MEETING REPORTS

SUMMARY OF THE INTERNATIONAL ATOMIC ENERGY AGENCY TECHNICAL COMMITTEE MEETING ON DEVELOPMENTS IN FUSION SAFETY, TORONTO, ONTARIO, CANADA, JUNE 7-11, 1993

The International Atomic Energy Agency (IAEA) Technical Committee Meeting on Developments in Fusion Safety was held June 7-11, 1993 in Toronto, Ontario, Canada, and was hosted by the Canadian Fusion Fuels Technology Project (CFFTP). The meeting was chaired by G. A. Vivian (CFFTP). The program, consisting of 38 papers and two panel discussions, was attended by 56 fusion reactor safety specialists from around the world. The proceedings will be published in the *Journal of Fusion Energy*. The program was organized into nine sessions, which are summarized below.

In his introductory remarks, F. N. Flakus, IAEA Scientific Secretary, stated that radiation safety has been an integral part of the IAEA fusion research program since its inception. This is the fifth in the series of meetings on fusion safety, following the Jackson Hole meeting in 1989. Radioactivity is not produced directly by fusion as it is for fission, so we have more control by choice of materials. Safety guidelines are continually evolving from the International Commission on Radiological Protection (ICRP) and other agencies. The "optimization of protection" principle should be applied early in the planning phase, rather than retrospectively. After deuterium-tritium-fueled reactors are developed, advanced fuels producing less induced radioactivity can be further explored.

NATIONAL DEVELOPMENTS: G. A. VIVIAN, CHAIR

Y. Seki (Japan) reported that the main safety research and development (R&D) priorities for Japan are tritium safety and activation product mobilization. A preliminary prioritization of subtasks emphasizes the following:

1. information essential for experimental reactor licensing
2. information for experimental reactor improvement
3. information for a demonstration reactor (DEMO) and long-term needs.

An urgent, continuous review of prioritization is ongoing via two national committees. Some key developmental tasks are

1. emergency plasma shutdown
2. frequent activated dust removal
3. emergency gaseous tritium removal systems.

Tritium safety R&D priorities in Japan are

1. inventory distribution, especially in plasma-facing components (PFCs) and blanket
2. permeation and leakage
3. behavior under accident conditions in the confinement and in the environment.

Currently, the only identified long-term DEMO need is for a good tritium barrier in the cooling system. International collaboration will be carried out via the International Thermonuclear Experimental Reactor (ITER) and via the Organization of Economic Cooperation and Development/International Energy Agency (IEA) Environment, Safety, and Economics (ESE) program.

B. N. Kolbasov (Russian Federation) reported that data are available from large tritium factories on radioactive waste generation and effluents, sources of atmospheric tritium effluents, and environmental tritium transport. These data will be useful for predicting ITER design needs and for validation of tritium environmental transport models. Additional experimental data are available on studies of tritium migration in soil using HTO and seven foodstuffs. Tritium dose factors have been estimated from effluent and environmental data for a tritium factory. The differences between international and Russian tritium radiation criteria were identified, with special attention given to insoluble compounds, soluble organics, and tritiated nucleic acid precursors. Insoluble compound limits are about $\frac{1}{50}$ of those of HTO in the lungs because they are retained in the body much longer.

W. Gulden [Next European Torus (NET)] reported implications from NET predesign safety studies. The small stored energy inventories (no criticality excursion hazard) suggest that fusion power plants can rely on passive safety designs. The lack of practical fusion safety experience requires the use of conservative approaches, providing safety margins to satisfy regulatory requirements. Recommended accidental dose targets and limits are

$\leq$1 mSv for in-plant transients and accidents and expected ex-plant initiators

$\leq$100 mSv for unexpected ex-plant initiators.

