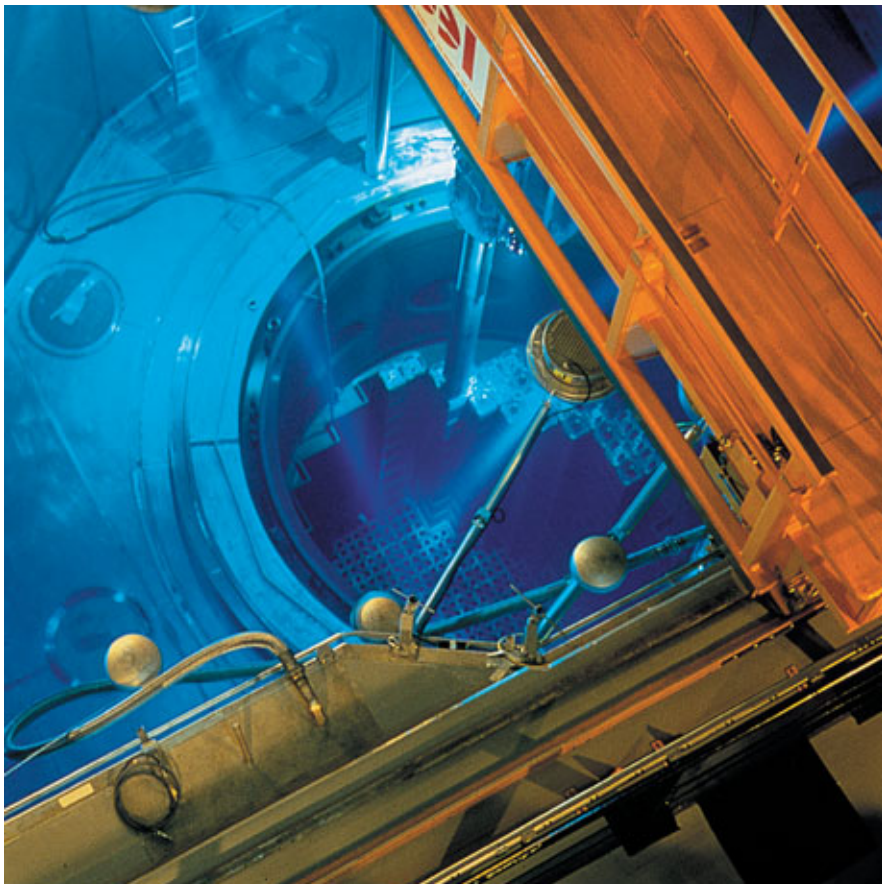
SAFETY AND RESIDUAL POWER

Nuclear reactor safety assessment involves the notion of residual power, related to radioactivity and caused by the deexcitation of unstable nuclei formed during fission reactions in the core. This energy, which continues to be released after reactor shutdown, must be removed under all circumstances to avoid the risk of damage from overheating.



C. Pauquet/Phototheque EDF

Core of a pressurized water reactor during fuel loading at the EDF Civaux plant. Before being unloaded, the spent fuel of a PWR remains inside the closed reactor vessel for 3-4 days so that it is partially deactivated.

After the **chain reaction** has stopped in the nuclear **reactor**, the **fuel** continues to release power. This is referred to as residual power or residual heat and is created by **radioactive isotopes** present in the **core**. Seen from the safety and radiological protection angle, these isotopes raise many different types of problems: thermal (heat to be removed), radiological (risk of personnel or general public being exposed to a **radiation** field in the highly unlikely event of a severe accident), or physico-chemical (resistance of materials exposed to irradiation in a hypothetical incident or accident situation, with the risk of **radiolysis**). Within this context, the assessment of this residual power is largely a matter of nuclear physics (see box C, ***The decay of heavy nuclei and the resulting radiation***).

