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FAST REACTOR FUEL DESIGN AND DEVELOPMENT

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1. INTRODUCTION

All natural and enriched uranium fission reactors produce fissile plutonium by conversion of the fertile uranium 238 isotope which constitutes over 99% of natural uranium. The salient difference between fast and thermal reactors is that whereas the thermal reactors can utilise only about one per cent of natural uranium by conversion and thermal neutron fission of the recycled plutonium, the fast reactor can utilise about 50 times as much of the uranium(1). It is generally agreed that the amount of natural uranium in the world which can acceptably be extracted taking environmental and economic considerations into account, is limited, and that if only thermal reactors are employed to use it, the reactors installed by the end of this century will consume the available ore in their life operation even with plutonium recycle in thermal reactors. However, if the fast breeder is used to extract energy from the plutonium produced in thermal reactors, and also to convert uranium to plutonium itself, then the uranium based fission reactors can meet world energy demands for over 500 years at 1975 energy demand levels.

Since fast reactors use plutonium at ca 20% concentration with 80% uranium, with a high heavy atom burn-up, and the thermal reactors use ca 5% concentration at relatively low heavy atom burn-up, the fast reactor significantly minimises the amount of material which is brought into contact with a given amount of plutonium in extracting the energy from it, and therefore minimises the amount of plutonium contaminated waste material to be dealt with.

The case for the breeder reactor is clear then. It must be available for commercial exploitation at the end of this century unless massive development of fossil fuels, or some other energy source, is undertaken to replace and expand on the energy which will be generated by thermal reactors at that date.

Three phases of Fast Breeder introduction can usefully be delineated, namely

(i) The current period before substantial programmes of Commercial Breeders are installed and in which plutonium stocks are being steadily accumulated by conversion of uranium in thermal reactors.

(ii) An intermediate period when these stocks have been invested in Fast Reactors and the achievable Fast Reactor installation rate is determined by uranium conversion into plutonium in thermal reactors, by the inventory and breeding ratio of the fast reactor, taking into account reprocessing characteristics.

(iii) The long term phase when all fissile power is generated by fast reactors, and the fast reactor cycle doubling time determines the possible energy growth rate.

Phase 1 will last for about 15 years, and Phase 2 for some 50 years.

2. REACTOR PARAMETER OPTIMISATION

In the UK, it is customary to combine the thermal and fast reactor components of the nuclear power System in selecting a single set of fast reactor fuel design parameters to cover the whole period under consideration. Two criteria of System Performance are highlighted, that is Discounted System Generating Cost and Total Uranium Demand: another relevant parameter is Annual Uranium demand. This approach can be justified on the grounds that the UK electrical generating system will eventually require a large contribution from LMFBRs, and that the relatively minor nominal cost savings which could attach to introducing a different fuel design for a limited initial installation programme do not warrant the extra development work involved. In this context it must be appreciated that the practical development and endorsement of the detail of a fuel design and the associated fuel cycle occupies a decade, and is not to be changed lightly. In these particular UK optimisations referred to above, plutonium is not considered as a fuel for Thermal reactors.

Parameter optimisation is normally carried out in two parts. The first part does not incorporate the precise detail of actual fuel designs, but does incorporate essential 'smeared' features and limitations of designs, such as core pressure drop, peak cladding temperature, control rod volume fraction. In addition, a large input is concerned with reactor installation program, fabrication and reprocessing costs, ore prices, interest rates, reactor capital cost, out-pile fuel hold-up time, reactor refuelling time and such information: the optimisation is not equally sensitive to variations in all these items. From this optimisation, the dependence of the two performance criteria on such parameters as core height, pin diameter and linear rating, clad thickness, can be determined. Typical plots are shown in figure 1, from work by C E Iliffe and his colleagues. Such plots enable near-optimum parameters to be isolated, which can then be explored in greater depth in terms of detailed fuel designs in a second stage optimisation, where mechanical engineering constraints on such parameters as burn-up, clad thickness, wrapper thickness, are now incorporated. An example is shown in figure 2 of this second stage which effectively incorporates estimates of fuel performance based on codified properties of materials. It should not be concluded that this process proceeds mechanistically: in practice, considered restraints or judgments are put in which condition the answers. These derive from engineering and performance judgments on what will turn out to be achievable, for example in terms of reactor temperatures, practicable engineering, etc. Table 1 shows designs arrived at by this procedure for a 1300 MW(e) reactor which are conditioned in detail by

(a) the use of a 142 mm across/flats wrapper tube

(b) a desire to keep the rotating shield and pool reactor vessel sizes to a practical minimum on engineering grounds.

