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# THE STUDY OF A MOCK-UP OF THE S.G.H.W.R. CORE IN DIMPLE

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1. Introduction.

A mock-up of the 100MW(E) SGHW prototype core has been taken critical in DIMPLE using 68 of the standard prototype boiling channels. The first approach to critical experiment was designed to simulate the initial start-up conditions of the prototype as closely as possible. This experiment is described, together with the subsequent measurements of buckling and core perturbation effects, and the results of the measurements are compared with theoretical predictions in section 2.

2. The DIMPLE mock-up of S.G.H.W.R.

The first measurements made in the DIMPLE core mock-up of the prototype S.G.H.W.R. have now been analysed. This core consists of 68 standard S.G.H.W.R. boiling fuel elements arranged in a similar configuration to that of the S.G.H.W.R. There is a central chequerboard of 20 x 1.24% and 20 x 1.56% elements, surrounded by an outer zone of 28 x 2.28% elements, as shown in Figure 1. This core differs from the S.G.H.W.R. in the following respects:

(i) The core contains 68 elements compared to the initial loading of 104 in S.G.H.W.R.

(ii) No experimental fuel elements are present in the initial DIMPLE core.

(iii) The initial DIMPLE core has no significant radial reflector.

The size of the DIMPLE core is governed by the size of the core tank (8' 6" D.) but it is large enough to provide a very accurate check of the calculational methods which will be used later in the analysis of the performance of the prototype. The effect of experimental fuel elements and the radial reflector will be studied in later versions of the DIMPLE mock-up core. This programme is outlined in SGHW/PWP/P(66)25[1].

3. Approach to critical experiment.

The first experiment was an approach to critical, simulating as closely as possible the approach which will be carried out with near zero boron concentration in S.G.H.W.R. To this end, perturbations which will be present in the S.G.H.W.R. at that stage were simulated in the DIMPLE core, and the source and detector positions were chosen to provide some information as the shape of the approach curves to be expected in the S.G.H.W.R..

The core layouts for DIMPLE and the S.G.H.W.R. are shown in Figures 1 and 2 respectively. The perturbations present in the DIMPLE core were:

(a) An empty pressure tube containing a K-tube (pulsed source) 3" O.D. x 17" long resting on the bottom of the pressure tube. The centre of the K-tube was about 5 cm. above the bottom of the fuel.

(b) Mock-ups of empty pencil loops in positions 009 and G13 (Figure 1). These consisted of an outer aluminium tube (I.D. 3.00", O.D. 3.25"), a stainless steel pressure tube, (I.D. 1.5", O.D. 1.875"), and an inner aluminium liner, (I.D. 0.4", O.D. 0.986").

(c) $BF_3$ counters positioned in empty search tubes in the moderator. The counters were standard 1" O.D. x 8.5" long counters of various sensitivities.

No simulation of the oscillator was included in this core, but a mock-up of the oscillator will be available later in the programme when a measurement will be made of its reactivity worth.

The source used was a Po/Be source with an activity of about 1.3 curies at the time of the measurement. The source and counters were both positioned 32 cm. above the bottom of the $UO_2$ (i.e. 60 cm. above the tank bottom). This hieght is just below the centre of the flooded portion of the fuel in DIMPLE when the moderator is at partial dump level (flooded height is 72 cm.) With this arrangement, meaningful approach curves are not obtained until both source and counters are inside the flooded region and the measured approach curves shown in Figure 3 indicate that significant results are not obtained until the $D_2O$ is at least 15 cm. above the source-detector plane. Above the DIMPLE partial dump level, (72 cm. of fuel flooded), all the counters give meaningful approach curves. The shapes of these curves vary with the separation of source and counter. The counter at the edge of the core gives an approach curve which is approximately linear from partial dump level onwards. Counters nearer the source in the centre of the core give curves which are successively less linear (due to direct source neutron effects), the extreme case being the counter 37 cm. from the source which consistently overestimates the critical height until the last stages of the approach.

