STUDIES TO SINGLE SUBASSEMBLY FLOW MONITORING WITH A COMPLETE 7 ELEMENT ARRAY UNDER SODIUM

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SUMMARY

A core restraint system in a fast reactor serves to limit fuel element movement leading to reactivity changes and misalignment of control rod drives and instrumentation. To guarantee proper control rod function the upper ring of the passive restraint system for the SNR-300 should keep subassembly displacement below 20 mm, whereas a free bowing up to 25 mm does not impair subassembly handling. With respect to single subassembly instrumentation the influences of subassembly displacement on temperature and flow monitoring were not exactly known.

As a part of the SNR-300 R & D programme a complete clamped array, consisting of 4 full size fuel elements and 3 blanket elements was tested for more than 4000 hours at 600°C in the AKB sodium loop at Interatom, Bensberg. The test was split into two phases and the total cluster was prestrained in the second phase to simulate 15 mm subassembly displacement at the level of the upper bearing pads. Although this test was mainly considered as an endurance test to demonstrate the integrity of prestrained core elements, efforts were made to study the feasibility of single subassembly flow monitoring with this full size model of a core section. Subassembly mass flow was monitored by identical probe type eddy current flow meters, held centrally above the outlet of corresponding subassemblies by means of a simplified instrumentation plate. This plate could be displaced 50 mm axially and, to either side, 15 mm radially, increasing to a total radial displacement of 30 mm in case of the prestrained array.

The combination of instrument plate displacements in either direction offered an outstanding opportunity to investigate the feasibility of single subassembly flow monitoring, simulating conditions of subassembly displacement as could occur in a core restraint system during reactor operation. In addition, argon gas could be injected through a capillary into the bundle of the central subassembly, either continuously or discontinuously to check also the feasibility of gas bubble detection by the eddy current flow monitor.

The interesting and somewhat unexpected results of systematic studies show clearly that the monitor flow signal is rather strongly affected by probe displacement, detecting even flow reversal in case of blanket elements neighboured by fuel elements. These effects are clearly hydraulic ones and are attributed to broadening of effluent coolant "jets" and their dragging action in case of flow reversal. This picture obtained from quasi-steady state measurements is refined and supported by dynamic measurements giving some idea about the flow fluctuations detected by the flow monitors of the various subassemblies.

From these results it can be concluded that the tested arrangement—with the flow monitors above the respective subassembly outlets—is certainly not feasible in case of blanket rows with low coolant flow, neighboured by fuel elements with high coolant flow.

This picture may, however, change completely if the flow probes are inserted into the head of the subassemblies as during another similar test to be conducted in early 1975. First results of this test hopefully can also be presented.

1. Introduction

Much attention has been paid to the phenomena of core element bowing in fast reactors, especially in view of reactivity variations, control rod movements and the core element handling. Core restraint systems serve to limit the element movements in order to guarantee proper operation and handling of core elements. The SNR restraint system is a passive one, consisting of two ferritic steel rings, one below the core, the other above. This restraint system is designed to keep the free bowing below 25 mm and the displacement in the element head region below 20 mm for reasons of handling and reactivity changes [1].
Apart from these problems caused by element displacement relatively few details are known how reactor safety and control measurements are affected, although the problem is recognized. It seems obvious that single subassembly instrumentation mounted in a plate "tree" or similar structure above the core as foreseen for most prototype fast reactors might operate improperly if the subassembly to be sensed becomes misaligned or axially displaced.
An experimental study was therefore conducted during an endurance test of a complete clamped array of seven full-size subassemblies to investigate the feasibility of single subassembly flow monitoring and fission gas detection. The results of these investigations are presented and discussed in this paper.

2. Short description of the subassembly array

As part of the research and development program for the SNR-300, a complete clamped array of seven full-size subassembly dummies has been tested thoroughly in the AKB-sodium loop at Interatom. This array consisting of 4 fuel element dummies and 3 blanket dummies of the SNR type was built up to model a core section as shown schematically in fig. 1 together with a scheme of the test section. This test, mainly considered as an endurance test to demonstrate the integrity of the cluster over more than 4000 hours at nominal SNR-300 thermohydraulic conditions was split into two phases. In the first phase normal alignment was studied whereas during the second phase the array was prestrained in such a way as to simulate bowing causing 15 mm misalignment of the subassembly head.
Apart from the purpose to demonstrate integrity and feasibility of subassembly design this array was used to evaluate the feasibility of single subassembly flow monitoring as part of special subassembly instrumentation foreseen in several fast reactors. Since this array modelled a full-size core section combining different types of subassemblies with accordingly different mass flow mixing above the outlet, it offered an outstanding opportunity for an experimental feasibility study.

