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Inert matrix fuel strategies in the nuclear fuel cycle: the status of the initiative efforts at the 8th Inert Matrix Fuel Workshop

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The 'raison d'être' of the Initiative for Inert Matrix Fuel (IMF) is to contribute to Research and Development studies on inert matrix fuels that could be used to utilise, reduce and dispose both weapon- and light water reactor-grade plutonium excesses. In addition to plutonium, the amounts of minor actinides are also increasing. These actinides have to be consequently disposed in a safe, ecological and economical way.

The promising strategy that consists of utilising plutonium and minor actinides using a once-through fuel approach within existing commercial nuclear power reactors e.g. US, European, Russian or Japanese Light Water Reactors (LWR), Canadian Pressured Heavy Water Reactors, or in future transmutation units, has been emphasised since the beginning of the initiative. The approach, which makes use of inert matrix fuel is now studied by several groups in the world [1,2]. This option has the advantage of reducing the plutonium amounts and potentially minor actinide contents prior to geological disposal. The second option is based on using a uranium-free fuel leachable for reprocessing and by following a multi-recycling strategy [1,2]. In both cases, the advanced fuel material produces energy while consuming plutonium or the minor actinides. This material must, however, be robust. The selected material must be the result of a careful system study including inert matrix – burnable absorbent – fissile material as minimum components and with the addition of stabiliser. This yields a single-phase solid solution or more simply if this option is not selected a composite inert matrix–fissile component.

In screening studies e.g. [3–5] pre-selected elements were identified as suitable. In the 90s an IMF once-through strategy was adopted considering the following properties:

- neutron properties i.e. low absorption cross-section, optimal constant reactivity, suitable Doppler coefficient e.g. [6],
- phase stability, chemical inertness, and compatibility e.g. [7],
- acceptable thermo-physical properties i.e. heat capacity, thermal conductivity e.g. [8],
- good behaviour under irradiation i.e. phase stability, minimum swelling e.g. [9], retention of fission products or residual actinides e.g. [10],
- optimal properties after irradiation with insolubility for once through then out e.g. [11].

This once through then out strategy may be adapted as a last cycle after multi-recycling if the fission yield is not large enough, in which case the following property is required:

- good leaching properties for reprocessing and multi-recycling [12].

The field of research work involved several R&D activities including:

- Pre-selection and basic studies on inert material candidates such as MgO [13], $MgAl_2O_4$ [14], $(Ca,Zr)O_{2-\xi}$ [15], $(Y,Zr)O_{2-\xi}$ [16], $ZrSiO_4$ [3], ZrN [17], SiC [18], $^{11}B_4C$ [19], AlSi, Mo, Zr [20], Zircaloy, or stainless steel was based on thermodynamic and neutronic properties noted above.
- Fabrication campaign of the material comprising the matrix components, the fissile, the phase stabiliser, and the burnable poison.

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- Testing in irradiation facilities such as accelerators, research reactors or neutron sources.
- Study of the application for utilisation in specific reactors [21], with emphasis on reactivity, safety studies including studies of loss of coolant accident (LOCA), reactivity initiated accident (RIA) [22] and severe accidents [23].

The options comprise: *homogeneous materials*: solid solution (solsol) as oxide, nitride or metal (alloys), and *heterogeneous materials*: composites (cercer, cermet or metmet) with the above noted candidates.

These materials may be used as cylindrical pellets, prismatic designed blocs, or as micro-spheres utilised as sphere pack or kernels. They are utilised at the level of assembly as prismatic (vertical or horizontal) set up such as in light water reactors, pressured heavy water reactors or liquid metal fast reactor, or, as spherical such as in a high temperature reactor. The *assembly* may be *homogeneously* or *heterogeneously* loaded with the IMF, and the reactor *core* may be *homogeneously* or *heterogeneously* loaded with IMF assemblies. These three levels, i.e. pellet, assembly and core, of IMF utilization in LWR are considered within a homogeneous-heterogeneous concept scheme as depicted in Fig. 1.