The counter positions proposed for S.G.H.W.R. are shown in Figure 2. On the basis of the DIMPLE experiment it appears probable that the curves obtained from the counter 2 pitches from the source in the centre of the core will substantially overestimate the critical height until k-eff reaches about 0.98. The counter near the edge of the core should produce a much more satisfactory approach curve, giving reasonable estimates of the critical height at an early stage in the approach.

4. Reactivity worths of core perturbations.

Subsequently the reactivity worths of the various perturbations were determined by measuring the change in critical height and the height coefficient of reactivity as each perturbation was removed. The results of these measurements are given in Table 1 below.

Table 1. Effects of perturbations on reactivity worths of S.G.H.W.R. mock-up

| | |
|---|---|
| (i) Reactivity change when pencil loops were removed from core (O 09 and G13) | +(0.56 ± 0.02)% |
| (ii) Reactivity change when standard empty moderator displacement tubes placed in O 09 and G13 | -(0.08 ± 0.01)% |
| ∴ (iii) Reactivity change when pencil loops replaced by displacement tubes | +(0.48 ± 0.02)% |
| (iv) Reactivity change when pressure tube containing K-tube is removed from J10 and replaced by a 1.24% fuel element | +(0.75 ± 0.03)% |
| (v) Reactivity change on insertion of single $BF_3$ counter (12 EB 40) in the centre of the core (position K11) at a height of 42 cm. above the bottom of the fuel. | -(0.07 ± 0.01)% |

The errors quoted on the measured reactivity changes are random errors. Systematic errors of up to ± 5% due to uncertainty of delayed neutron data may be present. The worth of the two pencil loop mock-ups in DIMPLE has been calculated using JANUS and ZADOC. The calculated value of 0.47% agrees well with the measured value of 0.48 ± 0.02%.

## 5. Critical axial buckling of mock-up core in clean condition (Core SGM1).

After removing the perturbations in the first core, axial flux scan measurements were made and an axial buckling obtained. This buckling has been used in ZADOC to obtain an eigenvalue using the cross-sections and other data tabulated in Appendix 1.

| | |
|---|---|
| Flooded height of fuel (with $H_2O$ coolant at 20°C. and no boron) | 109.67 cm. |
| Axial buckling | 4.75 ± 0.05 $m^{-2}$ |
| Eigenvalue (k-eff) | 1.006 ± 0.001 |

This eigenvalue is in excellent agreement with those for $UO_2$ fuel given in section 5 of reference 2, which refer to uniform cores rather than chequer-boards. For this SGM1 core, the radial distribution has been calculated by ZADOC and thus any error in the calculated effective radial buckling will produce an equivalent error in the eigenvalue. Analysis of the six chequer-board cores studied in the earlier DIMPLE programme[2] indicates that ZADOC underestimated the effective radial buckling in every case, the discrepancies varying from 0.1 to 0.4 $m^{-2}$. Similar analysis will be applied to this core, but it is possible that when the calculated radial distribution is corrected to the measured radial distribution, the eigenvalue may be increased by a small amount.

## 6. Void coefficient of the mock-up core.

Critical height and reactivity change with height measurements have been made with the coolant changed to 25 : 75 wt.% $D_2O/H_2O$ mixture (core SGM2) and to 50 : 50 wt.% mixture (core SGM3). The measurements of reactivity change with height ($d\rho/dh$) are compared with ZADOC predictions in Table 2 below.

Table 2. Critical height and height coefficient

| Core | Coolant | | Critical moderator height hc. (from bottom of fuel) | $d\rho/dh$ of critical core %/cm. | |
|---|---|---|---|---|---|
| | $D_2O$ wt. % | $H_2O$ wt. % | | Experiment | ZADOC |
| SGM1 | - | 100.0 | 109.67 | 0.136 ± 0.003 | 0.165 |
| SGM2 | 25.2 | 74.8 | 111.83 | 0.139 ± 0.003 | 0.164 |
| SGM3 | 50.2 | 49.8 | 117.02 | 0.137 ± 0.002 | 0.156 |

The ZADOC prediction of $d\rho/dh$ decreases slightly with increasing moderator height (as expected) whereas the measured values are constant within the experimental errors. The calculated absolute values are significantly greater than the measurements, as has been observed previously in a wide range of experimental cores. Part of the discrepancy is due to the underestimate of critical height by ZADOC.

