AAEC/E233

AAEC/E233

AUSTRALIAN ATOMIC ENERGY COMMISSION

RESEARCH ESTABLISHMENT
LUCAS HEIGHTS

URANIUM SILICIDE FUEL ELEMENTS IN HEAVY WATER MODERATED NATURAL URANIUM REACTORS

by

D.B. McCULLOCH
J.H. WHITFIELD

July 1972

ISBN 0 642 99473 0

AUSTRALIAN ATOMIC ENERGY COMMISSION

RESEARCH ESTABLISHMENT

LUCAS HEIGHTS

URANIUM SILICIDE FUEL IN HEAVY WATER MODERATED NATURAL URANIUM REACTORS

by

D. B. McCULLOCH

J. H. WHITFIELD

ABSTRACT

Some aspects of using natural uranium silicide fuel elements in heavy water moderated reactors are studied with particular attention to reactivity limited fuel burnup. Both pressurised heavy water cooled and boiling light water cooled reactor types are considered. It is shown that with suitable redesign of the fuel element and/or pressure tube geometry to take advantage of the thermal properties of U_3Si, substantial improvements in fuel burnup may be expected in comparison with similar UO_2 fuelled reactors.

National Library of Australia card number and ISBN 0 642 99473 0

The following descriptors have been selected from the INIS Thesaurus to describe the subject content of this report for information retrieval purposes. For further details please refer to IAEA–INIS–12 (INIS: Manual for Indexing) and IAEA–INIS–13 (INIS: Thesaurus) published in Vienna by the International Atomic Energy Agency.

BURNUP; BWR TYPE REACTORS; COOLANTS; FUEL CHANNELS; FUEL ELEMENT CLUSTERS; FUEL RODS; GEOMETRY; HEAT TRANSFER; NATURAL URANIUM REACTORS; NUCLEAR FUELS; PHWR TYPE REACTORS; PRESSURE TUBES; REACTIVITY; REACTOR LATTICE PARAMETERS; REACTOR LATTICES; URANIUM SILICIDES

CONTENTS

1. INTRODUCTION

It has been suggested (e.g. Pon et al. 1964) that replacement of UO_2 by a fuel material having a higher uranium density could lead to significant reductions in power generation costs for natural uranium heavy-water moderated reactors. The savings were claimed to arise primarily from increased reactivity which permits longer fuel lifetimes, although some of the potential gain in this area might in practice be traded for improved control characteristics, greater operational flexibility, or design for greater integrity in fuel and core structure.

There is general acceptance that the obvious high-density fuel candidate, uranium metal, is unsuitable for this type of reactor owing to its very high corrosion rate in high temperature ($\sim 300^{\circ}C$) water, which would lead to severe circuit-contamination problems in the event of any fuel cladding failures. Uranium silicide, U_3Si, has been suggested as a possible alternative combining a reasonably high uranium density (~ 15 g cm^{-3}) with reasonably low parasitic absorption by the alloying elements, and having good corrosion resistance, high thermal conductivity and adequate high temperature stability.

The purpose of the study reported in the present paper is to examine briefly the reactor physics advantages which might be obtained from the use of U_3Si fuel elements in both boiling light water cooled (BLW) and pressurised heavy water cooled (PHW) heavy water moderated reactor systems. The study was not intended to be exhaustive, and no attempt at optimisation, either nuclear or economic, has been made. Rather a reactor physics comparison has been made of U_3Si and UO_2 fuels in similar reactor types on the basis of a few simple, and it is hoped well-chosen, ground rules. The calculations were made using the METHUSELAH scheme of lattice calculations for liquid moderated reactor cells (Alpiar 1964, Brinkworth and Griffiths 1966).

2. URANIUM SILICIDE

It appears unlikely that the entirely pure U_3Si phase of the U-Si complex has ever been studied experimentally. Materials data are therefore rather uncertain and sparse. Bardsley (1968), in his review of the U-Si system lists some data for U_3Si, which we have used in this study, and which agree well with data given by Chalder et al. (1967).

It should be noted that:

a) the tetragonal/cubic phase transition probably occurring at $\sim 765^{\circ}C$ was assumed to be of no consequence. A maximum fuel centre temperature of $\sim 875^{\circ}C$, that is $\sim 50^{\circ}C$ below the peritectoid decomposition temperature was accordingly taken as acceptable;

b) practical densities of 14.94 g cm^{-3} and 15.42 g cm^{-3} were assumed for U_3Si in BLW and PHW reactor studies respectively. These may be somewhat pessimistic, but in the absence of reliable data, it was felt that similar ratios between practical and theoretical densities as those applying to UO_2 fuels in the corresponding reference reactor designs formed a reasonable assumption. These density reductions could be regarded as providing some voidage allowance which might prove necessary to accommodate swelling resulting from irradiation damage and fission product gas release;

c) the heat transfer data used are given in the Appendix.

3. BLW-HWM REACTOR APPLICATIONS

Studies of natural uranium fuelled heavy water moderated reactors with boiling light water coolant such as the Natural Uranium Steam Generating Heavy Water Reactor (NSGHWR) and the CANDU Boiling Light Water Reactor (CBLWR) have shown the necessity for rather severe technology extrapolations to compensate their inherently low excess reactivity margins, and consequently shortened fuel reactivity lifetimes. The reactivity penalty is due mainly to parasitic neutron absorption in the light water coolant, and also to increased ^{238}U resonance absorption.

The direct coolant absorption alone accounts for some 3 per cent in reactivity, even for the as yet little-tested technology of small clearances between fuel pins and very low channel average coolant densities assumed in these designs. The positive void coefficients of reactivity remain large, and pose severe safety and control problems which will probably be tractable only because of the long thermal time constants associated with rather large diameter pins of the comparatively poorly heat-conducting UO_2.

The UO_2 fuel elements for these reactors are designed to be limited simultaneously by maximum permissible centre temperature and by tolerable surface heat flux burnout margins. The channel design is therefore closely associated with the properties of UO_2, and it is unlikely that the full potential benefit from the use of U_3Si will be achieved by mere direct substitution for UO_2 in the same channel geometry, involving as it must, a reduction in fuel rating without compensating savings in the number of fuel pins to be fabricated or number of channels for a given reactor power. The improved temperature and thermal conductivity characteristics of the U_3Si are in this case poorly utilised, and control problems are severely aggravated, since the positive void coefficients of reactivity are only slightly reduced, whilst the fuel thermal time constants are an order of magnitude faster.

