MEASUREMENT OF BLOCKAGE IN DEFORMED LWR MULTI-ROD ARRAYS

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ABSTRACT

This paper critically reviews the current methods used for measuring blockage in multi-rod arrays and discusses their application. A new definition which overcomes the deficiencies of the previous methods is proposed. Also examples of the application of automatic computerised techniques to directly measure rod strain, blockage, sub-channel blockage and perimeter changes from photographs of sections through deformed arrays are presented.

1. INTRODUCTION

The fuel rods in a modern Pressurised Water Reactor (PWR) have Zircaloy-4 cladding and are internally pressurised during manufacture to improve thermal conductivity at the UO_2 pellet-cladding interface(1) and to reduce mechanical interaction between pellet and cladding during service.(2) In the event of a hypothetical loss-of-coolant accident (LOCA) the loss of water from the reactor core causes a degradation in heat transfer from the fuel rods and they may increase in temperature. The extent of their temperature transients is determined by the source of heat in fission product decay in the fuel pellets, the transfer of this heat to the cladding, and its transfer from the cladding by the external heat transfer mechanisms. The latter depends upon the size of the breach and the operation of the emergency core cooling systems (ECCS). Thus it is possible that the cladding may reach a temperature where the differential pressure between the fuel rod and coolant is sufficient to cause plastic distension and diametral increases of 60% can be achieved,(3) also any loss of ductility resulting from irradiation is restored rapidly above 650°C.(4) Since the spacing of PWR rods is such that adjacent rods straining by 32% will touch there is the possibility that sufficient restriction of the coolant sub-channels can occur in such circumstances to inhibit the efficacy of the ECCS.

In the USA the owners of a Light Water Reactor have to satisfy LOCA licensing requirements specified in Appendix K of the Code of Federal Regulations.(5) One of these requirements is that "calculated changes in core geometry shall be such that the core remains amenable to cooling". Thus to satisfy these requirements experiments to determine the deformation characteristics of internally pressurised multi-rod arrays are being investigated in laboratory(6-9) and in reactor tests.(10) Also heat transfer experiments are being carried out on pre-deformed arrays.(11-13)

2. GENERAL BLOCKAGE DEFINITIONS

The generally accepted definition of blockage(14) (or coolant channel restriction) is given below and shown schematically in Fig. 1.

$$B\% = 100 \times \frac{\text{difference in cross-section between swollen and unswollen rod}}{\text{original coolant channel cross-sectional area}}$$

This definition gives B = 0% for no deformation and B = 100% if all the rods deform into squares of side p, where p is the rod pitch, see Fig. 2a and Fig. 2b.

The extreme case of 100% general blockage is not obtainable experimentally. However, at reasonably high rod strains the situation depicted in Figure 2c can be obtained, i.e. where swollen rods extend beyond the boundaries defined by the rod pitch. This situation is observed when the rods are not restrained by neighbours or a surrounding shroud and the strain is > 33%, or where the rod has moved from its original position in the bundle, as in Figure 3, which shows a cross-section from B-3(14) of the ORNL multi-rod burst test programme.

In this situation two options can be exercised in the evaluation of final rod area:

1. Total area method

Measure the area of each rod in the deformed bundle. Then use the blockage definition shown in Fig. 1.

2. Mask method.

Assume that the blockage should be evaluated only within the area defined by the original coolant channel area. Then use the blockage definition shown in Fig. 1.

Both of these options have been used by investigators, see Table 1, and each has advantages and drawbacks.

The first method, 'total area method', makes no allowances for movement of the rods. Thus an array of swollen rods, each of which has moved, leaving an 'open lattice', has exactly the same numerical blockage value as an array in which the individual rods have deformed to the same extent but have not moved, when obviously there is a difference in coolant flow area, see Fig. 4a. In addition, 'local' blockage values of > 100% are perfectly feasible, see Fig. 4b, if the rods swell beyond their lattice spacings. Also, if the outer rods of a highly deformed bundle swell beyond the original lattice dimensions, total blockages > 100% can be obtained. In both situations the result can therefore be misleading.

The second method, the 'Mask Method',(15) see Fig. 5, cannot produce total blockage figures > 100%. However, the disadvantage is that the positioning of a mask, by representing the original bundle dimensions, is a subjective decision, when the rods have moved out of position during a test. A mask could be placed precisely if fiducial markers are incorporated in bundles before testing. However, this has not been a feature of experiments carried out so far and their presence could interfere with the experimental conditions. A further disadvantage is that the strained portion of the rods outside the mask is ignored when in a real situation it would be contributing to flow blockage.

