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# Some Considerations on Gas Cooling for Fast Breeders

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# Some Considerations on Gas Cooling for Fast Breeders

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## 1. Introduction

One of the first studies performed in the frame of the Karlsruhe Fast Breeder Project was concerned with helium cooled fast breeders. One of the results that was reported briefly at the 1963 ANS Conference in Salt Lake City was that indeed high power densities of the order of .5 to 1 MWth/kg fissile material needed for fast breeders could be attained. The well-known difficulties for gas cooling, namely the big heat exchangers, the large amount of pumping power required, and especially the lack of good high temperature cladding material were realized.

Recently, studies on gas cooling of fast breeders have been resumed. Partly, because considerable technical improvements have made the use of gaseous coolants for fast breeders attractive again, and partly, because several problems of the sodium cooled fast breeders are still not quite clear, for instance the problem of superheat of sodium with the possible consequence of fast positive reactivity ramps, as well as that of the power coefficient. Also in the case of steam cooling some problems of stability are open, and the breeding ratio is fairly low. The Karlsruhe Nuclear Research Center in the frame of its Fast Breeder Project is actively engaged to solve the problems of sodium and steam cooled fast breeders, and our intentions concerning these cooling media are going on unchanged, but we keep an eye on gas cooling.

## 2. He and $CO_2$ as coolants of a fast reactor

It has been known since a long time that the nuclear properties of helium and carbondioxide as coolants of fast breeders should be very good. They promise high breeding ratios both intern and total, and a small coolant void coefficient. But as mentioned above, the reasons for considering gas cooling now are considerable technical improvements that have been made recently. We will list and discuss the most important of them.

Partial roughening allows a considerable increase in power density in the core and/or a reduction in the required pumping power. This is of particular value with gas coolants which have "per se" not very good heat transfer properties. Rough surfaces are only present in a small portion of the fuel pins where wall temperatures are the highest (about half of the core length, which means 25 % to 30 % of the total pin length), thus avoiding supplementary pressure drops where they are not required.

A further improvement could be given by a variable partial roughening with which it is possible to maintain constant, at the maximum nominal value, the fuel element wall temperature in the second half of the fuel elements. Some figures are given in section 4 below. The variable roughening, though, increases the cost of fuel cladding and its usefulness depends on an optimization of fuel cycle and capital costs involved.

It is interesting to notice that the use of rough surfaces in contact with steam may be more difficult, due to the corrosive properties of steam at high temperatures.

### 2.3 Development of Vanadium alloys with good creep properties at high temperatures

It has been always the philosophy of Karlsruhe to adopt the strong cladding concept. It seems indeed rather risky to assume that collapsed claddings remain integer in a high fast neutron flux, for burn-ups of 50,000 MWd/t and above, and with hot spot maximum wall temperatures in excess of 700 $^{\circ}$C, but, of course, this point must await experimental proof, or disproof, on a large number of pins. This philosophy dictated the choice of the cladding for the steam cooled reactor: a temperature of 730 $^{\circ}$C average in the thickness of the cladding at the point of maximum hot spot temperature required the use of Inconel 625. This material has 9 % of Molybdenum and 4 % of Niobium which affect the breeding ratio quite considerably. To withstand even higher temperatures with Nickel-based alloys, compatible with steam, it would require an even higher percentage of these elements, or others even worse, with disastrous consequences on breeding. Recently, Vanadium-based alloys with not very high content of Niobium have been developed. These alloys have creep properties much better than Inconel 625 and equivalent effect on breeding. Unfortunately, they are not compatible with superheated steam at high temperatures, and, maybe, not even with $CO_2$. They are however with helium.

With fuel element cladding made by a Vanadium-based alloy and helium cooling it is therefore possible to reach core outlet temperatures of 720°C or higher, which can be used for a gas turbine or to reduce drastically the size of the heat exchangers in case of two main circuits and steam turbine. All these points will be discussed in the practical example of section 4.

