Engineering 2 (2016) 59–62

Contents lists available at ScienceDirect

Engineering

journal homepage: www.elsevier.com/locate/eng

Views & Comments

The Lead Fast Reactor: An Opportunity for the Future?

Alessandro Alemberti

Ansaldo Nucleare SpA, Genova 16159, Italy

1. Introduction

As one of the six reactor concepts selected in the Generation IV Technology Roadmap, the lead fast reactor (LFR) has become very attractive in recent years, and its development is pursued in several countries [1,2]. The attractiveness of the LFR is justified by the intrinsic characteristics of the system, which are able to completely satisfy the goals of the Generation IV International Forum (GIF). The system's enhanced safety is a particularly important characteristic, as safety is becoming one of the key criteria in the choice of a next-generation nuclear system.

This paper briefly outlines the various on-going initiatives dedicated to the development of lead technology. The use of lead as a coolant permits a complete change of the design approach and provides several possibilities for innovation that will be briefly described here.

2. Why a lead fast reactor?

This section analyzes the main LFR system characteristics according to recent developments of the technology.

2.1. Sustainability

The lead-cooled reactor ensures the sustainability of the energy source in the long term. The LFR is initially loaded using mixed uranium plutonium oxides (MOX) or more advanced fuels such as uranium nitrides, relying on existing light water reactor (LWR) technology for MOX or developing new and advanced production and reprocessing fuel cycles. When the fuel is discharged from the reactor, it is reprocessed to extract only the short-lived fission products (decaying in the order of a few hundred years) to be properly disposed of (e.g., by geological repository). After reprocessing, the fuel is re-introduced into the reactor, adding very common natural or depleted uranium instead of enriched uranium as is currently done in LWRs. In this way, the abundance of the world's uranium reserves becomes approximately 50 to 100 times greater, compared to the amount required by today's technologies (which use only 1%–2% of the fuel loading to produce energy). Because of the reduced quantity of uranium required in the LFR life, the time of exploitation of this energy source is extended from hundreds to thousands of years. This characteristic is common to any fast reactor system, and provides a new approach for the full use of natural resources and an enormous reduction of long-lived radioactive waste production.

In fact, one of the most important problems of nuclear energy lies at the social level, and is not yet resolved by current technology: the production of long-lived radioactive waste that requires storage in dedicated repositories for hundreds of thousands of years. Fast reactor technology addresses and solves this problem. As noted in the previous paragraph, the waste from the supply chain consists only of fission fragments with a decay time of a few hundred years, making the disposal of this radioactive waste more economically viable and reliably manageable. The plutonium and minor actinides are recycled within the reactor because it is able to achieve a "closed cycle" of the fuel. The underlying technology is based on the fact that, after some time inside the reactor, plutonium and the minor actinides reach an equilibrium quantity; the products of the nuclear reactions are burnt in such a way that no new production of such elements takes place. Storing only fission products in the final repository not only decreases the size of the repository itself but also increases the safety of the final storage, due to the reduction in decay heat to be removed. However, the most significant effect is the reduction of the final storage period required to reach a low, natural radioactivity level: only a few hundred years, instead of the hundred thousand years required for the current technology.

2.2. Safety

The LFR is characterized by a high degree of safety, as it is based on the use of liquid lead as a heat transfer fluid. Unlike other fluids, lead requires no pressurization (the boiling temperature of lead at atmospheric pressure is 1743 °C); nor does its use accidentally produce hydrogen or other explosive gases. The use of lead allows the introduction of decay heat removal systems in the primary circuit, relying on the fact that their operation is guaranteed by fundamental physical laws and requires no external power supply. (Such systems are generally referred to as actively actuated/passively operated, but for some designs, solutions have been identified in which both the activation and operation are performed in a passive way.) These passive systems ensure their operation even in the case of extreme events, with the final goal

http://dx.doi.org/10.1016/J.ENG.2016.01.022

of preventing the dispersion of radionuclides outside the containment building. As a result, even in the case of an extreme accident, the LFR is expected to have no impact on the environment outside the containment building, greatly increasing the social acceptability of this technology.

Finally, some initiatives under development envision the fuel reprocessing plant to be co-located with the reactor; consequently, once the initial loading of the fuel is complete, the site is fed only by natural uranium coming in, and only fission products leave the plant. This greatly reduces the probability of accidental pollution due to transportation and actuates a very high level of security in terms of diversion of the fuel use. With the support of the LFR Provisional System Steering Committee (PSSC), the Reactor Safety Working Group of the GIF has recently published a white paper on safety that can be freely downloaded from the GIF website [3].

