TENSILE AND ELECTRICAL PROPERTIES OF COPPER ALLOYS IRRADIATED IN A FISSION REACTOR – S. A. Fabritsiev (D.V. Efremov Institute, St.Petersburg, Russia), A. S. Pokrovsky (Scientific Research Institute of Atomic Reactors, Dimitrovgrad, Russia), S. J. Zinkle and A. F. Rowcliffe (Oak Ridge National Laboratory), D. J. Edwards and F. A. Garner (Pacific Northwest National Laboratory), V. A. Sandakov (Scientific Research Institute of Atomic Reactors, Dimitrovgrad, Russia), B. N. Singh (Risø National Laboratory, Roskilde, Denmark) and V.R. Barabash. (ITER Joint Central Team, Garching, Germany)

OBJECTIVE

The objective of this report is to summarize the postirradiation tensile and electrical resistivity data on copper and copper alloys irradiated in the SM-2 reactor as part of a US-RF collaborative experiment. This study provides some of the data needed for the ITER research and development Task T213.

SUMMARY

Postirradiation electrical resistivity and tensile measurements have been completed on pure copper and copper alloy sheet tensile specimens irradiated in the SM-2 reactor to doses of ~0.5 to 5 dpa and temperatures between ~80 and 400°C. Considerable radiation hardening and accompanying embrittlement was observed in all of the specimens at irradiation temperatures below 200°C. The radiation-induced electrical conductivity degradation consisted of two main components: solid transmutation effects and radiation damage (defect cluster and particle dissolution) effects. The radiation damage component was nearly constant for the doses in this study, with a value of ~1.2 nΩ-m for pure copper and ~1.6 nΩ-m for dispersion strengthened copper irradiated at ~100°C. The solid transmutation component was proportional to the thermal neutron fluence, and became larger than the radiation damage component for fluences larger than ~5 × 10^{24} n/m^2. The radiation hardening and electrical conductivity degradation decreased with increasing irradiation temperature, and became negligible for temperatures above ~300°C.

PROGRESS AND STATUS

Introduction

This report summarizes in tabular form all of the tensile and electrical resistivity measurements that have been made on pure copper and copper alloy sheet tensile specimens irradiated in the SM-2 reactor as part of a U.S.-RF collaborative experiment. Information concerning the experimental details and some of the initial results have been presented in previous progress reports [1,2]. Two papers summarizing many of the results will be published in the proceedings of the 7th International Conference on Fusion Reactor Materials held in Obninsk, Russia, in September 1995 [3,4]. A paper on the high-temperature helium embrittlement behavior of copper and dispersion-strengthened copper alloys has also been prepared [5].

The materials were irradiated in the form of sheet tensile specimens and transmission electron microscopy disks for about 45 days in the Channel 4 and core positions of the water-cooled SM-2 reactor in Dimitrovgrad, Russia. Some of the specimens in the Channel 4 position were irradiated inside a 1.5 mm Cd shroud in order to reduce the thermal neutron flux. The irradiation produced damage levels of 0.5 to 1.6 dpa in the Channel 4 position, and 3.5 to 5 dpa in the Core position. Typical fast (E>0.1 MeV) and thermal neutron fluences were $1.4 \times 10^{25}/m^2$ and 0.9×10^{25} n/m^2, respectively in the unshielded regions of Channel 4, $1.4 \times 10^{25}/m^2$ and 0.2×10^{25} n/m^2, respectively in the Cd-shielded regions of Channel 4, and $7.2 \times 10^{25}/m^2$ and 1.0×10^{25} n/m^2, respectively in the Core positions. Specimens were irradiated at temperatures of ~100 and ~200°C in Channel 4, and ~100, ~240 and ~350°C in the Core.

Results and Discussion

Tables 1-11 summarize the tensile data obtained on the irradiated materials. All of the tensile measurements were performed in vacuum (~10^{-4} Pa) at a temperature close to the irradiation temperature. Most of the STS sheet tensile specimens had gage dimensions of 11 × 3.5 × 0.25 mm. Some of the STS specimens had a thickness of 0.5 mm. The LTS sheet tensile specimens had gage dimensions of 30 × 4 × 1 mm. The tensile tests were performed at a cross-head speed of ~1 mm/minute, which produced initial strain rates of 5.6×10^{-4}/s and 1.5×10^{-3}/s in the LTS and STS specimens, respectively.

Considerable radiation hardening was observed in all specimens at irradiation temperatures below 200°C. The irradiated yield strength in specimens strengthened by dispersoids or cold-working was comparable for the Cd-shielded and unshielded regions of Channel 4, indicating that these changes in neutron spectrum had a relatively minor effect [4]. In contrast, significantly higher levels of strength were observed in pure copper and Cu-B specimens irradiated in the unshielded regions of Channel 4 compared to Cd-shielded regions. By comparing the tensile results in Tables 1-11 with literature data, it is concluded that severe radiation embrittlement (uniform elongation <1%) occurs in copper alloys irradiated at temperatures ≤100°C for doses above ~0.01 to 0.1 dpa [3,4]. On the other hand, irradiation at temperatures above 150-180°C causes only moderate embrittlement for doses up to ~5 dpa.

