Study of the temperature effects on ULYSSE reactor for training and qualification of operating personnel

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Abstract

For the training of reactor personnel, study on temperature effects is conducted on ULYSSE reactor, in which both water and graphite play a important role in temperature effects. The experiment is performed by changing intentionally the water temperature. Analysis of the recorded parameters gives an insight on the temperature effects, showing that the reactor is mainly sub moderated, by conception, participating to the safe operation of the reactor. The temperature coefficient of water, related to dilatation effect, of graphite, related to capture cross section variation with temperature, and the global coefficient (water + graphite) are found. The experiment also shows that the apparent temperature coefficient that is "lived" by the operator is not constant through the time. Indeed, it depend on the kinetic of the temperature variation in water and in graphite, the latter presenting a significant inertia. Finally, from the understanding of these temperature effects, empathise is given on there impact on the safe reactor operation, particularly in the occurrence of an accidental situation.

1. Introduction

As a part of the CEA (French Atomic Energy Commission), the National Institute for Nuclear Science and Technology (INSTN) provides both academic and professional courses in all disciplines related to nuclear energy applications, including the physics and operation of nuclear reactors. Theoretical courses and training courses on simulators are completed by experimental work on a training reactor which ensure a practical and comprehensive understanding of the reactor operation.

Experimental courses concern the control of the critical during fuel loading, the approach to critical, the control rod calibration, the measurement of rod weight by rod drop, the temperature effects, the role of the delayed neutrons, exercises on reactor operation and control, the operation of neutron detectors, and radioprotection measurements. For all these experiments, empathies is given to the safety of the reactor operation. Thus, for the training and qualification of reactor personnel and regulators, this global approach that includes experimental work contribute to improved safety in reactor operation.

We report here experiments conducted in this frame work on the training reactor ULYSSE which is a 100 kW Argonne reactor that as been designed for teaching. The experiment developed here concerns the study of the temperature effects and the determination of temperature coefficients related to water and graphite. It is shown that the kinetics of the temperature variation in water and in graphite result in an overall temperature coefficient that is strongly time dependant. Finally, empathise is given on the impact of temperature effects on the safety and security of reactor operation, particularly in the occurrence of an accidental situation.

2. Reactor description

ULYSSE reactor is a water moderated and cooled, graphite reflected system using MTR type fuel elements with highly enriched uranium.

The core of the reactor is located in the center of a concrete block (6 m in diameter, 4 m height) that ensure radiation shielding. The aluminium vessel, which is surrounded by a graphite external reflector, contains the annular core. Figure 1 shows the horizontal section of the core and its surrounding. The vessel has a diameter of 90 cm and a height of 1,5 meter. It contains 24 fuel elements on an external crown, 24 graphite elements on an internal crown, a central graphite reflector (60 cm in diamater) and graphite wedges between these components. The graphite components placed in the core have an aluminium cladding. Each fuel element is constituted by an aluminium boxe containing 11 fuel plates separated by a distance of about 4,7 mm where water, which is the main moderator, flows. For the study of temperature effects, a thermocouple placed in water againts a plate of a fuel element is used in order to accurately measure the water temperature in the core.

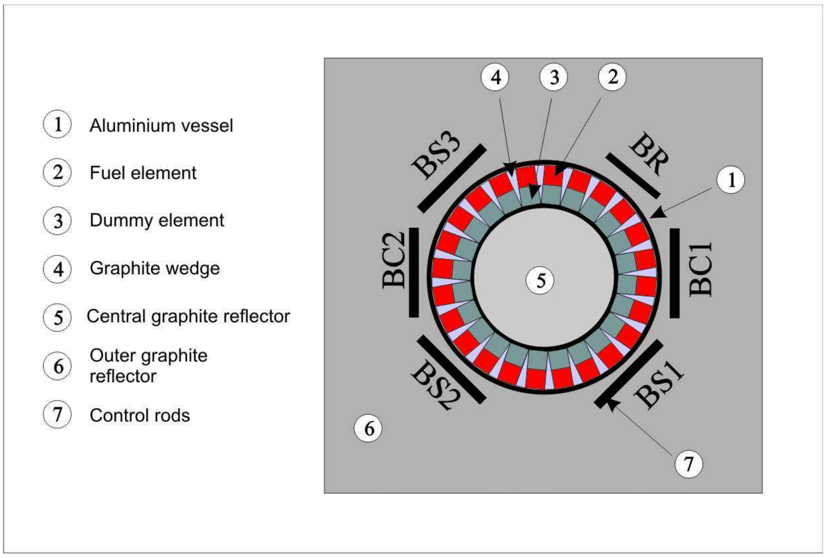

FIG. 1.

