INTERNATIONAL THERMONUCLEAR EXPERIMENTAL REACTOR

ITER EDA NEWSLETTER

VOL. 6, NO. 10

OCTOBER 1997

INTERNATIONAL ATOMIC ENERGY AGENCY, VIENNA, AUSTRIA

ISSN 1024-5642

EXPERIMENTAL VALIDATION OF DECAY HEAT CALCULATIONS FOR ITER

by N.P. Taylor, EU Visiting Home Team Personnel, and H-W Bartels, ITER Joint Central Team

This article reports an international benchmark exercise to determine nuclear data and activation code uncertainties in the context of decay heat projections for ITER, the subject of a workshop, held at the ITER San Diego Joint Work Site, October 2 - 3, 1997, under a Task Agreement between JCT and the Japanese Home Team. In view of the importance of the new results, JCT opened this meeting to other Home Teams to allow interested specialists to participate if they wish.

Background

In ITER or in a fusion power plant, decay heat will arise after plasma shutdown from the energy released in the decay of the products of neutron activation, mainly in the plasma-facing components (first wall, blanket, divertor and limiters).

Although this decay heat is at a much lower level than that in a fission plant, in the event of a postulated accident in which cooling is lost, structural melting of the vessel is physically impossible but the energy is sufficient to cause a modest temperature transient in structural materials. The elevated temperature may promote the mobilization of tritium and solid activation products, presenting a potential radiological source term in the unlikely event that the confinement barriers have also been breached or bypassed in the accident.

A further consequence of a high temperature may be a chemical reaction between beryllium (used as a plasma-facing surface coating) and steam escaping from a failed coolant channel within the vacuum vessel. This reaction produces hydrogen at a rate which is a strong function of temperature; at sufficiently high temperatures enough hydrogen might be produced to present an explosion hazard which could challenge the confinement.

There is thus strong motivation to limit accidental temperature transients and to ensure that the design provides for removal of decay heat, preferably by passive means. Safety studies assess the efficiency of the design in this regard, by computer models which require as a starting point an accurate knowledge of the decay heat level, and its distribution in both space and time after shutdown.

Decay Heat Calculations

Computation of decay heat is performed by sophisticated computer codes which solve the large number of coupled differential equations (the Bateman equations), which govern the generation and decay chains for the many nuclides involved. They rely on a large volume of nuclear data, both neutron activation cross sections and radioactive decay data. The activation data is typically stored in a data library and provides partial reaction cross sections for all neutron reactions in a comprehensive range of nuclides, together with branching ratios to various isomeric states in the product nucleus. This data is tabulated as a function of neutron energy. The decay data provides nuclide lifetimes and decay branching ratios, again for a comprehensive range of nuclides.

In the context of ITER safety studies, a number of postulated loss-of-cooling accidents have been analyzed. For these, the decay heat source needs to be well characterized in the stainless steel and copper components of the first wall, blanket, limiters and divertor, and also in the tungsten of parts of the divertor and baffles. Calculations of decay heat densities have been performed using the REAC and FISPACT codes for ITER EDA safety assessment. For the activation and decay data, files of the Fusion Evaluated Nuclear Data Library (FENDL) have been used, in particular FENDL/A-2.0 and FENDL/D-2.0. Another important input to these calculations are the neutron flux spectra in the various components; these have been obtained from 1, 2 and 3-D models employing the neutronics codes ANISN, Bonami-XSDRNPM (SCALE-4.3 modular system), TWODANT, TRIPOLI and MCNP.

