Super prompt critical operations

Reactor pulse

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Abstract

When the positive reactivity added to a critical core is equal to the effective delayed neutron franction, β_{eff}, prompt criticality is achieved. That corresponds to a positive reactivity of 1$. Super prompt critical states arise when the reactivity insertion is above this one dollar limit. Essentially, in this state of operation, the delayed neutrons do not control the reactor period, and the power grows exponentially.

TRIGA reactors such as the GSTR are able to withstand this power excursion by design, due to the decrease in the thermal non-leakage probability caused by the fuel temperature effect. From pulsing, it is possible to compute the prompt neutron lifetime, the negative temperature coefficient and the specific heat of the core. The Fuchs-Nordheim model approximation will be tested against the experimental values obtained.

Despite larger errors associated with larger prompt reactivity insertion, the Fuchs-Nordheim model is shown to be in good agreement with the measured data, with the correct correlations between the prompt reactivity insertion and the different parameters of the core (peak power, period, shape of the power time distribution, ...).

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Chapter 1

Theory

When the positive reactivity added to a critical core is equal to the effective delayed neutron franction, β_{eff}, prompt criticality is achieved. That corresponds to a positive reactivity of 1\$. Super prompt critical states arise when the reactivity insertion is above this one dollar limit. Essentially, in this state of operation, the delayed neutrons do not control the reactor period, and the power grows exponentially.

TRIGA reactors such as the GSTR are able to withstand this power excursion by design, due to the decrease in the thermal non-leakage probability caused by the fuel temperature effect. From pulsing, it is possible to compute the prompt neutron lifetime, the negative temperature coefficient and the specific heat of the core. The Fuchs-Nordheim model approximation will be tested against the experimental values obtained.

1.1 Super prompt criticality

TRIGA reactors have a particular fuel design in which a fuel temperature increase causes a negative feedback loop, causing the reactivity to decrease by modifying the thermal non-leakage probability. This is what allows this reactor design to pulse, as opposed to the power reactors, where power generation infers that the fuel high temperature cannot be designed to have such a high negative reactivity feedback.

However, even though a voluntary pulse is not possible in a power reactor, it can happen in a specific accident, rod ejection. In that case, one control rod is ejected suddenly from the core, causing this pulse and damaging the fuel cladding of the neighboring fuel elements.

1.2 Fuchs-Nordheim model

The Fuchs-Nordheim model describes the time behavior of a reactor with a large prompt negative temperature coefficient, the case of the GSTR, when there is a sudden insertion of a large amount of positive reactivity. This model is based on two primary assumptions about the reactor behavior during the pulse, namely that the delayed neutrons can be neglected and that all heat generated remains in the fuel. Those assumptions can be intuitively considered pretty good considering the timescale of a pulse, of the order of tens to hundreds of milliseconds.

The model relates parameters of flux, reactivity, temperature change and energy released. In the following, we will consider the notations given below:

l = Prompt neutron lifetime
α = Prompt negative temperature coefficient
C = Total heat capacity of the core available to the prompt burst energy release
$\Delta\bar{T}$ = the change in average core temperature produced by the prompt burst
Δk_p = The portion of the step reactivity insertion which is above prompt critical.

If an insertion of reactivity is made, the reactor power will initially increase as $e^{\frac{t}{\tau}}$, where τ is the period and t the time.

$$\tau = \frac{l}{\Delta k_p} \tag{1.1}$$

$$\Delta k_p = (p\$ - 1) * \beta_{eff} \tag{1.2}$$

Using the assumption of constant heat capacity and adiabatic conditions, we can obtain that the reactor temperature will rise by $\frac{\Delta k_p}{lt}$ until the reactivity insertion beyond prompt critical is just compensated by the fuel temperature rise. The reactor power peaks at this time and then falls while the core temperature continues to increase to a maximum value double the temperature at peak power.

$$\Delta\bar{T} = \frac{2\Delta k_p}{\alpha} = \frac{E}{C} \tag{1.3}$$

The total energy release during the pulse is given by:

$$E = \frac{2C\Delta k_p}{\alpha} \tag{1.4}$$

The peak power is:

$$P_{max} = \frac{C(\Delta k_p)^2}{2l\alpha} + P_0 \tag{1.5}$$

However, we have that $P_0 << P_{max}$, so the initial power value can be neglected.

