ATR-A1 IRRADIATION EXPERIMENT ON VANADIUM ALLOYS AND LOW-ACTIVATION STEELS* H. Tsai, R. V. Strain, I. Gomes, A. G. Hins, and D. L. Smith (Argonne National Laboratory), H. Matsui (Tohoku University)

SUMMARY

To study the mechanical properties of vanadium alloys under neutron irradiation at low temperatures, an experiment was designed and constructed for irradiation in the Advanced Test Reactor (ATR). The experiment contained Charpy, tensile, compact tension, TEM, and creep specimens of vanadium alloys. It also contained limited low-activation ferritic steel specimens as part of the collaborative agreement with Monbusho of Japan. The design irradiation temperatures for the vanadium alloy specimens in the experiment are ≈200 and 300°C, achieved with passive gas-gap sizing and fill-gas blending. To mitigate vanadium-to-chromium transmutation from the thermal neutron flux, the test specimens are contained inside gadolinium flux filters. All specimens are lithium-bonded. The irradiation started in Cycle 108A (December 3, 1995) and is expected to have a duration of three ATR cycles and a peak fluence of 4.5 dpa.

OBJECTIVE

The principal objective of the ATR-A1 irradiation experiment is to obtain mechanical property data for vanadium alloys irradiated at two low temperatures (≈200 and 300°C). Such data, important for fusion first-wall/blanket applications, are presently lacking.

DESCRIPTION OF EXPERIMENT

Advanced Test Reactor (ATR)

The ATR is a light-water-moderated and -cooled reactor with highly enriched uranium in plate-type fuel. The cooling water enters the reactor core, which is 1.22 m (4 ft) high, from the top at a nominal temperature of ≈52°C. Forty fuel elements are arranged in a serpentine pattern that forms four corner lobes and one central lobe. The ATR-A1 experiment is a drop-in capsule occupying the A-10 irradiation channel in the southeast lobe. Compared to other available irradiation positions, the A-10 channel has among the highest fast neutron fluxes and lowest thermal fluxes in ATR. Although the reactor is water cooled, with double encapsulation and other precautions, lithium can be used as the thermal bond for the specimens in the subcapsules. Lithium bonding ensures a high degree of temperature uniformity and impurity control for the vanadium alloy specimens.

The nuclear power for the southeast lobe where the ATR-A1 experiment resides is 25 MW and is projected to remain at that level for the duration of the experiment. (This power level is somewhat lower than the initial forecast of 27 MW, the design specification for the vehicle. The reduced power would thus have a corresponding effect on the specimen temperature and fluence. All temperature and dpa data reported in this article are based on the actual 25 MW power.)

Irradiation Vehicle

The irradiation vehicle is a drop-in capsule consisting of four segments and a handling fixture. The test specimens are contained in lithium-bonded subcapsules that are placed in the gas-filled capsule segments. Configuration of the capsule segments is shown in Fig. 1. The upper two capsule segments (AC4 and AC3) each contain three subcapsules, the third segment (AC2) contains five subcapsules, and the bottom segment (AC1) contains four subcapsules. With a few exceptions, the capsule segments are constructed to the ASME Boiler & Pressure Vessel Code, Section III. The materials for both the capsule tube and end fittings are Type 304 stainless steel. The tubing for the bottom and top segments has an OD of 0.580 in. and an ID of 0.546 in., and that for the two middle segments has an OD of 0.580 in. and an ID of 0.540 in. The

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variations of the inside diameter, i.e., gap width, in conjunction with the fill gas selection, provide the test temperature control for the subcapsules. The fill gases are 15%Ar-85%He for segment AC4; pure He for AC3 and AC2; and 5%Ar-95%He for AC1. All gases are purchased pre-blended. The fill gas is pressurized to 130 psig at room temperature to partially counterbalance the ATR system pressure of ≈335 psig.