The components of residual power

The radiation emitted after the chain reaction has been stopped is traditionally divided into three categories of emitters. The first category concerns the actual **fission products** that are created when **fissile nuclei** such as uranium-235 (^{235}U) or plutonium-239 (^{239}Pu) break up (generally splitting in two). This category is followed by two categories of **heavy nuclei**, the first of which concerns uranium-239 (^{239}U) and neptunium-239 (^{239}Np). ^{239}U is born when a **neutron** is **captured** by ^{238}U, while ^{239}Np is formed by β^- **decay**, in turn yielding ^{239}Pu, also through β^- decay. The last of the three categories concerns **actinides** other than the initial fuel. They include neptunium (Np), the isotopes of plutonium (Pu), americium (Am) and curium (Cm), as well as some uranium isotopes (^{232}U, ^{234}U, ^{236}U).

The impact of these three categories as a function of cooling time, i.e. the time after the end of the chain reaction, can be summed up in three points[1] for a uranium oxide fuel attaining a **burn-up** of 33 000 MW·d/t and initially **enriched** with 3.25% ^{235}U (figure 1): **delayed** fissions predominate for the first ten seconds; then the major contribution comes from fission products for a period of 100 years, after which the actinides are more significant than the fission products; ^{239}U and ^{239}Np account

(1) Reference: Huynh Tan Dat: creation of the physical library and development of the Pepabac system (Fakir software package) using the Pepin and Apollo I codes (note ref. CEA-N-2815, December 1996).

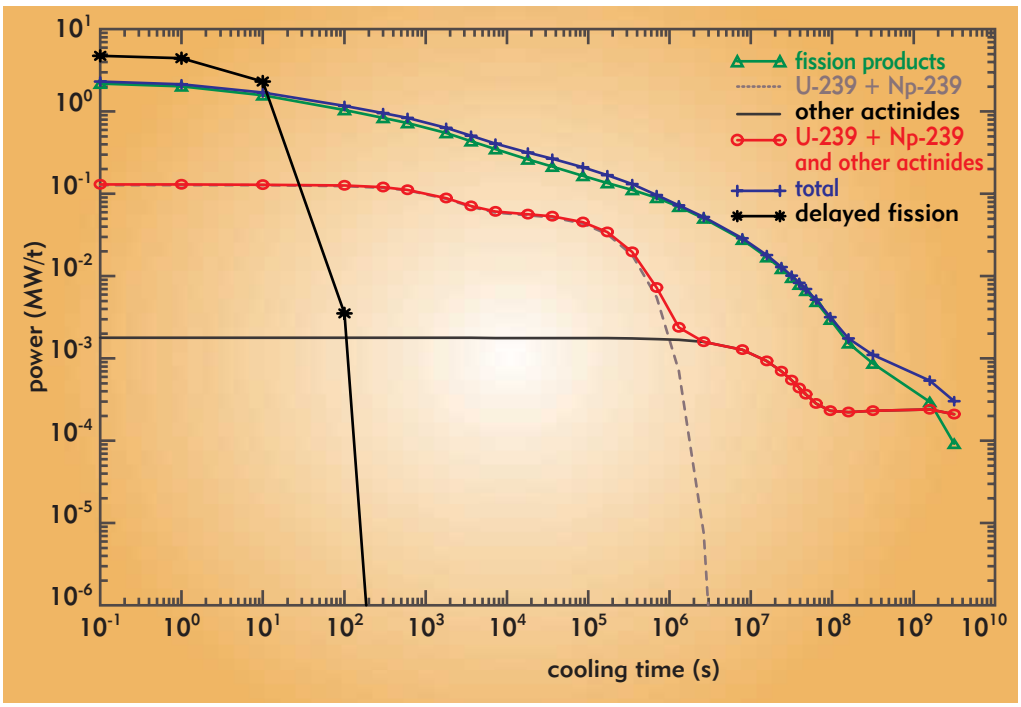


Figure 1. Residual power of UOX fuel (enriched with 3.25% uranium-235) for a burnup of 33,000 MW·d/t as a function of cooling time.

for 5 to 10% of the total power for the first ten days of cooling, after which their role becomes negligible. The contribution of actinides is amplified in two cases (figure 2): when the **burnup** increases and when the initial fuel is mixed (MOX). The power released by delayed fissions – which is high for very brief periods – is not included in the total power in either case, as it depends on the injected negative reactivity.

