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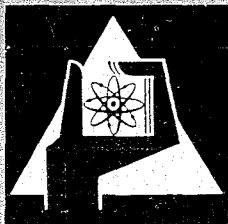
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Institut für Neutronenphysik und Reaktortechnik

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M. Dalle Donne, E. Eisemann, F. Thümmler, K. Wirtz

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[*]Work performed within the association in the field of fast reactors between the European Atomic Energy Community and Gesellschaft für Kernforschung mbH., Karlsruhe.

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TEMPERATURE GAS COOLED REACTORS

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HIGH TEMPERATURE GAS COOLING FOR FAST BREEDERS[*]

M. Dalle Donne[**], E. Eisemann, F. Thümmler, K. Wirtz
Kernforschungszentrum Karlsruhe

REVISED ABSTRACT

There are several reasons that make gas cooling for fast reactors attractive. They have been discussed elsewhere [1] [2]. The main problem for the development is a reliable and satisfying fuel element. Presently we are considering three possibilities for high temperature fuel design.

a) $(U,Pu)O_2$ or $(U,Pu)C$ fuel in a Vanadium alloy cladding

b) Cermets with $(U,Pu)O_2$ particles in a Chromium matrix.

c) Ceramic coated particles.

All three fuels would allow relatively high gas outlet temperatures above $720^{\circ}C$, which allow the use of a direct gas turbine cycle with a net plant efficiency above 40 %.

Nuclear calculations for 1000 MWe cores have been performed in order to examine the nuclear potential of these different types of fuel. In all cases the coolant pressure is considerably higher than the pressure normally used in thermal gas cooled reactors. The special safety aspects that appear in connection with gas cooled fast reactors are briefly discussed although so far no own work has been done in this respect.

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1. INTRODUCTION

The reasons that make gas cooling for fast breeders attractive have been discussed elsewhere /⁻1_7 /⁻2_7. The possibility of high gas outlet temperatures, high plant efficiency, high breeding ratio, cheap fuel cycle potential, good inherent safety features are only a few of them.

A very recent study on gas cooling of fast breeder reactors has been performed by the ENEA-Working-Team on Fast Reactor Evaluation /⁻3_7 where experts of ten european countries participated. This study emphasized the same arguments. Also the studies of GULF-General Atomic have stressed these points /⁻4_7. There is also the aspect that finally the use of gas turbines in a direct cycle might become feasible and may lead to a considerable reduction of capital costs. There is no question that this way will not be an easy one.

Presently helium is the favoured gas. Its main advantage compared for instance to carbon dioxide is that the pressure drop in the core is lower /⁻5_7 and that it is possible to use it in connection with carbide fuel. Carbide seems to be a natural development of the oxide fuel line presently adopted, and offers great advantages as far as fuel cycle and fuel inventory are concerned. From a european point of view it is worthwhile to mention that in the big natural gas sources, for instance in the Netherlands, a sufficient supply of helium is available even for a major program and that this helium can be recovered from the refinery process at reasonable cost. The disadvantage of helium is that the storage of great amounts is much more difficult than with carbon dioxide. The fact that carbon dioxide is cheap and can easily be stored in great quantities may be a reason for using it as a coolant for removing the decay heat in emergency situations if not air itself can be used.

Presently there ar many open questions, mainly with respect to the fuel design. They are very well summarized in the above mentioned ENEA-report and one is probably not wrong in stating that there is no fuel design available that could be the basis of a convincing and preferable

concept of reference design of a fast gas cooled prototype or a 1000 MWe
demonstration plant. This means that the main effort at present has to be
directed to fuel and fuel element development. Next to this safety should
be the area of development effort. But this area is strongly linked to
the final fuel concept.

Presently at Karlsruhe we are considering three types of fuel.
For each type we also perform some controlling calculations about the
fuel potential in a 1000 MWe helium cooled fast power reactor to get an
idea of the plutonium inventory, breeding ratio, doubling time, etc. In
all cases we assume an out of pile time for reprocessing and refabrica-
tion of 0.75 years and 2 % plutonium losses in reprocessing.