The present tensile results demonstrate that low temperature radiation embrittlement may have a considerable impact on the use of high-strength copper alloys for ITER structural applications. Low temperature radiation embrittlement is found to be very sensitive to the irradiation temperature. For precipitation hardened and dispersion strengthened copper alloys, 150°C appears to be a critical temperature for manifestation of embrittlement. The high-strength alloys embrittle dramatically at irradiation temperatures below 150°C, with uniform and total elongations close to zero. The plastic flow at the deformation zone is unstable under these irradiation conditions. At irradiation temperatures above 150-180°C, the precipitation hardened and dispersion strengthened alloys have a satisfactory level of ductility, with irradiated elongations in the range of 50 to 90% of the unirradiated values. It is recommended that the minimum operating temperature for copper alloys intended for structural applications in fusion energy systems should be 180°C, unless uniform elongations <1% can be accomodated in the design.

Tables 12-20 summarize the unirradiated and irradiated room temperature electrical resistivity data. The electrical resistivity measurements were performed using standard 4-point probe techniques on the STS and LTS sheet tensile specimens (before and after irradiation) prior to postirradiation tensile testing. The accuracy in the resistivity measurements was ±0.3 nΩ-m (±0.03 μΩ-cm). The electrical resistivity data could be separated into two components, a solid transmutation component $\Delta\rho_{tr}$ which was proportional to thermal neutron fluence and a radiation defect component $\Delta\rho_{rd}$ which was nearly independent of dose at damage levels >0.5 dpa [4]. The saturation value for $\Delta\rho_{rd}$ was ~1.2 nΩ-m for pure copper and ~1.6 nΩ-m for the DS copper alloys irradiated at 100°C in positions with a fast-to-thermal neutron flux ratio of 5. Further discussion of the tensile and electrical properties obtained in this study are given in refs. 3,4.

The $\Delta\rho_{tr}$ component depends primarily on the thermal neutron flux. It is determined by the transmutation rate (mainly Ni and Zn solutes) and has a weak dependence on the fast neutron flux and irradiation temperature. The $\Delta\rho_{rd}$ component is determined mainly by the level of radiation damage (which approaches a saturation level during irradiation at low temperatures for damage levels above ~0.1 dpa), and reduces practically to zero as the irradiation temperature approaches 250°C. The increase in $\Delta\rho_{rd}$ correlates with the increase in yield strength, $\Delta\sigma_{Y irr}$, since both of these properties are determined by the density of defect clusters. A comparison of the dose dependence of $\Delta\rho_{rd}$ for samples irradiated with and without Cd shielding in Channel 4 indicates that irradiation with thermal neutrons results in an increase in $\Delta\rho_{rd}$ (i.e., defect density), probably because of some effect of Ni and Zn on dislocation loop formation and the development of defect complexes. The magnitude of $\Delta\rho_{rd}$ appears to be ~30% higher in the DS copper alloys compared to pure copper, most likely because of partial dissolution of the oxide particles. Transmission electron microscopy will be performed on the irradiated materials to provide further information about the effect of neutron spectrum on the microstructural evolution in pure copper and the copper alloys.

Since the electrical (and to a lesser extent, tensile) properties of copper alloys are influenced by the solid transmutation generation rate, fusion engineering data on irradiated copper alloys should preferably be obtained in facilities where the solid transmutation rate is comparable to the fusion condition. The Core position of the SM-2 reactor produces fusion-relevant solid transmutation rates in copper, but most other mixed spectrum reactors may require spectral tailoring to reduce the Ni and Zn transmutation rates to fusion-relevant levels [4].

Future Work

Transmission electron microscopy and immersion density measurements will be performed on the irradiated TEM disks. In addition, the microstructure of the strained gage regions of several broken tensile specimens will be examined by TEM to provide further insight into the mechanisms responsible for the poor work hardening behavior and low ductility of copper alloys irradiated at temperatures below 180°C. The He content of several irradiated TEM disks will be measured and compared to measurements performed in Russia as part of a round-robin testing program.

Acknowledgements

Research sponsored in part by the Office of Fusion Energy, U.S. Department of Energy under contracts DE-AC05-96OR22464 with Lockheed Martin Energy Research Corp and DE-AC06-76RLO 1830 with Battelle Memorial Institute.

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Table 1. Tensile Properties of Copper and Cu Alloys Irradiated in the Lower Part of the SMT-1 Capsule (LTS geometry, Cd-shielded region)

Alloy, heat treatment	Capsule	Floor	Fluence (Φt), 10^{20} n/cm^2		T_{irr}, °C	T_{test}, °C	σ_y, MPa	σ_u, MPa	δ_{un}, %	δ_{to}, %
			E>0.1 MeV	E<0.68 eV						
Cu pure 350C, 1h	6	1	8.6	2.27	85	100	268	269	0.6	4.4
						400	75	113	10.6	24.0
Cu + B1 350C, 1h	5	1	12.1	2.27	85	100	381	394	0.25	0.6
						400	263	263	0.12	1.3
Cu + B2 350C, 1h	5	2	17.8	2.92	88	100	411	413	0.16	1.8
						400	316	322	0.33	2.3
MAGT-0.2 as wrought	6	2	12.7	2.92	88	100	538	544	0.3	0.6
						400	262	263	0.3	0.6
Cu 99.999% as wrought	3	2	15.3	2.93	88	100	350	388	0.42	1.9
Cu 99.999% 550°C, 2h	4	2	17.8	2.92	88	100	187	216	12.0	16.4
GlidCop Al15+B as wrought	1	2	17.8	2.92	88	100	385	391	0.38	0.5
GlidCop Al15 + B, induction brazed	2	2	12.7	2.92	88	100	322	322	0	0
						400	163	163	0.16	0.33
GlidCop Al25 (no B) as wrought	1	1	12.1	2.27	85	100	520	538	0.4	2.5
						400	195	200	0.58	7.3
GlidCop Al25+B as wrought	2	1	8.6	2.92	88	100	519	519	0.24	0.24
GlidCop Al25 (no B) 20% c. w.	3	1	10.3	2.27	85	100	458	469	0.41	3.9
						400	211	228	0.5	9.0
GlidCop Al25 + B 20% c. w.	4	1	12.1	2.27	85	100	420	447	0.5	0.67
						400	273	280	0.67	3.8

