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SUMMARY OF THE WORKSHOP ON ADVANCED REACTORS WITH INNOVATIVE FUELS

Paul Scherrer Institut, Villigen, Switzerland
21-23 October 1998

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OECD Nuclear Energy Agency

Workshop on

ADVANCED REACTORS WITH INNOVATIVE FUELS

Paul Scherrer Institut, Villigen, Switzerland
21-23 October 1998

SUMMARY

Outline

- Motivation, scope and goals
- Workshop organisation
- Participation
- Technical programme
- Session summaries and panel discussion on international co-operation
- List of participants

Motivation, scope and goals

Plutonium and minor actinide recycling in thermal and fast reactors is being studied in many countries with the aim of maintaining and developing fuel cycle options which can be adjusted to changing demands and constraints. The challenge is to move towards an economically and socially sustainable nuclear energy system based on advanced reactors – advanced water-cooled reactors, fast reactors and perhaps accelerator-based, hybrid reactors – and new types of fuel cycles which help to minimise the waste arising.

In this context, topics of interest are: the multiple recycling of plutonium in thermal reactors, enhanced consumption of surplus plutonium in thermal and fast reactors, reduction of the uranium demand of thermal reactors to stretch the fissile material resources, transmutation of minor actinides to extract fission energy and reduce the quantity and toxicity of the actinide waste, etc.

The scope of the Workshop is comprised of the reactor physics, fuel material technology, thermal-hydraulics and core behaviour of advanced reactors with different types of fuels and fuel lattices. Reactor types considered are water-cooled and fast reactors as well as hybrid reactors with fast and thermal neutron spectra. Emphasis is on innovative concepts and issues related to the reactor.

The purpose of the Workshop is to enhance information on R&D activities and to identify areas and research tasks where international co-operation can be strengthened. In this context, particular goals are to identify the roles which can be played by existing experimental facilities as well as possible needs for new experimental facilities. The conclusions of the technical sessions are synthesised and have been discussed by a round table on international co-operation.

Workshop organisation

General chairman	***Scientific advisory committee***
W. Kröger, PSI	Y.I. Chang, ANL, USA
Local organising committee	M. Delpech, CEA, France
P. Wydler	P. D'hondt, SCK-CEN, Belgium
C.A. Degueldre	D. Haas, ITU-CEC
G. Ledergerber	K. Hesketh, BNFL, UK
J.M. Paratte	H. Mouney, EdF, France
A. Stanculescu	M. Nakagawa, JAERI, Japan
Workshop secretariat	M. Ochiai, JAERI, Japan
R. Van Doesburg	S. Pillon, CEA, France
R. Ringele	E. Sartori, OECD/NEA

Participation

The Workshop was attended by 110 participants from 18 countries and four international organisations.

The participation by establishment type was as follows:

Research laboratories and university institutions	70%
Industry	20%
Utilities and safety/regulatory organisations	10%

The full list of participants is provided in Appendix 2.

Technical programme

The Workshop was organised in four plenary sessions during which 22 presentations were made, followed by three parallel sessions during which 23 papers were presented. The final plenary session was devoted to the session summaries and to a panel on international co-operation. The complete technical programme is as follows.

Wednesday, 21 October 1998

1. Opening session

Chair: W. Kröger (PSI)

9:15 Welcome introduction
W. Kröger (PSI)

9:45 The viewpoint of Swiss nuclear utilities
H. Fuchs (ATEL), *H. Mouney* (EdF)

10:45 Scope and goals of the Workshop
P. Wydler (PSI)

2.1. Plenary Session I: Advanced U/Pu oxide-based reactors (invited papers)

Chair: A. Zaetta (CEA)

11:00 Pu utilisation in PWR and FR
S. Pillon, J. Tommasi, M. Delpech (CEA), *H.M. Beaumont* (NNC),
T. Newton (AEA Technology)

11:30 Plutonium multirecycling in a 100% MOX core with a high moderation ratio
G. Youinou, M. Delpech (CEA)

12:00 Aspects of uranium recycle in light water reactors
K.W. Hesketh, R. Hagger (BNFL)

14:00 The concept of a breeding PWR
H. Tochihara, Y. Komano, M. Ishida (MHI)

14:30 Study on fast spectrum BWR core with breeding characteristics
T. Yokoyama, R. Yoshioka, Y. Tsuboi, Y. Sakashita, S. Matsuyama (Toshiba)

15:00 Conceptual core design of a resource-renewable BWR and long-term energy supply
R. Takeda, M. Aoyama, J. Miwa (Hitachi)

15:30 Process development for DUPIC FUEL fabrication
K. Bae, H. Choi, J. Lee, M.S. Yang, H. Park (KAERI)

2.2 Plenary Session II: Uranium-free reactors (invited papers)

Chair: R.J.M. Konings (ECN)

16:30 U-free Pu fuels for LWRs: CEA/DRN strategy
J. Porta, M. Delpech, A. Puill (CEA)

17:00 Radiation stability of inert matrix fuels
H. Matzke (JRC ITU)

Thursday, 22 October 1998

2.2 Plenary Session II: Uranium-free reactors, *cont.* (invited papers)

Chair: R.J.M. Konings (ECN)

8:00 Disposition of excess plutonium by the ROX-LWR system
H. Akie, *T. Yamashita* (JAERI)

8:30 Reactors with Th/Pu based fuels
J. Tommasi, *A. Puill*, *Y.K. Lee* (CEA)

2.3 Plenary Session III: Reactors with non-oxide fuels (invited papers)

Chair: M. Nakagawa (JAERI)

9:00 Metallic fuel for fast reactors
L.C. Walters, *G.L. Hofman*, *T.H. Bauer*, *D.C. Wade* (ANL)

9:30 Fuel cycle systems with nitride fuel for transmutation
T. Osugi (JAERI)

10:00 A fast spectrum Pu burner reactor with nitride fuel
J. Tommasi (CEA), *H.M. Beaumont* (NNC), *T.D. Newton* (AEA Technology)

3. International activities (invited papers)

Chair: K. Hesketh (BNFL/NEANSC)

10:45 Introduction, NEA standpoint
K. Hesketh (BNFL/NEANSC)

