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# RADIOCHEMICAL PROBLEMS OF FUSION REACTORS
## I: FACILITIES

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# RADIOCHEMICAL PROBLEMS OF FUSION REACTORS—I: FACILITIES

## 1. INTRODUCTION

Knowledge on the properties of hydrogen plasmas at high temperatures and the techniques for their confinement and heating has increased enormously in the last two decades. As a consequence, it is widely accepted today that the feasibility of controlled nuclear fusion as an energy alternative for mankind will be demonstrated before the end of the current century and that commercial fusion power reactors will be operational in the first quarter of the next one.

At the same time, it has been recognized that this kind of reactors will place very stringent demands on their constituent materials, and research programs to select or develop these materials have started. The determination of the contents of the programs has been facilitated by several conceptual fusion reactors which have been worked out in detail in recent years through extrapolations and assumptions based on current knowledge and ideas.

Work in progress can be divided, in a first approximation based on the materials studied, into two large groups. The first covers the materials which shape the region exposed to the intense fluxes of energetic neutrons and particles originating from the reacting plasma and to the components of the plasma itself. These include the first wall and the other structural materials of the blanket. The second group corresponds to the materials required by the other fundamental and auxiliary functions. One of these is tritium breeding, as current conceptual reactors are fuelled by the D-T cycle. Table 1 summarizes the most important functions, candidate materials and phenomena studied.

Most aspects of the work on materials of the first group involve the study of neutron-induced atom displacements, helium blistering and other aspects of radiation damage, hot-atom effects, neutron activation and transmutations, charged particle reactions, and similar phenomena, all of which are of immediate interest to radiochemists and basic radiation chemists. Other problems, such as hydride formation in gas and solid phases, chemisorption, etc., appeal to a wider audience of chemists. The same is valid for the second group of materials. The recovery of the tritium bred in the blanket, the control of its concentration, the fabrication of superconducting materials, and other processes, are of basic chemical interest or contain an important chemistry component.

For these reasons, Commission V.7, as the IUPAC body with responsibility on nuclear materials activities, has been looking over the field for some time, with the view to try to stimulate a wider participation of the chemical community in the identification and clarification of these problems.

Revision of current work and projections shows that the research activity is concentrated in studies for the selection of materials belonging to the first group. For instance, 95% of the 1981 USA budget for fusion materials research fell in this area. While this large disproportion may partially reflect a professional bias, as fusion-related research is predominantly done by physicists, most of it is no doubt due to the perception that the most demanding and critical problems arise at the interface with the hot plasma.

It appears from these considerations that a significant chemical contribution will depend in large part of the availability of appropriate irradiation facilities capable of simulating fusion reactor conditions. These conditions are rather unique, involving neutron fluxes peaked at 14-MeV energy of average intensity $5 \cdot 10^{13}$ to $5 \cdot 10^{14}$ $cm^{-2}s^{-1}$, loads to the first wall (including $D^+$, $T^+$ and $He^{++}$) of the order of 0.5-1 $MW/m^2$ (and higher in some reactor concepts) and energetic electromagnetic and synchrotron radiation. On this basis, the Commission decided to try to evaluate, as a first step, the current situation regarding irradiation facilities for fusion materials experiments.

The results obtained are given below. The report does not intend to examine in detail the possibilities of chemical work in the area, though some general comments on the subject are made.

