CONTINUING IRRADIATION OF FERRITIC STEELS: EXPERIMENTS HFIR-CTR-62 AND -63 -- K. E. Lenox, R. L. Klueh, and R. L. Senn (Oak Ridge National Laboratory)

OBJECTIVE

The objective of this experiment is to evaluate the microstructure, tensile properties, and Charpy impact properties of irradiated ferritic steels. These two capsules are follow-up experiments to the ferritic steel irradiations performed in HFIR-CTR-47, -48, -49, -50, -53, -54, -55 and -56.

SUMMARY

The design and structure of the HFIR-CTR-62 and -63 capsules is described, including detailed descriptions of the specimen materials. The two capsules contain ferritic steel specimens, along with a few austenitic stainless steel TEMs, intended for irradiation at either 300°C or 400°C until a peak of thirteen dpa is achieved at the center of the capsule. The two capsules, containing eighty-eight one-third size Charpy specimens, 208 TEMs, and thirty-two tensile specimens, have been assembled and are currently scheduled to begin irradiation in the HFIR in April of 1995.

PROGRESS AND STATUS

Introduction

HFIR-CTR-62 and -63 have been designed and fabricated and are scheduled to start irradiation in the HFIR in April of 1995. The capsules will be irradiated until a peak of thirteen dpa is achieved in specimens at the reactor midplane. These two capsules are follow-up experiments to HFIR-CTR-47 and -48, which contained Charpy specimens, and HFIR-CTR-49, -50, -53, -54, -55 and -56, which contained tensile specimens. HFIR-CTR-62 contains only Charpy specimens and HFIR-CTR-63 contains Charpy, tensile, and TEM specimens. The differences from previous ferritic steel irradiations are described, as well as the specimen matrix and specimen holders used in the current experiment, along with the thermal analysis required to design the specimen holders.

Differences from Related Previous Experiments

These two experiments contain some important elements not found in the previous irradiations of ferritic steels (HFIR-CTR-47, -48, -49, -50, -53, -54, -55 and -56). These elements include new specimen materials and types and new analysis techniques. In addition to the conventional Cr-Mo steels (with and without nickel) contained in the previous capsules, CTR-62 and -63 contain new reduced-activation ferritic steels and nickel-doped alloys. In the prior irradiations, one-half size Charpy specimens were irradiated, and one-third size specimens are being irradiated in this experiment. Also, sheet SS-3 tensile specimens are being irradiated in these two capsules, whereas rod tensile specimens were irradiated in CTR-49, -50, -55, and -56. CTR-62 and -63 also contain TEM specimens which were not included in the previous experiments. The majority of the TEMs are ferritic steels, but a few of them are made of austenitic stainless steel; all of the austenitic specimens are TEMs. Density measurements and transmission electron microscopy analysis of the TEM specimens will be made after irradiation. In addition, the fracture surfaces of the Charpy specimens from these two experiments will be examined using scanning election microscopy (SEM) after initial testing.

Specimen Matrix

CTR-62 contains only Charpy specimens, while CTR-63 contains Charpy, tensile, and TEM specimens. The layout of the specimens in each capsule and the desired temperatures are shown in Figs. 1 and 2. Both capsules contain flux monitors at the locations shown in Figs. 1 and 2. The loading lists for the capsules and the alloy compositions of the specimen materials are shown in Tables 1-3.

Specimen Holders

The three types of specimen holders required for the experiment are shown in Figs. 3, 4, and 5. Fig. 5, the Charpy holder, is a configuration and design that has not been used in previous experiments. The other two holders are nearly identical to those used in a previous series of experiments, JP-9 through -16[1], but with slight modifications. Each holder type is discussed in more detail below.

