MEETING REPORT

SECOND INTERNATIONAL ENERGY AGENCY WORKSHOP ON BERYLLIUM TECHNOLOGY FOR FUSION, JACKSON LAKE LODGE, WYOMING, SEPTEMBER 6-8, 1995

The Second International Energy Agency International Workshop on Beryllium Technology for Fusion was held September 6-8, 1995, at Jackson Lake Lodge, Wyoming. Forty-four participants, who represented Europe, Japan, the Russian Federation, and the United States including representatives from both government laboratories and private industry, took part in the workshop. Cochairs of the workshop were G. R. Longhurst [Idaho National Engineering Laboratory (INEL)] and M. Dalle Donne [Forschungszentrum Karlsruhe (FzK)]. This is the second workshop in this area conducted under the auspices of the International Energy Agency (IEA). The first was held at Karlsruhe, Germany, in October of 1993. Prior to IEA sponsorship, similar workshops were held at the INEL in 1988 and at Clearwater Beach, Florida, in 1991.

The workshop was divided into six technical sessions and a "town meeting" panel discussion. Technical sessions addressed the general topics of (a) thermomechanical properties; (b) manufacturing technologies; (c) radiation effects; (d) plasma/tritium interactions; (e) safety, applications, and design; and (f) joining and testing. Highlights of the various sessions follow.

In the thermomechanical properties session, chaired by A. Gervash (Efremov Research Institute), experience in the thermal fatigue of beryllium was discussed by E. B. Deksnis. Joint European Torus (JET) researchers found that castellations do not substantially improve the lifetime of plasma-facing components (PFCs) made of beryllium. Citing a lack of data on Poisson's ratio for modern grades of beryllium and on any thermomechanical properties of liquid beryllium, Deksnis noted that heat loadings of 10 to 15 MW/m^2 generated barrel-shaped distortions in the tiles, while 400 MJ/m^2 loadings in short times, such as generated by giant edge-localized modes, generated removal of 3 mm of beryllium in a single event on the JET divertor tiles. R. D. Watson [Sandia National Laboratories (SNL)] reviewed low-cycle thermal fatigue testing done at the SNL electron beam-heating test facility. Heat loads of 80 MW/m^2 for 0.06 s produce experimental results that agree well with modeling predictions. Researchers at SNL have tested a variety of materials and note that high-purity S-65C and DshG-200 beryllium are relatively resistant to cracking. M. Rödig described thermal shock testing of beryllium coupons in the JUDITH electron beam facility at Forschungszentrum Jülich (KFA). JUDITH is capable of 400 mA at 150 kV for times of 1 ms to steady state. Current rise time is 100 μs, and raster frequencies of 100 kHz with 100-mm deflections are possible. Water at 40 bars and a 10 ℓ/s flow rate provides active cooling. Researchers at KFA observed cratering in beryllium samples subjected to power levels in excess of 2.8 MW/m^2 and swelling at lower power levels. They also found that high-BeO-content grades such as the Russian TR-30 grade experienced more severe cracking than other grades. S. Abeln presented information on elevated-temperature stress-strain behavior of the beryllium powder product. In tests from room temperature to 1000°C and strain rates from 0.001 to 1 s^{-1}, researchers found that all grades of beryllium are strain-rate sensitive and that sensitivity increases with temperature. S. G. Torres presented a similar discussion for S-200E beryllium tested at temperatures ranging from 300 to 1100°C in both longitudinal and transverse directions at the quasi-static strain rate of 5.5×10^{-4} s^{-1}. Researchers at Lawrence Livermore National Laboratory (LLNL) observed smooth stress-strain curves without yield points or serrations, which were usually independent of the strain direction and the strength of which decreased with increasing temperature, as expected. J. Linke described a program for comparing high-heat-flux test results of beryllium plates brazed to copper heat sinks before and after being exposed to neutron irradiation. Tests of unirradiated samples showed emissivities varying from 0.40 to 0.43 due to deposits of copper from fabrication operations or coming from the electron gun used for heating. R. E. Guiniatoulline described results of analysis of beryllium-copper diffusion joints after high-heat-flux testing. Five-mm-thick tiles of TGP-56 beryllium and oxygen-free high-conductivity copper were diffusion bonded and subjected to thermal cycling tests in the electron beam test facility at SNL. Analysis of the bond layer showed distinct phases of Cu_2Be, $CuBe_2$, and CuBe along with the beryllium-copper solid solution. Cracking was observed to develop on cooldown of the specimens.

