly with the mass of water in the tank, approximately 0.35% per inch. Before starting the power calibration, we can compute this datum.

In our case, we know that the water level is 13 inches below the upper lip of the tank. So it is possible to read from table A.1 the value for the adjusted heat constant. In our case, $H = 28.396$.

Then, the slopes $S_{i,j}$ can be computed, with i the sensor number and j the time point:

$$S_{i,j} = \frac{y_{i,j} - y_{i,0}}{x_{i,j} - x_{i,0}} \tag{1.3}$$

We then only need to make sure the unit conversion are made, by multiplying by 1000 for MW to kW and by 60 for minutes to hours, and we can finally compute the measured thermal power output:

$$P_{kW} = \frac{\sum_{i=1}^{N} \frac{1000*60*S_{i,j}}{H}}{N} \tag{1.4}$$

1.3 Procedure

Now that the calculations are ready, we need to measure our unknowns. Several steps are important:

1. Preparation
2. Calibration
3. Adjustment

1.3.1 Preparation

This step traces all the necessary actions to take before starting up the reactor. As seen previously, the tank water level should be adjusted to be as close as possible to 10 inches below the upper lip of the tank. Since tank water removal is not designed in the TRIGA reactors, one needs to be careful or risk overfilling the tank. The water must be cooled down, to at least 25°C. In our calibration, the water temperature was around 17°C at startup.

As discussed, to help create a flow within the tank, a water mixer is to be installed. Moreover, obviously, a second temperature probe will be inserted in the tank. This sensor should be held in place so as to not mess with the measurements by being moved by currents.

The lights can be turn off. They would not be significantly impacting the measurements, but it is an easy steps to take to improve them.

Finally, when the water temperature is low enough, the reactor cooling system will be shut down. This includes the closing of the primary pump suction and discharge valves, the purification system valve and the ^{16}N diffuser water valve.

1.3.2 Calibration

To actually calibrate our instruments, we first obviously need to start up the reactor. When that is done, the power is increased to around 80% of nominal power. In the GSTR case, that represents between 750 and 900 kW. It is to be noted that if a large error is suspected in the instrumentation readings, the calibration should be done first at low power in order to estimate the delta. However, a re-run at the higher power will be necessary.

Then, we can start actually measuring the temperatures in the two (or more) sensors. The time interval and time length to be used are recommended at 2 minutes intervals for 20 to 50 minutes, when the thermal power output measured has stabilized. The first few data points may be discarded as they may not be representative of the system.

1.3.3 Adjustment

Due to time constraints, and the fact that a real calibration is coming up within the month, this part was not covered. Considering the results seen in the following sections, an adjustment might be necessary. Indeed, a 7% relative difference was observed between the power-indicating channel and the actual measured thermal power. The regulations forces the instruments to be adjusted within 1.5% of the thermal power obtained during the calibration.

In order to adjust the instrumentation, they can simply be moved vertically in the tank. By doing so, they receive a different flux of particles and give a correct ouput. This method is easier than actually adjusting the gain in each of the detectors, which would see some other parameters adjusted too.

This positional adjustment of two detectors is made while in AUTO mode, and the reactor is controlled in MANUAL mode for the third detector adjustment.

Once this is done, the reactor can be set back to normal operations, by turning the cooling and purification systems on. A safe shut down can then be done, and the water mixer and temporary temperature probes can be removed.

Chapter 2

Results

This report shows that at an aimed 850 kW of thermal power, based on the NP1000 detector, the actual thermal power output measured is 910 kW. All three detectors in the reactor (NM1000, NPP1000 and NP1000) display a lower than measured thermal power output (respectively 840, 870 and 850 kW). This discrepancy can be caused by badly calibrated instruments. This section shows the results, based on the data available in the appendix B, and discuss the associated uncertainties.

2.1 Power calibration results

As can be seen in figure 2.1 and table B.1, the measured actual thermal ouput after 45 minutes is 910 kW. This value is 7% higher than expected if the instruments were correctly calibrated. This is troublesome, since it would mean that the reactor reaches full power when the command control readings are around 930 kW, and that higher displayed power would be in excess of the licensed 1000 kW for the reactor operations. This would not have any impact on the reactor safety, but could be seen as a violation of the steady-state operational limits by the NRC.

One possible explanation, else than the apparent need for a adjustment of the instruments position or the uncertainties, would be the presence of 8 inches beam tube in the reactor during the power calibration. This could isolate part of the water in the tank and reduce the amount of water to which the heat is transferred. However, a quick calculation shows that this is unlikely to be (solely) responsible for the high difference observed between measured thermal power and readings from the three detectors.