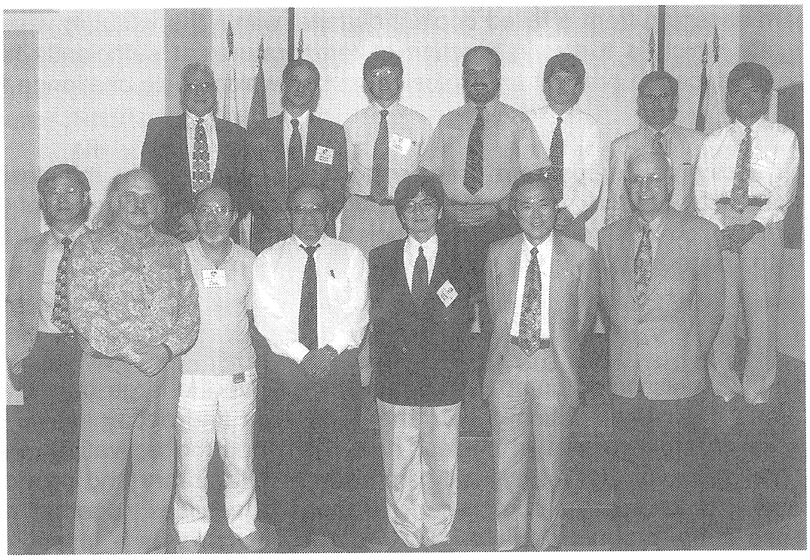
The results of these accident analyses, under a range of conservative assumptions, show that the peak temperatures reached are always within acceptable limits and do not lead to hazardous consequences. However the margin by which this is achieved is not large, particularly in view of the strong temperature dependence of the beryllium/steam reaction rate. It is therefore important to have a good knowledge of the uncertainties in the analysis, in particular of those in the decay heat values which are the starting point of the study. In the temperature transient calculations, a safety factor of 1.2 is applied to the global decay heat values, to allow for an estimated 20% uncertainty in its calculation, except for the divertor region, where 1.3 has been used, to allow for the higher expected uncertainty in tungsten decay heat, mostly due to strong spectrum shielding, spectrum softening, and Doppler effect. It is important to note that it is mostly the global ITER decay heat energy released during the first few days after plasma shutdown that is important for safety studies. Minor deviations in time and location have no significant impact on the results of thermal transient studies.

Measurements of Decay Heat

Whilst most of the nuclear data in the FENDL library is based on evaluations of experimental measurements, there have been no suitable integral measurements of decay heat in structural materials irradiated in fusion-typical neutron spectra, which might provide a basis for validation of the codes, data and calculational procedures used in decay heat prediction. It is to fill this gap that a series of experiments were performed using the Fusion Neutronics Source (FNS) at the Japan Atomic Energy Research Institute (JAERI).). Other substantial ITER related R&D work with 14 MeV neutrons is performed at FNS and the Italian Frascati Neutron Generator (FNG) at ENEA in the areas of nuclear heating, activation, and neutron streaming. This work, although important for ITER, is not reported in this article.

Coupled to the experiments, an international benchmark exercise was launched, in which users of the principal activation and decay codes and data would perform calculations of decay heat for comparison with the measurements. This is the first time that such an exercise has been attempted for decay heat modeling in a fusion neutron spectrum.

The experiments at JAERI (see box on the next page) enabled a range of sample materials to be irradiated in the 14 MeV neutron flux of the FNS, and then the decay energy measured in the samples at a series of times after the irradiation, using the highly sensitive Whole Energy Absorption Spectrometer (WEAS). Two series of irradiations were performed, of 5 minutes and of 7 hours duration, with decay energy measured at times up to about one hour and 100 days respectively. In addition to the WEAS measurement, a calorimetric system is being constructed to confirm the prediction independently.



Participants in the Workshop

DECAY HEAT MEASUREMENTS AT JAERI

Measurement of the decay energy in small samples irradiated in a high-energy neutron flux has been possible using facilities at JAERI, Tokai, Japan:

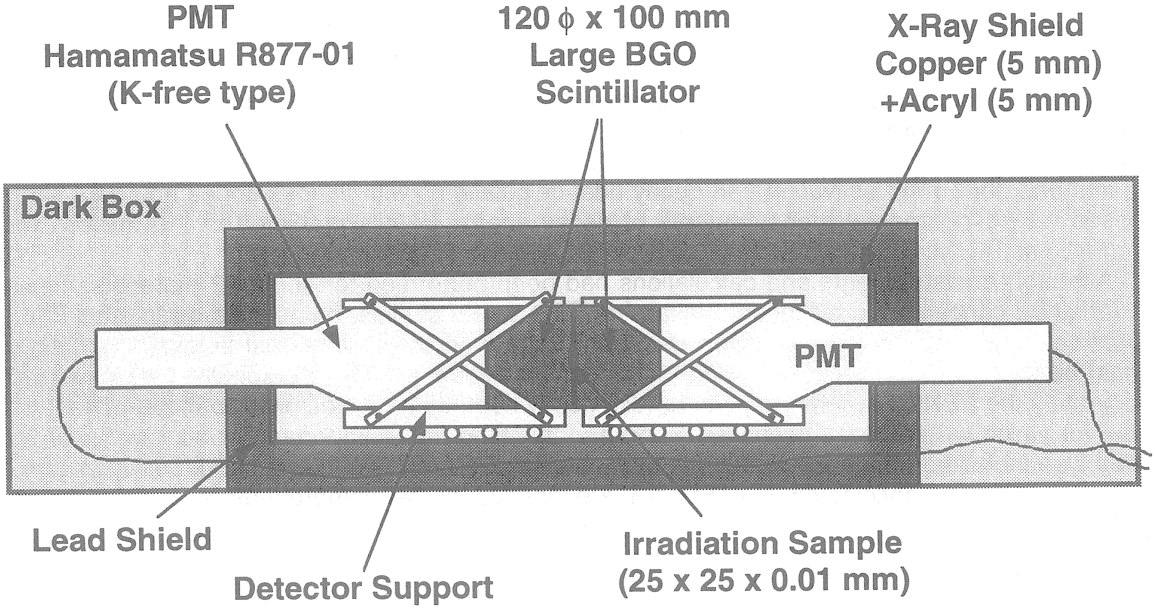
- The **Fusion Neutronics Source** is the 14 MeV neutron source.
- A **Whole Energy Absorption Spectrometer** has been developed to measure the decay energy.