From the equations derived above, we can say that the energy release from a pulse vary linearly with the prompt reactivity insertion, and the peak power vary as the second power of the prompt reactivity insertion. Both the energy release and the peak power depend on the specific heat of the core C.

Moreover, the full width at half maximum can be linked to the prompt reactivity insertion:

$$FWHM = \frac{4l cosh^{-1}(\sqrt(2))}{\Delta k_p} \tag{1.6}$$

From equation 1.6, one can deduce the prompt neutron lifetime:

$$l = \frac{FMWH * \Delta k_p}{4cosh^{-1}(\sqrt(2))} \tag{1.7}$$

The negative temperature coefficient and the specific heat of the core can be approximated for the TRIGA fuel by:

$$\alpha = 11 * 10^{-5} + 8 * 10^{-8}(\bar{T} - T_{ini}) \tag{1.8}$$

$$C = (740 + 1.48(\bar{T} - T_{ini})) * N \tag{1.9}$$

N = Number of fuel elements in the core (125)

Those approximations will be compared to the measurements made in the results section.

1.3 Procedure

In order to pulse the reactor, it must first be in a critical state. At that point, the transient rod is pneumatically withdrawn from the core, in a very short time span. As soon as the rod extraction caused a positive reactivity insertion higher than a dollar, the reactor enters the super prompt critical state and the power increases extremely quickly to a high value. In a TRIGA reactor, the fuel temperature negative reactivity feedback then kicks in and counteracts the reactivity insertion from the rod withdrawal.

The final steady state depends on the reactivity insertion and the fuel itself (its heat transfer characteristics notably). If no action is performed after the pulse, the reactor would stabilize at a power depending on the initial value. A rule of thumb states that you need 0.25 cents of reactivity per kW. Hence, a pulse of $2.50 would, without a SCRAM, stabilize the power at 1000 kW. However, that is true considering a low initial power. Had the initial power been higher, the steady state of the reactor would stabilize at higher power, exceeding the license limits.

Consequently, before pulsing the reactor, the automatic SCRAM on high power needs to be checked. The pulse rod should drop within a seconds of its extraction, and the other three control rods after 15 seconds. In order to do so, it is possible to simulate a high power peak by sending a current to the NPP1000 detector. Due to the high power increase, it is also important to monitor the fuel temperature, to make sure the fuel cladding doesn't suffer any unexpected stress.

Once the checks are done, the pulses can be initiated by putting the reactor in a stable critical state. Using the transient rod calibration curve, it is possible to obtain the desired height to be extracted from the core to generate a given pulse reactivity insertion. The results, mainly the power readings, are then automatically computed by the control computer and can be analyzed.

Chapter 2

Results

In this section, the prompt neutron lifetime, the negative temperature coefficient and the specific heat of the core will be measured and compared to the approximate values usually used. The results are based on the data given by the computer for the power as a function of time and the fuel temperature.

2.1 Results

The higher the prompt reactivity inserted, the higher the peak power and the thinner its distribution. Figure 2.1 shows the pulse for various insertion of positive reactivity, with a maximum peak power obtained of 1.2 GW.

The neutron lifetime is computed by using the full-width at half maximum values, obtained from the data. Table 2.1 gives the results for various prompr criticality insertion values. The approximate value used is 38 μs, which seems correct for low prompt reactivity insertion, and thus for critical states. However, the higher the prompt reactivity insertion, the higher the neutron lifetime observed.

Prompt reactivity insertion ($)	Neutron lifetime $l(\mu s)$
1.5	39.98
1.75	44.28
2.0	45.99
2.3	49.30
2.3	48.55

Table 2.1: Neutron lifetime for various prompt reactivity insertion

The negative temperature coefficient can be computed from the average change in temperature

