CRITICALITY STUDIES FOR THE TRANSPORT OF UNIRRADIATED PWR ASSEMBLIES

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SUMMARY

The transport of low enrichment unirradiated PWR fuel involves no criticality risk in the absence of water. However, an adequate sub-criticality margin must remain in the event of water leaking into the package, even taking into account the worst credible configuration to be anticipated as a result of any accident.

TRACTEBEL has estimated the subcriticality margins in worst case situations anticipated as a result of a vertical 9 m drop of a FRAMATOME RCC-3 or RCC-4 fresh fuel package, loaded with two 15x15 or 17x17 fuel assemblies and fitted with copper or borated stainless steel neutron absorber plates.

In the worst-case scenario considered, both fuel assemblies have slid along their supports until their bottom nozzle legs came into contact with the end of the package. As a result of damage to the lower grid, the two outermost rows of pins were free to diverge outward. The reactivity increase led to a slight reduction in enrichment limit only with 12 ft fuel and borated stainless steel absorbers.

Furthermore it was assumed that can damage would allow a number of pellet to pile up in the space between assemblies. The resulting reactivity increase became noticeable only with a large number of free pellets, much larger indeed than anything to be expected.

The Monte Carlo code MONK, developed and distributed by the ANSWERS Service (AEA Technology, UK) was used. The versatility of its geometry package made it easy to set up a realistic 3D model of the postulated accident configurations.

INTRODUCTION

IAEA regulations (Safety Series N° 6, art. 567) require that a maximum number of packages per consignment N be defined to satisfy the following conditions:

(a) 5N undamaged packages without anything between the packages would be subcritical;
(b) 2N damaged packages with hydrogeneous moderation between packages to the extent which results in the greatest neutron multiplication would be subcritical;

French practice prescribes a $k_{eff} < 0.95$ limit for case (a) and $k_{eff} < 0.98$ limit for (b); we will concentrate on the latter case, considering an infinite array of damaged packages, leading to an essentially infinite transport index N.

FRAMATOME's fresh fuel package models RCC-3, RCC-4 and RCC-4 XL are designed to hold 2 PWR fuel assemblies, from 14x14 to 18x18 and up to 14 ft long. Hinged brackets hold the fuel on a support frame which is enclosed in a cylindrical shell. Between the fuel assemblies are two neutron absorbing plates which constitute a "flux trap" arrangement when the package is flooded. Fig. 1.1 shows a half frame with a fuel assembly and an absorber plate in place.

When fitted with borated stainless steel plates (1.4 wt% natural boron), the packages are qualified for transporting 15x15 or 17x17 fuel enriched up to 4.9 wt %; with copper plates, the limit is 4.2 % for 15x15 fuel and 4.3% for 17x17. It was shown that an adequate subcriticality margin was available under all circumstances, even in the worst anticipated accident situation as determined from drop and fire tests, carried out according to regulations.

Following recent regulatory concern regarding the consequences of a vertical drop of a loaded fresh fuel package, critcality safety analyses were carried out assuming partial fuel disassembly as a result of such a drop.

A worst case configuration, illustrated by fig. 1.2 and 1.3, was set up following discussion of the mechanical behaviour of the fuel an package during a 9m vertical drop (previous evaluations had concentrated on slightly off-horizontal drop tests):

- the fuel support frames became loose from the shell, affecting fuel spacing (the spacing is minimal in the configuration illustrated by fig. 1.2);
- the fuel remained in contact with the support frame, held in place by the brackets;
- however these did not prevent the fuel from sliding downward along its support, coming into contact with the lower end of the shell;
- spacer grids got ripped in the process, leaving the lower ends of the two outermost rows of pins free to move arbitrarily within the shell;
- the frame stayed in place, length-wise;
- a limited number of pins could burst, freeing pellets to pile up on the bottom.