It is therefore clear that complete redesign of the fuel channel is required to take advantage of the thermal properties of U_3Si. In an earlier less general study (McCulloch and Hesse, unpublished) an incentive was indicated for use of U_3Si rods larger in diameter than the UO_2 rods of the reference design, provided this could be accommodated within practical coolant conditions while maintaining reasonable fuel ratings. Only simple considerations of peak local surface heat flux were used to assess fuel-coolant heat transfer feasibility and this is superseded in the present work by channel burnout calculations based on the Barnett (1965) correlations for rod clusters.

Rod diameters and fuel rating are varied in such a way that the central temperature limitations of the U_3Si is not exceeded. The coolant conditions are then adjusted to give sensible mass flow and pressure drop conditions, whilst maintaining the same steam exit quality as, and not too different burnout margins from the reference UO_2 design. This is a more practical approach to the rating/burnout/pressure drop problem than that used in the previous study, although the burnout margin was somewhat flexibly treated since the uncertainties of the correlation for changing geometries may be such that fully reliable results could be guaranteed only by direct experimental tests. For this reason, also, some movement outside Barnett's correlated range of heated and hydraulic diameters was permitted in some cases. It must be stressed that the conclusions of the study depend on the premise that the reasonable trends in dry-out margins indicated by the correlation used will be attainable in practice.

4. PHW REACTOR APPLICATIONS

The potential sources of improved reactor physics performance are perhaps less evident in this application than in the case of the boiling light water cooled system. A priori, the gains in reactivity would seem likely to be less, since parasitic absorption in the lattice cell, particularly in the coolant, is already small. However, the higher uranium density in the fuel could be expected to lead to some gain in reactivity through increased fast fission and reduced resonance capture in ^{238}U. A further gain in these areas may again result from the thermal properties of U_3Si permitting larger diameter rods than can be used with UO_2. In this reactor, there are no problems arising from high positive power coefficients with coolant voiding, and channel burnout is less of a problem than in the BLW reactor. Direct substitution of U_3Si fuel could possibly therefore lead to improved economics by allowing the power output per pressure tube to be increased.

5. CALCULATIONS

Some features of the calculations are common to both the BLW and PHW reactors, and should be noted as follows:

Burnup was calculated in all cases to $\int (k_{eff} - 1)\, dt = 0$. This is equivalent to assuming infinite fuel shuffling, with no allowance for any operational reactivity requirements. The resulting burnup figures are therefore maximum values, and may exceed, perhaps by the order of some 1,000 MWd/te, those achievable in practical operation. A buckling of 6.6×10^{-5} cm^{-2} was assumed for all BLW lattices, and 9.6×10^{-5} cm^{-2} for the PHW lattices. These values are typical of power reactors of these types. A radial power form factor of 1.2 was used in all cases.

The calculations were made with the METHUSELAH II scheme and a number of ground rules were assumed as follows:

(i) All U_3Si lattices have the same heavy water investment per MW sent out as the appropriate UO_2 reference lattice. A few cases were also run in which the lattice pitch was adjusted to keep the power output per unit core volume constant instead. The changes in burnup so produced were negligible.

(ii) Fuel element cladding throughout is of the same thickness as the appropriate UO_2 reference design.

(iii) The calandria tube thickness is proportional to diameter; the pressure tube thickness varies with both diameter and inlet pressure, and incorporates a corrosion allowance of 0.15 cm.

(iv) The insulating gap (pressure tube to calandria tube) is constant.

(v) The practical density for U_3Si was taken as the same fraction of theoretical density as for the UO_2 density of the appropriate reference design. This course leaves some allowance for thermal expansion or fission product release.

It should be noted that there are some areas in which the METHUSELAH II scheme has shortcomings. Fast fission may be incorrectly estimated for light water cooled clusters compared with heavy water cooled ones even though the ^{238}U fast cross-sections recommended by Hicks and Hopkins (1967) have been used in the appropriate way. The relation between the BLW set and the PHW set of calculations may therefore be incorrect, although the within-set comparisons are probably adequate. However, the scheme is still entirely untested against any U_3Si experimental reactor physics data, which as far as we are aware do not exist. There is also some evidence from comparison with experimentally determined irradiated fuel isotopic compositions that the reactivity lifetimes given by METHUSELAH II may be low, and should therefore be regarded as suitable

for intercomparison only, rather than as absolute values.

5.1 BLW-HWM Lattices

The performance of the U_3Si fuelled reactor lattices is, in all cases, compared with that of a natural UO_2 reference design, the principle features of which are given in column A of Table 1. These parameters were current at some stage of the joint UKAEA/AAEC design study, and although reasonable do not necessarily represent the optimum configuration for this type of reactor.

The axial power profile, and the radial form factor for this reference design were used in a cluster fuel element heat transfer programme PABOIC (Power And Burn-Out In Clusters - see Appendix) to investigate temperature profiles and burnout margins in a number of U_3Si cluster-cum-channel geometries. The limiting centre fuel temperature for any axial position in the peak rated pin of the peak rated reactor channel was set nominally at 875°C. The inlet enthalpy of the coolant and the exit steam quality were kept sensibly the same as the reference design, and the mass flow and coolant area adjusted to give reasonable pressure drops and acceptable (within the terms of Section 3) burnout margins in the peak channel.

The cluster and channel configurations given in Table 1 were selected from this survey for burnup calculations on the following bases:

Clusters B and C are of identical geometry to the reference UO_2 design. In B, the reactor average fuel rating is reduced to maintain the same channel power, surface heat fluxes, burnout margins, etc. as the reference design. The U_3Si temperatures are therefore low throughout. In C, the rating was retained at the reference design value, with consequent increases in heat fluxes and channel power, and a reduction in burnout margin.