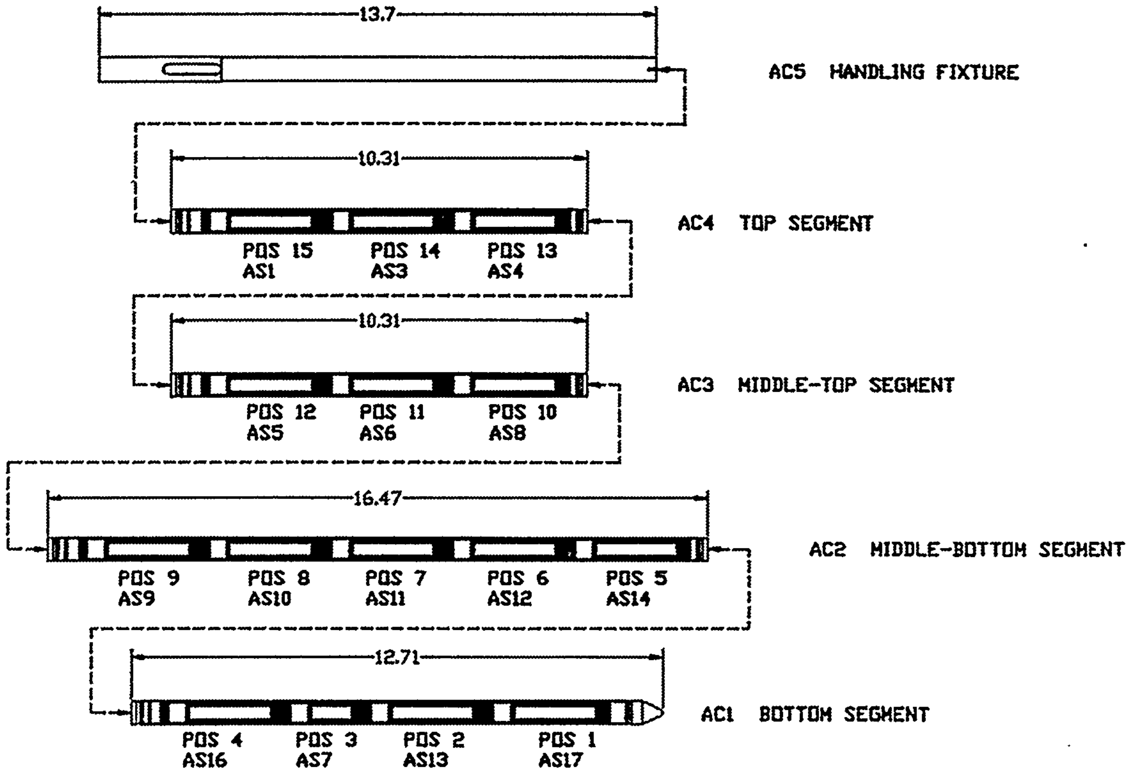

Fig. 1. Schematic of ATR-A1 Showing Capsule Segments and Subcapsule Locations

The test specimens are contained in 15 subcapsules, numbered AS1, AS3 through AS14, AS16 and AS17. Their locations in the capsule segments are shown in Fig. 1. Subcapsules AS4 and AS16 contain only ferritic steel specimens; the remaining subcapsules contain only vanadium alloy specimens. The subcapsule end fittings and tubes are Type 304 stainless steel. The end fittings center the subcapsule in the capsule segments, thereby maintaining the gas gap between the two. The dimensions of all but one subcapsule, are 0.530 in. OD x 0.500 in. ID x 3.07 in. long. The exception is SA7, which has the same diameters but a length of only 2.00 in.

A gadolinium filter set, consisting of a tube, a top end disk and a bottom end disk, is used in each subcapsule to reduce the thermal neutron flux. The filter tubes for all but two subcapsules (SA3 and AS10) are 0.490 in. OD x 0.354 in. ID. For SA3 and SA10, which contain disk compact tension (DCT-A) specimens with an outside diameter of 0.378 in., the filter tube is thinned to produce an inside diameter of 0.390 in. These two subcapsules are located away from the midplane of the reactor (see Fig. 1) to limit their exposure to a level commensurate with the reduced filter thickness. The end disks for all filters are 0.490 in. dia. and 0.075 in. thick. Pretest physics calculations indicate that the filter thicknesses are adequate for the irradiation and will limit vanadium-to-chromium transmutation at discharge to <0.5 wt.%, the compositional tolerance of the as-procured alloy materials.

A predetermined weight of lithium is charged in each subcapsule to provide the heat transfer medium. The lithium, in the form of a solid disk, is loaded into the subcapsules first. After the specimens and filter are loaded, the subcapsule is heated to melt and settle the lithium and wet the surfaces. All operations with exposed lithium are performed in a glovebox with an ultrahigh-purity helium atmosphere.