Safety and residual power

It must be remembered that residual power is generated by unstable nuclei formed in the reactor under normal operating conditions. These nuclei **deactivate** after reactor shutdown or fuel unloading by emitting α, β, and γ radiation.

To take the example of a uranium oxide fuel (UOX) irradiated in a water-cooled reactor under nominal operating conditions (38.25 MW/tU), the residual power immediately after shutdown is approximately 2.3 MW/tU, which represents about 6% of rated power. Residual power can be divided up as follows: 94% is due to fission fragments, 5.6% to all the ^{239}U and ^{239}Np, and 0.12% to the other actinides. The power from delayed fissions due to delayed neutrons and dependent on the injected negative reactivity must also be added to the residual power value.

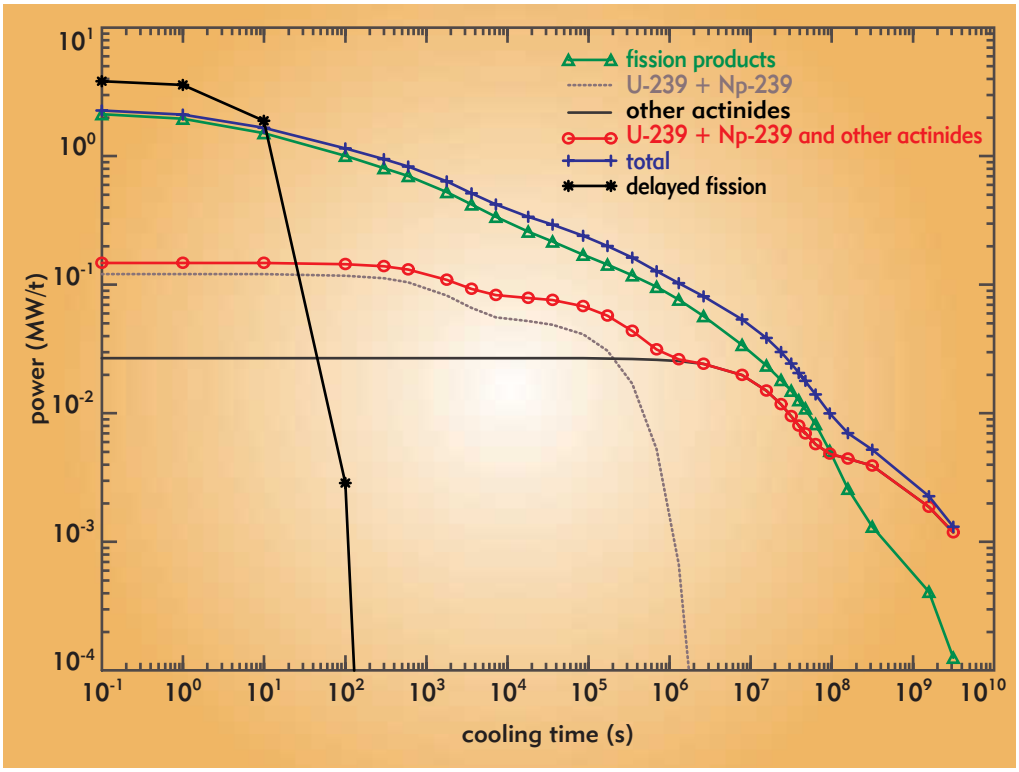
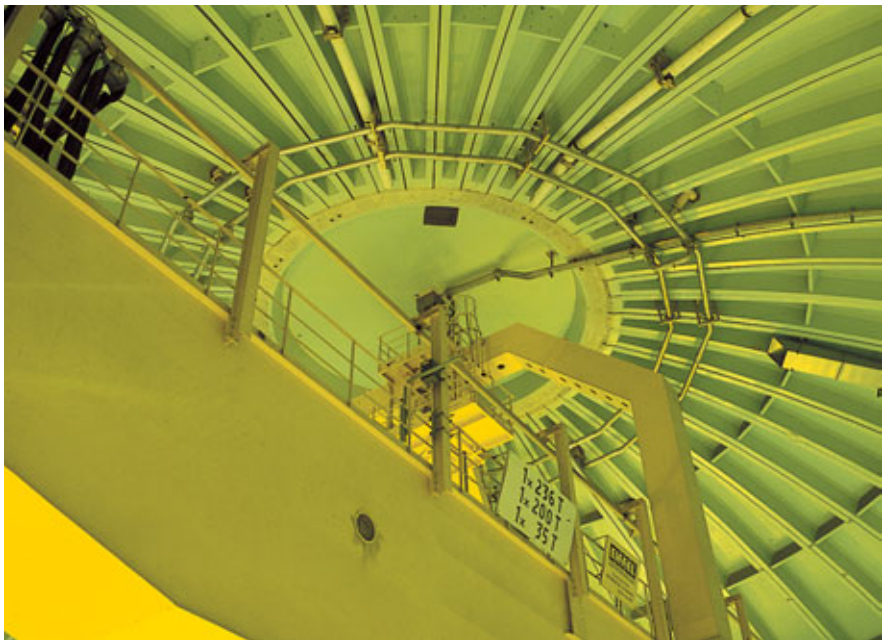