The main features of the subassembly dummies and their respective nominal mass flow rates are listed in table I for completion and as reference to the nomenclature used hereafter.

3. Instrumentation of the subassembly array

The mass flow through each of the subassemblies was individually monitored by identical probe-type eddy current flowmeters (ECF's) of Interatom design [2]. These flowmeters were held in a simplified instrumentation plate centered above the respective subassembly outlet and surrounded by cylindrical flow channels of smaller diameter than that of the subassembly outlet (fig. 2).

This simplified instrumentation plate could be continuously displaced from its normal position up to 50 mm in the axial direction and up to 15 mm in the radial direction to either side. In case of the prestrained array the total possible radial displacement from the central position increased to 30 mm but was restricted to one direction only. Since all the flowmeters were held in this instrumentation plate they could be displaced simultaneously from their normal position, that is, centered 190 mm above the respective subassembly.

The eddy current flowmeter can, with some modifications of its primary excitation [3], serve as a fission gas detector to indicate fuel pin failures. An argon gas injection device was provided to investigate the feasibility of fission gas detection by ECF's and the influence of simulated subassembly bowing on detection. The gas could be injected either continuously or discontinuously through a capillary into the pin bundle of the central subassembly simulating fission gas release and its transport through bundle and mixing device to the detector.

For completeness it should be mentioned that all subassemblies except the central one were provided with instrumentation to measure and monitor the pressure drop across representative bundle sections. The pressure losses remained constant during the experiments described hereafter which indicates an absence of anomalous hydraulic behaviour during the tests.

4. Experimental approach

Most of the experiments were conducted during the second test phase with the prestrained array to achieve the highest possible radial displacement. Since this displacement was limited to one side only, the symmetry of the effects due to displacement had to be investigated during the first test phase with an unstrained cluster. The effects of radial displacements were found to be symmetric within the limits of accuracy except at higher axial displacements where this symmetry is slightly distorted. This distortion can be attributed to different mass flows through adjacent subassemblies and the effects of radial displacement thus considered as being symmetrical. The results obtained with the prestrained cluster during the second test phase are therefore valid for either direction of radial displacement. These experiments were conducted under stationary and isothermal nominal SNR-300 hydraulic conditions (see table I) as follows.

Starting from the normal position - axial and radial displacement being zero - the instrument plate was stepwise displaced radially up to its value of 30 mm and then returned in intermediate steps to its zero position. This experimental procedure was applied to different axial displacements up to the maximum value of 50 mm and repeated for decreasing axial displacement. Thus a matrix of data was obtained which, after normalization to the zero-zero position can be interpreted as normalized velocity plane.

Each experimental value was computed as the mean value of 130 successive readings using digital data acquisition and on-line analysis. The calibration of all ECF's was checked frequently during the experiments and, if necessary, corrections were applied. It should, however, be pointed out that the ECF measures the velocity of sodium in that vicinity in which the primary electromagnetic field builds up and this measurement is an average over the velocity profile sensed [4]. Thus, without going into details far beyond the scope of this paper, the measurements are not point measurements and should be treated as "integral" ones.
The results, however are certainly valid for any probe-type inductive flowmeter used as single subassembly flow monitor.

5. Experimental results and interpretation

Systematic studies yielded quite interesting and somewhat unexpected results in view of the feasibility of single subassembly flow monitoring during reactor operation. Fig. 3 shows an example of a normalized velocity plane as obtained in case of fuel subassemblies and illustrates the influence of displacement in either axis, which causes a signal decrease to as much as about 80% of its normal value in this case.
The decrease in signal with increasing axial displacement was readily attributed to the broadening of the effluent coolant "jets" and the corresponding reduction in velocity. Based on this simple model the reduction of velocity was calculated, adapting eq. (1) to the actual experimental conditions [5].

$$V = \frac{const}{x} \sqrt{\frac{I}{\rho}} \qquad (1)$$

V = jet center velocity

x = distance from outlet

I = impuls (= $\rho \int v^2 dF$ = const)