Table 1. Fusion Reactor Candidate Materials

| Function | Materials considered | Phenomena studied |
|---|---|---|
| Blanket structure | Austenitic steels<br>High-strength Ni-based alloys<br>Ferritic steels<br>Ti-based alloys<br>Nb, V and Mo refractory alloys<br>Sintered Aluminium Product (SAP, 90 % Al, 10 % $Al_2O_3$)<br>Graphite<br>SiC | Neutron-induced atom displacement. Sputtering. Surface exfoliation from He blistering. Phase stability. Creep and fatigue effects. H diffusion and embrittlement. Chemical impurification from neutron activation. Chemical interaction with coolants and breeding matls. |
| Breeding | Liquid Li (natural or enriched in $^6Li$)<br>Li-Pb and Li-Pb-Bi alloys<br>Li-Al compounds<br>"Flibe" (molten $2LiF.BeF_2$)<br>Ceramic compounds ($Li_2O$, $Li_2ZrO_3$, etc.) | Liquid metal handling. Compatibility with blanket structure. Neutron activation. Corrosion. Tritium handling and separation. Safety. In-situ T recovery from ceramic matls. Fabrication and characterization of Li compounds. |
| Moderation | Breeding materials<br>Graphite | |
| Neutron multiplication | Be<br>Pb<br>Eu | Efficiency of multiplication. Association and compatibility with breeding matls and moderators. |
| Cooling | Liquid metals (Li, Na, NaK)<br>Molten salts ("flibe" and nitrate-nitrite mixtures)<br>Pressurized water<br>Liquid He (for superconducting coils)<br>Pressurized He | Corrosion, Radiation effects. Compatibility with blanket and other matls. |
| Magnetic field generation | Superconducting coils: NbTi, $Nb_3Sn$, $V_3Ga$<br>Normal coils: Cu, Al | Radiation effects. Compatibility with insulators. Cryogenic effect on insulators. |
| Electrical insulation | Ceramics (MgO, spinel, $Al_2O_3$, SiC, $Si_3N_4$)<br>Organic polymers for low fluence regions (epoxies and polyimides) | Same as above and neutron and gamma damage. Screening of matls and properties. |
| Radiation shielding | Borated water<br>$B_4C$<br>Pb<br>Concrete | Compatibility and stability. |

## 2. EVALUATION

The evaluation was made on the basis of the information available to the Commission plus a questionnaire on the adequacy of the existing facilities which was submitted to scientists working in the subject in leading laboratories. The questions asked were: (1) Is the availability of irradiation facilities useful to study fusion reactor materials adequate? (2) If so, list those facilities you know in which these studies can be made, including any summary specifications you may have of them. (3) If not, indicate which facility or facilities are considered necessary by you and state broadly the general specifications and requirements you would place on their design. Also, if possible, estimate it approximate cost. (4) Are you aware of any such facility in construction or planned? If so, give the specifications you know. (5) Do you consider that an international project to build such facility is adequate at the current stage of fusion research? (6) If so, how should this project be implemented? (F.i., as an IAEA project financed by special contributions of the member states and built and housed in some international research centre under the IAEA aegis, or as other alternative). (7) Give any further comments you may have on the subject of this questionnaire.

The answer received and the rest of the information were collated together to give shape to the conclusions given below.

## 3. CONCLUSIONS

As with fission reactors in the case of fission, the optimum irradiation facility for fusion materials research is a fusion test reactor of high fluence and appropriately large irradiation volume. This does not exist at the present time and will certainly not be available for at least 20 years or so. Consequently, current experiments are made in facilities which, while lacking the integral radiation characteristics of a fusion reactor, are considered to have the capacity to simulate a partial aspect of the action of a real fusion environment on the material researched.

Up to now, facilities used for this purpose are of 3 principal types, viz.: (1) accelerator-based neutron sources; (2) fission reactors; (3) ion accelerators.

Qualitatively, accelerator-based 14-MeV neutron sources are the best choice available to simulate neutronic effects on the fusion first wall and blanket, where the 14-MeV neutron flux from the D-T reaction is the predominant component. However, ordinary commercial sources are low in intensity (point total emission about $5 \cdot 10^{12} s^{-1}$ maximum) and small in irradiation space. The existing source of highest flux is probably RTNS-II (Rotating Target Neutron Source II) at the Lawrence Livermore Laboratory, USA, which at full power delivers $1 \cdot 10^{13}$ $cm^{-2}s^{-1}$ to a volume of about 0.2 $cm^3$. In this source, neutrons are produced via the $^3H(d,n)^4He$ reaction. Other sources with Be targets that generate neutrons peaked at 15 MeV by $^9Be(d,n)^{10}B$ have usable fluxes and test volumes still smaller.