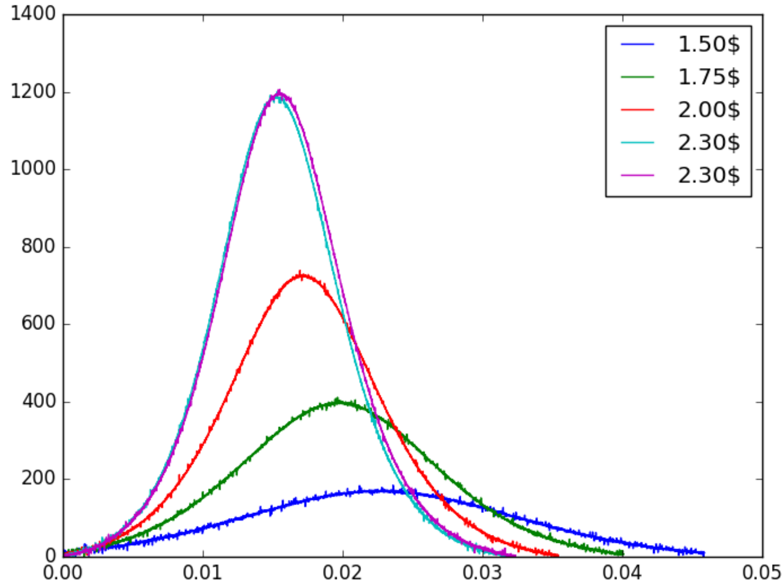

FIGURE 2.1. Pulses of the GSTR.

in the core and the prompt reactivity inserted. The average core temperature is obtained by approximation on the peak fuel temperature, considering a factor two between the peak factor and the average, hence a perfect temperature gradient in the core. The values obtained are presented in table 2.2, with an average of $9.3*10^{-5}$. This is quite far from the approximation from equation 1.8, with an error between 15 and 35%.

We can see on figure 2.2 that the negative temperature coefficient varies linearly with the average core temperature, with a R^2 value of 0.998.

$$\alpha = 4.38*10^{-5} + 3.486*10^{-7}(\bar{T} - T_{ini}) \tag{2.1}$$

Prompt reactivity insertion ($)	Average ΔT (Celsius)	α ($\$/Celsius$)	Estimate
1.5	92.7	$7.5*10^{-5}$	$1.17*10^{-4}$
1.75	120.8	$8.7*10^{-5}$	$1.20*10^{-4}$
2.0	147.2	$9.5*10^{-5}$	$1.22*10^{-4}$
2.3	174.5	$1.0*10^{-4}$	$1.24*10^{-4}$
2.3	174.2	$1.0*10^{-4}$	$1.24*10^{-4}$

Table 2.2: Negative temperature coefficient for various prompt reactivity insertion

The specific heat of the core can also be measured for various prompt reactivity insertion following Fuchs-Nordheim model. Table 2.3 shows the results, with an error between 2 and 8%

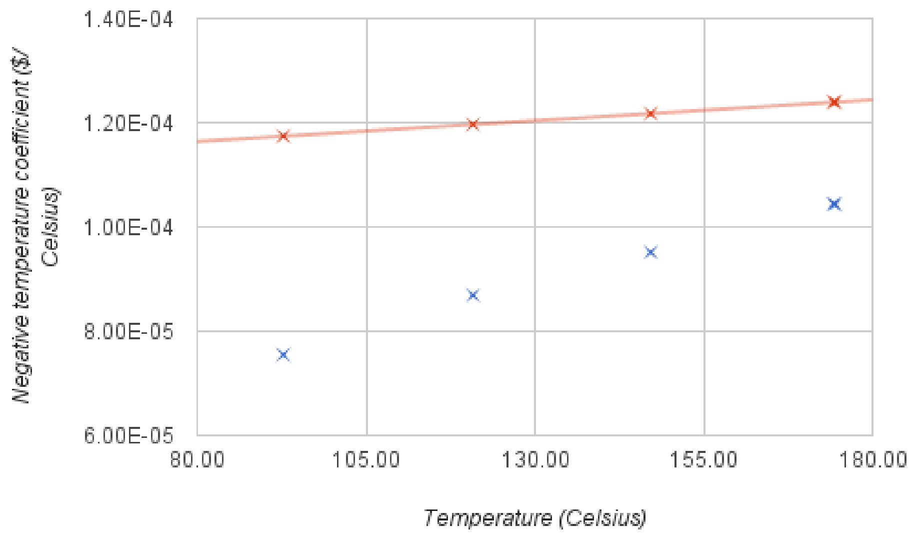

FIGURE 2.2. Negative temperature coefficient vs temperature.

between the measured value and the estimate, the measured value using the average negative temperature coefficient calculated previously.