ρ = density

The calculated decrease in velocity agreed reasonably well with the experimental results as illustrated also in fig. 3 for all of the fuel elements. The tendency of the measured velocities to deviate from the calculated ones at larger axial displacements most probably reflects the mixing of adjacent "jets" which was not considered for the calculations.
The decrease of flow signal with radial displacement should be directly related to the velocity profile of the effluent "jet". It is, however not easy to prove this more qualitative explanation since these profiles are not exactly known and are smoothed in an unknown manner due to the "integral velocity measurement" of the ECF.
In case of the blanket elements with low coolant mass-flow the normalized velocity planes (one is shown on the left of fig. 4) display a very complicated influence of displacement on subassembly flow monitoring. Besides an increase in flow signal up to more than four times its normal value in case of axial displacement which probably can be attributed to "jet mixing", the detection of reversed flow is rather interesting and unexpected. These "negative" velocities or flow reversals are attributed to the dragging action of the "jets" from neighbouring fuel elements with higher coolant mass flows [6]. Due to this dragging action the formation of rather large quasi-stable eddies in the plenum is not unlikely as will be discussed later.
The simple "jet model" can not be applied in these cases since it is unable to explain neither negative velocities nor the increase in velocity, due to mixing with adjacent jets. Due to the more technological aspects of this feasibility study no attempt was made to refine this model.
The discussed effects are clearly hydraulic ones and not at all connected with differences in the two types of subassemblies considered. Another blanket element with higher mass-flow (about 11 kg/s) showed a normalized velocity plane very similar to those obtained for the fuel elements (right side of fig. 4).

6. Approximate velocity coefficients

The overall picture derived from quasi-stationary measurements and interpreted with the help of a simple "effluent jet"-model can be supplemented and refined by dynamic measurements and analysis of the velocity fluctuations. Although such measurements were not performed the standard deviation of the computed mean value of 130 successive readings can be interpreted as an approximative value for the integral power spectral density of velocity fluctuations, eq. (2).

$$\sigma^2 = \frac{\sum^{N} |X_i - \bar{X}|^2}{N - 1} \rightarrow \int \emptyset_v \text{ (f) df} \qquad (2)$$

$\emptyset_v(f)$ - power spectral density
f - frequency

This approximation should give at least some measure of the velocity fluctuation, although there is a definite frequency limitation due to the scanning time which was somewhat less than 1 second in our case. However, the standard deviation was used to evaluate the velocity coefficient C_v, eq. (3).

$$C_v = \frac{\sqrt{\int \emptyset_v (f)\, df}}{\bar{v}^2} \longrightarrow \frac{\sigma}{\bar{v}^2} \qquad (3)$$

Again, this evaluation gives an approximation only and the results should be interpreted as such. The dependence of the velocity coefficient upon the velocity of coolant flow (given as dimensionless Reynolds number, $C_v = f(Re)$) is illustrated in fig. 5 together with representative analog recordings of ECF-signals.
There are two definite groupings for the curves $C_v = f(Re)$ following the empirical relationship as given in eq. (4).

$$C_v(Re) = C_1 \cdot Re^{-C_2} + C_3 \qquad (4)$$

$C_1 \ldots C_3$ - constants

and illustrated in fig. 5 as the region covering all the respective experimental curves of one group.
The velocity coefficients, $C_v = f(Re)$, for all the fuel elements and the blanket element with high mass flow are similar and considerably smaller than those for the blanket elements with low mass flow, which are similar again. This behaviour not only supports strongly the picture of counterflow development but also the hydraulic nature of this phenomena. In addition these rather intensive low frequency velocity fluctuations could be valued as an indication for the existence of larger quasi-stable eddies in the region above the blanket outlet. With respect to the approximative analysis the existence of those assumed eddies will be investigated during future experiments employing on-line Fast Fourier Analysis of flow signals.

The eddy current flowmeter can in principle also serve as a fission gas detector in cases of pin failures, and experiments have been conducted to determine sensitivity of detection and the influence of subassembly displacement. These experiments have ascertained that a single fuel pin defect can be detected if the fission gas is released within 2 seconds or less at end-of-life pressure. Displacement of the ECF yielded similar effects as in the case of flow measurements although the influence of displacement on fission gas detection was not as pronounced as discussed for the flow measurements. However, it can be stated here that misalignment and displacement between the ECF and the subassembly to be sensed decrease the detection limit in a similar manner as in case of flow measurements.

