KERNFORSCHUNGSZENTRUM

KARLSRUHE

November 1967

KFK 689

Institut für Neutronenphysik und Reaktortechnik

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GESELLSCHAFT FÜR KERNFORSCHUNG M. B. H.

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# Gas Cooling for Fast Breeders

by

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(Paper prepared for the Winter Meeting of the American Nuclear Society, Chicago, November 5 - 9, 1967)

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Taken all work on fast breeders together, probably more than 90% of the effort is directed to sodium cooling. The technical and economical success of sodium cooling seems probable but nevertheless is still not yet granted. I only mention the unsolved problem of preventing superheat of sodium in case of cooling channel blockage, the problem of power coefficients, and the economical question whether it will be possible to design and construct reliably the big sodium components like heat exchangers and pumps. In case of steam cooling questions of cladding material, nuclear stability, and neutron economy are open. One of the first studies at the Karlsruhe Nuclear Research Center in connection with the breeder project was concerned with helium cooling. One of the results that was reported at the 1963 ANS Meeting at Salt Lake City was that indeed high-power densities in the order of .5 to 1 MWth/kg fissile material could be attained. But the great difficulties for gas cooling were also realized, to mention only the big heat exchangers, the great pumping power, and especially the lack of good high-temperature cladding material. Therefore, the arguments I mentioned would not justify to take up again the question of gas cooling if not important developments had made the use of gaseous coolants for fast reactors attractive again. Let me mention only a few ones [1].

The development in the field of prestressed concrete pressure vessels for very high pressures is well-known [2]. A concrete vessel for 100 atm has been recently built in Germany and tested successfully at full pressure. It has been concluded that pressures up to 175 atm will be possible. Concrete vessels are not only cheaper than steel vessels, they are also safer because their great mass makes a sudden catastrophic failure highly improbable. The British have demonstrated that it is possible to keep the walls in case of gas cooling at low temperatures, a problem that would be much more difficult with steam.

The use of partially roughened fuel element surfaces originally advocated by Fortescue has been adopted for the AGR power stations in the U.K.. Partial roughening allows a considerable increase in power density and a reduction in the required pumping power. Rough surfaces must only be present in a small portion in the fuel pins where wall temperatures are the highest thus avoiding a supplementary pressure drop where it is not required.

More important are the new aspects in the field of fuel elements . Alloys on the base of high vanadium contents with extremely good creep properties at high temperatures have been developed as canning materials. Due to their relatively low content of niobium they do not affect unduly the breeding ratio. We are sorry not to be able to report on the detailed composition of the alloys. We are presently looking into their behavior under irradiation. The out-of-pile tests look promising and surface temperatures in the region of 800°C seem feasible. This would allow h elium outlet temperatures up to about 720°C. This brings us into the neigborhood of temperatures where the use of gas turbines becomes interesting.

Until fairly recently big gas turbines have been considered as not available. After stating this in the 1965 Foratom Congress at Frankfurt (Germany) in view of the development of future high-temperature reactors [3], several European industries have announced that gas turbines of 250, 500 and even 1.000 MW are feasible. Estimated costs for a 250 MW gas turbine set including the heat exchanging components are around 5 million $ [4]. The availability of gas turbines stimulated further attention to the fuel element questions of a gas cooled breeder. In our opinion, the helium temperature of 720°C is practically the upper limit when using metal clad pins. Cladding metals suitable for higher temperatures such as tungsten, tantalum, molybdenum, niobium would unduly decrease the breeding gain. On the other hand, in a gas turbine cycle contrary to the case of steam cycle, further increases of temperatures are very effective in improving the plant efficiency and reducing the capital costs. It is known that in thermal high-temperature reactors other types of fuel elements allow much higher helium temperatures. The success of experiments like Dragon and Peach Bottom is one more reason to look into gas cooling for fast breeders and the idea of extrapolating also the fast breeder into these temperature regions seems appealing. Quite generally, it seems that gas cooling for nuclear reactors, thermal ones as well as fast breeders, depends on whether really very high temperatures in the core finally become feasible. If the future development of nuclear fuels would allow gas temperatures in the core around or better well above 1.000°C there would be a chance for reducing drastically the gas pressure. That would open the way to true cost reductions independent of whether gas turbines or steam generators are used and also independent of whether the hot gas is used at its core or at a lower temperature (for instance by mixing with cool gas). Therefore, the goal for the present development must be high temperature fuel.