11:00 Thorium fuel cycle options for advanced reactors: Overview of IAEA activities
P.E. Juhn (IAEA)

11:30 Transmutation and future systems: Overview of the activities supported by the European Commission
M. Hugon (European Commission DG XII)

12:00 Recent progress of the EFTTRA research on fuels and targets for transmutation of actinides and fission products
J.N.C. van Geel (JRC ITU), *R. Comnrad* (JRC Petten), *R.J.M. Konings* (ECN), *G. Muehling* (FZK), *J. Rouaoult* (CEA), *G. Vambenepe* (EDF SEPTEN)

4. Parallel Sessions (contributed papers)

Parallel Session 1 – Advanced U/Pu oxide based reactors

Thursday, 22 October 1998

Chair: A. Zaetta (CEA)

14:00 The LR-0 reactor possibilities for MOX type fuel pins research
C. Svoboda (Rez)

14:20	First criticality of LWR-PROTEUS: A new programme of integral experiments for advanced and innovative LWR fuels *T. Williams*, *P. Grimm*, *R. Seiler*, *S. Pelloni*, *A. Stanculescu*, *R. Chawla* (PSI)
14:40	Conceptual designing of water-cooled reactors with increased or reduced moderation *T. Okubo, T. Kugo, T. Shirakawa*, *S. Shimada*, *M. Ochiai* (JAERI)
15:00	Study of advanced LWR cores for effective use of plutonium *T. Yamamoto* (NUPEC)
15:40	Investigation of the fuel temperature coefficient of innovative fuel types *J.L. Kloosterman* (Univ. Delft)
16:00	Role of fast reactors in solving power problems in future *A.P. Ivanov*, *V.M. Poplavski*, *A.M. Tsiboulia* (Obninsk)
16:20	Some issues of ^{233}U fuelled SNPS reactor nuclear safety *E. Ivanov, V. Tsvirko, Y. Tsarenko* (Obninsk)

Parallel Session 2 – Uranium-free reactors

Thursday, 22 October 1998

Chair: R. J. M. Konings (ECN)

14:00	Preliminary evaluation of a BWR with CERMET fuel core loading *L. Zanotti*, *G. Rouviere, S. Baldi*, *J. Porta* (CEA)
14:20	Reactor physics analysis of plutonium annihilation and actinide burning in CANDU reactors *P.S.W. Chan*, *M.J.N. Gagnon*, *P.G. Boczar* (AECL)
14:40	Neutronics of inert matrix Pu fuel rods in a UO_2 PWR environment *S. Pelloni*, *J-M. Paratte*, *A. Stanculescu*, *R. Chawla* (PSI)
15:00	Some neutronic properties of an inert matrix for the definition of a 100% IMF core *J. Porta*, *S. Baldi*, *B. Guigon* (CEA)
15:20	Inert matrix and thoria fuels for plutonium burning in LWRs *S. Coelli*, *C. Lombardi*, *A. Mazzola*, *E. Padovani*, *M. Ricotti* (POLIMI), *E. Marmo* (FN), *T. La Torretta, F. Vettraino, G. Zappa* (ENEA)
16:00	Concepts and first fabrication studies of inert matrix fuel for the incineration of Pu *M. Burghartz*, *G. Ledergerber, F. Ingold*, *T. Xie*, *F. Botta* (PSI), *K. Idemitsu* (Fac. of Eng. Kyushu Univ., Japan)
16:20	Uranium-free burner reactor dedicated to minor actinides transmutation *N. Messaoudi, J. Tommasi, M. Delpech* (CEA)
16:40	Silicon carbide as an inert matrix fuel for CANDU reactors *R. Verrall, H.R. Andrews, I.M. George, P.J. Hayward, P.G. Lucuta, S. Sunder,* *M.D. Vlajic, V.D. Krstic* (AECL)
17:00	Plutonium rock-like fuel behaviour under RIA conditions *T. Nakamura*, *H. Akie*, *K. Okonogi*, *M. Yoshinaga, K. Ishijima*, *H. Takano* (JAERI)
17:20	Irradiation damage in inert matrix of uranium-free fuels *M. Beauvy, C. Dodane, P. Raison* (CEA), *S. Bouffard* (GANIL)

Parallel Session 3 – Reactors with non-oxide fuels

Room OSGA/UG5

Thursday, 22 October 1998

Chair: T. Osugi (JAERI)

14:00 Conceptual core design for uranium metallic fuelled liquid metal reactor
S.J. Kim, Y.I. Kim, Y.J. Kim, C.K. Park (KAERI)

14:20 Dynamic behaviour of nitride LMR core during unprotected transients
B.C. Na, J-C. Garnier, P. Lo Pinto, M. Delpech (CEA)

14:40 Thermal decomposition behaviour of UN and U0.8Pu0.2N
M. Kato, T. Hiyama, J. Kurakami (PNC)

15:20 Review of the Russian molten salt reactor technology studies
V.V. Ignatiev (Kurchatov), *K.F. Grebenkine* (RFNC)

15:40 The concept of nuclear incineration of PWR spent fuel in a transmuter with liquid fuel
M. Hron (Rez)

16:00 Study of an accelerator driven system operating in an epithermal spectrum with a constant k_{eff}
P.A. Landeyro, M. Guidotti (ENEA), *P. Neuhold* (ANSALDO)

Friday, 23 October 1998

5. Closing session

Chair: W. Kröger (PSI)

8:30 Future perspectives
W. Kröger, P. Wydler (PSI)

Session summaries
Session Chairpersons

Panel discussion on international co-operation
H. Fuchs (ATEL, CH), *P.E. Juhn* (IAEA), *H. Mouney* (EdF, F), *M. Nakagawa* (JAERI, J), *M. Salvatores* (CEA, F), *Ph. Savelli* (OECD/NEA), *L.C. Walters* (ANL, USA)

Introduction to PSI's large facilities
E. Steiner (PSI)

6. Visit to PSI's large facilities

Accelerator complex – T. *Sigg*

PROTEUS critical facility – *T. Williams*

SINQ spallation neutron source – *G. Bauer*

Hot laboratory – *G. Ledergerber*

Note: Preceding the ARWIF'98 Workshop the partners of the "Initiative for Inert Matrix Fuel" held the Annual Inert Matrix Fuel Workshop on Reactor Physics and Materials (PSI, 19-20 October 1998).

