Investigations of Local Blockage Formation and Dependance on Fuel Element Spacing

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Summary

The operating temperature of nuclear power reactor fuel rods must be held within design limits to prevent fuel and fission product release. This is especially so in the high core power density LMFBRs where local cooling disturbances can not only initiate accident scenarios but also influence plant availability, e.g., by causing defects in the fuel rod can. Such disturbances, the result of local blockages, might be formed of granular material transported with the coolant flow and sieved by narrow sections in fuel subassemblies or breeding elements. A detailed analysis of potential material sources has shown that fuel particles released from defective fuel pins are the most likely cause of so-called local primary blockages in high power core zones. It is clear that the local velocity field, and the possibility of wake formation with high separation capacity on granular impurities in the flowing coolant, are important for source term considerations. However, transport mechanisms, including sedimentation processes in the total primary coolant flow paths, will have to be investigated for each reactor design independently.

The spacer concept is of extreme importance to the understanding of local blockage formation, by particle bed agglomeration, inside fuel subassembly arrays. This has been shown at GKSS by theoretical considerations and by experimental studies of the blockage formation process. Both grid-type and wire-wrapped spacers were considered because they show fundamental differences in behavior: in grid spaced fuel elements, particles of adequate grain size form radially-extensive blockage beds of limited thickness; in wire-wrapped elements, a natural sieving process leads to axial particle agglomeration which is limited to only one subchannel at the same axial level, with a relatively small radial bed dimension. When considering the thermal load on canning material, the developing temperature field in areas of blockage is of special interest. Phenomenological evaluation has clearly shown that the obtaining of an important local temperature increase with grid-spaced elements follows release of a relatively large particle mass, which forms radially extended and thick blockages with low porosity. Under similar circumstances, however, wire-wrapped bundles develop enforced crossflow between subchannels, mostly only the larger particles contribute to forming a blockage, the resulting porosity is high and the remaining coolability will result in only a limited increase of temperature at "hot spots".

In view of the probability for critical blockage formation in the LMFBR as well as the enhanced cooling capability in assumed blockages, wire wrapped spacing shows some advantages even in the case of geometrically deformed subchannel configurations.

1. Introduction

Studies of the formation of local coolant flow disturbances and local blockages in the core region of sodium cooled fast breeder reactors are performed to furnish detailed information upon the very initial phase of accident scenarios. Blockage formation processes were found to be strongly influenced by both geometrical and hydraulic boundary conditions of FBR subassemblies, especially as regards the spacer design.

For grid-spaced fuel subassemblies, experimental and theoretical results on local blockage growth by particulate matter have been available for several years /1, 2, 3, 4/. In addition, more sophisticated modelling, looking to further development has been done /5/. For comparison, an investigation of a similar type as in /2/, with out-of-pile experiments, has been performed at GKSS with a wire-wrapped test section /6/. Our theoretical assessment, comparing the wire-wrapped rod bundle boundary conditions to those of the grid-spaced type, has exposed substantial differences in their relative particle screening capabilities and transport mechanisms /7/. This result is shown schematically in Fig. 1. The smallest passage dimension for an intact wire-wrapped bundle geometry is given by the interpin gap; this should lead to a preferential axial growth of blockages if particles are large enough to be sieved out of the coolant flow. The radial extension of blockage should be substantially limited in the wire-wrapped spacer design. Details of the tests, the parameters and the main results are given below.

In grid-spaced bundles, a horizontal particle bed with strong radial growth tendency has been found /1/. The preferential radial transport was identified as due to flow distribution around the upstream wake of a blockage. This spread is especially enhanced if the sinking velocity of particles is larger than the axial component of the coolant flow velocity. As can be seen from Fig. 3 at constant density, this is indeed the fact for larger grains.

A comparison of the blockage formation characteristics of the two spacer concepts is now possible.

2. Experimental Equipment and Test Programm

In order to investigate the formation and growth of blockages and the distribution of particulate matter in the bundle, a glass test section was built with the geometrical configuration of a typical FBR fuel element and with wire-wrapped spacers (see Fig. 2). The bundle is assembled in a cylindrical glass tube with an inner diameter of 50 mm. Further geometrical data of the test section are given below.