The measured increase in critical height on introducing $D_2O$ into the coolant may be used with the values of $d\rho/dh$ from Table 2 to check the ZADOC prediction of void coefficient. In view of the significant changes in core composition involved, care must be taken to define the reactivity change in terms of the parameters of one particular core, e.g. using a one-group expression and assuming a constant radial buckling

$$\frac{d\rho}{dh} = -\frac{2\pi^2 M_z^2}{k\text{-inf}} \left(\frac{1}{h}\right)^3 \qquad (1)$$

where $M_z^2$ is the axial migration area, and

h is the extrapolated height of the core.

If the critical core heights before and after the addition of $D_2O$ to the coolant are $H_A$ and $H_B$ respectively, expression (1) above can be integrated to give:

$$\rho_A - \rho_B = -\frac{H_B^3}{2} \left(\frac{d\rho}{dh}\right)_B \left\{\frac{1}{H_A^2} - \frac{1}{H_B^2}\right\} \qquad (2)$$

or $$\rho_A - \rho_B = -\frac{H_A^3}{2} \left(\frac{d\rho}{dh}\right)_A \left\{\frac{1}{H_A^2} - \frac{1}{H_B^2}\right\} \qquad (3)$$

Expressions (2) and (3) are not equivalent since (2) refers to reactivity defined in terms of core B, while (3) refers to reactivity defined in terms of core A parameters. The measured reactivity changes in core SGM1 have therefore been compared with theoretical predictions by treating separately the reactivity scales obtained from the $d\rho/dh$ measurements in the three different cores.

Table 3. Comparison of measured and predicted reactivity changes with coolant composition

| Core | Coolant | | $\rho \times 10^2$ | | |
|---|---|---|---|---|---|
| | | | Scale based on SGM1 | Scale based on SGM2 | Scale based on SGM 3 |
| SGM1 | $H_2O$ | Expt.<br>Theory | 0.000<br>0.000 | $-0.307 \pm 0.020$<br>$-0.267$ | $-1.080 \pm 0.025$<br>$-1.031$ |
| SGM2 | Exp $D_2O/H_2O$ | Expt.<br>Theory | $+0.287 \pm 0.020$<br>$+0.259$ | 0.000<br>0.000 | $-0.745 \pm 0.022$<br>$-0.685$ |
| SGM3 | 50/50% $D_2O/H_2O$ | Expt.<br>Theory | $+0.925 \pm 0.028$<br>$+0.952$ | $+0.681 \pm 0.024$<br>$+0.717$ | 0.000<br>0.000 |

These comparisons can then be interpreted in terms of the overall core void coefficient as shown in Table 4 below.

Table 4. Void coefficient in SGHWR mock-up in DIMPLE (20°C. Zero boron)

| | SGM1 reactivity scale | SGM3 reactivity scale |
|---|---|---|
| Experiment | $- 0.016 \pm 0.001$ | $- 0.018 \pm 0.001$ |
| ZADOC | $- 0.016$ | $- 0.018$ |

The agreement between theory and experiment is very satisfactory.

## 7. Conclusions.

7.1 A mock-up of the 100 MW(E) S.G.H.W.R. prototype core has been taken critical in DIMPLE using 68 of the 104 standard boiling channels. The first approach to critical experiment was designed to simulate the initial start-up condition of the prototype with a near zero boron content in the $D_2O$ moderator. It has been shown that with the neutron source and detector positions proposed for the prototype start-up, sensible critical approach curves will be obtained when the $D_2O$ moderator is 18 cm. above the source-detector plane, from counters situated some distance from the neutron source. A counter only 37 cm. from the source was significantly affected by direct source neutrons and was found to overestimate the critical height until the last stages of the approach experiment.

7.2 The reactivities associated with pencil loops, moderator displacement tubes, a K-type pulsed source tube and a $BF_3$ counter were measured and are reforded in Table 1.

7.3 After all the perturbations had been removed, the axial buckling of the clean core (SGM1) with $H_2O$ coolant was determined. This buckling was used in a ZADOC core calculation based on the physical and cross-section data listed in Appendix I and found to give an eigenvalue of 1.006 ± 0.001.