Session summaries and panel discussions on international co-operation

Introduction

Papers on the different technical topics were presented partly in the plenary sessions and partly in parallel sessions. In order to provide a general overview of all presentations to participants and with the objective of facilitating the discussion during the panel, the session chairmen presented their summaries and conclusions first.

For the purpose of guiding and focusing the presentations and discussions, Peter Wydler had prepared in consultation with the panel members a questionnaire containing the key issues to be addressed. This questionnaire, together with summarised answers given during the discussions is enclosed as Appendix 1.

The structure of this summary consists of:

- the summary of the sessions;
- the summary of the panel discussion;
- the questionnaire with summarised answers and conclusions.

Session summaries

Chairmen: ***Alain Zaetta*** **(CEA Cadarache)**
Rudy Konings **(NRG Petten)**
Masayuki Nakagawa, Toshitaka Osugi **(JAERI, Tokai-mura)**
Kevin Hesketh **(BNFL Springfields)**

Summary of sessions on advanced U/Pu oxide based reactors – Chair: A. Zaetta

A summary of papers presented during the first session of the workshop on advanced U/Pu oxide based reactors, during which presenters outlined the main issues in plutonium management, renewable resources and the closed fuel cycle, is given below.

A variety of light water and fast reactors using different fuels are capable of fully incorporating plutonium into their fuel cycles; options range from “concentration” (plutonium without uranium) to “dilution” which requires the presence of slightly enriched uranium. A number of PWR concepts that use uranium-free plutonium fuel include APA, while the CAPRA programme established a concept necessitating a high plutonium concentration in fast reactors to counterbalance minor actinides absorption. Plutonium utilisation in LWRs can also be enhanced with highly moderated 100% MOX cores with moderation ratios ranging from 4 to 6 for PWRs, and from 6 to 7 for BWRs. The recycling of reprocessed uranium in LWRs, an essential element in closing the fuel cycle, was considered a relevant issue because it contains minor actinides, and needs treatment like other transuranic elements. Fuel fabrication that makes use of recycled uranium must also be competitive with conventional fuel cycles, and utilities must act to facilitate this process by careful consideration of technological solutions. Uncertainties regarding production of ^{232}U (as well as the daughter product ^{208}Tl) should be addressed within an international framework such as the NEA/OECD Working Groups.

MOX fuel breeding for PWRs and BWRs aims at effective resource utilisation, and is based on current PWR and BWR technologies. Innovative PWR concepts, such as tight hexagonal lattices, were presented in a breeding PWR case study in Japan whereby the breeding ratio is 1.1 with a D_2O moderated heterogeneous core design with fertile zones. Two innovative BWR concepts using tight lattice configurations were also discussed. The first concerned a RBWR (Resource-Renewable BWR) which operates with mixed oxide fuel within an epithermal spectrum and displays a breeding ratio of 1.0, while the other case involved a BBWR (Breeding BWR) with a fast neutron spectrum and a breeding ratio >1. However, the presence of rare earth elements in the fuel cycle may deteriorate core characteristics such as the breeding ratio. A negative void reactivity effect can be achieved with the presence of the cavity-can in the streaming channel structure; furthermore, the reactor has a potential to transmute minor actinides.

KAERI is currently developing a concept to increase uranium resource utilisation in CANDU reactors. DUPIC (Direct Use of Spent PWR Fuel in CANDU reactors) fuel technology uses spent PWR fuel (35 GWd/t) that can be directly fabricated into a reusable fuel for CANDU reactors (additional 15 GWd/t). Fuel characteristics are markedly different from standard CANDU fuel types. International co-operation has already been established through the IAEA and an experimental programme is underway. This research aims at achieving competitive costs.

JAERI is involved in the design of several innovative MOX fuelled PWRs and BWRs, with an ambitious goal to achieve 100 GWd/t burn-up and three-year cycle length with a water-cooled full MOX core. Proposed designs feature moderation ratios and plutonium contents of 2.6 with 12 per cent for PWRs, and Pu content, and 2.0 with a 16 per cent for BWRs, respectively; they are feasible from the perspective of reactor physics parameters.

A more fundamental approach is being investigated at IRI, in establishing fuel temperature coefficients (FTC) for several fuel types from MOX fuel to uranium-free inert matrix fuel, two of which included reactor-grade and weapons-grade plutonium. All fuels, including those containing weapons-grade plutonium, have negative FTCs.

Experimental research facilities

Zero power facilities for reactor physics analyses are needed for the validation of data and codes. The LR-0 facility, for example, is suited for a simulation of a VVER 1000 and 440 with a hexagonal lattice configuration, and for conducting basic neutron physics experiments. A weapons-grade MOX programme was proposed for VVER 1000.

The PROTEUS facility in Switzerland has developed a three-year LWR experimental programme using real fuel assemblies with some generic research and development aspects. The programme is supported by Swiss utilities and is being conducted in two experimental phases for BWRs and PWRs.

Conclusion

Three conclusions can be drawn regarding the various fuel technologies and reactor design issues discussed above:

- *First*, fuel performance improvements can occur by enhancing MOX fuel burn-up and re-using spent fuel, as exemplified in the DUPIC and URT concepts. Such improvements in the fuel cycle will also act to reduce costs.

- *Second*, there is a wide range of options in terms of consumption and breeding using plutonium in LWRs and FRs. The implementation of such options are strongly linked to the *time scale* considered. Research and development concerning various plutonium utilisation routes are thus justified.

- *Third*, there are several specific issues concerning present and future research and development. Current facilities – which include irradiation facilities, zero power reactors, hot laboratories and nuclear data management centres – operate under strong restrictions. Thus, often research and development needs that arise cannot be adequately addressed. It is therefore important to maintain and develop R&D "tools", and to define the role of international organisations within this context as that of co-ordinating, fostering and providing guidance. In order to achieve this objective in the short-term, it is necessary to create a comprehensive survey report that acts to clarify the needs, develop strategies and gain the support of all partners.