As a consequence, reactivity was expected to increase due to the following effects:

- as the fuel slid off its supports while these stayed in place and the neutron absorbers as well, effectiveness of the latter would be reduced;
- displacement of the peripheral fuel pins would increase the neutronic coupling between both assemblies, increase the effective fuel cross-section and introduce localised extra moderation (assuming the package was flooded);
- the presence of loose pellets might have an effect, which would be maximal if they got stuck between the two "flared" assemblies as shown on fig. 2.6.

THE MONK5W METHOD

Use of MONTE-CARLO methods along with detailed 3-D geometric modelling is standard practice for criticality work. Dispensing with "cell smearing" greatly simplifies discussion of the applicability of experimental validation to a given practical situations.

The Monte-Carlo criticality code MONK has a lot of interesting features among which we note:

- a hierarchical geometry description scheme, allowing detailed geometric modelling with little or no added computing cost;
- the WOODCOCK tracking scheme which extends the geometric capabilities of the code while speeding up tracking through very heterogeneous systems;
- the SUPERHISTORY powering scheme, to control the well-known biases on k and σ, associated with MONTE-CARLO criticality calculations;
- a WYSIWYG facility called SCAN for drawing cross-sections through the system, covering both the standard geometry package and "hole" geometries associated with WOODCOCK tracking.

The standard MONK has a nuclear data library with 8800 energy groups which is essentially equivalent to a point library and is suitable for just about any criticality work. In contrast, MONK5W which is integrated in WIMS 7 (formerly known as WIMS E) uses the standard WIMS library, ensuring consistency with reactor work.

It must be noted that WIMS has been successfully used with most types of thermal systems. Resonance self-shielding in MONK5W is treated by the subgroup method, which means the accuracy of the code is not affected by the geometric particulars of the problem being solved.

MONK's validation shows an overall trend is to over-estimate $\mathbf{k_{eff}}$ by about 0.01; however to be on the safe side, we apply an error margin 0.01 to allow for the effect of uncertainty on the nuclear data.

THE GEOMETRIC MODEL

Our 2-D model of the unperturbed situation consisted of

- a "hole" material zone representing the active section of a fuel assembly, with fuel columns, cans and guide tubes represented explicitly (grids and nozzles were ignored);
- standard material zones representing the support plates and neutron absorbers (other structural elements of the frame were not considered important).

The accident situation required a 3-D model, with additional hole material zones to represent the bent pins (fig. 2.5) and loose pellets (fig. 2.6).

The "flaring out" of the outer rows of pins was approximated by tilting sheets of pins while leaving pins within a sheet parallel to each other. Each sheet was modelled by a cuboidal body filled with a SQUARE hole. The degree of distortion of the lattice is characterised by the horizontal displacement d of the lower end of the outer row of pins; the second row is displaced by d/2.

The loose pellets were conservatively assumed to pile up inside the wedge-shaped void left between two assemblies by the distorted rows of pins. This wedge void was filled with a TRIANGLE hole representing a packed hexagonal array of fuel columns or a similarly tight-packed cluster of pellets. The amount of damaged allowed for is characterised by th number of layers in the cluster.

RESULTS

Figures 3.1 and 3.2 express k_{eff} (including uncertainties) as a function of the displacement d of the outermost pin row, allowing for uncertainty on collision modelling and nuclear data (0.01) and for sampling uncertainty (3σ).

At zero displacement, k is near the 0.95 limit which applies to undamaged packages, with 4.9wt % enriched fuel and borated stainless steel plates with 1.4 wt% of natural boron or with 4.3% fuel and copper plates (4.2% in the case of 15x15 fuel).

With d increasing from 0 to the limits imposed by the available volume, keff increases gradually to reach a rather flat maximum, then decreases when enhanced neutron leakage cancels out the coupling effect between adjacent assemblies.

Around the maximum, the 0.98 limit is exceeded in the 12 ft case with borated stainless steel plates, which led to reduce the enrichment limit from 4.9% down to 4.7 wt %. The picture is similar with copper but without exceeding the limits; variations are much smallet in the 14 ft case, with no excess observed.