Figure 2. Residual power of MOX fuel (enriched with 5.30% plutonium) for a burnup of 60,000 MW·d/t as a function of cooling time.



Cl. Pauquet/Framatome

Partial view of the spray system installed under the roof of a PWR containment building, designed to provide additional reactor cooling from outside the vessel, when needed. It is one of the systems used to ensure residual heat removal under all circumstances and, in particular, in the event of emergency shutdown.

The residual power of an irradiated reactor core after shutdown represents a limiting factor in reactor operation, because of safety requirements imposing the need to preserve core integrity at all times. This power, together with the emitted radiation spectra, must be evaluated for a reactor operating under normal conditions and under hypothetical accident conditions.

Normal operating conditions

The core cooling system must be designed to remove residual heat effectively after shutdown in order to preserve core integrity. The same applies to the cooling system of the spent fuel pool where spent fuel **assemblies** are stored. The transportation and processing of spent fuel must take account of thermal considerations (temperature reached in spent fuel shipping containers) and the radiological protection required around these containers and in processing plants. This calls for information concerning the gamma radiation and neutron spectra emitted by the spent fuel. In addition, underwater transportation must consider the problem of **radiolysis**, which implies knowledge of the energy released in the water.

S. Jezequel/Cogema

Unloading a spent fuel container in the port of Cherbourg. The heat given off by residual power is one of the problems to be considered by designers of shipping containers.

Calculation of isotopic concentrations

For safety and radiological protection purposes, three quantities must be determined, varying according to the time period elapsed after the **control rods** have dropped. It is this event that stops the **chain reaction**, thereby shutting down the reactor. These three quantities are: *residual power* (α, β and γ radiation), *neutron emission* and its *energy spectrum*, as well as the *radioactivity of each* ***isotope***. They are deduced from the concentration $N_J(t)$ of the isotope J, identified by (A_J,Z_J), and then by computing the specific activity $\lambda_J N_J(t)$ where λ_J is the **decay** constant of the isotope J ($\lambda_J = \mathrm{Log}2/T_J$, T_J being the half-life). The γ emission energy spectra of the irradiated **fuels** are deduced by summation, based on these specific activity values, and taking into account the γ emission lines of each isotope. The total residual power is also determined by summation, this time by weighting the specific activity of each isotope with its decay heat Q_J. This method, which consists in computing the concentration $N_J(t)$ of each isotope J, is thus referred to as the summation method. Residual power can be determined in other ways.

Concentration calculation methods

The concentration $N_J(t)$ of each isotope satisfies a coupled, linear, differential equation system known as the Bateman equations. The principle is illustrated here for fission products, with the understanding that a similar form is valid for ^{239}U + ^{239}Np and for the other actinides. This equation system is expressed by:

$$\frac{\partial N_J(t)}{\partial t} = \sum_f Y_{Jf} N_f(t) \tau_f(t) + \sum_i \tau_i(t) N_i(t) b_{i\to J} + \sum_K \lambda_K N_K(t) b_{K\to J} - \tau_J(t) N_J(t) - \lambda_J N_J(t)$$

where:

Y_{Jf} is the independent yield for isotope J by fission of isotope f,

$\tau_i(t)$ is the microscopic reaction rate on isotope i,

$b_{K\to J}$ is the **branching ratio** of isotope K to isotope J (this ratio represents the fraction of isotope J formed for a decay of isotope K).