Summary of sessions on uranium-free reactors – Chair: R. Konings

Numerous fuel cycle systems for uranium-free reactors were discussed in this session, a summary of which is given in the table below (Table 1). For the purpose of this summary, four types of fuels considered in current uranium-free reactor programmes are outlined (Table 2). These fuels are being developed with four principal objectives in mind: capacity for plutonium burning, reduction of radiotoxicity and actinide transmutation, optimal use of natural resources, and improved safety.

Table 1. Fuel cycle systems for uranium-free reactors

Materials	Additives	Assembly	Core loading	Reactor	Strategy
Y-SZR	Er_2O_3	Homogeneous	Partial	BWR	Recycling
$MgAl_2O_4$	Gd_2O_3	Heterogeneous	Full	CANDU	Once-through
SiC	ThO_2			LWR	
CeO_2	UO_2			FNR	
THO_2	^{11}B				
Metals					

Table 2. Uranium-free fuel types and materials

Uranium-free reactor fuel type	Materials
SS-IMF	(Zr, Y, Pu, X) O_2
CERCER	(Zr, Y, Pu, X) O_2 in spinel or MgO
CERMET	(Zr, Y, Pu, X) O_2 in metal
Thoria	(Th, Pu) O_2

Promising reactor physics characteristics have been achieved for ZrO_2-based solid solution *inert-matrix fuel (IMF)* assemblies. Although fabrication technology is only available on a laboratory scale, 100% (homogeneous) IMF cores have been shown to reduce plutonium as effectively as for MOX fuels without requiring any further reprocessing treatment ("once-through"). The (low) thermal conductivity of this fuel type is one of the major uncertainties for its application.

Although not really inert, *thoria-based fuels (TD)* show good Pu burning capability for some LWRs and Na-cooled FRs. The technology for thoria-based fuels is partly available from experience from the past. Thoria-based fuel is also of great relevance from the point of view of resources.

Two other types of inert-matrix fuels are being studied. Research concerning the combination of CERamic fuel and a METallic matrix (*CERMET*) for PWRs, based on zirconia and a conducting metal, is mainly theoretical and little experimental work has been carried out. Materials composing the fuel have not yet been adequately defined, and burn-up studies and accident research, which offer good potential for CERMETs, are to be initiated. Much experimental work is being undertaken on CERamic matrix and CERamic fuel (*CERCER*), mainly for "once-through" burning of plutonium in LWRs. The fuel concepts for CERCER fuel are converging in the sense that the $MgAl_2O_4$ (spinel) is foreseen as matrix and plutonium (or americium) dissolved in stabilised zirconia as fuel. Issues to be addressed in R&D for CERCER include resistance to irradiation, reactor-initiated accidents (RIA) and increases in thermal activity.

Silicon carbide (SiC), which is proposed as an IMF for CANDU reactors, is currently not considered in fuel programmes in Europe and Japan.

Three main conclusions can be drawn from this session's presentations. *First*, no common strategy for uranium-free fuels is emerging. *Second*, materials issues are poorly addressed. *Third*, licensing procedures for new fuels may take from 15 to 20 years to complete.

Summary of sessions on reactors with non-oxide fuels – Chairs: M. Nakagawa and T. Osugi

The advantages and rationale behind the use of new non-oxide fuels and the properties and experimental work undertaken by institutes concerning these fuels was addressed in these sessions. Papers presented at the plenary and parallel session on reactors with non-oxide fuels covered the topics listed in Table 3.

Table 3. Matrix with number of papers per topic discussed

	Metal	Nitride	Molten salt
Reactor	1	3	
ADS			2
Fuel	1	1	1
Cycle		2	1

The advantages of the use of and research and development into non-oxide fuels lies in their:

- passively safe response to Anticipated Transients Without Scram (ATWS);
- high linear pin power and high thermal conductivity;
- excellent neutron economy;
- effective use of neutron for plutonium and/or minor actinide burning (high heavy metal density).

The large proliferation resistance of these fuels is illustrated in remote reprocessing and re-fabrication and the fact that non-oxide fuels are associated with MA and FP by the pyro-chemical process.

The following findings with regard to current programmes incorporating non-oxide fuels into reactor fuel cycles were presented:

- Tests on metallic fuel in fast reactors have yielded a very high burn-up capability in excess of 20 at%.
- Examination of core performance of the nitride fuel fast reactor (LMFBR) were presented together with the pyrochemical process which has the feasibility of recovering the radiotoxic ^{14}C and the expensive ^{15}N.
- Studies on large plutonium consumption in fast reactors within the context of the CAPRA programme revealed that pure PuN fuel dissolves properly during PUREX reprocessing operations, with a high Pu burning rate and dynamic performance of PuN core.
- The KALIMER liquid metal reactor design contains a uranium metallic fuelled core with a power of 390 MWt.
- In a comparative study of dynamic behaviour of a nitride fuelled LMR core and an oxide core, the ULOF (“unprotected loss of flow”) event displayed a larger Doppler feedback effect when it was necessary and smaller effect for nitride cores in unfavourable conditions.
- In a study of thermal decomposition behaviour of UN and ($U_{0.8}$ $Pu_{0.2}$) pellets, the initial thermal decomposition temperatures of UN and MN pellets was found to be at least 1800°C, in various atmospheres. In the higher temperature range, thermal decomposition occurred with vaporisation of metal.
- Molten salt reactor technology in Russia was reviewed and evaluated including aspects of fuel technology, container materials, components and fuel clean-up.
- Experimental work is being carried out in the Czech Republic on liquid fuel concepts, which have several advantages over traditional solid nuclear fuels. New reactor systems using liquid fuels provide for nuclear incineration of spent fuel from conventional reactors and a clean energy source.

Summary of session on international activities – Chair: K. Hesketh

The Chairman began the session with a brief summary of activities of the OECD/NEA Nuclear Science Committee of relevance to this conference. There then followed three invited papers by representatives of the IAEA, the EC and EFTTRA (a research collaboration comprising several European research organisations and the utility EdF). Major themes of these activities included thorium fuels, new reactors/new fuel cycles, evolutionary/advanced LWRs, P&T, ADS, materials and nuclear data acquisition and evaluation.

In the areas of advanced fuel cycles and partitioning and transmutation, each of these organisations are very active and there are extremely diverse research programmes in progress. The presentations highlight a number of important points:

- The level of activity clearly demonstrates an extraordinary degree of interest both at the scientific level and at the level of the politicians/fund providers.

