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15.5. Common technology and knowledge sharing
(Session Organizers: J.W. Davis, T. Kondo, G.R. Odette, P. Fenici and T. Kusunagi)

Common technologies and knowledge sharing

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Abstract

Organizers' intention: Materials research in fusion has extensively utilized the outcomes of fission and non-nuclear technologies. The opposite was not always true in the past years. Some of the knowledge and methodologies evolved in fusion, however, are now mature and can be spun off to more generic applications. Sharing of various common issues that may exist among the current technologies and fusion is expected to yield fruitful interactions and effective solutions. Typical of those are: enhancing accuracy in predicting neutron damage and various types of environment-assisted cracking, better ways of joining materials and detecting/preventing structural flaws and failure. © 1999 Published by Elsevier Science B.V. All rights reserved.

J.W. Davis: First, we ask Professor Odette to give an overview which will set the theme of this particular session. General discussions are made after presentations of all the prepared discussions. We plan to ask you three specific questions, which appear later, so that they work as effective guide lines. I would ask Professor Kondo to chair that part of this session.

G.R. Odette: I accepted this duty rather recently. This talk will be rather personal and probably narrow perspective relative to this very broad topic. The questions we are addressing are on the technology transfer between fusion and other technologies as well as fusion with itself. Attention is drawn primarily to the issues of predicting performance of materials in a hostile environment, and I am going to focus mainly on structural first wall and blanket material issues related with radiation environment. Considerations with other important aspects will be covered by other panels.

Looking through the problems in variety of radiation environments specific to each different system, I see relatively limited overlapping between those in the details. This leads me to a controversial but very rapid conclusion that opportunity is relatively limited for direct one-to-one transfer of research results in a technological sense from fusion to other technology. This conclusion, of cause, is accompanied by many exceptions.

There are greater opportunities in and outside the fusion community if we are going to predict responses of materials in terms of mechanical properties and fracture behavior localized in hostile or extreme conditions. I call such conveniently as science-based or physical-based engineering prediction, which is based on fundamental understanding in new technologies, analysis methods and broad conceptual approaches. A specific example of relative success can be illustrated with the embrittlement prediction of a reactor pressure vessel in LWR. As illustrated, there are variety of variables, and to characterize material responses, ultimate changes are the results not only of individual variables effects but interactions are also important. The methodology established relies on techniques of combining tools with experiments and quantitative understanding of atomistic processes, in which microstructural changes are related to fundamental property changes and eventually applied to predicting changes in engineering properties; e.g. transition temperature shift and structural integrity assessment of reactor pressure vessels. In that process, microstructural models associated with primary defect production and induced atomic transport phenomena with the roles of specific metallurgical elements are developed, and then statistical fits of the physical prediction for actual engineering data, including reactor surveillance test results, are utilized to provide regulatory predictions.

I have seen wider opportunity of sharing knowledge in the discussions this week in the fields like manufacturing. Hopefully some other panelists will take this up.

K. Asano: I am in charge of studying degradation of materials and components in nuclear power plants at an electric utility company. My point focuses to what are common between the technologies of fusion and our

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system. Fission reactors, typical in LWR, use ferritic materials for structure and some limited variety of materials inside the primary circuit. The materials used are generally mature in their technology bases, while in fusion, materials are in more variety and of developing stage. The environments in the two systems look quite different in neutron energy and thermal gradient, etc. As Professor Odette stated, I also do not see much common between the two systems in direct comparison. There are, however, some similar issues generic in the consequence of radiation-induced degradations, e.g. ductility loss, void swelling, element segregation etc. The so-called irradiation-assisted stress corrosion cracking (IASCC) can be a good example of common issue between LWR and fusion. In methodology, I see similarity in areas such as small specimen test techniques, NDE and structural design criteria with less ductile materials. Fusion technology focuses on wider ranges in thermal, chemical and radiation environments, which will benefit LWR technology. With support of mechanistic understanding, information and data from fusion will allow LWR community make better prediction by extrapolation. Finally, combating against lack of public awareness of the benefit of nuclear energy must be a common subject for both communities.