Fusion Neutronics Source (FNS)

14 MeV neutrons from D-T reactions are generated by a 2 mA deuteron beam impinging on a stationary tritium-bearing titanium target. The neutron flux at the sample location is in the range 3×10^8 to 3×10^{10} $n.cm^{-2}.s^{-1}$. Thin samples, 25 x 25 mm^2 and, typically, 10 µm thick, have been used, either metallic foil or powder sandwiched between tape.

Whole Energy Absorption Spectrometer (WEAS)

The decay energy in each irradiated sample was measured in the WEAS (see diagram), which comprises two large bismuth-germanate ($Bi_4Ge_3O_{12}$, BGO) scintillators (each 120 mm diameter ¥ 100 mm length) in a geometric arrangement which provides almost 100% detection efficiency for both beta and gamma-rays. Anode current from the two photomultiplier tubes corresponds to the decay energy in this system. Modest scintillation light decay time leads to low pulse pile-up even at high counting rates. Correction factors are applied for gamma-ray efficiency and for beta energy loss within the sample itself (less than 15%) and other minor effects. The overall experimental uncertainty totals between 6 - 10%.



The WEAS provides high sensitivity, less than 1 pW (equivalent to about 2 Bq of ^{60}Co), which is valuable for measurement of some materials with long half-lives. It also has a wide dynamic range, measurements up to 10,000 pW being possible.

Workshop

The details of the experiments performed, together with the resulting decay heat values, were communicated to the groups participating in the code comparisons in July 1997. A workshop was then held at the ITER San Diego Joint Work Site, October 2 - 3, 1997 (see photo), at which the results of the various calculations and their comparison with the experiments were presented and discussed.

Although measurements and calculations had been performed for some 32 materials, comparisons at the workshop concentrated on those relevant to ITER safety studies, namely stainless steel 316, copper and tungsten. Furthermore, most attention was paid to the timescale of interest in loss-of-cooling accident scenarios, up to three days decay following the longer irradiations in FNS.

Six groups participated in the code calculation comparisons, each using a different activation code: JAERI; TSI Research, California; University of Wisconsin-Madison; UKAEA Fusion; University of California, Los Angeles (UCLA); and ENEA with Bologna University, Italy.

Code Comparisons with Experiment

Most groups had performed a set of calculations using the FENDL/A-2.0 activation cross section library, some had performed further calculations with alternative libraries. Various decay data libraries were used. A large quantity of calculation/experiment (C/E) values had therefore been produced, with C/E varying as a function of decay time in each case. The table below provides a summary of the principal comparisons, in terms of indicative (C/E)-1 values expressed as a percentage, approximately averaged over the time period of interest. It also gives the estimated uncertainty associated with the experimental data.

(C/E)-1 values from the various code calculations

Code	Cross section library	Decay data library	SS 316		Copper	
		irradiation time:	5 min.	7 hr[1]	5 min.	7 hr[1]
ACT4	FENDL/A-2.0	ENSDF	< -10%	-10%	-10%	-10%
REAC-3	FENDL/A-2.0	FENDL/D-2.0	< -5%	-10%	-10%	< -5%
FISPACT97	FENDL/A-2.0	FENDL/D-2.0	< -10%	< -4%	-6%	< -4%
ANITA-4	FENDL/A-2.0	JEF-2	< -10%	+4%	-10%	+3%
DKR	FENDL/A-2.0	FENDL/D-2.0	< -4%	-6%	-10%	< -3%
DKRICF	FENDL/A-1.0	ENDF/B-V	< -10%	-30%	-15%	-15%
		Experimental uncertainty	6%	5%	5%	6%

[1] Only results up to 3 days cooling are considered.

For stainless steel 316 and copper, the comparison of calculation with experiment has given good results in most cases. A few discrepancies in these and other materials were identified, together with their probable cause in deficiencies in the basic nuclear data. This is being further investigated.