The reactor is operated using 6 rods, constitued by cadmium plates placed in a aluminium wagons. The rods are moved vertically in the external graphite reflector close to the core of the reactor as shown in figure 1. The rods include three safety rods, two shim rods and a regulating rod that allows a fine regulation of the reactor reactivity around criticality.

The water circuit is shown in figure 2. Water of the primary circuit is used as the main moderator and as the coolant. Once the water circuit is on, water flows from the bottom to the top of the vessel in between the plates after passing through the foot of each fuel element. When reaching the superior board of the vessel, water falls overboard and flows into the desactivation tank. The core of the reactor contains about 0,3 m^3 of water. The desactivation tank contains 3 chicans that increases the time needed for water to flow from the inlet to the outlet of the tank (about 5 mn). The tank contains 2,5 m^3 of water that can be heated up to 50 °C by the use of a resistive heater. Two pumps are successively used for water circulation in the primary circuit. The first pump (1 m^3/h) is typically used to upper the water level above the overboard level. The second pump is used for water circulation at a flow of 16 m^3/h. The primary circuit contains about 3 m^3 of water, so that is takes about 10 mn for water to accomplish a complete cycle. Water flowing from the pumps reaches the heat exchanger in which the secondary circuit is used to cool the water. For the study of the temperature effect, the water temperature is controled using the heater in the activation tank, the two pumps of the primary circuit and two water gates : the core inlet water gate and the secondary circuit water gate.

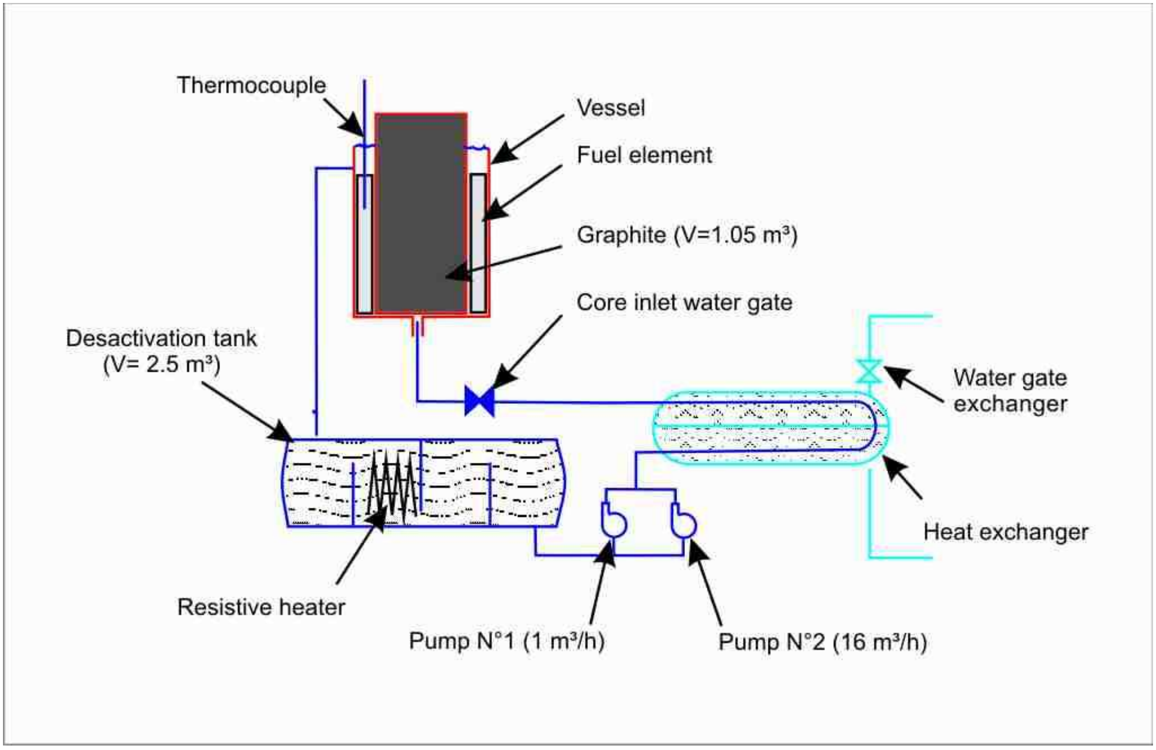

FIG. 2. Water circuit of ULYSSE reactor.