Table 1: Geometrical Test Bundle Data

pin diameter	7,0 mm	wire helix pitch	150 mm
pin pitch	8,3 mm	wrapped length	900 mm
pitch to diameter ratio	1,19	effective wire diameter	1,3 mm
		number of pins	30 (26+4 partial)

The wires of 1.5 mm diameter are inserted in 0.2 mm deep grooves machined into the surface of the rods. The azimuthal position and the helix direction of the wires are unique for all rods. As the lateral cross section in Fig. 2 shows, the flow area of the bundle near the glass tube wall is not filled completely with rods; in consequence a significant mass flow rate increase has been observed in this region during the tests. In order to reduce the influence from this area the position of the particle injection is located at one of the internal subchannels. Evaluation of the experimental results shows that the main fluid velocity in the central part of the bundle was about 4 m/s (see also Fig. 4). The axial distance of particle inlet from the outlet flange is about 600 mm.

The tests were performed in the Organic-Loop at the KfK Institute of Reactor Development. The test conditions and parameters are compiled in Table 2. The tests were performed under reactor-like conditions, with respect to subchannel geometry and coolant flow velocity. The main program included 17 tests. The injected particles varied in grain size from 0.125 mm to 2.5 mm and in particle quantities from 5 g to 15 g; this provided a volumetric equivalent of about 2 to 7 fuel pellets. From run 1 to run 14 tungsten silicide (WSi_2, $\rho = 9{,}4$ g/cm^3) particles were used; from run 15 to run 17 tantalum carbide (TaC, $\rho = 14.4$ g/cm^3) particles were injected.

The composition of each injected particle batch was inhomogenous in grain size distribution and sphericity. The distribution of grain size applied in the GKSS tests is shown in Fig. 3 for a batch with tungsten silicide particles. The distribution curve, noted to be considerably higher than data provided from other sources, is thought to be "conservative".

Each test run sequence was as follows: Following adjustment to obtain a constant coolant flow rate and preparation of a particle batch, particle injection was initiated. The high-speed camera was started at the same moment by signal from a control valve opening in the particle supply line. Particle injection and high speed film length were synchronized for a test time of the particle batch input time of about 4 seconds. In addition to the high-speed camera, documentation of the experimental results also includes still photos and direct visual observation.

Additional tests were performed at the end of the WSi_2-series given in Table 2, to investigate pump shut down effects and blockage reformation after pump restart, although it was evident that sintering effects or other physio-chemical influences of the real sodium/fuel system could not be simulated. Experiments without the loop, in stagnant liquid or in a dry bundle, completed the program.

3. Results and Discussion

Our analytical considerations have been entirely confirmed by the experiments. In wire-wrapped rod bundles the wire pitch is important for the seiving geometry and essential to the hydraulics in order to create enhanced mixing flow between neighbouring subchannels. Due to hydraulic forces, effects such as impact, collisions, and accelerations of the particles on their way through the bundle have been clearly observed /6/.

If particle fractions, small in comparison to the interpin gap dimension are injected, only a low number of grains are deposited randomly in the bundle; more often they become trapped up-stream of the helical wire. A certain accumulation and subsequent blockage desintegration occurs if the grain size is increased to the range between 1 mm and 2 mm. This unstable blockage growth, up to an axial length of about 15 mm and limited to a few subchannels only, was observed by continuing the particle injection during the experimental series. As could be expected, only large particles (grain size of about 2.5 mm) show a more systematic blockage formation capacity and lead to a remarkable and relatively stable axial blockage growth, especially in the input channel. An example of this, in the form of two photographs with 5 seconds time difference, is shown in Fig. 5.

Sphericity of particles is of particular importance regarding subchannel to subchannel transport. Larger particles with blockage initiating capacity need sphericity values around 0.5 to leave the input channel and subsequently create another blockage in a neighbouring subchannel. If blockages are formed very near to a canning defect (particle input) continous axial growth of this blockage, as well as formation of further blockages supplied from this material source, might be limited by reaching the input level and providing self-blocking of the particle source.