Table 2. Tensile properties of copper and Cu alloys irradiated in the upper part of the SMT-1 capsule (LTS geometry, unshielded region)

Alloy, heat treatment	Capsule	Floor	Fluence (Φt), 10^{21} n/cm^2		T_{irr}, °C	T_{test}, °C	σ_y MPa	σ_u MPa	δ_u %	δ_{tot} %
			E>0.1 MeV	E<0.68 eV						
Cu pure c. w.	3	1	1.85	1.4	88	100	444	44	0.2	1.5
						400	282	284	0.33	2.3
Cu pure 350C, 1h	5	3	1.3	0.97	85	100	302	319	0.5	3.5
	1	1	1.42	1.4	88	100	319	319	0.16	3.8
						400	119	124	9.1	20.0
Cu + B1 350C, 1h	2	3	1.3	0.97	85	100	418	419	0.3	2.4
						400	204	206	0.25	2.0
	2	1	2.27	1.4	88	100	393	413	0.33	2.7
Cu + B2 350C, 1h	1	3	0.82	0.97	85	100	494	497	0.1	1.0
						400	256	263	0.33	1.8
Cu + B1 c. w.	2	2	1.9	1.24	88	100	506	506	0.16	0.16
						400	193	200	0.9	4.0
Cu - Cr - Zr I	5	1	2.27	1.4	88	100	413	413	0.1	0.1
						400	348	350	0.25	0.5
Cu - Mo as wrought	1	2	1.2	1.24	88	100	199	206	0.33	1.4
						400	196	203	0.6	1.5
Cu - Be						100	550	575	3.0	5.0
	4	2	1.2	1.24	88	100	766	894	4.1	6.5
						400	516	663	5.7	6.0
MAGT-0.2 as wrought	4	1	1.42	1.4	88	100	549	550	0.3	0.6
						400	360	360	0.16	0.5
	4	3	0.82	0.97	85	100	519	519	0.1	0.1

Table 3. Tensile properties of copper and Cu alloys irradiated in the lower part of the SMT-1 capsule (STS geometry, Cd-shielded region)

Alloy, heat treatment	Capsule	Floor	Fluence (Φt), 10^{20} n/cm^2		T_{irr}, °C	T_{test}, °C	σ_y, MPa	σ_u, MPa	δ_{un}, %	δ_{tot}, %
			E>0.1 MeV	E<0.68 eV						
GlidCop AL25 + B as wrought	1	2	10.7	2.63	82	100	473	475	0.2	0.3
					82	100	474	485	0.8	0.8
Cu 99.999 ann 950°C 0.5 h	1	1	8	2.19	76	100	227	254	12.8	12.8
GlidCop Al25 (no B) as wrought	1	2	10.7	2.63	82	100	500	526	1.1	1.1
GlidCop Al25 (no B) 20% c.w.	2	2	15	2.63	82	100	515	526	0.7	0.7
Cu 99.999 ann 550°C	1	1	8	2.19	76	100	238	245	16.0	21.3
Cu 99.999, 80% c.w.	1	2	10.7	2.63	82	100	442	445	0.4	0.4
Cu pure c.w.	4	2	10.7	2.63	82	100	426	484	1.1	2.2
Cu pure ann. 350°C, 1 h	5	1	8	2.19	76	100	234	250	5.0	10.5
	5	1	8	2.19	76	100	241	250	8.5	8.5
	3	3	18.3	3.0	87	100	241	258	12.0	15.0
Cu + B2 c.w.	5	3	13.1	3.0	80	100	475	485	0.4	0.4
	5	3	17.1	3.0	80	100	457	473	0.6	0.6
Cu pure II c.w.	5	2	10.7	2.63	82	100	400	410	1.2	1.6
MAGT 0.2 as wrought	3	2	15	2.63	82	100	478	498	0.8	0.8
Cu 99.999 400°C 1h	1	1	8	2.19	76	100	217	254	13.7	14.3
GlidCop Al25 + B 20% c.w.	2	2	15	2.63	82	100	505	551	0.35	0.35
GlidCop Al15 + B as wrought	2	1	11.2	2.19	76	100	473	475	0.2	0.3
Cu+B1 c.w.	4	1	8	2.19	76	100	485	502	1.9	2.3

Table 4. Tensile properties of copper and Cu alloys irradiated in the upper part of the SMT-1 capsule (STS geometry, unshielded region)