3. EVALUATION AND DISCUSSION OF GENERAL BLOCKAGE MEASUREMENT METHODS

In this section the results of a few measurements of the type discussed above are presented to assess the likely differences obtainable using the two methods. The cross-sections of the test bundles B-3 and B-5, see Fig. 6, are from the ORNL multi-rod burst test programme.(6,16)

The blockage value for each section was measured using both the 'total area' and 'mask' methods. Additionally the blockage was measured over the remaining rods and successive outer layers were disregarded. This was done in order to assess the effects of the outer layer, which can experience temperatures and restraint that are unrepresentative of the rest of the bundle, on the total blockages. These results are given in Table 2. It can be seen that in both the 'total area' and 'mask' methods, the outer layer of rods influences the total blockage value.

In the 8 x 8, B-5 bundle the blockage value increases by 6-15% as each outer layer of rods is discarded. It should be noted that there is not a large difference, i.e. 1-2%, between the 'mask' and 'total area' blockage values for the whole bundle, but the difference increases to 3-5% when the outer layer is stripped from the bundle.

The B-3, (4 x 4) bundle shows a different trend, i.e. the blockage decreases when the outer layer is stripped off. This illustrates how small bundle tests cannot be totally representative of the behaviour of large numbers of rods in a 17 x 17 assembly which itself is surrounded by immediately adjacent assemblies.

The most satisfactory of the two methods of blockage measurement discussed so far is the 'mask' method because this takes into consideration any rod movement and eliminates the possibility of achieving total blockage values > 100%.

However, the blockage values obtained when the outer layer of rods is included are markedly different from those if this layer is excluded. Therefore in view of the unrepresentative nature of the outer layer of rods, it would seem sensible to consider them as a guard ring rather than an integral part of the bundle.

Hence it is recommended that for total blockage area measurement the 'mask' method should be used with the outermost layer of rods discarded, although there may be circumstances where rejection of the outer two layers of rods is necessary.

The general blockage method modified as suggested above only satisfactorily describes the coolant channel restriction in bundles in which there is limited rod to rod interaction and the individual sub-channels are similarly restricted. If this is not the case, as in Fig. 6, a method which is sensitive to individual sub-channels is required.

4. SUB-CHANNEL BLOCKAGE METHOD

The general blockage method does not provide an adequate description of the change in individual coolant flow channels as the local blockage given by the usual definition, see Fig. 1, is, in effect, the average blockage immediately around a particular rod. What is required for heat transfer calculations is a measure of how much of the original coolant channel area remains between four rods when they have distended to form either a closed or open sub-channel, see Fig. 7, because it is this which has a major effect on the temperature of the cladding surfaces in that sub-channel. Also it is important to know the perimeter of sub-channels and the extent to which they are closed.

4.1 DEFINITION OF 'SUB-CHANNEL BLOCKAGE'

The mathematical description of sub-channel blockage, see Fig. 8, is similar in form to the general blockage definition given in Fig. 1, in that for zero rod strains $B_{SC} = 0\%$ and for complete deformation into squares of side equal to the rod pitch, $B_{SC} = 100\%$.

The only major difference is that the areas of coolant channels, rather than rods are being utilised in the definition.

In measuring A_{SC}, the sub-channel area, the boundary, if the sub-channel is open, or partially closed, is taken to be the point where the gap between the neighbouring rods is narrowest, see Fig. 9.

4.2 TREATMENT OF BURSTS

When there is a burst opening somewhere on the sub-channel periphery, two possible options for measurement have been selected, see Fig. 10. These are labelled A and B and are directly comparable to the ORNL treatment(1) of burst cladding 'flare out'.

4.3 SUB-CHANNEL PERIMETERS AND ROD-GAPS

In multi-rod arrays where the distending rods are restrained from pushing one another apart interaction can close many of the rod to rod gaps isolating sub-channels(15-18) and ultimately bulges can become almost square. In situations where this has obviously occurred the perimeters, see Fig. 11a, and rod gaps, see Fig. 11b, are measured and expressed as percentages of the original values.