- There are many diverse driving factors underlying the various activities. These are determined by individual countries unique perspectives and perceived needs. There is clearly no one perspective that will apply to all countries and the multiplicity of perspectives must be respected.

- International activities are stimulating work in the area of advanced/innovative fuel cycles and reactors, both theoretical and experimental.

- There is a clear need for continuing co-ordination between the various international bodies involved to exploit synergies and avoid duplication.

Role of international organisations

At a time of stagnation in the industry outside Asia, there is a need to maintain continuity of competence until another period of plant construction begins. In the intervening period the industry needs to develop its knowledge of the boundaries of the technologies that are feasible, through research into advanced reactors and innovative fuel cycles. These two needs are complementary in that cultivating the R&D effort maintains competencies. The role of international bodies might therefore be:

- to continue to co-ordinate and stimulate R&D activities in the field;

- to continue to act as a central repository of knowledge and expertise;

- to continue to provide the infrastructure for such activities as nuclear data evaluation, where individual countries' resources are no longer sufficient;

- to continue to provide effective gearing of financial and human resources through collaborative projects;

- to continue to monitor the availability of experimental facilities and to facilitate the construction of new facilities, where needed, through co-operative projects;

- to continue to provide a respected source of authoritative advice both within and outside the industry.

Panel summary

Chair: ***Wolfgang Kröger, Peter Wydler***
Moderator: ***Hans Fuchs***
Members: ***Poong Eil Juhn, Henri Mouney, Masayuki Nakagawa, Massimo Salvatores, Philippe Savelli, Leon Walters***

The panel members were chosen to represent different types of organisation:

- *Utilities*: H. Fuchs (ATEL), H. Mouney (EDF)
- *Research organisations*: M. Nakagawa (JAERI), L. Walters (ANL)
- *International organisations*: P.E. Juhn (IAEA), Ph. Savelli (OECD/NEA)
- *Nuclear Science Committee*: M. Salvatores (CEA)

Peter Wydler opened the panel and explained its organisation. A discussion and the conclusions followed a first round of presentations by the panellists. (The summary gathers for each panellist the topics he discussed as well as answers to queries from the participants). Peter Wydler then gave the floor to Hans Fuchs, whose role was to moderate the panel discussion on international co-operation.

Masayuki Nakagawa **(JAERI)**

For the next 10-20 years energy resources seem to be assured. Starting around 2020-2030 *energy security problems* are likely to arise due to a shortage of natural resources; then nuclear energy will play an increased role. There is not much time to prepare for the developments and realisations needed. The issue of near term versus long term resources needs to be addressed, high quality scientists and engineers need to be trained and the necessary scientific budgets for following up on the different ideas need to be allocated.

The position of Japan is as follows: currently the nuclear share in electricity production is 40%, and this trend will continue particularly in view of the *reduction of CO_2 emissions*. This will determine the choice of energy resources, specifically in about 20 years, when the energy demand in Asia will be increasing and consequently energy security problems will rise. Asia is then expected to bypass the current energy consumption of all OECD Member countries combined. Japan's energy programme depends on this target time. It is important for Japan to implement the international agreement on reduction of CO_2 emissions. The Government of Japan has a plan to construct 15-20 new nuclear power plants for complying with the agreed reduction of 6%. One difficulty is finding new sites for NPPs. The option being studied is to introduce more innovative reactors that could be built nearer to urban areas.

Japan has no particular policy concerning the burning of plutonium. Originally MOX was meant for use in fast breeder reactors, but their building and exploitation has been delayed, in addition FUGEN will be closed down in 2005. Therefore, *new types of high-conversion or breeding reactors* are being studied. Intermediate storage of fuels would increase the flexibility of using plutonium.

Japan's proposal for co-operation concerns *"R&D on Inert Matrix Fuel (IMF)/Target System for Transmutation of Plutonium and Minor Actinides"*. The ongoing joint research concerns:

- *IMF system for effective Pu annihilation*. A workshop on IMF has held this same week involving the following organisations: PSI, JAERI, CEA, ITU, ECN, ENEA, POLIMI, etc. Information was exchanged on IMF materials (fabrication, thermo-physical properties, irradiation tests), core design (annihilation rate, safety analysis) and benchmark tests (burn-up of IMF pin/assembly)

- *IM for MA transmutation*. Joint research is being carried out between ECN, CEA, ITU, etc. This involves irradiation experiments at the HFReactor.

Some of these activities are carried out through a more informal co-operation and information exchange. The role for international organisations should be that of assisting in giving these activities a more stable framework. Proposal for future work is as follows:

- *Co-operation in the framework of the NSC*:

  – Co-operation items: R&D of IM (fabrication, thermo-physical properties, irradiation tests), core performance (burn-up of Pu/MA-IM, evaluation of integral nuclear data of MA by irradiation experiments), environmental safety analysis (direct disposal of spent IM).

  – Co-operation style: Information exchange (e.g. workshop), joint experiment.

  – Available facilities at JAERI: FCA (Doppler reactivity measurement), NSRR (fuel behaviour experiment under RIA conditions – U fissile).

- *Workshop on Very High Conversion Water-Cooled Reactors Research:* JAERI proposes to hold a workshop on this topic based on the following background:

  – Feasibility study on very high conversion water-cooled reactors with the objective of providing one possible option for long-term energy supply with experienced water reactor technology.

  – In the 1980s it was recognised that this is not easy to accomplish, but many studies led to designs that are more easily attained.

  – It is now worth pursuing the feasibility with increased emphasis, because conventional FBRs have encountered some difficulties.

  – Recent investigations give some promising results for further study.

  – The main purpose is to exchange information on such research and to promote it further. Useful results from previous studies carried out in the 1980s should be appropriately included.

  – Research areas to be included are: reactor physics, thermal-hydraulics, reactor safety, materials, etc.

  – Through this activity, further co-operation is intended to be considered in more detail.

Henri Mouney **(EDF)**

It is not obvious for utilities to give advice on long term R&D devoted to advanced reactors and innovative fuels. Utilities' short- and medium-term concern is that NPPs be *operated in an economical and safe manner*.

- A first priority is a continuous improvement of existing systems, their components and fuels. For that objective no new large tests are required.