The session on manufacturing technologies was chaired by Dalle Donne. E. A. Lilley described the development of new beryllium-copper alloys with high thermal conductivity and high strength to be used as heat sink materials at the first wall and divertor. R. G. Castro reported on the structure, properties, and performance of plasma-sprayed beryllium. This method is well suited to produce in situ beryllium coatings on the first wall and to renew and repair coatings after plasma operation. Secondary additions of hydrogen and the use of transferred arc spraying increase the density of the coating and thus the thermal conductivity and improve the bonding of the coating to the underlying surface. Three papers dealt with the problem of bonding beryllium to copper, which is used as armor on PFCs. The commonly used silver brazing is not suited for PFCs because silver under neutron irradiation produces cadmium, which because of its relatively high vapor pressure could cause problems in the plasma chamber. D. M. Dombrowski (Brush Wellman, Inc.), representing D. J. Butler (Northwest Technical Industries), illustrated the results of using an explosion-bonding technique. Cracks formed in the beryllium perpendicular to the bond line. Further development is planned. Dombrowski then presented results of bonding beryllium to copper alloys using a Brush Wellman proprietary method. The bonding strength obtained so far reaches a level of almost 50% of that obtained with silver. H. Kawamura [Japan Atomic Energy Research Institute (JAERI)] reported on compatibility tests between hot-pressed beryllium and oxygen-free copper. J. E. Hanafee (LLNL) presented interesting results on the use of lasers to cut beryllium, beryllium alloys, and beryllium/beryllium oxide components and to weld structural grades of beryllium. Y. Y. Kurochkin ended this session by reporting on a new method for bonding beryllium suited to joining in large flat or curved panels.

The session on radiation effects was chaired by Hanafee. Dalle Donne discussed recent efforts to model neutron-induced swelling in beryllium. He noted that the most important factor in controlling the mechanical behavior of fast-neutron-irradiated beryllium is the impurity content, which can strongly affect both the surface tension and the creep strength of the material. F. Scaffidi-Argentina presented results of long-time annealing experiments with beryllium from SIBELIUS and from BR2. Beryllium irradiated to higher doses (0.8 to 3.9×10^{21} n/cm^2, $E > 1$ MeV) showed much faster tritium release kinetics than beryllium with lower doses, probably because of the greater brittleness of the high-dose material. I. B. Kupriyanov described a study in which special grades of beryllium designed to be resistant to irradiation damage were irradiated in the SM-2 reactor to a dose of 3.7×10^{21} n/cm^2, $E > 1$ MeV, at temperatures of 550 to 780°C. After the irradiation, the tensile strength and yield strength values of the best grades showed strength characteristics similar to unirradiated commercial grades. K. Tatenuma discussed reprocessing technology developments for irradiated beryllium. This approach involves heat treating beryllium under a halogen gas atmosphere that allows the beryllium to be separated by sublimation. Kawamura described a new facility intended for postirradiation examination of neutron-irradiated beryllium. Tests planned include tritium release experiments, thermal conductivity measurements, and mechanical strength testing. N. Sakamoto described the new Oarai hot-cell electron beam irradiating system. It features a 50-kW, 30-kV electron beam for conducting thermal shock tests on beryllium. Finally, I. V. Mazul discussed a concept of integrated-effects demonstration tests of beryllium-copper PFC mock-ups in the SM-2 fission reactor. Mock-up demonstration samples have been exposed to heat loads of 2 MW/m^2 with neutron fluences of 5×10^{20} n/cm^2.

In the plasma/tritium interactions session, chaired by Watson, seven papers on the general topic of plasma/surface interactions with beryllium were presented by Russian participants. B. N. Kolbasov presented work by S. N. Korshunov on beryllium self-sputtering yields at normal incidence up to 800°C. Up to 600°C, the maximum value, 0.32 atom/ion, was attained at 1.5-keV ion energy. At 800°C, the yield increased to 0.75 atom/ion. V. N. Chernikov (Institute of Physical Chemistry, Russian Academy of Sciences) presented research on gas swelling of beryllium from implanted 2- and 10-keV deuterium ions at 300, 500, and 700 K. Gas losses from specimens implanted at 300 K are due to a concentration-induced deuterium migration from the damaged matrix containing pressurized bubbles. At high fluences, interconnected labyrinth channels are formed, leading to experimentally observed abrupt gas re-emission. Model predictions of hydrogen implantation, bubble formation, and gas release by S. L. Kanashenko et al. were presented. Thermal desorption measurements of deuterium and helium implanted at 300 K into beryllium were conducted by Chernikov and studied by thermal desorption spectroscopy, transmission electron microscopy (TEM), and scanning electron microscopy. V. Kh. Alimov studied the depth profile of deuterium ions implanted into beryllium at 9 keV at 300 and 700 K. Secondary ion mass spectrometry (SIMS), RGA, and TEM methods were used. The high concentrations of atomic deuterium could be explained by (a) the trapping of deuterium atoms in vacancy-type defects and (b) the formation of beryllium hydroxide as a result of the reaction deuterium atoms with BeO. Studies of hydrogen implanted into beryllium were done by M. I. Guseva and measured using SIMS and the elastic recoil detection technique. Practically all of the hydrogen atoms are located in bubbles in molecular form (H_2), and only a small part (1.4%) is in the solution in the narrow surface layer. N. N. Vasiliev presented plans for using MAGRAS, a magnetron-type high-sputtering device with electrical discharge burning in crossed electrical and magnetic fields with a water-cooled beryllium target as the cathode. MAGRAS has hydrogen or argon ion energy up to 600 eV, a heat flux on target up to 500 W/cm^2, and steady-state operation. MAGRAS will be used to study beryllium dust formation for the the International Thermonuclear Experimental Reactor (ITER) safety program.