TABLE 1

	pin O.D	linear rating	Pins/SA	Core Length	Core Power(th)	Relative Cumulative Ore to 2049	Core Sub-Assemblies
Base Oxide	5.84	425 w/cm	325	1000 mm	2993 MW	1.00	342
Advanced Oxide	6.73	550 w/cm	271	1000 mm	3238 MW	0.80	342

It is concluded from surveys of this kind that for the UK groundrules and system, a fast reactor fuel pin outside diameter of ca 6½ mm is optimised for both system cost and uranium utilisation, when coupled with a linear rating of 550 w/cm. The core corresponding to a 1300 MW(e) reactor would consist of 342 sub-assemblies. However, there is as yet no large scale experience that pins with this linear rating will have adequate reliability and burn-up for commercial operation, although experience with 2 such sub-assemblies to 7.0% and 8.6% peak burn-up has been obtained in DFR. If necessary, it would be possible to fall back either to pins of a similar diameter, but a peak linear rating of 475 w/cm, giving one further row of sub-assemblies, ie a core of 396 sub-assemblies, or to 325 pin sub-assemblies with a peak linear rating of 425 w/cm and retaining the original core size of 342 sub-assemblies. In all these cases, the precise pin size would be designed for maximum use of the constant available core pressure drop. The UK reactor design philosophy is based on being able to provide safety circuit instrumentation to every core and radial blanket sub-assembly if that is eventually seen to be desirable. In practice this places a design requirement on the rotating shield for instrumentation access. An increase in core size by an additional row of sub-assemblies would require either an increase in rotating shield size to accommodate the additional instrumentation or a decrease in the number of radial blanket sub-assemblies. The present position therefore is that the Reference design proposed by NPC and the AEA for CFR will be a 271 pin oxide design peak rated at 550 w/cm, with a back-up design of 325 pins rated at 420 w/cm.

3. PERFORMANCE CONSIDERATIONS

All countries operating experimental fast reactors have shown that pin burn-ups substantially above 10% of all heavy atoms can be achieved: a peak of 20% has been achieved in the UK without pin failure although it will be appreciated that this burn-up has been with some irradiation parameters differing from those which will obtain in large commercial reactors. There is a development phase still to be undertaken in which the dependence of achievable burn-up on a number of variables such as fuel density, method of pin support, fuel oxygen/metal ratio, operating temperatures, fabrication route and reprocessing considerations needs to be further explored. This is not a feasibility exercise for fast reactor fuel, it is an optimisation one in which reliability and, fuel endurance, and therefore economics, are the main considerations. Although a great deal of information has been aggregated in this area using experimental reactors such as BOR 60, EBR II, Rapsodie and DFR, there is an important final phase to be completed using fuel elements with plutonium/uranium 238 ratios, damage dose/burn-up ratios and flow conditions appropriate to large Commercial reactors and which can now be achieved in the existing Prototype reactors of ca 250 MW(e).

An important area which requires further study is the full assessment of the neutron-dose dependent phenomena of neutron-induced void swelling and irradiation creep in metal components. The magnitude of neutron induced void swelling is determined by the material and its fabrication history, it is a function of reactor temperature and changes in temperature, it is dependent on neutron exposure dose and probably on the stress history to which the material has been exposed. The phenomenon is generally of more concern in sub-assembly structural components than in fuel pins, due to the increase in component dimensions and to the distortions which it can cause, which in turn result in inter sub-assembly interference and loading.

The PFR core design predated the discovery of neutron void swelling in irradiations carried out in DFR. PFR uses a bottom-cantilivered 'freestanding' core design, in which each sub-assembly is detached from its neighbours and with the core having the desirable negative bowing reactivity coefficient. The discovery of void swelling and associated bowing of sub-assemblies in the reactor radial flux gradients, gave strong impetus to the selection of a low swelling wrapper material. From information available from the DFR programmes and parallel particle accelerator programmes carried out by Harwell, the nickel base alloy Nimonic PE16 was selected and is now the reference wrapper material for PFR and CFR. Figure 3 shows some comparative data on DFR fuel pins clad in this material and UK tubes of some austenitic stainless steels: a substantial part of the pin diameter change is due to void swelling. The selection of PE16 was made essentially for its consistent low swelling behaviour. It is the development intention to provide an alternative low swelling austenitic or ferritic steel wrapper to the designers, fabricators and reprocessors to avoid the less desirable characteristics of the nickel base alloys in the fuel element context. In this connection, the simulation techniques which Harwell have developed using heavy ion, electron and proton bombardment, and giving atom displacement rates two orders of magnitude higher than those in fast reactors, are seen as valuable development tools. The near term attack is to attempt to usecommercial type alloys of restricted composition ranges and carefully specified fabrication processing, perhaps with specific alloying additions. In this category are the austenitic steels FV548, and silicon and titanium adjusted 316 type steel, and the ferritic alloy FV448. The longer range attack includes the systematic study of austenitic, ferritic and nickel base alloys and key constituents, adventitious impurities and mechanical working processes. It is here that the simulation techniques are seen as a particularly valuable sorting tool. It is encouraging that there are distinct indications that a pattern of connectivity is beginning to emerge between certain characteristics of alloys and their swelling behaviour, with metallurgically stable compositions showing the least swelling: figure 4, from work carried out at Springfields[2] illustrates this point.

