Trends of publications and patents on metallic fuel development for fast reactors

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Higher breeding ratio, high thermal conductivity, shorter doubling time and high plutonium production make metallic fuels a viable solution compared to oxide/nitride/carbide/silicide fuels for cost-effective commissioning of many power reactors. Metallic fuels lend themselves to compact and simplified reprocessing and re-fabrication technologies, a key feature in a novel concept for the deployment of fast reactors. Satisfactory physical and technical characteristics of fuel rods with metallic fuel have been demonstrated at high burn-ups, and comparatively easy reprocessing of spent fuel using the pyro-metallurgical method makes this fuel relevant in fast reactors development. The present work is complemented with a scientometric study.

Keywords. Metallic fuels, patents scientometric analysis, publication trends, thermal properties.

RESEARCH work related to the development of metallic fuels for fast reactors has taken a leap in recent years. A metallic fuel core gives better neutron economy than an oxide fuel core because the neutron energy spectrum is harder. Therefore, a metallic fuel for liquid metal cooled fast breeder reactors (LMFBR) can respond better to requirements such as conversion/breeding ratio, actinide burning, long core life, or a compact core. Metallic fuels have a high breeding ratio and hence short doubling time together with high burn-up and high linear heat ratings. Higher fissile atom density compared to oxide counterpart results in higher breeding ratio for the metallic fuels. Metallic fuel has high thermal conductivity than the conventional oxide fuel, rendering it with significantly more safety benefits than the latter. With higher thermal conductivity and hence better heat transfer coefficient, the centre temperature of metallic fuel remains low. Therefore, for a given reactor power metallic fuels are a lot cooler. Hence during transient, the early positive Doppler reactivity increment is small compared to oxide fuels. In addition, reactor power can be reduced more quickly with metallic fuels. The inherent safety of the metallic fuel was successfully demonstrated with two separate tests with off-normal conditions and was carried out at the experimental breeder reactor (EBR) II. The reactor from full power was subjected to two accidental (simulated) conditions; one with loss of primary coolant flow and the other with loss of heat sink[1–3]. In both cases, the reactor was shut down without scram. Metallic fuel allows adopting a straightforward reprocessing technique by pyro-metallurgical processes combining electro refining and cathode processing, which allows most of the actinides to recycle in the fuel cycle, thereby extracting additional energy and shorter cooling period of the spent fuel. The cathode product remains alloyed as well as highly radioactive. This prevents both diversion of fissile material and proliferation of nuclear weapons. The high-level waste emerging from this process will decay to the background in only hundreds of years as against a million years from the conventional reprocessing plants. Development of metallic fuels is an evolving area and there are excellent reviews providing wide coverage for specific and general readers. However, the chronological development of the literature consists of journal articles, conference papers, technical reports and patents, and summarizing them is rather difficult. The developments in scientometrics in this area will be of specific interest to the general researcher and a new researcher who has initiated research in this field. The objective of this article is to combine the information available by experts on metallic fuels and also by information scientists to analyse the publications trends in the area.

Bibliographic databases are the representative samples of research carried out in any field. In view of the importance of such work, excellent reviews have been published. However, the work included all the literature published in journals and conference proceedings and technological innovations in the form of patents, even though they are limited in number. The aim of the present work is to analyse bibliographic details of the patents, journal articles, conference papers and technical reports for a comprehensive scientometric study in this area. In

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addition, the evaluation includes the broad current global research trends in the area of metallic fuels with specific emphasis on the R&D activities in India, where the construction of fast reactors is at the advanced stage of completion.

Methodology

The bibliographic databases like INIS from IAEA [period: 1970–2012], INSPEC from Institution of Engineering and Technology [period: 1898–March 2013], *Web of Science* from Thomson Reuters [period: 1900–March 2013], *Scopus* from Elsevier Publishers [period: 1960–March 2013] are used for eliciting published records in the area of research. Records of *Derwent Innovations Index* from Thomson Reuters [period: 1963–March 2013], which gives value-added patent information from *Derwent World Patent Index* as well as patent citation information from *Patents Citation Index* are used for patent details on metallic fuels.