2.3. Economics

Experience shows that it is very difficult to quantify the total cost of the construction and operation of new, advanced systems. It must also be noted that even the construction cost of a well-known technology such as the LWR systems is subject to wide cost variations and significant increases with respect to the initial predictions. Obviously, the uncertainties of correctly forecasting investments are higher in the case of prototypes or demonstrators of a new technology. However, for the LFR, certain characteristics suggest an important potential for excellent economic performance. These characteristics are strongly connected to the specificity of the coolant.

(1) The inert chemical nature of the coolant can be used at the design level to simplify the reactor system. For example, the LFR does not require the installation of complex and expensive intermediate systems to isolate the primary coolant from its ultimate secondary coolant, normally water. The current designs envision once-through steam generators at high pressure. Numerical simulations show that the secondary cycle performance can reach values greater than 40%.

(2) The very high boiling temperature of lead prevents any localized coolant boiling. As a result, the safety challenges found with other coolants do not apply and the system is intrinsically protected by the characteristics of the coolant itself.

(3) The primary coolant can be maintained at near atmospheric pressure. This fact eliminates the need to introduce an expensive and sometime very complex system to maintain the correct pressure operation level, such as in the LWR technology. It is also important to note that working conditions at atmospheric pressure, together with the pool design, practically result in the elimination of loss-of-coolant accidents (LOCAs), again greatly simplifying the safety provisions and thereby leading to significant positive effects on economics.

Although it is difficult to reach a conclusion on the achievable economic level of an LFR system, the above statements strongly indicate that some advantages are already present in the use of such a technology and that these advantages are due to the basic properties of the selected coolant.

2.4. Proliferation resistance and physical protection

As mentioned above, the LFR fuel cycle is designed to not produce plutonium or minor actinides. Instead, the LFR can recycle the existing spent fuel by the separation of the fission products. As has also been mentioned, some LFR concepts co-locate the fuel reprocessing facilities within the reactor site in such a way that only natural uranium is transported to the site and only the relatively short-lived fission products leave the site for storage or disposal. The LFR core can be designed for a long or very long core life, presenting clear advantages in terms of the corresponding increase of the time between refueling. This increased time greatly reduces the proliferation risk associated with spent fuel operations. Finally, the need for remote handling of spent fuel provides a basic contribution to physical protection, as is the case for other reactor designs.

In answer to the heading of this section, “Why a lead fast reactor?”, the statements above provide a short overview of the main reasons behind the development of this completely new technology, which is potentially able to change the current nuclear energy scenario.

3. Lead fast reactor research and development needs

A large number of the major LFR design problems have been tackled and solutions have been developed over the last 20 years. Issues such as the seismic behavior of the reactor, the pressurization of the primary side due to a steam generator tube rupture, the risk of coolant freezing, and others have been the subject of research activities leading to viable solutions with demonstrated effectiveness. However, an issue still exists that must be addressed in detail: The effects of the corrosion attack of liquid lead on structural materials are still an open question that requires some development.

The corrosion attack of liquid lead is mainly due to the dissolution of the principal constituents of a material into the liquid lead. Nickel, chromium, and iron have different solubility levels in liquid lead and the concentration of these dissolved elements increases with temperature. In a uniform temperature pool, reaching the saturation level of the dissolved elements is sufficient to stop the dissolution; however, in a reactor, which is characterized by a temperature difference between cold and hot plenums, the residual dissolution level must be addressed with specific provisions.

Since nickel has the highest dissolution concentration, Russian scientists developed a technique using materials without nickel, the so-called ferritic-martensitic steels, which can be passivated using oxygen dissolved in liquid lead. The technique is based on the protection of the steel by an oxide layer. Although such an oxide layer can be removed by the flowing liquid lead, if an adequate level of oxygen is present, the oxide forms again and a “self-protection” mechanism takes place. This technique is central to the Russian BREST-OD-300 project, which is based on past developments of the lead-bismuth reactor used in military submarines. The technique is effective, although a defined range of oxygen concentration must be assured inside the liquid lead; special devices to add or remove oxygen have been developed in order to address this problem. Moreover, the BREST-OD-300 requires special steels that are enriched in silicon, which promotes the formation of the oxide layer.

