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NEW BOILING SALT FAST BREEDER REACTOR CONCEPTS *

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Concepts of fast breeder reactors fueled with fused chlorides of uranium, plutonium, sodium and/or potassium and cooled directly with boiling coolant are discussed including the SAWA reactor boiling homogeneously with aluminium chloride as coolant, and the WARS reactor boiling heterogeneously with metallic mercury as coolant.

Some preliminary calculations for 1000 MWt reactors of both types were performed. The characteristics considered are: SAWA concept: 6000 litre core, 0.33 MW/l, cooled with 1340 kg of $AlCl_3$ per second; WARS concept: 10 500 litre core, 0.40 MW/l, cooled with 3300 kg of Hg per second.

1. LIQUID FUELS FOR FAST BREEDER REACTORS

Liquid fuels, irrespective of their chemical properties, have a number of advantages discussed earlier [1, 2]. Such fuels can be applied in thermal reactors as well as in fast breeders. Molten salt can be considered as one of the more convenient forms of liquid fuels. Fused salts as liquid fuel for nuclear reactors were discussed by Briant and Weinberg [3]. The fluorides were choosen as being most appropriate. The experimental programme was developed at Oak Ridge National Laboratory (USA) by Weinberg, MacPherson and Grimes [4, 5]. A result of these investigations is the 10 MWt reactor called MSRE. The fuel in this reactor is a mixture of fluorides LiF-BeF_2-ZrF_4-ThF_4-UF_4 with melting point of about 450°C. The construction material is INOR-8. The MSRE is as yet the only working reactor fueled with molten salts. Its recent successful operation [6] is an encouragement for this type of reactors.

The application of fused salts in fast breeder reactors promises well. Such a system combines advantages of fast reactors and of liquid fuels, but eliminates disadvantages [7]. The properties of such fuels were discussed by Goodman [8], Wehmeyer [9] and Bulmer et al. [2]. The increasing interest in fast breeder reactors [10] is bound to cause fused salt fuels to receive still more attention [11-13].

2. COOLING

The cooling system is a decisive element in reactor design, especially in fast breeders [14].

Two methods of heat removal from a reactor core containing liquid fuel can be distinguished in general:

a) External cooling, when the heat is removed from the fuel circulating outside the core. In such a case the fuel inventory in the system is approximately twice that in the core alone.
b) Internal cooling, when the heat is removed from the fuel by the coolant circulating through the core. The fuel inventory is of course less than in the case of external cooling.

Irrespective of the above mentioned cooling methods one can additionally distinguish two other systems:

c) The indirect cooling system, when the coolant is separated from the fuel by means of membrane.
d) The direct cooling system, when the coolant is brought into direct contact with the fuel.

Recently the interesting idea of a direct contact metallic coolant-metallic fuel immiscible system was presented by Hammond and Humphreys [15]. For fused chloride fuel for fast breeders the concept was discussed by Alexander [11], and recent remarks were made by Moore and Fawcett [16] and Killingback [17].

3. BOILING SALT REACTORS

Fused chloride fuels for fast breeder reactors with direct and indirect cooling systems have been the object of investigations in this laboratory since 1960 [18-21]. In this paper the new concept of boiling salt fast breeder reactors is presented. Two reactor concepts will be considered: the SAWA concept [22, 23] and the WARS concept [24, 25]. In both systems the fuel consists of plutonium trichloride as fissionable material, uranium trichloride as fertile material, and sodium and/or potassium chloride as diluent. In both types the coolant is boiling, and thus is partially in the liquid and partially in the vapour state. The two types differ in the following manner. In the SAWA concept cooling is realised by direct homogeneous boiling of aluminium chloride in the core, while in the WARS concept there is direct heterogeneous boiling of metallic mercury in the core. So the main specific feature of both ideas is that the coolant takes the heat from the core by boiling and transfers it directly to heat exchanger or turbine. The reactor proposed may be regarded as a pseudo-gas-cooled type because the gas is evolved in the fuel phase. It must be noticed that the vapour pressure of the coolants ($AlCl_3$ and Hg_{met}) at 750-800^{o}C is by about six to seven orders of magnitude higher than the vapour pressure of plutonium and uranium chlorides, which assures that the part of the cooling system which contains vapour can not reach nuclear criticality.

The specific features of both concepts are listed in table 1 and shown in fig. 1. For comparison some data for the non-boiling fused chloride reactor core calculated by Nelson et al. [26] are given.

Besides the data given in table 1 a number of features may be ascribed to the proposed reactor concepts which one can consider as advantages. These are:

a) simple geometry of the reactor core vessel, which simplifies also the construction of the whole system,
b) minimal inventory of fuel in the reactor cycle due to the use of internal cooling eliminating fuel flow outside of the core,
c) the irradiated fuel reprocessing system may be organized "under one roof" with the reactor system,
d) the double breeding cycle ^{232}Th-^{233}U and ^{238}U-^{239}Pu seems to be realisable [27],
e) the expected high temperature coefficient of volumetric expansion leads to an increase in safety. From preliminary calculations [28] it follows that the thermal expansion of the fuel volume in the WARS concept is an order of magnitude higher than in the case of non-boiling salt fuel, and in the SAWA concept it is several times higher yet than in the WARS.
f) a relatively higher breeding ratio, caused by the minimizing of the amount of coolant in the core. The mass of the vapour bubbles con-