In the thermal reactors the use of graphite is the basis for the higher temperatures. Graphite is, however, a good moderator and in a fast reactor the amount of graphite must be kept as small as possible. To have an idea of the possibilities with graphite, we performed a calculation assuming graphite coated particles with a kernel with a diameter of 1.4 mm of mixed uranium and plutonium carbides with 120 $\mu$ thick coating in a graphite matrix. German industry has stated the possibility to produce such particles. The particle packing was assumed to be about 74% which seems possible by blending particles of 2 different sizes. This type of very big coated particles seems technically feasible today and allows fuel pins that contain about 50 volume per cent of carbon in addition to the carbides. The behavior of this type of fuel will also be studied under irradiation. Before we discuss the nuclear and thermal behavior of this fuel in a reactor, we like to mention another development line that is trying to improve the breeding gain still retaining relatively high temperatures.

F. Thuemmler of the Institute of Materials Research at the Karlsruhe Nuclear Research Center has developed a method for compacting metal coated particles by hot compression to produce a cermet with a very small amount of metal [5].

The fuel particles remain more or less round and are well separated from each other. It is hoped that with this system it will be possible to have fission products retaining. Fig. 1 and 2 show cermets with 20% and 35% molybdenum. These pictures are shown only to demonstrate the metal coating and the result of the compacting of the coated particles into a solid structure. Molybdenum will not be the metal of our choice as coating material for a breeder fuel. Much better would be chromium that has a rather high melting point and is much better from a neutronic point of view. Chromium coating is studied at the moment and we have had first positive results. Other coating materials are under study. Fig. 3 shows a pin which is the result of the high pressure (800 atm) high temperature (1600°C) compression process in a helium atmosphere, with and without clad. The pin is with molybdenum coated particles.

To assess the potential of the fuels described, we calculated examples of reactors for 1.000 MWe power plants, the fuel being plutonium uranium carbide in the case of carbon coating and oxides in the case of metal coating. The tables 1 to 3 show results of the thermodynamic and of the four group two dimensional neutronic calculations, the four groups being condensed from the Russian 26 group ABN cross section set.

In table 1 fuel elements with metal cladding, two of them based on the vandium alloy are considered. Three reactors have been calculated, one reactor with heat exchangers and 2 others at different pressures operating with a gas turbine. In all three cases the cladding behaves even at the maximum hot spot temperature (725°C, 845°C, and 835°C respectively) like a free standing tube (strong can). The first reactor produces helium at 600°C, the cladding is the well-known inconel 625. The breeding ratio is 1.3 and the rating .74 MWth/kg fissile material. The internal conversion ratio is such to guarantee a small reactivity swing for the chosen burn-up.

The doubling time is 12 years, the cooling void-coefficients only .98 \$. Rather large spacing between the pins which is allowed by the nuclear properties of the coolant offsets completely the better heat transfer properties of steam. With the use of variable roughening it is conceivable that the total pumping power would be about 4% of the electrical output which is equal to the best values so far of the Hinkley Point B AGR.

The second reactor uses the vanadium alloy and has practically the same geometry, breeding ratio, rating, doubling time, and void-coefficient as the first one. The gas outlet temperature has been raised from 600 to 720°C suitable for a gas turbine. In the third reactor the helium is at 175 atm which is about the same pressure as in our Karlsruhe steam-1 design [6]. Such a reactor looks very promising with respect to net efficiency, average rating, breeding ratio, etc.