The other possibility, to have high gas temperatures with fuel elements based on graphite coated particles has also been considered. The DRAGON experiment has shown that these particles can withstand very high temperatures and burn-ups. However, preliminary calculations show that with coated particles of sizes technically feasible now, the breeding ratio tends to be too low. An interesting alternative could be Zirconium-coated particles, but these so far have not been studied experimentally.

### 2.4 Use of gas turbines

Recent improvements in high temperature alloys have made it possible that several companies (among them Gutehoffnungshütte in Germany) have announced that gas turbines of very large size are technically feasible. A helium gas turbine of 1,000 MW would be only 27 m long including the three compressors /‾5_7 in comparison with the 40 m to 50 m of a 500 MW steam turbine, and the longest blades would be in the case of the gas turbine less than half in length than those of a steam turbine. All this implies of course that gas blowers and compressors of very large sizes can be manufactured as well.

Concluding, one can say that the Vanadium alloy claddings and partial roughening allow, even with the high power densities required by fast reactors, helium temperatures high enough to give in a gas turbine cycle decent thermodynamic efficiencies. Prestressed concrete pressure vessels permit very high pressures without unduly high costs. If the elegant solution proposed by Lockett [6] of placing gas turbine units of 250 MW in the wall of the vessel is possible, then one can make use of the inherent safety of a concrete vessel against loss of coolant. Another possibility to use this inherent safety feature is that of a double cycle with steam turbines, where the heat exchangers are included in the concrete vessel. If the whole primary cycle is not included in the concrete vessel, the tubes carrying the gas through the walls of the vessel should be dimensioned in such a way that the sudden break of a tube would produce a reduction of coolant pressure still controllable by the reactor scrams and by the blowers.

It has been stated that the main AEC objections to the gas cooled fast reactor proposed by General Atomic are: "difficulty of emergency cooling, stringent limitations on steam and helium leaks, use of relatively high pressure and high pumping power" [7]. These points applied to the fast reactor with gas turbine cycle could be answered as follows. It is obvious that with the gas turbine cycle the danger of steam inleakage in the helium circuit is avoided. Leakage of helium has been kept in the helium cooled reactors (PEACH BOTTOM, DRAGON, AVR) to a value less than 0.1 % per day. The pumping power is not so high with the use of partial or variable roughness on the fuel elements, and in any case blowers or compressors of sufficient power seem feasible. High pressure is unavoidable, but light water reactors at 140 atms are already operating, and the trend is to go to even higher pressures (up to 175 atms). Emergency cooling could be attained by water flooding, which could be possibly used also during charge discharge operations. The Vanadium alloy cladding is not compatible with steam at high temperatures, but it is with water at lower temperatures and for relatively shorter times.

## 3. Comparison between He and $CO_2$

Helium and carbon dioxide have practically the same nuclear properties when used in a fast reactor. Helium has slightly better heat transfer properties for pressures below 150 atms [8] but this difference almost disappears with the use of rough surfaces. The choice between these two coolants must therefore depend on other criteria.

There is a number of technical advantages in the use of $CO_2$:

3.1 Cost: $CO_2$ is 270 times less expensive than He per unit weight and 24 times per unit volume. With $CO_2$ the leakage problem are therefore orders of magnitude less severe than with He. "Much thought and ingenuity have been devoted to achieving leak-tight circuits in the helium reactors, and to minimizing the other helium losses which could occur in operation, for example in fuel handling. The design of blower-seals arranged for the recovery of the coolant outflow has received close attention, as has the development of main circulators with gas-bearings. It has been demonstrated that the leakage of helium in normal operation can be kept down to very small quantities, so small in fact that an occasional accidental loss could be the determining factor" [9].

3.2 Storage and transport: $CO_2$ can be stored and transported in liquid phase, while He is normally, now, stored and transported at 200 atms. This means, that, if one has helium at 100 atms and at an average temperature of $430^{\circ}$C in the core main circuit, one needs a storage capacity equal to 36 % of the total volume of He primary circuit, supposing that this capacity should be equivalent to two reactor fillings. And this is obviously an extra cost in respect of $CO_2$.