Alloy, heat treatment	Capsule	Floor	Fluence (Φt), 10^{21} n/cm^2		T_{irr}, °C	T_{test}, °C	σ_y, MPa	σ_u, MPa	δ_{un}, %	δ_{tot}, %
			E>0.1 MeV	E<0.68 eV						
MAGT-0.2 as wrought	2	3	1.2	1.25	86	100	529	564	0.5	0.5
	2	2	1.36	1.36	89	100	548	564	0.2	0.2
Cu pure ann 350°C, 1hr	1	1	2.3	1.42	80	100	245	262	14.7	16.0
Cu + B3 as wrought	3	4	1.57	1.1	81	100	179	296	2.5	3.2
	1	2	2.17	1.36	89	100	197	376	2.7	4.6
Cu + B1 c.w.	4	3	1.2	1.25	80	100	388	403	2.4	3.4
Cu-Mo-B as wrought	1	3	1.91	1.25	86	100	633	695	1.1	5.6
	1	3	1.91	1.25	86	100	432	461	0.7	0.9
Cu + B2 c.w.	3	3	1.91	1.25	86	100	470	472	0.3	0.3
	3	2	2.17	1.36	89	100	430	469		
	3	2	2.17	1.36	89	100	412	412	0.1	0.1
Cu + B2 ann	4	1	1.45	1.42	93	100	317	329	0.65	2.0
					80	100	341	349	1.2	6.5
	4	5	0.73	0.9	75	100	308	317	1.0	4.3
	4	1	1.45	1.42	93	100	275	280	0.6	2.6
Cu pure II c.w.	9	4	0.99	1.1	81	100	482	488	0.2	0.3
Cu pure c.w.	2	1	1.45	1.42	93	100	398	402	0.3	0.45

Table 5. Tensile properties of copper and Cu alloys irradiated in the lower part of the SMT-2 capsule (LTS geometry, Cd-shielded region)

Alloy, heat treatment	Cap-sule	Floor	Fluence (Φt), 10^{20} n/cm^2		T_{irr}, °C	T_{test}, °C	σ_y, MPa	σ_u, MPa	δ_{un}, %	δ_{tot}, %
			E>0.1 MeV	E<0.68 eV						
Cu + B2 350C, 1h	5	1	12	2.66	196	200	233	240	0.3	3.2
MAGT-0.2 as wrought	5	2	17.9	3.4	196	200	235	242	1.3	2.7
	5	2	17.9	3.4	196	200	224	228	1.1	3.7
Cu 99.999% as wrought	3	2	14.9	3.4	196	200	126	155	19.7	23.0
Cu 99.999% 550C, 2h	4	2	14.9	3.4	196	200	104	144	12.7	17.8
GlidCop Al15 + B as wrought	2	1	10	2.66	176	200	244	255	0.7	7.8
GlidCop Al15 + B, ind. brazed	2	2	14.9	3.4	196	200	290	302	0.33	4.1
GlidCop Al25 (no B) as wrought	1	1	10	2.66	176	200	275	288	0.5	6.0
GlidCop Al25 + B as wrought	2	1	10	2.66	176	200	287	300	0.6	3.8
GlidCop Al25 (no B) 20% c. w.	3	1	10	2.66	176	200	338	350	0.5	4.0
GlidCop Al25 + B 20% c. w.	4	1	10	2.66	176	200	255	265	0.5	1.5

Table 6. Tensile properties of copper and Cu alloys irradiated in the upper part of the SMT-2 capsule (LTS geometry, unshielded region)

Alloy, heat treatment	Cap-sule	Floor	Fluence (Φt), 10^{21} n/cm^2		T_{irr}, °C	T_{test}, °C	σ_y, MPa	σ_u, MPa	δ_{un}, %	δ_{tot}, %
			E>0.1 MeV	E<0.68 eV						
Cu pure c. w.	2	1	2.65	1.64	207	200	79	118	27.0	30.3
Cu pure 350C, 1h	1	1	1.66	1.64	207	200	165	175	8.8	13.3
Cu + B1 350C, 1h	3	2	1.4	1.45	198	200	94	130	24.2	35.3
Cu + B2 350C, 1h	1	2	1.4	1.45	198	200	218	241	7.5	13.2
Cu + B1 c. w.	2	2	2.22	1.45	198	200	105	177	12.5	24.3
Cu - Cr - Zr I	2	3	1.52	1.13	180	200	305	318	0.1	2.8
Cu - Cr - Zr II	3	3	0.96	1.13	180	200	228	238	0.83	2.0
	3	3	0.96	1.13	180	200	200	200	1.0	1.0
Cu - Be	4	3	1.52	1.13	180	200	704	818	7.0	7.7
MAGT-0.2 as wrought	3	1	1.66	1.64	207	200	255	263	0.3	3.2
Cu-Si-Ni-Cr as wrought	1	3	0.96	1.13	180	200	560	583	0.5	1.2
MAGT-0.05 as wrought	4	2	2.22	1.45	198	200	92	162	18.5	27.2

Table 7. Tensile properties of copper and Cu alloys irradiated in the lower part of the SMT-2 capsule (STS geometry, Cd-shielded region)

Alloy, heat treatment	Cap-sule	Floor	Fluence (Φt), 10^{20} n/cm²		T_{irr}, °C	T_{test}, °C	σ_y, MPa	σ_u, MPa	δ_{un}, %	δ_{tot}, %
			E>0.1 MeV	E<0.68 eV						
Cu pure II c.w.	7	3	21.4	3.51	178	200	134	148	26.7	27.0
Cu pure c.w.	7	3	21.4	3.51	178	200	203	214	9.2	11.7
Cu pure, as wrought	6	3	21.4	3.51	178	200	246	274	17.1	18
Cu-0.2 Al, as wrought	7	3	21.4	3.51	178	200	174	294	0.7	1.0
Cu-0.16Zr	6	3	21.4	3.51	178	200	270	277	0.5	0.6
Cu pure ann 350°C	8	3	21.4	3.51	178	200	164	175	5.0	6.3
Cu + B1 350°	8	3	21.4	3.51	178	200	175	186	6.4	8.4
GlidCop Al25 (no B) 20% c.w.	7	2	17.5	3.08	180	200	332	424	2.4	5.9
GlidCop Al25 + B 20% c.w.	7	2	17.5	3.08	180	200	388	432	1.6	3.4
GlidCop Al15 + B 70% c.w.	7	2	17.5	3.08	180	200	415	481	1.3	2.8
GlidCop Al15 as wrought	7	1	13.1	2.51	161	200	239	272	1.9	4.4
Cu 99.999, 80% c.w.	7	1	13.1	2.51	161	200	135	175	21.2	22.0
GlidCop Al25 + B, as wrought	6	2	14.5	3.08	180	200	262	311		
GlidCop Al15 + B, ind. braz.	7	1	13.1	2.56	161	200	275	275	0	0
Cu 99.999, 550°C, 2h	6	1	13.1	2.56	161	400	47	60	16.5	22.0
Cu + B1 c.w.	8	2	17.5	3.08	180	400	115	124	4.5	5.1
Cu + B1 c.w.	8	2	17.5	3.08	180	100	391	408	1.5	3.3
MAGT-0.2, as wrought	8	2	17.5	3.08	180	100	264	289	0.7	0.7