Currently irradiation creep is seen perhaps as an even more important phenomenon for design consideration. Broadly, irradiation creep strain shows a linear dependence on stress and neutron dose, and can be greater at higher temperatures. The specific condition it gives rise to in sub-assemblies is bulging of the wrapper at the region of high flux due to the differential pressure across the wrapper. In the UK, extensive low temperature, lower dose data have been acquired from DFR by D Mosedale and his colleagues using stressed helices. More recently, data have been obtained from helices at higher temperatures, and from in-pile tensile creep machines operated in DFR on Harwell programmes mounted by D R Harris and his colleagues. At the time of writing, these latter machines with continuous strain read-out are showing a temperature dependence which is not monotonic. This will be an active area of study in PFR with data obtained from helices and pressurised tubes, and from actual PFR wrappers using under-sodium measuring equipment operating on scribe marks on wrappers. Present DFR data do not show the marked dependence of irradiation creep on the material composition which void swelling exhibits. It may be that in due course, both swelling and irradiation creep considerations will condition the practical selection of wrapper and cladding alloys.

In order to characterise the consequences of these phenomena, the following table shows the number of full power days at which action is required with PFR wrappers in a central core position and from the outer core ring, either to limit the bow to one which can be comfortably handled by the charge machine (when sub-assemblies are rotated and reinserted), or to limit bulging interference to an acceptable level of total core distortion.

PFR Full power/full flow days to an action point

	PE16		CW 321	
	Bow	Dilation	Bow	Dilation
Ring 2	472	169	154	175
Ring 11	355	387	264	400

These compare with a minimum of 360 full power days for 102 peak burn-up.

From a totality of considerations, but principally core distortions and seismic excitation, it has been decided to concentrate on a passively restrained core design for CFR. The designs being examined have two above-core restraint planes and a compliant wrapper cross-section at the restraint positions to achieve restraint load equalisation and obviate jamming, and the associated reactivity additions which could result from unjamming and core compaction. Two powerful analytical codes SABOW, developed by NPC Whetstone, and CRAMP, developed by Harwell, incorporating friction efforts, have led to the conclusion that, granted the codes are reasonably accurate, the on-power and shutdown loads in a Restrained Core using PE16 wrappers are comfortably acceptable. The experimental endorsement of the codes using both single and multi-sub-assembly compaction and loading rigs is under discussion. The current opinion is that UK CFRs will use passively restrained cores, and a decision to this effect is expected during 1977.

4. MANUFACTURING CONSIDERATIONS

Substantial amounts of core and breeder fuel very similar to preliminary CFR designs, have been made for PFR by BNFL at their Windscale Plutonium Plant and Springfields Uranium Plant; in the latter case both oxide and carbide fuels have been made. Radial blanket oxide designs are sufficiently close to thermal reactor ceramic fuels that no question of feasibility of large scale manufacture exists. The Windscale Plutonium Line was laid out on a Large-Scale basis with sealed face operation. It has generally operated on a cycle involving coprecipitation, fabrication of annular pellets of ca 95% bulk density ground to close tolerances, pin closure by swaging and fusion sealing, assembly of gridded hexagonal sub-assemblies of 142 mm across flats dimensions, each with 325 pins. A significant amount of development fuel has incorporated alternative features such as vibrocompacted oxide, alternative cladding and wrapper alloys, wire wrap support, larger diameter pins and welded end cap pin closure.

Salient considerations of BNFL in reviewing experience in the fabrication of PFR fuel have been the minimising of exposure of personnel to radiation, and minimising the generation of plutonium contaminated equipment and waste material. These considerations have been made against a background policy of ensuring the maximum security of the plutonium during working and in transit, and taking full account of the reprocessing and refabrication stages of the total fuel cycle.