5. CHARACTERISATION OF A MULTI-ROD CROSS-SECTION USING THE GENERAL AND SUB-CHANNEL METHODS

Figure 12 is a cross-section from a 4 x 4 multi-rod cluster which was used in a materials test(17) to study the mechanism of rod to rod interaction. To obtain the data necessary for characterising such a cross-section, according to the methods described in this Paper manually, is exceedingly tedious and then it has to be processed. At the Springfields Nuclear Laboratories computer based measurement and processing of such data has been developed using an image analysis system, (IBAS supplied by Kontron GmbH), so that the entire operation can be done semi-automatically to a degree of accuracy equal to that of manual methods. Figures 13-16 present the results of characterising Fig. 12 using the methods discussed in this paper. It is proposed that the multi-rod sections arising from tests in the 'FOURSQUARE' and 'MERLIN' rigs at the UKAEA Springfields Nuclear Laboratories(9) will be characterised in this way so that hey can be compared with previous work and provide detailed information on individual sub-channels for heat transfer calculations.

6. CONCLUSIONS

The generally accepted definition for blockage in a deformed multi-rod array does not adequately describe the blockage if there is rod movement and swelling beyond the original bundle lattice boundary.

The general blockage definition fails to describe the local blockages found within an extensively deformed bundle.

The behaviour of the outer layer of rods is likely to be unrepresentative of the rest of the bundle.

7. RECOMMENDATIONS

To obtain the most satisfactory value for general blockage in a multi-rod experiment the outer row of rods should be excluded from the measurement and the area of the remainder should be measured by the 'mask' method.

In addition to the measurement of individual rod strains and general blockage, the rod to rod gaps, sub-channel areas and perimeters should be measured when rod to rod interaction has occurred.

8. ACKNOWLEDGEMENT

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TABLE 1

Methods for defining blockage as currently used by various laboratories investigating the deformation of cladding in multi-rod arrays

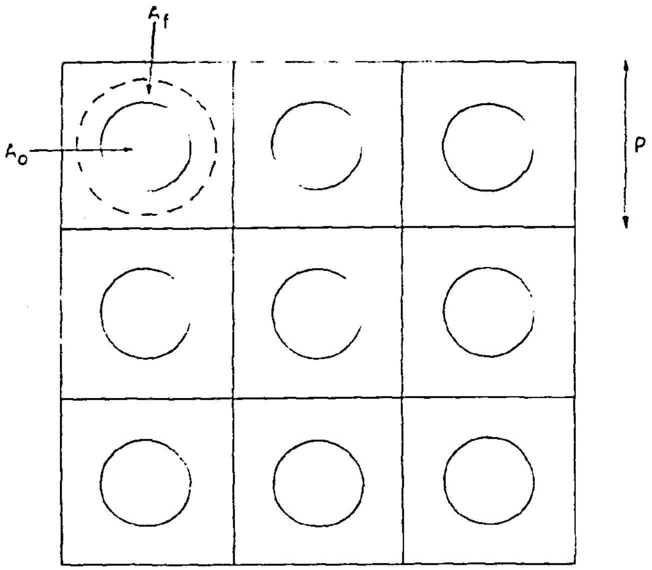
Group	Blockage definition eqn. (1)	Unmasked bundle	Masked bundle
UKAEA	/	/	/
ORNL	/	/	
JAERI	/	/	/
KfK*	/	/	

*Methods under review

TABLE 2

Blockage values obtained using the total area and mask methods

Specimens from ORNL Multi-rod tests[6,16]	% Blockage total area method				% Blockage mask method			
	whole bundle	1st layer stripped	2nd layer stripped	3rd layer stripped	whole bundle	1st layer stripped	2nd layer stripped	3rd layer stripped
8 x 8 array B-5								
(20.0 cm)	63	76	73	79	62	69		
(17.0 cm)	59	67	73	61	57	64		
(72.8 cm)	65	74	89	93	64	70		
4 x 4 array B-3								
(45.2 cm)	77	70	-	-	59	55	-	-



P = ROD PITCH

A_o = ORIGINAL (UNSTRAINED) CROSS-SECTIONAL AREA OF ROD

A_f = FINAL (STRAINED) CROSS-SECTIONAL AREA OF ROD

$B(\%) = \frac{(A_f - A_o)}{(p^2 - A_o)} \times 100$ FOR ONE ROD (LOCAL BLOCKAGE)

$B(\%) = \frac{100}{n} \sum_{i=1}^{n} \frac{(A_{f_i} - A_o)}{(p^2 - A_o)}$ FOR A BUNDLE OF n RODS (TOTAL BLOCKAGE)