Decay heat in tungsten is an important issue, as it dominates the local heat generation in the divertor region of ITER during postulated loss-of-cooling accident scenarios. However, it presents some particular difficulties, both to modelers and experimenters. Although there are 5 naturally-occurring isotopes of tungsten, in ITER the dominant contribution to decay heat is the beta-decay of ^{187}W with a half-life of one day, formed by neutron radiative capture in ^{186}W. The $^{186}W(n,g)$ cross section contains many resonances, in particular a giant one at about 20 eV, in which most of the reactions occur. The effects of resonance self-shielding thus become important, and calculations for ITER using infinite-dilution multigroup data tend to severely over-estimate the ^{187}W production rate and hence the decay heat.

Decay heat in the ITER divertor has been the subject of extensive modeling work, with sophisticated 3-D geometrical neutronic models to properly account for the resonance self-shielding effects. Two independent groups performing separate calculations with different Monte Carlo and activation codes were the University of Wisconsin-Madison, who used MCNP4A and DKR, and UKAEA Fusion at Culham, using TRIPOLI-3 and FISPACT. Although some of the detail of their results varied, the two calculations were in close agreement on the decay heat from ^{187}W. Agreement between the calculations is encouraging, but validation is still required by reliable integral experiments.

However, in the decay heat measurements at FNS the neutron spectrum is predominantly 14 MeV, with few neutrons at the low energy of 20 eV, so that the contribution of the ^{186}W(n,g)^{187}W reaction to the total decay heat in tungsten is small. Furthermore, a substantial proportion of the decay energy of some tungsten isotopes is in gamma-rays of low energy, many below the energy discrimination point normally set in the counting electronics, leading to a significant experimental uncertainty. Thus the present experiments have not provided an adequate basis for code and data benchmarking although intercomparisons between the code results did reveal consistency.

Further tests to address this issue are planned on the FNS facility at JAERI. An arrangement of steel, water and beryllium moderating materials will be used to obtain a neutron spectrum typical of that found in ITER plasma-facing components, and which can be well-characterized. A sandwich of tungsten foils and thin samples will be irradiated in this spectrum, and the decay energies in each foil measured to provide a spatial distribution of decay heat for comparison with further code calculations. Further improvements of the experimental assessment of tungsten decay heat are foreseen.

Conclusions

The experimental decay heat measurement program at FNS, JAERI, combined with the code calculations at the various institutions participating in this benchmark activity, has provided a unique check of the uncertainties associated with the computation of decay heat in ITER-relevant materials. For stainless steel 316 and for copper, the results of the comparison give confidence in the decay heat values calculated in analyses of postulated decay heat transient accidents in ITER, although the predominantly 14 MeV neutron spectrum in FNS has meant that some low neutron energy reactions of potential importance in ITER have not yet been adequately tested. Further experiments in a modified arrangement providing a typical ITER spectrum are planned. The results of the present activity support the conclusions of the present ITER safety assessment with respect to decay heat, because of the use of conservative safety factors; further work will help to reduce the uncertainties.

In tungsten, particular experimental and calculational problems arise. Neutronic and activation modeling of decay heat in the ITER divertor has shown good agreement between two independent calculations, but experimental validation is required. The planned further series of measurements on FNS will address this.

Whilst confirming generally acceptable agreement between code calculations and experiment for stainless steel and copper (within 10% at the times of interest for ITER safety studies), a number of particular discrepancies were identified.

Maintenance of an internationally-accepted library of activation data is essential for the ITER project to be able to present a sound and well-validated safety assessment. The FENDL/A-2 library fulfills this requirement, and is the result of very substantial international effort over many years. In order that it may continue to be of value, it is most important that an international effort is continued to provide for its maintenance and updating.

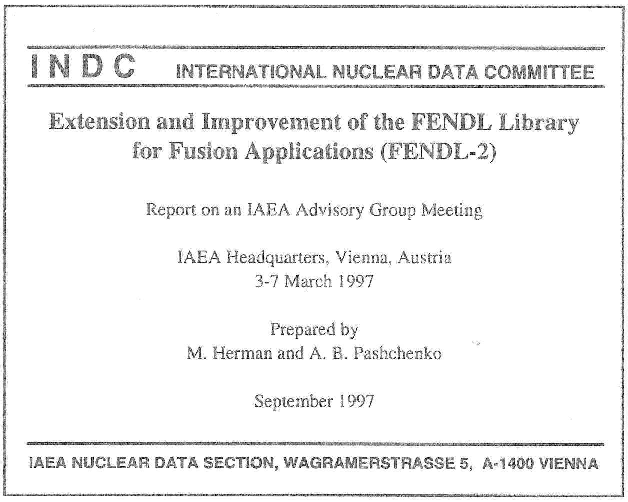
LIST OF PARTICIPANTS

EU:	JA:	US:	JCT:
G. Cambi	Y. Ikeda	E.T. Cheng	H-W. Bartels
D.G. Cepraga	F. Maekawa	H.Y. Khater	H. Iida
R.A. Forrest		M.E. Sawan	G. Saji
J-Ch. Sublet		M.Z. Youssef	R. Santoro
			N.P. Taylor (EU VHTP)