A comparison of these mechanisms to results from grid-spaced bundle experiments shows that flow induced particle deviation around blocked flow paths occurs as well. Fig. 4 shows the evaluation of the local axial fluid velocity in the surroundings of a blockage. High-speed films show that no strong velocity loss takes place. Some times even a particle acceleration has been observed due to an increased subchannel mass flow rate around the blocked volume. The axially oriented seiving capacity of the interpin gap in the wire-wrapped bundle leads to "column like" particle beds compared to "plate like" beds observed in the up-stream front of grids /12/, taking into account differences in dimensions and limiting effects (see schematics in Fig. 1). Such smaller dimensions and the preferentially axial flow in wire-wrapped bundles keep those particle beds more porous and thus better coolable. The start-up procedure of MOL-7c, as an inpile example /8/, and the circumferential temperature distribution examination near spacing points, in out-of-pile experiments /9/, justify the assumption that local hot spot temperatures may rise only some ten degrees above the coolant average values.

Initial study and orientation experiments /10/ have begun for distorted bundle geometries. If the grain source is assumed to occur in a narrowed subchannel, the critical grain size for seiving might also be reduced. If blockage occurs in this narrow subchannel, radial dimensions of the blockage are even lower than in the normal case. Considering axial growth there may be no difference. In the case of subchannel widening, particles are swept to the next "bottleneck". Changes in geometry by deformation as well as by vibration effects lead to blockage desintegration and reaccummulation downstream, whereever the geometry of gaps and the particle size allows. In wire-wrapped bundles, the observation of preferential growth along single subchannels seems to be valid generally as our first experiments have shown /6, 10/.

4. Final Remarks

Since experimental results on blockage formation in rod bundles with spacer grids as well as with wire-wrapping now are available it seems justified to include them in future safety considerations. Taking the grid spaced elements as a worst case, a totally blocked subchannel first has been considered /11/ followed by a partial blocking system with a non-vortex wake. This "plate-type" blockage has been used for wire-wrapped bundle investigations as well /e.g. 12/. It is strongly recommended to reassess this situation including the results presented here. Results from study of wire-wrapped bundles in no case indicate the existance of remarkable wakes or their influences on blockage formation, as known from grid spaced bundles.

From the engineering point of view, the local blockage formation as an initiating event for accident scenarios seems to be less critical for wire-wrapped spacing. The results suggest that the blockage arrangement may be quite sensitive to delayed neutron detection. This is an important point with respect to plant availability. Further investigations may be worthwhile to confirm the effectiveness of this form of blockage distribution.

We also expect that some special situations in deformed bundle geometry are important for further investigations of blockage formation in wire-wrapped bundles. Additional experiments concerning the formation process of blockage in distorted bundles are under consideration.

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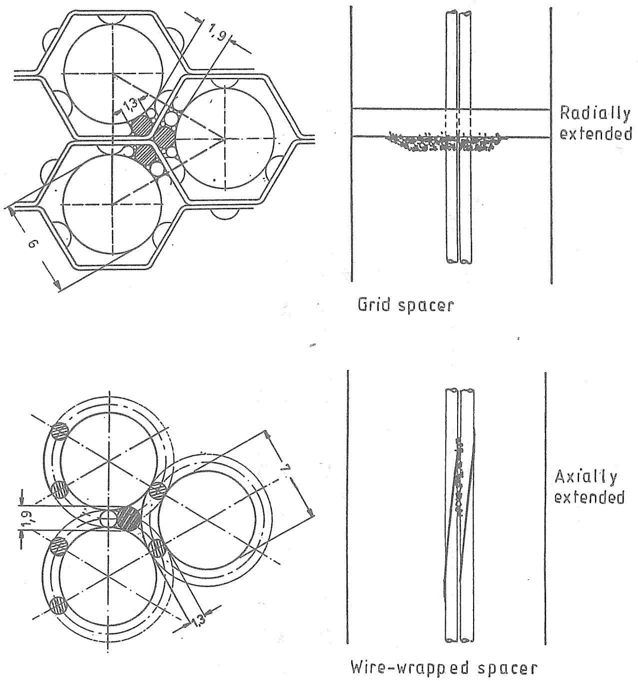