This implies a vulnerable tritium inventory $\leq$150 g. System tritium inventories have been estimated to total ~2 kg ($\pm$50%) for the basic performance phase of NET. The preliminary Confinement Release Fraction (CRF) required for NET to meet conservative dose targets is 0.1% of inventory, which is 20 times more stringent than the ITER target. The CRF values require substantiation by detailed accident sequence analyses, with emphasis on containment pressure suppression and detritiation. A preliminary tritium plant analysis indicates that care is required to prevent failure propagation from the fuel cleanup system to other tritium plant systems, especially the isotope separation system. Loss-of-flow accidents (LOFAs) and ex-vessel loss-of-coolant accidents (LOCAs) without plasma shutdown can result in severe in-vessel damage, especially to the divertor. The dose from tritiated organics may be similar to the HTO atmospheric dose, since the chronic effective dose equivalent is on the order of 100 times higher. The NET radioactive waste has a slightly larger volume than from a fission reactor, but orders of magnitude lower toxicity.

TRITIUM SAFETY: R. V. CARLSON, CHAIR; G. R. LONGHURST, SUMMARY

T. Hayashi (Japan) described technology development at the Japan Atomic Energy Research Institute Tritium Process Laboratory, which has triple confinement (apparatus, glove box, and room). Researchers are developing membranes for hydrogen isotope removal, laser-Raman spectroscopy for tritium inventory measurement, and waste treatment methods.

H. Dworschak [Commission of the European Communities (CEC)] reported on the European Tritium Handling Experimental Laboratory (ETHEL) at the Joint Research Center (JRC), Ispra. These researchers will investigate tritium parameters in materials, tritium loss mechanisms, confinement and cleanup systems, and techniques for tritium monitoring and control using chambers with volumes of 5 and 350 m^3. C. Housiadas (CEC) discussed tritium control in ETHEL, which will be licensed for 100 g of tritium.

P. L. Taylor (United States) described tritium behavior in the Doublet III-D reactor (DIII-D) tokamak carbon tiles. The tritium inventory of the tiles was reduced from 15 to <1.8 mCi by grit blasting, ultrasonic washing in alcohol, and baking, and most of the tritium was found to be within 20 μm of the surface.

K. M. Crosswait (United States) discussed passive safety in a helium-cooled blanket with the HT-9 structure and found that good thermal conduction outward from the first wall (provided by beryllium) is desirable to prevent creep rupture during LOFA conditions.

The most important issue is the technology and requirements for measuring tritium inventories. The precision required for tritium measurements and accountability in fusion systems needs to be resolved. Better methods are needed for determining how much tritium is resident on surfaces, sieve beds, storage beds, etc. The mechanisms important for tritium releases inside rooms and structures need to be studied. It is especially important to know how much credit can be assumed for tritium holdup in accidental spills. Policies must be developed and refined for dealing with tritium that is unaccounted for. There appears to be public misunderstanding of tritium risks compared with other radioactive materials issues. Ways of dealing with tritiated waste need to be studied and developed. More knowledge is needed about tritium interactions with materials. Selectively permeable membranes may be developed for concentrating tritium-bearing gases, thereby easing the task of collection, fixation, or isotope separation. The amount of tritium retained on surfaces and in solids should be quantified. This has implications for uptake pathways, especially as organically bound tritium. Safety analyses require information on what conditions cause tritium release from structural materials and how tritium can be fixed to the surfaces.

OPERATIONAL SAFETY: H. DWORSCHAK, CHAIR

In this session, it was emphasized that tritium burning fusion devices should not require emergency planning for the general public. Recommended accidental release dose limits should not be exceeded even for the worst-case events. Neither the public nor the operator exposure should exceed established dose limits from chronic releases. Passive safety is a basic strategy for attaining these goals. However, the high mobility of tritium hinders passive safety and requires the application of complementary safety measures. Two approaches are envisaged: minimizing the vulnerable tritium inventory, and confinement supported by active barrier systems. Compartmentalization is reliable but affects the design of the facility. So far, a reliable data base on tritium permeation barriers is not available. Several presentations have shown that such tritium transport can be affected by unforeseen phenomena as a result of the extreme concentration ranges. The tritium concentration range spans 12 orders of magnitude and involves several physical and chemical phenomena that are difficult to identify and appreciate at low concentrations.