Because of the small irradiation space, these sources cannot accept samples large enough for many tests, such as the study of the modification of mechanical properties. Also, the fluences obtainable with them are too low to generate He in-depth concentrations which simulate those formed under real fusion conditions by $(n,\alpha)$ reactions on Fe, Cr, Ni and other alloy components. Because of this, their main use is to correlate, with respect to the formation of other important component of radiation damage, atom displacement, the action of the high-energy neutrons from these sources with that produced by fission neutrons from reactors. Once this correlation is established, samples of appropriate size to study the effect are irradiated in the much larger volumes available in fission reactors and the results extrapolated to fusion conditions.

Fast reactor fluxes are capable to simulate atom displacements to damage levels similar to those expected in a fusion reactor but, because of the low cross-section of the reactions involved for fission neutrons, they fail to simultaneously generate adequate concentrations of He and, therefore, to provide data on the interaction of He concentration with atom displacements and on joint effects. In its turn, He formation can be achieved in mixed-spectrum reactors in the special case of Ni-containing alloys (and in those which can accept small amounts of Ni dissolved for the purpose), where He is produced in-situ by the consecutive reactions $^{58}Ni(n,\gamma)^{59}Ni(n,\alpha)^{56}Fe$ while the fast flux produces atomic displacements. The simulation can be improved by special experimental techniques, such as neutron spectrum "tailoring".

Because of these possibilities and of the relatively large irradiation space available in them, fission reactors are the most frequently used sources for fusion materials studies, as their advantages more than compensate their disadvantages. Table 2 gives a list of some of the reactors used in Europe and the USA for testing materials which are, or can be, applied to fusion materials work.

As to direct ion bombardment with accelerators, the technique is limited to a very small and very thin surface zone. In spite of this, it is widely used to study the basic mechanisms of microstructural evolution of irradiation effects, as a high damage level with high helium content can be obtained with it in a relatively short time.

The application of all these techniques has given preliminary answers to many questions put forward by fusion technology concepts regarding isolated effects. Though this work will continue and many more answers will be obtained, the lack of large 14-MeV neutron sources is recognized as a serious limitation, as a high-intensity, large volume 14-MeV neutron source would allow to irradiate samples of sufficient size to generate useful data directly and, also, to verify with appropriate accuracy (not attainable with the RTNS-II) results obtained in fission reactors. While these reactors will still be the principal test facilities until a fusion test reactor is built because of their large irradiation space, there is wide consensus that the availability of such sources will introduce qualitative changes in the possibilities of fusion materials experimentation. They will be, also, appropriate for radiochemistry and blanket chemistry work because of its large irradiation space.

The USA fusion programme includes the construction at Hanford, Wash., of a 14-MeV neutron source of this type, the Fusion Materials Irradiation Test Facility, FMIT. In it, 100 mA of 35 MeV deuterons from a linac will impinge on a liquid Li target. The average flux expected is $1.4 \cdot 10^{15}$ $cm^{-2}s^{-1}$ for 10 $cm^3$ volume and $2.2 \cdot 10^{14}$ $cm^{-2}s^{-1}$ for 500 $cm^3$ volume. This is two orders of magnitude higher in flux than the RTNS-II for 50 times the volume and one order of magnitude higher for 2500 times the RTNS-II irradiation volume.