F.A. Garner: I would speak about what I understand as common issues in material response to a number of different irradiation environments. Most of technology transfer has been made from fast breeder reactors to fusion but such era is now ending. At the moment, radiation-induced degradation is a common issue in the following three communities which I have been involved;

(1) fusion;
(2) LWR;
(3) accelerator driven nuclear transmutation with spallation neutrons.

Relative to the fast breeder, temperature range is lower and helium/dpa ratio is high with unexpectedly large hydrogen inventory. In LWR, dpa is low but nuclear transmutations can occur substantially due to thermal neutrons where helium and hydrogen interact with each other.

Early works have not explored the problem to that extent. In the spallation system, transmutation gets whole meaning. One of the important key issues, therefore, is storage of more hydrogen when large amount of helium exists in materials and it could influence the phenomena such as irradiation creep and IASCC. This never occurs in a fast breeder and such a hydrogen formation issue has been dismissed in breeder technology. It could be a critical factor, for example in PWR and spallation devices. Those considerations are good examples of the feedback of what fusion materials study has accomplished.

T.D. de la Rubia: I will take off where Professor Odette stopped, and focus on how do we use computer simulation to try to understand radiation damage in a solid. Since there is no single computer program to solve all materials problems of atomic to continuum mechanics scale, they are divided in various time and spatial scales, and the approach of molecular dynamics is used. Those need to be combined through some techniques, for which generic Monte-Carlo method is used. For atomic scale defects, for example, we could learn about diffusion of defects and impurities, their interactions with each other, and with grain boundaries by fitting to the Monte-Carlo tool, which are stochastic to allow you transport the system over many orders of magnitude in time scale as you possibly want to.

In order to understand complicated radiation damage process, it is necessary, however, to refer the results to concomitant experiments of fundamental level, and the validation is inevitable to develop it into theory. Fusion has been benefited by this technique, as it lacks in proper radiation test tools to examine the changes under operating conditions. For example there are common issues with the area of ion plantation in semiconductors, which is a 140 Billion/year industry. Key function is the prediction of fundamental properties of materials exposed to radiation. Through the computer simulation and theoretical modeling, fusion can share many problems with various other industries.

F. Tavassoli: Let me move the scale to large components. I have been involved in early decisions of fusion and ITER. Austenitic stainless steel was employed for the reference structure regarding that the material was extensively used in PWR and FBR, which was a technology transfer from fission technology.

There are several examples: In fission technology, early extensive employment of type 304 steel was shifted to 316 as the latter behaved better. This was a good start. Concerning the low activation, PWR faced the issue and took low Co material by using Ni ore produced in Canada. In fusion, low activation ferritic steels have been developed. The low activation ferritic steel, F82H for example, was the one which only Japan could make, but now the type of materials are handled in European industry also.

In the phase of advanced technology, we have made a number of innovative developments. Some examples are: Application of HIP. Fully austenitic diverter cassettes made by hipping is used in fusion. The issue of age-embrittlement of ferrite rich cast elbow in PWR can be replaced with the one made by the large size powder metallurgy. Secondly, the welds of ferritic to austenitic steels in LWR have a problem of forming weak martensite layers due to inappropriate Cr distribution. The technique of using composition graded multi-layered composite as a transition can reduce such a problem.

Thirdly, design rules in LWR do not consider irradiation effects. Fusion is running further in this respect. Finally, in database, fusion has covered lower temperature range of austenitic stainless steels, which will benefit the general needs in unirradiated materials.

H. Stumm: I would touch briefly three points in materials technology: i.e. low activation materials, design with brittle materials, and component mockup tests.

A variety of low activation materials which have been developed and will be developed in future, particularly with their results of characterization and extensive database, can be useful in other fields. One of the benefits of such research in reducing the risk of long life radio activity is the accumulation of detailed knowledge on minor impurities, which can be utilized in manufacturing technology.

Most low activation materials under consideration cannot be free from brittleness under fusion neutron environment. The effort of establishing structural design with brittle materials will provide good basis for general application and better understanding of failure mechanisms.