FIG. 1. GENERAL BLOCKAGE DEFINITION

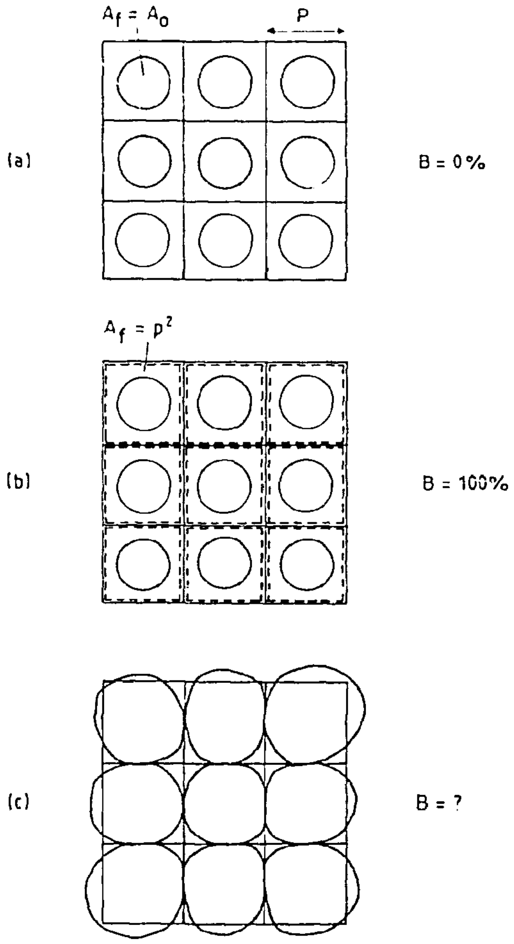
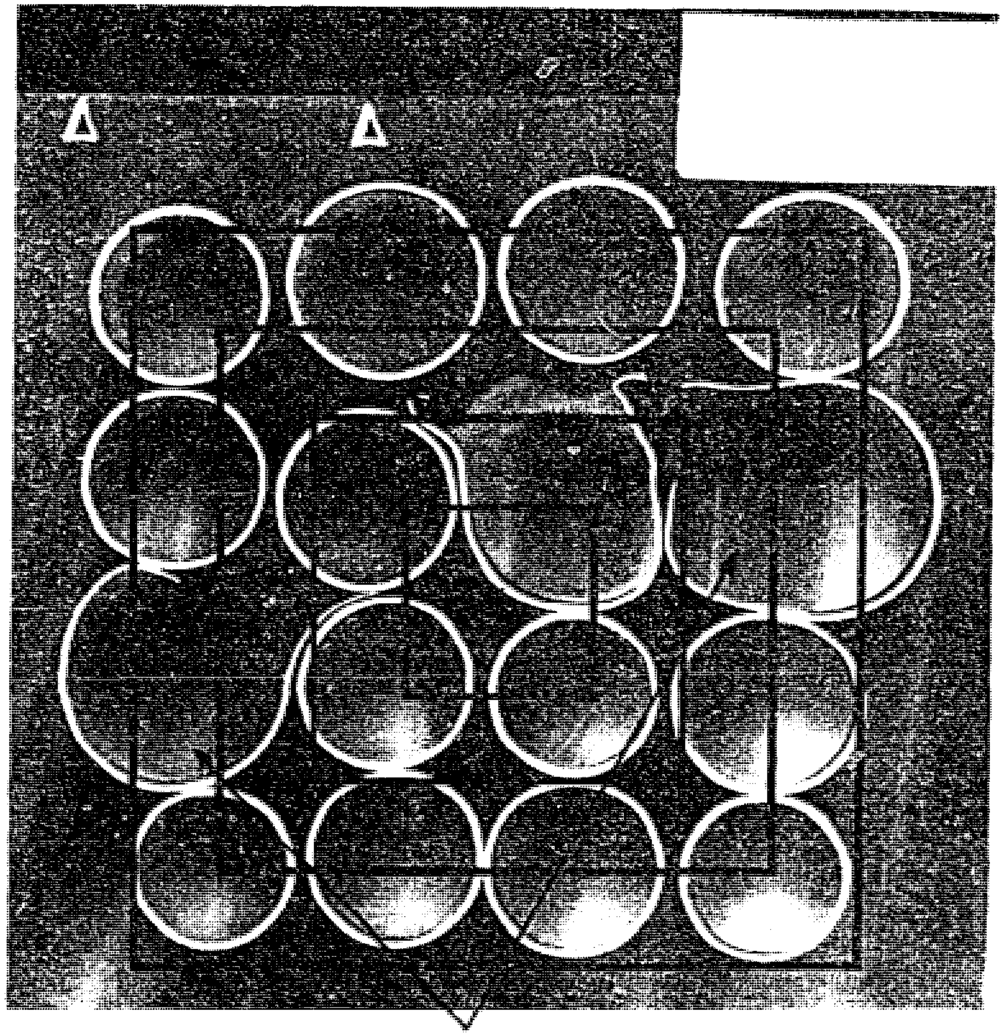