Clusters D, E, F and G are all of 18-rod geometry, since it was clear that the temperature/conductivity properties of U_3Si were such that comparable channel powers to the UO_2 reference design could be obtained from only 18 U_3Si rods with similar fuel ratings. Since there are also some advantages in retaining an already proven production pressure tube, these four clusters were arranged in the reference design pressure tube whilst the rod diameter and fuel rating were varied together with the flow conditions so that the nominal 875°C maximum temperature was approximately attained at the centre of the peak rod of the peak cluster, and the channel exit quality was held constant. Cluster D has the maximum pin diameter which can be accommodated in this pressure tube whilst maintaining pin-pin gaps etc. as for the reference design. Although the calculated burnout margin is smaller than for the reference design (1.22 compared with 1.33) this does not necessarily make the design impracticable for

reasons as discussed above. The remaining clusters illustrate the effect of reducing rod diameter and increasing rating in a fixed pressure tube.

Cluster H is again of 18 rods, but in a smaller diameter pressure tube. The fuel rating is the same as for the UO_2 reference design, and the rod diameter is such that the peak pin of the peak cluster has a maximum centre fuel temperature close to 875°C. The pressure tube diameter is chosen so that the pin-pin gaps etc. of the reference design are maintained, and flow conditions are adjusted for the same exit quality. The burnout margin is now only 1.09, but the case is retained as representing the limiting condition for an 18-rod cluster at the reference design fuel rating.

For each of the channels considered, the pressure and calandria tube thicknesses were adjusted in accordance with the ground rules, maintaining the gap between them constant. The lattice pitch was then calculated to give the same D_2O investment per unit channel power as the reference UO_2 design, and the appropriate METHUSELAH II calculation, with burnup, executed.

Finally, to indicate the improvement which might be available by substituting a suitable U_3Si fuel element in an already fixed UO_2 reactor lattice, Case J is a re-run of Case E, with the lattice pitch reduced to that of the reference UO_2 design.

The results of all the BLW reactor calculations are given in Table 2.

5.2 PHW Lattices

The reference natural UO_2 reactor with which the U_3Si lattices are compared is in this case the Canadian 'Pickering' reactor, the principal features of which are given in column A1 of Table 3. The axial power profile and radial form factor for this reactor were used in an alternative option of the PABOIC code to investigate temperature and heat transfer conditions for the comparative U_3Si lattices. The channel outlet conditions were maintained constant in all cases, and the inlet pressure, flow, etc. adjusted to suit.

Lattices B1, C1, and D1 have identical channel geometry to the reference UO_2 design. In B1, the reference fuel rating is retained to give increased channel power and is accompanied by a reduced burnout margin. In C1, the fuel rating is decreased to provide the same channel power and burnout margin as the reference design. In D1, the fuel rating is increased to give a maximum centre fuel temperature of approximately 875°C in the peak pin of the peak channel. This is accompanied by a further reduction in burnout margin compared with B1.

In lattice E1, the rod diameter is reduced so that with the same fuel rating as the reference design, the channel power is maintained constant. The pin-pin spacings etc. are maintained at the reference design values, and the

pressure tube diameter reduced accordingly. The burnout margin calculated is very similar to that for lattice B1.

In lattice F1, the reference design fuel rating and pin-pin spacings are retained. The rod diameter is increased so that the maximum centre temperature in the peak pin of the peak cluster is approximately 875°C. The pressure tube diameter is increased to suit the resulting cluster. The burnout margin is similar to lattices B1 and E1.

Pressure and calandria tube thickness adjustments were made in accordance with the ground rules whilst maintaining the gap between them constant. The lattice pitch for each pressure tube was then calculated to maintain the D_2O investment per unit channel power the same as that for the reference UO_2 lattice.

Finally, in lattices G1, J1 and H1, the reference UO_2 reactor uranium rating and pressure tube were retained, but the fuel cluster was reduced from 28 rods to 19. In G1, the rod diameter was chosen to retain the reference reactor channel power; in H1 and J1 the rod diameter was chosen to give 875°C maximum local fuel temperature in the peak pin of the peak rated channel. J1 has the same lattice pitch as the reference UO_2 reactor, whilst for H1 the pitch corresponds to the same D_2O/MW as the reference design.

The lattice data for each of these systems are given in Table 3 and the results of the METHUSELAH II burnup calculations in Table 4.

6. DISCUSSION OF RESULTS

6.1 BLW-HWM Lattices

The results of Table 2 in all cases show a clear advantage in attainable burnup for the U_3Si lattices. The 18-rod clusters of U_3Si all give greater power output per channel than the reference design, and the progressively falling terminal burnup through lattices D to G, in which the channel diameter is held constant whilst the rod diameter is reduced, shows the vital importance of minimising the coolant volume in this type of reactor.

The lattice H pressure tube design represents an attempt to make maximum use of the properties of U_3Si. The resulting increase of 20 per cent in channel power and 3200 /MWd/teU in terminal burnup compared with the reference UO_2 design, whilst maintaining the same fuel rating, represent a tremendous improvement in reactor performance. The burnout margin, however, has fallen from 1.33 to 1.09 and even allowing our reservation regarding the correlation used, would clearly require extensive experimental study before it could be assumed even to approach practical feasibility.

Lattice E, however, with a slightly larger rod diameter (8 per cent) and slightly downrated fuel (12 per cent) shows a slightly greater channel power whilst maintaining and even slightly bettering the reference UO_2 design burnout margin. The improvement in terminal burnup is reduced to about 1700 MWd/teU, which is, however, still very much worthwhile. It seems likely that a more detailed optimisation study than is at present warranted would show a compromise between lattices E and H to have a terminal burnup of around 10500 MWd/teU with an acceptable burnout margin. In addition, the number of fuel elements for a given reactor power is approximately halved, and the number of pressure tubes reduced by some 20 per cent, both features being significant potential sources of cost reduction.

It is of interest to note that lattice E has the additional benefit of using the standard pressure tube, possibly therefore allowing the substitution of U_3Si for UO_2 in an existing reactor at a later date. The reduction in the above discussed benefits entailed by such a course, where the lattice pitch is restricted to that of the reference UO_2 design, is shown by comparison of cases E and J to be only 150 MWd/teU. It appears therefore that even when constrained by the core structure of an existing UO_2 reactor, the 18-rod U_3Si fuel elements are likely to offer superior gains to those obtainable by direct U_3Si substitution in the original UO_2 36-rod fuel geometry.