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Fig.1: Comparison of seeving geometry and blockage form between grid and wire-wrapped spacer

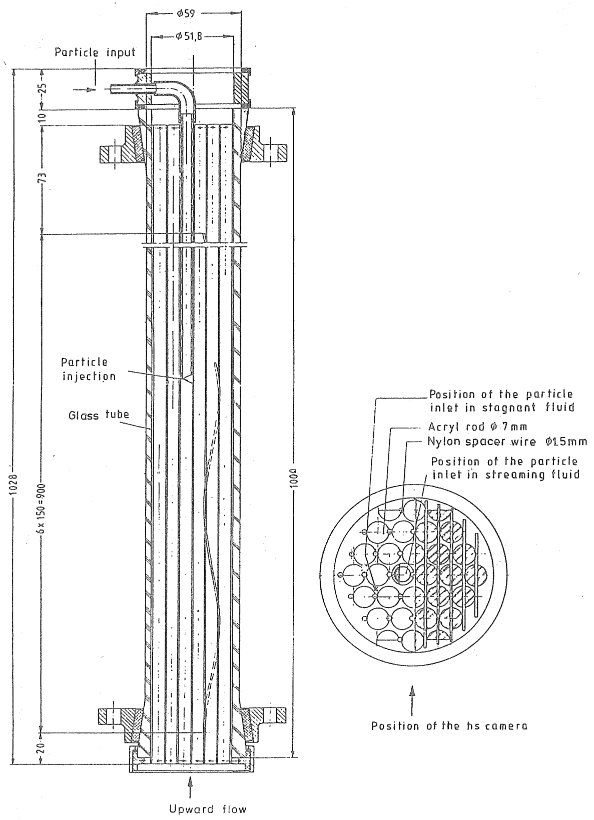

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Fig. 2: Testsection with a wire-wrapped 30-rod bundle

Run No.	Grain size d_1-d_2 (mm)	Dosage of particles Quantity/batch (g)	Input time (s)	Material	Flow $\bar{V}_{bundle}$ (m/s)	Remarks
1	0.06 - 0.125	5	< 5	WSi_2	2.8	
2	0.25 - 1	5	< 5	WSi_2	4.2	
3	0.25 - 1	10	< 5	WSi_2	4.2	double quantity
4	1 - 2	5	< 5	WSi_2	4.2	
5	0.25 - 1	5	< 5	WSi_2	4.2	
6	1 - 2 0.25 - 1	5 10	< 5 < 5	WSi_2 WSi_2	4.2	maximum of particle volume
7	1 - 2	5	< 5	WSi_2	2.8	
8	1 - 2	10	< 5	WSi_2	2.8	
9	0.25 - 1	5	< 5	WSi_2	2.8	
10	1 - 2	5	< 5	WSi_2	2.8	
11	0.25 - 1	5	< 5	WSi_2	4.2	
12	0.25 - 1 1 - 2	5 5	< 5 < 5	WSi_2 WSi_2	4.2	
13	-	-			4.2 → 0	no particle input, pump "stop"
14	1 - 2	5	< 5	WSi_2	∿ 0.5 4.2 0	varied flow rates
15	∿ 2.5	5	> 5	TaC	∿ 1.2	single particle input
16	∿ 2.5	5	> 5	TaC	∿ 2.8	
17	∿ 2.5	5	> 5	TaC	0.5 ↔ 2.8	varied flow
-	0.5	100		Bz		Tests in stagnant fluid