Dosimeters for determining the spectral and spatial distributions of neutron flux are incorporated in the ATR-A1 experiment. Two spectral/spatial sets and three spatial sets are loaded in selected subcapsules. The monitoring materials are Fe, Ti, Nb, Cu, Mn-20% Cu, and 0.1% Co-Al for the spectral data and Fe and 0.1% Co-Al for the spatial data. All monitoring materials are wires of ≈0.030-in. dia. x 0.15-in length. The wires are individually contained in high-purity vanadium capsules sealed with a laser weld. The placement of the dosimeters in the ATR-A1 subcapsules is shown in Table 1.

Six melt-wire temperature monitors, three for low temperature (≈200°C) and three for high temperature (≈300°C), are included to provide data on the peak temperature experienced during the irradiation. The monitoring materials are Pb/Sn alloy, Se, Sn, and Bi for the low-temperature monitors and Sn, Bi, Pb, and Zn for the high-temperature monitors. All materials are in the form of 0.025 to 0.030-in. dia. wires or particles and sealed in vanadium alloy holders. Locations of the temperature monitors in the capsule are given in Table 1.

Thermal Analysis

Physics calculations were performed by both ATR and ANL personnel to predict the gamma heating rates in test specimens and construction materials in the ATR-A1 experiment. Based on the calculated gamma heating rates (as functions of axial position), the capsule, subcapsule, and specimen temperatures were calculated with the THTB heat transfer code. The predicted specimen temperatures in the subcapsules, based on a 25-MW lobe power, are summarized in Table 2.

Damage Calculation

Damage (displacement per atom, or dpa) in the vanadium alloy specimens was predicted by ATR personnel on the basis of a lobe power of 27 MW. Correcting for the reduced lobe power of 25 MW and using the projected irradiation duration of 133 EFPDs, peak damage is estimated to be 4.54 dpa near the core midplane. The spatial distribution of damage as affected by the axial flux profile is shown in Table 2.

U.S. Vanadium Alloy Test Matrix

The key variables of the U.S. test matrix are

- Material (Heats 832665, T87, T89, T90, T91, T92, BL-47 and the boron-doped BL-70) (see Table 3),
- Heat treatment conditions (final vacuum annealing at 1000°C for 1.0 or 2.0 h),
- Weldment (EB, laser, and resistance),
- Irradiation temperatures (≈200 and 300°C).

The test specimen types are Charpy, tensile, compact tension, transmission-electron-microscope disks, and biaxial creep (pressurized tubes); a summary of the test matrix is presented in Table 4.

Pressurized creep specimens of vanadium alloys are being irradiated for the first time. The creep specimens are 0.180 in. OD x 0.160 in. ID x 1.0 in. long tubes with welded end plugs. The tubing is produced by a repeated drawing/cleaning/annealing process on a piece of V-4wt.%Cr-4wt.%Ti material from the 832665 heat. The circumferential plug-to-tube welds are made with an electron-beam welder in vacuum. The specimen is then pressurized, through a 0.010-in. dia. hole in the top end plug, with high-purity helium in a high-pressure chamber. The final closure weld of the 0.010-in. dia. hole is made with a laser through the quartz window in the chamber. The pressure loadings and calculated hoop stresses in the specimens are shown in Table 5.

JP Vanadium Alloy Test Matrix

The main variables of the JP vanadium test matrix are material and temperature. The major JP vanadium alloys are V-4Cr-4Ti-0.1Si, V-3Fe-4Ti-0.1Si and V-5Cr-5Ti-1YSiAl. A small number of specimens are made from the U.S. V-4Cr-4Ti (Heat 832665) for comparison purposes to check the effects of specimen geometry on measured data. A summary of the JP test matrix is given in Table 6.