6.2 PHW Lattices

Perhaps somewhat surprisingly, the results of Table 4 show that U_3Si fuel in PHW type reactor lattices gives very similar potential gains in terminal burnup to those of the most favourable of the BLW configurations. In the PHW lattices, however, the differences in terminal burnup between the alternative U_3Si configurations considered are, with one exception, very small. The exception is the 19-rod cluster lattice G1, in which the pins occupy very little of the channel volume and which would be unlikely to be chosen as a practical configuration.

Of the remaining more realistic cases, it is of interest to note that lattice D1, which is the least attractive from the pumping power/pressure drop points of view also shows the least favourable improvement in burnup. It seems clear that there would be little difficulty in choosing channel configurations with U_3Si to give channel power at least equal to that of the reference UO_2 designs, acceptable flow and burnout margin conditions, with improvement in terminal burnup in excess of 2000 MWd/teU.

Again, by comparison of lattices H1 and J1 it is clear that most of the benefit available from a correctly designed U_3Si fuel element would still be available even if the lattice pitch were restricted by placing the U_3Si fuel in an existing UO_2 reactor.

7. ALTERNATIVE METHODS OF CALCULATION

In view of the semi-empirical nature of some aspects of the METHUSELAH lattice calculation, and the lack of evidence from comparison with experimental data that it is able to deal effectively with U_3Si fuel elements, it was considered worthwhile to compare results for oxide and one U_3Si lattice in both BLW and PHW systems using an entirely independent method of calculation.

The method selected was the WIMS scheme (Askew et al. 1966) using the DSN option in 18 energy groups for the main transport routine. The lattices selected for study were oxide lattice A, and silicide lattice B for the BLW system, and oxide lattice A1 and silicide lattice B1 for the PHW system.

The results of the WIMS calculations together with those of the corresponding METHUSELAH runs are shown in Table 5. Although the absolute values of the terminal burnup given by METHUSELAH II and WIMS show the expected substantial difference, both schemes show similar margins of improvement between oxide and silicide for both the reactor systems. This gives confidence in the general conclusion regarding potential advantages of U_3Si based on the METHUSELAH II runs for the full spectrum of lattice configurations studied.

8. RECENT DATA CONSIDERATIONS

Since the study so far described was completed, Dr. D. G. Walker has communicated privately that more recent data (Fereday et al. 1969) on irradiation swelling in U_3Si suggests it may be necessary that the cans be strengthened by increasing their thickness to 0.7 mm, and that a central void be left in the fuel element, reducing its effective density to around 13.0 g cm^{-3}. Since continuing development work is likely to improve these material properties the data are probably of transitory validity only, and do not justify a complete ab initio recalculation of the U_3Si/UO_2 performance comparison. Instead, an approximate estimate was made of the effects of the data, by carrying out burnup calculations only on a few selected lattices.

We have estimated the consequences of the can thickness change to the results of this report by scaling the fractional can absorption in each U_3Si lattice and relating the resultant reactivity decrease to terminal burnup. The reduction in terminal burnup in all cases is close to 200 MWd/teU.

To estimate roughly the effect of the central voids, we have repeated

burnup calculations for BLW lattices B, D and J, and PHW lattices B1 and J1 using a fuel density of 13.0 g cm^{-3}. All other parameters were maintained as in the original calculations. The results for terminal fuel burnup are compared in Table 6.

The combination of central fuel void and thicker cans in the U_3Si lattices leads to burnup reductions in the range 400 to 1000 MWd/teU. Even if development work yields no success in controlling the present levels of irradiation swelling in U_3Si, which is unlikely, it seems that the measures required to accommodate it, whilst reducing the margin of superiority of U_3Si over UO_2 in the burnup sphere, in no way changes the qualitative sense of the advantages already established in the preceding sections of this report.

9. CONCLUSIONS

The present study has shown a very favourable case for consideration of U_3Si fuel as an alternative to UO_2 in either the boiling light water cooled or pressurised heavy water cooled type of natural uranium heavy water moderated power reactor. In either case, for U_3Si density of about 15 g cm^{-3} the terminal burnup on the basis of $\int (k_{eff}-1)\, dt = 0$ shows potential for improvement by some 2000 MWd/teU or more. Much of this potential can still be realised, even when the U_3Si lattice is constrained by the core structure of an existing UO_2 reactor. Approximate calculations in the light of recently available irradiation swelling data for U_3Si suggest these burnup gains may be reduced by up to about one half by the consequential reductions in effective fuel density and increased can thickness. The improvements are nevertheless still well worthwhile.

For boiling light water cooled reactors the presently assumed heat transfer and phase change data for U_3Si would appear to allow very similar performance from an 18-rod cluster to that currently obtained from 36-rod clusters of UO_2. Assuming fabrication costs for UO_2 and U_3Si to be not too dissimilar, this would entail a further significant saving in fuel costs in addition to that from the improved burnup performance, since it appears that reactor fuel ratings similar to those for the UO_2 fuelled BLW reactor could probably be used while still maintaining acceptable dryout margins. In this context, however, it must be clearly borne in mind that the dryout correlation used is not necessarily reliable in predicting the effects of the changes in cluster/channel geometry covered in the present study. On the other hand, our assumption of constant steam quality at outlet is not essential, and any deficiencies in calculated dryout margins may well be amenable to changes in channel flow conditions which we have not considered. Meanwhile, the

importance of designing the channel geometry to minimise the coolant/fuel ratio in this type of reactor if maximum fuel utilisation is to be achieved has been clearly shown to hold as much for U_3Si as for UO_2.

Similar improvements can be expected in the performance of pressurised heavy water cooled reactor lattices, where it appears that the fuel cluster can be reduced to 19 rods of U_3Si compared with 28 rods of UO_2 without channel power penalties. In this case however, the burnup improvement is rather insensitive to the fuel/pressure tube geometry and there would appear to be little difficulty in designing for fuel ratings and channel powers at least equal to those of the reference UO_2 reactor. Broadly similar cost savings to those for the boiling light water cooled reactors might therefore reasonably be anticipated.