The effect of loose pellets was investigated starting from the configuration which led to the largest value of k (17x17 fuel, 12 ft long, 4.3% enrichment, copper plates, d=85 mm.)

Assuming two sheets of pins have lost all their pellets over 30 cm and all these end up between the flared pins as shown of fig. 2.6, we then have the equivalent of 51 fuel columns, 20 cm long.

We have model cases with 15, 20, 25, 30, 35 and 40 layers or 37, 60, 88, 121, 160, 203 fuel columns: k increases slowly and exceeds 0.98 only above 88 colums which does not seem realistic.

CONCLUSIONS

Consideration of a vertical drop, with the fuel sliding off its support and pins flaring out below the lowermost brackets, led to a slight reduction in enrichment limit only for 12 ft fuel and with borated stainless steel plates. Pin damage, with loose pellet piling up in the bottom, is no source for concern.

The versatility of MONK's geometry package was crucial in allowing easy realistic 3-D modelling of the configurations which were considered in this study

REFERENCES

Regulations for the safe Transport of Radioactive Material. 1985 Edition (As Amended 1990). Safety Series N° 6, VIENNA, 1990, IAEA.

Grimshaw et al. Improvements to the Subgroup Option and the QA of MONK5W. Winfrith report AEEW-R 2411

Davies. Calculations with MONK5W using MONK6 Validation Testcases and the ZEBRA8 cell Models. Winfrith report RPD/ND/1297

Grimshaw. A Database of Verification and Validation Testcases for a MONK5W Quality Assurance Procedure. Winfrith report RPD/ND/1296

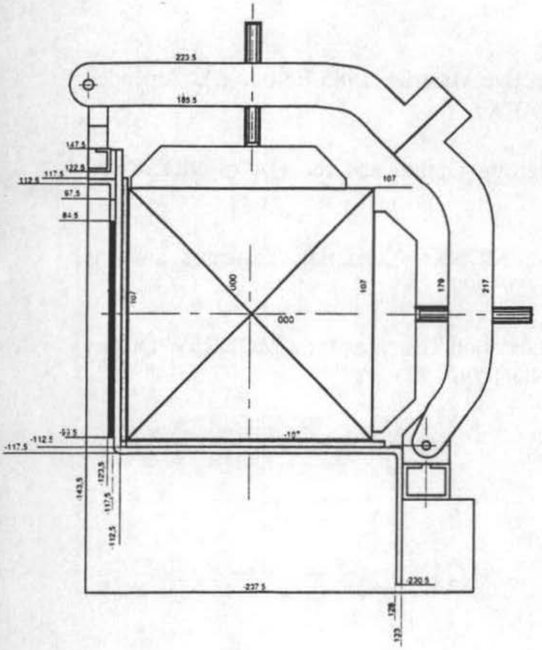

Fig.1.1: Transverse cut though half-frame

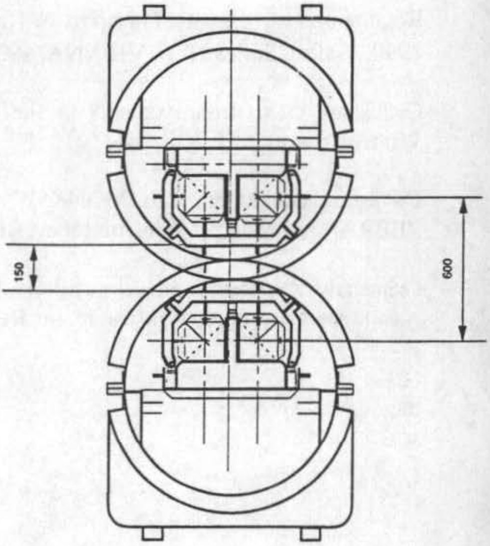

Fig.1.2: Postulated reduction in fuel spacing.