Since 1995, when the first IMF workshop was organised at PSI [24], the IMF workshops have been held each year. They involved discussions on the specific

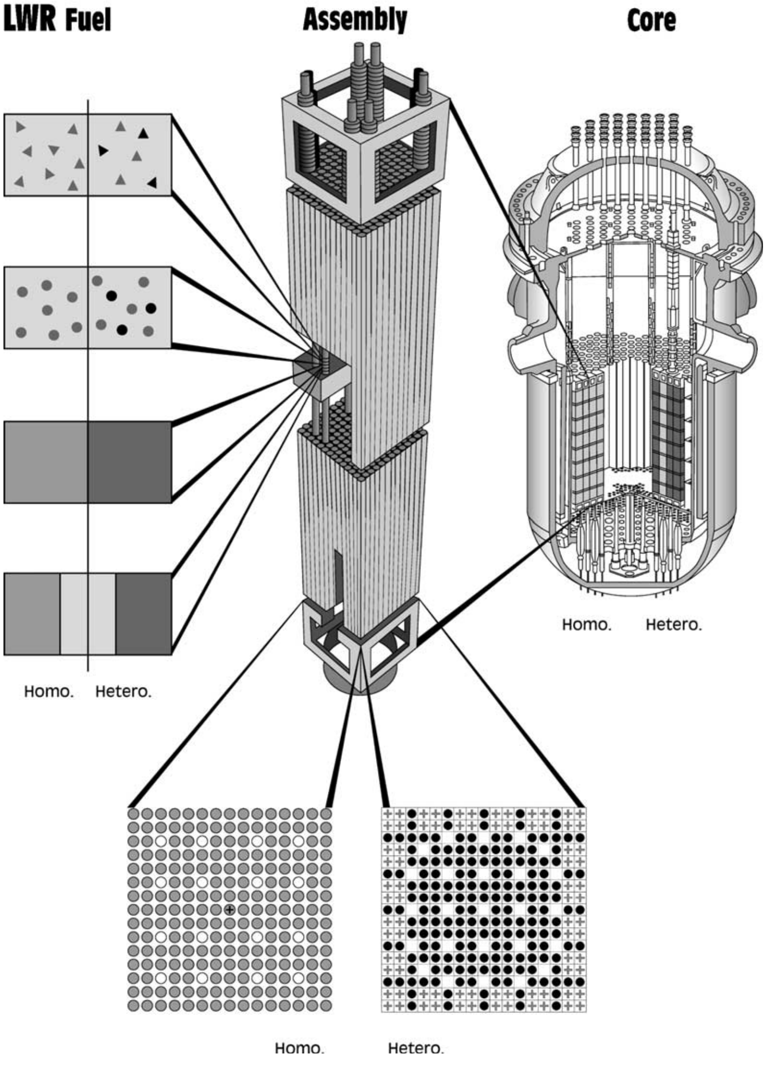

Fig. 1. The three levels for IMF utilization in LWR considering homogeneous/heterogeneous systems at the pellet level, the assembly level and the core level (black/dark: U phase; grey: IM/IMF phase).

topic of inert matrix fuel for the incineration of actinides, focusing on homogeneous or heterogeneous strategies. Long-term irradiations of pellets consisting of inert matrices for burning fissile material have started in 90s e.g. at the SILOE facility, Grenoble [25] or at the JRR3, Tokai [26], and new irradiations are in progress e.g. at the HBWR, Halden [27] or HFR, Petten [28]. If emphasis is carried out on the utilisation of IMF in existing reactors, however studies concerns also fast systems such as gas cooled reactors [29] or liquid metal reactors [30], or advanced surcritical or subcritical [31] systems. Neutronic calculations were performed with emphasis on safety. Discussions also concerned the use of harder neutron spectrum in the upper part of BWR cores for transmutation. The groups from the IMF initiative are also currently studying the back end of the IMF part of the cycle. The solubility of the inert matrix material is a key point what ever be the option: for reprocessing [12] or for geological disposal [11]. The latter also must include natural analogue cases, which is already the case for zirconia (ZrO_2) [32] and for spinel ($MgAl_2O_4$) [33].

Today, even if no recommendation for a given reactor type emerge for the Generation-IV roadmap [34], a certain emphasis has to be given by GIF members to high temperature gas reactors (HTR). Here again IMF may play a relevant role. The three levels where IMF may be utilized in HTR's are also described by a homogeneous/heterogeneous approach with spherical fuel (kernel), spherical assembly (pebble) and cylindrical core as presented in Fig. 2. This may be a topic for advanced research mainly concerning the behavior of selected inert matrix materials at high temperature.

The status of the IMF initiative in 2002 may be summarised as follows.