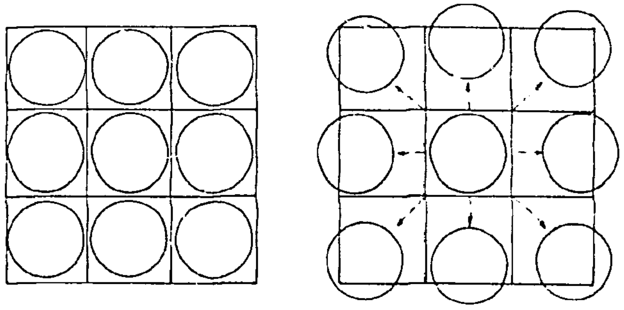
FIG. 2. EXAMPLES OF BLOCKAGE



LOCAL BLOCKAGE
OF > 100%

FIG. 3. CROSS-SECTION OF ORNL MRBT B-3[14] WITH
SUPERIMPOSED MASK

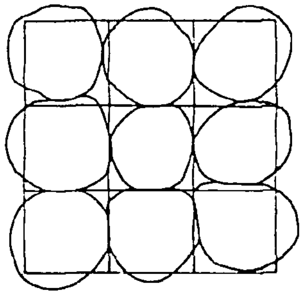
(a) ASSUME IDENTICAL ROD STRAIN IN EACH BUNDLE