Such materials need, however, to be qualified for nuclear use in terms of neutron flux and consequent displacements per atom (dpa), resistance to the working conditions of a nuclear power plant, and readiness for nuclear applications. Due to the shortage of reactors providing a fast flux test section, the goal of qualifying new materials is a real challenge; it may take as many as 10–20 years to reach the correct level of irradiation needed to achieve new material qualification.

Due to this important limitation, European researchers chose to use already qualified materials such as those used for sodium-cooled reactors; such materials are already qualified at a high dpa level with a fast neutron flux. R&D is now being performed in several directions to find a way to limit to reasonable levels the corrosion effect on austenitic steels. Several approaches are promising in principle:

(1) For the cladding, ad-hoc coatings can be developed along with different coating techniques.

(2) American Iron and Steel Institute (AISI) 316L shows no attack at temperatures below 400 °C, so it can be used for many components.

(3) Alumina-forming austenitic (AFA) steels are a recent and promising solution. They provide a very stable oxide layer of alumina at very low oxygen concentrations in flowing liquid lead.

(4) Other approaches try to reduce the attack of the coolant by modifying the chemical composition of the coolant itself.

In summary, a number of different directions are currently being investigated, which are aimed at finding a safe and reliable solution to the effects of the corrosion. Several directions have recently shown promising results that support further investigation and promote confidence in a possible and soon-to-be found solution.

4. Past experience and present initiatives around the world

The first proposals to use heavy liquid metal coolants for reactors started as far back as 1942 in the US. However, after some very preliminary tests, researchers encountered difficulties related to corrosion of the structural materials and longer doubling time of the LFRs. The US effort was stopped, with some results being published in the 1950s [4].

In contrast, Russian scientists and industries actively pursued R&D activities on heavy liquid metal applications and reached significant and very interesting developments. In the 1950s, military application of heavy liquid metal technology started with studies related to the use of lead-bismuth eutectic (LBE) as a coolant for nuclear reactors for marine propulsion. The main approach used to address the corrosion of the materials was the use of the oxide passivation technique, cited in the previous paragraph.

In 1963, the first nuclear submarine with an LBE-cooled reactor was put into operation. In the 1970s, several nuclear submarines of the “Alfa-class” (North Atlantic Treaty Organization (NATO) terminology) or “Lira-class” (Union of Soviet Socialist Republics (USSR) terminology) were operational. In total, including two land-based prototypes, 80 reactor-years of experience and feedback were accumulated during the reactors’ operation. A number of problems were encountered during this period, such as water leakage from steam generators, the formation of solid oxides causing flow blockage in the core, coolant freezing, and polonium production. The lessons learned from this early set of experiences enabled Russian scientists to find solutions for each of the identified issues related to the use of LBE.

In Europe, the first studies on LBE and lead coolant began in 1995, in connection with the development of the accelerator-driven system (ADS) concept, and were followed by conceptual designs of critical reactors. A number of facilities have been built and are presently in operation.

Within the GIF, activities on the LFR concept started in 2006. The collaboration is carried out on the basis of a memorandum of understanding (MoU) signed by the European Community, the Russian Federation, Japan, and Korea. The US and China participate in the MoU activities as observers.

Several initiatives related to the development of the LFR technology are currently in progress in various countries. A brief overview of these initiatives is given below.

4.1. Russian Federation

The Russian Federation is obviously the most advanced country in terms of LFR development. The previous experience gained with submarine propulsion is presently being used in the development of two main projects.

The SVBR-100 is an LBE-cooled, 100 MW_e reactor that uses a design directly derived from the submarine reactors. The design is in an advanced phase and is expected to be financed by a private/public partnership.

The BREST-OD-300, a 300 MW_e lead-cooled reactor, is completely financed by public funds and it is expected to begin construction in 2016–2017. In this design, the technology developed for LBE-cooled systems has been adapted to a pure lead coolant. Very interesting systems for passive residual heat removal are envisioned, and the main justification of the designers for such development is stated in terms of sustainability and safety. The BREST is also expected to have a reprocessing plant co-located within the reactor site, with obvious advantages in terms of the practical elimination of fuel transportation. Some basic information on BREST-OD-300 development and features can be found in Ref. [5].