Table 8. Tensile properties of copper and Cu alloys irradiated in the upper part of the SMT-2 capsule (STS geometry, unshielded region)

Alloy, heat treatment	Cap-sule	Floor	Fluence (Φt), 10^{20} n/cm²		T_{irr}, °C	T_{test}, °C	σ_y, MPa	σ_u, MPa	δ_{un}, %	δ_{tot}, %
			E>0.1 MeV	E<0.68 eV						
Cu + B3 as wrought	6	2	2.54	1.59	169	200	136	139	1.3	4.5
Cu pure ann 350° C	6	1	2.69	1.66	174	200	50	54	2.5	9.0
Cu pure c.w.	6	4	1.84	1.29	178	200	133	136	7.0	7.5
Cu + B1 ann 350°C	6	1	2.69	1.66	174	200	132	216	8.0	10.4
Cu + B1 c.w.	6	3	2.23	1.46	176	200	151	175	9.5	19.0
Cu + B2 c.w.	6	3	2.23	1.46	176	200			11.6	23.5
Cu pure spec. as wrought	6	5	1.36	1.05	159	200	229	231	19.6	20.0
MAGT-0.05 as wrought	6	5	1.36	1.05	159	200	103	130	3.7	5.9
Cu + B1 ann 350°C	6	1	2.69	1.66	174	400	73	88	4.1	5.1

Table 9. Tensile properties of copper and Cu alloys irradiated in the Core subcapsule #1 (100°C, STS geometry)

Alloy, heat treatment	Capsule	Floor	Fluence (Φt), 10^{20} n/cm² E>0.1 MeV	Fluence (Φt), 10^{20} n/cm² E<0.68 eV	T_{irr}, °C	T_{test} °C	σ_y, MPa	σ_u, MPa	δ_{un}, %	δ_{tot}, %
Cu + B3	2	1	51	7.7	120	100	254	254	0.2	0.2
as wrought	2	15	54	8.0	90	100	410	415	0.2	0.2
MAGT-0.2 as wrought	1	1	51	7.7	120	100	386	386	0	0
Cu pure, ann 350°C 1h	1	1	51	7.7	120	100	187	253	19.5	20.7
Cu + B1 ann 350°C 1h	2	14	65	9.1	100	100	246	301	3.0	3.3
Cu + B2 ann 350°C 1h	2	16	47	7.0	80	100	313	349	1.3	1.5
Cu-Mo-B as wrought	2	15	54	8.0	90	100	452	498	0.25	0.5
GlidCop Al25 (no B) as wrought	1	16	44	7.0	80	100	511	541	0.5	0.65
GlidCop Al25 (no B) 20% c.w.	1	15	54	8.0	90	100	525	566	0.4	0.4
GlidCop Al25 + B 20% c.w.	1	15	54	8.0	90	100	482	482	0.1	0.1
GlidCop Al15 + B as wrought	1	14	65	9.1	90	100	289	333	0.3	0.3
Cu 99.999 80% c.w.	1	14	65	9.1	100	100	274	288	15.8	17.0
Cu 99.999 ann. 550°C 2h	1	14	65	9.1	100	100	198	258	9.5	12.5

Table 10. Tensile properties of copper and Cu alloys irradiated in the Core subcapsule #3 (240°C, STS geometry)

Alloy, heat treatment	Capsule	Floor	Fluence (Φt), 10^{20} n/cm² E>0.1 MeV	Fluence (Φt), 10^{20} n/cm² E<0.68 eV	T_{irr}, °C	T_{test}, °C	σ_y, MPa	σ_u, MPa	δ_{un}, %	δ_{tot}, %
MAGT-0.2 as wrought	3	2	74	8.4	265	250	341	366	3.3	3.3
Cu + B1 ann 350°C 1h	3	1	60	7.3	265	250	191	208	6.0	6.0
Cu pure, ann	3	3	78	8.7	260	250	154	187	16.5	17.8
Cu 99.999, 550°C 2h	3	14	52	6.6	230	250	145	180	17.8	20.0
GlidCop Al25 no B, 20% c.w.	3	13	64	7.6	230	250	276	324	2.0	5.1
Glidcop Al25 + B as wrought	3	12	77	8.6	240	250	317	361	0.9	1.1
GlidCop Al25 no B as wrought	3	12	77	8.6	240	250	350	426	1.5	3.4
Cu 99.999, 80% c.w.	3	14	52	6.6	230	250	221	244	17.7	23.2

Table 11. Tensile properties of copper and Cu alloys irradiated in the Core subcapsule #4 (350°C, STS geometry)