In discussing failure rate data for glove box components and cleanup systems, L. C. Cadwallader (United States) drew on experience from the Los Alamos National Laboratory Tritium Systems Test Assembly (TSTA) and compared them to fission facility experiences. Cooperation between classified and unclassified tritium handling facilities to broaden the data base would benefit the entire fusion community. Glove box confinement and tritium cleanup are important for future experiments that may contain kilograms of tritium.

P. J. Allsop (Canada) demonstrated that HTO behaves as an independent water species on molecular sieve dryers. These components are crucial to any large-scale detritiation system at the current state of the art of confinement barriers. Without due account, this phenomenon can bias the anticipated performance.

J. M. Miller (Canada) argued that tritium sorption in construction materials is significant and can comprise a significant fraction of the chronic emission. Adsorption-desorption rates and surface contamination levels of tritium on stainless steel have been measured by W. T. Shmayda. Tritium labeled organics are an unexpected component of the airborne tritium concentration, as shown by the presentation of Y. Belot (France). Their contribution to the body burden is currently unknown.

R. V. Carlson (United States) summarized the operational experiences and tritium safety at the TSTA, highlighting the performance of systems and typical failure mechanisms. One noteworthy avenue for tritium mobility is stainless steel containment breach by corrosion in the presence of highly tritiated water. Regulatory authorities in the United States are imposing more and more stringent quality assurance/quality control procedures, including extensive personnel training, in an effort to improve operational safety. Another regulatory issue arising in tritium laboratory operations is the accounting of tritium and inventory control for safeguards purposes.

S. Ciattaglia (Italy) reported on preliminary operational radiation exposure estimates for NET/ITER tritium systems. More design and operations details will be needed for accurate exposure quantifications.

ACCIDENT ANALYSIS: Y. SEKI, CHAIR

This session consisted of five papers treating different aspects of fusion reactor safety analysis. H. Th. Klippel (The Netherlands) gave NET/ITER analysis results for three exvessel LOCAs, two in-vessel LOCAs, and three LOFAs using the RELAP5/MOD3 thermal-hydraulic system analysis code. The results of the analyses indicate that a loss of forced coolant flow through the first wall rapidly caused dryout in the first-wall cooling pipes. If plasma burn continues, melting in the first wall starts within ~130 s after dryout.

M. Ogawa (Japan) described basic experiments related to the loss of vacuum event in a fusion experimental reactor. Experiments were carried out to obtain the exchange flow rate and the rate constant of carbon monoxide chemical reactions. These experimental results were compared with the existing correlations. Inclusion of activation product dust behavior is suggested.

R. Blomquist (Sweden) gave parametric analysis results of pressure transients in NET building compartments under LOCA conditions. Pressure buildup was estimated in the ring header room of NET following a guillotine break in a 390-mm ring header. The relations between compartment free volume, peak compartment pressure, loop data, and pressure suppression arrangement are summarized in a plot.

Some reference accident sequences of NET/ITER tritium systems were described by S. Ciattaglia (Italy). Failures that could give rise to the release of tritium, formation and ignition of oxygen-hydrogen mixtures, or containment pressure transients were examined.

C. F. Forrest (Canada) described two large-scale test facilities at the Stern Laboratory available for the study of thermofluid accidents in fusion reactors. Both facilities are being used to provide experimental data for safety code verification on flashing water jets in fission reactor containments.

SAFETY ASSESSMENT: K. BRODEN, CHAIR

R. Meyder (Germany) discussed superconducting coil system safety analysis with the MAGS code. Stored magnetic energy in future experiments is ~100 GJ. A magnet quench can lead to high temperatures and stresses. The coolant manifold promotes a high quench propagation speed. The MAGS code is comprised of several codes that deal with specific aspects of coil behavior: electrical current density distribution, magnetic field distribution, heat propagation, helium coolant flow, boundary conditions between codes, and quench detection and propagation. The code has successfully predicted quench propagation phenomena from the Large Coil Test experiment. There are significant differences between the insulation temperature and the cable space temperature. Pressure and quench effects during inleakage of air or steam need to be studied in the future.

M. Saito (Japan) reported on the General Evaluation Methodology for Safety Analysis of Fusion Experiments, applied to the ITER conceptual design activity (CDA) reactor. The researchers considered 12 functions, 6 areas, 8 boundaries, and 4 interface boundaries. They selected 25 ITER design-basis events (events with frequencies $> 10^{-6}$ per year) and defined the corresponding safety requirements.