3. Temperature effects

When a reactor is operated at any appreciable power, the energy produced by fission reaction induces the heating of the fuel, the moderator and other materials present in the core of the reactor. The increase in material temperature lead to a modification of the core reactivity ρ. This effect is characterised by the temperature coefficient α, defined as the ratio of the variation in core reactivity to the variation in temperature T :

$$\alpha = \partial\rho / \partial T$$

The temperature coefficient can be either negative or positive depending on the reactor design.

If the overall temperature coefficient of a reactor is negative, the reactivity decreases with increasing temperature.This will in turn induce a decrease of the reactor power and thus of the temperature. Such a reactor, which is sub-moderated, is said to be stable since it can be self regulated through the temperature effect.

If the overall temperature coefficient of a reactor is positive, the increase in temperature leads to an increase in core reactivity and thus reactor power and core temperature. This type of reactor, which is over moderated, has not a ideal design from the point of veiw of safety since it is not self regulated by the temperature effect.

For new reactors, safe operation calls for the design of reactors that are stable at all time. For reactors that are in operation, the reactor characteristics can be changed in order to improve the reactor stability. For example, before the Chernobyl accident, the RBMK reactors where over moderated below 700 MW and sub moderated above that value. After the accident, the fuel enrichment of RBMK reactors has been increased from 1,8 to 2,4 % resulting in sub moderated reactor at any power.

The global temperature coefficient can be writen as the sum of coefficients corresponding to the various temperature effects occuring within the components of the core.

Doppler effect that takes place in the fuel results from the variation of the macroscopic capture cross section due to the thermal kinetic energy. It induces broadening of the resonance bands in ^{238}U. The corresponding temperature coefficient is negative and is typically on the order of -1 to –3 pcm/°C.

The increase in temperature results in an decrease in the density of materials that influence the reactivity through the variation of neutron scattering and absorption probability. Dilatation effect is particularly important for liquids and gases present in the reactor. In water, the decrease in density results both in a decrease of neutron moderation and neutron capture. However predominant decrease in moderation gives rise to a negative temperature coefficient, with values typically ranging from - 10 to - 40 pcm/°C. In the case of boricated water the decrease of neutron capture by boron with density results in positive boron related coefficients. For safety reason, the boron related coefficient have to be kept lower (in absolute value) than that of pure water , through the control of the boron concentration, in order to obtain an overall negative coefficient.

Variation in the thermal kinetic energy results in a modification of the neutron velocity ν for thermal neutrons. Since the neutron reaction cross sections depends on the neutron velocity, variation in temperature induces a modification of the neutron reaction probability in the various components of the core. This effect can give rise either to positive or negative thermal coefficients depending on the reactor conception.

In the case of graphite, a significant change in the diffusion length L is observed. By definition :

$L^2 = 1 / 3\, \Sigma_a \Sigma_s$,

where Σ_a and Σ_s are, respectively, the abosrption and scattering macroscopic cross sections. Σ_a that follows a $1/\nu$ thus varies a $1/\sqrt{T}$, while Σ_s does not exhibit significant change with temperature. Thus temperature increase results in the decrease of neutron absorption leading to positive temperature coefficient.

4. Temperature effects on ULYSSE reactor

On ULYSSE reactor, water and graphite have a major contribution to the temperature effects. Water, with a total volume of 0,3 m^3, is the main moderator and flows between the fuel plate. Graphite with a total volume of about 1,05 m^3, act as a reflector and occupied the centrale part of the core. Doppler effect has no significant influence on the overall coefficient since the fuel is highly enriched.

Thus the overall temperature coefficient $\alpha_{overall}$ is the sum of the water coefficient α_{water}, related to dilatation effect, and the graphite coefficient $\alpha_{graphite}$, related to variation in neutron velocity.