Alloy, heat treatment	Cap-sule	Floor	Fluence (Φt), 10^{20} n/cm^2		T_{irr}, °C	T_{test}, °C	σ_y, MPa	σ_u, MPa	δ_{un}, %	δ_{tot}, %
			E>0.1 MeV	E<0.68 eV						
MAGT-0.2 as wrought	4	1	60	7.3	400	350	188	203	2.7	4.0
Cu + B3 as wrought	4	14	52	6.6	350	350	94	97	1.0	1.5
Cu pure ann 350°C	4	1	60	7.3	400	350	203	244	8.9	13.5
GlidCop Al15 + B as wrought	4	13	64	7.6	350	350	142	164	3.8	6.3
GlidCop Al25 + B 20% c.w.	4	12	77	8.6	360	350	190	239	5.6	8.6
Cu 99.999, 80% c.w.	4	13	64	7.6	350	350	67	85	11.0	13.0
GlidCop Al25 no B 20% c.w.	4	12	77	8.6	360	350	194	224	6.3	16
Cu 99.999, 550°C 2h	4	13	64	7.6	360	350	110	130	9.6	13.8
GlidCop Al25 no B as wrought	4	2	74	8.4	400	350	155	196	3.3	4.8

Table 12. Electrical resistivity of copper and Cu alloys irradiated in the lower part of the SMT-1 capsule (LTS geometry, Cd-shielded region)

Alloy	Cap-sule	Floor	ρ_{nonirr} μΩ-cm	ρ_{irr} μΩ-cm	ρ_{irr}/ρ_{non} %	Φt_{fast}, 10^{21} n/cm^2 E>0.1MeV	Φt_{therm}, 10^{20} n/cm^2 E<0.68 eV	T_{irr}, °C
Cu, pure anneal 350°C, 1 h	6	1	1.676	1.882	12.0	0.86	2.27	85
Cu+B1 anneal 350°C, 1 h	5	1	1.728	2.001	15.8	1.21	2.27	85
Cu+B2 anneal 350°C, 1 h	5	2	1.767	1.971	11.6	1.78	2.92	88
MAGT 0.2 as wrought	6	2	2.071	2.268	9.5	1.27	2.92	88
GlidCop Al15+B 70% c. w.	1	2	1.886	2.115	12.1	1.78	2.92	88
GlidCop Al25+B 20% c. w.	4	1	1.965	2.194	11.6	1.21	2.27	85
GlidCop Al25+B as wrought	2	1	1.923	2.163	12.5	0.86	2.27	88
Cu 99.999% as wrought	3	2	1.689	1.909	13.1	1.53	2.92	88
Cu 99.999% anneal 550°C, 2 h	4	2	1.686	1.894	12.2	1.78	2.92	88
GlidCop Al25 (no B) 20% c. w.	3	1	1.972	2.180	10.6	1.03	2.27	85
GlidCop Al15+B induct. brazed	2	2	2.027	2.249	11.0	1.27	2.92	88
GlidCop Al25 (no B) as wrought	1	1	1.948	2.178	11.8	1.21	2.27	88
GlidCop Al15+B as wrought	1	2	1.892	2.178	14.9	1.78	2.92	88

Table 13. Electrical resistivity of copper and Cu alloys irradiated in the upper part of the SMT-1 capsule (LTS geometry, unshielded region)

Alloy	Cap-sule	Floor	ρ_{nonirr} µΩ-cm	ρ_{irr} µΩ-cm	ρ_{irr}/ρ_{nonirr} %	Φt_{fast}, 10^{21} n/cm^2 E>0.1MeV	Φt_{therm}, 10^{21} n/cm^2 E<0.68 eV	T_{irr}, °C
Cu pure anneal 350°C, 1 h	1	1	1.683	2.281	33.2	1.42	1.4	88
Cu+B1 anneal 350°C, 1 h	2	1	1.720	2.350	36.7	2.27	1.4	88
Cu+B2 anneal 350°C, 1 h	1	3	1.775	2.146	20.9	0.82	0.97	85
MAGT 0.2 as wrought	4	1	2.059	2.643	28.4	1.42	1.4	88
Cu pure c. w.	3	1	1.741	2.339	34.3	1.85	1.4	88
Cu + Be	4	2	6.190	7.149	15.5	1.2	1.24	88
Cu-Mo as wrought	3	2	2.016	2.774	37.6	1.55	1.24	88
Cu + Cr + Zr	5	1	2.107	2.997	42.3	2.27	1.4	88
Cu + B1 c. w.	2	2	1.758	2.274	29.4	1.9	1.24	88

Table 14. Electrical resistivity of copper and Cu alloys irradiated in the lower part of the SMT-1 capsule (STS geometry, Cd-shielded region)

