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# REACTIVITY POWER COEFFICIENT DETERMINATION OF THE IPR-R1 TRIGA REACTOR

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## ABSTRACT

The aim of this paper is to present the experimental results of the power coefficient of reactivity of the IPR-R1 TRIGA reactor at the Nuclear Technology Development Center – CDTN. Because of the prompt negative temperature coefficient, a significant amount of reactivity is needed to overcome temperature and allow the reactor to operate at high power levels. The reactivity needed to operate the IPR-R1 Reactor at 250 kW is around 1.6 $ (1264 pcm). The determined isothermal temperature coefficient of reactivity is 0.44 ¢/°C, and the average fuel power reactivity coefficient is -0.88 ¢/kW.

## 1. INTRODUCTION

The TRIGA fuel elements are filled with homogeneous metallic mixture of the moderator zirconium-hydride combined with 20%-enriched uranium. The feature of these fuel-moderator elements is the prompt negative temperature coefficient of reactivity, which automatically limits the reactor power to a safe level in the event of a power excursion [1, 2, 3]. Because of this coefficient, a significant amount of reactivity is needed to overcome temperature and allow the reactor to operate at high power levels.

This paper reports the results of a set of experiments to determine the isothermal temperature coefficient, the fuel power coefficient, $\alpha_P(F)$, and the power coefficient of reactivity. The isothermal temperature coefficient was measured by observing the reactivity change as core temperature is raised by other means while the reactor is operating at a very low, effectively zero power level. When the reactor is at zero power there is no fission energy being released in the fuel, and the entire reactor core can be characterized by a single temperature. The results obtained demonstrated that the fuel temperature coefficient is the main contributor to the reactivity power coefficient of the TRIGA reactor.

## 2. METHODOLOGY

Temperature is one of the operating conditions that affects the reactivity of a reactor core: a change in temperature will cause a change in reactivity. The direction of the change, whether it is positive or negative, and its magnitude are of great importance from the standpoint of the reactor safety and control. To understand this statement, consider the accidental introduction of positive reactivity and the consequent increase in power and temperature. If the reactivity effect of the increase in temperature is negative, the reactor will tend to level out at a new, higher power without external manipulation of controls, such a reactor is stable and inherently safe. If, on the other hand, the reactivity effects were positive, the reactor would tend to "run away", and its safety would depend entirely on external control.

If the temperature change is uniform throughout the core, as would be in an homogeneous reactor, the temperature effect on the reactivity can be expressed by a simple temperature coefficient, $\alpha_{ISO}$, defined as the change in reactivity per degree change in temperature [4]:

$$\alpha_{ISO} = \frac{\Delta\rho}{\Delta T} \tag{1}$$

where $\Delta\rho$ and $\Delta T$ are the change in reactivity and temperature, respectively. The negative reactivity feedback, $\Delta\rho_T$, produced by a temperature increase $\Delta T$ is then

$$\Delta\rho_T = \alpha_{ISO}\,\Delta T \tag{2}$$

assuming that $\alpha_{ISO}$ is constant over the range of temperature $\Delta T$. This $\alpha_{ISO}$ is sometimes called the isothermal temperature coefficient or the zero-power temperature coefficient [4].

Heterogeneous reactor changes in temperature during operation are not uniform, that is, they are not the same in the moderator as in the fuel. In such a reactor we have to distinguish between the reactivity arising in the cooling, or moderator, and that arising in the fuel, and, accordingly, define a coolant temperature coefficient, $\alpha_T(M)$, and a fuel temperature coefficient, $\alpha_T(F)$. These coefficients, which depend on different factors, will in general be different in magnitude and in response time. Effects that depend on the instantaneous state of fuel, for instance, resonance absorption (Doppler effect) or thermal distortion of fuel elements, are regarded as prompt, while effects that depend on the moderator or coolant are delayed (neutron energy spectrum and thermal expansion of moderator material).

The coefficient $\alpha_T(M)$ in a reactor is not measurable as a separate quantity, since is not possible to raise the temperature of the coolant without raising the temperature of the fuel. The quantity that can readily be determined is the isothermal temperature coefficient, measured by observing the reactivity change as core temperature is raised by other means while the reactor is operating at a very low power level (zero power). Under such conditions the temperatures of the cooling and the fuel are effectively the same.