A most important aspect of plutonium plant philosophy arises from considering how to utilise stocks of plutonium in the form of plutonium oxide, and new arisings in the form of plutonium nitrate from a separation plant. With regard to the former point, fuel is already being fabricated for PFR by the physical mixing of plutonium and uranium oxides prior to sintering, and no especial problems have been encountered or are envisaged. With regard to the longer term situation, when the plutonium will be used for making fast reactor fuel as soon as it arises from thermal or fast reactor fuel reprocessing, it is arguable that a route starting with Pu/U nitrate and omitting dry handling could have considerable advantages particularly in respect to minimising operator doseage in the fuel fabrication plant.

This was recognised in the UK in 1970 and since then an increasing proportion of the overall fabrication development programme has been devoted to gel vipak fuel. This concept is based on two grades of spherical granules produced by a gel precipitation process and these are vibro-compacted in the fuel pins. The long term development objectives are for a remotely operated and maintained fabrication plant with minimum operator doseage, minimum plutonium contaminated waste and minimum discharge of plutonium to the environment.

Gel precipitation development on mixed oxide is centred at AERE Harwell and trial quantities of spheres have been made there and fabricated into experimental PFR pins at Windscale: figure 5 shows some of the large spheres, each about 1 mm in diameter. Complementary work on UO_2 spheres has been carried out at BNFL Springfields; a plutonium pilot plant rated at 1 te/annum has been designed and constructed by BNFL at Windscale and is currently being commissioned. Fuel from this plant will cover large scale PFR irradiation trials both of the homogeneous concept, in which both granule sizes are mixed oxide and a'U' fines concept where the fine granules may be uranium oxide. It is noted that the vibro-gel fuel concept would enable plutonium to be stored as mixed oxide granules at one of a small range of enrichments ready for blending and immediate loading into fuel pins.

Development work on the pellet route is centred on the PFR production plant at Windscale. Considerable progress has been made in extensive trials on sintering to size with the object of eliminating grinding. Irradiation experiments are also being mounted in PFR on solid pellets at various smear densities for comparison of performance with the standard annular pellet.

Other areas of development which have emerged from experience with the provision of components for PFR fuel and the fabrication of PFR fuel under industrial conditions in an industrial type facility include:

(i) Development of alternative manufacturing routes for fuel element components, notably continuing development of the routes for the fabrication of wrappers and grids which has led to both improvements in quality and reduction in cost.

(ii) Improvement in the detail design of the fuel element for example the evolution in the fuel pin end closure design from the swage closure of the first PFR charge to the superior butt welded end cap closure for CFR.

5. REPROCESSING CONSIDERATIONS

It is an important longer term requirement of fast reactor fuel that it can be reprocessed relatively soon after reactor discharge and the plutonium returned to fuel new reactors. The reprocessing requirement is that fuel breakdown can be undertaken reliably and with a relatively short cooling period, and with a minimum of material being contaminated by plutonium giving rise to cycle losses and a storage problem. This part of the fuel cycle is not yet highly developed, but substantial consideration has been given to reprocessing techniques and details of fuel design to facilitate dismantling for reprocessing. The two major design directions relevant are in the support method used for pins, that is, gridded or wire-wrapped, and there are arguments for both styles. The UK has a background of grid support for fast reactor fuel based on performance considerations, and is therefore trying to optimise this style from reprocessing considerations, whilst at the same time acquiring irradiation experience with wire-wrapped designs. The intention is to remove the pins from the wrapper/grid assembly prior to shearing the pins into short lengths for nitric acid leaching. Active development is proceeding on a grid style which will adequately meet the several objectives of inexpensive grid manufacture, negligible damage to pins during assembly, adequate pin support in service, and rapid and easy withdrawal of the pin cluster for reprocessing.

6. CFR DESIGN SELECTION

The operation of reactors such as PFR will produce information from irradiation trials covering fuel design concepts, design details, operating parameters and materials which will lead to modifications to the Reference design selections which have been, and are being, made for Commercial Reactors. Nevertheless, Reference Designs and back-up positions have been chosen by all active Organisations for their Commercial Breeders.

The following table lists the relevant parameters of CFR 1 core fuel and alternative positions which will be maintained.