RODS REMAIN ON THEIR LATTICES

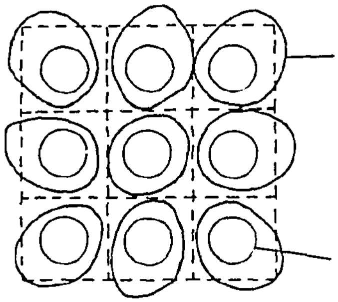
RODS NOT RESTRAINED-
AND MORE APART

BOTH GIVE THE SAME BLOCKAGE VALUE USING TOTAL AREA
METHOD BUT FLOW AREAS ARE OBVIOUSLY DIFFERENT

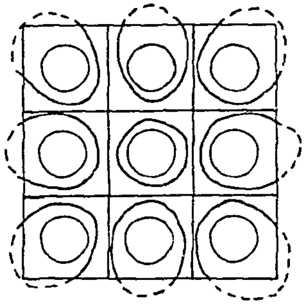


(b) TOTAL BLOCKAGE >100%

FIG. 4. DEFICIENCIES OF THE 'TOTAL AREA' METHOD

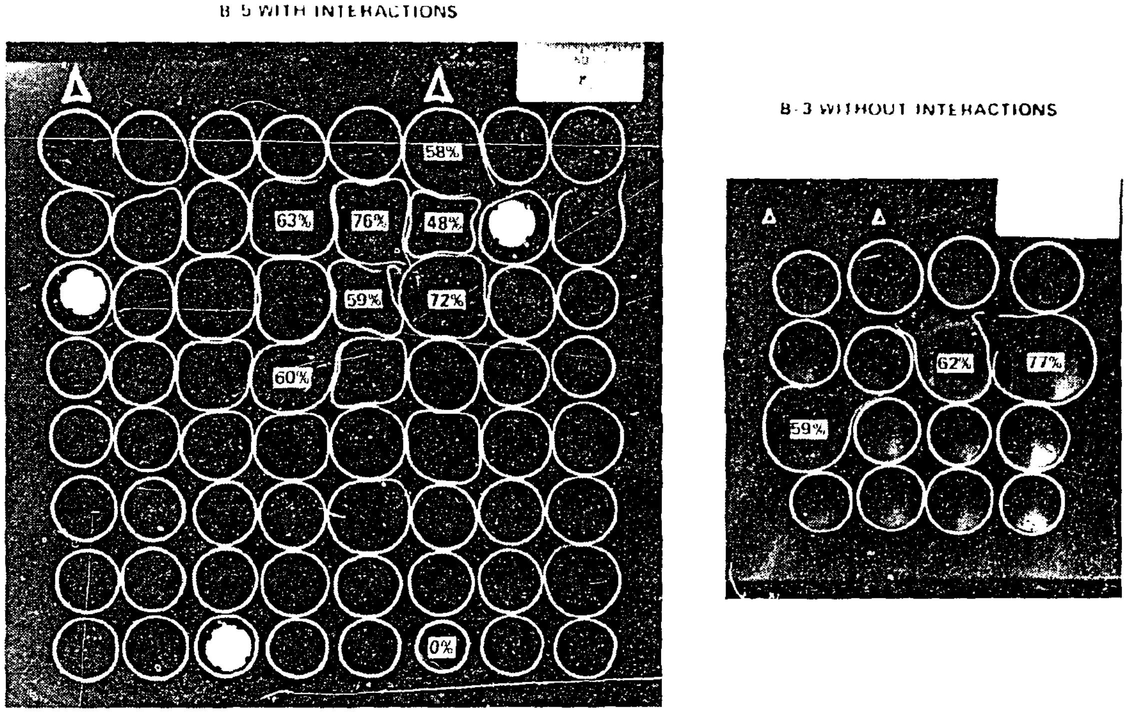


A TRANSPARENT 'MASK' REPRESENTING THE ORIGINAL LATTICE IS LAID OVER THE SPECIMEN



ONLY THE AREA INSIDE THE 'MASK' IS MEASURED
THIS ELIMINATES THE POSSIBILITY OF TOTAL BLOCKAGE > 100%

FIG.5.
'MASK' METHOD FOR MEASUREMENT OF BLOCKAGE


B-5 WITH INTERACTIONS

B-3 WITHOUT INTERACTIONS

FIG.6. CROSS-SECTIONS OF TEST BUNDLES FROM THE ORNL MULTI-ROD TEST PROGRAMME[16]

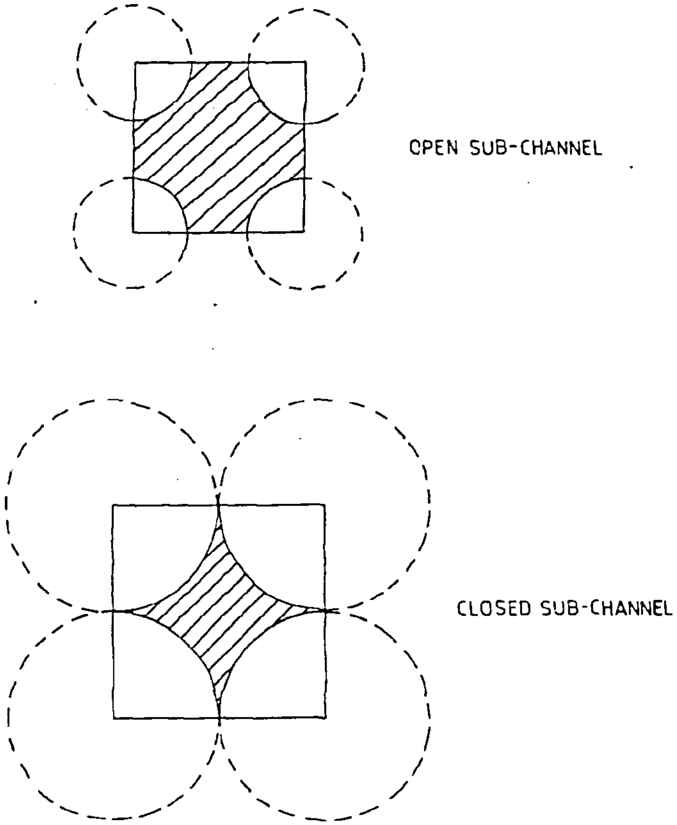
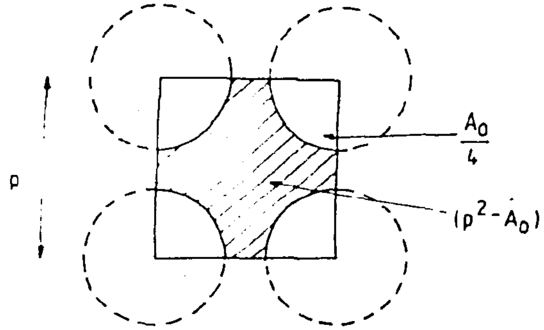