7.4 The coolant in all 68 channels was changed to 25/75 wt.% $D_2O/H_2O$ (core SGM2) and then to 50/50 wt.% $D_2O/H_2O$ (core SGM3), and the critical height and reactivity change with height measured at each stage. These measurements have been interpreted to give an average core void coefficient of − 0.017 ± 0.001 in agreement with the ZADOC prediction.

## LIST OF REFERENCES


1. Experimental physics programme for the study of a mock-up of the S.G.H.W. prototype in DIMPLE.

   A. J. Briggs, I. Johnstone — SGHW/PWP/P(66)25

2. The measurement of radial buckling in DIMPLE.

   C.-E. Wikdahl — AEEW - R 503

## APPENDIX 1

### Data used in the METHUSELAH/ZADOC calculations for the S.G.H.W. mock-up experiments in DIMPLE

The mock-up experiments are designed to duplicate the prototype situations as closely as possible. The emphasis is on providing a final check of the methods of calculation which will be used on the prototype and hence it is essential that the data used in such calculations should be the same as those used for the fuel management scheme.

A discussion of the cross-sections used in the METHUSELAH library is given in AEEW - R.397. The more important 2200 m/s cross-sections are given in Table A1.1 below.

Table A1.1. 2200 m/s cross-sections used in METHUSELAH

| | U-235 | U-238 | Pu-239 | Pu-241 |
|---|---|---|---|---|
| $\sigma_a$ | 683.7 | 2.718 | 1025.3 | 1401.4 |
| $\sigma_f$ | 582.0 | - | 738.9 | 965.1 |
| $\eta$ | 2.074 | - | 2.091 | 2.10 |
| $\nu$ | 2.438 | - | 2.901 | 3.05 |

The nominal fuel enrichments have been used as with calculations for the S.G.H.W. prototype. The major differences between the mock-up and prototype cores are that the zircaloy pressure tube has been replaced by an aluminium tube, and the displacement tube is 50% thicker in DIMPLE. For the prototype calculations, a zircaloy composition of 98.275% zirconium, 1.5% tin, 0.125% iron and 0.1% chromium is used. Assuming the METHUSELAH values of cross-section, F.R. Allen has computed the effective cross-section of the zircaloy in the GLEEP spectrum and has obtained 0.00164 $cm^2/gm$, of which 0.00029 is epithermal contribution. This agrees with the GLEEP swing value of 0.00165 ± 0.00002 $cm^2/gm$.

The nominal composition of the aluminium is 0.3% iron, 99.5% aluminium and 0.2% silicon. The 2200 m/s value for this nominal composition is 0.00520 $cm^2/gm$. The GLEEP swings give 0.00513 ± 0.00005 $cm^2/gm$ for the pressure tube, 0.00523 ± 0.00005 $cm^2/gm$ for the calandria tube and 0.00510 ± 0.00005 $cm^2/gm$ for the displacement tube. The results are standardised against a pure aluminium sample. Errors in the epithermal component are thus negligible. An error of 1% in the zircaloy cross-section gives an error of about 0.004% in reactivity. An error of 1% in the aluminium cross-section gives an error of about 0.08% in reactivity.