My last point is on a different subject. The first wall structure is complicated in the sense that materials used are with multi-layer structure of different kinds including stainless steel, Cu and Be, which are hipped together through complicated process. Intensive research is being made on the structural responses under simulated operating conditions. This creates a lot of critical problems to be solved such as NDE, crack propagation behavior and failure mode in those complicated materials and structures, which are quite challenging. Those require good scientific basis, and the outcomes are expected to be applied to the design of fusion specific systems like ITER and also to various other fields.

T. Shimakawa: I would like to discuss structural design in fusion reactor. Looking at the effect of neutron irradiation on structural metals, we recognize that toughness generally decreases, while strength properties increase. In research works, only the reduction of toughness is paid attention. In the designing, however, both changes are considered. Regarding the relationship between neutron exposure and structural integrity assessment, the following view is the basis of our thinking: When crack length is small, allowable stress is determined by the net section collapse criteria, and thus it is considered as stress-dominant, while crack gets larger the J-R criteria need to be applied, which is toughness-dominant. In a simple relationship crack length versus allowable stress, you can see that neutron exposure shifts the plot of the former upward and the latter downward. In the designing of LWR and FBR, the two parameter criterion has been developed. In the plot of Lr (stress parameter) vs. Kr (fracture parameter) the screening can be made clearly. I am applying this criterion to the ITER design.

Assuming a semi-elliptical crack formed on the surface of an in-vessel component structure made of austenitic stainless steel, a calculation I made has yielded a result as typically shown in Fig. D4a-1, where neutron irradiation shifts the appropriate criterion from the net section collapse to the *J–R* criterion. You may recognize that the ratio of the limit (curve) vs. the data points shows the safety margin to fracture, which increases with neutron irradiation due to increase of the strength properties.

I would therefore propose a proper screening of parameters for components. In the Japanese activity, we consider materials, structural configuration and operating condition on that line, design criterion is extracted by comparing elastic-plastic design limit for virgin materials, elastic design limit for irradiated materials and fracture mechanics design limit for further irradiated materials. The two parameters approach in the Nuclear Electric R6 Code developed in the UK is considered applicable to make a screen of criterion.

J.W. Davis: Thanks for the contribution of every presenter, and now I invite panel members to the front stage, and ask Professor Kondo to lead the discussion.

T. Kondo: The topic of this session is recognized as quite comprehensive and the total scope can never be covered in limited time. Referring to the preceding discussions, I would conveniently categorize the subject areas into the following three categories:

(1) The aspect of industrial basis of manufacturing qualified materials; (2) the science–technology interfaces which are expressed alternatively by Professor Odette as ‘physical basis’; (3) methodologies and techniques such as small specimen tests, simulation and modeling, structural design methods and NDE. The fields of speciality of panel members are also conveniently categorized.

By the way, I would like to invite Professor Odette for cochairing with me, particularly for the second topic.

The item (1) asks how do we secure industrial basis regarding possible exotic nature of most fusion materials. The item (2) has already been well illustrated by Professor Odette and some subsequent presenters. In this concern, I would also point out that the issue of the intergranular stress corrosion cracking (IGSCC) experienced in LWR plant, has less similarity with the one predicted in fusion because critical parameters are different. For example, carbon content in material was critical in IGSCC as it is caused by thermal sensitization, whereas the irradiation-assisted cracking (IASCC) cannot be mitigated by controlling carbon chemistry as it is governed by totally different parameters. The latter is an interesting coincidence between LWR and fusion, and indeed can be a good common subject.

Before starting, is there any strong opinion against what we had discussed? Are there any comments or proposals?

S. Ishino: Fusion is a long-term mission over generations. For younger people education issue must be one of the important subjects of common concern. I would propose to add this topic.

T. Kondo: It is a good suggestion, education must be included. Now let's move to the general discussion.

E. Kuramoto: In the study of fundamental features of mechanical properties, e.g. interaction between moving dislocations and radiation-induced defects/precipitates (Cu, etc.), usually classical string model is still useful. In near future, however, this must be done in a big model lattice by MD method. Do you think this is possible in near future? And do you expect new development in this field?