Table 1. Loading Diagram of ATR-A1 Specimens and Monitors

					US								JP				
Pos.	Subcap. No.	Target Temp.	Test Mat'l	Tier	DCT	CVN	TS	MT	Creep	TEM	T.Mtr	F.Mtr	DCT	CVN	TS	TEM	Creep
15	AS1	200	V	Top	0	0	2	0	A5	--	--	Gr.(2)	0	4	4	--	0
				Bot	0	3	1	0	0	--	--	--	0	2	4	--	0
14	AS3	200	V	--	9	0	0	0	0	--	MW0	--	3	0	0	--	0
13	AS4	200	FS	Top	0	0	0	0	0	--	MW0	--	0	12	12	--	0
				Bot	0	0	0	0	0	--	--	--	0	12	15	126	0
12	AS5	200	V	Top	0	0	2	0	0	--	--	--	0	4	4	--	J3
				Bot	0	3	1	2	0	65	--	--	0	2	2	--	0
11	AS6	200	V	Top	0	0	2	0	A2	--	--	--	0	4	4	--	0
				Bot	0	3	1	4	0	50	--	--	0	2	0	--	0
10	AS8	200	V	Top	0	0	2	0	A3	--	MW0	--	0	4	4	--	0
				Bot	0	3	1	0	0	--	--	--	0	2	4	64	0
9	AS9	300	V	Top	0	0	2	0	A1	--	--	--	0	4	4	--	0
				Bot	0	2+4*	1	0	0	41	--	--	0	2	4	--	0
						* 1.5CVN											
8	AS10	300	V	Top	0	0	2	0	A10	--	--	Sp.(6)	0	4	4	--	0
				Bot	0	3	1	0	0	50	--	--	0	2	4	--	0
7	AS11	300	V	Top	0	0	2	0	A7	--	MW0	--	0	4	4	--	0
				Bot	0	3	1	4	0	24	--	--	0	2	0	--	0
6	AS12	300	V	Top	0	0	2	0	A11	--	--	Gr.(2)	0	4	4	--	0
				Bot	0	3	1	0	0	--	--	--	0	2	4	41	0
5	AS14	300	V	Top	0	0	2	0	0	--	MW0	--	0	4	4	--	J2
				Bot	0	3	1	0	0	--	--	--	0	2	3	23	0
4	AS16	300	FS	Top	0	0	0	0	0	--	--	Gr.(2)	0	12	12	--	0
				Bot	0	0	0	0	0	--	--	--	0	12	15	126	0
3	AS7	300	V	Bot	0	3	1	2	0	--	--	--	0	0	0	--	0
2	AS13	300	V	--	10	0	0	0	0	--	MW1	--	3	0	0	--	0
1	AS17	200	V	Top	0	0	2	0	A4	--	--	Sp.(6)	0	4	4	--	0
				Bot	0	3	1	0	0	--	--	--	0	2	4	--	0
Grand Totals			V 300C		10	21	16	6	4	115			3	30	35	64	1
			V 200C		9	15	15	6	4	115			3	30	34	64	1
			FS 300C		0	0	0	0	0	0			0	24	27	126	0
			FS 200C		0	0	0	0	0	0			0	24	27	126	0

Table 2. Predicted Specimen Temperature and DPA in ATR-A1 Subcapsules[1]

Position	Subcap. Number	Test Mat'l	Gas Gap (mils)	Gas Composition	Target Temp. (°C)	Predicted Temp. (°C)2	Predicted dpa
15 (top)	AS1	V	8	He-15%Ar	200	138	0.68
14	AS3	V	8	He-15%Ar	200	185	1.42
13	AS4	FS	8	He-15%Ar	low	261	2.11
12	AS5	V	5	He	200	200	2.92
11	AS6	V	5	He	200	220	3.42
10	AS8	V	5	He	200	244	3.83
9	AS9	V	5	He	300	270	4.14
8	AS10	V	5	He	300	285	4.46
7	AS11	V	5	He	300	282	4.54
6	AS12	V	5	He	300	278	4.38
5	AS14	V	6	He	300	282	3.98
4	AS16	FS	8	He-5%Ar	high	333	3.71
3	AS7	V	8	He-5%Ar	300	284	2.92
2	AS13	V	8	He-5%Ar	300	243	2.25
1	AS17	V	8	He-5%Ar	200	202	1.42

[1]Based on current projection of 25 MW lobe power and 133 EFPDs exposure.
[2]Averaged specimen temperatures in subcapsules, some with two tiers of specimens. In subcapsules with creep specimens, upper-tier temperature may be slightly lower and lower-tier temperature may be slightly higher than indicated, due to reduced gamma heating from low-mass creep specimen in upper tier.