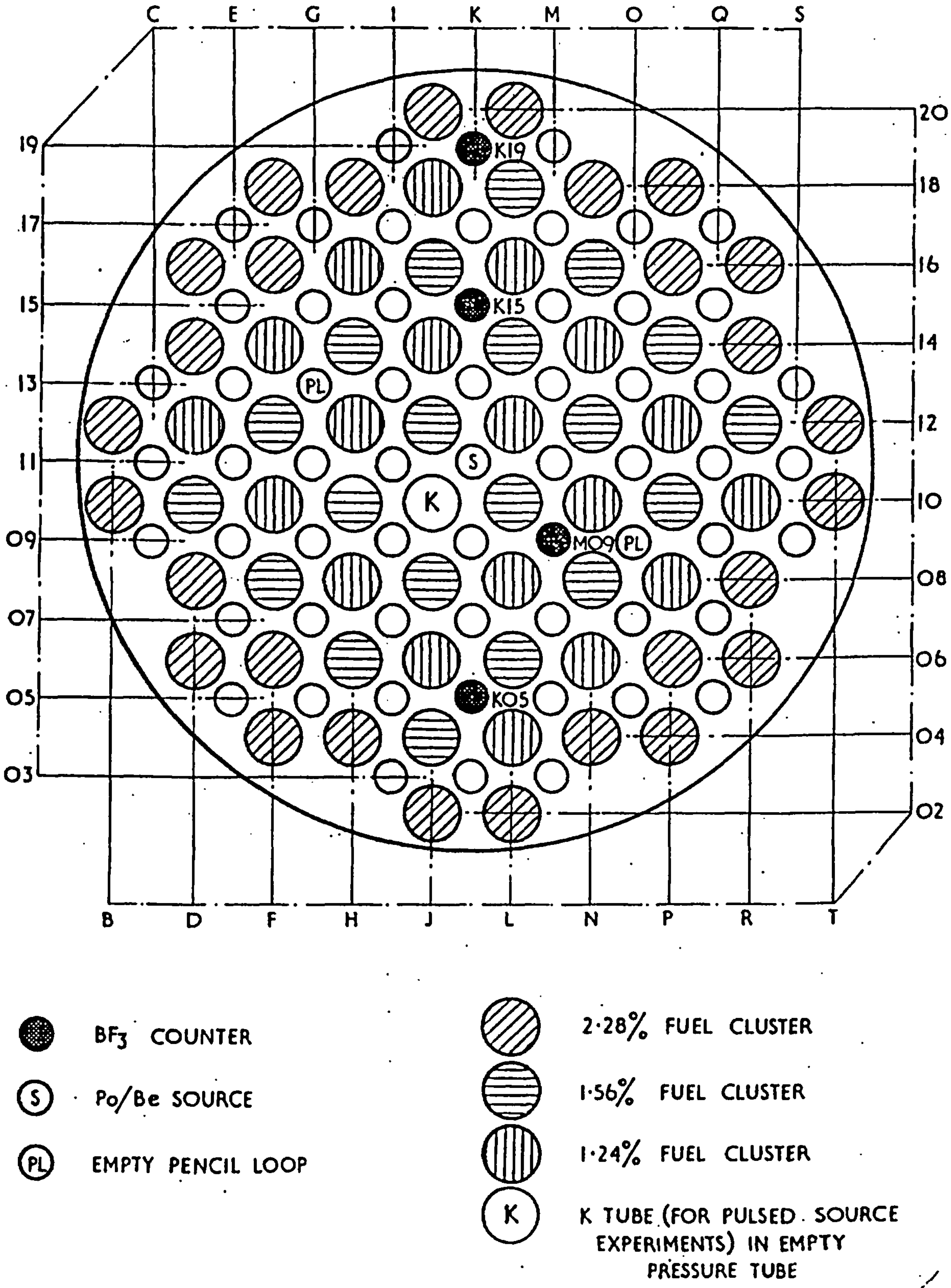
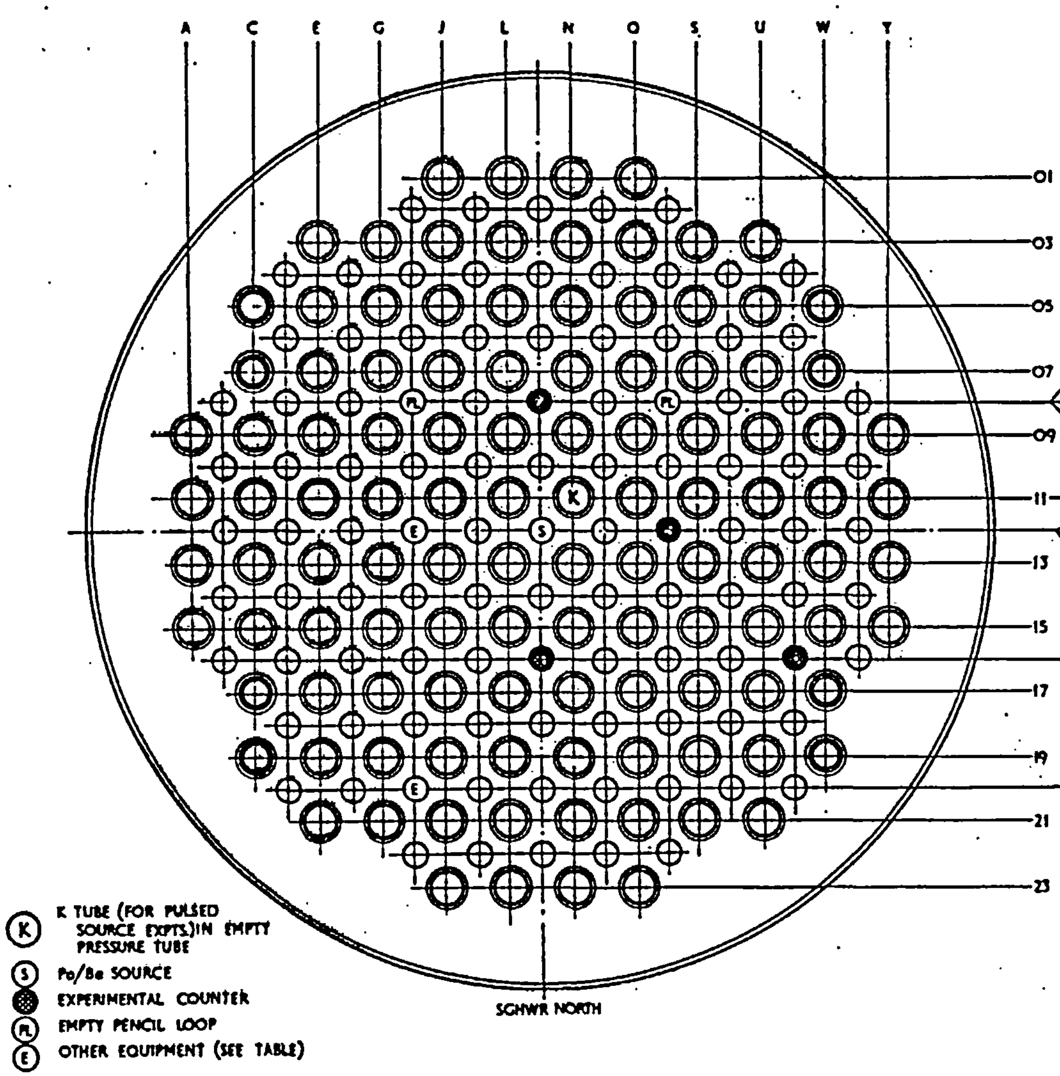