Prompt reactivity insertion ($)	Specific heat of the core ($W.s/Celsius$)	Estimate
1.5	112280	109657
1.75	123245	114855
2.0	129377	119724
2.3	133916	124774
2.3	131243	124731

Table 2.3: Specific heat of the core for various prompt reactivity insertion

It is possible to see on figures A.1 to A.4 that the experiment agrees with the trend predicted by the Fuchs-Nordheim model. Indeed, the fuel temperature and the pulse energy correlates linearly with the prompt reactivity insertion (respectively $R^2 = 0.998$ and $R^2 = 0.999$). Moreover, the inverse dependance of the FWHM and the pulse period with the prompt reactivity insertion is confirmed.

The peak power also clearly shows a second degree polynomial trend, on figure 2.1.

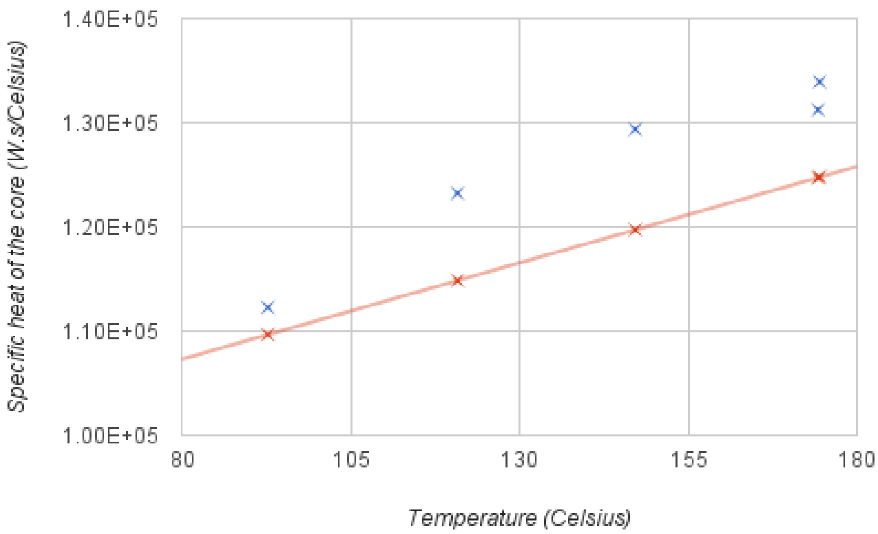

FIGURE 2.3. Total heat of the core vs temperature.

2.2 Uncertainties

Several uncertainty sources must be considered. First and foremost, the prompt reactivity insertion is estimated through the use of the calibration curves. In that regards, the uncertainties observed when calculating this curve propagates here. In the case of the GSTR, it has been shown that the transient rod might be slightly off-centered, skewed toward the top of the core [1].

A telling way to obtain parts of the uncertainties in the system is to compare the two measurement made for a maximum pulse, with a \$2.3 prompt reactivity insertion. One can see that even though the conditions are supposed to be identical, some differences can be observed. Indeed, table 2.4 presents the relative errors.

This table does not represent all the uncertainties in the system, it merely illustrates a potential impact. It is however useful to give us an idea of the uncertainties of the measurements.

One can see then that the estimates for α and C are not very precise, and could gain to be calculated again, using figures 2.2 and 2.3.

Parameter	Relative difference
Reactivity	0%
FWHM	1.5%
Pulse energy	2.3%
Pulse period	1.7%
Fuel temperature peak	0.3%
Neutron lifetime	1.5%
Specific core heat	2.3%
Prompt negative temperature coefficient	-0.3%

Table 2.4: Relative difference between the different parameters for identical prompt reactivity insertion

Chapter 3

Conclusion

Even though the usefulness of pulsing a nuclear reactor is debatable, and confined to very specific irradiation tasks, the fact that it is possible while respecting the safety of the reactor is quite remarkable. This project showed that the estimates used for the stotal heat of the core were relatively good when applied to low prompt reactivity insertion, but degraded the higher it got. The opposite effect was observed for the prompt negative temperature coefficient.