The following are some of the keywords used for searching records pertaining to metallic fuels from these databases: U–Pu–Zr, U–Pu alloy, uranium plutonium alloy, uranium plutonium zirconium, IFR fuels, Integral Fast reactor fuels, Metal Fuels, metallic alloy fuel, metallic based fuel, metallic dispersion fuel, metallic driver fuel; metallic fast-reactor fuels, metallic fuel, metallic fuel-cladding, metallic fuels, metallic Magnox fuel, metallic nuclear fuel, metallic nuclear fuels, metallic plutonium-containing fuel, metallic SFR fuel, metallic spent fuel, metallic spent fuels, metallic test fuel, metallic Th, U and Zr fuels, metallic Transmutation fuel, metallic transmutation fuels, metallic U–10Zr fuel, metallic U–Pu–Zr fuel, metallic uranium fuel, metallic uranium fuels, metallic uranium-fissium fuel, metallic-fuel, metallic-U fuel, metallic-uranium fuels, metallic-uranium tubular fuel, SFR fuel, Sodium-Cooled Fast Reactor Fuel.

The following properties or processes are used to refine the records to limit to the area of review: pyrometallurgical reprocessing, pyroprocessing, smear density, swelling, thermal characterization, thermophysical characterization, thermophysical properties, breeding, chemical interaction, fuel clad chemical interaction (FCCI), fuel cladding, etc.

Trends of publications and patents

When the above-mentioned databases are compared, the INIS database covers maximum number of records on metallic fuels and there are overlaps in records among the databases. It has found 572 individual published documents on the topic published during 1954–2013. Figure 1 presents the chronological trend of publications in various publication media. Recent years have witnessed an upsurge in the number of publications. More than 56% of the literature published on metallic fuels is found to be non-conventional (literature which is not easily available in commercial markets) in nature.

Publications growth

The affiliations of the authors of the published papers are treated as the origin of the research and used for identifying the country of research for a particular piece of information. The publication records show that only a few countries (28) are pursuing research on metallic fuels. The trend of research activities is revealed through the number of publications (inset, Figure 1).

Institutional publications productivity

The study has analysed the research institutes involved in metallic fuels research all over the world. As the number of countries involved in research in this area is less, the number of institutes working on this field is also less. The 157 individual institutes are identified from the affiliations of the authors and some leading institutes in terms of number of publications are listed in Table 1, with their span of research (duration between first publication year and last publication year).

Domianary publication productivity

The contents of the research publications were analysed and the present work has arrived at the following seven areas of metallic fuels research: fuel cladding interaction, fuel processing, physical and mechanical properties, preparation and fabrication, radiation damage, failure mechanism and spent fuel reprocessing.

The published literature is segregated according to the above categorization and it has found that majority of research is concentrated on fuel fabrication and preparation. Figure 2 gives the year-wise trend of research activities in various fields and the proportion of published documents in these areas.

Most productive journals

The published journal articles on metallic fuels are distributed over 61 individual journals publishing from various parts of the world. Some of the leading journals (impact factor in parenthesis) publishing metallic fuels related articles are: *Transactions of the American Nuclear Society* (not available), *Journal of Nuclear Materials* (2.05), *Denryoku Chuo Kenkyusho Hokoku* (not available), *Nuclear Technology* (0.6), *Journal of Nuclear Science and Technology* (0.71), *Annals of Nuclear Energy* (0.91) and *Nuclear Engineering and Design* (0.77). Since the number of journals publishing articles in the field is small