FIGURE 1. CORE SGM 1 – CORE STATE FOR APPROACH TO CRITICAL EQUIPMENT




| EQUIPMENT | EXPL. OR PROTECTION | LOCATION | IN USE: Z.E. COLD | IN USE: Z.E. HOT |
|---|---|---|---|---|
| 1 S.D. ION CHAMBER<br>2 FISSION COUNTERS<br>2 PROPORTIONAL CTRS. | P | H08 | YES<br>YES<br>YES | YES<br>YES<br>YES |
| 1 FISSION COUNTER<br>1 PROPORTIONAL CTR. | E | M08 | YES<br>YES | YES<br>NO |
| 2 SD ION CHAMBERS<br>1 FISSION CTR.<br>1 PROPORTIONAL CTR. | P | P08 | YES<br>YES<br>YES | YES<br>YES<br>YES |
| PULSED NEUTRON SOURCE | E | N11 | YES | NO |
| REACTIVITY OSCILLATOR | E | H12 | YES | NO |
| 1 FISSION COUNTER<br>1 PROPORTIONAL CTR. | E | R12 | YES<br>YES | YES<br>NO |
| Po/Be SOURCE | P | M12 | YES | YES |
| 1 FISSION COUNTER<br>1 PROPORTIONAL CTR. | E | M16 | YES<br>YES | YES<br>NO |
| 1 FISSION COUNTER<br>1 PROPORTIONAL CTR. | E | V16 | YES<br>YES | YES<br>NO |
| B.C.C. ION CHAMBER | E | H20 | | |