Table 2. Some Fission Reactors

| Country | Designation and place | Flux dens.($10^{14}$ $cm^{-2}s^{-1}$) | |
|---|---|---|---|
| | | Thermal | Fast E > 0.1 MeV |
| USA | ORR, O. Ridge(1) | 2.4 | 3.0 |
| | HFIR, O. Ridge(2) | 24 | 15 |
| | EBR-II, ANL(3) | - | 30 |
| | FFTF, HEDL(4) | - | 60 |
| Belgium | BR 2, Mol | 9 | 7 |
| Germany | MERLIN, Jülich | 1 | 0.4 |
| | DIDO, Jülich | 2 | 1 |
| | KNK II, Karlsruhe | - | 20 |
| UK | PLUTO, Harwell | 1.8 | 1.6 |
| | DIDO, Harwell | 2 | 1.6 |
| Denmark | DR 3, Risø | 1.5 | 0.45 |
| France | HFR, Grenoble | 8-13 | - |
| | OSIRIS, Saclay | 3 | 5 |
| | SILOE, Grenoble | 5 | 5 |
| Italy | ESSOR, Ispra | 4 | 1.1 |
| Netherlands | HFR, Petten | 3.3 | 4.5 |

(1) Probably the only fission reactor dedicated to fusion materials research. Irradiations are made in 6 cylinders 1.7 l each (total space 10 l).

(2) Irradiation space is 6 cylinders of 150 $cm^3$ each.

(3) Irradiation capsules of 100 $cm^3$.

(4) Test volume larger than EBR-II.

The FMIT, originally scheduled for 1985-86, has been significantly delayed by budgetary cuts in 1981-82. Its cost is about $ 150 million, roughly 10 times the RTNS-II cost.

For blanket and first wall surface chemistry, plasma sources of enough intensity could also be used. A way to have sources of this type available soon is to provide experimental space in the big fusion devices now under construction (at a cost of about $ 500 million each) for plasma physics purposes, such as the European JET at Culham and the American TFTR at Princeton (the second one started operation at the end of 1982). The installation of chemistry rigs in these devices would allow to extend, at low cost, the possibilities of fusion materials reseach and development work.

The general opinion on the construction of an international facility for fusion materials irradiation studies is that the idea is premature at the present time and that it would be more advisable to design and incorporate irradiation devices to existing projects, as just indicated. It must be noted in this respect, however, that the construction and operation of the FMIT jointly with the European Community, Japan and Canada is under consideration in the USA to end the budgetary difficulties of the project (Ref. 12).

Participants in the detailed elaboration of recent conceptual design of fusion reactors or devices report that present candidate materials are unsatisfactory in many instances and that extensive and deeper work on them or substitutes is still necessary. This stresses the urgency of improving the possibilities to study fusion reactor materials by developing new test facilities with high priority.

## 4. RECOMMENDATIONS

As a general conclusion of the evaluation, it may be stated that, while many contributions to fusion materials research and development, such as accurate measurements of 14-MeV neutron data, selection of materials of low activation cross-section, lithium and tritium processing, and similar ones, can be made through radiochemistry work with existing irradiation facilities or by purely chemical studies, the detailed investigation of reactor first-wall and blanket chemistry requires better simulations of the fusion reactor environment than those presently available.

On the basis of this conclusion, of the particulars of the survey and of the previously known fact that the involvement of chemists in fusion materials research is minimal, Commission V.7 recommends:

1. That research chemists and radiochemists in nuclear institutions where fusion research is made get acquainted with this work and try to contribute to the identification and solution of fusion materials problems.

2. That special attention is given, in this context, to the interaction of the plasma and the plasma radiation with the first wall and the blanket.

3. That chemical experimentation possibilities for this kind of interaction studies be incorporated in the design of all large facilities built for plasma physics research in the future.

4. That studies be made to incorporate similar possibilities to existing installations whenever possible.

5. That measures be taken to finish as soon as possible those relatively large high-energy neutron sources planned or under construction, such as the FMIT in the USA. In the particular case of this facility, the Commission feels that its transformation in an internationally financed project currently under consideration as a solution to its financial difficulties should be encouraged.

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