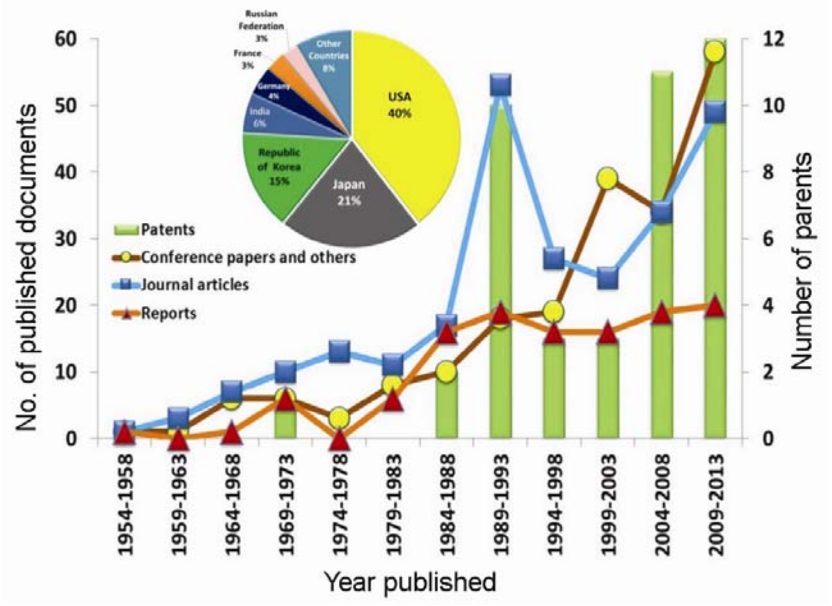

Figure 1. Chronological trend of the published literature on metallic fuels. (Inset) Leading countries pursuing research on metallic fuels and break-up of their publications share.

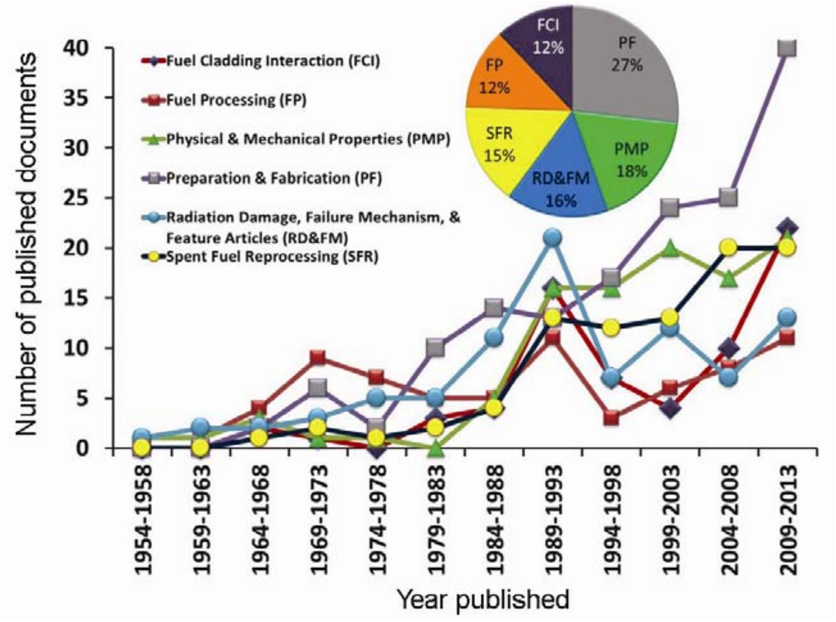

Figure 2. Trend of published literature on various aspects of metallic fuels research. (Inset) Break-up of literature based on the micro-fields.

Table 1. Most active research institutes and their research span in the area of metallic fuels worldwide

Research institute	No. of publications	Research span (years)
Argonne Nat. Lab., IL, USA	148	53
Korea Atomic Energy Research Institute, Republic of Korea	91	19
Central Research Institute of Electric Power Industry, Japan	89	26
Idaho National Laboratory, USA	35	39
Bhabha Atomic Research Centre, India	23	34
European Commission Joint Research Centre, Germany	18	19
Japan Atomic Energy Agency, Japan	17	25
Indira Gandhi Centre for Atomic Research, India	13	20
Commissariat a l’Energie Atomique, France	10	53

with high impact, a new comer in the field can carry out the literature survey easily.