EQUIPMENT IN CORE DURING Z.E.
(FROM SGHW/CP27(6))

FIGURE 2. SGHWR PROTOTYPE CORE PLAN

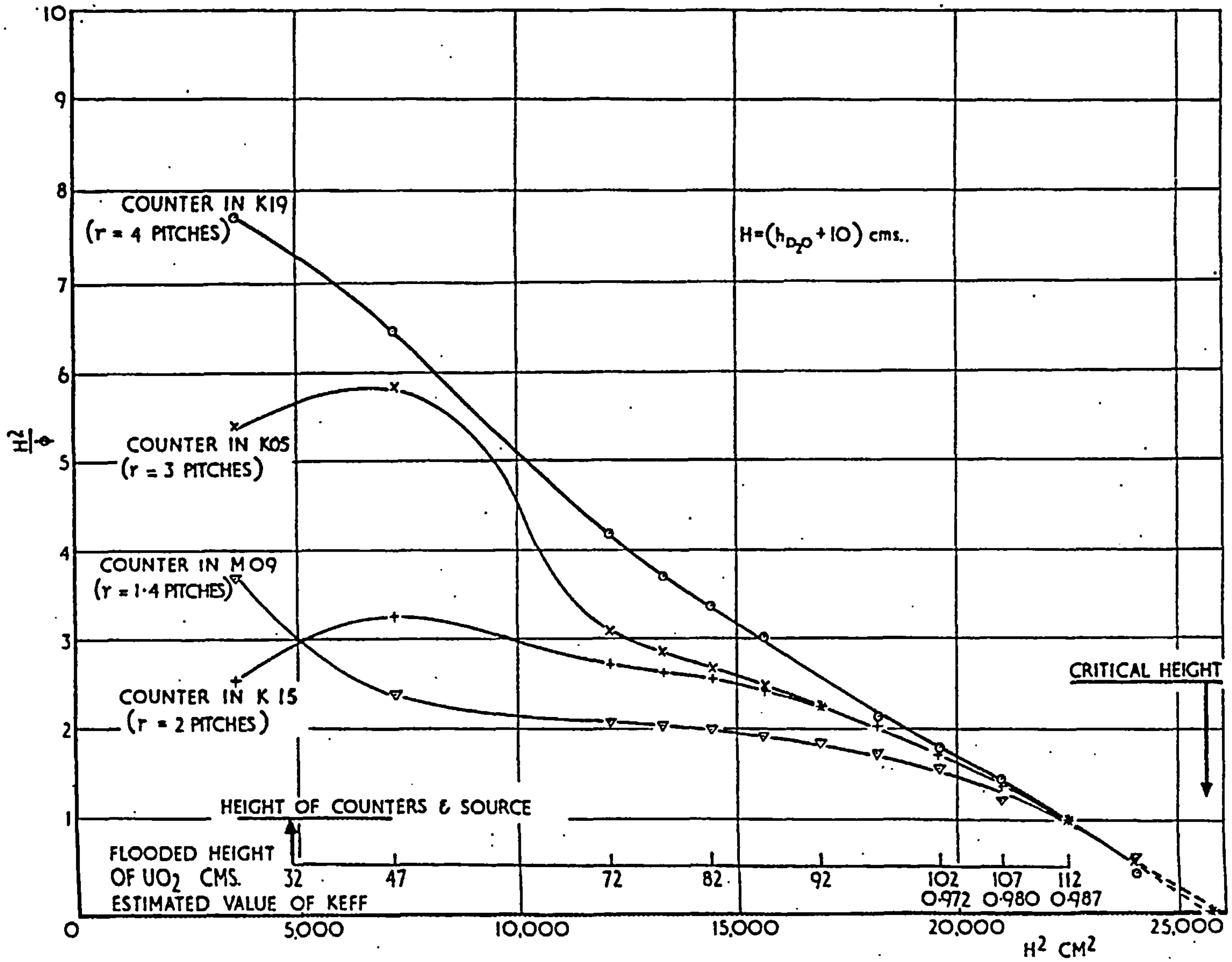



FIGURE 3. APPROACH CURVES DIMPLE CORE SGM I