5. Experimental

When operated at its nominale power of 100 kW, the water temperature, initialy at about 20 °C, is typically increased up to 25 °C. This corresponds to a relatively small evolution of temperature for the study of temperature effetcs in the frame of a training course. Thus, it has been choosen to operate the reactor at a low power (20 W) and to vary the water temperature artificially by the mean of actions on the water circuit, using a resistive heater to heat the water in the desactivation tank and using the heat exchanger to cool the water. The experiment used to study the temperature effect is carried out as follow.

In the initial state the reactor is operated at 20 W with the core inlet water gate closed, the pumps of the primary circuit turned off, the water gate of the exchanger opened and the water in the desactivation tank heated at about 50°C.

Maintaining the reactor at a constant power by the use of the regulation rod, the following actions are successively carried out. The water gate of the exchanger is closed. The core inlet water gate is open. At t = 0, the first pump of the primary circuit is turned on until a flow rate of 1 m^3/h is obtianed, then the second pump is turned on. This induces the successive injection of cooled water from the exchanger and of heated water from the desactiavtion tank. The position of the regulation rod, moved to keep the power constant, as well as the water temperature are recorded as a function of the time. Once a steady temperature is reached, after about 15 minutes, the water gate of the exchanger is opened in order to cool the water of the primary circuit. The position of the regulation rod and the water temperature are still recorded for 10 minutes. The obtained data, with the use of the calibration curve of the control rod, are analysed to study the temperature effect.

6. Experimental results

Figure 3 shows the recorded variation in water temperature and in the position of the regulation rod as a function of time during the experiment.

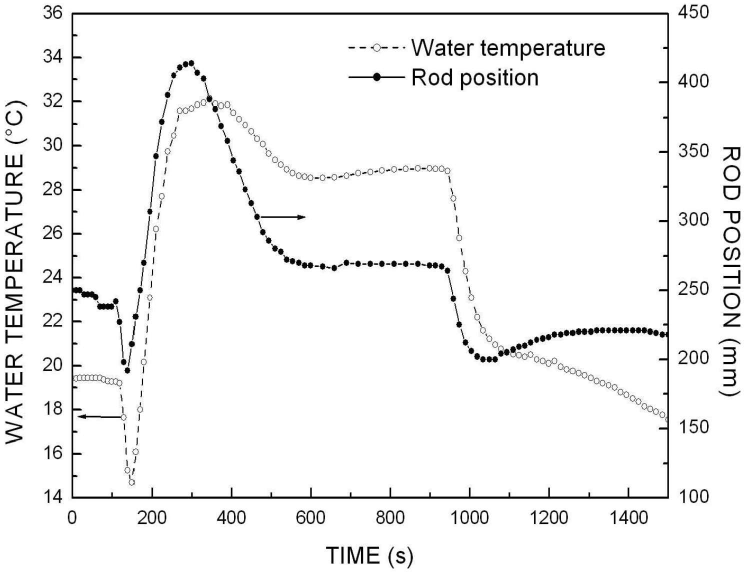

FIG. 3. Recorded variation in water temperature and regulation rod as a function of time during the experiment.

The temperature variation is explained as follow. At t = 0 s, the water temperature is initaily at 19,5 °C. The core inlet gate and the pumps P1 and P2 are sucessively turned on. At t = 120 s, the temperature start to decrease down to 14,7 °C, as the result of the injection of water previously cooled in the heat exchanger. Between t = 140 s and t = 350 s, the temperature increases as the result of the injection of water previously heated in the desactivation tank. Between t = 350 s and t = 900 s, the water temperature decreases as the result of heat exchange between water and graphite, those reaching a temperature equilibrium of 29 °C. At t = 900 s, the exchanger gate is opened, inducing a decrease of the water temperature when water from the exchanger reaches the core at t = 960 s. One can observe two different gradiants for the water temperature decrease. From t = 960 s to t = 1060 s, a sharp temperature decrease can be associated to water cooling while no significant heat transfert from graphite to water takes place. From t = 1060 s, heat exchange from graphite to water results in a slower decrease of water temperature.

Figure 3 shows that the position of the regulation rod, given in millimeters, follows the evolution of the water temperature. For the determination of the temperature coefficients, the variation in core reactivity has been calculated using the recorded regulation rod positions and the calibration curve for the regulation rod. Figure 4 shows the relative variation of the core reactivity as a function of time, in reference to the core reactivity at t = 0.