3.3 Machinery: Helium has a specific heat five times higher, but a density 11 times lower than that of $CO_2$. It requires then machines 2.2 times bigger in volume or 2.2 faster. The low density of helium would require a large number of compressor and turbine stages in the case of direct cycle with gas turbine.

3.4 Natural convection: It is more effective in $CO_2$ than in He. Although natural convection of both gases is orders of magnitude less effective than in sodium, the difference between $CO_2$ and He is still significant in case of failure of the blower. Good natural convection properties, however, lead to thicker insulation of the concrete pressure vessel.

$CO_2$, however, especially at high temperatures and irradiations is not an inert gas. With inhibiting additives it is possible to reach temperatures in the range of $650^{\circ}C$ to $675^{\circ}C$, and the problem might be simplified in fast reactors by the absence of graphite. But, if one wants even higher temperatures for the gas turbine, the cost of the materials required might be too high, and one doesn't see what material to use to clad the fuel elements without unduly reduce the breeding gain, unless the mentioned Vanadium alloys prove to be compatible with $CO_2$.

Another great disadvantage of $CO_2$ ist that the Mach number is very low. This could cause some concern in the machinery, but it is particularly dangerous in the core: the pressure drop through the core is with $CO_2$ three to four times higher than with He. Vibration problems could arise. The very thin pin fuel elements could require very strong transversal supports, with consequent increase of pressure drop in the core.

These last two points made us prefer helium, especially because we want to look into the possibility of using the direct gas cycle in the turbine, but one should remember that $CO_2$ could be a very interesting development if the problem of compatibility at high temperature is solved.

## 4. Two numerical examples

Tables 1, 2 and 3 show the results of calculations performed for two reactors.

The first reactor produces helium at 600°C. The cladding is Inconel 625. The breeding ratio and the rating are quite good (1.3 and 0.74 MWth/kg fissile respectively), the internal conversion ratio is such to guarantee a small reactivity swing for the chosen maximum burn-up. The doubling time is 12 years and the coolant void coefficient only +0.98 ¢.[*] The diameter of the core is not much greater than that of the steam cooled reactor (330 cm versus 263 cm [10]). The diameter of the pins is bigger than the usual in a fast core and they are therefore robuster. The rather large spacing between the pins, which is allowed by the good nuclear properties of the coolant, makes the difference between maximum hot spot temperature and maximum nominal wall temperature rather small: 79°C versus 145°C for the steam reactor [10], both calculated without coolant mixing, and this 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 value, so far, of the AGR (Hinkley Point B offer).

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[*] A rough extrapolation of the present results indicated that with a helium pressure of 175 atms a rating of 1.2 MWth/kg fissile would result. The doubling time would then be 7.5 years.

The second reactor has practically the same breeding ratio, rating, doubling time, void coefficient and geometry as the first, but it produces helium at 720°C. This temperature could be used in a rather complex gas turbine cycle, but capable to produce a net plant efficiency of 40 %, such as that suggested by Gutehoffnungshütte [11]. In this cycle, the size of the heat exchangers is probably not smaller than that required by a steam cycle, however, the gas turbine is considerably smaller than the equivalent steam turbine, and the heat exchangers are at temperatures and pressures much lower, therefore, they may be made of less expensive material. The danger of inleakage of steam in the primary circuit is avoided, and the problem of accuracy and control of tubes and weldings is less stringent with consequent savings.

A second way of using the 720°C is to have a relatively simple gas turbine cycle, with reduced capital costs but with a net plant efficiency of only 35 %. A third way is to use still a steam cycle but with very much reduced size of heat exchangers. The choice between these three ways must be the object of a more accurate evaluation of capital and cycle costs involved.