Table 3. Nominal Compositions of the Heats

832665	V-4wt.%Cr-4wt.%Ti.	T87	V-5wt.%Cr-5wt.%Ti.
T89	V-4wt.%Cr-4wt.%Ti.	T90	V-6wt.%Cr-6wt.%Ti.
T91	V-3wt.%Cr-4wt.%Ti.	T92	V-6wt.%Cr-3wt.%Ti.
BL-47	V-4wt.%Cr-4wt.%Ti.	BL-70	V-4wt.%Cr-4wt.%Ti., (250 appmB)

Specimen Loading in Subcapsules

The specimens in all subcapsules except SA3, SA7 and AS13 are loaded in two tiers, with the bottom tier providing a base to support the specimens in the upper tier. Subcapsules SA3 and SA13 contain exclusively DCT-A specimens, which are cylindrical disks stacked on top of one another. Subcapsule 7 is short and contains only one tier of specimens. Loading of the U.S. and Japanese vanadium alloy specimens in the subcapsules are mixed to achieve a high packing density.

A total of 154 tensile specimens, 144 Charpy specimens, 19 DCT-A specimen, 10 creep specimens, and 610 TEM disk are loaded in the ATR-A1 experiment. The locations of these specimens in the subcapsules are shown in Table 1.

IRRADIATION CONDITIONS AND SCHEDULE

The ATR-A1 experiment is scheduled to be in the core for three cycles: 108A, 108B, and 109A. Projected cycle durations are 42, 42, and 49 EFPDs, respectively. Discharge at the end of Cycle 109A is scheduled on May 5, 1996. ATR projects the lobe power to be constant at 25 MW for the three cycles.

Table 4. U.S. Vanadium Alloy Test Matrix

T (°C)	Material[1]	MCVN	PCVN	SS-3	Matron	DCT	Creep	TEM
300	832665 (Pri. Anneal)	4	3	3	2	3	4	16
	832665 (Sec. Anneal)	4		2		3		10
	832665, EB Weld			2				
	832665 Lz, TIG Weld	2		1				1
	BL-47	4		2		2		10
	BL-47 TIG Weld	4[2]						
	T89							10
	T87			2	2	2		16
	T91			2	2			16
	BL-70							10
	T92			2				16
	T90							10
	Total	18	3	16	6	10	4	115
200	832665 (Pri. Anneal)	5		3	2	3	4	16
	832665 (Sec. Anneal)	4		2		2		10
	832665, EB Weld							
	832665 Lz, TIG Weld	2		2				1
	BL-47	4		2		2		10
	T89							10
	T87			2	2	2		16
	T91			2	2			16
	BL-70							10
	T92			2				16
	T90							10
	Total	15	0	15	6	9	4	115

[1]Primary Anneal: 1000°C for 1.0 h.
Secondary Anneal: 1000°C for 2.0 h.
[2]1.5 CVN size specimens.

Table 5. Calculated Hoop Stress in Creep Specimens

Target Temp.(°C)	Specimen No.[1]	Fill Pressure (psi, @24°C)	Predicted Irradiation Temp. (°C)	Midwall Hoop Stress (MPa)
300	A1	0	262	0
	A10	950	273	96
	A7	1421	272	143
	A11	1910	265	189
	J2	1825	272	191
200	A5	0	134	0
	A4	1133	196	99
	A2	1706	214	154
	A3	2284	235	214
	J3	2189	193	197

[1]Prefix A denotes U.S. specimen and prefix J denotes JP specimen.

Table 6. JP Vanadium Alloy Test Matrix

T (°C)	Material	CVN	TS	DCT	Creep	TEM
300	V-4Cr-4Ti-0.1Si	7	9		1	6
	V-3Fe-4Ti-0.1Si	5	8	3		3
	V-5Cr-5Ti-1YiSiAl	14	18			25
	V-4Cr-4Ti (832665)	4				0
	Other V Alloys					30
	Total	30	35	3	1	64
200	V-4Cr-4Ti-0.1Si	10	9		1	6
	V-3Fe-4Ti-0.1Si	5	8	3		3
	V-5Cr-5Ti-1YiSiAl	10	17			25
	V-4Cr-4Ti (832665)	5				0
	Other V Alloys					30
	Total	30	34	3	1	64

FUTURE ACTIVITIES

Details are being discussed with ATR on the optimal method of disconnecting the capsule segments at ATR after the irradiation. The disconnected capsule segments will then be shipped to ANL for disassembly. Opening of the subcapsules to remove the lithium bond and to retrieve the test specimens is expected to be a routine operation, based on past experience. The cleaned specimens will be disseminated to participating U.S. and Japanese laboratories for postirradiation examination and testing.