Overall however, the Fuchs-Nordheim model is shown to be in good agreement with the measured data, with the correct correlations between the prompt reactivity insertion and the different parameters of the core (peak power, period, shape of the power time distribution, ...).

The maximum pulse value for the GSTR is $2.3, due to the worth of the transient rod and the reactivity of its neighboring fuel elements. The GSTR is licensed for a pulse at $3. The reactor was still able to pulse at 1.3 GW for a short amount of time.

Appendix A

Detailed data tables

This appendix presents the raw data from the experiment in table A.1. It then explicits the various calulcation steps in table A.2. The detailed figure for each parameter are also given in this appendix.

Table A.1: Raw data

Reactivity ($)	FWHM (ms)	Pulse energy (MWs)	Pulse period (ms)	Fuel temperature peak (C)
2.3	9.80E+00	1.30E+01	2.88E+00	3.84E+02
2.3	9.95E+00	1.33E+01	2.93E+00	3.85E+02
2	1.21E+01	9.81E+00	3.55E+00	3.30E+02
1.75	1.55E+01	6.94E+00	4.56E+00	2.78E+02
1.5	2.10E+01	4.06E+00	6.17E+00	2.21E+02

Table A.2: Calculated data

Reactivity ($)	Prompt neutron lifetime (μs)	C ($W.s/Celsius$)	α (C/$)
2.3	48.55	1.31E+05	1.045E-04
2.3	49.30	1.34E+05	1.043E-04
2	45.99	1.29E+05	9.51E-05
1.75	44.28	1.23E+05	8.69E-05
1.5	39.98	1.12E+05	7.55E-05

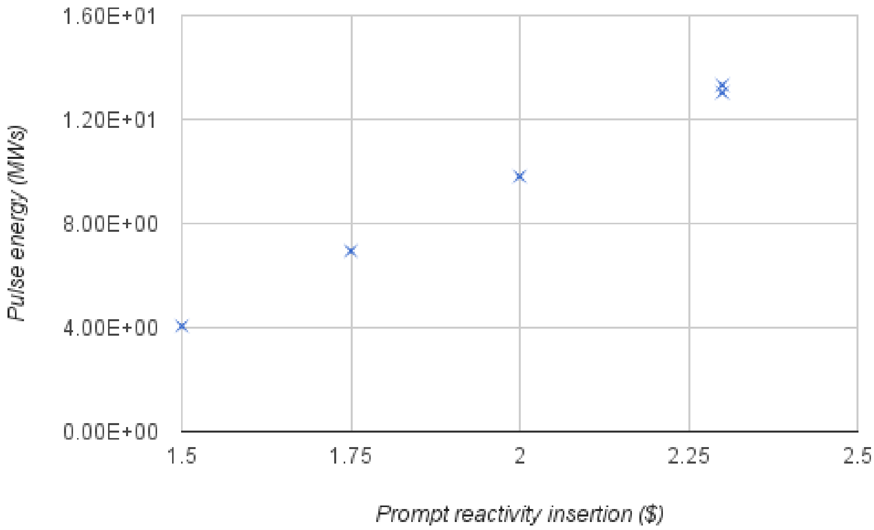

FIGURE A.1. Pulse energy as a function of the prompt reactivity inserted.