## 5. Conclusions and future trends

The success of the three high temperature helium cooled thermal reactor experiments, namely DRAGON, PEACH BOTTOM and AVR, has raised the interest of the technical world in this type of reactor. Recent is the decission to build in Geesthacht, Germany, a high temperature thermal reactor, helium cooled, and with a gas turbine of 21 MWe. Representatives of The Nuclear Power Group (TNPG) in England have proposed to build, in place of new AGR type reactors, DRAGON type reactors [12]. This tencency has been confirmed by the recent DRAGON-THTR Assessment Meeting in Brussels [13]. Many private companies in Germany and abroad have stated their interest in building big closed cycle helium turbines.

The idea of extrapolating this type of reactor, namely a high temperature helium cooled thermal reactor, to a high temperature helium cooled fast reactor seems appealing. Many reactor components are practically unchanged, the core of course is different, and the helium pressure is considerably higher, with all the problems that go with it.

If one assumes, that, starting from a certain date, say 1990, the majority of reactors built will be fast, there is no reason to think that only one type of fast reactor will be constructed, like there is not only one type of thermal reactor being made now.

In the United States three private firms have recently won utility sponsorship for their fast reactor projects: General Electric for sodium and steam, Westinghouse for sodium, and General Atomic for gas /¯14_7. We in Karlsruhe are actively engaged in sodium and steam cooled fast breeders and our intentions are going on unchanged. Indeed, especially a steam breeder seems to require considerable less reactor components development work than a high temperature gas breeder with a direct gas turbine cycle. In particular the Vanadium-cladded fuel elements and the big gas turbine require a great deal of research and development work yet. However, a gas breeder seems to have a lot of potential and seems to be the best reactor in the long run: breeding ratios and therefore fuel costs appear to be comparable to those of sodium breeders, and capital costs even lower than those of a steam breeder due to the adoption of the gas turbine cycle and concrete pressure vessel. Further increases of breeding ratio could be achieved if the collapsed cladding concept with stainless steel cans proves to be sound, for instance by means of fuel venting, (increase in breeding gain of about 0.2) with the consequent possible adopting of carbide fuels in place of oxides (further increase in breeding gain of 0.15).

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Table 1

| Reactor composition | Reactor for steam turbine plant | Reactor for gas turbine plant |
|---|---|---|
| Coolant | Helium | |
| Core thermal output (MWth) | 2500 | |
| Total thermal output (inclusive of heat produced in blankets)(MWth) | 2759 | 2764 |
| <u>Core and axial blanket</u> | | |
| Fuel | $UO_2$-$PuO_2$ | |
| Diameter D of the core (cm) | 330.4 | |
| Height H of the core (cm) | 131.6 | |
| H/D | 0.3983 | |
| Core volume (liters) | 11,280 | |
| Blanket thickness (cm) | 40 | |
| Length of the gaseous fission products store chamber (cm) | 75 | |
| Form of subassembly cross section | hexagonal | |
| Subassembly wall thickness (cm) | 0.3 | |
| Subassembly wall material | X8 Cr Ni Mo V Nb 16 13 stainless steel | |
| Fuel pins diameter (cm) | 0.827 | |
| Cladding thickness (cm) | 0.043 | |
| Cladding material | Inconel 625 | Vanadium Alloy |
| Coolant volume fraction | 0.5489 | |
| Structural material volume fraction | 0.07 | |
| Cladding material (inclusive of supporting grids) volume fraction | 0.0778 | |
| Fuel and fertile material volume fraction | 0.3033 | |
| Fuel and fertile material density | 0.87 of theoretical | |
| <u>Radial blanket</u> | | |
| Thickness (cm) | 40 | |
| Form of subassembly cross section | hexagonal | |
| Subassembly wall thickness (cm) | 0.3 | |
| Subassembly wall material | Incoloy 800 | |
| Pins diameter (cm) | 1.25 | |
| Cladding thickness (cm) | 0.055 | |
| Cladding material | Incoloy 800 | |
| Coolant volume fraction | 0.241 | |
| Structural and cladding material volume fraction | 0.183 | |
| $UO_2$ volume fraction | 0.576 | |
| $UO_2$ density | 0.87 of theoretical | |