The session on safety, applications, and design was led by Kawamura. M. A. Pick (JET) gave a very interesting and enlightening presentation on the practical aspects of tokamak operations with beryllium. A large staff and extensive facilities are needed to support the required processes for health and safety. These may not yet be adequately considered in the ITER project. Kolbasov summarized work by Yu. A. Ponomarev et al. on the development of real-time beryllium air concentration monitors in Russia. One approach uses a small plutonium source to activate beryllium on a filter paper, which is then counted to determine activity. The other approach uses an electric spark to fluoresce beryllium on the filter, which is then analyzed spectrally. V. Barabash discussed beryllium application in the ITER

PFC design and research and development programs. He discussed a number of critical issues that must be resolved. M. C. Billone presented recommended design correlations for S-65 beryllium. These can be used for beryllium produced by vacuum hot pressing, cold pressing with sintering, and hot isostatic pressing. Mazul addressed using physical vapor deposition coatings as armor for the ITER divertor target. Three possible applications were considered: in situ repair of eroded tiles, joining of beryllium to copper, and initial fabrication of shapes for components.

The joining and testing session (originally called Thermomechanical Properties II) was chaired by Dombrowski. This session primarily focused on beryllium technology for divertor manufacture. Three of the papers concentrated on bonding of beryllium to copper, an area critical for application of beryllium armor in ITER. One paper discussed the manufacture of monolithic beryllium divertor prototypes. The final paper discussed beryllium surface reactivity and hydrogen retention experiments. Various beryllium-to-copper-bonding approaches have been initiated in the last year, many of which were quite novel. Some very promising results have been achieved. Gervash described recent experimental results for a wide range of bonding techniques: silver-based brazing, diffusion bonding, joint rolling, explosive bonding, and hot isostatic pressing. The most successful experiments were made with joint rolling and hot isostatic pressing, although silver-based brazing and diffusion bonding had reasonable results. A tensile-type test and shear test were used for preliminary evaluation of bond strengths; this is one of the first times that both types of tests were performed on beryllium-to-copper bonds. Bond strengths determined by a tensile-type test were as high as 212 MPa at 350°C. Shear strengths as high as 160 MPa were measured at 350°C. The authors plan to construct a beryllium-to-copper joint with cadmium in it. They will then test the fusion community hypothesis that cadmium formed by neutron irradiation from silver-based brazing will leak out of the joint during elevated-temperature operation. B. Odegard summarized beryllium-to-copper-bonding efforts in the United States. He described diffusion-barrier-based brazing, diffusion bonding, electroplating copper onto beryllium, and hot isostatic pressing. Two processes will utilize complex layers with explosively bonded diffusion barriers. Sakamoto reported property measurements on sintered compacts of beryllium and copper powder. These results will be used in JAERI experiments investigating a functional-gradient-layer technique for bonding beryllium to copper. Based on thermal conductivity and coefficient-of-thermal-expansion properties, it was concluded that a 50/50 vol% beryllium-copper mixture is the lowest copper concentration layer that should be used in a functional gradient structure on the beryllium side of the bond. Vasiliev described manufacture and quality assurance testing on monolithic beryllium hypervapotrons recently tested at JET. Swirl-tape-cooling technology was contrasted with the hypervapotron concept. Preliminary high-heat-flux testing was done with electron beam equipment. The high-heat-flux testing was followed by nondestructive evaluation using acoustic methods. V. P. Shestakov presented results on the effect of deuterium-hydrogen glow discharge on the surface chemistry of beryllium surfaces. Auger analysis was used to investigate samples exposed to temperatures up to 1000 K. Significant carbon coverage was observed. Shestakov also presented plans for the study of hydrogen retention in beryllium after neutron irradiation. The Inesh-3 equipment for making those measurements was described.