FIG.7.
'OPEN AND CLOSED' SUB-CHANNELS



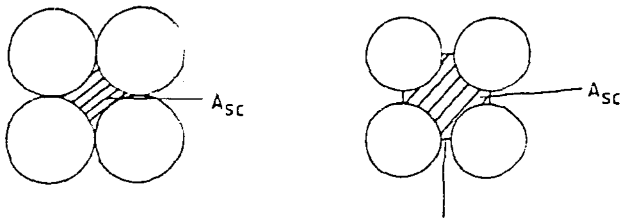
A_0 = ORIGINAL UNSTRAINED ROD CROSS-SECTIONAL AREA
p = INTER-ROD SPACING (PITCH)
A_{sc} = FINAL SUB-CHANNEL CROSS-SECTIONAL AREA
B_{sc} = SUB-CHANNEL BLOCKAGE (%)

$$B_{sc} = \left[1 - \frac{A_{sc}}{(p^2 - A_0)}\right] \times 100\,\%$$

FIG.8.
MATHEMATICAL DESCRIPTION OF SUB-CHANNEL BLOCKAGE

'CLOSED' SUB-CHANNEL

'OPEN' SUB-CHANNEL



BOUNDARY WHERE GAP BETWEEN SURROUNDING RODS IS NARROWEST

PARTIALLY CLOSED SUB-CHANNEL

LINKED SUB-CHANNELS

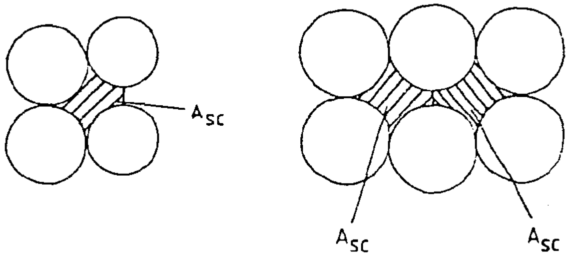
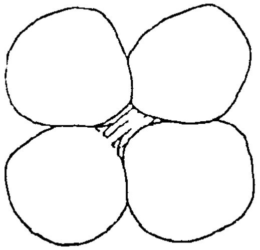


FIG. 9.

SUB-CHANNEL BOUNDARY

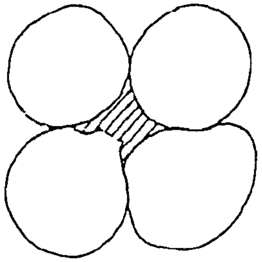
OPTION A - CORRESPONDS TO A MAXIMUM BLOCKAGE



1) APPROXIMATE THE SHAPE OF THE BURST ROD JUST PRIOR TO ITS BURSTING

2) MEASURE THE SUBSEQUENT AREA AND PERIMETER

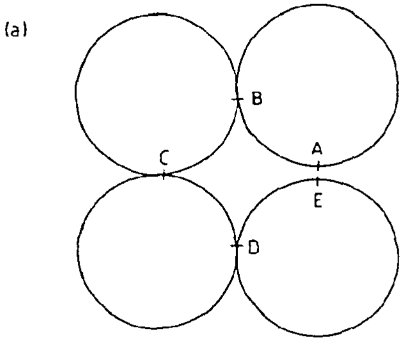
OPTION B - CORRESPONDS TO A MAXIMUM BLOCKAGE



1) JOIN THE ENDS OF THE BURST OPENING WITH A STRAIGHT LINE

2) MEASURE THE SUBSEQUENT AREA AND PERIMETER

FIG. 10. TREATMENT OF BURST 'FLARE OUTS'



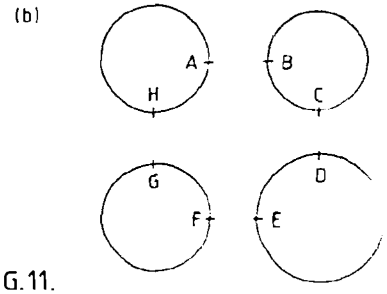
SUB-CHANNEL PERIMETER p_{sc} = ABCDE

ROD GAP g^1_{sc} = AE

AS PERCENTAGES

$$P_{sc} = \frac{p_{sc}}{\pi d} \times 100\% \quad \text{(d = ORIGINAL ROD DIAMETER)}$$

$$G^1_{sc} = \frac{AE}{(p-d)} \times 100\% \quad \text{(p = ROD PITCH)}$$



$p_{sc} = BC + DE + FG + HA$

g^1_{sc} = CD g^3_{sc} = HG

g^2_{sc} EF g^4_{sc} = AB

FIG. 11.