Table 2

| Heat transfer data | Reactor for steam turbine plant | Reactor for gas turbine plant |
|---|---|---|
| Core inlet coolant temperature (°C) | 260 | 380 |
| Core outlet coolant temperature (°C) | 600 | 720 |
| Maximum nominal surface fuel element temperature (°C) | 646 | 766 |
| Length of roughened pin (cm) | 70.6 | 69.9 |
| Temperature averaged in the thickness of the cladding at the point of maximum hot spot temperature (calculated without mixing)(°C) | 725 | 845 |
| Maximum fuel temperature (°C) | 2000 | 2110 |
| Maximum fuel pin rate (W/cm) | 439.6 | |
| Core power density (kW/liter) | 222 | |
| Coolant pressure at core inlet (kg/cm$^2$) | 100 | |
| Pressure drop in reactor (kg/cm$^2$) | 1.76 | 2.07 |
| Ratio pumping power required by reactor to core thermal output with constant roughness/with variable roughness* | 0.0132/0.0109 | 0.01827/0.0147 |
| Pumping power required by reactor with constant roughness/with variable roughness (MW) | 33/27.2 | 45.6/35.8 |
| Steam cycle | | |
| Maximum steam pressure (kg/cm$^2$) | 120 | |
| Maximum temperature of superheated steam (°C) | 540 | |
| Reheat temperature (°C) | 540 | |
| Reheat pressure (kg/cm$^2$) | 50 | |
| Thermodynamic efficiency | 43.4 % | |
| Net efficiency (assuming total pumping power in the circuit equal to 66 MW) | 39.8 % | |
| Net electrical output (MWe) | 1098 | |

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*The pumping power has been calculated assuming a helium density equal to that of helium at the core inlet.

Table 3

| Nuclear data | Reactor for steam turbine plant | Reactor for gas turbine plant |
|---|---|---|
| Internal conversion ratio | 0.94 | 0.957 |
| Total breeding ratio of core | 1.30 | 1.314 |
| portion of core | 0.881 | 0.893 |
| portion of axial blanket | 0.182 | 0.1825 |
| portion of radial blanket | 0.237 | 0.2385 |
| Volume ratio $\frac{\text{fertile}}{\text{fissile}}$ in region 1 of core | 8.89 | 9.17 |
| Volume ratio $\frac{\text{fertile}}{\text{fissile}}$ in region 2 of core | 6.81 | 7.03 |
| Fissile mass in region 1 of core (kg of Pu-239 +Pu-241) | 1488 | 1447 |
| Fissile mass in region 2 of core (kg of Pu-239 +Pu-241) | 1884 | 1832 |
| Total fissile mass in core (kg of Pu-239 +Pu-241) | 3372 | 3279 |
| Average rating in region 1 of core (MWth/kg fissile) | 0.918 | 0.945 |
| Average rating in region 2 of core (MWth/kg fissile) | 0.603 | 0.620 |
| Average rating in core (MWth/kg fissile) | 0.742 | 0.763 |
| Ratio of middle to max. power density in axial direction | 0.799 | 0.801 |
| Ratio of middle to max. power density in radial direction | 0.828 | 0.831 |
| Neutron life (sec) | $0.416 \times 10^{-6}$ | $0.435 \times 10^{-6}$ |
| Doppler constant -T dk/dT (T in °K) | $0.548 \times 10^{-2}$ | $0.694 \times 10^{-2}$ |
| Coolant density coefficient $\frac{dk}{k} / \frac{d\rho}{\rho}$ | $-3.33 \times 10^{-3}$ | $-3.19 \times 10^{-3}$ |
| Reactivity variation due to loss of coolant ($) | +0.98 | +0.93 |
| Maximum burn up (MWd/t | 55,000 | |
| Doubling time (considering a whole generation of gas breeders) (years) | 12.0 | 11.2 |