From 1995 to 2002, seven workshops (three in Switzerland, one in Italy, one in France, one within a European Community organisation, and one in the Netherlands) were organised, involving 350 participants, from 17 countries (Switzerland, France, Japan, Italy, Netherlands, Russia, United States of America, United Kingdom, Republic of Korea, Belgium, Germany, Israel, India, Australia, Canada, Czech Republic, Sweden), 3 international organisations (OECD, CEC,

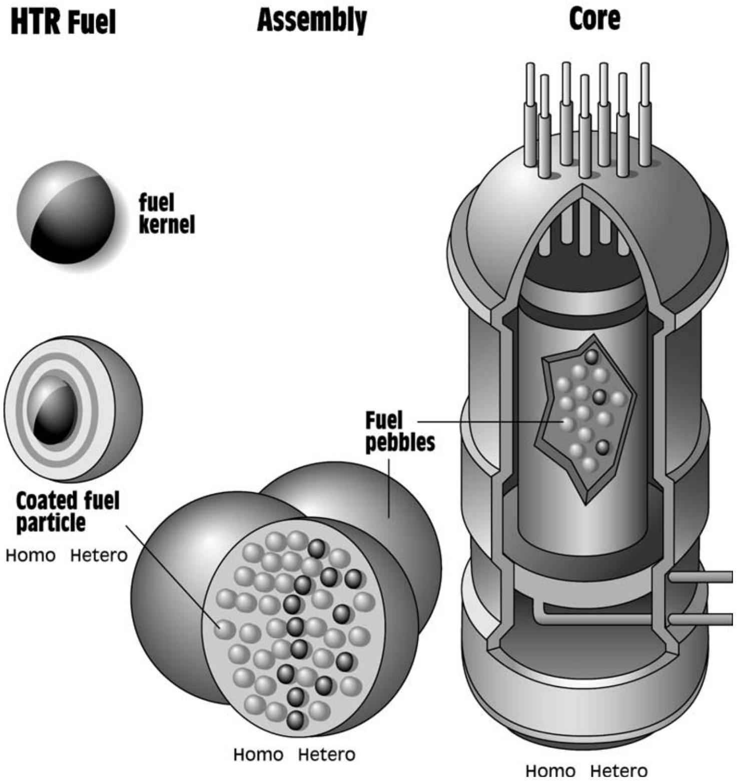

Fig. 2. The three levels for IMF utilization in HTR considering homogeneous/heterogeneous systems at the kernel level, the assembly (pebble) level and the core level (black/dark: U phase; grey: IM/IMF phase).

IAEA), from Universities (Osaka, Delft, Michigan, Polytechnics Milan, Aachen, Ben Gourion, Lausanne, Ontario, New Mexico, Purdue, Paris, Geneva, Kyushu), National Laboratories (PSI, CEA, CNRS, ENEA, NRG, JAERI, JNC, KAERI, IPPE, FZJ, LANL, ORNL, PNL, ITU, VNIINM, ANSTO, AECL), and from the Industry (BNFL, COGEMA, FRAMATOME ANP, SKODA, NRG, ...). During these eight last years 86 papers were published in two scientific journals (Journal of Nuclear Materials, and Progress in Nuclear Energy) along with 88 communications published in five internal reports. In addition, samples and data were exchanged with direct interactive cooperative activities such as joint irradiation and benchmark.

The IMF8 was the first workshop from the initiative held outside Europe and was the consequence of the intensive activity of Japan in the initiative. IMF8, was attended 60 participants for numerous presentations and discussions over ten Sessions as follows.

1. In-pile irradiation, with results from the on-going irradiation in Halden, NRSS and JRR3.
2. Basic properties 1, with material science of Pu IMF, its preparation as cermet, cercer or solsol.
3. Basic properties 2, with thermal conductivity, mechanical properties, compatibility between phases and effect of thermal shocks.
4. Reactor physics 1, with calculation of partial core loading, of solsol in PWR, of cercer in VVER.
5. Reactor physics 2, with advanced concepts in PWR and cermet in VVER.
6. Reactor physics 3, with specific effects such as Doppler effects.
7. IMF1, for future potential utilisation in fast systems.
8. IMF2, with metal, nitrides fabrication and characterisation.
9. Ion irradiation 1, with accelerators, He, ions, e^-, Xe, spinel, zirconia.
10. Ion irradiation 2, with zirconate pyrochlore, cercer, and analysis after irradiation.

The papers presented in these proceedings are not in the original order of presentation, they follow however an order along the nuclear fuel extension provided by the implantation of IMF.

Results gained from these IMF studies focussed on optimised conditions for their utilisation. Non-viable solutions are documented and will be eliminated. Possible IMF solutions together with their reactor-linked conditions (cycle length, safety parameters, etc.) are currently defined taking into account the spent fuel disposition (multi-recycling or once through). Through the activities of the Initiative the construction of the basis knowledge of inert matrix fuels is being established.

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