Table 2 shows the same for the carbon coated fuel. The coolant outlet temperature is now 930°C, the maximum fuel surface temperature 1293° C, the coolant pressure 100 atm. The net efficiency is 50%, the breeding ratio 1.3 and the loss-of-coolant reactivity .93 \$, the doubling time about 10 years.

Table 3 shows the same data for a chromium coated fuel for the pressures 100 and 175 atm. The outlet temperature being 720°C, the breeding ratio is 1.36, slightly better than in the case of carbon coating. We consider the value of these results to be only in demonstrating that gas cooling of fast breeders with a variety of different fuel and canning materials is feasible. We shall not enter into any design studies before we have no definite results on fuel and cladding. For this we need the irradiation tests.

There are other basic problems in the design of a gas cooled reactor that have to be cleared before any real project studies could be started. One is a reasonable and safely operating independent second shut-down system. On the other hand, much engineering experience could be gained from projects like Peach Bottom and Dragon. The Karlsruhe Nuclear Research Center is not entering right now into the project of a gas cooled fast breeder, but we are keeping an eye on this development that might become of importance in coming years. Perhaps it should be mentioned also that there are several big industries in Europe that seem to be interested to participate in our studies. Our paper is only to indicate the present line of our approach to the problems of gas cooling of fast breeders.

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Table 1

| METAL CLAD FUEL | steam turbine plant | Reactor for gas turbine plant (100 atm) | gas turbine plant (175 atm) |
|---|---|---|---|
| Diameter of the core (cm) | 330, 4 | 330, 4 | 263, 2 |
| Height of the core (cm) | 131, 6 | 131, 6 | 131, 6 |
| Core volume (liters) | 11.280 | 11.280 | 7.160 |
| Cladding | Inconel-625 | Vanadium alloy | Vanadium alloy |
| Fuel volume fraction | 0, 3033 | 0, 3033 | 0, 3033 |
| Coolant volume fraction | 0, 5489 | 0, 5489 | 0, 5489 |
| Structural and cladding volume fraction | 0, 1478 | 0, 1478 | 0, 1478 |
| Fuel pin diameter (cm) | 0, 827 | 0, 827 | 0, 659 |
| Total fissile mass in core (kg of Pu-239 + Pu-241) | 3372 | 3.279 | 2.195 |
| Core inlet coolant temperature ($^{o}$C) | 260 | 380 | 380 |
| Core outlet coolant temperature ($^{o}$C) | 600 | 720 | 720 |
| Maximum nominal surface fuel element temperature ($^{o}$C) | 646 | 766 | 757 |
| Maximum hot spot temperature ($^{o}$C) | 725 | 845 | 835 |
| Maximum fuel pin linear power (W/cm) | 439, 6 | 439, 6 | 439, 6 |
| Coolant pressure at core inlet (kg/cm$^2$) | 100 | 100 | 175 |
| Ratio pumping power required by reactor thermal output | | | |
| with constant roughness | 0, 0132 | 0, 0183 | 0, 0161 |
| with variable roughness | 0, 0109 | 0, 0147 | 0, 0131 |
| Total thermal output (inclusive heat produced in blankets) (MWth) | 2, 759 | 2.764 | 2.832 |
| Net efficiency | 39, 8 % | ~ 40 % | ~ 40 % |
| Core power density (kW/liter) | 222 | 222 | 349 |
| Average rating in core (MWth/kg Pu-239 + Pu-241) | 0, 742 | 0, 763 | 1, 14 |
| Internal conversion ratio | 0, 94 | 0, 957 | 0, 90 |
| Total breeding ratio | 1, 30 | 1, 314 | 1, 31 |
| Doppler constant $-T \frac{dk}{dT}$ (T in $^{o}$K) | $0,548 \cdot 10^{-2}$ | $0,694 \cdot 10^{-2}$ | $0,65 \cdot 10^{-2}$ |
| Reactivity variation due to loss of coolant ($) | + 0, 98 | + 0, 93 | + 1, 42 |
| Doubling time (years) | 12, 0 | 11, 2 | 7, 5 |