In practice, it is impossible to measure $\alpha_T(F)$ directly, in the core, since the effective fuel temperature cannot be measured. However, $\alpha_T(F)$ is the main contributor to the power coefficient of reactivity, which can be measured. To understand the effect of the operating power level on reactivity of the core, assume that the mean temperature of the coolant and its rate of flow are kept the same at all power levels. An increase in power level must then cause an increase in the fuel temperature, where it is generated, into the coolant that carries it away. Under these conditions it is obvious that an increase in power level will cause a negative change in the reactivity. The power coefficient of reactivity is defined as

$$\alpha_P = \frac{\Delta\rho}{\Delta P} \tag{3}$$

where $\Delta P$ is the change in power. Thus, in a change of power level the change in the reactivity is

$$\Delta\rho_P = \alpha_P \Delta P \tag{4}$$

To obtain the contribution of the fuel to $\Delta\rho_P$ and thus the fuel power coefficient, $\alpha_P(F)$, in a reactor, we have to subtract $\Delta\rho_T(M)$, the effect arising in the moderator due to the change in moderator temperature, $\Delta T(M)$. An approximate value for $\Delta\rho_T(M)$ would be:

$$\Delta\rho_T(M) = \alpha_{ISO}\,\Delta T(M) \tag{5}$$

Then, the fuel power coefficient of reactivity is given by

$$\alpha_P(F) = \frac{\Delta\rho_P(F)}{\Delta P} \tag{6}$$

## 3. THE IPR-R1 TRIGA REACTOR

The IPR-R1 TRIGA Reactor core consists of a lattice of cylindrical fuel-moderator elements and graphite elements. The 250 kW core configuration has 63 fuel elements composed of 58 original Al-clad elements and 5 fresh SS-clad fuel elements. The elements are arranged in five concentric rings, and the spaces between the rods are filled with water that acts as coolant and moderator. The power level of the reactor is controlled with three control rods: a Regulating rod, a Shim rod, and a Safety rod. Fuel temperature was obtained through the use of an instrumented fuel element with thermocouples embedded in the zirconium centerline pin. Fuel temperature measurements were taken in the position B1 (ring B). The inlet and outlet coolant temperatures were measured by using two type K thermocouples inserted in two channels in the core, close to the position B1. A schematic view of the present core configuration, and the position of the thermocouples are shown in Figure1.

TRIGA reactor utilizes solid fuel elements in which the zirconium-hydride moderator is homogeneously combined with 20 %-enriched uranium. The feature of these fuel-moderator elements is the prompt negative temperature coefficient of reactivity, which automatically limits the reactor power to a safe level in the event of a power excursion [1, 2, 3].

## 4. EXPERIMENTAL RESULTS

### 4.1. Isothermal Temperature Coefficient Measurement

In this experiment, the reactor was shut down for one week, so the reactor was xenon poisoning free with low background signal. Prior to startup the core temperature was lowered to about 26.3 °C. When the temperature was found to be steady, the reactor was started-up and went to a power of 10.6 W, following normal startup procedures. The reactor stayed at a steady power level of 10.6 W for about 5 minutes in the manual mode of operation. At the end of this period, it was recorded the exact position of the control rods. After, the power level was raised to 265 kW with the Shim rod (the other two control rods were untouched to the end of the experiment). The reactor operated at this power level until the coolant water was heated to 45 °C. Then, the power was returned to 10.6 W, and the steady core temperature and the Shim rod position were recorded.

The reactivity change ($\Delta\rho$) was determined from the Shim rod calibration curve, showed in Figure 2, considering the critical Shim rod positions at 10.6 W, when a steady temperature was reached. The average isothermal temperature coefficient, for the temperature interval involved, was computed using Eq. (1), and it was found 0.44 cents/°C. Table 1 shows the data obtained in the experiments.