Indeed, in order to compensate for the 7% relative difference from the mass of water only, the real water level would need to be at around 22 inches below the upper lip of the tank. Considering the dimension of the tank, 7 ft 8 inches in diameter and 24 ft 9.25 inches in height, this represents

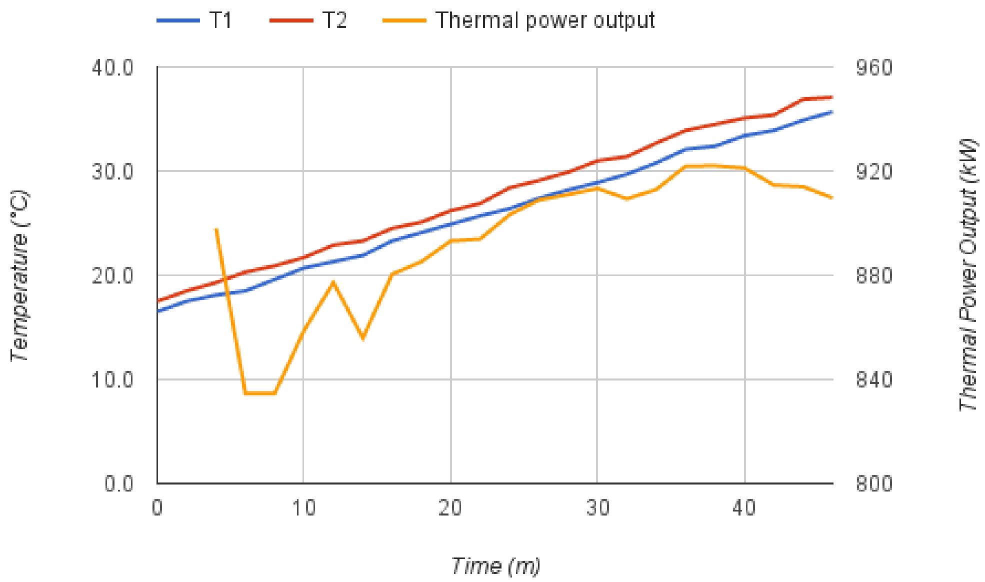

FIGURE 2.1. Power calibration of the GSTR.

around 575 gallons of water to be accounted for. The 8 inches beam tube, assuming a conservative 8 inches diameter and a 24 ft 9.25 inches height, would only account for 65 gallons, moreover not completely insulated, the aluminium clad being quite conductive. The mass and heat capacity of this cladding would also not have a consequent impact on the system's heat constant.

One thing that can be noted is the fact that the graph is not extremely stabilized yet after 46 minutes. In the figure 2.1, the first aberrant point was taken off while still considered in the slope calculation. A real suppression of this point gives the same thermal power output, 910 kW.

2.2 Uncertainties

The two sensors used presents some uncertainties in their measurements. T_1 sensor, the temporary water temperature instrument is a 2252 ohm Resistance Temperature Device detector, with an accuracy of ±0.3% + 0.3°C and a repeatability of 0.1°C. The permanently installed water temperature instrument, T_2, is a 100 ohm RTD presenting an accuracy of ±0.2°C, and a ±1% linearity.

A quick calculation of the minimum and maximum measured thermal power output was done, by taking into account the probes uncertainties. It is important to note that given the asymmetric uncertainties given for the temporary probe, and the mix of percentage and absolute errors, this simple computation is likely false. Nonetheless, it can give an idea of the uncertainties we are dealing with.

The principle of this method is to consider the uncertainty ranges of temperatures measured at each time step, and to compute the smallest and biggest slopes based on these ranges. This gives us a rough minimum and maximum value for the measured thermal power output.

$$\begin{aligned} S_{min,(i,j)} &= \frac{y_{min,(i,j)} - y_{max,(i,0)}}{x_{i,j} - x_{i,0}} \\ S_{max,(i,j)} &= \frac{y_{max,(i,j)} - y_{min,(i,0)}}{x_{i,j} - x_{i,0}} \end{aligned} \tag{2.1}$$

$$\begin{aligned} P_{min,kW} &= \frac{\sum_{i=1}^{N} \frac{1000*60*S_{min,(i,j)}}{H}}{N} \\ P_{max,kW} &= \frac{\sum_{i=1}^{N} \frac{1000*60*S_{max,(i,j)}}{H}}{N} \end{aligned} \tag{2.2}$$

The detailed results are presented in tables B.2, B.3 and B.4. It can be seen that the minimal thermal power output obtained when considering the most disadvantageous combinations of probes uncertainties is 854 KW, while the maximum is 928 kW. This shows a wide range of error, which can potentially explain the high value obtained during the power calibration, if both the probes were performing at the highest and lowest end of their respective range.