It is probably unrealistic at this stage in view of the rather dubious nature of most data concerning the physical and metallurgical properties of U_3Si, and the problems of its fabrication, to embark on a detailed study of the fuel cost savings to be expected compared with UO_2 for optimised reactor designs. It can be said, however, that the potential gains are certainly sufficient to justify further studies of the Uranium Silicon/complex and the U_3Si phase in particular, if natural uranium heavy water moderated reactors are serious long-term contenders in the Australian power programme.

In this context, it is of sufficient importance to merit stating again, that a significant proportion of the burnup improvement compared with UO_2 which might be expected from an optimised U_3Si design, could probably still be achieved by substituting a suitable U_3Si fuel element into the pressure tubes of an already existing UO_2 reactor.

10. ACKNOWLEDGEMENTS

We are grateful to many colleagues who have contributed to this study by discussions and advice concerning their specialised disciplines. In particular Messrs. G.W.K. Ford, J. Rodd, J.H. Price and A. Chapman were valued consultants in the fluid heat transfer field; Dr. R. Smith, Dr. D.G. Walker, Dr. K.D. Reeve and Mr. J. Bardsley were willing sources of materials information; Mr. G. Robinson prepared and ran the WIMS comparisons; Mrs. J.A. Musgrove, Mrs. J.I. Faulkner and Miss J. Bursell assisted in compilation of data and computer calculations.

11. REFERENCES

Alpiar, R. (1964) - UKAEA Report, AEEW-R135.

Askew, J.R., Fayers, F.J. and Kemshell, P.B. (1966) - J. Brit. Nuc. En. Soc. 5 (4), 564.

Bardsley, J. (1968) - AAEC/TM487.

Barnett, P.G. (1965) - UKAEA Report, AEEW-R463.

Brinkworth, M.J. and Griffiths, J.A. (1969) - UKAEA Report, AEEW-R480.

Chalder, G.H. et al. (1967) - AECL Report, AECL2874.

Elliot, J.N. (1963) - AECL Report, AECL-1673.

Fereday, M.A., Chalder, G.H. and Cotnam, K.D. (1969) AECL Report, AECL-3111.

Hicks, D. and Hopkins, D.R. (1964) - UKAEA Report, AEEW-R397.

Jensen, J.C. (1962) - Savannah River Laboratory Report, DP-784.

Pon, G.A. et al. (1964) - AECL Report, AECL-2010.

Schludi, H.N. and Whitfield, J.H. (1967) - AAEC/TM405.

TABLES 1 - 6

TABLE 1

DETAILS OF BOILING LIGHT WATER COOLED LATTICES

Clusters / Lattice Details	UO_2	U_3Si							
	A	B	C	D	E	F	G	H	J
1. Fuel Cluster									
No. Rods in Cluster	36	36	36	18	18	18	18	18	18
Rod diam. (cm)	1.680	1.680	1.680	2.424	2.200	2.100	2.000	2.040	2.200
Fuel Density (g cm^{-3})	10.22	14.94	14.94	14.94	14.94	14.94	14.94	14.94	14.94
Average Fuel Temp. (^oC)	541	330	372	410	414	416	418	413	414
Zr-2 Clad. Outside Diam.(cm)	1.756	1.756	1.756	2.500	2.276	2.176	2.076	2.116	2.276
Clad. Temp. (^oC)	261	261	262	265	267	268	269	265	267
H_2O Coolant Density (g cm^{-3})	0.2905	0.2898	0.2879	0.2871	0.2872	0.2868	0.2865	0.2869	0.2872
H_2O Coolant Temp. (^oC)	250	250	248.5	250	251	251	252	249	251
Burnup Rating (W/g Fuel)	9.014	6.167	9.841	7.318	8.667	9.359	10.207	9.841	8.667
2. Pressure Tube (Zr-2)									
Inside Diam. (cm)	13.00	13.00	13.00	13.00	13.00	13.00	13.00	11.20	13.00
Outside Diam. (cm)	13.51	13.51	13.51	13.51	13.51	13.51	13.51	11.68	13.51
3. Calandria Tube (Mg Alloy)									
Inside Diam. (cm)	16.95	16.95	16.95	16.95	16.95	16.95	16.95	15.12	16.95
Outside Diam. (cm)	17.10	17.10	17.10	17.10	17.10	17.10	17.10	15.27	17.10
4. Moderator (D_2O)									
Purity (wt.% H)	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028
Density (g cm^{-3})	1.078	1.078	1.078	1.078	1.078	1.078	1.078	1.078	1.078
Temp. (^oC)	77	77	77	77	77	77	77	77	77
Lattice Pitch	34.00	34.00	41.32	37.06	36.69	36.49	36.28	35.68	34.00

... contd/

TABLE 1 (Contd.)

DETAILS OF BOILING LIGHT WATER COOLED LATTICES

Clusters / Lattice Details	UO_2	U_3Si						
	A	B	C	D	E	F	G	H	J
5. Heat Transfer Data									
Reactor Average Fuel Rating (W/gU)	10.22	6.41	10.22	7.60	9.00	9.75	10.60	10.22	9.00
Max. Fuel Temp., Peak Pin, Peak Channel (^{o}C)	1891		735	885	878	874	870	870	878
Average Channel Power (kW)	3306	3306	5275	4083	3983	3932	3877	3889	3983
Fractional Pumping Power	0.003	0.003	0.007	0.003	0.001	0.001	0.001	0.005	0.001
Average Channel Pressure Drop (kg cm^{-2})	3.44	3.44	6.61	3.37	1.34	0.98	0.75	5.21	1.34
Average Channel Mass Velocity (g cm^{-2} sec^{-1})	126	126	192	153	110	97	88	186	110
Coolant Inlet Pressure (kg cm^{-2})	43.6	43.6	43.6	43.6	43.6	43.6	43.6	43.6	43.6
Average Heat Flux for Peak Channel at Closest Point to B/O (W cm^{-2})	64.5	64.5	105.0	111.1	125.4	128.6	131.0	128.4	125.4
Minimum B/O Margin, Peak Channel	1.33	1.33	1.20	1.22	1.35	1.39	1.42	1.09	1.35

KEY TO TABLE 1 LATTICE DATA

A UO_2 Reference Design.

B U_3Si Reference fuel geometry, pressure tube diameter and channel power.

C U_3Si Reference fuel geometry pressure tube diameter and fuel rating $(W(gU)^{-1})$.