Patenting companies

The assignees of the patents filed in the field were analysed and we arrived at a list of top assignees and companies: Denryoku Chuo Kenkyusho (seven patents); Toshiba KK (seven patents), Genshi Nenryo Kogyo KK (six patents), Korea Atomic Energy Research Institute, Daejeon (five patents), Nippon Genshiryoku Jigyo KK (five patents), Korea Hydro and Nuclear Power Co Ltd (four patents); United States Secretary of the Navy (four patents), Boeicho Gijutsu Kenkyu Honbuch (individual) (three patents); Guindon L (GUIN-Individual) (three patents) and Mitsubishi Jukogyo KK (three patents). Japanese companies hold maximum number of patents in the field. It is important to mention that an attempt has been made to provide salient developments in the R&D on metallic fuels based on the published reviews, and it is not exhaustive.

Metallic fuels R&D – current status

For efficient breeding, fast reactor fuels must contain significant amounts of plutonium along with the major constituents of uranium (238 and 235). Uranium has three allotropic modifications from room temperature up to its melting point, namely: α-phase (orthorhombic, RT – 669°C), β-phase (tetragonal, 669–772°C) and γ-phase (bcc, 772–1132°C). The α-phase is anisotropic, resulting in dimensional instability in terms of anisotropic growth and irradiation-induced cavitational swelling when uranium alone is used as a reactor fuel in thermal reactors[4]. Plutonium is completely soluble in γ-uranium, but up to 20% in β-uranium and up to 16% in α-uranium. Plutonium enhances the swelling rate in each of these three phases by increasing the diffusivity in the alloy. Moreover, binary uranium–plutonium alloy alone cannot be used as reactor fuel because of the formation of low temperature eutectic with the cladding constituents (e.g. iron and nickel) adjacent to the cladding. The solidus temperature (above which melting begins) of the alloy is also low to allow any practical design of the reactor. Thus an alloying addition will be necessary to increase the solidus temperature as well to improve the compatibility with cladding material. Several studies have been conducted on U–Pu–Mo in UK and France[5,6], and on U–Pu–Fs (fissium), U–Pu–Ti and U–Pu–Zr in USA[7]. Large swelling was observed in all these fuels. Chromium, titanium and zirconium result in adequate increase in the solidus temperature of the fuel. But, zirconium is unique amongst these alloying elements because it enhances the compatibility between the fuel and the stainless steel cladding material by suppressing the inter-diffusion of fuel and cladding constituents[8]. The maximum allowable concentration of zirconium is to be kept at 10 wt% in the ternary alloy of U–Pu–Zr. Quartz moulds are normally used in injection casting process to fabricate metallic fuels. Too much zirconium will increase the liquidus temperature (above which only liquid state prevails) of the alloy well beyond the softening point of fused quartz moulds. In that case, the latter cannot be used for fabrication of metallic fuels in the injection casting process.