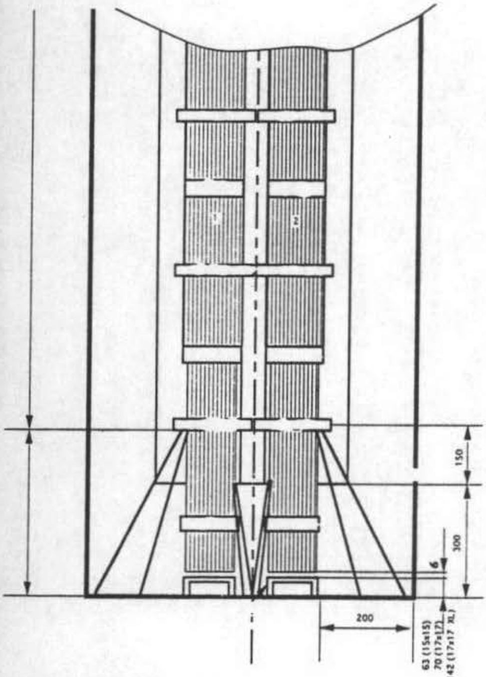

fig. 1.3: damaged package, horizontal view

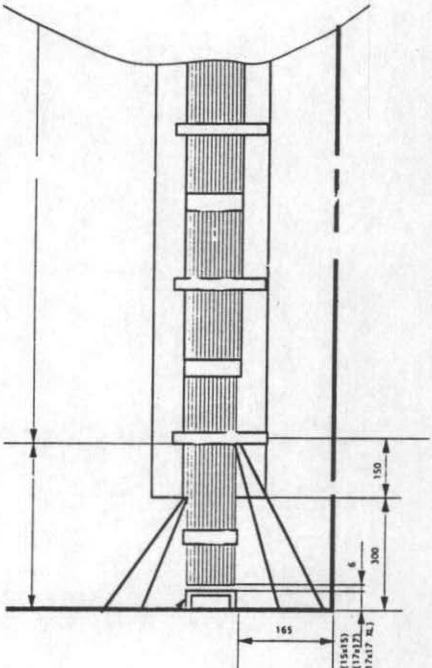

fig. 1.4: damaged package, vertical view

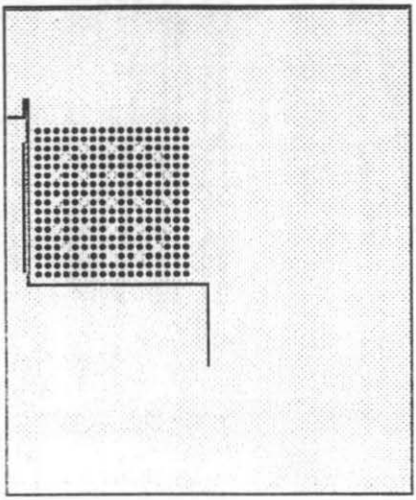

fig. 2.1: undamaged part of fuel

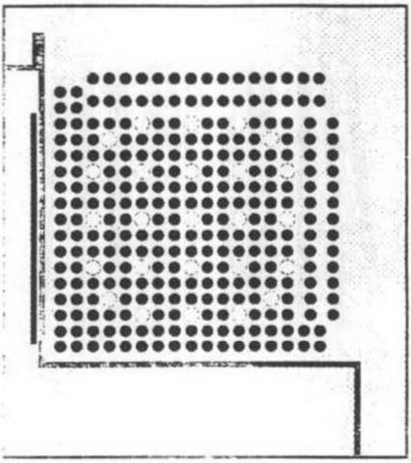

fig. 2.2: damaged fuel, transverse cut below grid

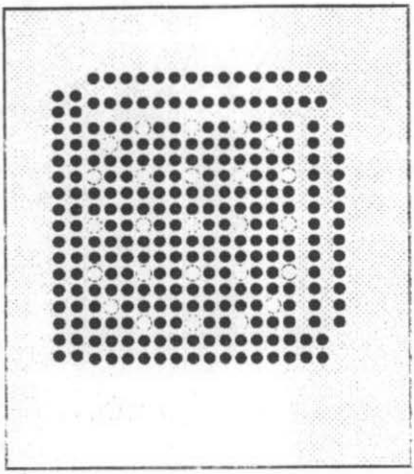

fig. 2.3: damaged fuel, transverse cut below frame