Table 2

| Graphite Coated Particles | Reactor for gas turbine plant |
|---|---|
| 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 Sylicon carbide volume fraction | 0, 2428 |
| Hydraulic diameter of coolant channel (cm) | 1, 462 |
| Total fissile mass in core (kg of Pu-239 and Pu-241) | 3077 |
| Core inlet collant temperature ($^{o}C$) | 590 |
| Core outlet temperature ($^{o}C$) | 930 |
| Maximum nominal surface fuel element temperature ($^{o}C$) | 1293 |
| Maximum nominal fuel element temperature ($^{o}C$) | 1430 |
| Coolant pressure at core inlet ($kg/cm^2$) | 100 |
| Ratio pumping power required by reactor to core thermal output (smooth surface) | 0, 91 % |
| Total thermal output (MWth) | 2829 |
| Net efficiency | ~50 % |
| Core power density (kW/liter) | 222 |
| Average rating in core (MWth/kg Pu-239 and Pu-241) | 0, 813 |
| Internal conversion ratio | 0, 966 |
| Total breeding ratio | 1, 31 |
| Doppler constant $-T \frac{dk}{dT}$ (T in $^{o}K$) | $2,0 \cdot 10^{-2}$ |
| Reactivity variation due to loss of coolant ($) | + 0, 93 |
| Doubling time (years) | 9, 7 |

Table 3

| CHROMIUM CERMET FUEL | Reactor for gas turbine plant 100 atm | 175 atm |
|---|---|---|
| Diameter of the core (cm) | 330, 4 | 263, 2 |
| Height of the core (cm) | 131, 6 | 131, 6 |
| Core volume (liters) | 11.280 | 7.160 |
| Fuel volume fraction | 0, 3049 | 0, 3049 |
| Coolant colume fraction | 0, 5489 | 0, 5489 |
| Chromium and structural material volume fraction | 0, 1462 | 0, 1462 |
| Fuel pin diameter (cm) | 0, 827 | 0, 659 |
| Total fissile mass in core (kg of Pu-239 + Pu-241) | 3203 | 2163 |
| Core inlet coolant temperature ($^{o}$C) | 380 | 380 |
| Core outlet coolant temperature ($^{o}$C) | 720 | 720 |
| Maximum nominal surface fuel element temperature ($^{o}$C) | 766 | 757 |
| Maximum fuel pin linear power (W/cm) | 439, 6 | 439, 6 |
| Coolant pressure at core inlet (kg/cm$^2$) | 100 | 175 |
| Ratio pumping power required by reactor to core thermal output with constant roughness | 0, 0183 | 0, 0161 |
| Ratio pumping power required by reactor to core thermal output with variable roughness | 0, 0147 | 0, 0131 |
| Total thermal output (inclusive heat produced in blankets) (MWth) | 2797 | 2840 |
| Net efficiency | ~ 40 % | ~ 40 % |
| Core power density (kW/liter) | 222 | 349 |
| Average rating in core (MWth/kg Pu-239 + Pu-241) | 0, 78 | 1, 16 |
| Internal conversion ratio | 0, 99 | 0, 92 |
| Total breeding ratio | 1, 37 | 1, 36 |
| Doppler constant $-T \frac{dk}{dT}$ (T in $^{o}$K) | $0,60 \cdot 10^{-2}$ | $0,54 \cdot 10^{-2}$ |
| Reactivity variation due to loss of coolant (\$) | + 0, 90 | + 1, 34 |
| Doubling time (years) | 9, 4 | 6, 6 |

