1. INTRODUCTION

In the current structure of nuclear power, light water reactors (LWRs) are predominant over a small number of heavy water reactors (HWRs), and even smaller number of fast breeder reactors (FBRs). However, an increase of FBR share can be predicted for the future, taking into account their unique properties. First of all, there is the capability of nuclear fuel breeding by involving ^{238}U into the fuel cycle. Secondly, there is the fast reactor's flexibility permitting its use as plutonium incinerators and minor actinides transmutation. Thus, unless new sources of energy are found, the development of nuclear power will be necessarily based on fast breeder reactors.

For the next few decades, saving of uranium resources by nuclear fuel breeding will not be of primary importance for countries with a significant nuclear power sector. This is caused by a number of factors, namely: (a) accumulation of plutonium as a result of reprocessing of spent fuel of the operating NPPs; (b) release of considerable amount of plutonium and enriched uranium owing to disarmament; (c) decrease of uranium consumption in the military industry; (d) slowing down of the rate of nuclear power development; and (e) ready availability of fossil fuels (natural gas and oil).

The development of fast reactors has been delayed in countries characterised by advanced market economics, because of relatively slow primary energy consumption growth and availability of fossil fuel resources. On the other hand, in countries with more rapid energy consumption growth and limited indigenous uranium ore resources, fast reactor development is continuing. In due course, when it is economically necessary, fast reactors will almost certainly make the major contribution to the world's energy supplies. There will undoubtedly be further improvement of the technology to achieve the highest standard of safety, non-proliferation, environmental protection and economics.

By now, several developed and advanced developing countries have passed the stage of demonstrating technical feasibility, safety and reliability of FBRs. Starting from the mid 1970s, advanced FBR designs have been developed in a number of countries, these designs meeting the most strict safety requirements and assuring their competitiveness with LWRs in terms of electricity generation cost. These are primarily the demonstration European fast reactor EFR, the commercial fast reactor BN-800 in the Russian Federation, the demonstration fast breeder reactor DFBR in Japan and the prototype fast breeder reactor PFBR in India (rated power of 1500 MW(e), 800 MW(e), 600 MW(e) and 500 MW(e), respectively).

There is a widespread opinion that the existing water, gas and liquid metal cooled reactor systems can meet present safety standards quite adequately, and are expected to do so for the foreseeable future. Nevertheless it is essential to continue the search for greater safety because: (1) no opportunity to improve technology should be ignored; (2) safety standards may be raised by the regulatory authorities; (3) nuclear power plants suitable for countries or regions with less developed infrastructure will be needed; and (4) more cost-effective ways of meeting existing safety standards may be found.

Now, because of the delay in the fast reactors commercial introduction, there is an opportunity to investigate alternative technical solutions. The objective is to obtain complete knowledge of their characteristics allowing to make, when the time has come, the best choice for the reactor design for concrete realization. Reactor designs using gas, steam, lead and lead-bismuth alloy coolants are considered as possible alternatives.

The appropriate choice of the primary coolant is of great significance for achieving high FBR performances. This determines also the main design approaches of FBR and, to a great extent, the technical and economical characteristics of the nuclear power plant.

Among all liquid metal coolants, it is sodium that has gained the widest acceptance. This coolant has been chosen for liquid metal cooled fast reactor (LMFR) because of its good thermal and physical properties. Sodium offers the possibility to achieve high specific power densities in the core and thus for a short doubling time. This was the world-wide strategic line of fast reactor development in the 1960s, and is continued in some countries presently. For this very reason, when considering various liquid metal coolants for FBR in the 50-ies, sodium was given preference, although initially, in the former USSR, lead-bismuth coolant was also considered.

Large experience has been already gained with sodium cooled fast reactor operation. The use of sodium as a coolant poses fire danger in case of its leakage and interaction with air or water. Operating experience testifies the possibility of coping with the mentioned problem, but the quest for excellence calls for future improvement in LMFRs technology.