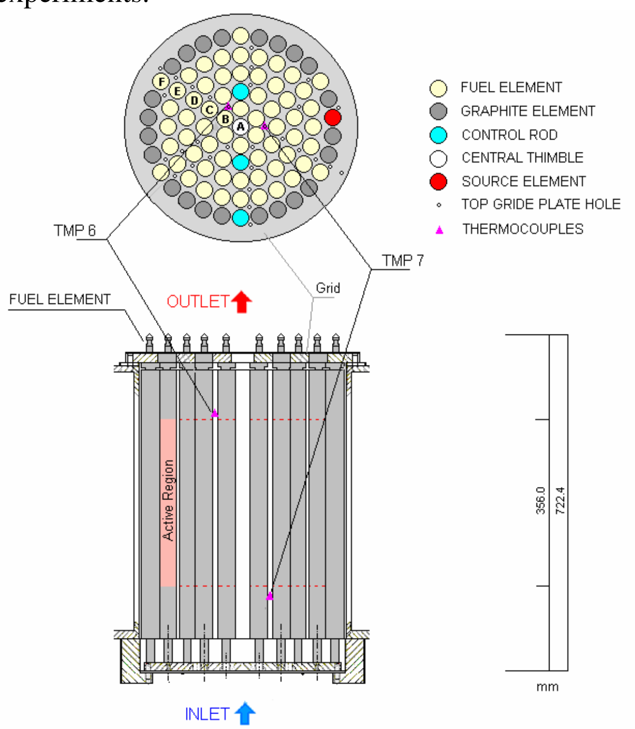


**Figure1. IPR-R1 TRIGA Reactor core.**

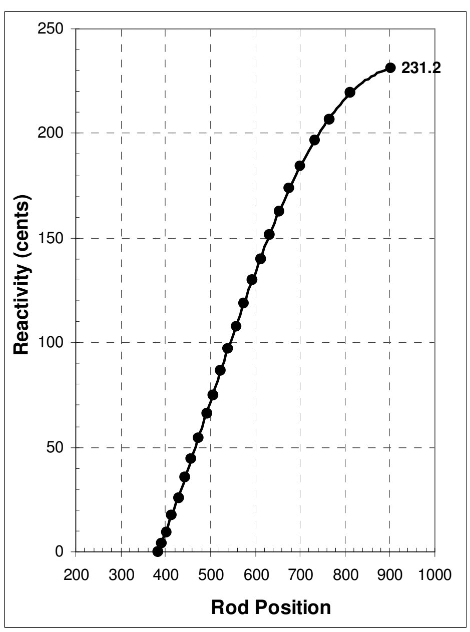


**Figure 2. Integral curve of the Shim rod – core with 63 F. E.**

**Table 1 – Results of isothermal temperature coefficient of reactivity obtained at 10.6 W**

| | |
|---|---|
| **Initial Data** | |
| Shim rod position | 426 |
| Reactivity ρ | 26.0 ¢ |
| Steady Water temperature | 26.3 °C |
| Steady Fuel temperature | 24.2 °C |
| **Final Data** | |
| Shim rod position | 429 |
| Reactivity ρ | 27.8 ¢ |
| Steady Water temperature | 30.4 °C |
| Steady Fuel temperature | 29.9 °C |
| Δρ | 1.8 ¢ |
| ($\Delta T_{H2O}$) | 4.1 °C |
| **Isothermal Temperature Coefficient, $\alpha_{ISO}$** | **0.44 ¢/°C** |

### 4.2. Fuel Power Coefficient of Reactivity Measurement

The experiment was performed by increasing the reactor power, and, consequently, the fuel temperature by withdrawing the Shim rod in a number of steps at once. Initially, the reactor was critical at 10.6 W until thermal steady-state conditions were reached in the core. Then it was introduced 13.5 ¢ of reactivity by withdrawing the Shim rod. The power raised until a specific value, and also the fuel and coolant temperatures. This procedure was repeated introducing different quantities of reactivity in the core, 24.5 and 35.0 cents. The results are presented in Table 2. The value of the reactivity introduced, and the final power level, at which the power rise ends, provided the date for determining the average power coefficient of reactivity in the power interval involved (Eq. 3), as shown in the fifth column.

In order to obtain the fuel power coefficient of reactivity, $\alpha_P(F)$, a correction based on the experiment described in item 4.1 was applied for the rise in coolant temperature during the increase in power. Comparing the second, sixth, and seventh columns, it is noted that the rise in coolant temperature has contributed only with a small fraction to the observed negative effect.