Fig. 1 $UO_2$ / 20 vol % Mo-cermet isostatically hot compressed

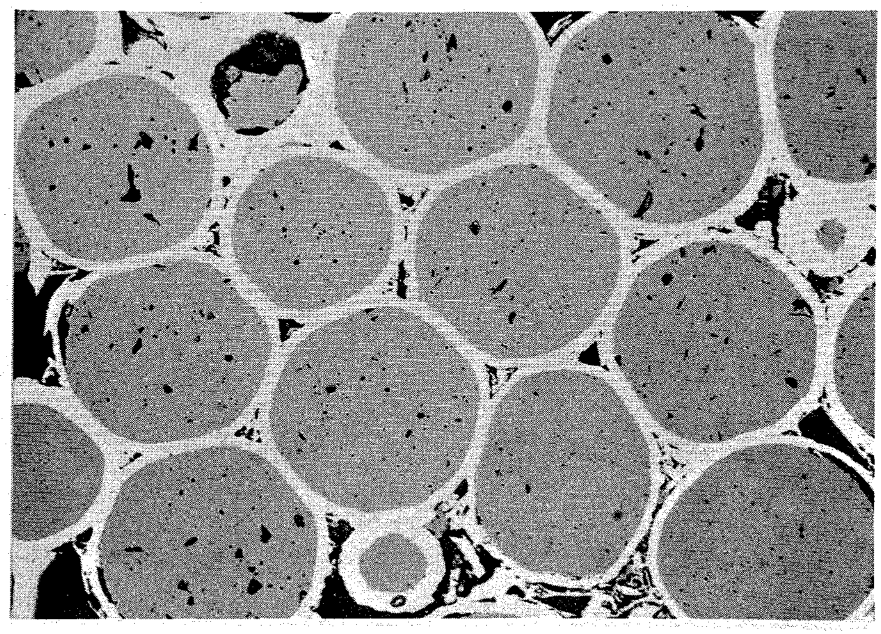

Fig. 2 $UO_2$ / 35 vol % Mo-cermet isostatically hot compressed

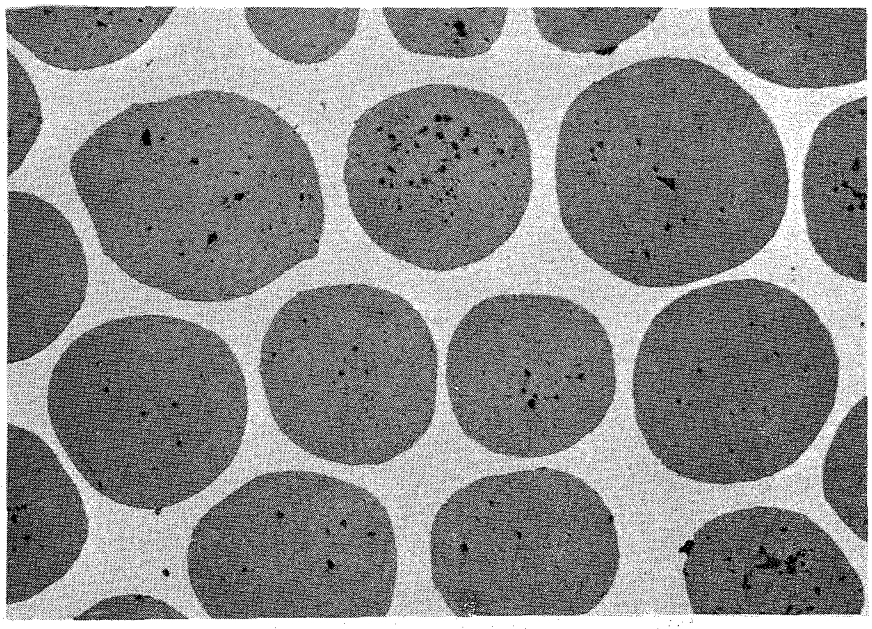

Fig. 3 Cylindrical specimen, hot compressed

a) with metal cover

b) without metal cover