	Reference	Alternative features
Core Style	Passively Restrained	
Core Length	1000 mm	800 mm
Pin Diameter (o.d.) and	6.5 mm)	5.8 mm)
Pin Peak Linear Rating	550 w/cm)	420 w/cm)
Core Pressure Drop	0.75 Mn/m^2	-
Wrapper Material	Nimonic PE16	Austenitic or Ferritic steel
Pin Support	Honeycomb Grids	Wire wrapped
Fuel Density (smear	~ 82%)	~ 90%)
and form)	Vibrocompacted)	Pellet)
Cladding	316-type steel	Other Austenitic steels
Pins per sub-assembly	271	325
Peak clad temperature	670°C	-
Pin Style	Bottom Plenum Integral upper and lower breeder	
Burn-up	Not less than 10% (peak)	

The present intention is to arrange the detailed core layout so that by the time the target burn-up is reached, the inter-sub-assembly clearance will have been taken up by sub-assembly wrapper dilation. However, this may well turn out to be an unnecessarily restrictive design position. For CFR 1, the radial breeder, in an annular zone surrounding the (central) core, will be depleted uranium oxide clad in wire wrapped 316-type steel cladding. Active consideration is being given to adjustable gagging to minimise variations in temperatures in the sodium impinging on the above core structure.

The variables tabulated above are included in the PFR irradiation programmes. The outline barchart shown in figure 6 gives guidance on the expected progress of key items establishing reliable and economic CFR fuel designs.

7. CONCLUSIONS

It is clear that although specific problems may be encountered in particular designs in reaching economically high burn-up in fast reactor oxide fuel pins for large reactors, these problems will yield to straightforward development studies. There is still a significant design/development/endorsement phase to be carried through in the demonstration of restrained core designs which CFR 1 will provide, and with useful contributions from the operation of other reactors with restrained core styles. From the fuel aspect, fuels which will work satisfactorily in Commercial Breeders can be specified now. The task which remains is to delineate fuel which will be attractive for large installation programmes in terms of fabrication, reactor performance and endurance, and reprocessing. The programme timetables scheduled for CFR 1 show that it is possible to carry through the fuel development component of this task by the early 1990's if the system is pursued steadily and with adequate resources. This is the timing required if fast breeder reactors are to be introduced as the major energy source to take over from thermal reactors in the first half of the coming century.

REFERENCES

(1) The Fast Breeder Reactor - Energy without depletion of Natural Resources. R D Vaughan and A A Farmer. Proc Inst Mech Eng, p 163, vol 190 30/1976.

(2) Electron Vacancy Concentration and Void Swelling in some austenitic stainless steels and nickel based alloys. J S Watkin. ASTM 8th International Symposium, St Louis 1976.