G. R. Longhurst (United States) discussed the use of the Tritium Plasma Experiment (TPE) to evaluate ITER PFC safety. The TPE is designed to achieve plasma parameters similar to those expected in the ITER divertor. Since the cost of fission power is largely due to the costs of compliance, it would be valuable for fusion reactors to be able to avoid many of those costs through careful design. The TPE will be able to study the performance of ITER PFC under bombardment by an energetic tritium plasma, to evaluate heat removal, surface erosion, tritium permeation and retention, and to simulate LOFA and LOCA events.

G. Cambi (Italy) described the probablistic safety assessment for the main accident scenarios associated with failures originating in the in-vessel plant area of NET. The researchers use functional fault and event trees to identify problem areas, do risk assessments, compare results with safety criteria, and provide feedback to the design. The accident frequencies were $<10^{-4}$/yr, and the doses were <0.1 Sv. The doses were due mainly to activation products in the primary coolant, mobilized by pressurization from a coolant line break. The Risk-Spectrum code will be used extensively in the future.

Yu. G. Prokofiev (Russian Federation) described safety studies in Russia. The Council on Safety Problems of Fusion Reactors, which considers safety standards and safety assurance procedures and plans related to R&D work, has produced several documents on fusion safety. These researchers are improving the accuracy of the relative biological effectiveness and quality factor for tritium. For a liquid-metal-cooled system, they find that the reliability is lower than required by ITER. Construction of a 14-MeV neutron irradiation facility should have high priority.

PANEL ON INTERNATIONAL ACTIVITIES: V. A. CHUYANOV, CHAIR; S. J. PIET, SUMMARY

V. A. Chuyanov, session chair [ITER Joint Central Team (JCT)], highlighted the importance of international activities to fusion and fusion safety. He stressed that in the past, fusion safety studies were mainly theoretical exercises, but they must now move into a more practical stage for ITER. Panel members then made introductory statements and later answered questions from the audience.

V. A. Chuyanov stated that his remarks were personal and informal, not a formal JCT position. Although it would be convenient to take the CDA concepts as a basis for the engineering design activities (EDA), this is not possible because of internal inconsistencies in the CDA concept, including artificial constraints on the machine size and vertical stability problems, and because of nonworkable elements, including the divertor, runaway electron protection, the first wall, and the blanket.

F. N. Flakus (IAEA) mentioned new International Basic Safety Standards for radiation protection being formulated by a group of international agencies. The draft may be finalized at a meeting in December 1993.

G. R. Nardella [U.S. Department of Energy (DOE)], explained the IEA Cooperative Program on ESE Aspects of Fusion Power. Four countries (the European Communities, Japan, Canada, and the United States) signed the agreement in June 1992.

G. Saji (ITER-JCT) presented ITER objectives and general safety considerations. Safety issues arise from the fact that it is a true nuclear facility, much larger than existing machines like the Joint European Tokamak (JET), the Tokamak Fusion Test Reactor (TFTR), and JT-60U, with substantial fusion power that must be transported safely to a heat sink. The hazards are much lower than with fission.

A. C. Bell (JET) described the JET project along with some general lessons from licensing activities for tritium use.

P. Rocco (JRC, Ispra) commented on the activation advantages of vanadium alloys versus steels. The advantage ranges from nil to over two orders of magnitude, depending on the issue (early accident dose, maintenance contact dose, waste management decay heat, and waste management contact dose).

W. Gulden (NET) briefly mentioned the various European contributions to fusion safety: The Safety and Environment Program inside the CEC Technology Program, contributions to ITER, and Safety and Environmental Aspects of Fusion Power (SEAFP) study, the Low-Activation Materials (LAM) Program, and the Blanket Program's safety and environmental relevant work. SEAFP objectives include the following:

1. Avoid the need for public evacuation due to the worst accidents.
2. Use LAMs to the extent possible.
3. Use environmentally friendly neutron multipliers.
4. Reduce tritium inventories.
5. Adopt materials capable of resisting high neutron fluences.
6. Consider decommissioning.
7. Include reliable remote maintenance techniques.