Tensile Specimen Holder (Fig. 3)

Four tensile specimens and eight filler pieces (made of the specimen material) are held against an HT-9 alloy central core by a two piece aluminum alloy holder. The entire assembly is slid into an HT-9 sleeve. Small spacer tabs on the top and bottom of the aluminum holder are used to maintain the gas gap required for temperature control. The two notches along the length of the aluminum holder have been added to allow for gas flow in the case of a blocked control gap and for easier disassembly after irradiation. Additional gas gap spacer tabs were added on each side of the notch on the top and bottom of the aluminum holder.

TEM Specimen Holder (Fig. 4)

The TEM specimens are stacked into a stainless steel tube that is held within an aluminum alloy holder. The tube and the TEMs are kept within the holder by stainless steel end caps. Unlike previous TEM specimen holders, the length of the holder above and below the stainless steel tube is symmetric.

Charpy Specimen Holder (Fig. 5)

The Charpy holder is similar to the holder used for the tensile specimens. Four one-third size Charpy specimens are stacked together into an aluminum alloy holder that is slid into an HT-9 sleeve. In this case the aluminum holder is in one piece, but it does have the same notches and gas gap spacer tabs found on the tensile specimen aluminum holder.

Thermal Analysis

All of the external components of CTR-62 and -63 are identical to the previous JP-9 through -16 series of capsules, and the specimens holders are similar. Due to the similarities of CTR-62 and -63 to the previous JP series, and since the JP series of capsules underwent extensive one- and three-dimensional analyses, no additional calculations were performed on the capsule components of the

CTR-62 and -63 capsules. See Ref. 1 for a description of the analysis of the JP-9 through -16 series of capsules.

Due to the configuration of the specimen holders used in CTR-62 and -63 (Figs. 3-5), one-dimensional, cylindrical geometry heat transfer calculations were sufficient to characterize the temperature distribution in the holders and the specimens. (This was also demonstrated in the calculations for JP-9 through -16.[1]) The BASIC code, GENGTC[3] , was used to perform one-dimensional analysis of the specimen holders and to determine the size of the control gap required to maintain the desired temperatures.

The density, thermal conductivity, and linear expansion properties of each material region is needed for GENGTC calculations. The properties for material regions that contained more than one alloy, (e.g., a specimen holder with two different alloys), were determined by calculating the actual density and determining an average thermal conductivity and linear expansion based on the volume fraction of each material in the specimen holder. All of the material properties were treated as constants for the GENGTC calculations.

The heat generation rate (HGR) in the CTR-62 and -63 capsules was assumed to follow the profile determined in the TTT capsule experiment[3]:

$$\textit{normalized HGR profile} = 0.99768 - 0.00619595z - 0.00687997z^2$$

where z is the distance of the specimen from the reactor horizontal midplane, in inches. The peak HGR values given in the TTT experiment were modified to allow for the current reactor operating level of 85 MW, as opposed to the 100 MW operation during the TTT experiment. For the aluminum alloy components of the capsule, the peak HGR was (34.4 W/g)(85/100) = 29.2 W/g. For the steel components, mainly specimens, the peak HGR was (54.6 W/g)(85/100) = 46.4 W/g.

The material properties, HGRs, design temperatures, calculated temperatures and gas gap sizes from the heat transfer calculations are shown in Table 4 for CTR-62 and in Table 5 for CTR-63. The average and peak temperatures shown are for the specimens, not for the holders.

CTR-63 contains eight temperature monitors, two in the center core of each tensile specimen holder (see Fig. 3). The melt capsules will be inspected with radiography after irradiation to confirm that the desired temperatures were obtained.

FUTURE WORK

Once irradiation is complete, the capsules will be disassembled and the specimens, flux monitors, and temperature monitors will be recovered for testing. The tensile, Charpy, and TEM specimens, and temperature monitors will be tested at Oak Ridge National Laboratory. The flux monitors will be sent to Battelle Pacific Northwest Laboratories for examination by L. F. Greenwood.