The three types of fuel are:

a) $(U,Pu)O_2$ or $(U,Pu)C$ fuel in an especially developed
   Vanadium alloy cladding.

b) Cermets with $(U,Pu)O_2$ particles in a Chromium matrix.

c) Ceramic coated particles.

2. VANADIUM CLAD FUEL PINS

A series of alloys based on Vanadium, Titanium, Niobium and Silicon
are being developed by H. Böhm of the Materials Laboratory of the Karlsruhe
Centre in collaboration with the Metallgesellschaft [6] [7]. These alloys
have very good creep properties at high temperatures given essentially by
the low content of Titanium and the presence of Silicon. They suffer less
from high temperature embrittlement after irradiation in a fast flux than
Nickel based alloys or steels. There are no compatibility problems with
helium and with oxide or carbide fuels up to $800^{\circ}C$ or even above. One of
these alloys containing 10 % of Niobium was used in our previous calculations
[1] [2], the resulting breeding ratio being 1.31. Recent experiments in-
dicate that an alloy without Niobium and with 96 % V, 3 % Ti, 1 % Si after
20000 hours at $850^{\circ}C$ show practically the same stress rupture strength as
Niobium containing alloys. This type of alloy was therefore used in our
latest calculations, the main results of which are given in Table I. One

can see that the breeding ratio is now 1.52. Of the 21 points increase in breeding, 13 are due to the elimination of Niobium, the rest to the reduction in core size with consequent hardening of the neutron spectrum. These breeding ratios have been calculated with the old data for plutonium alpha $\sqrt{\ }8\_7$. Preliminary calculations with new alpha-values show that the breeding ratios would be decreased by about 0.04. The fissile plutonium inventory is 2800 kg for a reactor of 1000 MWe; the system linear doubling time is about 11 years, the fuel cycle cost is 0.7 mills/kwh.

Preliminary calculations with carbide fuel show that the fissile plutonium inventory would be reduced to about 1800 kg.

The helium temperature at core outlet is $720^{\circ}C$ and the resulting maximum hot spot temperature at clad midwall is $845^{\circ}C$. At this temperature the chosen clad material is such that the cladding behaves for the whole core life like a free standing tube. Using a gas turbine cycle with three compressors, three coolers and one recuperator we get from the work of Bammert a net plant efficiency of about 41 % $\sqrt{\ }9\_7$.

Because of this good performance we consider this fuel type promissing, especially because we adopt for the fuel pins the conservative strong clad concept. We shall irradiate in the next few months some Vanadium clad pins with oxide and carbide fuel under full pressure and temperature conditions in our thermal reactor FR-2. Irradiations of Vanadium alloy clad specimens in fast fluxes are being performed. So far we are not yet sure about their embrittlement after irradiation with high fluences and at temperatures above $800^{\circ}C$. H. Böhm will report on these results in due time.

3. CHROMIUM CERMETS

In the Karlsruhe Materials Laboratory we have developed a new type of cermet $\sqrt{\ }10\_7$ $\sqrt{\ }11\_7$. This is obtained by isostatic compression by means of a gas at temperatures up to $1600^{\circ}C$ and pressures up to 800 atms of metal coated uranium oxide particles. The resulting cermet contains a small amount of metal (20 to 30 %). The particles are well separated and still relatively round. The first cermets of this type were made with Molybdenum particles, although this metal is not suited for a fast reactor because of its high neutron absorption. Later it was possible to produce Chromium coated particles

and the relative cermets. Figure 1 and figure 2 show cermets with 20 % and 35 % Molybdenum respectively. Figure 3 and figure 4 with 20 % and 30 % Chromium. In both cases the cermets with higher percentage of metal present a more uniform pattern and better rounded particles, although in both cases the particles are well separated by the metal. It is to be expected therefore that the fission product retention is better with the higher percentage of metal. The dimensional stability under irradiation should be good with particles containing some porosity. It is possible to attach during the process of hot compression a thin metal clad to the surface of the compressed pin. In our samples we used a 0.2 to 0.3 mm thick steel, Niobium or Vanadium can.