Table 1

Characteristics	SAWA	WARS	Nelson et al. [26]	
			Homogeneous	Heterogeneous
Cooling system	Boiling $AlCl_3$ internal direct	Boiling Hg_{met} internal direct	Liquid Na, external indirect	Liquid Na, internal indirect
Temperature of coolant (^{o}C)				
outlet	800	740	740	660
inlet	280	600	625	570
Vapour of coolant, outlet				
kg/sec	1340	3300	-	-
litres/sec	33200	32800	-	-
Whole core volume (litres)	6000 (vapour and liquid)	10000 (vapour and liquid)	10000 (liquid only)	10000 (liquid only)
Core power (MWt)				
Specific power (kW/litre of salt)	333	400	400	400
Liquid fuel composition (mol % (U, Pu)Cl_3) (without coolant)	50	50	30	50
Volumetric thermal expansion coefficient (vol % per ^{o}C)	1 (liquid salt and vapour bubbles)	1 (liquid salt and vapour bubbles)	0.03 (salt only)	0.03 (salt only)
Pressure (bars)	20	40	low	low

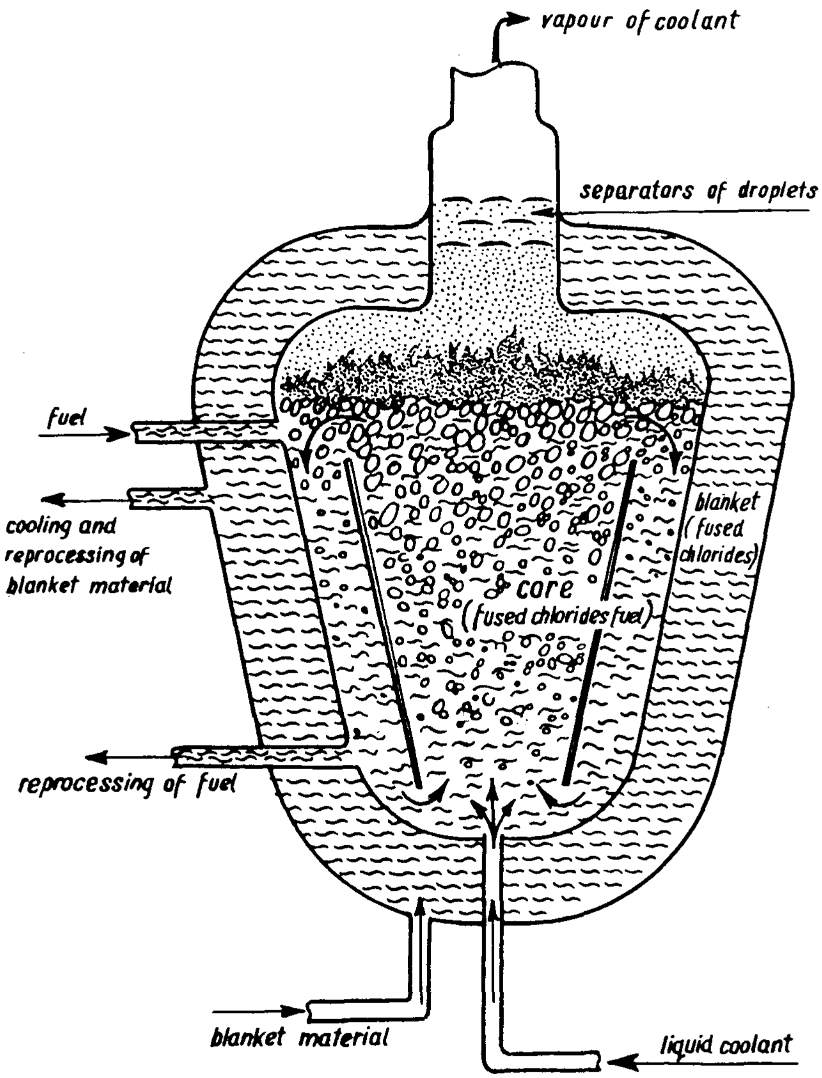

Fig. 1. Cross section showing the main elements of a boiling salt fast breeder reactor.

stitutes only about $\frac{1}{50}$ of the mass of the liquid state.

Along with the advantages described above, a number of problems are also introduced which must be solved in further investigations. These concern mainly the lack of data about the boiling mechanism of liquid dissipating heat homogeneously and heterogeneously, the mechanism of initiation, growth, stability and motion of aluminium chloride and mercury vapour bubbles in the liquid salt, the separation of the bubbles from the salt phase, the neutron transport mechanism, criticality, safety-related effects in a microscopically unstable boiling system, etc. Also corrosion effects of molten chlorides on construction materials and corrosion by fission product, and especially by metallic mercury in the WARS concept, are of great importance. The danger of leakage of liquid fuel from the relatively high pressure system must be taken into account. At present all these problems must be treated as disadvantages of the proposed reactor concepts.

4. SAFETY CONDITIONS

The safety coefficient of both the SAWA and WARS concepts is expected to be relatively high. Safety is primarily related to the thermal expansion coefficient of the fuel. The volumetric thermal expansion coefficient is $3 \times 10^{-4}\ ^{\circ}C^{-1}$ and the corresponding decrease in reactivity would be about 1.5% per $1^{\circ}C$ temperature increase. But beyond this the expansion reactivity effect is much further increased by void formation. A prompt increase of temperature due to a rise of power causes in the SAWA concept an intensification of boiling which leads to an increase in the void or vapour volume in the fuel material, and a decrease of reactivity. To avoid oscillation of the fuel system due to high instability of the reactivity, an appropriate geometry for the system in the region of the free boiling surface would be applied [29].

The Doppler effect is expected to be also negative. Okrent [30] reported that the Doppler effect is in general negative in the case of large fast reactors with fuel of intermediate enrichment.

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