Indian perspective

In the long term, the Indian fast reactor programme will be based on metal fuel to achieve faster growth of nuclear power. Future commercialization of the FBR fuel cycle necessitates the use of metallic fuel along with the pyroprocess recycling, which can be less costly than oxide fuel reprocessing. Metal fuels have high thermal conductivity, high fissile and fertile atom densities, low doubling time and ease of fabrication compared to other ceramic fuels. Metallic fuel was the first to be selected for the experimental fast reactors in the 1950s in USA and UK[9]. Clementine, the first fast reactor in the world, used ^{239}Pu metal as fuel. EBR-I in USA used high enriched uranium metal containing >90% ^{235}U as fuel and the Enrico Fermi reactor was fuelled with U–Mo alloy. Uranium alloys have been used in the fuel elements in the CO_2 cooled first-generation nuclear power plants in UK and France. The DFR in UK utilized the U–Mo alloy fuel and also the U–Cr alloy. The fuel of Mark-I and Mark IA of EBR-II was uranium with the addition of 5 wt% fissium. This is an alloy that approximates the equilibrium concentration of the metallic fission product elements left by the early pyro-metallurgical reprocessing of EBR-II fuel. After various design changes to improve the performance, the fuel composition was changed from U–Fs to U–Zr. Later, an integral fast reactor (IFR) concept was developed[10]. The fuel of choice was an alloy of uranium, plutonium and zirconium, designated U–20Pu–10Zr, where the compositions are given in wt%. A larger number of U–Pu–Zr fuel pins were irradiated in EBR-2 and FFTF to high burn-up (20 at.%)[9,10].

Two design concepts: Two design concepts have been proposed for the metallic fuel development programme for FBRs in India[11]. These are: (a) mechanically bonded pin with U–15 wt%Pu alloy as fuel and (b) sodium-bonded pin with U–15 wt% Pu–6 wt%Zr alloy as fuel.

T91-grade steel (modified 9Cr1-Mo steel) has been used as the cladding material in these designs. For mechanically bonded binary alloy fuel design, the use of zirconium liner is envisaged between the fuel and cladding material. To ensure proper bonding, the cladding material with zirconium layer will be swaged onto the fuel slug. This will also ensure that no gap remains between zirconium, cladding material and the fuel. To accommodate irradiation-induced fuel swelling, the fuel slug is designed with two semicircular grooves filled with helium gas placed diametrically opposite to each other[12]. For this mechanically bonded fuel design, the smear density, which is important for accommodating fuel swelling, can be kept favourably around 70–85%, as against 70% for sodium-bonded fuel design. In the isothermal holding experiments (700°C, 1000 h of heating) carried out with diffusion couple between U, Zr and T91 it has been established that Zr liner acts as an effective barrier to prevent any possible FCCI.

The diffusion reaction at the U/Zr interface was found to be significantly high at 750°C, whereas at Zr/T91 the diffusion reaction was sluggish in nature. The inter-diffusion between U–6 wt%Zr and T91 at 700°C resulted in the formation of (U, Zr) $(Fe, Cr)_2$, Zr-rich and Zr-depleted layers at the interface, whereas at 750°C the reaction between these two caused eutectic melting resulting in the formation of U_6Fe, $U(Fe, Cr)_2$ and $Zr(Fe, Cr)_2$ phases[13].

Fuel-clad chemical interaction: The major drawbacks of metallic uranium and plutonium and some of their alloys are unusual irradiation growth and swelling attributed to anisotropic crystal structure. With the addition of proper alloying elements and following proper heat treatment the isotropic phases are made predominant, which enhances the dimensional stability. FCCI has been recognized as one of the major concerns for metallic fuels because of the formation of low melting eutectic[14]. FCCI can occur in either of the following ways. Lanthanide fission products form low melting eutectics with iron, which is one of the major constituents of cladding material. Moreover, the fuel itself forms low melting eutectics with iron and other minor constituents of the cladding material (e.g. Ni, Cr).

It is often suggested to incorporate a liner between fuel and cladding to prevent FCCI. Diffusion couple tests of U–Zr or U–Zr–Ce alloys with ferritic martensitic steel such as HT9 or T91 have shown that metal foils of Zr, Nb, Mo, Ta, V and Cr are effective in inhibiting inter-diffusion between these fuels and steel. Eutectic melting was not observed in any diffusion couples using these diffusion barriers at 800°C (ref. 15). Among them, V and Cr exhibited the most promising performances as a diffusion barrier material. The addition of transuranic elements (TRUs) to the fuel alloy for burning is known to reduce the melting temperature of the alloy, which lowers the safety margin and can promote FCCI. It has been observed that addition of the zirconium steadily increases the solidus temperature of metal fuel. This makes plausible the addition of elements, e.g. Pu and Np, which lower the solidus temperature of alloy fuel and also form low melting eutectics with iron[16].