T.D. de la Rubia: I think, in the absence of testing means, like in fusion without 14 MeV neutrons, it is quite important to have models of multi scales such as we have developed. Emphasis must be placed on fundamental understanding of materials properties with both modeling and experiments. In my view, fusion materials community is lacking terribly in this respect. They are not serious about having no proper test means, and they are not aware of what we have done in other community. They are far behind.

F. Tavassoli: One time I was asked in a simulation community saying "You are spending 800M$ to construct IFMIF. Can you predict behavior of fusion materials by the simulation technique with one tenth of such investment?" They told us so.

T.D. de la Rubia: I do not know how answer comes from. I am not saying to solve every problem, but I think it is a combination of fundamental experiments and understanding at a theoretical level. It will help us developing models. May be far away. But the amount of money we are spending is way below the critical level, and the nucleation has not been brought to a growth stage yet. Professor Odette said that theory makes nothing, but we are making fair progress. Fusion community will realize this as a big advantage.

T. Kondo: Concerning the relationship of the availability of key test means and the progress of our knowledge, I always think of the following: If the FMIT had been brought into construction as it was proposed, experiments with intense 14 MeV would have started in around 1990. The status of development both in theory and engineering as well as the discussion we are making here, would have been totally different from the present. In that sense we have been running very inefficient works, being all based on simulations and guesses. This is just an injection, and I am not opposing either of those two different views.

G.R. Odette: Concerning Professor Kuramoto's question, in making scale for prediction, I think you get to be smart enough to make a shortcut. Basically, I would prefer simpler thing first, and tests with experiments simple then go on to do more complicated things. You discussed the process from fundamental to engineering prediction with dislocation dynamics, of three dimensional, may be getting defects in it, etc. I do not think we should wait to connect fundamental to engineering until dislocation dynamics gets into place. It may be important, but we can still do tensile tests and many simple experiments really organizing them in understanding the models and connecting them properly. We will get many answers to reach a comprehensive model that we ought to have ultimately.

T. Kondo: Let us jump to the topic No. 3. It is meaningful to discuss about design. Do design workers require very precise physical model? Maybe yes in principle, but in other view, one can do sophisticated design without precise physical understanding of the phenomena of concern. I state this referring to the experience of Monju accident.

T. Shimakawa: As I have been concerned with FBR design in Japan, I have paid special attention to that accident. In the process of design with a lot of discussion, we estimated possible failure modes of the components. Nothing had occurred in what we have considered, while the accident occurred where we missed to check the problem. In the design for ITER it is difficult to secure safety on all the components. For important components, I expect to apply more sophisticated design methods. The scale of accident is low in fusion relative to LWR and FBR. We are discussing to introduce the concept, e.g. the damage tolerance design.

G.R. Odette: In reactor operation, we experience something unexpected in the design stage, such as corrosion cracking in steam generators. But it works, LWR was designed about 40 years ago, and it was a very successful design. But they are still facing continuously to new problems in operation. So we should think not only design but also building an understanding base to allow flexibility that gives flexibility to operation, which will ultimately make fusion system successful.

T. Kondo: I think that so far we have focused mainly on standard process of understanding things, but there is another important area of sharing common empirical knowledge, which is the transfer of simple experiences of unexpected material damage or plant failures. We should make approaches from both sides.

E. Diegele: Let me comment on what Dr Shimakawa presented. He mentioned about the design against fracture rule, which was called R-6 of Great Britain, and Dr Tavassoli mentioned about ITER structural design criteria. We are just bringing both together, implementing the R-6 Code as a part of ISDC (ITER Interim Structural Design Code), which means that in the next version of the ISDC-R6 rule will be implemented as a rule for elastic-plastic fracture mechanics.

H. Takahashi: It is my opinion that industrial basis and science and technology should keep active interaction. We have serious problems of poor information flow among technical communities in Japan. Typically, we have rather little communication between fusion and fission technologies despite that fusion needs supply of technology basis from FBR community including industries. The breeder development, made as a national project, has accumulated significant technology basis in the industry, but the access from fusion has been limited because of their policy of closed operations. I would ask you all, how better interactions could be activated.