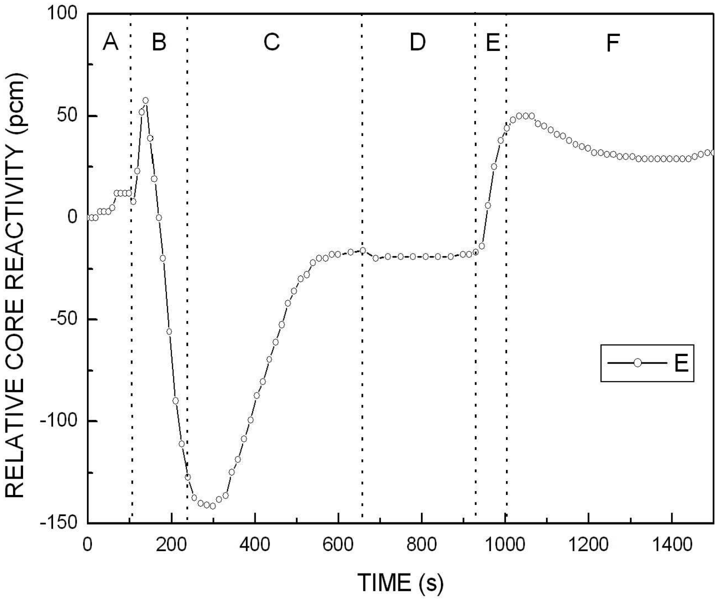

FIG. 4. Relative core reactivity as a function of time, in reference to reactivity at t = 0.

From the variation in water temperature, one can extrapolate the variation in graphite temperature as shown in Figure 5. At t = 0 s the water and graphite temperatures are at equilibrium. During the fast variation of water temperature, from t = 0 to 250 s, one can assume that there is no significant heat exchange between water and graphite. From t = 250 to 850 s, heat exchange from water to graphite results in the successive graphite temperature increase before an equilibrium is reached between water and graphite temperature. After t = 900 s, when the exchanger is turned on, the graphite temperature stills constant up to t = 1060 s when significant heat exchange occurs from graphite to water and results in graphite temperature decrease.

7. Data analysis

From the experimental results, on can observe that core reactivity varies in an inverse way with the water and graphite temperature, except for t = 1100 to 1400 s, where the core reactivity shows a decrease with decreasing water and graphite temperature. Thus, for the major part of the time and in particular during the fast variation of the core reactivity, the overall temperature coefficient is negative. This is a factor that ensure a safe operation of the reactor regarding the temperature effect.

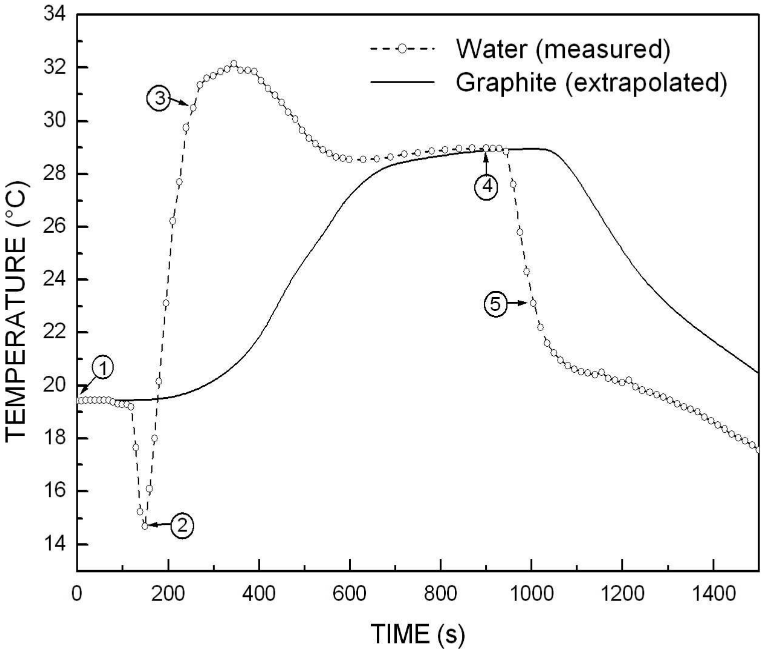

FIG. 5.