Swelling: For U–Zr-based metallic fuel, the phase transformation ($\gamma_2 \leftrightarrow \alpha$-Zr + δ-UZr_2) is observed above and below 660°C (ref. 17). In the initial stage of irradiation, $\alpha + \delta$-phase field prevails in the most volumetric part of the fuel, whereas the hottest part of the fuel remains at the high-temperature $\gamma_1 + \gamma_2$ or γ field. At reactor temperatures, the metal fuel manifests anisotropic swelling as it does not possess single-phase cubic symmetry. U–Mo alloy exhibits single-phase cubic symmetry and has good thermal conductivity. But addition of trans-uranium elements for burning in this alloy leads to drastic reduction in its solidus temperature. For this, a superior alloy ‘U-10M’ has been recommended, where M stands for optimal combination of molybdenum, titanium and zirconium. Addition of titanium, molybdenum and zirconium increases solidus temperature for the fuel and widens the cubic phase range by decreasing the onset temperature for the cubic[18].

For a typical fuel pin, the metal fuel slug undergoes significant swelling upon irradiation, due to the generation of fission gases. Fuel-clad contact occurs within 1–2 at.% peak burn-up. The data show that prior to making contact with the cladding tube, the metallic alloy fuel swells rapidly due to its high fission-enhanced creep rate and irradiation growth. A higher swelling implies higher fission-gas diffusivity and higher creep rate in the central region of the fuel. As a result of fluid-like behaviour in the hotter central part of the fuel, in this region the fuel is in a hydrostatic stress state. At the same time, the cooler and stronger outer shell is in a state of tensile stress[19]. The effect of these tensile stresses on swelling and creep in the outer fuel zone explains the larger radial than axial swelling and thus observed anisotropy in swelling. The outer anisotropic swelling leads to large radial cracks, presumably because there is insufficient time to relax radial stresses by means of creep.

With the progress of irradiation, the fuel swells and the gap between the fuel and cladding material closes. After the gap closes, lanthanide fission products are believed to migrate towards the periphery of the fuel cross-section and cause FCCI[20]. Additives such as Pd and In could be used to stabilize the lanthanides as intermetallic compounds[18,21]. Palladium forms separate intermetallic phase with lanthanides and in the process helps in binding lanthanides, which could have otherwise caused FCCI. The density of indium is much less than that of palladium, whereas their neutron cross-sections are comparable. As palladium is expected to displace less uranium, it would have less effect on reactivity compared to indium.

Reprocessing: The metallic fuels will be reprocessed by the pyrochemical route. The development of pyroprocessing technologies started in the 1980s with electrorefining methods for separating actinide elements from fission products[22]. Pyro-metallurgical and electrochemical processing[23,24] were the key elements in the IFR programme of the US. Details of pyro-process equipment and plan for demonstration of this process in the Fuel Cycle Facility at the Argonne-Idaho site are available in the literature[25,26]. All these operations must be carried out in hot-cell facility, as the fuel from the reactor will be highly radioactive.

Computer codes: An engineering code, named Fuel Engineering and Structural analysis Tool (FEAST), was developed to predict the irradiation behaviour of U–Zr and U–Pu–Zr metallic alloy fuel in sodium-cooled fast reactors. Based on gas bubble coalescence and growth by random and/or biased migration of gas bubbles occurring in the grain boundaries, this model of fission gas swelling has been developed[27]. The gas release is modelled by open bubbles and tunnel formation. The upgraded version of the code is known as FEAST-METAL and various parameters, e.g. burn-up, smear density, axial variation of the clad hoop strain and fission gas release behaviour could be predicted satisfactorily for some test pins selected under EBR-II irradiation conditions. In the first phase, according to a fixed number of gas atoms per bubble group, the fission gas bubble growth is modelled. For this, both small and large bubble groups were selected. Small bubbles, which are nucleated at the phase boundaries normally grow into large bubbles by gas migration. Bubble morphology for each phase structure is captured by selecting the number of atoms per bubble and the shape of the bubbles is in a phase-dependent form. It has been found that a 10% gas-swelling threshold is appropriate for a wide range of gas bubble sizes. Other modelling codes, viz. LIFE-Metal and ALFUS are available in the literature[28,29].