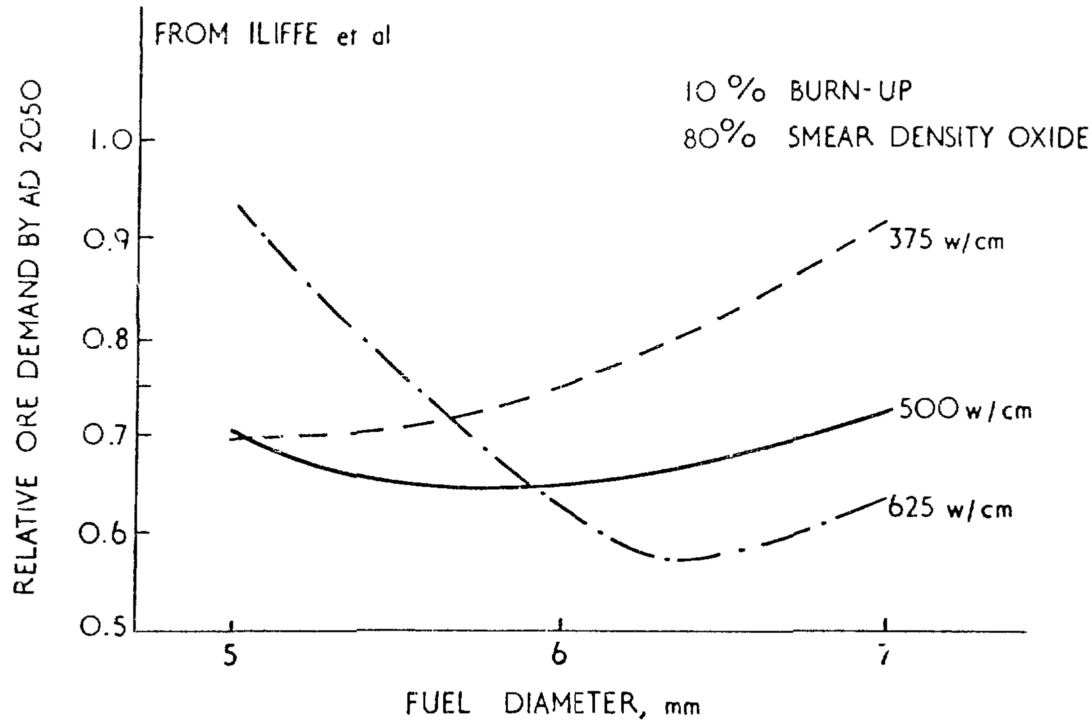


FIG. I. URANIUM UTILISATION AS A FUNCTION OF OXIDE PIN DIAMETER AND LINEAR RATING

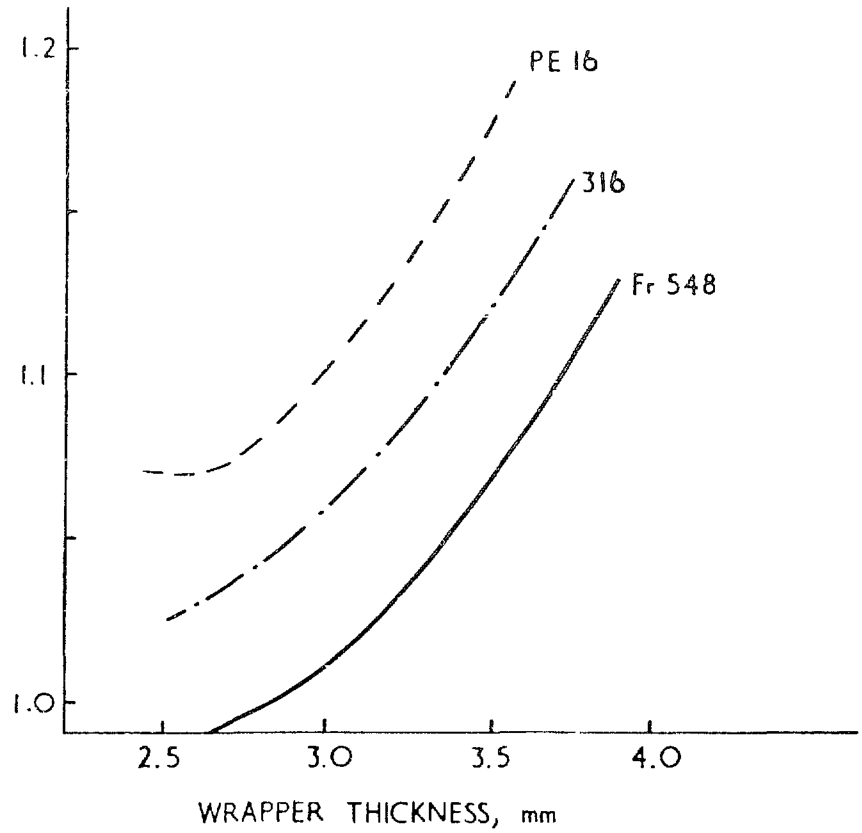


FIG. 2. RELATIVE URANIUM DEMAND AS A FUNCTION OF WRAPPER THICKNESS & MATERIAL