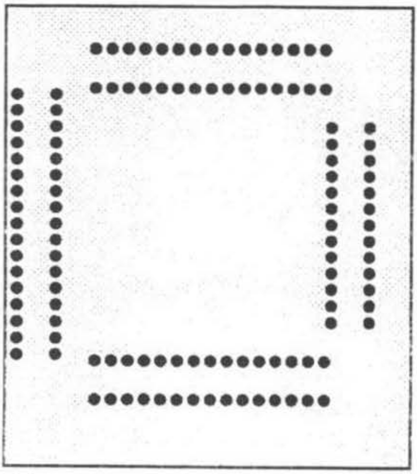

fig. 2.4: damaged fuel, transverse cut near bottom

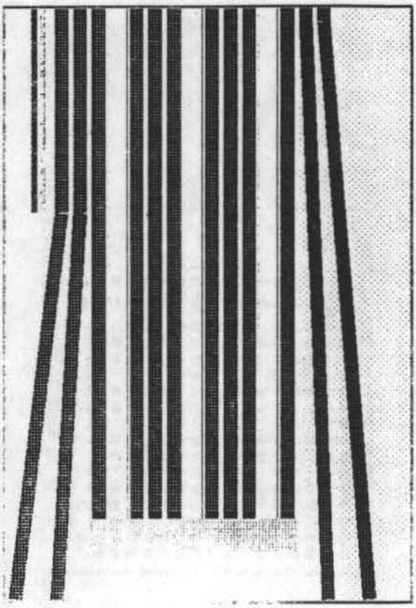

fig. 2.5: damaged fuel with pins "flaring out"

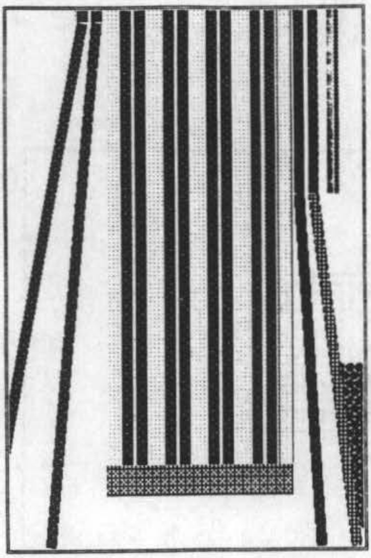

fig. 2.6: damaged fuel with loose pellets piled up

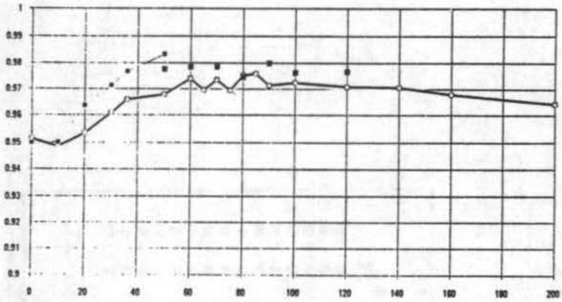

fig. 3.1: keff (d) for 17x17, 12ft

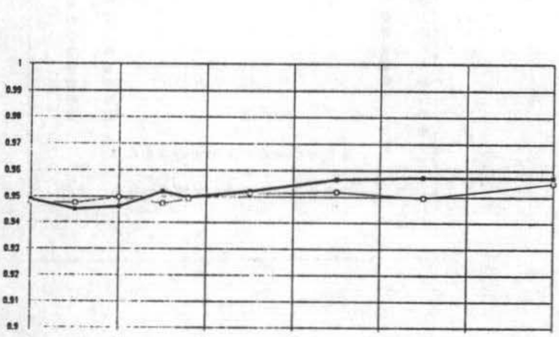

fig. 3.2: keff (d) for 17x17, 14ft