D U_3Si 18 rods of maximum possible diameter in reference pressure tube. Fuel downrated to give T_{max} of 875^{o}C.

E U_3Si 18 x 2.2 cm diameter rods in reference pressure tube. Fuel rated for T_{max} = 875^{o}C.

F U_3Si 18 x 2.1 cm diameter rods in reference pressure tube. Fuel rated for T_{max} = 875^{o}C.

G U_3Si 18 x 2.0 cm diameter rods in reference pressure tube. Fuel rated for T_{max} = 875^{o}C.

H U_3Si 18 rods of diameter giving T_{max} of 875^{o}C at reference fuel rating. Pressure tube diameter reduced to suit cluster.

J U_3Si As case E, but with lattice pitch as reference UO_2 design.

TABLE 2

RESULTS OF METHUSELAH II CALCULATIONS FOR BOILING LIGHT WATER COOLED LATTICES

Parameter \ Lattice	UO_2	U_3Si						
	A	B	C	D	E	F	G	H	J
Initial k_∞	1.105	1.116	1.140	1.131	1.128	1.126	1.123	1.147	1.118
Initial k_{eff}	1.074	1.089	1.103	1.099	1.095	1.092	1.088	1.113	1.089
Terminal Burnup (MWd/teU)	8190	10660	10640	11300	9860	9190	8480	11360	9710
Initial Void Coefficient of Reactivity*	+0.026	+0.020	+0.025	+0.022	+0.031	+0.035	+0.040	+0.024	+0.026
Fuel Thermal Time Const. (sec)	10.4	1.0	1.0	2.0	1.6	1.5	1.3	1.4	1.6

*Here defined as $\Delta k_{eff}/\frac{\Delta\rho}{\rho}$ calculated for 10% reduction in the normal coolant operating density, ρ.

KEY TO TABLE 2 LATTICE DATA

A UO_2 Reference Design.

B U_3Si Reference fuel geometry, pressure tube diameter and channel power.

C U_3Si Reference fuel geometry pressure tube diameter and fuel rating $(W(gU)^{-1})$.

D U_3Si 18 rods of maximum possible diameter in reference pressure tube. Fuel downrated to give T_{max} of 875°C.

E U_3Si 18 x 2.2 cm diameter rods in reference pressure tube. Fuel rated for T_{max} = 875°C.

F U_3Si 18 x 2.1 cm diameter rods in reference pressure tube. Fuel rated for T_{max} = 875°C.

G U_3Si 18 x 2.0 cm diameter rods in reference pressure tube. Fuel rated for T_{max} = 875°C.

H U_3Si 18 rods of diameter giving T_{max} of 875°C at reference fuel rating. Pressure tube diameter reduced to suit cluster.

J U_3Si As case E, but with lattice pitch as reference UO_2 design.

TABLE 3

DETAILS OF PRESSURISED HEAVY WATER COOLED LATTICES

Clusters / Lattice Details	UO_2	U_3Si						
	A1	B1	C1	D1	E1	F1	G1	H1	J1
1. Fuel Cluster									
No. of Rods in Cluster	28	28	28	28	28	28	19	19	19
Rod Diam. (cm)	1.440	1.440	1.440	1.440	1.140	1.610	1.384	1.660	1.660
Fuel Density (g cm^{-3})	10.45	15.42	15.42	15.42	15.42	15.42	15.42	15.42	15.42
Average Fuel Temp. (^oC)	774	457	396	491	410	485	464	498	498
Zr-2 Clad. Outside Diam. (cm)	1.520	1.520	1.520	1.520	1.220	1.690	1.464	1.740	1.740
Clad. Temp. (^oC)	298	304	298	307	300	306	320	313	313
D_2O Coolant Density (g cm^{-3})	0.846	0.846	0.846	0.846	0.846	0.846	0.846	0.846	0.846
D_2O Coolant Temp. (^oC)	272	272	272	272	272	272	272	272	272
Burnup Rating (W/g Fuel)	16.590	18.112	11.794	22.135	18.112	18.112	18.112	18.112	18.112
2. Pressure Tube (Zr-2)									
Inside Diam. (cm)	10.350	10.350	10.350	10.350	8.512	11.363	10.350	10.350	10.350
Outside Diam. (cm)	11.372	11.374	11.372	11.376	9.412	12.454	11.372	11.372	11.372
3. Calandria Tube (Zr-2)									
Inside Diam. (cm)	12.912	12.914	12.912	12.916	10.972	14.014	12.912	12.912	12.912
Outside Diam. (cm)	13.212	13.214	13.212	13.216	11.272	14.314	13.212	13.212	13.212
4. Moderator (D_2O)									
Purity (wt.% H)	0.0278	0.0278	0.0278	0.0278	0.0278	0.0278	0.0278	0.0278	0.0278
Density (g cm^{-3})	1.091	1.091	1.091	1.091	1.091	1.091	1.091	1.091	1.091
Temp. (^oC)	59	59	59	59	59	59	59	59	59
Lattice Pitch	28.60	34.98	28.60	38.27	27.94	38.97	28.60	33.25	28.60

... contd/

TABLE 3 (Contd.)

DETAILS OF PRESSURISED HEAVY WATER COOLED LATTICES

Lattice Details \ Clusters	UO_2	U_3Si							
	A1	B1	C1	D1	E1	F1	G1	H1	J1
5. Heat Transfer Data									
Reactor Average Fuel Rating (W/gU)	18.82	18.82	11.79	23.00	18.82	18.82	18.82	18.82	18.82
Max. Fuel Temp., Peak Pin, Peak Channel (^{o}C)	2344	783	615	874	630	875	754	873	873
Average Channel Power (kW)	4744	7570	4744	9251	4744	9463	4744	6826	6826
Average Channel Pumping (kW)	6.3	23.0	6.3	40.3	12.3	30.5	1.1	8.6	8.6
Channel Pressure Drop (kg cm^{-2})	2.5	5.8	2.5	8.3	4.9	6.2	0.45	2.4	2.4
Coolant Inlet Pressure (kg cm^{-2})	105.5	110.1	105.5	113.6	108.9	110.5	105.3	102.6	102.6
Peak Channel Max. Surface Heat Flux (W cm^{-2})	111	177	111	216	138	199	187	230	230
Peak Channel Min. B/O Flux Surface Flux	1.73	1.53	1.73	1.43	1.55	1.53	2.03	1.60	1.60