4.2. Europe

In Europe, initial developments were carried out within the accelerator-driven system concept, with the aim of producing energy while burning the radioactive waste of previous generations’ reactors. Following this line of action, a number of European Commission (EC)-sponsored projects were launched, the most important of these being PDS-XADS, EUROTRANS, ELSY, LEADER, MATTER, SILER, HELIMNET, MAXSIMA, and MYRTHE. For the interested reader, more information on these projects can easily be found online.

Since these initial efforts, R&D activities have been concentrated on an industrial-sized reference plant, the European lead fast reactor (ELFR), sized at 600 MW_e (based on a previous conceptual design carried out in the ELSY project), and on a smaller demonstrator called Advanced Lead Fast Reactor European Demonstrator (ALFRED), sized at 125 MW_e. Both conceptual designs were carried out within the framework of the LEADER project and are exhaustively detailed in Ref. [6].

Current activities are concentrated on ALFRED, being the first LFR to be realized in Europe. Romania has proposed a site for ALFRED at the Nuclear Research Center, located in Mioveni. A consortium between the main players was formed in 2013 and is composed of Ansaldo Nucleare (Italy), European Nuclear Energy Agency (ENEA) (Italy), Institute for Nuclear Research Pitesti (ICN) (Romania), and Centrum výzkumu Řež (CV-REZ) (Czech Republic). The main aim of the consortium is to advance the development of lead technology to the point of starting the construction of the demonstrator. The present work plan envisions R&D activities up to 2023, followed by the construction of the reactor. However, such a schedule is strongly dependent on the availability of funding and may be subject to important delays should a mechanism not be identified to supply an adequate level of funding.

Roughly within the same timeframe, SCK·CEN is carrying out the design of multi-purpose hybrid research reactor for high-tech applications (MYRRHA), an LBE-cooled, accelerator-driven system that can be used as an irradiation facility and as a supporting installation for the fuel and material qualification of fast reactors. Obvious and strong synergies exist between MYRRHA and ALFRED, and the European organizations involved in one development actively participate in the other project’s development. The members of these two projects accept new international participants on a case-by-case basis.

4.3. Japan

In Japan, especially after the Fukushima event, R&D turned back to basic research. Some conceptual designs are still in the analysis phase while basic research is carried out on materials and materials compatibility with lead and LBE. However, Japan is still active in the LFR development through its participation in the GIF, and is providing very important information regarding safety principles and applications, based on previous experience of accidents and lessons learned through them. Japanese developments can be found in Ref. [7].

4.4. Korea

Korea signed the GIF-LFR MoU in December 2015. Korea participates in GIF LFR activities through the involvement of the Seoul National University (SNU) and with the development of URANUS [8], a small modular LBE-cooled concept fueled with uranium oxide. The reactor is an underground concept with a long-lasting core (20-year refueling cycle) featuring passive safety systems. The reactor uses natural circulation on the primary side, and SNU promoted a benchmark exercise at the international level through Organization for Economic Co-operation and Development Nuclear Energy Agency (OECD-NEA) to verify the system computer code capabilities to predict this essential part of the design. SNU is also pursuing the design of the PEACER-300 reactor with plutonium-burning capabilities, which is able to recycle all minor actinides in its closed-fuel cycle.

4.5. The US

Although the US was one of the first countries to attempt to use heavy liquid metals as a coolant for nuclear reactors, its present initiatives are very limited but are expected to grow. From the design perspective, two main initiatives have been carried out: the SSTAR [9] and GEN4. Both are aimed at the development of small modular reactors, characterized by small dimensions and very long-lasting cores.

From the R&D perspective, some interesting progress was made in the issue of corrosion with the development of a coextrusion technique using structural materials in conjunction with layers of corrosion-resistant materials. The US was active in the GIF from the start of the LFR PSSC activities. Although holding only an observer status, American delegates participate very actively in the group activities, providing important direction for future developments. In addition, the Westinghouse Electric Corporation recently expressed its interest in a small modular LFR development.

4.6. China

LFR activities in China have traditionally been carried out by the Institute of Nuclear Energy Safety Technology (INEST), within the Chinese Academy of Sciences. From the start of these activities, INEST pursued the development of an accelerator-driven system for both power production and waste transmutation. The rather aggressive program and schedule of the China Lead-based Reactor (CLEAR) envisions the construction of CLEAR-I (10 MW), followed by CLEAR-II (100 MW) and CLEAR-III (1000 MW) [10]. A dual mode of operation of CLEAR-I (critical and sub-critical) is envisaged. While this first phase of development uses LBE, the subsequent development steps envision the use of pure lead. Strong synergies are also expected to take place between the parallel developments of fusion through the use of lead-lithium.