Alloy	Cap-sule	Floor	ρ_{nonirr} µΩ-cm	ρ_{irr} µΩ-cm	ρ_{irr}/ρ_{nonirr} %	Φt_{fast}, 10^{21} n/cm^2 E>0.1MeV	Φt_{therm}, 10^{20} n/cm^2 E<0.68 eV	T_{irr}, °C
Cu + B3 c.w.	3	1	1.942	2.111	8.7	1.12	2.19	76
Cu + B1 c.w.	4	1	1.858	2.046	10.1	0.8	2.19	76
Cu + B1 anneal	1	3	1.742	2.099	20.5	1.31	3.0	87
Cu + B2 anneal	2	3	1.719	2.085	21.3	1.83	3.0	87
Cu pure anneal	5	1	1.681	1.905	13.3	0.8	2.19	76
Cu pure II c.w.	5	2	1.779	1.989	11.8	1.07	2.63	82
Cu pure c.w.	4	2	1.751	1.969	12.5	1.07	2.63	82
Cu - Mo - B as wrought	4	3	1.915	2.179	13.8	1.31	3.0	87
MAGT-0.2 as wrought	3	2	2.043	2.282	11.7	1.5	2.63	82
Cu + B2 c. w.	5	3	1.801	2.108	17.0	1.31	3.0	87
GlidCop Al25 (no B) 20% c. w.	2	2	1.948	2.266	16.3	1.5	2.63	82
GlidCop Al25 (no B) as wrought	1	2	1.981	2.264	14.3	1.07	2.63	82
GlidCop Al25 + B as wrought	1	2	1.991	2.298	15.4	1.07	2.63	82
Cu 99.999% ann. 950°C, 0.5 h	1	1	1.699	1.918	12.9	0.8	2.19	76
Cu 99.999% anneal 400°C, 1 h	1	1	1.692	1.904	12.5	0.8	2.19	76
GlidCop Al15 + B as wrought	2	1	2.018	2.308	14.4	1.12	2.19	76
GlidCop Al15 + B ind. br.	2	1	2.243	2.435	8.5	1.12	2.19	76
GlidCop Al15 + B 70% c. w.	2	2	1.941	2.218	14.3	1.5	2.63	82
Cu 99.999% 80% c. w.	2	2	1.727	1.943	12.5	1.5	2.63	82
GlidCop Al25 (no B) 20% c. w.	2	2	1.933	2.203	13.9	1.5	2.63	82
Cu 99.999% ann. 550 °C, 2 h	1	1	1.686	1.880	11.5	0.8	2.19	76

Table 15. Electrical resistivity of copper and Cu alloys irradiated in the upper part of the SMT-1 capsule (STS geometry, unshielded region)

Alloy	Capsule	Floor	ρ_{nonirr} μΩ-cm	ρ_{irr} μΩ-cm	ρ_{irr}/ρ_{nonirr} %	Φt_{fast}, 10^{21} n/cm^2 E>0.1MeV	Φt_{therm}, 10^{21} n/cm^2 E<0.68 eV	T_{irr}, °C
Cu + B3 c. w.	1	2	1.911	2.500	30.8	2.17	1.36	89
Cu + B1 c. w.	4	3	1.819	2.359	29.7	1.2	1.25	86
Cu + B1 anneal	3	1	1.736	2.461	41.8	2.3	1.42	93
Cu + B2 anneal	1	1	1.762	2.455	39.3	2.3	1.42	93
Cu pure anneal	4	1	1.700	2.336	40.0	1.45	1.42	93
Cu pure II c. w.	2	4	1.776	2.287	28.7	0.99	1.1	81
Cu pure c. w.	2	1	1.750	2.434	39.1	1.45	1.42	93
Cu - Mo - B	1	4	2.026	2.579	27.3	1.57	1.1	81
MAGT-0.2 as wrought	2	3	2.048	2.692	31.4	1.2	1.25	86
Cu + B2 c. w.	3	2	1.789	2.412	34.8	2.17	1.36	89

Table 16. Electrical resistivity of copper and Cu alloys irradiated in the lower part of the SMT-2 capsule (STS geometry, Cd-shielded region)

Alloy	Capsule	Floor	ρ_{nonirr} μΩ-cm	ρ_{irr} μΩ-cm	ρ_{irr}/ρ_{nonirr} %	Φt_{fast}, 10^{21} n/cm^2 E>0.1MeV	Φt_{therm}, 10^{20} n/cm^2 E<0.68 eV	T_{irr}, °C
Cu + B1 c.w.	8	2	1.858	2.021	8.8	1.75	3.08	180
Cu + B1, 350°C anneal	8	3	1.742	1.998	14.7	2.14	3.51	178
Cu + B2, 350°C anneal	7	1	1.719	1.925	12.0	1.31	2.51	161
Cu pure II c.w.	7	3	1.779	1.934	8.7	2.14	3.51	178
Cu pure c.w.	7	3	1.751	1.909	9.0	2.14	3.51	178
Cu - Mo - B as wrought	7	3	1.915	2.217	15.8	2.14	3.51	178
MAGT-0.2 as wrought	8	2	2.043	2.186	7.0	1.75	3.08	180
Cu + B2 c. w.	7	1	1.801	1.988	10.4	1.31	2.51	161
GlidCop Al25 (no B) 20% c. w.	7	2	1.948	2.133	9.5	1.75	3.08	180
GlidCop Al25 (no B) as wrought	8	2	1.981	2.135	7.8	1.75	3.08	180
GlidCop Al25 + B as wrought	6	2	1.991	2.150	8.0	1.45	3.08	180
Cu 99.999% ann. 950°C, 0.5 h	7	1	1.699	1.852	9.0	1.31	2.51	161
GlidCop Al15 + B as wrought	7	1	2.018	2.246	11.3	1.31	2.51	161
GlidCop Al15 + B ind. br.	7	1	2.243	2.263	0.9	1.31	2.56	161
Cu 99.999% 80% c. w.	7	1	1.727	1.842	6.7	1.31	2.51	161
Cu 99.999% ann. 550°C, 2 h	6	1	1.686	1.829	8.5	1.31	2.56	161

Table 17. Electrical resistivity of copper and Cu alloys irradiated in the upper part of the SMT-2 capsule (STS geometry, unshielded region)