7. Conclusions on the feasibility of subassembly flow monitoring

The experimental results of this investigation lead to the conclusion that the tested arrangement should not be integrated into the reactor safety system, unless modifications are made. According to the calculated displacements and misalignments due to subassembly bowing [1] during fast reactor operation the resulting changes in flow signal are on the same order of magnitude as to be expected for serious coolant channel blockages. The tested arrangement is certainly not feasible for blanket mass flow monitoring, especially in cases of blanket rows adjacent to fuel element rows. Due to the rather large velocity fluctuations fission gas detection will also be impaired unless frequency analysis methods can be applied successfully to discriminate between fluctuations and gas bubbles.

This rather pessimistic picture may however change completely if the ECF-probe is inserted into the head of the respective subassembly. It can be expected that neither the flow reversal nor the dragged eddies, causing strong velocity fluctuations will extend into the head of a subassembly. Furthermore, unless bowing-induced displacement does not lead to destruction of the probe by contact, the net effect of this displacement on flow signal should be reduced to a great extent.
Similar experiments as those described and discussed here with a modified instrumentation plate, allowing insertion of the ECF-probes are under way and some first results of which might be presented as a supplement.

Table I Summary of subassembly structure and hydraulic characteristics

POSITION (SEE FIG.1)	1	2	3	4	5	6	7
TYPE OF SUB-ASSEMBLY	FUEL	FUEL	FUEL	BLANKET	FUEL	BLANKET	BLANKET
NAME	MARS	MERKUR	JUPITER	JUNO	PLUTO	HERMES	VESTA
NUMBER AND TYPE OF SPACERS	14 VARIOUS TYPES	14 BRAZED FERRULE	14 EGG BOX TYPE	6 INTE-GRATED HELICAL FINS/PIN	14 VARIOUS TYPES	HELICAL WIRE WRAPPED	6 INTE-GRATED HELICAL FINS/PIN
PINS DIAM.(mm)	166 6.0	166 6.0	166 6.0	91 9.5	166 6.0	91 9.5	91 9.5
TIE RODS	3	3	3	NONE	3	NONE	NONE
MASS FLOW+ (kg/s)	20.9	19.8	21.8	2.6	17.5	1.85	9.65
COOLANT+ OUTLET VELOCITY (m/s)	3.67	3.48	3.83	0.46	3.07	0.33	1.70

+AT NOMINAL CONDITIONS 94.1 kg/s total mass flow and 550°C (total pressure drop across the array = 3.60 ± 0.26 bar, mean value during total test time)

References

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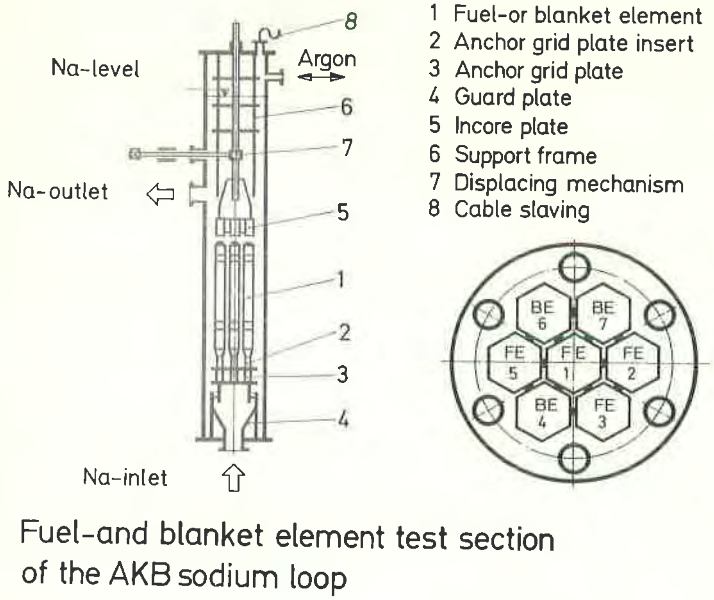

fig. 1 Schematic diagram of the test section and arrangement of the seven-subassembly-array (FE-fuel element, BE-blanket element)