ENVIRONMENTAL ASPECTS (A): W. GULDEN, CHAIR

Discussions in this session dealt with the determination of public doses due to releases during normal operation and accidents, including the important prerequisite of source term quantification. G. Cambi (Italy) described work on accidental source term quantification. Key models and correlations, such as chemical reactions of PFC materials with air and water, however, still need validation against experiments.

T. J. Dolan (United States) reported plans to monitor tritium around the TFTR experiment to help validate tritium environmental transport codes.

W. Raskob (Germany) described assessments of public doses due to unit releases of various isotopes representing first-wall erosion products, corrosion activation products, and HTO. Improvements are still needed in the areas of fusion-relevant isotopes, tritium transport in the food chain, and tritium ingestion doses.

C. Housiadas (CEC) discussed licensing requirements for the ETHEL facility regarding routine tritium emissions.

M. B. Kalinowski (Germany) surveyed tritium inventories, emissions, and dose estimates from many facilities. He suggested that the uncertainties of tritium source terms and resulting doses should be estimated and reported. S. K. Ho (United States) presented an integral safety approach reducing complex interactions to simple correlations. First results indicate the need for additional assessment, including thermal hydraulics in the coolant loops, thermal dynamics in rooms, chemical reactions, and aerosol transport.

ENVIRONMENTAL ASPECTS (B): A. C. BELL, CHAIR

B. C. J. Neil (Canada) discussed the derived emission limit (DEL) for HT from the Darlington tritium removal facility. They considered site specific factors, derived an emission-to-dose ratio for critical groups, and then set an appropriately conservative DEL, to ensure that the public dose limit will not be exceeded. Actual emissions are far below the DEL. Ingestion is the most significant pathway. Organically bound tritium levels have not yet been calculated.

R. E. Hollies (Canada) discussed the safety aspects of organic coolants, which can permit critical heat fluxes up to 10 MW/m^2. Problems with auto-oxidation of coolant leaks were solved during the early years of organically cooled fission reactor operation, with no fires during 15 subsequent years. The main problem is radiolytic decomposition amounting to ~1 tonne/h for an ITER-sized reactor, which could be reprocessed using a hydrocracker plant about $\frac{1}{40}$ the size of an oil refinery.

LICENSING: S. J. PIET, CHAIR

G. Sgalambro (Italy) observed trends toward passive safety, avoidance of evacuation and land contamination, and lower radiation protection requirements (reduced to 20 mSv/yr to workers and 1 mSv/yr to the public in the report ICRP-60, 1990). He proposed a 10-mSv goal for a worst-case fusion reactor accident because of future technology improvements, conservatism in accident analyses, and similarity to limits for new fission reactors. He proposed classifying systems and components as "safety relevant" if they are important to safety and "safety essential" if their failure would lead to exceeding the dose limits.

A. C. Bell (CEC-JET) discussed lessons from the JET experience. "As low as reasonably achievable" and "best practical technology" are required by regulators. Regulatory dose limits were lowered during the project. Because of public inquiry, delays, and associated costs, it is difficult to increase the inventory limit or dose limits that have already been set. He advocates setting inventory and effluent limits high enough to allow for operational flexibility. The need for "N-Stamp" (safety class) equipment should be avoided, if possible.

A. Natalizio (Canada) discussed lessons learned from fission plants. Regulations always become more stringent over time. Regulatory requirements change, and design targets become regulatory requirements. Public concern focuses on worst-case accidents and waste management. With small safety margins, the volume of safety analysis and supporting R&D is large. He advocates the setting of a safety objective for fusion experimental reactors that would require the same level of safety as for fission experimental reactors currently being designed or recently placed into operation. He believes that fusion reactors will have a significant safety and environmental advantage, and therefore, this advantage should be used to reduce the regulatory debate, for example, by demonstrating large safety margins. Low dose targets are desirable to demonstrate superiority to fission and to avoid future backfits, but higher dose targets are desirable to prevent future regulations from becoming too stringent and to contain costs.