Table II shows the results of a calculation performed with fuel elements of a cermet with $(U,Pu)O_2$ with 20 % Chromium metal. These are rather similar to those obtained with the Vanadium clad pins. Molybdenum cermets are already being tested under irradiation, Chromium cermets will be irradiated shortly in FR-2. At the same time we are attempting to produce Vanadium coated particles and later Vanadium cermets.

The cermet line could give a good alternative to the more classical system of ceramic fuel contained in metal tubes due to the likely good fission products retention qualities of these cermets and their excellent thermal conductivity. It perhaps involves a new pin concept due to the possibility of strong bonding between fuel and can with higher strength properties. However, this is a relatively new type of fuel for fast reactors and it requires a great deal of experimental work yet.

4. CERAMIC COATED PARTICLES

700 to 750°C is probably the maximum helium temperature at core outlet possible with a metal clad type of fuel element. It appears that the only possibility of increasing this temperature considerably, say in the region 900 to 1000°C, is the use of an all ceramic core with fuel particles coated by graphite and/or Silicon carbide. This would mean an increase of plant net efficiency up to 50 % or a reduction of plant capital costs of the order of 10 to 15 %, where, due to the already low fuel cycle costs of a fast reactor, this second alternative seems more appealing.

We have therefore performed a calculation assuming as fuel coated particles with a 1.4 mm diameter kernel of mixed uranium and plutonium carbides and a triplex 120 μ thick coating (two layers of graphite, one of Silicon carbide) contained in a graphite matrix. The total amount of carbon in the fuel is about 50 volume percent in addition to the carbides. This type of particles is the same as those so successfully tested for thermal reactors. However, the kernel diameter is considerably bigger. The results of this calculation are illustrated by Table III. In this connection it is interesting to mention the gas cooled fast reactor presently under study in the U.K. $\angle$ 12 $\angle$. Here the coated particles are directly cooled by the helium flow. This has a double advantage, i.e. reduction of the quantity of graphite in the core with consequent improvement of the breeding and very effective heat transfer due to the large fuel surface per unit core volume. This completely novel type of fuel elements could of course present problems especially hot spot problems. But there are other difficulties in using coated particles in fast reactors. The presently developed pyrolitic graphite cannot withstand the very high fast fluence (10^{23} nvt) required in a fast commercial reactor at high temperatures $\angle$ 3 $\angle$. Silicon carbides seems to be much better in this respect (the dimensional change is only 0.1 % at 1200°C and 10^{22} nvt fast fluence $\angle$ 3 $\angle$) but it is a very brittle material. We have performed rough calculations which show that a Silicon carbide layer alone cannot so well withstand the pressure of fission products produced inside the particle kernel, as in the case of a triplex type of particle in a thermal reactor, where the outer shell of pyrolitic graphite keeps the Silicon carbide unter compression. In a fast reactor the outer layer of graphite would crack before reaching the required fluence and would not keep Silicon carbide under compression. Our calculations have been confirmed by recent irradiation results from Oak Ridge $\angle$ 13 $\angle$ which show a fractional fission gas release of 10^{-4} for particles with a Silicon carbide outer layer against 10^{-8} for triplex particles.

It seems to us therefore that the development of coated particles for fast reactors should go in the direction of, firstly, improving the dimensional stability of graphite in a fast flux (even if this task will not be an easy one because a lot of work has been done already for thermal reactors) and, secondly, to decrease the degree of brittleness of Silicon carbide. At the same time, different types of multilayer coatings should be tried.

5. SAFETY

We have not yet performed detailed safety studies on gas cooled fast reactors, but we think it worthwhile here to mention a few of the characteristic safety questions.