Chapter 3

Conclusion

All three detectors in the GSTR (NM1000, NPP1000 and NP1000) display a lower than measured thermal power output (respectively 840, 870 and 850 kW versus 910 kW). This discrepancy can of course be caused by badly calibrated instruments. In that case, the three detectors will need to be re-calibrated soon in order to give the operators the correct thermal power output, and not be in violation of the GSTR license. Other causes could be thought of to explain this difference.

One of the potential other causes was the presence of a quite new 8 inches beam tube, which might have been isolating some water and thus lower the actual amount of water in the tank. However, a quick calculation shows that this is unlikely to be the cause, at least by itself. Another potential cause for the consequent discrepancy could be a lack of luck with the temperature probes, the uncertainties at the extreme end of the range being able to account for some of the difference. That would also be quite unlikely to be the sole reason, since most values for both detectors are in agreement with one another.

The second calibration, which was performed the next day at the facility brings some more light to this power calibration. It was done in different conditions (xenon, ambient humidity and heat, etc), yet it showed similar results, all power instruments reading lower than the actual measured power. The alternative explanations can thus be invalidated. The power channels were adjusted and are now all correctly calibrated.

In regards of the present analysis, it remains to be seen how to be more confident in the data collected, so as to not have needed a re-run of the calibration. In our case, a longer data point gathering could have helped, as well as adding another probe to lower the measurement uncertainties. The reactor tank water was still a way off of the 60°C limit, and more points could have been measured had we not been contrained by time.

APPENDIX A

ADJUSTED HEAT CONSTANT

This appendix presents the adjusted heat constant for the USGS GSTR as a function of the level of water in the tank. A correction of 0.35% per inches of water below the upper lip is applied.

Water level below the upper lip	Adjusted heat constant
5 inches	27.612
6 inches	27.709
7 inches	27.806
8 inches	27.904
9 inches	28.002
10 inches	28.1
11 inches	28.198
12 inches	28.297
13 inches	28.396
14 inches	28.495
15 inches	28.595

Table A.1: Adjusted heat constant

APPENDIX B

Detailed data tables

This appendix presents the data measured during the power calibration on September 7, 2016 at the USGS GSTR facility, as well as the detailed calculation to compute the actual thermal power output.

Time (min)	T_1 (°C)	T_2 (°C)	S_1 (°C/min)	S_2 (°C/min)	$P_{th,1}$ (kW)	$P_{th,2}$ (kW)	$P_{th,avg}$ (kW)
0	16.5	17.5					
2	17.5	18.5	0.5000	0.5000	1056	1056	1056
4	18.1	19.3	0.4000	0.4500	845	951	898
6	18.5	20.3	0.3300	0.4600	697	972	835
8	19.6	20.9	0.3600	0.4300	761	909	835
10	20.7	21.7	0.3957	0.4171	836	881	859
12	21.3	22.9	0.3982	0.4321	841	913	877
14	21.9	23.3	0.3911	0.4190	826	885	856
16	23.3	24.5	0.4083	0.4250	863	898	880
18	24.1	25.1	0.4167	0.4212	880	890	885
20	24.9	26.2	0.4205	0.4250	888	898	893
22	25.7	26.9	0.4219	0.4243	891	897	894
24	26.4	28.4	0.4203	0.4346	888	918	903
26	27.4	29.1	0.4216	0.4387	891	927	909
28	28.2	29.9	0.4220	0.4404	892	930	911
30	28.9	31.0	0.4206	0.4439	889	938	913
32	29.7	31.4	0.4192	0.4415	886	933	909
34	30.8	32.7	0.4206	0.4436	889	937	913
36	32.1	33.9	0.4252	0.4475	898	945	922
38	32.4	34.5	0.4246	0.4482	897	947	922
40	33.4	35.1	0.4251	0.4468	898	944	921
42	33.9	35.4	0.4235	0.4423	895	934	915
44	34.9	36.9	0.4230	0.4421	894	934	914
46	35.7	37.1	0.4225	0.4386	893	927	910

Table B.1: Detailed data

Time	T_1 (°C)	$T_{1,min}$ (°C)	$T_{1,max}$ (°C)	$S_{1,min}$ (°C/minutes)	$S_{1,max}$ (°C/minutes)
0	16.5	16.4	16.9		
2	17.5	17.3	18.0	0.20	0.80
4	18.1	17.9	18.6	0.25	0.55
6	18.5	18.3	19.0	0.23	0.43
8	19.6	19.4	20.1	0.31	0.46
10	20.7	20.5	21.2	0.36	0.48
12	21.3	21.1	21.8	0.35	0.45
14	21.9	21.7	22.4	0.34	0.43
16	23.3	23.1	23.8	0.39	0.46
18	24.1	23.9	24.6	0.39	0.46
20	24.9	24.7	25.4	0.39	0.45
22	25.7	25.5	26.2	0.39	0.45
24	26.4	26.2	26.9	0.39	0.44
26	27.4	27.2	27.9	0.39	0.44
28	28.2	28.0	28.7	0.40	0.44
30	28.9	28.7	29.4	0.39	0.43
32	29.7	29.5	30.2	0.39	0.43
34	30.8	30.6	31.3	0.40	0.44
36	32.1	31.9	32.6	0.42	0.45
38	32.4	32.2	32.9	0.40	0.44
40	33.4	33.2	33.9	0.41	0.44
42	33.9	33.7	34.4	0.40	0.43
44	34.9	34.7	35.4	0.40	0.43
46	35.7	35.5	36.2	0.40	0.43