F.A. Garner: I would like to provide an example about the dynamics of some of the things we have been talking about, and to use an example of accelerator production of tritium which is going on right now. As I talked earlier, in accelerator driven transmutation environment, there are a lot of differences. First of all transmutation is not a right word for what happens in spallation environment. We see enormous amount of helium and hydrogen that we normally do not expect so much. So we are providing data necessary to design such a device. Large number of specimens are being tested by small specimen test technique. We are seeing there a classic problem, like used to be in fusion, they are using as-received properties.We are providing a handbook for anticipated changes before we test data. This is always the situation of where technology transfer is needed. The designers are way ahead of data generation and insisting us saying "You are irradiating specimens for 20 years!". We have to come back after or at the midway of their design with the results to let them reconsider. This is an actual problem when you are working with designers. They cannot afford to wait, and they want you to reach back into your fusion experience. For the moment we need to feed back the experiences obtained in FBR and fusion. We hope that the experiment does not give us the results too much different.

T. Kondo: We recognize now that we have the subject to be discussed more than expected. Now let us come back to the first item, the industrial basis.

F. Tavassoli: Before that, let me talk about Monju accident. We had Phenix accident of similar kind. There was panic experienced in both cases. We learned that if you had a proper method of detecting the leak and apply it, then you could have managed the accident better. We cannot predict everything. Some of the things are those we learn with experience. The second thing we have learned is that most of the time, problems occur in the areas which we have not worked on. Quality assurance should be made even on those we do not consider critical.

T. Kondo: In Monju accident we have learned how easily a predictive thought can make mistake. In the earlier safety consideration, where large scale leakages generally were assumed to be the most critical, and it was thought to be conservative to assume that the large scale leakage was to cover all other levels of leakages, but it was totally wrong. True critical condition was rather of some intermediate scale leakage, where appropriate supply of oxygen to keep sodium burning could shift temperature much higher than anticipated and the burning products, sodium peroxide, and hydroxide attack the steel flooring to threaten a catastrophic hazard process. Shame is that the whole FBR communities in the world have not been seriously aware of it.

Now we touch on the industrial basis and the strategy with materials innovated specifically for fusion. Let me ask one question. Do we go with the limited variety of the current candidate materials, e.g. ferritic steel, vanadium alloys and SiC–SiC composites for the next twenty years. I wonder if fusion power technology does not need further material innovation?

P. Fenici: We have a lot of materials for ITER, and we hear many times on mockup construction of this experimental reactor. My feeling is that DEMO will use completely different materials. The point is, which is difficult to say at the moment, but there are a lot of works going on in the world in general industrial fields. We notice the high temperature materials, ceramics and their composites are increasingly studied for many applications. So we need to have also a clear study on possible fusion reactors, in order to guide materials development. Unfortunately fusion is not a rich, but rather poor program for the moment, compared to electronics. I also have a comment on Dr de la Rubia's predictive models, and may be fusion community does not do much. We did a lot in past, and programs are changing. In Europe, reactor oriented programs are accepted more or less. We should pay more attention to such type of work, I agree with you. The materials that we will have in the next decade will go through quite a lot of changes. As somebody (Odette) said, which I fully agree, that we have to profit the other developments. In other fields there are quite a lot of working going on. Some are made cyclically as intermetallics which are repeated every 20 years. As many speakers pointed out, we should consider simultaneously the method of using quasi-brittle materials.

G.R. Odette: Electronic industries have been empirical. They make use of the exploit of radiation effect studies of this community while we are not taking advantage of it.

T.D. de la Rubia: It is correct. But probably it is not a good example to refer to semiconductor industry because their driving force for doing this work is very different. They are basically empirical, but they need to earn money. They cannot design semiconductors without fundamental understanding of impurities, etc. It is okay, but I said before that fusion community should consider the use of this knowledge before it is too late.

G.E. Lucas: I was struck by the amount of knowledge sharing that is going on. I thought of an old expression, 'Necessity is the mother of invention'. The lack of information, design code or the knowledge that is filled in are the result of necessity. I was struck by a new expression which is that 'Poverty is the father of knowledge sharing' because as the fusion budget has been cut and the scientists have found other things to do. And those other things are, we bring our tools to other areas and bring back new tools.