The helium pressure chosen in our calculation is 100 atms. This rather high pressure is dictated by the very high power density required in a fast core. We believe that it is not unrealistic. It has been proven by experience in Germany /‾14_7 that it is possible to build prestressed concrete pressure vessels capable to withstand such a pressure. It is known that the concrete vessel offers a higher degree of safety in comparison with a steel vessel. In general the coolant pressure required by a gas cooled fast reactor lies in the region of 50 to 120 atms (this last figure refers to carbide fuel) and is considerably higher than that required by the most advanced gas cooled thermal reactors. This, together with the much smaller heat capacity of the core, makes the depressurisation accident much more severe than in a thermal reactor.

Preliminary calculations show that a depressurisation accident does not damage the core if the control rods can act within 10 to 30 seconds after the start of the accident and the pressure ratio between initial and final pressure is not higher than 50 to 70. This means that for pressures higher than 50 to 70 atms a secondary containment capable of withstanding some pressure (2 to 3 atms) is required. This of course is not a terrible economic penalty when a double containment is required anyway.

It is interesting to notice that ceramic cores are probably inherent safe in respect of this accident, in the sense that they don't even require the acting of the control rods. This effect is produced by the fast acting Doppler coefficient.

In comparison to sodium or steam cooled fast reactors gas cooled ones have an almost negligible loss of coolant reactivity coefficient. This, together with the fact that spert-type accidents possible with sodium, here cannot occur, has the consequence that big reactivity ramps are not possible in gas cooled fast reactors.

A curious fact is that fast reactors are safer than gas cooled thermal reactors in the case of water ingress in the primary circuit. Indeed, contrary to the thermal ones, fast reactors lose reactivity if the water contained in one or two heat exchangers enters in the primary coolant circuit /¯15_7 /¯16_7.

A very important point for the safety of the gas cooled fast reactor is the functioning of the coolant blowers. The helium natural convection helps very little. While a thermal reactor can probably operate as much as 30 minutes without power supply to the blowers, a fast reactor cannot for more than 1 or 2 minutes. The reliability and availability of the blowers should be then greatly enhanced by means of sufficient redundancy in the blowers and diversity in the blowers energy supply.

6. CONCLUSIONS

1. With gas cooled fast reactors it should be possible to have a system doubling time of about 11 years with oxide fuel and about 7 years with carbide. These values compare rather favourably with the corresponding values with sodium, in spite of the slightly higher plutonium inventories, because of the overcompensating effect of the better breeding. They are of course much better than those possible with fast steam cooled reactors.

2. The real advantage compared with sodium lies in the possibility of considerably reduced capital costs, especially in the case of direct cycle. If it is possible to develope a fuel element with Silicon carbide coated particles capable of withstanding a large fast fluence, then even higher helium temperatures and further reductions in capital are possible.

3. The direct cycle with gas turbines requires considerable development work for reactor components, but much of this is already under way in Germany for high temperature helium cooled thermal reactors.

4. A great deal of work is necessary to develope fuel elements capable of producing helium at temperatures interesting for gas turbines. We have started a three pronged effort with:

   a) mixed oxides or carbides canned in an especially developed Vanadium alloy,

   b) cermets obtained by isostatic compression of metal coated particles,

   c) graphite and/or Silicon carbide coated particles,

The last type of fuel is the one which allows the highest temperatures, but it has probably the smallest chance of success.

5. Fast reactors require considerably higher gas pressures than thermal gas cooled reactors, especially in the case of carbide fuel. This could mean supplementary reactor component development work and it means certainly more stringent engineered safeguards, such as the adoption of a high pressure double containment and of a reliable and redundant system of blowers.