- The improvements made and suggested at the Workshop are promising and sometimes surprising, but they represent in essence old good ideas.

Management of plutonium is a major concern and the following options can be envisaged:

- Burn-it or waste it in conventional reactors.

- Save natural resources through improved use of ^{238}U and ^{232}Th because fissile materials will be needed in a few decades. The Japanese concept of breeding PWRs seem to be a promising option and should be studied further.

The U-free fuel concepts are a very long-term option for the utilities but of interest for minor actinides transmutation only (French law requests that this option be studied).

The non-oxide fuels are interesting. This option should be investigated for the long-term for licensing purposes.

Research and development in the nuclear field is an insurance for keeping the nuclear option alive, especially now when a decreasing proportion of nuclear power is observed in the world.

In summary, *maintaining competitiveness* of power plants in the deregulated market is the keyword for utilities. In order to stay competitive with existing plants, high burn-up is the key issue. Competing with gas fired plants using co-generation will be difficult. This can be achieved in the new plants such as the EPR by increasing the power to 1400-1800 MWe not on the load follow but on the base load basis. Such reactors would be operated for 40-50 years. Because staying competitive is not easy, the time between now and when these new types of plant will be built should be used to get prepared to stay competitive. In order to achieve this:

- the existing R&D work plan should be kept alive;

- both realistic and dream objectives should be explored/investigated with the appropriate level of research;

- this can be done through international co-operation and sharing;

- the regulatory framework needs to be stable and political willingness to continue is required.

***Poong Eil Juhn* (IAEA)**

There is a need to *maintain the scientific knowledge base* for a long-term perspective of nuclear power. Recently the World Energy Congress has started to recognise the role of nuclear power in supplying a stable energy resource. In addition there is a need *to curb the release of* CO_2 and no new major energy resource is forthcoming to replace fossil fuels, besides nuclear. Renewable energies represent less than 1% of the current energy supply and could grow at most to a range between 5-20% over the next 50 years. CO_2 reduction can be achieved through nuclear power. Advanced reactors are important in this respect. In order to fit next generation's needs such reactors have to be inherently safe and understandable to the public. Nitride and metal high-density fuels could be a solution, as they seem to meet such criteria.

International organisations can co-ordinate this development and *bring about a consensus of the directions to be taken*. For the long-term there is a need for saving uranium resources and starting in 20-30 years thorium should be utilised as its ore deposits are larger than those of uranium. In any case it should become part of future strategies. The possible benefits of using *thorium together with uranium* should be identified; preliminary studies show a potential benefit for radiotoxicity reduction compared to exclusive uranium fuel cycles.

In developed countries there are at present no further plans for constructing new large size reactors. Only Asian countries have such plans. However for the implementation of nuclear technology *expert professionals need to be available*. This is possible only if R&D continues. The nuclear field attracts fewer students today, and a sharing among Western and Oriental countries might be one way to preserve this technology. A single developing country cannot afford to construct large size reactors higher than 1000 MWe due to small grid capacity, but is limited to small or medium size reactors in the 100-500 MWe range. Sharing electricity between neighbouring countries, regional co-operation and issues of common waste repositories should be developed with help from the different international organisations.

Nuclear energy will play a role, according to a discussion that has taken place at the last IAEA General Conference, if it stays economically competitive, if it will be proliferation resistant, if it has relatively simple waste problems and if it is inherently safe. One example mentioned is a Russian design lead-bismuth cooled fast reactor fuelled with uranium/plutonium nitrides and with stainless steel cladding having a power of 150-300 MW. A critical experiment is envisaged and a demonstration plant sould be built over the next 20 years. There are also reinvigorated nuclear energy research initiatives (NERI) of the US DOE for the next seven years.

***Massimo Salvatores* (CEA)**

At present we do not see a growing nuclear energy scenario, even though there is a clear role for nuclear energy. The issue of lifetime extension of NPPs gives the context for the near term.

Concerning fuel cycle questions, there are particular difficulties with regard to launching new large-scale projects. Which type of R&D, if any, is required?

Concerning *innovative reactors* there are three different *objectives* depending on the different perspectives and four major challenges for R&D:

- extending current fuel burn-up, full U utilisation in an evolving technology with emphasis on economy and use of energy resources;

- providing means for managing plutonium and burning actinides if needed in a safe and economical manner;

- for a visionary long-term: concepts with enhanced burn-up – simplified fuel cycles giving rise to less waste, conformance with deterministic safety requirements (Weinberg and Orlov proposals).

For all three, high burn-up fuels and concepts are the central issues. We have to find the best way for achieving these objectives, following criteria such as *safety, economy and simplified concepts*.

The challenges for R&D are:

- At the *study level*: International co-operation on *harmonising views* (taking into account the diverse perspectives) is required and co-ordination between laboratories where financing is available though in a limited way.

- *Fuel and materials*: There are many new candidates for R&D, the basic properties need to be assessed; results of today's studies on paper need to be confirmed in the laboratory. Databases need to be set up for the purpose. Moreover, it should be established where behaviour under irradiation for validation of new fuels is required. Validation of fuels takes a long time and many different fuels have been discussed and proposed during the Workshop. Analytical experiments should complement laboratory experiments; modelling of materials from a fundamental point of view is essential, thus exploiting knowledge from experimental databases.

- *Simplified fuel cycles*: The IFR is still an excellent example, meeting the requested criteria. Assessment of what other experiments are needed for validation should be made.

- *Experimental facilities*: Zero power facilities have a high relevance for neutronics studies and are essential, but at present funding is difficult; new lattice experiments are needed, new materials data are required. Hardly any facilities exist that could satisfy all needs in reactor physics for future long-term programmes. Irradiation facilities will be required covering thermal and fast neutron spectra. By the year 2010 all fast spectrum irradiation facilities might be phased out. International co-ordination and co-operation will have to play a role and help sharing needed facilities with new advanced loops required for testing e.g. new coolants. JAERI has proposed joint experiments for high temperature reactors. A new attitude towards opening the facilities is also emerging in Europe. There are promising co-operative initiatives in the EU projects as exemplified by the EFFTRA meeting held this week.