The overall temperature coefficient can be calculated using the recorded data for two different temperatures of water and graphite, those being at the equilibrium. Taking, respectiveley, an initial and a final temperature T and relative core reactivity Δρ at t = 0 and t = 900 s, the overall coefficient is calculated using the following formula :

$$\alpha = \frac{T_{final} - T_{initial}}{\Delta\rho_{final} - \Delta\rho_{initial}}$$

With the recorded data, an overall coefficient of – 1,9 pcm/°C is found. Thus the overall coefficient is negative ensuring a self stabilization of the reactor when the power and the temperature are increased.

The water coefficient can be determined from the recorded data taking final and initial states for which the graphite temperature stays constant while the water temperature varies. Thus according to states shown in figure 5, one can calculate the water coefficient obtained from three couples of states : between ①and ②, between ② and ③, and finally between ④ and ⑤. Calculations give water coefficients ranging from – 12,1 to –11,2 pcm/°C with a mean value of –11,8 pcm/°C. Thus, an increase in the water temperature induces a decrease of the core reactivity. The water coefficient is negative confirming that water dilatation results mainly in a reduction of the neutron moderation and thus of the fission probability.

The overall coefficient being the sum of the water and graphite coefficients, the graphite coefficient can then be deduced from the previously calaculations. Taking into account the mean value of the water coefficient, we found a graphite coefficient of + 9,9 pcm/°C. In contrast to water, graphite exhibits a positive coefficient, so that an increase in the graphite temperature induces an increase in the core reactivity. This increase is related to the decrease in neutron absorption when the thermal kinetic energy and thus the neutron velocity is increased.

The experimental results can be analysed to get an insight in the time evolution the apparent temperature coefficient that is "lived" by the operator who regulates the reactor. Indeed, since water and graphite temperatures are not evolving in a same way, the overall temperature coefficient is not constant through the time.

When water and graphite are at equilibrium at the same temperature, i.e. during intervals A and D in Figure 4, the apparent apparent α is close to $\alpha_{overall,}$ i.e - 2 pcm/°C.

When the water temperature rapidly changes, while the graphite temperature is constant due to its inertia, the apparent α is close to α_{water}, i.e - 11,8 pcm/°C. This contribute to a rapid change in the core reactivity with time that needs a rapid variation of the control rod position. This situation occurs during time intervals B and E.

During interval C, the apparent α slowly shift from α_{water} to $\alpha_{overall}$, with the increasing contribution of graphite to the temperature effect as a result of heat exchange from water to graphite.

During interval F, the apparent α undergo more complicated changes. The initial apparent α, at t = 900 s, is equal to $\alpha_{overall}$. The final apparent α will also reache $\alpha_{overall}$ when water an graphite are again at equilibrium. During interval F, the apparent α is successively "strongly negative" (equal to α_{water}) , sligtly positive and sightly negative, as can be seen by observing the core reactivity variation in Figure 4. It is important to point out the overall coefficien is slightly positive during a transient time interval for which both the water and graphite temperature are decreasing, so that the core reactivity is decreasing during that time interval. Thus, from the point of view of safety, it is acceptable to have a positive $\alpha_{overall}$ at that time.

Thus, not only the values of the temperature coefficients are important, but also the physical effect to which there are related and the kinetic of the corresponding temperature variation.

8. Conclusions

From the understanding of these temperature effects, empathise can then be given on there impact on the safety and security of reactor operation.

At first, we have seen that variation in water temperature can induce large changes in the core reactivity that has to be taken into account for reactor operation. For example, during interval B (in Figure 4), the relative core reactivity is changed by 200 pcm due to the water temperature change.

It was also shown that the kinetic of the temperature variation has to be taken into account. Thus, in low level enriched reactor, Doppler effect plays an important role in the reactor stability even if the Doppler related α is generally much smaller than the other temperature coefficients related to dilatation. Indeed, Doppler effect takes place in the fuel, i.e. where the temperature instantaneously varies with the power. Thus, Doppler effect has a major contribution in the self regulation of the reactor.

Finally, in the occurrence of an accidental situation it is necessary to anticipate the reactivity variation with temperature. For example, its is important to keep in mind that an accidental situation leading to the injection of cooled water in the core of a sub moderated reactor will contribute at first to an increase of the reactivity and thus in turn of the power.