Table B.2: Uncertainty consideration for the temporary temperature probe

Time	T_2 (°C)	$T_{2,min}$ (°C)	$T_{2,max}$ (°C)	$S_{2,min}$ (°C/minutes)	$S_{2,max}$ (°C/minutes)
0	17.5	17.1	17.9		
2	18.5	18.1	18.9	0.12	0.88
4	19.3	18.9	19.7	0.26	0.64
6	20.3	19.9	20.7	0.34	0.60
8	20.9	20.5	21.3	0.33	0.52
10	21.7	21.3	22.1	0.34	0.50
12	22.9	22.5	23.3	0.38	0.52
14	23.3	22.9	23.7	0.36	0.47
16	24.5	24.1	24.9	0.39	0.49
18	25.1	24.6	25.6	0.38	0.47
20	26.2	25.7	26.7	0.39	0.48
22	26.9	26.4	27.4	0.39	0.47
24	28.4	27.9	28.9	0.42	0.49
26	29.1	28.6	29.6	0.41	0.48
28	29.9	29.4	30.4	0.41	0.47
30	31.0	30.5	31.5	0.42	0.48
32	31.4	30.9	31.9	0.41	0.46
34	32.7	32.2	33.2	0.42	0.47
36	33.9	33.4	34.4	0.43	0.48
38	34.5	34.0	35.0	0.42	0.47
40	35.1	34.5	35.7	0.42	0.46
42	35.4	34.8	36.0	0.40	0.45
44	36.9	36.3	37.5	0.42	0.46
46	37.1	36.5	37.7	0.41	0.45

Table B.3: Uncertainty consideration for the permanent temperature probe

$P_{1,min}$ (kW)	$P_{1,max}$ (kW)	$P_{2,min}$ (kW)	$P_{2,max}$	$P_{mes,min}$ (kW)	$P_{mes,max}$ (kW)
420	1692	254	1859	337	1776
526	1164	545	1357	536	1260
491	917	712	1260	602	1089
658	979	691	1105	675	1042
758	1017	720	1055	739	1036
737	953	809	1092	773	1023
722	908	753	997	738	953
816	980	816	1033	816	1006
819	965	795	989	807	977
822	953	831	1008	826	980
823	944	822	984	823	964
816	927	884	1035	850	981
834	937	872	1013	853	975
835	931	870	1002	852	966
829	918	889	1013	859	966
829	914	859	977	844	945
849	929	889	1001	869	965
878	954	909	1016	893	985
848	920	894	996	871	958
858	927	881	979	870	953
843	908	854	947	848	928
852	915	886	977	869	946
852	912	857	944	854	928

Table B.4: Probes uncertainty consideration for the thermal power output calculation

Appendix C

Power instrumentation

This appendix presents the three different detectors used at the GSTR facility to compute the reactor thermal power output.

C.1 NM1000

The NM1000 is a wide range, digital instrument. It is a fission chamber which can compute power from 0.0001 W to 1.2 MW. It is not linked to a SCRAM system, but contains a couple of interlocks.

C.2 NP/NPP1000

The NP1000 and NPP1000 are similar instruments. They are analog ionization chambers, with a range of 10 kW to 2 GW, so they can follow reactor pulses but are mostly useless at startup. They are connected to two types a SCRAM, high power and loss of high voltage.

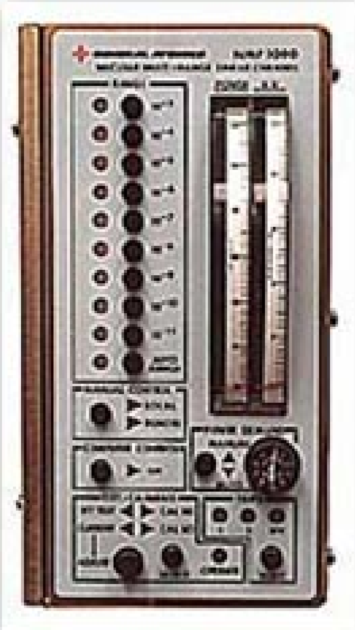

FIGURE C.1. NM1000.

FIGURE C.2. NP/NPP1000.

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