We should keep the door into the future open through concrete actions on:

- databases on basic material properties;

- benchmarks for intercomparing performances and scenarios for innovative concepts;

- joint experiments, in particular in the field of irradiation and neutronics.

There is a clear *role for the Data Bank* to accomplish several of these actions or to help their promotion.

This should be complemented by a *review of needed facilities*. A general review is being carried out to this purpose by the CSNI within the SESAR group in which one chapter is devoted to reactor physics needs. This requires to be expanded for the specific needs discussed at the Workshop. Discussion between participants in the Workshop and members of the SESAR group should assure that consistent conclusions are reached and recommendations made. (Pierre D’hondt assures this link as member of both groups.)

***Philippe Savelli* (OECD/NEA)**

Nuclear energy is seen in the OECD within the context of such global issues as *sustainable development* for which favourable conditions need to be created. There are three dimensions to this:

- the economic aspects;
- the human and social aspects;
- the environmental aspect.

Energy is one of the key areas in this and careful analysis is under way. It is a pillar for sustainable development, but could also become an obstacle to it.

The global aspects considered by NEA for nuclear energy are:

- competitiveness (recent study shows an erosion of nuclear compared to gas fired plants);
- maintaining a high level of safety: new reactors and fuel design development;
- safe waste management/minimisation of nuclear waste, deep geological repository, reduction of radiotoxicity.

An additional issue concerns the availability of resources for the long-term future.

Most issues addressed at the Workshop are relevant in the more general context of OECD views. The role of international organisations is that of stimulating the work (see summary of K. Hesketh) as today nuclear energy is facing difficulties. The role of the NEA and of other international organisations is to help Member countries keep their options open, to keep governments informed, to anticipate potential issues, e.g. risk of losing knowledge and data, and launch initiatives in line with Member countries' requirements. The discussion taking place at this Workshop is timely in the context of the NEA's *redefinition of strategic objectives* in particular as concerns nuclear science. Some of the main areas of possible contributions by the NSC and the Data Bank are maintenance and development of databases and the addressing of more basic issues related to materials and their behaviour.

In conclusion all the new ideas discussed at the Workshop should allow to gather information that would serve to show the extent to which nuclear energy is a sustainable source of energy: what approaches need to be continued, *organisation of necessary infrastructure* to achieve competitiveness and maintenance of resources, managing waste and maintaining high level safety records. There is a need to establish the right costs associated with the different energy systems and to “internalise externalities”. Currently used methodologies, which do not include the full cost of energy for the society, may lead to distortion of the energy markets.

Leon Walters **(ANL)**

The situation in the USA is unique compared to other countries with large nuclear programmes; through administration policy there is no possibility of reprocessing spent fuel, so there is no excess of separated plutonium. However, an excess of weapons-grade plutonium for strategic needs has been declared, which will be to a large extent irradiated as MOX in existing reactors and thus transformed to the “spent fuel standard.” The large energy potential of the plutonium in spent fuel and the enormous energy in our uranium resources is not recognised with by the current administration in the USA. The fast reactor option is the only sensible way to realise this benefit to humankind.

The idea of burning plutonium and transmuting fission products has re-emerged in the USA, but still there is little incentive for research as politically perceived. However, involvement of the USA on the issues discussed at this Workshop should take place in a co-operative way. The USA has a great deal to offer in terms of fuel performance experience with all types of fuel including dispersion fuels.

The issues of particular importance in this Workshop that are associated with reducing the separated plutonium inventory have provided many new research opportunities and challenges for your young engineers and scientists. As well, this research will keep your facilities viable. It is important that new young people keep moving into the nuclear business such that we *establish a continuity of expertise across generations*. This new research activity helps meet this objective.

A question was raised concerning the need to develop *proliferation resistant fuel cycles* that address the issues raised by opponents to nuclear energy. The IFR along with other similar technologies such as the Russian pyroprocess offer solutions to the proliferation issue. For some opponents, it is possible that we can convince them we have solutions. For others, the proliferation concern is yet another barrier to erect against nuclear energy development. These opponents could never be swayed otherwise. Thus, to develop yet better proliferation resistant technologies is probably fruitless. Our advocates must continue to send the message that we are penalising humankind by depriving them of the promise of unlimited energy by responding to these issues where perfectly good solutions exist and have existed for some time.

Hans Fuchs **(ATEL)**

M. Fuchs directed the discussion on international co-operation and shared the concern of the lack of research resources for meeting the new challenges ahead.

He reported on the recent *decisions by the Swiss government* concerning nuclear energy. These include the extension by 10 years of the operating licence for NPP Mühleberg, an authorisation for a 15% power increase for NPP Leibstadt and an intent to discuss both a go-ahead for a low/medium level waste repository and the question of limiting the life-time of existing NPPs (above 40 years). These discussions do not mean phasing out nuclear power, as a proposal for a new federal law would foresee the possibility of a referendum for new NPPs. The problem of reducing air pollution will remain; it is far from the target emissions envisaged which cannot be achieved without the use of nuclear energy. This is also true for CO_2 emissions.

If we take a vision towards the period 2025-2050 we note that in the years 2020/2025 we will have about 8 billion people and in 2050 about 10 billion. It is not clear whether by then the population will have stabilised. The coming decades will thus bring an *energy challenge*; the envisaged consumption of fossil fuels will be a challenge to the environment. Important local problems will first emerge such as air pollution, which will become more and more regional and global, limiting our choices of energy sources.

Concerning resources, available capital is also not so abundant; the time is ripe for strategic thinking for R&D. The situation concerning fuels, reactors and schemes is similar to the 60s, when we had many proposals by researchers, occasionally called "paper moderated and ink cooled reactors". *Strategic decisions are required concerning scenarios* on fuel types and reactor types, as to which developments are robust for the different scenarios, because we do not know exactly what the future will bring in the next decades. During this period in which we have to adapt for changes we will face turbulent scenarios; knowing turbulence is ahead, let's fasten our seat belts, turn on our grey cells and try to solve the problems together.

Wolfgang Kröger **(PSI)**

Switzerland, at the heart of Europe, although not a member of the EU, hosted the seminar because PSI is able to contribute to the *development of innovative ideas* in nuclear energy through its unique facilities, e.g. the hot laboratory where research on plutonium and actinides is carried out, the PROTEUS zero power facility for research in reactor physics and the SINQ spallation neutron source as well as the SLS synchrotron light source in the future. To widen the support for their continued operation, PSI is interested in making the facilities available for international projects.