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TABLE I   Main Parameters of a 1000 MWe GCFR

| Vanadium clad oxide fuel	
Diameter of the core (cm)	300
Height of the core (cm)	120
Core volume (liters)	8470
Cladding	Vanadium alloy (96 % V, 3 % Ti, 1 % Si)
Fuel volume fraction	0.298
Coolant volume fraction	0.552
Structural material (16/13 S.S.) volume fraction	0.073
Cladding volume fraction	0.077
Fuel pin diameter (cm)	0.74
Clad thickness (mm)	0.4
Core inlet coolant temperature ($^{\circ}$C)	410
Core outlet coolant temperature ($^{\circ}$C)	720
Maximum nominal surface temperature ($^{\circ}$C)	765
Maximum midwall clad hot spot temperature ($^{\circ}$C)	845
Maximum fuel pin linear power (W/cm)	480
Coolant pressure at core inlet (kg/cm^2)	100
Pressure drop in core (kg/cm^2)	4.4
Total thermal output (inclusive of heat produced in blankets) (MWth)	2497
Plant net efficiency with gas turbine cycle	40.8 %
Core power density (KW/liter)	272
Total fissile mass in core (kg of Pu 239 + Pu 241)	2800
Average rating (MWth/$_{\text{kg Pu 239 + Pu 241}}$)	0.892
Maximum mean burn-up (MWD/t)	55,000
Oxide density	83 % of theoretical
U 235 in blankets	0.4 %
Internal conversion ratio	0.897
Total breeding	1.517
Breeding gain ($\frac{\text{Excess Pu atoms produced}}{\text{Total atoms fissioned}}$)	0.477
Doppler constant - T $\frac{dk}{dT}$ (T in $^{\circ}$K)	0.644 x 10^{-2}
Reactivity in coolant (\$)	0.67
System linear doubling time (years)	11.0

TABLE II   Main Parameters of a 1000 MWe GCFR

| Chromium cermet with oxide fuel	
Diameter of the core (cm)	300
Hight of the core (cm)	120
Core volume (liters)	8470
Fuel volume fraction	0.300
Coolant volume fraction	0.552
Chromium and structural material (16/13 S.S.) volume fraction	0.148
Fuel pin diameter (cm)	0.74
Core inlet coolant temperature ($^{\circ}$C)	410
Core outlet coolant temperature ($^{\circ}$C)	720
Maximum nominal surface temperature ($^{\circ}$C)	765
Maximum fuel pin linear power (W/cm)	480
Coolant pressure at core inlet (kg/cm^2)	100
Pressure drop in core (kg/cm^2)	4.4
Total thermal output (inclusive of heat produced in blankets) (MWth)	2486
Plant net efficiency with turbine cycle	40.8
Core power density (KW/liter)	272
Total fissile mass in core (kg of Pu 239 + Pu 241)	2862
Average rating (MWth/$_{kg\ Pu\ 239\ +\ Pu\ 241}$)	0.869
Maximum mean burn-up (MWD/t)	55,000
Oxide density	83 % of theoretical
U 235 in blankets	0.4 %
Internal conversion ratio	0.897
Total breeding ratio	1.51
Breeding gain ($\frac{Excess\ Pu\ atoms\ produced}{Total\ atoms\ fissioned}$)	0.469
Doppler constant - T $\frac{dk}{dT}$ (T in $^{\circ}$K)	0.458 x 10^{-2}
Reactivity in coolant ($)	0.64
System linear doubling time (years)	11.1

TABLE III   Main Parameters of a 1000 MWe GCFR

Graphite coated particles	
Diameter of the core (cm)	330.4
Height of the core (cm)	131.6
Core volume (liters)	11,280
Fuel volume fraction	0.2072
Coolant volume fraction	0.55
Graphite and Silicon carbide volume fraction	0.2428
Hydraulic diameter of coolant channel (cm)	1.462
Core inlet coolant temperature (^{o}C)	590
Core outlet coolant temperature (^{o}C)	930
Maximum nominal fuel element surface temperature (^{o}C)	1293
Maximum nominal fuel element temperature (^{o}C)	1430
Coolant pressure at core inlet (kg/cm^{2})	100
Pressure drop in core (kg/cm^{2})	0.75
Total thermal output (inclusive of heat produced in blanket) (MWth)	2829
Net plant efficiency with gas turbine cycle	50 %
Core power density (KW/liter)	222
Total fissile mass in core (kg Pu 239 + Pu 241)	3077
Average rating (MWth/$_{\text{kg Pu 239 + Pu 241}}$)	0.92
Maximum mean burn up (MWD/t)	55,000
Carbide density	90 % of theoretical
U 235 in blankets	0.4 %
Internal conversion ratio	0.966
Total breeding ratio	1.31
Breeding gain ($\dfrac{\text{Excess Pu atoms produced}}{\text{Total atoms fissioned}}$)	0.31
Doppler constant - T $\dfrac{dk}{dT}$ (T in ^{o}K)	2.0 x 10^{-2}
Reactivity in coolant (¢)	+0.93
System linear doubling time (years)	16.2