KEY TO TABLE 3 LATTICE DATA

A1	UO_2	Reference Design.
B1	U_3Si	Reference pressure tube, fuel geometry, fuel rating ($W(gU)^{-1}$).
C1	U_3Si	Reference pressure tube, fuel geometry channel power.
D1	U_3Si	Reference pressure tube, fuel geometry. Rating for T_{max} = 875°C.
E1	U_3Si	Reference fuel rating and channel power by reduced rod and pressure tube diameters.
F1	U_3Si	Reference fuel rating. Rod diameter for T_{max} = 875°C.
G1	U_3Si	19 rods. Reference pressure tube and fuel rating. Rod diameter for reference channel power.
H1	U_3Si	19 rods. Reference pressure tube and fuel rating. Rod diameter for T_{max} = 875°C.
J1	U_3Si	As case H1, but reference lattice pitch.

TABLE 4

RESULTS OF METHUSELAH II CALCULATIONS FOR PRESSURISED HEAVY WATER COOLED LATTICES

Parameter \ Lattice	UO_2	U_3Si						
	A1	B1	C1	D1	E1	F1	G1	H1	J1
Initial k_∞	1.114	1.154	1.126	1.157	1.154	1.149	1.137	1.152	1.132
Initial k_{eff}	1.080	1.113	1.097	1.110	1.118	1.106	1.100	1.113	1.101
Terminal Burnup (MWd/TeU)	8140	11040	10810	10350	10710	10810	8960	10710	10430
Initial Void Coefficient of Reactivity*	+0.016	+0.021	+0.019	+0.022	+0.017	+0.024	+0.016	+0.023	+0.021
Fuel Thermal Time Const.(sec)	7.6	0.7	0.7	0.7	0.4	0.9	0.6	0.9	0.9

*Defined here as $\Delta k_{eff}/\Delta\rho/\rho$, calculated for 10% reduction in normal coolant operating density, ρ .

KEY TO TABLE 4 LATTICE DATA

A1 UO_2 Reference Design.

B1 U_3Si Reference pressure tube, fuel geometry, fuel rating $(W(gU)^{-1})$.

C1 U_3Si Reference pressure tube, fuel geometry, channel power.

D1 U_3Si Reference pressure tube, fuel geometry. Rating for $T_{max} = 875^oC$.

E1 U_3Si Reference fuel rating and channel power by reduced rod and pressure tube diameters.

F1 U_3Si Reference fuel rating. Rod diameter $T_{max} = 875^oC$.

G1 U_3Si 19 rods. Reference pressure tube and fuel rating. Rod diameter for reference channel power.

H1 U_3Si 19 rods. Reference pressure tube and fuel rating. Rod diameter for $T_{max} = 875^oC$.

J1 U_3Si As Case H1, but reference lattice pitch.

TABLE 5

COMPARISON OF METHUSELAH II AND WIMS RESULTS

FOR SOME SELECTED LATTICES

Lattice		Initial K_{eff}		Terminal Burnup (MWd/teU)		U_3Si Burnup Gain (MWd/teU)	
		Meth.	WIMS	Meth.	WIMS	Meth.	WIMS
BLW	UO_2 'A'	1.074	1.062	8190	9160	2470	2810
	U_3Si 'B'	1.089	1.073	10660	11970		
PHW	UO_2 'A1'	1.080	1.064	8140	8140	2900	2010
	U_3Si 'B1'	1.113	1.084	11040	10150		

TABLE 6

TERMINAL BURNUP VARIATION WITH U_3Si DENSITY

FOR SOME SELECTED LATTICES

Fuel \ Lattice		BLW			PHW	
		B	D	J	B1	J1
Terminal burnup MWd/teU	U_3Si 15 g cm^{-3}	10,660	11,300	9,710	11,040	10,340
	U_3Si 13 g cm^{-3}	10,500	10,910	9,270	10,250	9,920
	UO_2 Ref.	← 8,190 →			← 8,140 →	

APPENDIX

REACTOR CHANNEL THERMAL AND HYDRAULIC CALCULATIONS

A.1 GENERAL CONSIDERATIONS

The U_3Si fuel elements considered in the study have necessitated changes from the standard reference UO_2 reactor channel designs in fuel rod diameter and the number of rods in the cluster, fuel rating and pressure tube diameter. These changes significantly affect the required coolant pressure and flow conditions, and it is necessary to adopt some ground rules to limit the number of possible combinations of hardware and conditions.

First, it was decided that reference lattice steam conditions would be retained in all cases, and to this end the reactor coolant conditions at the channel outlet are always those of the reference design. This requires variation of the coolant inlet temperature and pressure and of the mass flow to accommodate changes in channel power and geometry.

For changes in fuel cluster and channel geometry, reference UO_2 design parameters are retained as far as possible. The spacings between fuel pins in the innermost ring of the cluster, between pins in adjacent layers, and between the outermost ring of pins and the pressure tube is always maintained at the reference UO_2 design values. The pressure tube thickness is varied to accommodate, at constant working stress (about 24000 psi), changes in its internal diameter and coolant inlet pressure, assuming that a corrosion allowance of 0.16 cm is made in all cases, including the reference UO_2 designs. The pressure tube to calandria tube insulating gap is kept constant, and the calandria tube kept at constant working stress by maintaining the ratio of its inner to outer diameter constant.

The PABOIC programme was written for the IBM 360/50 computer to do the heat transfer/channel hydraulics calculations for the wide range of reactor configurations considered in this study. Both boiling and totally sub-cooled channel conditions can be calculated, and the programme provides temperature profiles, burnout margins, pressure drops, pumping power, etc. in both peak and average channels for a reactor of given channel geometry, fuel composition, axial and radial form factors, and average fuel rating.