REFERENCES

1. R. L. Senn, "Status of U.S./Japan Collaborative Program Phase II HFIR Target Capsules," pp. 8-20 in *Fusion Reactor Materials Semiannual Progress Report for the Period Ending September 30, 1987*, DOE/ER-0313/3, U.S. DOE, Office of Fusion Energy, 1988.

2. H. C. Roland, *GENGTC, A One-Dimensional CEIR Computer Program for Capsule Temperature Calculations in Cylindrical Geometry*, ORNL-TM-1942, Oak Ridge National Laboratory, Oak Ridge, Tennessee, December, 1967.

3. I. I. Siman-Tov, "The HFIR Instrumented (JP Type) Target Temperature Test (TTT) Capsule," pp. 10-17 in *Fusion Reactor Materials Semiannual Progress Report for the Period Ending March 31, 1987*, DOE/ER-0313/2, U.S. DOE, Office of Fusion Energy, 1988.

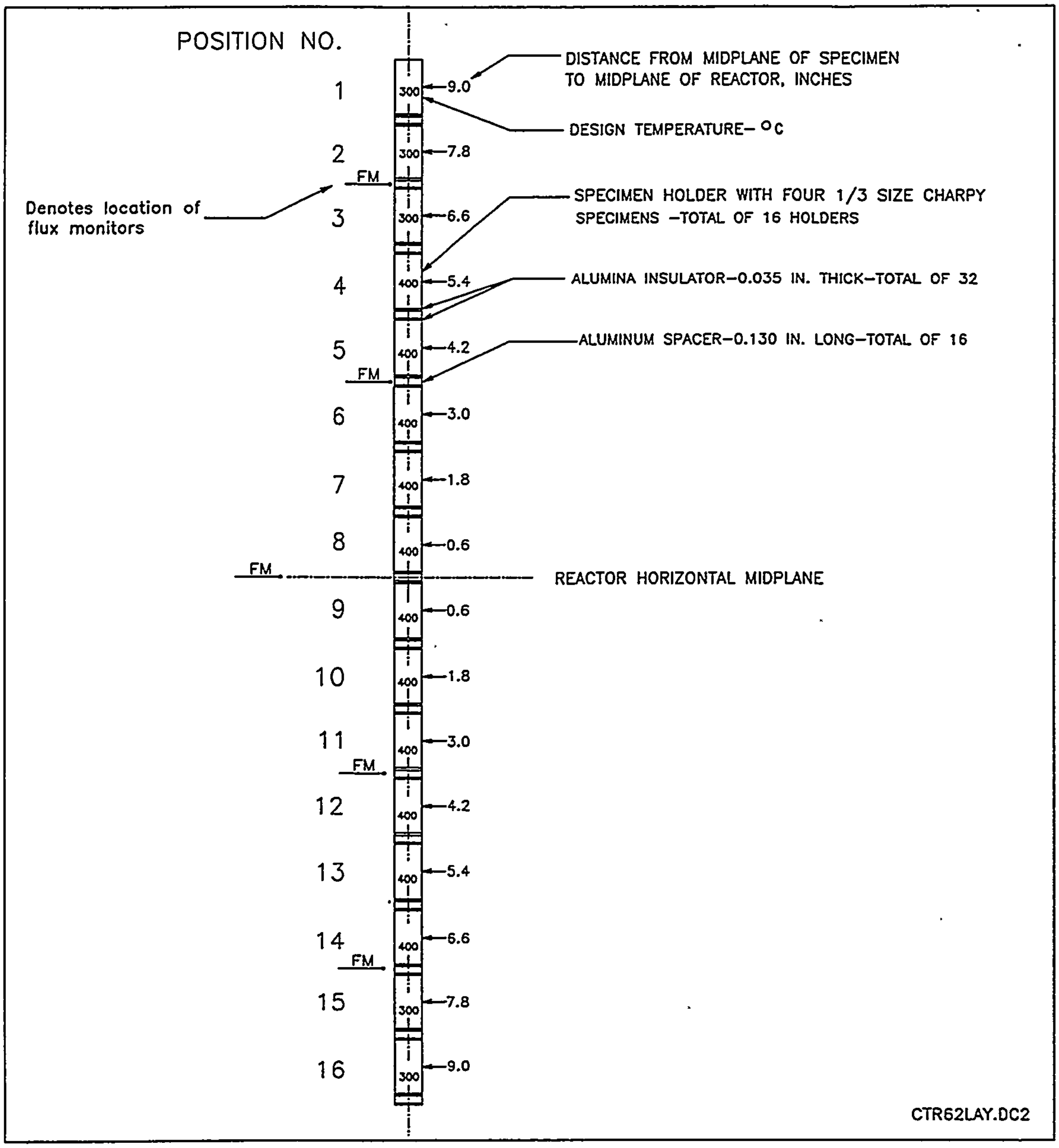

Fig. 1. Specimen layout and desired irradiation temperatures for HFIR-CTR-62.