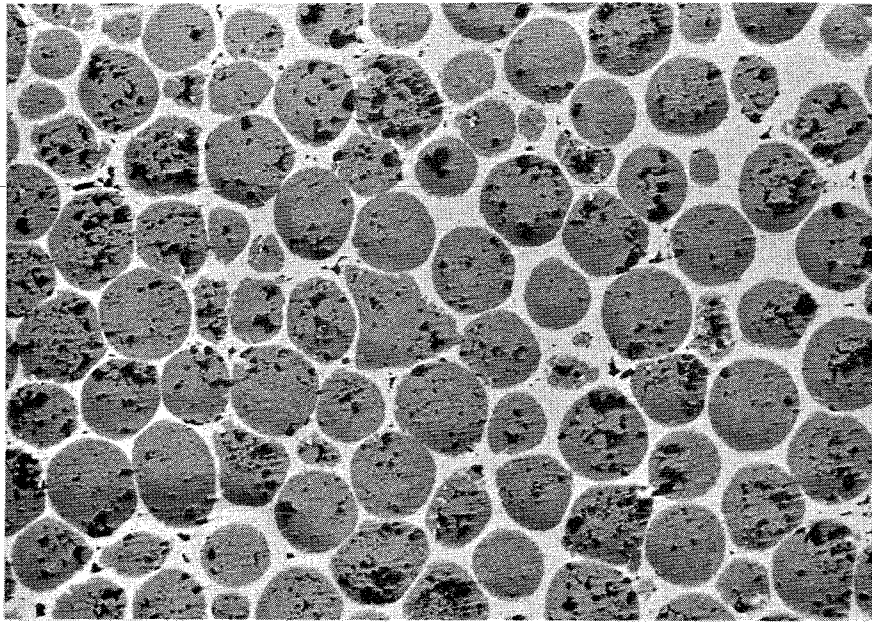Fig. 1   UO$_2$/20 % Mo-cermet isostatically hot compressed
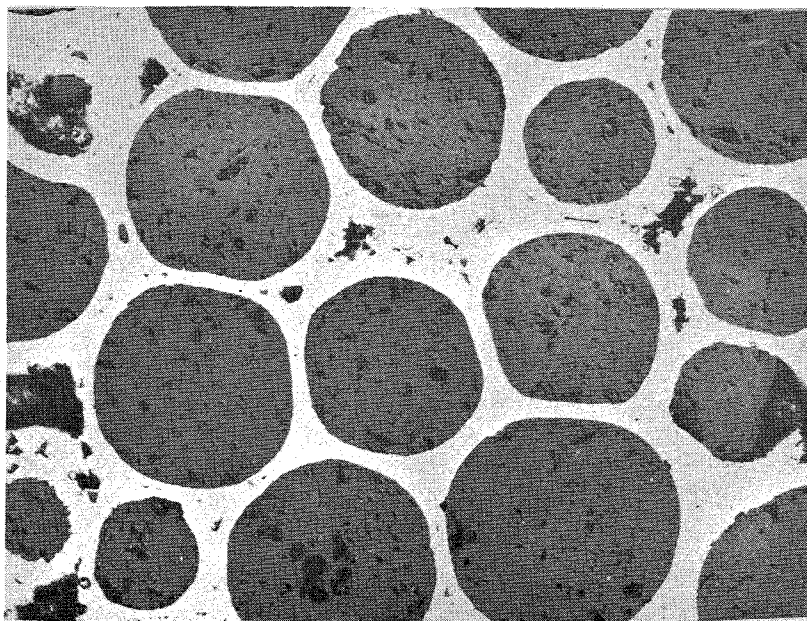
100 μm