A.2 SOME NOTES ON THE PABOIC PROGRAMME

A.2.1 Key to Symbols

The symbols to be used in this Appendix to describe the data and methods of the PABOIC programme are defined as follows:

A'	Channel flow area
A	Constant in Barnett critical heat flux correlation
B	" " " " " " "
C	" " " " " " "
De	Equivalent hydraulic diameter of the channel
f	Friction factor
G	Mass flow rate
H	Enthalpy of coolant
K	Thermal conductivity
L	Channel heated length
n_i	Number of fuel pins in i^{th} layer
P	Pressure of coolant
Pr	Prandtl number
q_i	Heat generation in fuel in i^{th} layer
r	Radius of fuel rod
Re	Reynold's number
T	Temperature
Z	Channel axial co-ordinate
ΔH	Inlet subcooling $(H_{SAT} - H_o)$
ØAV	Average heat flux across cluster, burnout correlation
ρ	Density of coolant
λ	Latent heat of vaporisation of coolant

A.2.2 Coolant Data

The thermodynamic properties of heavy water were obtained from Elliot (1963) and those for light water from standard steam tables.

The specific volumes, enthalpy, etc. of liquid and vapour phases are programmed in tabular form at one deg C intervals. Three point quadratic interpolations in the independent variable, temperature, is used to obtain the values appropriate to the prevailing conditions. The effect of pressure on these values, at near saturation conditions is neglected. The saturation temperature is expressed as an empirical relationship in terms of pressure, as given by Jensen (1962).

Thermal conductivity and viscosity of the liquid are expressed as empirical relationships in terms of pressure and temperature. Prandtl number $\frac{\mu C_p}{K}$ was obtained using both the tables and relationships.

A.2.3 Heat Transfer Coefficient

The Dittus-Boulter relationship

$$h = \frac{0.023\ K\ Re^{0.8}\ Pr^{0.4}}{De}$$

is used for the heat transfer coefficient, h, from the cladding surface to the coolant, and is obtained using the above coolant properties as a function of pressure and temperature. The heat transfer coefficient typically varies by about 5 per cent from inlet to outlet conditions.

A.2.4 Power Distribution

Since a detailed axial power distribution is generally not available, the approximation of a truncated cosine is assumed. An axial form factor, given as input data, is then used to obtain the extrapolated length of the core and hence the corresponding axial power profile.

A.2.5 Conservation Equations

The steady state one dimensional equations of conservation of mass, momentum and energy are used to obtain the pressure-temperature distribution along the heated channel.

Mass: $$\frac{\partial G}{\partial z} = 0$$

Momentum: $$\frac{\partial (G^2/\rho)}{\partial z} + \frac{fG^2}{2\rho De} = \frac{\partial P}{\partial z}$$

Energy: $$\frac{\partial (GH)}{\partial z} = \frac{1}{A'} \sum_{i=1} \pi r_i^2 n_i q_i$$

These equations are programmed and integrated along the heated channel. Iteration is made on pressure at the nodal points until the required convergence is reached. The friction factor f is expressed in the following form

$$f = 0.213\ Re^{-0.214}$$

and varies only by a few per cent along the heated channel length.

A.2.6 Burnout or Critical Heat Flux Correlation

The correlation equation used was obtained from Barnett (1965),

$$\phi_{AV} \times 10^{-6} = \frac{A\lambda/649 + B\Delta H}{C + L} \quad ,$$

where A, B, C were given by Barnett's equations (7) with P(1) through P(11) from the 'Annulus plus Rod Bundle' column of his Table 7. The expression allows via its coefficients for the differing heat fluxes in successive layers of fuel

pins, and the critical heat flux calculated is therefore the bundle average value.

Although a pressure correction term is included in the expression, the correlation strictly applies only to light water coolant at about 1000 psi. All the light water cooled channels of the present study were at approximately 620 psi inlet pressure, and the calculated burnout margins must therefore be considered as comparative rather than absolute. A similar reservation applies to the pressurised heavy water cooled channels where the inlet pressures were about 1500 psi, and where, in addition, it is generally found that practical dryout margins tend to be some 10 per cent lower than in light water cooled counterparts.

A.2.7 Fuel Element Temperature Distribution

The radial temperature distribution in a fuel pin is obtained from:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(rK\frac{\partial T}{\partial r}\right) + q_i = 0$$

Axial conduction in the fuel pins is small and is neglected throughout. The heat generation term, q_i, is zero in the cladding region, and is assumed radially uniform in the fuel pellets.

The thermal conductivity of the Zircaloy-2 fuel cladding is taken as 0.1555 $Wcm^{-1}(^oC)^{-1}$ and independent of temperature.

For uranium dioxide fuel, the thermal conductivity, k, and fuel/can interface thermal resistance, F, were taken as

$$k = \frac{42.553}{500+T}\ Wcm^{-1}(^oC)^{-1}, \quad F = 1.766^oC\ W^{-1}cm^2$$

For uranium silicide, two sets of data were used.

In Boiling Light Water Lattices,

$$k = 0.1500 + 3.868 \times 10^{-4}\ T - 4.30 \times 10^{-7}T^2\ W\ cm^{-1}(^oC)^{-1}$$

$$F = 0.8333^oC\ W^{-1}cm^2$$

following Schludi and Whitfield (1967).

In pressurised Heavy Water Lattices,

$$k = 0.2026 + 10^{-5}T + 1.595 \times 10^{-7}\ T^2\ W\ cm^{-1}(^oC)^{-1}$$

$$F = 0.6625\ ^oC\ W^{-1}cm^2\ .$$

Both k formulae were based on least-squares quadratic fits to experimental

data. The 'BLW' formula, however, was based on early data terminating at only 65°C. This formula is therefore extrapolating unreliably to the temperature range 300-900°C applicable to the U_3Si in the present study. By the time the PHW lattices were studied, experimental data for k between 300°C and 900°C had become available from which the 'PHW' formula was derived by least squares fitting.

A comparison of the k values given by the two formulae between 300 and 900°C is

T =	300	500	700	900	°C
BLW k =	0.2223	0.2109	0.1751	0.1048	W $cm^{-1}(^{o}C)^{-1}$
PHW k =	0.2200	0.2476	0.2880	0.3412	W $cm^{-1}(^{o}C)^{-1}$.

The agreement is quite close in the range of <u>average</u> fuel element temperatures for the U_3Si lattices studied, and since the BLW formula was pessimistic compared with the later conductivity data, it was not considered worthwhile to re-run the BLW heat transfer and lattice burn-up calculations with the later conductivity data.

The difference in interface thermal resistance coefficients has negligible effects on the results.