Table 2: Test conditions and parameter

GKSS
FORSCHUNGSZENTRUM GEESTHACHT GMBH

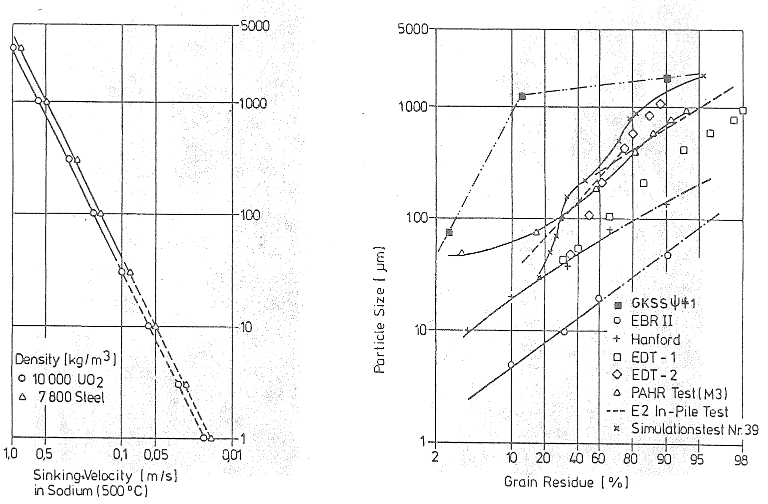

Fig.3: Particle size distributions of impurities, fuel and thermite in liquid sodium correlated with calculated sinking velocities

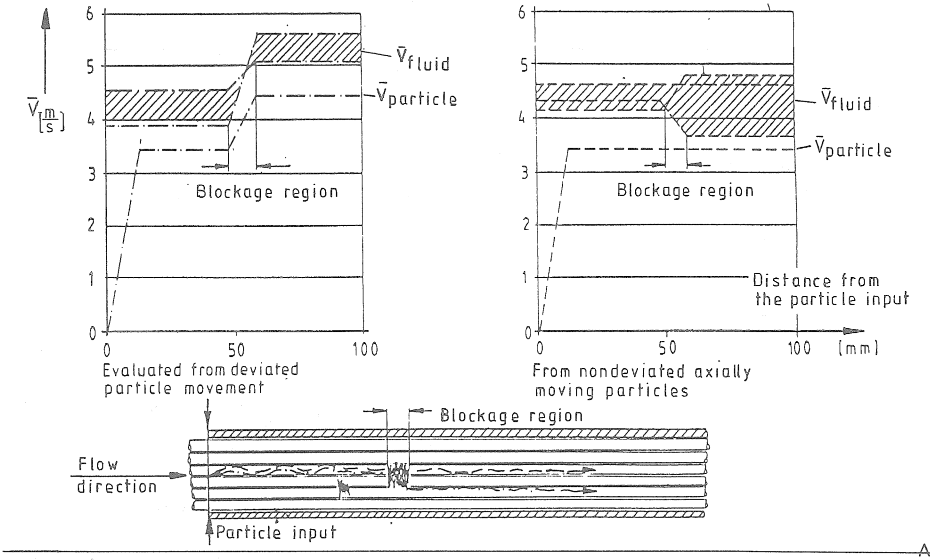

Fig.4: Fluid velocity evaluated from the particle movement

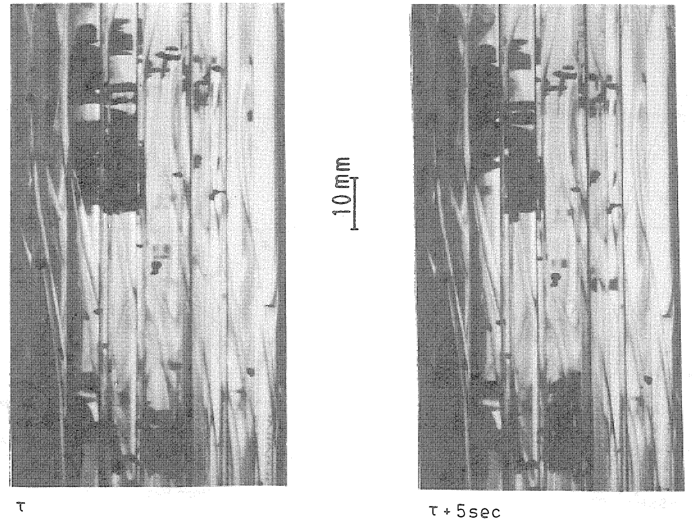

Fig.5: Blockage formation in a rod bundle with wire - wrapped spacers, pin ϕ 7mm (TaC - particle of ~ ϕ 2,5 mm)