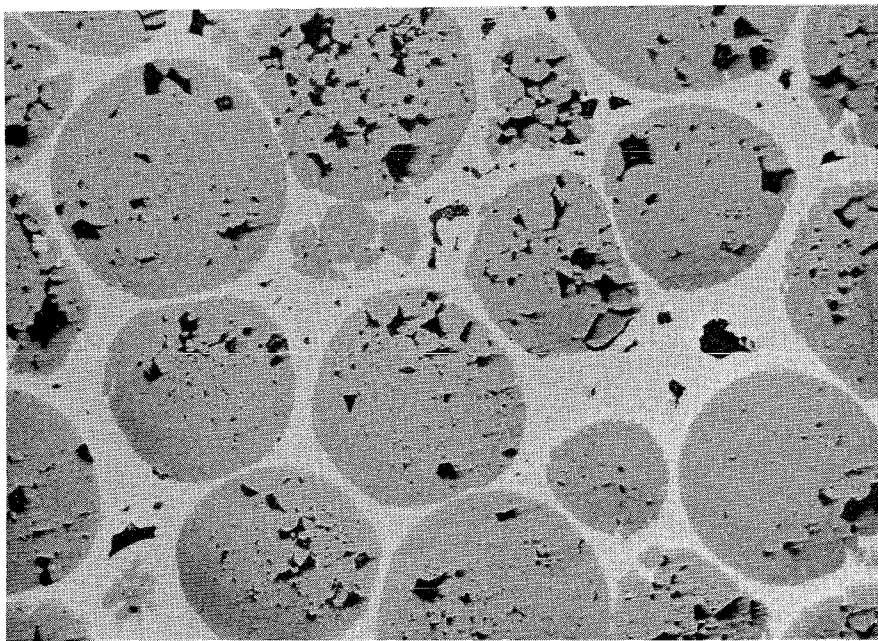Fig. 2   UO$_2$/35 % Mo-cermet isostatically hot compressed
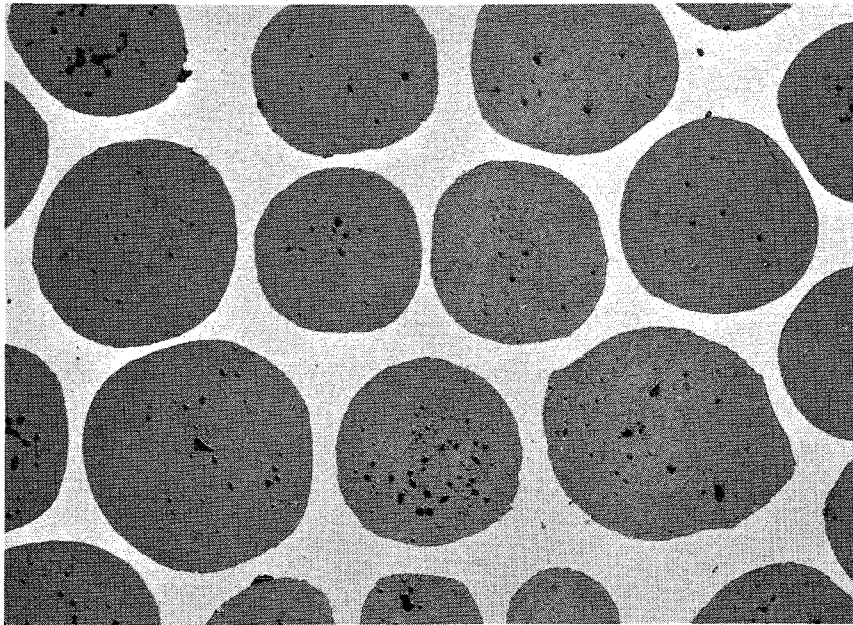
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Fig. 3   UO$_2$/20 % Chromium cermet isostatically hot compressed
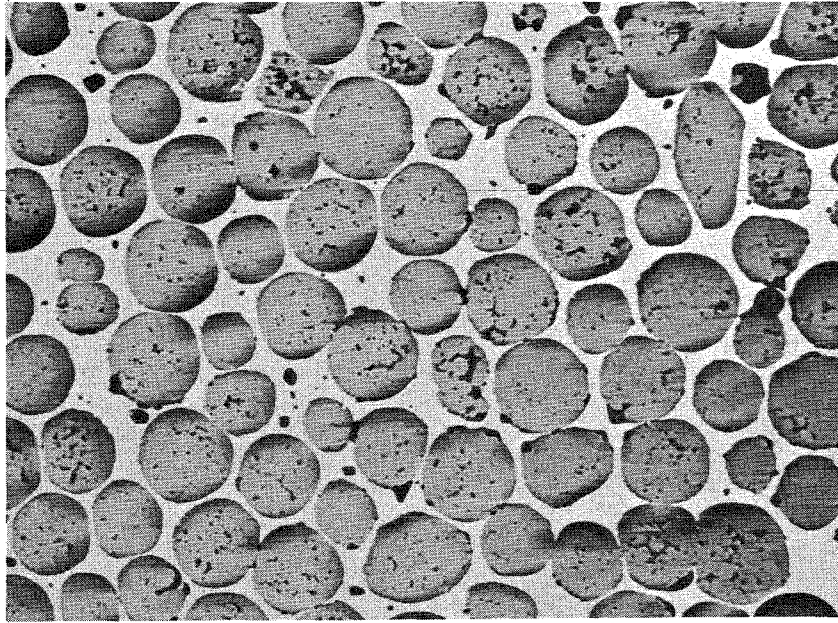