To study various physics parameters, two-dimensional diffusion calculations were carried out on U–Pu–Zr fuelled FBR cores as a function of various reactor parameters, e.g. zirconium content in the fuel, reactor power, smear density and number of rows in radial blankets[30].

Indian experience

In the pursuit of generation and supply of long-term sustainable nuclear energy, India is following its nuclear power programme in three stages. After successfully demonstrating commercially viable and safe operation of the pressurized heavy water reactors (PHWRs) belonging to the first stage, the focus is now on the liquid metal fast breeder reactors (LMFBRs) in the second stage of India's nuclear power programme. The main objective here is to breed uranium (233) in the blanket sub-assemblies of the reactors until sufficient amount is obtained to start the self-sustaining thorium–uranium (233) fuel cycle to be used in the third stage. Plutonium burning and breeding will be necessary for this purpose. This will be met with uranium–plutonium (plutonium coming from the first stage) fuel cycle along with blanket breeding of uranium (233) till the onset of the third stage. Therefore, the fuel in the second stage must possess good breeding characteristics for the above reasons together with high burn-up for reducing fuel cycle cost.

There is a huge demand and growth rate expected for nuclear power in India, which can be met through the use of metallic fuels in fast rectors that promise high breeding ratio and low doubling time[30–32]. They are relatively easy to fabricate and have high thermal conductivity and lower heat capacity[33–36]. Two design concepts have been proposed for the metallic fuel development programme for FBRs in India[12,37–39], mechanically bonded U–Pu binary alloy and sodium-bonded U–Pu–Zr ternary alloy fuel. T91-grade steel (modified 9Cr1-Mo steel) is chosen as the cladding material in both of these designs. In the former, it is proposed to use U–15 wt%Pu alloy as fuel, having mechanically bonded pin with a zirconium liner between the fuel and the cladding material. This is to prevent the fuel-cladding chemical interaction. T91 cladding tube having Zr barrier layer will be swaged on the fuel slug. No physical gap between barrier layer and fuel slug is to be expected. Helium-filled semicircular grooves are to be provided diametrically opposite each other in the fuel slug for the accommodation of irradiation-induced fuel swelling and fission gases. Smear density will vary between 75% and 85% (refs 37, 38, 40). The second proposed concept is sodium-bonded pin with ternary U–15 wt%Pu–6 wt%Zr alloy as fuel. Technology related to sodium bonding has already been developed. Test irradiation of this type of fuel is planned in near future.

Patent content analysis

There are many patents filed on pool-type fast reactor design with metallic fuel and reactor vessel accommodating the liquid metal coolant and on ternary U–Pu–Zr alloy nuclear fuel having breeding ratio more than conventional U–Pu mixed oxide fuel. Another fuel based on UAl_x group composition distributed in U–Mo–Al ternary alloy matrix and its fabrication method is proposed. Proliferation-resistant accident-tolerant capsular autonomous reactor design is patented. The use of yttrium, lanthanum and/or rare earth elements as substitutes for zirconium has been proposed in actinide-rich fuel when mixtures of plutonium, minor actinides and uranium are used as fuel material. Due to removal of zirconium, waste disposal problem of Zr-93 is eliminated. Typical composition for fast reactor includes 79% uranium, 20% plutonium and 1% yttrium by weight. As the fuel is not sufficiently diluted, there is not much compromise in terms of neutron economy and reactor core size increase for the same power level. Minor actinides are substituted by part or all for plutonium and uranium in case of an actinide-burner reactor. Waste disposal becomes easier for short half-lives of yttrium, lanthanum and/or rare earth elements after irradiation. These are immiscible with uranium and plutonium. Uranium and plutonium combine to form the major phase and the rare earths combine with neptunium in a minor phase. The mechanical properties of the fuel are expected to improve as this minor phase pins the fuel structure[41].