On the right-hand side, the first term represents the appearance of isotope J by fission of isotopes f per unit time. The second and third terms show the appearance of isotope J per unit time, by **capture** (on i) and by decay (of K) respectively. The fourth and fifth terms represent the disappearance of isotope J, by capture and radioactive decay respectively.

These equations can be solved numerically or analytically with some restrictions. To solve them and calculate the residual power, certain physical constants must be known, such as **cross sections** (for τ_i), fission yields (Y_{Jf}), decay constants λ_J, and deexcitation heat Q_J. At present, the neutron spectra used to compute reaction rates τ_i are determined by the Apollo2 or **Monte Carlo** Tripoli codes. The Bateman equations are solved using the Pepin2-Darwin calculation code.

The same principle applies for components other than fission products, such as ^{239}U + ^{239}Np and the other actinides.

Hypothetical accident conditions

An appropriate spraying system is designed and sized to ensure effective cooling of the core following emergency shutdown in the event of accident. In order to ascertain the **dose equivalent** rates in the vicinity of the reactor, gamma and neutron radiation spectra must be determined. The energy deposited (β and γ) on the plant monitoring devices (wiring, electronics) must be lower than a threshold allowing them to fulfill their function. Knowledge is required of many parameters, such as the γ radiation spectra emitted by the degraded core and by the fission product fraction released in the reactor building, and the β radiation energy spectrum. Three quantities must be calculated from the concentration of a given isotope (see box).

Residual power: uncertainties

Knowledge of residual power has a strong impact on reactor safety, whether it concerns thermal aspects (residual heat) or radiological protection (ascertaining the radiation spectra emitted and the dose equivalent rates). The uncertainty σ concerning this variable, estimated as precisely as possible on the basis of nuclear constants now available (JEF-2 data library), remains high. It is due to elementary uncertainties concerning basic data (**cross sections**, efficiencies, deexcitation heat, **half-life** of each **nuclide**), data relating to reactor operating conditions and, lastly, to computer model uncertainties. Depending on the impact on safety, engineers must add 1, 2 or even 3 σ to the calculated

Supervising the positioning of fuel elements in the spent fuel pool at the EDF Civaux plant. Spent fuel pool cooling circuits are designed to withstand a failure in a heat removal unit.

Claude Cieutat/Mediatheque EDF

residual power, the margin increasing with the severity of the hypothetical accident. This has an economic impact, as σ is in the region of 10% at short cooling times. This situation can be clearly illustrated by the following example. At the end of a normal operating cycle of a reactor core, the transfer of spent fuel assemblies to the spent fuel pool implies optimum cooling of both containers and contents. The spent fuel is first placed in the reactor vessel for 3 to 4 days so that it can be partially deactivated. A 4% uncertainty regarding the residual power represents an extra delay of one day before unloading and transfer to the pool. For an operating cycle of 300 days, this uncertainty results in 0.3% lost energy production.

The libraries only provide some of the uncertainties regarding basic data. Models calling on correlations are used for uncertainties that are not given. For example, if the uncertainty concerning a deexcitation energy Q of a given isotope cannot be found, the mean uncertainty for the energy of isotopes with a similar half-life is adopted. This is because the difficulty in measuring Q depends on the **isotope half-life** time. If the half-life is just a few seconds, it is far more difficult to measure than if it is several