A recent seminar of the EU addressing issues of nuclear energy in changing times has arrived at interesting conclusions: as already pointed out by Ph. Savelli, sustainable development and the role of nuclear power can be expected to receive increased attention. Competitiveness is one of the goals, but at fair prices where external costs are internalised. In this context, PSI is involved in developing a set of *indicators for assessing current and future energy systems and technologies* which allows all systems to be put into perspective and could provide a basis for judgement and comparison. In addition, we have to understand the *relation between safety and cost* and approach it in a new way (it must not be a contradiction per se).

Recognising that the future starts now, we have to take appropriate actions which may be summarised as follows:

- Find new forms of bilateral, trilateral and international co-operation taking advantage of the open research market and of support which can be given by the EU, the NEA and the IAEA.
- Develop strategies for nuclear energy to regain its role and support in our society (answering the many remaining technical questions alone is not sufficient) and get the young generation involved in new ways.

Specific actions

NSC has reviewed the proposals made in general terms during the Workshop at its Bureau meeting on 15 December 1998. The NSC Working Party on Physics of Plutonium Recycling and Innovative Fuel Cycles (WPPR) was charged to investigate at its next meeting (4-5 February 1999) how the specific proposals made can be implemented within its work programme and to provide a summary and conclusions for the NSC meeting of 2-4 June 1999.

It was suggested that *in two years time a new workshop* should be held reviewing the use of irradiation facilities, sharing of work and projects and, more generally, preparing a report on the status and development of research infrastructure.

Appendix 1

Questions Addressed by the Workshop on Advanced Reactors with Innovative Fuels

(answers in italic)

1. What are the principal issues regarding

   - plutonium utilisation, uranium resources, and waste management strategy:

     – *enhancing* UO_2 *and MOX fuel utilisation in current LWRs to reduce costs*;

     – *reducing separated plutonium stocks by means of evolutionary and innovative concepts (e.g. highly moderated MOX loaded LWRs, Inert Matrix Fuels (IMF))*;

     – *preserving fissile inventories as an energy resource for the future (e.g. tight hexagonal PWR lattices, thorium fuels)*;

     – *minimising waste by effectively burning MAs and transmuting long-lived FPs*;

     – *ensuring energy security for the long-term.*

   - optimum use of facilities and resources:

     – *R&D necessary to keep nuclear option alive*;

     – *international co-ordination of R&D programmes*;

     – *enhancing co-operation and sharing of resources among highly developed and developing countries*.

   - reactor and fuel technology:

     – *enhanced safety and proliferation resistance*;

     – *simplified fuel cycles*;

     – *material problems of non-oxide fuels for plutonium burning and transmutation*;

     – *long licensing procedures for new fuels to be taken into account*.

2. Which of the technical issues are:

   - adequately dealt with by industry:

     – *safety and economics issues relating to operation of existing plants*;

     – *cost reduction in next-generation plants*;

     – *fuel behaviour and safety of evolutionary concepts.*

- in the focus of current R&D programmes:
  - *very high burn-up and other concepts to improve fuel utilisation*;
  - *advanced oxide-fuel based designs to improve TRU burning capability*;
  - *non-oxide fuels for plutonium burning and transmutation, enhancing inherent safety and improving public acceptance*;
  - *resource-efficient, innovative LWR concepts*;
  - *thorium based concepts*.
- still not tackled:
  - *common strategy for IMF concepts*;
  - *material problems related to new fuels (e.g. low thermal conductivity of IMF)*.

3. Can the existing zero-power reactors and irradiation facilities cover short- and long-term needs? What is the remaining lifetime of the facilities? Do they have to be replaced and/or do we need new facilities?
   - *maintenance and lifetime extension of R&D facilities to be addressed*;
   - *needs to be clarified in survey report (co-ordination with SESAR group)*;
   - *new irradiation facilities needed (by ~2010 all fast spectrum irradiation facilities might be phased out)*.
4. How can the available resources best be utilised taking current circumstances into account?
   - *effort to make diverse perspective a pre-requisite for stronger co-ordination of projects*;
   - *opening and sharing of facilities and experiments*;
   - *improved cross fertilisation e.g. between reactor physics and material science*;
   - *strengthening of analytical work in parallel with and as a complement to experimental fuel and materials studies*;
   - *exploiting knowledge from experimental databases*.
5. How can the dialogue between the R&D community, decision makers and the public be improved?
   - *through the role of nuclear energy in sustainable development (especially vis-à-vis greenhouse gas production), including comparative assessment of energy systems (with emphasis on "renewable")*;
   - *dialogue on options to improve safety (goal: inherent safety) and waste management*;
   - *dialogue on energy resources for the long-term future*;
   - *dialogue on environmental criteria for energy production systems.*

6. What is the role of international organisations:

   - in clarifying the issues and fostering consensus:

     – *co-ordinate and stimulate R&D activities*;

     – *provide respected source of authoritative advice*;

     – *harmonisation of views (i.e. taking into account diverse perspectives).*

   - as hubs for the exchange of basic nuclear data and computer codes:

     – *act as central repository of knowledge and expertise*;

     – *provide the infrastructure for activities such as nuclear data evaluations where individual countries' resources are no longer sufficient.*

   - in safekeeping/validating/improving nuclear data and computer codes:

     – *act as central repository of knowledge and expertise*;

     – *maintain the state-of-the-art of computer codes, databases and benchmarks*;

     – *help to establish continuity of expertise across generations*.

   - in securing and providing for sharing human and financial resources:

     – *through collaborative projects*.

   - in utilising existing/fostering construction of new facilities:

     – *monitor status of facilities*;

     – *facilitate maintenance and construction through co-operative projects*.

7. Which specific issues in the nuclear science domain would benefit from international studies or projects to be co-ordinated by the NEA or another international body?

   – *co-operation on R&D on IMF for transmutation of plutonium and MAs*;

   – *workshop on very-high conversion water-cooled reactors research*;

   – *database for innovative fuels (basic properties and irradiation experiments).*

Appendix 2

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