**Table 2 – Fuel power coefficient of reactivity for the power intervals measured**

| Final Power (kW) | $\Delta\rho_P$ Inserted (¢) | $\Delta T(F)$ (°C) | $\Delta T(M)$ (°C) | $\alpha_P$ (Eq. 3) (¢/kW) | $\Delta\rho_T(M)$ (Eq. 5) (¢) | $\Delta\rho_P(F) = \Delta\rho_P - \Delta\rho_T(M)$ (¢) | $\alpha_P(F)$ (Eq. 6) (¢/kW) |
|---|---|---|---|---|---|---|---|
| 12.6 | 13.5 | 23.8 | 4.0 | -1.07 | 1.76 | 11.74 | -0.93 |
| 26.1 | 24.5 | 42.7 | 4.7 | -0.94 | 2.07 | 22.43 | -0.86 |
| 38.9 | 35.0 | 64.1 | 5.3 | -0.90 | 2.33 | 32.67 | -0.84 |
| **Average power coefficient of reactivity $\alpha_P = -(0.97 \pm 0.09)$ ¢/kW** | | | | **Average fuel power coefficient of reactivity $\alpha_P(F) = -(0.88 \pm 0.05)$ ¢/kW** | | | |

### 4.3. Loss of Reactivity with Power Increase

The forced reactor cooling system was not operating during the experiment, and the initial water temperature at zero power was 31.3 ºC.

The reactor was brought up to criticality at 10.6 W. The excess reactivity was increased in steps up to 1.60 $, by withdrawing the Shim rod. All other control rods were completely withdrawn. The power increased with each increasing step, then reached a new, steady, higher level. From the fact that the power level is limited for a given reactivity insertion, one can conclude that the power coefficient of reactivity is negative. The reactivity was determined from the calibrated Shim rod curve, considering each critical rod position. The reactivity change $\Delta\rho$ was derived from the position of the Shim rod before and after each step. Table 3 presents the results obtained.

Figure 3 presents the power coefficient of reactivity, $\alpha_P$, as function of reactor power level. This figure also shows the associated reactivity loss to achieve a given power level. The curve is almost linear and gives a power coefficient of, approximately, 0.65 cent/kW. Because of the prompt negative temperature coefficient, a significant amount of reactivity is needed to overcome temperature and allow the reactor to operate at higher power levels in steady state operation. The power defect, that is the change in reactivity taking place between zero power and full power, is around 1.6 $ (1264 pcm).

Figure 4 relates the temperatures in the fuel element and coolant to a given steady state power level, measured by thermocouples. The temperature of the fuel element ($T_F$) rises from about 29 ºC, at zero power, to 271.4 °C at 262.9 kW. The water temperature increases, but just a little with the increasing power level (from 31.3 ºC to 45.8 °C). These values are shown in Table 3.

**Table 3 – Power coefficient and loss of reactivity obtained for several power levels**

| P (kW) | $T_M$ (ºC) | $T_F$ (ºC) | Shim Rod Position | ρ (¢) | Δρ (¢) | Σ Δρ (¢) | ΔP (kW) | $\alpha_P$ (¢/kW) |
|---|---|---|---|---|---|---|---|---|
| 0.01 | 31.3 | 28.9 | 418 | 21.5 | 0 | 0 | 0 | 0 |
| 5.3 | 33.2 | 40.8 | 430 | 28.5 | 7.0 | 7.0 | 5.0 | -1.40 |
| 17.0 | 34.6 | 59.2 | 447 | 39.0 | 10.5 | 17.5 | 11.0 | -0.95 |
| 21.2 | 34.9 | 67.0 | 453 | 42.5 | 3.5 | 21.0 | 4.0 | -0.88 |
| 40.3 | 35.9 | 94.3 | 476 | 57.0 | 14.5 | 35.5 | 18.0 | -0.81 |
| 66.8 | 37.7 | 129.0 | 502 | 73.5 | 16.5 | 52.0 | 25.0 | -0.66 |
| 111.3 | 39.6 | 185.5 | 546 | 100.5 | 27.0 | 79.0 | 42.0 | -0.64 |
| 154.8 | 41.2 | 225.8 | 589 | 127.0 | 26.5 | 105.5 | 41.0 | -0.65 |
| 208.8 | 43.2 | 251.7 | 642 | 156.5 | 29.5 | 135.0 | 51.0 | -0.58 |
| 238.5 | 44.5 | 263.5 | 670 | 170.5 | 14.0 | 149.0 | 28.0 | -0.50 |
| 254.4 | 45.5 | 269.4 | 685 | 177.5 | 7.0 | 156.0 | 15.0 | -0.47 |
| 262.9 | 45.8 | 271.4 | 692 | 181.0 | 3.5 | 159.5 | 8.0 | -0.44 |