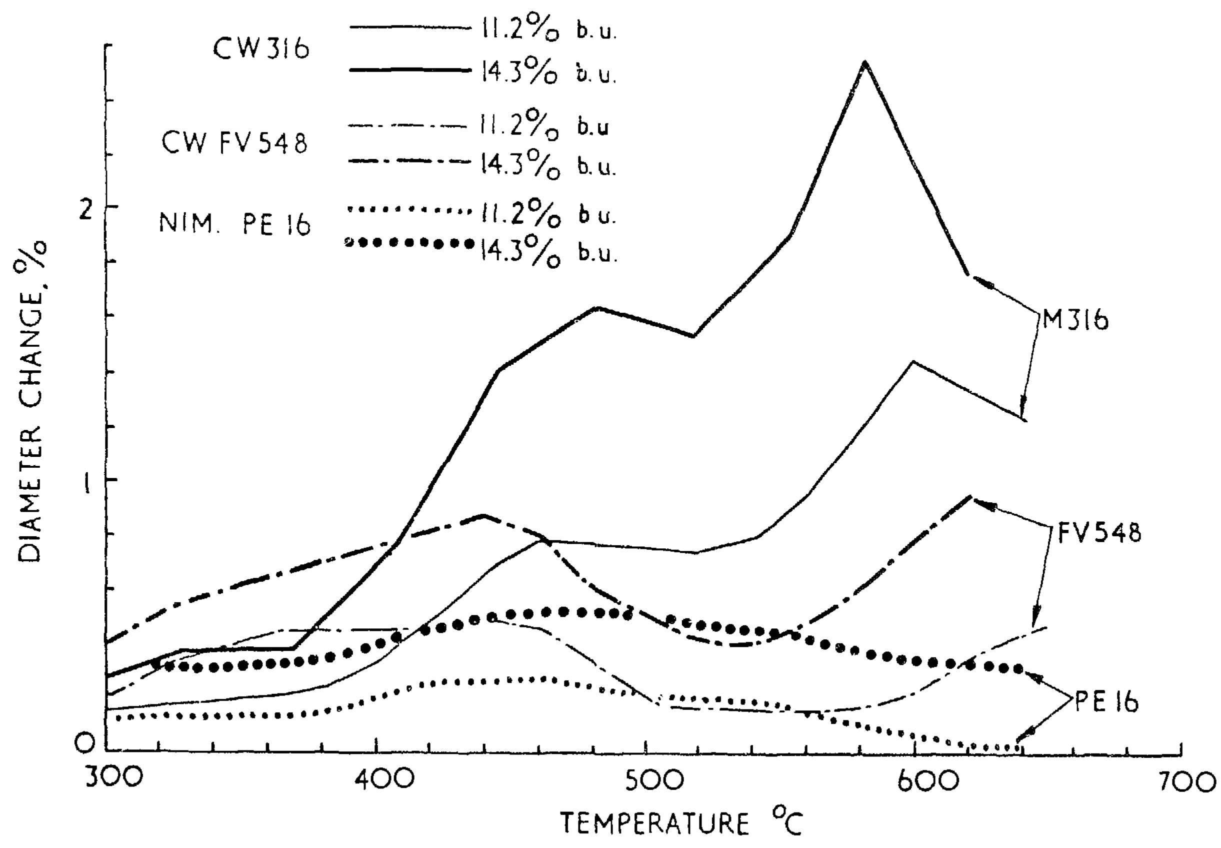


FIG.3. THE INFLUENCE OF CLAD MATERIAL AND BURN-UP ON PIN DIMENSIONAL CHANGES OBSERVED IN DFR

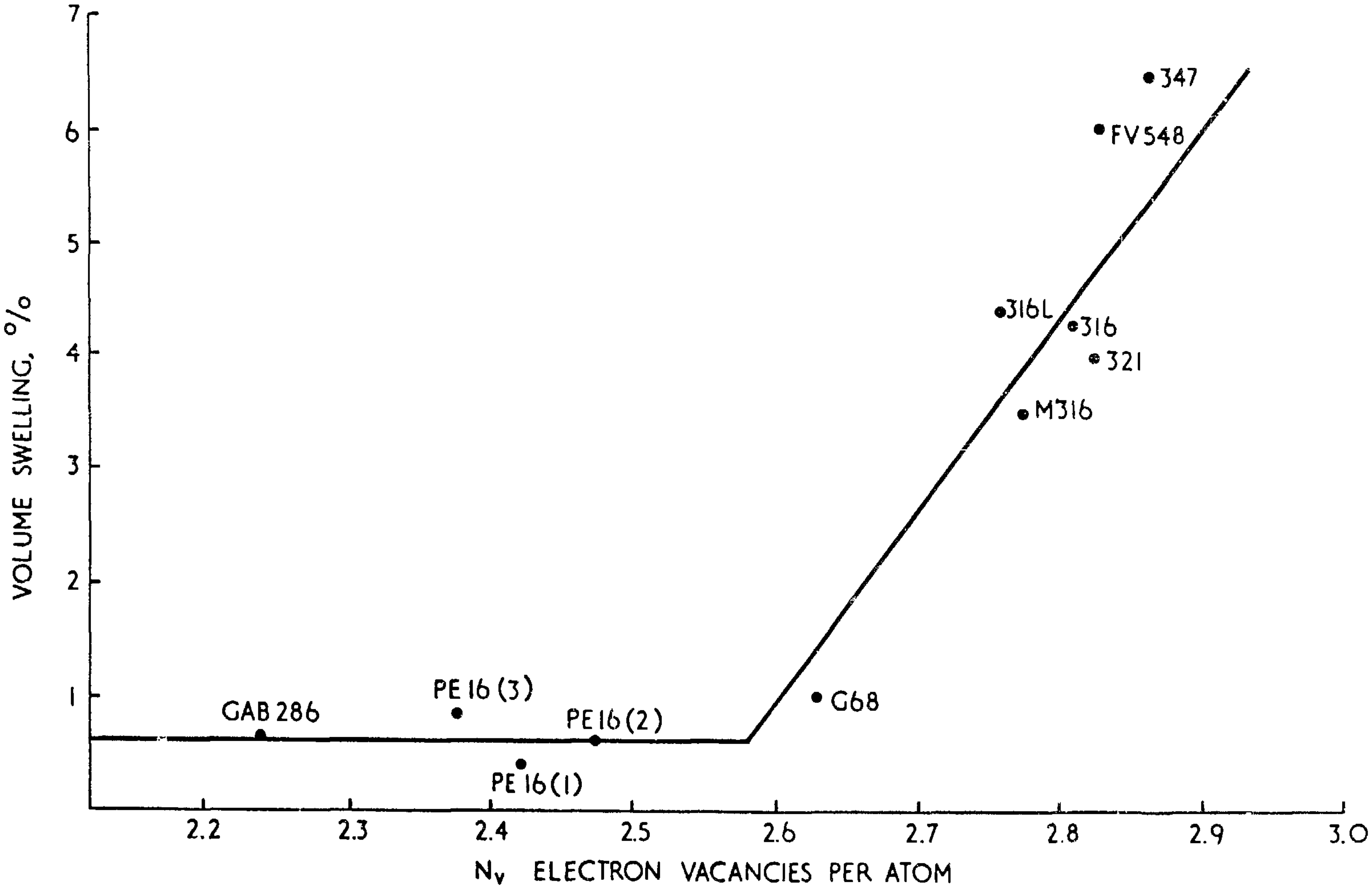
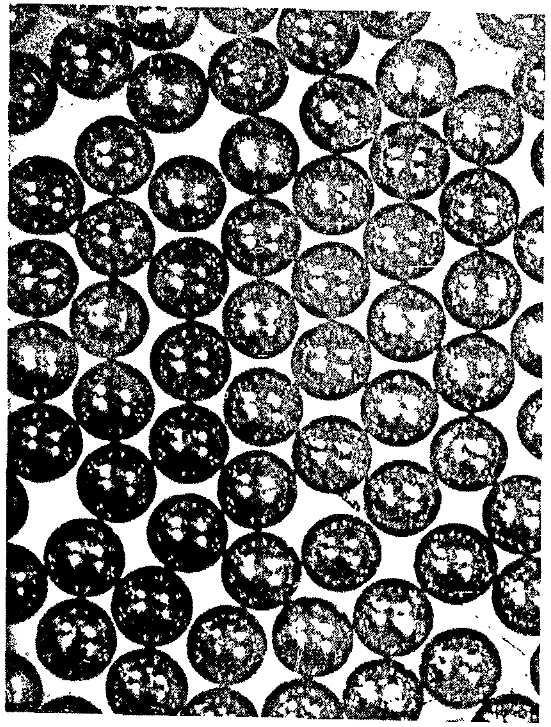