Metal fuel sub-assemblies with co-extruded metal elements into a spiral, multi-lobed shape have been patented. The spiral ribs of the multi-lobed fuel element provide structural support to the fuel element, which may facilitate reduction in the quantity or elimination of spacer grids that might otherwise have been required. This reduces the hydraulic drag on the coolant and increases the amount of heat that can be transferred to the coolant at a lower fuel element temperature[42,43]. To reduce the chemical interaction between fuel for a nuclear reactor (U–Pu binary or U–Pu–Zr ternary alloy) and stainless steel cladding material (HT9 or D9), the use of zirconium layer in between has been proposed. The barrier layer may contain alloying metal selected from the group consisting of zirconium, titanium, niobium and molybdenum[44].

A nitride-coated layer on the inner surface of the cladding tube is proposed, where a liquid metal will be filled between the metallic fuel core and the cladding tube. Stabilized fast reactor metal fuels containing actinide fuel with yttrium, lanthanum and/or rare earth stabilizers are also patented. There is a proposal for metallic fuel element container (cladding material) made of alloy containing Ni–Cr–Co, which has high creep strength at high temperature. The thickness of the tube would have to be at least one-tenth of the outer diameter and 10–30% of the inner volume is left free for accommodating fission products and fuel swelling. One of the patents proposed a binary/ternary fuel composition containing a metal dopant, e.g. titanium, palladium, silver and/or mixture of these to extend the fuel burn-up. These dopants are to be distributed in the fuel matrix uniformly to pin the fission products by forming alloys with them. This prevents the migration of lanthanides towards cladding material, which otherwise would result in FCCI[45].

Conclusion

In this article an attempt has been made to exhaustively search the published literature, and analyse the results in the area of metallic fuels. This concept of the literature search and scientometric analyses will provide volumetric information which is vital for young researchers who have just started work in the area. An upward growth in the number of published articles indicates the increasing interest in metallic fuels research. Very few countries or institutions are working in this field, and fabrication of the fuels is the favourite area of research. USA, Japan and Korea are the leading countries pursing research in the area, and Japanese companies hold maximum number of patents in the field. *Transactions of the American Nuclear Society*, *Journal of Nuclear Materials*, *Denryoku Chuo Kenkyusho Hokoku* and *Nuclear Technology* are the key journals publishing metallic fuels-related articles. The results of the literature search can be used as a document for research and strategic planning. To meet future energy demands, India will have to depend on the development and deployment of fuels with high breeding ratio and low doubling time. Metallic fuels are reported to be efficient in meeting these requirements. Ease of fabrication by injection casting route in combination with pyro-metallurgical reprocessing appears to be promising for metallic fuels for fast reactors to have proliferation-resistant integrated fast reactor concept with reactor, fuel fabrication and reprocessing facility, all located in adjacent areas. Work related to development of fast reactor fuels based on metallic fuels, viz. binary U–Pu and ternary U–Pu–Zr alloys has been initiated in India encompassing various aspects, e.g. fabrication of the sodium/metallic-bonded fuel pin, studies on out-of-pile thermophysical and thermodynamics properties of fuel alloys, fuel-clad chemical compatibility, etc. The challenges ahead include closing the gaps in fuel cycle within the shortest possible time, sustained planning in test irradiation with feedback utilization before its large-scale commercial deployment and minimizing the overall fuel cycle cost for commercial competence.

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