A town meeting-type panel discussion was led by Longhurst. Watson, Pick, Chernikov, Dalle Donne, and Kawamura were panelists. The theme of the discussion was "how shall we prioritize efforts in beryllium research in light of current budget restrictions?" Watson initiated the discussion by presenting results of a beryllium panel convened in the United States to examine the status of knowledge and ongoing activities in support of beryllium usage in ITER. Among the findings of that panel were

1. The estimated cost for qualifying beryllium for use in ITER was $229 million.

2. Only partial validation of beryllium for ITER construction is currently possible because of time and budgetary limitations.

3. While the database for mechanical properties at room temperature of industrial beryllium grades is generally complete, the database is incomplete for elevated temperatures (up to 600°C), and almost nothing is available for plasma-sprayed beryllium.

4. Thermomechanical properties of beryllium are poorly understood at elevated temperatures.

5. Test data are needed on beryllium irradiated in fast-flux reactors at elevated temperatures.

6. Interactions of beryllium with hydrogen isotopes, especially tritium, are not well understood, and additional research is needed to evaluate hazards of tritium inventory and release in beryllium PFCs.

7. Joining of beryllium to substrates requires considerable development, especially in brazing using nonactivating materials.

8. There is a need for rapid air concentration measurement and better techniques for screening personnel sensitivity to beryllium.

Pick indicated that beryllium had many salutary effects as a plasma-facing material, but he prefers carbon-carbon fiber composite materials for the divertor. Tritium retention in all these materials is still an important issue, and it is not clear how the combination of materials that will result from plasma-induced redistribution of beryllium and carbon will respond in this regard. In a later discussion, Pick also supported the need for a reliable, accepted, inexpensive real-time measurement capability for beryllium air concentrations. Chernikov reviewed the many concerns that he has for beryllium in ITER. He also prefers a carbon-carbon fiber composite for the divertor because of its better performance in erosion and heat transfer. Dalle Donne reviewed the problem of neutron irradiation effects on beryllium. In the ITER basic performance phase, the beryllium volume swelling should not be very high (<2%). Also, the quantities of tritium produced would be small, and the tritium release should occur very slowly. However, the neutron-irradiation-induced embrittlement of beryllium could pose a problem. For the ITER extended performance phase, beryllium swelling could be large; i.e., 10% or more. Experiments at high temperatures (400 to 700°C) up to fluences of 5×10^{22} n/cm^2

($E > 1$ MeV) are urgently needed. These experiments can be performed in reasonable times only in fast fission reactors. Kawamura, the final panel member, voiced agreement with the comments made by the other panelists and echoed the concern that there is yet much to be learned for beryllium to be successfully used in ITER. A number of comments were received from the floor. L. A. Jacobson expressed concern that the information flow between designers and material scientists may not be as efficient as it should be. G. J. London reminded participants that there still is no large-scale demonstration of plasma-spray capability, and this will have to be achieved before that technology can be considered viable for ITER.

In summary, the workshop was very successful. The main objectives of bringing key members of the fusion beryllium community together was certainly met. There were 44 participants registered and 35 papers presented. Considerable work has been done since the last workshop, but there are still major research needs by the community. This was the first beryllium workshop that included researchers from the Russian Federation, and they added greatly to the success of this workshop. It was the consensus of the participants that another beryllium workshop should be held in another 2 yr. The participants agreed that holding the workshop in conjunction with another fusion or materials meeting makes sense in order to conserve travel expenses. The organizers will pursue such an opportunity and make the community aware of plans as they develop. The organizers also thank the staff of Jackson Lake Lodge for its fine support, which helped make the event a success.

Glen R. Longhurst

Fusion Safety Program
Idaho National Engineering Laboratory
P.O. Box 1625
Idaho Falls, Idaho 83415

A. Gervash

D.V. Efremov Scientific Research Institute
of Electrophysical Apparatus
18931 St. Petersburg
Russia

M. Dalle Donne

Forschungszentrum Karlsruhe-INR
Postfach 3540, D-76021 Karlsruhe 1
Germany

J. E. Hanafee

Lawrence Livermore National Laboratory
P.O. Box 808, L-481
Livermore, California 94551-9900

R. D. Watson

Sandia National Laboratories at Albuquerque
P.O. Box 5800
Albuquerque, New Mexico 87123

H. Kawamura

JAERI Oarai Research Establishment
Oarai-machi, Higashi, Ibaraki-gun, Ibaraki-ken, 311-13
Japan

D. M. Dombrowski

Brush Wellman, Inc.
17876 St. Clair Avenue
Cleveland, Ohio 44110

October 10, 1995