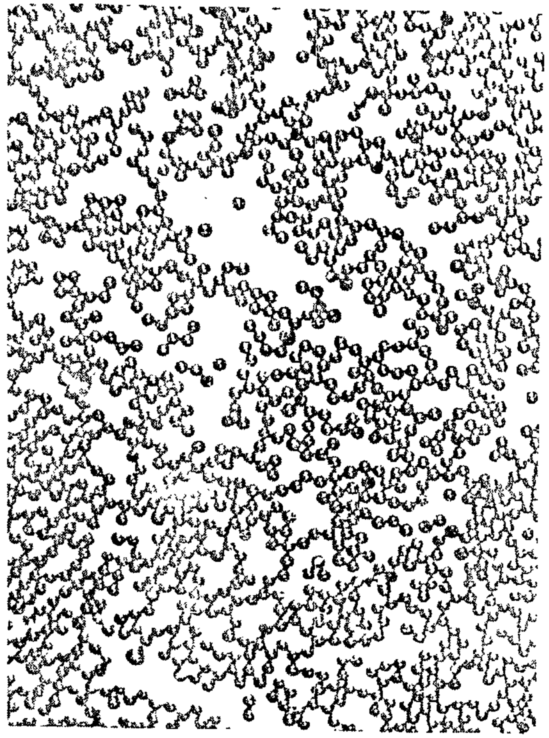
FIG. 4 SWELLING AT 30 dpa AND 600°C AGAINST ELECTRON VACANCY CONCENTRATION

EXTERNAL MICROGRAPHS OF (U/30% Pu) O_2



1 mm

LARGE SPHERES x 15



SMALL SPHERES x 30

FIG. 5.

FIGURE 6

CFR FUEL DEVELOPMENT