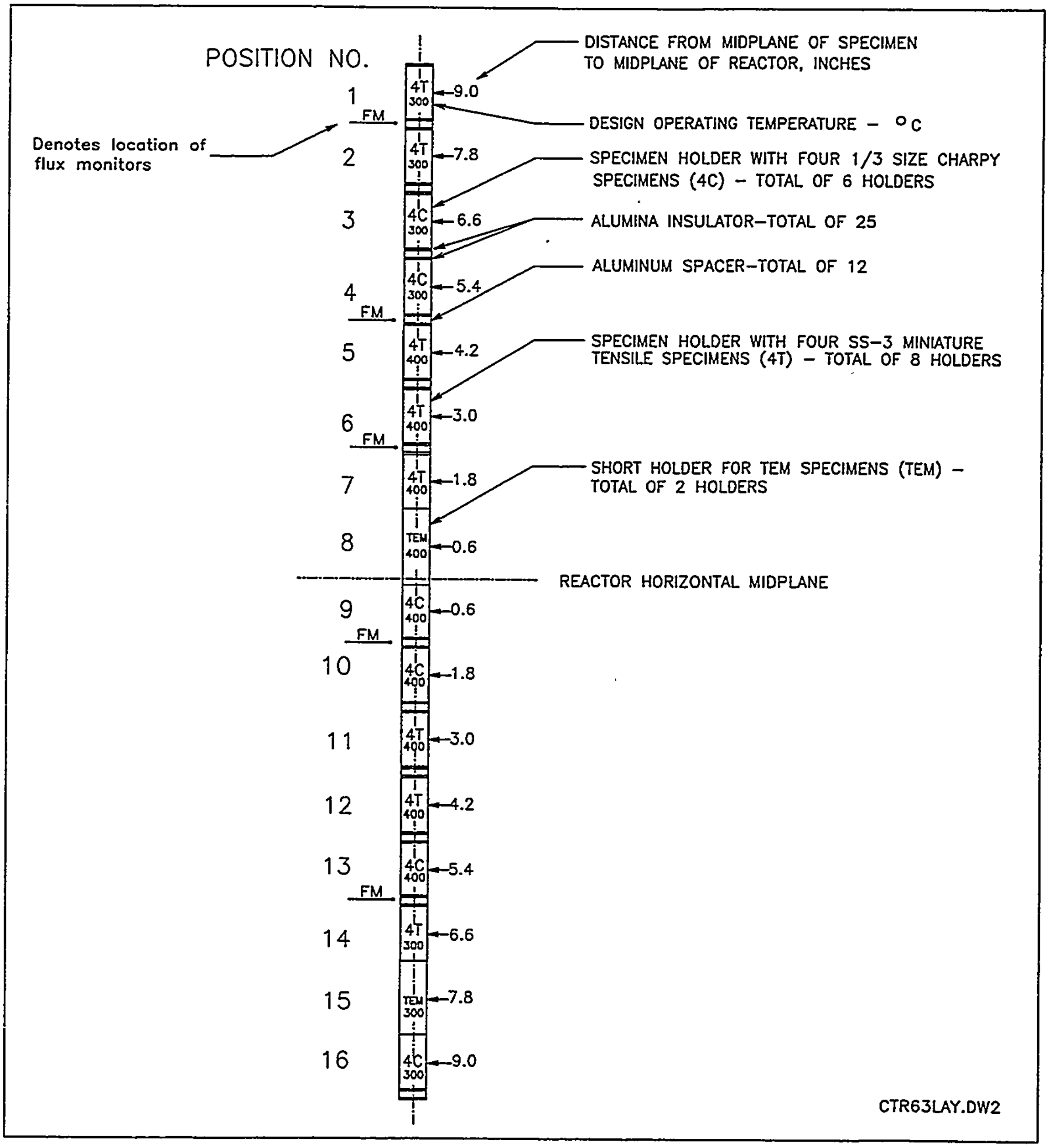

Fig. 2. Specimen layout and desired irradiation temperatures for HFIR-CTR-63.

Table 1. Loading list for HFIR-CTR-62

Position	Specimen	Alloy	Temperature
1	Charpy	12Cr-1MoVW-2Ni	300°C
2	Charpy	Mix (1, 3, 15, 16)	300°C
3	Charpy	9Cr-1MoVNb	300°C
4	Charpy	10Cr-0.5MoVNb	400°C
5	Charpy	Mix (4, 6, 12, 13)	400°C
6	Charpy	9Cr-2WVTa-2Ni	400°C
7	Charpy	12Cr-1MoVW-2Ni	400°C
8	Charpy	12Cr-1MoVW	400°C
9	Charpy	9Cr-1MoVNb	400°C
10	Charpy	Mix (7, 8, 9, 11)	400°C
11	Charpy	9Cr-1MoVNb-2Ni	400°C
12	Charpy	9Cr-2WVTa	400°C
13	Charpy	8Cr-2WVTa	400°C
14	Charpy	Mix (4, 6, 12, 13)	400°C
15	Charpy	12Cr-1MoVW	300°C
16	Charpy	9Cr-1MoVNb-2Ni	300°C

Notes: Each position will contain four Charpy specimens. The positions identified as "Mix" contain the same type of specimens as those of the postion number shown in parentheses, the actual alloys in these mixed positions are summarized as follows:

Pos	Temp (°C)	Alloy Mix
2	300	12Cr-1MoVW-2Ni, 9Cr-1MoVNb, 12Cr-1MoVW, 9Cr-1MoVNb-2Ni
5	400	8Cr-2WVTa, 9Cr-2WVTa-2Ni, 9Cr-2WVTa, 10Cr-0.5MoVNb,
10	400	12Cr-1MoVW-2Ni, 12Cr-1MoVW, 9Cr-1MoVNb, 9Cr-1MoVNb-2Ni
14	400	8Cr-2WVTa, 9Cr-2WVTa-2Ni, 9Cr-2WVTa, 10Cr-0.5MoVNb,

Table 2. Loading list for HFIR-CTR-63

Position	Specimen	Alloy	Temperature
1	Tensile	12Cr-1MoVW, 12Cr-1MoVW-2Ni	300°C
2	Tensile	9Cr-1MoVNb, 9Cr-1MoVNb-2Ni	300°C
3	Charpy	8Cr-2WVTa	300°C
4	Charpy	8Cr-2WVTaB	300°C
5	Tensile	10Cr-0.5MoVNb, 8Cr-2WVTa	400°C
6	Tensile	8Cr-2WVTaB, 12Cr-1MoVW-1Ni	400°C
7	Tensile	12Cr-1MoVW, 12Cr-1MoVW-2Ni	400°C
8	TEM	All Steels	400°C
9	Charpy	8Cr-2WVTaB	400°C
10	Charpy	Mix (9, 9, 9 13C)	400°C
11	Tensile	9Cr-1MoVNb, 9Cr-1MoVNb-2Ni	400°C
12	Tensile	9Cr-2WVTa, 9Cr-2WVTa-2Ni	400°C
13	Charpy	Mix (7C, 8C, 9C, 11C)	400°C
14	Tensile	8Cr-2WVTaB, 8Cr-2WVTa	300°C
15	TEM	All Steels	300°C
16	Charpy	Mix (1C, 3C, 15C, 16C)	300°C