EXCERPTS FROM A LETTER SENT ON 18 NOVEMBER 1997 BY DR. GENN SAJI TO THE SPECIALISTS INVOLVED IN FUSION NUCLEAR DATA ACTIVITIES

Dear Fusion Nuclear Data Community Colleagues,

This e-mail is to thank for many years' of your effort in developing reliable nuclear data for fusion development by providing validated FENDL nuclear data libraries, in particular this year's official release of FENDL/A-2.0, FENDL/D-2.0 and FENDL/C-2.0 sublibraries from the IAEA Nuclear Data Section. We, at the Safety, Environment and Health Division (SEHD) of ITER Joint Central Team, generated practically all of our activation data bases of ITER Non-Site Specific Safety Report (NSSR-2) by using FENDL/A-2 and D-2, supported by Dr. Ed. Cheng of the US Home Team. The data bases include data for activation source terms, decay heat curves, activation data for dose-release conversion factor calculations, activation characteristics data for waste management and decommissioning studies, data for occupational safety assessment, data for effluent and emission calculation, etc. Early October, we completed the first draft of NSSR-2 in total of about 1300 pages in 10 Volumes and an Appendix. At the 6th Safety Meeting, we organized two weeks ago to review the first draft of NSSR-2, the participants were unanimous in stating that NSSR-2 is a significant improvement in ITER safety analysis and documentation, responds very well to the Home Teams needs, and provides a good basis to start discussion with regulatory authorities. A large credit for this achievement goes to the high quality nuclear data bases calculated by using FENDL/A-2 and D-2.



INDC INTERNATIONAL NUCLEAR DATA COMMITTEE

Extension and Improvement of the FENDL Library for Fusion Applications (FENDL-2)

Report on an IAEA Advisory Group Meeting

IAEA Headquarters, Vienna, Austria
3-7 March 1997

Prepared by
M. Herman and A. B. Pashchenko

September 1997

IAEA NUCLEAR DATA SECTION, WAGRAMERSTRASSE 5, A-1400 VIENNA

In my understanding, FENDL sublibraries are released timely to support ITER EDA activities, in particular for activation calculation for safety and environment to be used for NSSR-2. Knowing that the sublibraries are approved after going through extensive verification and validation procedures among the international nuclear data specialists for many years, I am convinced that they are the first comprehensive and reliable nuclear data, in regulatory quality, for fusion neutronics environment, where nuclear transmutation reactions by high energy neutrons are very important. Your activity provided us a strong confidence in activation data used in NSSR-2.

About one month ago, we organized an ad hoc workshop to look into validation of decay heat at ITER San Diego JWS. This workshop was organized by SEHD as part of an activity to determine the level of uncertainties in calculations of decay heat in ITER safety studies. This is a code validation activity in which participants had performed activation and decay heat calculations, with various codes and data libraries, for comparison with experimental measurements of decay energy in foils irradiated in the Fusion Neutronics Source (FNS) at JAERI.

Although measurements and calculations had been performed for some 32 materials, comparisons at the workshop concentrated on those relevant to ITER safety studies, namely stainless steel 316, copper and tungsten. Furthermore most attention was paid to the time-scale of interest in loss-of-cooling accident scenarios, up to three days decay following the longer irradiation in FNS. Personally, I was amazed to see how accurately the FENDL sublibraries can predict decay heat, as long as limited to these materials (except tungsten, for which we still need continued work) and this time frame important for accident analyses. The workshop also indicated needs for continued maintenance effort of FENDL and needs for validation of other materials not currently anticipated in ITER but are needed to be comprehensive and for future fusion reactors.

Sincerely, Genn Saji Genn Saji Head, Safety, Environment and Health Division
ITER Joint Central Team

Items to be considered for inclusion in the ITER Newsletter should be submitted to B. Kouvchinnikov, ITER Office, IAEA, Wagramerstrasse 5, P.O. Box 100, A-1400 Vienna, Austria, or Facsimile: +43 1 237762, or e-mail: c.basaldella@iaea.org (phone +43 1 206026392).

Printed by the IAEA in Austria
December 1997

97-05342