INEST participates in Generation IV activities as an observer, but the growth of the staff involved in the CLEAR project is impressive, promoting optimism for the future of such an initiative in China. The KYLIN-series LBE experimental loops have been constructed to perform structural material corrosion experiments, thermal-hydraulics tests, and safety experiments. In order to validate and test the key components and integrated operating technology of the lead-based reactor, the lead alloy-cooled non-nuclear reactor CLEAR-S, the lead-based zero-power nuclear reactor CLEAR-0, the lead-based virtual reactor CLEAR-V, and the high-intensity neutron generator HINEG is under construction.

5. Conclusions

From the start of the Generation IV activities, it was evident that the LFR had a very strong potential to satisfy all the GIF goals. Due to previous experience and the expected corrosion problems of lead and LBE liquid coolants, most of the efforts of Generation IV were in the direction of fast reactors using sodium coolant. However, recent advancement has been made in terms of provisions and materials that are able to withstand flowing liquid lead corrosion. This fact, along with the obvious advantages offered by lead coolant in terms of safety, has provoked renewed interest from researchers and developers, as can be seen in the fast evolution of several initiatives around the world. The technological merits of the LFR and its compliancy with the goals of Generation IV are substantial prerequisites for finding an adequate level of financing to bring nuclear energy to a new level in the near future.

Acknowledgements

The author wish to thanks all participants of the Generation IV LFR System Steering Committee for the useful discussions among the group and the information exchanged as part of the GIF collaboration activities.

References

[1] US DOE Nuclear Energy Research Advisory Committee, Generation IV International Forum. A technology roadmap for Generation IV nuclear energy systems. USA: US DOE Nuclear Energy Research Advisory Committee, Generation IV International Forum; 2002. Report No.: GIF-002-00.

[2] GIF Policy Group. Technology roadmap update for Generation IV nuclear energy systems. USA: The OECD Nuclear Energy Agency for the Generation IV International Forum; 2014 Jan.

[3] Alemberti A, Frogheri ML, Hermsmeyer S, Smirno LAV, Takahashi M, Smith CF, et al. Lead-cooled fast reactor (LFR) risk and safety assessment white paper, revision 8 [Internet]. [cited 2014 Apr]. Available from: https://www.gen-4.org/gif/upload/docs/application/pdf/2014-11/rswg_lfr_white_paper_final_8.0.pdf.

[4] Weeks JR. Lead, bismuth, tin a nd their alloys as nuclear coolants. Nucl Eng Des 1971;15:363–72.

[5] Smirnov VS. Lead-cooled fast reactor BREST—project status and prospects [presentation]. In: International Workshop on Innovative Nuclear Reactors Cooled by Heavy Liquid Metals: Status and Perspectives; 2012 Apr 17–20; Pisa, Italy; 2012.

[6] Alemberti A, Frogheri M, Mansani L. The lead fast reactor: demonstrator (ALFRED) and ELFR design [presentation]. In: International Conference on Fast Reactors and Related Fuel Cycles: Safe Technologies and Sustainable Scenarios (FR13); 2013 Mar 4–7; Paris, France; 2013.

[7] Takahashi M. National status on LFR development in Japan [presentation]. In: 11th LFR Prov. SSC Meeting; 2012 Apr 16; Pisa, Italy; 2012.

[8] Choi S, Hwang IS, Cho JH, Shim CB. URANUS: Korean lead-bismuth cooled small modular fast reactor activities. In: Proceedings of ASME 2011 Small Modular Reactors Symposium; 2011 Sep 28–30; Washington, DC, USA. ASME Digital Collection; 2011. p. 107–12.

[9] Smith CF, Halsey WG, Brown NW, Sienicki JJ, Moisseytsev A, Wade DC. SSTAR: the US lead-cooled fast reactor (LFR). J Nucl Mater 2008;376(3):255–9.

[10] Wu YC, Bai YQ, Song Y, Huang QY, Zhao ZM, Hu LQ. Development strategy and conceptual design of China lead-based research reactor. Ann Nucl Energy 2016;87(Part 2):511–6.