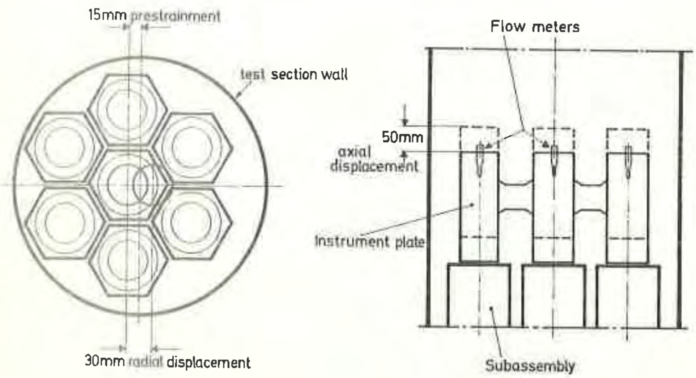

fig. 2 Schematic diagram of eddy current flowmeter mounting in the simplified instrument plate and indication of the directions of displacement

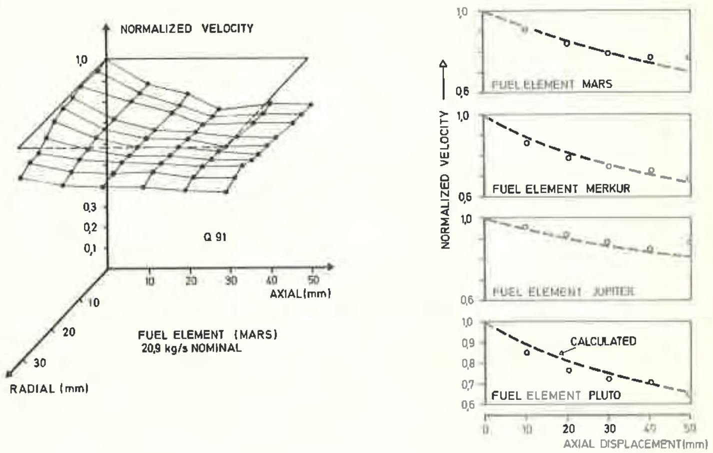

fig. 3 Normalized velocity plane for fuel element MARS (left); calculated and measured influence of axial displacement for all fuel elements (right)

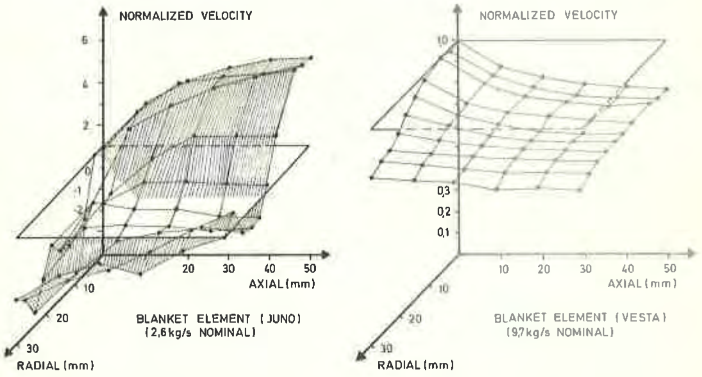

fig. 4 Normalized velocity planes for the blanket elements JUNO (left) and VESTA (right)

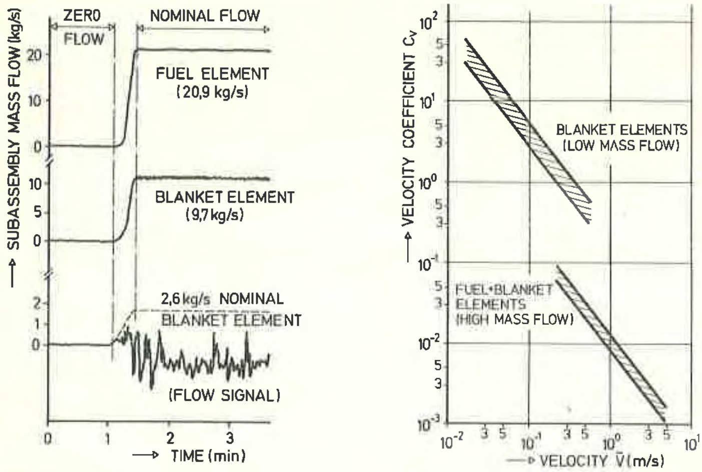

fig. 5 Analog signal track recordings for different subassemblies (left) and computed approximate velocity coefficients, given as experimental regions (right)