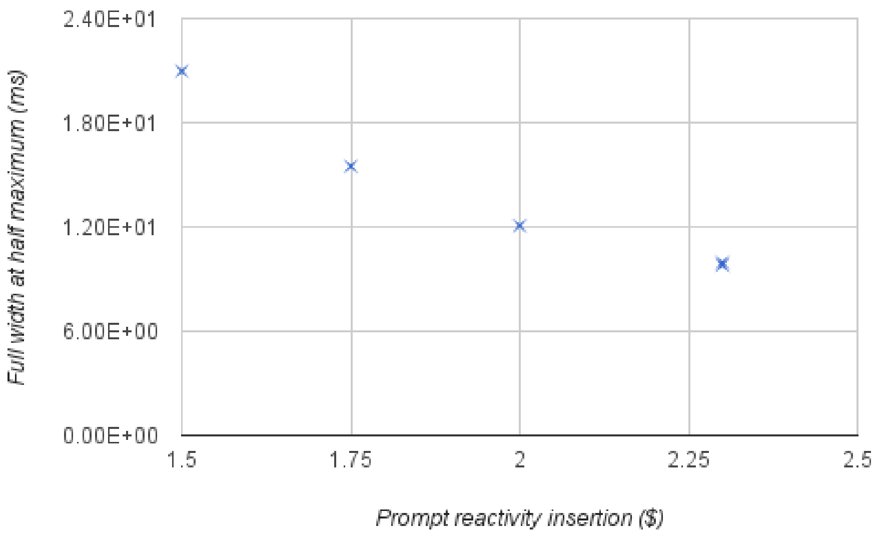

FIGURE A.2. Pulse FWHM as a function of the prompt reactivity inserted.

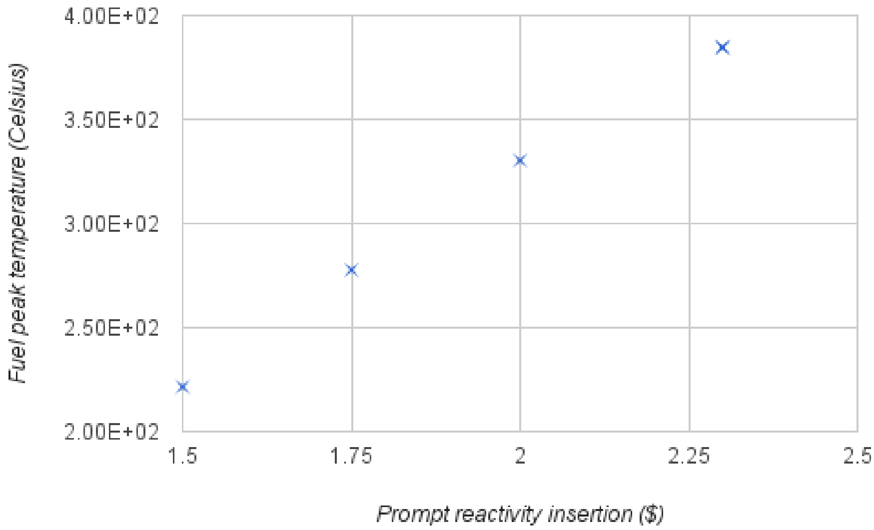

FIGURE A.3. Fuel temperature as a function of the prompt reactivity inserted.

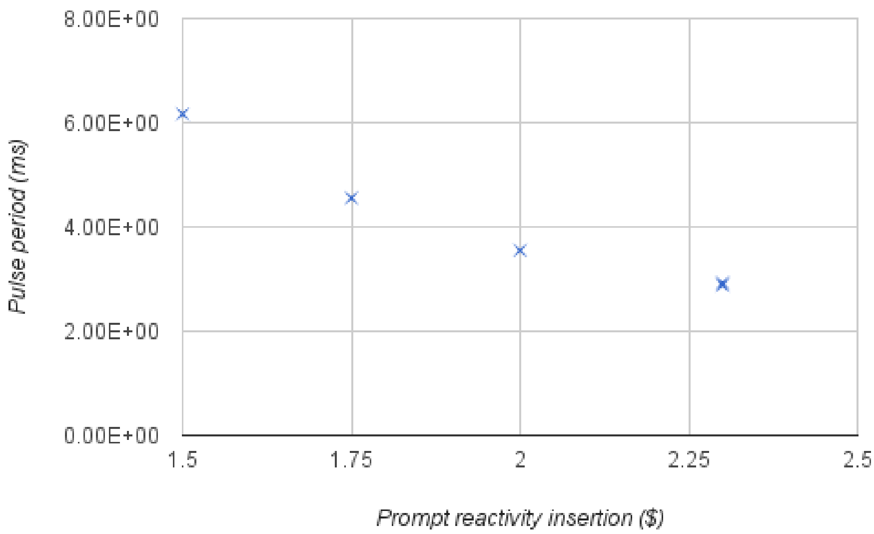

FIGURE A.4. Pulse period as a function of the prompt reactivity inserted.

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