218 μm

86 μm

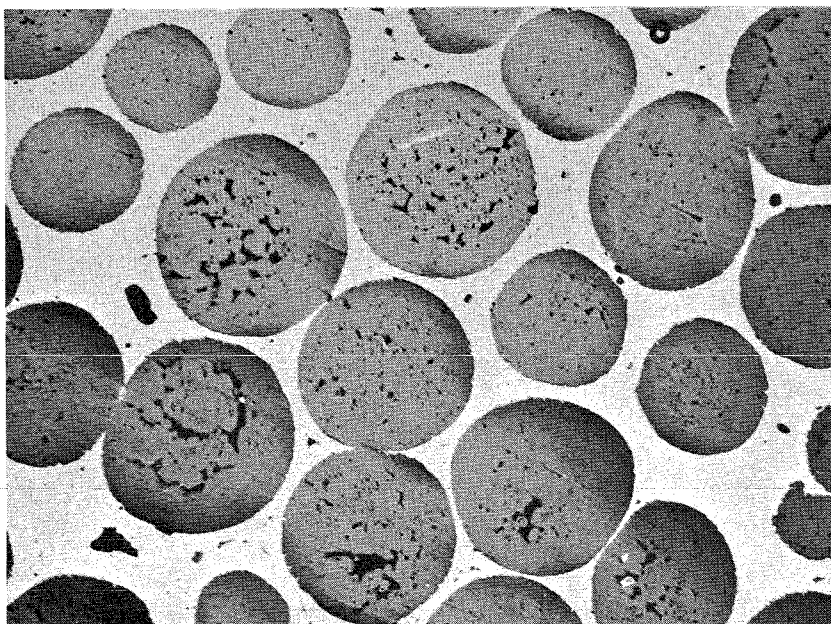Fig. 4   UO$_2$/30 % Chromium cermet isostatically hot compressed

200 μm

100 μm