WASTE MANAGEMENT: S. CIATTAGLIA, CHAIR

P. Rocco (CEC) discussed fusion reactor waste classification and management. Near surface burial is unlikely. He recommended classifying medium-level waste (MLW) as having contact dose rates between 2 and 20 mSv/h and heat generation rates between 1 and 10 W/m^3. Waste below or above this range would be low-level waste (LLW) or high-level waste (HLW). For an ideal fusion reactor, the first wall and divertor would be MLW, and everything else would be LLW. Use of LAMs is desirable to avoid generation of HLW. K. Broden (Sweden) discussed the quantification, treatment, packaging, and disposal (divided into shallow burial and geological disposal) of potential waste products from the NET experiment (70 kt with activity 70 PBq after 50 yr of interim storage). That waste could be accommodated in German repositories (Gorleben and Konrad) or in Swedish repositories (Subseabed Forsmark Repository under the sea and SFL-3).

W. T. Shmayda (Canada) discussed outgassing from tritiated stainless steel. During a furnace temperature ramp, the vapors emitted from the steel (mainly water) were trapped in bubblers then processed and analyzed. The thermal desorption spectra were reproducible but varied with service conditions (such as oil on samples) and storage times.

The generation of HLW should be avoided for public acceptance and lack of a repository at present. Each country should foresee a final repository. Plans for easy decommissioning and waste reduction should be initiated early in the design. We should exploit knowledge gained from fission reactor waste management and decommissioning.

CONCLUSIONS

The strong emphasis given to safety is a credit to the IAEA and ITER leadership. By the time of the next meeting in this series (in about 1996, possibly in Japan) the ITER EDA will have determined the major ITER parameters, and the safety analyses will be more refined. International cooperation, as exemplified by this meeting, will help guide the ITER project toward an experiment that can win public confidence. Optimization of safety may be crucial to the successful development of fusion power.

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SUMMARY OF THE 20TH EUROPEAN PHYSICAL SOCIETY CONFERENCE ON CONTROLLED FUSION AND PLASMA PHYSICS, LISBON, PORTUGAL, JULY 26–30, 1993

INTRODUCTION

The conference was organized by the Sociedade Portuguesa de Física and the Centro de Fusão Nuclear on behalf of the European Physical Society (EPS). It was attended by about 470 physicists from 40 countries. More than 100 participants were from outside Europe, in particular from the United States (50) and Japan (over 30). Also, a significant number of scientists (~30) came from Russia.

The program included 27 invited lectures and 370 contributed papers, which were either oral or poster presentations. The poster presentations are contained in *Europhysics Conference Abstracts*, Vol. 17C, Part III, Lisboa, July 1993 (J. A. Costa Cabral, M. E. Manso, F. M. Serra, and F. C. Schüller, Eds.). The invited lectures are expected to appear toward the end of 1993 in the journal *Plasma Physics and Controlled Fusion*.

The following topics were presented at the conference (the number of contributions is in parentheses):

1. tokamaks (83)
2. stellarators (25)
3. alternative confinement schemes (30)
4. plasma edge physics (73)
5. heating and current drive (55)
6. diagnostics (45)
7. inertial confinement fusion (ICF) (7)
8. general plasma theory (56).

FUSION REACTOR: NEW ITER AND ALTERNATIVE SOLUTIONS

A note of lasting controversy was introduced in the first presentation of the conference. In his invited talk, R. Parker, deputy director of International Thermonuclear Experimental Reactor (ITER)–Engineering Design Activities (EDA), Garching, outlined the partly new guidelines of the ITER task, namely,

1. safe extrapolation from present machines ("ITER must work")
2. reactor-relevant technology wherever possible
3. demonstration of economic fusion ("potential for attractive cost of electricity")
4. compared with fission, demonstration of easier waste disposal
5. simplicity of construction.

These highly ambitious requirements of ITER resulted in a substantial increase of the geometrical and technical machine parameters. Table I shows the major differences between the previous conceptual design [ITER–Conceptual Design Activities (CDA)] and the new values, together with those of a possible advanced tokamak reactor alternative.