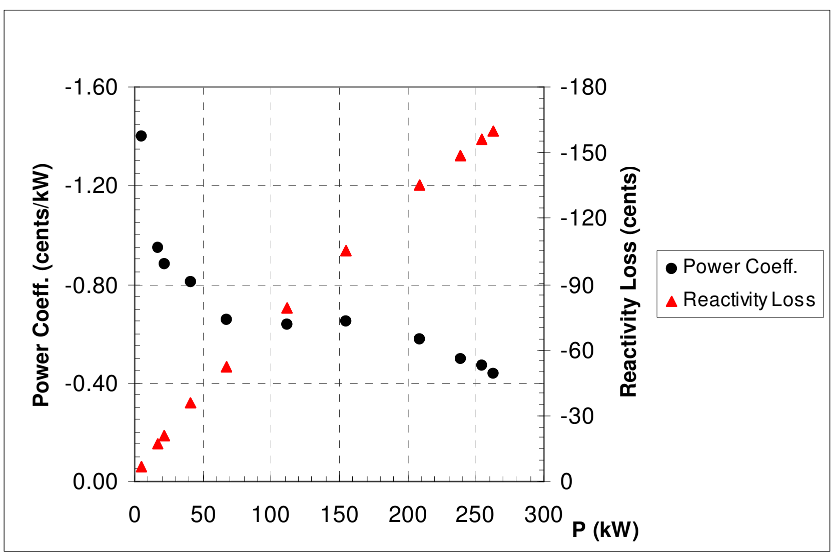


**Figure 3. Power coefficient of reactivity and reactivity loss versus reactor power level.**

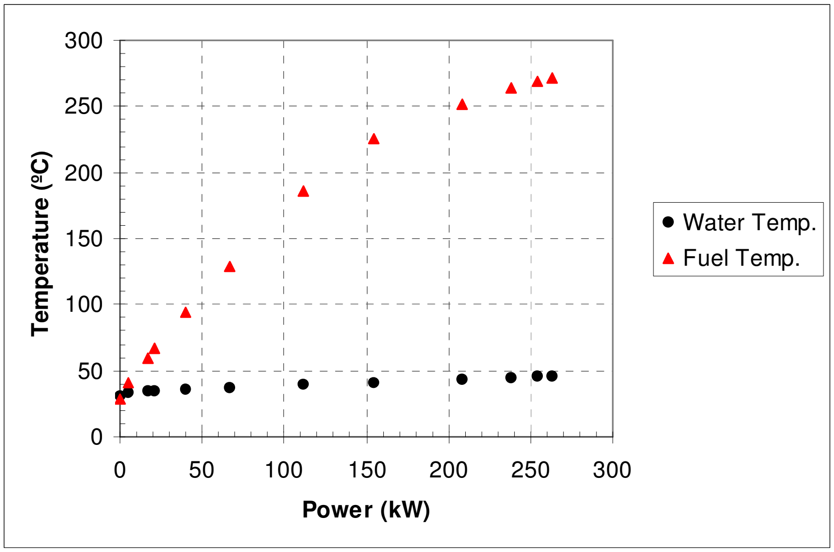


**Figure 4. Fuel and coolant temperatures versus reactor power level.**

## 5. CONCLUSIONS

The experiments were performed in the IPR-R1 TRIGA reactor with 63 fuel elements in the core. At first, it was determined the isothermal coefficient of 0.44 cents/kW. As it was shown, most of the negative reactivity change with increasing power must be attributed to the change in the fuel temperature (prompt coefficient). The delayed coefficient due to the water heating was very small. Then, we concluded that the power coefficient of reactivity of the fuel is the main contributor to the power coefficient of reactivity.

The fuel temperature increases from 29 ºC at 10.6 W up to 271.4 °C at 262.9 kW. The water temperature increase but a little with increasing power level. Due to the prompt negative temperature coefficient, a significant amount of reactivity is needed to overcome temperature and allow the reactor to operate at higher power levels. The average value of the temperature reactivity coefficient of the reactor is (-1.1 ± 0.2) ¢/ºC, as determined in [5]. The reactivity needed to operate the IPR-R1 reactor at 265 kW is around 1.6 $ (1264 pcm).

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