Alloy	Capsule	Floor	ρ_{nonirr} μΩ-cm	ρ_{irr} μΩ-cm	ρ_{irr}/ρ_{nonirr} %	Φt_{fast}, 10^{21} n/cm^2 E>0.1MeV	Φt_{therm}, 10^{21} n/cm^2 E<0.68 eV	T_{irr}, °C
Cu + B1 c. w.	6	3	1.819	2.304	26.7	2.23	1.46	176
MAGT-0.2 as wrought	6	6	2.048	2.429	18.6	1.74	1.2	178
Cu + B2 c. w.	6	3	1.789	2.311	29.2	2.23	1.46	176

Table 18. Electrical resistivity of copper and Cu alloys irradiated in the Core subcapsules #1 and #2 (STS geometry, 100°C)

Alloy	Capsule	Floor	ρ_{nonirr}	$\Delta\rho_{irr}$	Φt_{fast}, (E>0.1 MeV)	Φt_{therm}, (E<0.68 eV)	T_{irr},
			μΩ-cm	μΩ-cm	10^{21} n/cm^2	10^{20} n/cm^2	°C
GlidCop Al25 no B as wrought	3-1	16	2.074	0.446	4.7	7.0	80
GlidCop Al25 + B as wrought	3-1	16	2.074	0.575	4.4	7.0	80
GlidCop Al15 + B as wrought	3-1	14	2.099	0.604	6.5	9.1	100
GlidCop Al15 + B ind. brazed	3-1	16	2.338	0.355	4.4	7.0	80
Cu pure ann.	3-1	1	1.761	0.341	5.1	7.7	120
Cu 99.999 550 °C, 2h	3-1	14	1.735	0.382	6.5	9.1	100
Cu 99.999 80% c.w.	3-1	14	1.767	0.415	6.5	9.1	100
Cu + B2 ann. 350 °C	.3-2	14	1.801	0.46	6.5	9.1	100
Cu + B2 ann. 350 °C	3-2	16	1.801	0.281	4.4	7	80
Cu + B1 ann	3-2	14	1.817	0.519	6.5	9.1	100
Cu + B1 ann	3-2	16	1.817	0.393	4.4	7.0	80
Cu + B3 c.w.	3-2	15	1.959	0.326	5.4	8.0	90
Cu + B3 c.w.	3-2	1	1.959	0.417	5.1	7.7	120
Cu-Mo-B as wrought	3-2	1	1.960	0.419	5.1	7.7	120
MAGT-0.2	3-1	1	2.1	0.406	5.11	7.7	120

Table 19. Electrical resistivity of copper and Cu alloys irradiated in the Core subcapsule #3 (STS geometry, 240°C)

Alloy	Capsule	Floor	ρ_{nonirr}	$\Delta\rho_{irr}$	Φt_{fast}, (E>0.1 MeV)	Φt_{therm}, (E<0.68 eV)	T_{irr},
			μΩ-cm	μΩ-cm	10^{21} n/cm^2	10^{20} n/cm^2	°C
GlidCop Al25, no B, 20% c.w.	3-3	13	2.01	0.416	6.4	7.6	230
GlidCop Al25, no B, as wrought	3-3	12	2.017	0.362	7.7	8.6	240
GlidCop Al15 + B ind. brazed	3-3	12	2.109	0.463	7.7	8.6	240
GlidCop Al25 + B as wrought	3-3	12	2.074	0.498	7.7	8.6	240
GlidCop Al15 + B as wrought	3-3	14	2.147	0.4	7.8	8.7	260
Cu pure annealed	3-3	2	1.742	0.335	7.4	8.4	265
Cu 99.999 550 °C	3-3	14	1.759	0.297	5.2	6.6	230
Cu 99.999 80% c.w.	3-3	14	1.786	0.274	5.2	6.6	230
Cu 99.999 80% c.w.	3-3	13	1.786	0.281	6.4	7.6	230
Cu + B 1 annealed	3-3	1	1.8	0.397	6.0	7.3	265
Cu + B 2 annealed	3-3	1	1.810	0.340	6.0	7.3	265
MAGT-0.2	3-3	2	2.1	0.356	7.4	8.4	265

Table 20. Electrical resistivity of copper and Cu alloys irradiated in the Core subcapsule #4 (STS geometry, 350°C)

Alloy	Capsule	Floor	ρ_{nonirr}	$\Delta\rho_{irr}$	Φt_{fast}, (E>0.1 MeV)	Φt_{therm}, (E<0.68 eV)	T_{irr},
			μΩ-cm	μΩ-cm	10^{21} n/cm^2	10^{20} n/cm^2	°C
GlidCop Al25 no B 20% cw	3-4	12	2.056	0.181	7.7	8.6	360
GlidCop Al15 + B ind.brazed	3-4	2	2.088	0.273	7.4	8.4	400
GlidCop Al25 + B as wrought	3-4	2	2.110	0.302	7.4	8.4	400
GlidCop Al15 + B as wrought	3-4	13	2.19	0.21	6.4	7.6	350
Cu pure ann.	3-4	3	1.730	0.174	7.8	8.7	390
Cu 99.999 550 °C	3-4	12	1.735	0.239	7.7	8.6	360
Cu 99.999 80% c.w.	3-4	13	1.797	0.124	6.4	7.6	350
Cu-Mo-B as wrought	3-4	14	1.984	0.076	5.2	6.6	350
Cu-Mo-B as wrought	3-4	14	1.974	0.233	5.2	6.6	350
MAGT-0.2	3-4	1	2.098	0.169	6.0	7.3	400