In the earlier phases of breeder reactor development, especially in the 1950s and 1960s, high pressure gases, such as helium,CO_2 or superheated steam were studied. Between 1960 and 1970, H_2 O-steam cooled and D_2 O-steam cooled fast reactor concepts were studied in the USA and the former FRG. Helium cooled fast reactor concepts have been pursued as an alternative coolant concept in Europe and the USA. Some fuel development for a CO_2 cooled fast breeder has been continued on a small scale in the UK. Lead-bismuth alloy as a coolant was studied in the former USSR for propulsion and land based reactors.

However, the choice of liquid sodium as a coolant and principal design features of fast reactors were mainly determined in the 1960s, as already mentioned, by the requirement of high power densities in the reactor core (about 500 kW(th)/l for MOX fuel), and the need of a weakly moderating material with good heat transfer properties. The important fact was also that sodium is practically non-corrosive to stainless steal.

Presently, the availability of great amounts of fissile plutonium produced by thermal reactors and that released from now-redundant nuclear weapons in the USA, the Russian Federation, the European Union, and in some other countries with significant nuclear power sector and relatively slow primary energy consumption growth, has eliminated the initial requirements of short doubling time and high breeding ratio.

The changing of the strategic line, delaying of fast reactors commercial introduction and some drawbacks of sodium technology related in some demonstration LMFRs have given the rise to the question to reverse the trend of the last 20 years, which focused fast reactor R&D on one option — sodium cooled fast reactors. Some experts believe that a more generic exploratory research on the different options, including “revisited” ones, should be open again as in the early stage of fast reactor development.

Not only new innovative ideas as, for example, lead or lead-bismuth cooled fast reactors are being studied in Member States now, but almost all old ones mentioned above that have also a considerable innovative character: this is the cases of gas-cooled high temperature and superheated supercritical steam-cooled fast reactors. This is due to an increase of the gas turbines thermal efficiency from 35% to 50% within the last 10 years and to work on supercritical water/steam high performance LWR with thermal efficiency of 44% and high power density.

Considerable experience has been gained in the Russian Federation with lead-bismuth (PbBi) eutectic alloy application as reactor coolant. Since Bi is sufficiently rare and expensive metal, and also it is a source of volatile α-active ^{210}Po, the proposal to use lead as a coolant in power fast reactors is now under consideration in several countries. Lead based alloys are currently being considered for hybrid systems (accelerator driven fast reactors) in which the coolant could double as the spallation source for driving the core.

Techniques to counter the heavy metal coolant disadvantages are being developed, but in spite of this work and the apparent disadvantages of sodium, the consensus in favour of sodium remains strong. This is demonstrated by fact that "before lead-cooled fast reactor BREST-300 is built, MINATOM will first build a sodium-cooled LMFR BN–800"(E. Adamov, NW, 23 September 1999). Moreover, in the last few years sodium has been chosen in both China and the Republic of Korea for the respective fast reactor development project. This is a significant endorsement for sodium as a fast reactor coolant.

However, given that there is now this tendency for countries to have their own viewpoint and their own preferred option: evolutionary sodium-cooled LMFR models or an innovative one with new coolant (gas, steam, other than sodium liquid metal coolants), it is essential to clarify as far as possible the scientific issues related to the different innovative options and to exchange information on advances in development of traditional and innovative fast reactors.

That is why this report is devoted to the comparative assessment of general characteristics of a standard fast reactor coolant (sodium) and innovative ones, such as lead and lead-bismuth alloy.

2. TECHNICAL BACKGROUND

2.1. SODIUM- COOLED FAST REACTORS

LMFRs(liquid metal cooled reactor) have been under development for more than 50 years. Twenty LMFRs have been constructed and operated. Five prototype and demonstration LMFRs (BN-350/Kazakstan, Phenix/France, Prototype Fast Reactor/UK, BN-600/Russian Federation, Super Phenix/France) with electrical output ranging from 250 to 1200 MW(e) and large scale (400 MW(th)) experimental fast flux test reactor FFTF/USA have gained nearly 110 reactor-years. In total, LMFRs have gained nearly 310 reactor-years of operation.

In many cases the overall experience with fast reactors has been extremely good, the reactors themselves and, more frequently, particular components, showing good performance well in excess of design expectations. They also have been shown to have very attractive safety characteristics, resulting to a large extent from being low pressure system with large thermal inertia and negative power and temperature reactivity coefficients [2.1, 2.2].