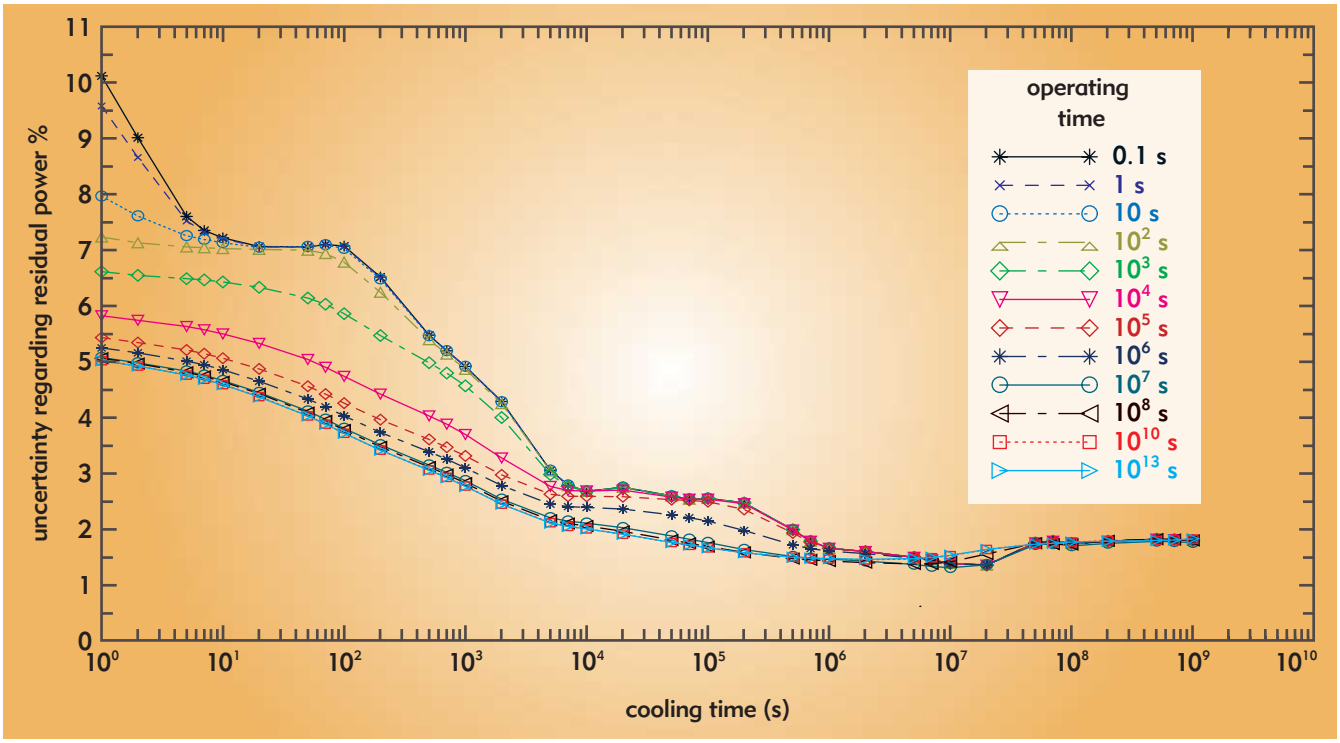


Figure 3. Curve showing uncertainties regarding the residual power of a PWR as a function of cooling time.

A. Gonin/CEA

The Osiris experimental reactor at CEA/Saclay, where fine integral measurements of residual power are carried out as part of the Merci experiment.

hours. In addition to elementary uncertainties regarding basic data, the correlations existing between the different elements of this data must be known in order to rebuild the overall uncertainty regarding total residual heat. In calculating the sum of the residual heat values released by each isotope, the sum of the respective elementary uncertainties are summed either quadratically or arithmetically, depending on whether they are independent or totally correlated, in order to determine the overall uncertainty (figure 3).

Essential fine integral measurements

Estimating residual power and related variables such as β and γ radiation spectra thus implies knowledge of cross sections and decay data concerning a large number of isotopes (about a thousand). Nuclear physics models can provide certain decay data missing from the libraries. The list of uncertainties concerning basic data is incomplete and correlations are frequently lacking. Considerable progress has been made in recent years. Now efforts must be pursued to carry out measurements and evaluations and to complete data using nuclear physics models. Computer models and the related basic data will ultimately be verified through fine integral measurements of residual power, like those to be carried out in the Osiris reactor at Saclay as part of the Merci experimentation program.

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