MEASUREMENT OF SUB-CHANNEL PERIMETERS AND ROD GAPS

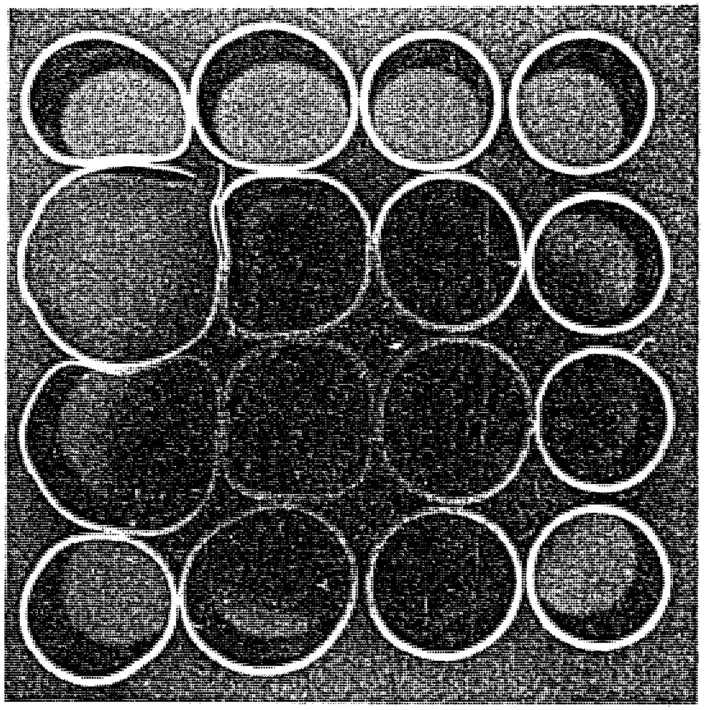


FIG. 12. CROSS-SECTION OF SNL MATERIALS TEST BUNDLE

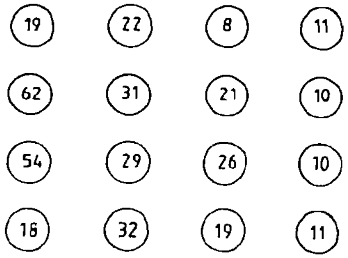
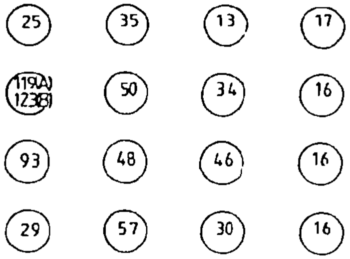


FIG. 13.
ROD STRAINS (%)



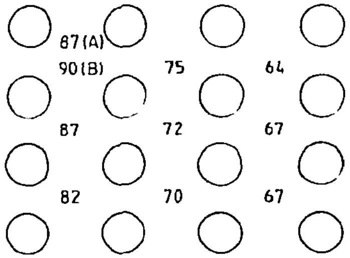
$$B\% = \frac{(A_f - A_0)}{(P^2 - A_0)} \times 100$$ - GENERAL BLOCKAGE DEFINITION

ROD No. 5 HAS A BURST OPENING AT THIS LEVEL

BLOCKAGE VALUE 'A' CORRESPONDS TO MINIMUM BLOCKAGE LIMIT

BLOCKAGE VALUE 'B' CORRESPONDS TO MAXIMUM BLOCKAGE LIMIT

FIG. 14. BLOCKAGE (%) - GENERAL DEFINITION (UNMASKED)

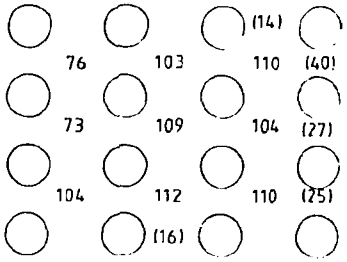


$$B_{sc} = \left[1 - \frac{A_{sc}}{(P^2 - A_0)}\right] \times 100\%$$

(A) CORRESPONDS TO MINIMUM BLOCKAGE

(B) CORRESPONDS TO MAXIMUM BLOCKAGE

FIG. 15.
SUB-CHANNEL BLOCKAGE (%)



$$\text{PERIMETER \%} = P_{sc} = \frac{p_{sc}}{\pi d} \times 100\%$$

$$\text{ROD GAP \%} = G'_{sc} = \frac{g'_{sc}}{(p - d)} \times 100\%$$

ROD GAPS ARE IN PARENTHESES WHERE NO GAP IS STATED THE RODS WERE TOUCHING

FIG. 16. SUB-CHANNEL PERIMETERS (%) AND ROD GAPS (%)