F.A. Garner: Being struck by the Lucas' last comments, I will provide some examples where necessity–poverty thing works out. In the breeder program we stumbled on the void swelling problem quite by accident. Swelling became a challenging subject, and enormous amount of effort was directed to solve this problem. Because of the space consideration in reactor irradiation, the necessity caused use of TEM disks as small specimens, which worked perfectly for study of void swelling. We were not focusing on anything else like radiation embrittlement or creep, and were successful to find four or five paths. We killed swelling, but with total expense of ductility.

Now, we discovered that ductility was the problem. As we had thousands of microscopy disks, this caused development of a variety of test methods such as punching, sheering and bending TEM disks. Now we are using a lot of sheer punch techniques and are sending these back to the LWR industry as the way to do tests.

But now, once again we are having problems. We have to demonstrate even the small size specimens can be applicable to especially something exotic as the spallation neutron thing. In convincing criticizers to the use of this technique, and engineers who immediately reject it, we went back to the old FBR and fusion things to perform extensive examinations to demonstrate the applicability of the technique. The paper I have here includes about 300 data points from that examination. This is an example of the mother-and-father kind of things that Dr Lucas was talking about.

K. Abe: Let me change the subject I think not only energy but also environment issues must be discussed. It is the responsibility of all people and industries to maintain environment in the aspect of reducing carbon dioxide in near future It became more and more important to develop nuclear energy including fission and fusion power generation. I do hope that electric utility companies take a lead in promoting fusion R & D. I would ask Dr Kusanagi to respond.

H. Kusanagi: Personally I am very interested in the problems of both carbon dioxide and energy resources. I am not able to provide an immediate answer to this question. I would ask Dr Asano from Tokyo Electric Power Company to help me.

K. Asano: I don't have much knowledge about the environment issues. However, as one of the persons working at an electric utility firm, I should make some comments. Nuclear plants are currently supplying only the base load part of power generation. Public demand for power supply, on the other hand, is continuously increasing. In order to keep up with such a trend, we are constructing power plants with the combined cycle gas turbines. Such power plants require rather frequent replacement of expensive components, which reminds me a concept of fusion reactor requiring also replacement of costly components at some 2 to 3 year intervals. I hear that even the components removed from fusion reactors will not be free from radioactivity even though radio activity can be reduced by use of low activation materials like this community is developing. In some rough idea, radioactivity of each component can be lower, but expected gross radioactivity inventory in the disposals from fusion could ultimately be almost comparable with those from LWR.

I am wondering whether a fusion reactor is similar to the combined gas turbine plant or to LWR in that waste disposal aspect? I am afraid I could not provide a direct answer to Professor Abe's question.

T. Kondo: It looks like that our discussion is extending to a grobal subject.

Sorry, but unfortunately the session is running out of time. The topic on environment is quite important, and we should always keep it in mind.

I must apologize also for having not been able to cover a few more subject of importance. Particularly I regret that the topics of education could not be covered within given time because of its very extensive nature. I might make a short comment about education of ourselves. A reactor designer should know everything that are necessary to integrate the system he handles, but actually one cannot do everything perfectly. In that sense those who really require education are designers, while we must be patient to attempt continuous dialogues with them, and the education must cover everything. But any way, we have to transfer the knowledge generated in our era to the next generation in a possible best form. This is another aspects of education, knowledge share and technology transfer.

In the final part of the session, we should touch on the database issue shortly. Let me invite my co-chair, Dr Davis for some comments on this topic. Dr Davis, you should be given at least one chance of expressing your own opinion as you have been trapped in chairing the session. Also, I ask you to conclude the whole session.

J.W. Davis: One of the contributions we have received is from such as ITER, which has the ability to consolidate a lot of research activities where development has been going on through past and current ITER program and the associated programs to yield a uniform material property database. On that database, now is finding applicability in a number of systems, whether or not in aerospace vehicles, new power reactors in conceptual design. This is a tremendous way to transfer the knowledge that we gain in fundamental and applied research to the design community, which can then transfer to alternative applications.

What I want to make a plug is to keep cards coming. Please send data so that we can continue developing knowledge and show the knowledge in engineering data.