Notes: Each position will contain either four tensile or four Charpy specimens or one TEM packet. The positions identified as "Mix" contain the same type of Charpy specimens as those of the position number shown in parentheses. The "C" refers to the positions in HFIR-CTR-62. The actual alloys in these mixed positions are summarized as follows:

Pos	Temp °C	Alloy Mix
10	400	8Cr-2WVTaB, 8Cr-2WVTaB, 8Cr-2WVTaB, 8Cr-2WVTa
13	400	12Cr-1MoVW-2Ni, 12Cr-1MoVW, 9Cr-1MoVNb, 9Cr-1MoVNb-2Ni
16	300	12Cr-1MoVW-2Ni, 9Cr-1MoVNb, 12Cr-1MoVW, 9Cr-1MoVNb-2Ni

Table 3. Chemical compositions of Cr-Mo steels with and without nickel additions and reduced-activation ferritic steels

	Composition, wt. %										
	9Cr-1MoVNb		12 Cr-1MoVW			10Cr-0.5MoVNb	9Cr-2WVTa	9Cr-2WVTa-2Ni	8Cr-2WVTaB	8Cr-2WVTa	316 SS[1]
	Standard[2]	2% Ni	Standard[2]	1% Ni	2% Ni						
C	0.091	0.070	0.21	0.20	0.21	0.10	0.098	0.098	0.093	0.10	0.018
Mn	0.35	0.35	0.51	0.47	0.48	0.76	0.39	0.38	0.23	0.10	1.57
P	0.008	0.008	0.011	0.01	0.011	0.004	0.014	0.014	0.001	0.005	0.004
S	0.004	0.004	0.004	0.004	0.004	0.005	0.003	0.003	0.001	0.002	0.005
Si	0.07	0.08	0.18	0.13	0.14	0.18	0.19	0.19	0.09	0.10	0.52
Ni	0.10	2.18	0.43	1.14	2.27	0.65	0.02	2.01	0.05	0.03	13.64
Cr	8.64	8.54	11.97	11.97	11.73	10.37	8.71	8.55	7.65	8.0	17.18
Mo	0.97	0.97	0.94	1.04	1.00	0.58	<0.01	<0.01		<0.10	2.22
V	0.21	0.22	0.27	0.31	0.31	0.21	0.23	0.23	0.18	0.20	0.003
Nb	0.064	0.068	0.018	0.015	0.015	0.16	<0.01	<0.01		<0.0002	0.02
Ta							0.06	0.06	0.038	0.04	<0.01
Cu	0.03	0.04	0.05	0.05	0.05	0.01	<0.001	<0.001		<0.05	0.01
Co	0.013	0.015	0.017	0.015	0.015	0.005					
Al	0.013	0.015	0.030	0.017	0.017	0.007	0.021	0.021	0.01	<0.02	0.005
B	<0.001	<0.001	<0.001	<0.001	<0.001	0.0075	<0.001	<0.001	0.034	<0.003	<0.001
W	0.01	<0.01	0.54	0.53	0.54		2.17	2.15	1.98	2.0	
Ti	0.002	0.002	0.003	0.003	0.003		<0.01	<0.01		0.005	<0.01
N	0.050	0.054	0.020	0.016	0.017	0.032	0.016	0.016	0.0018	0.005	0.005
Fe	BAL	BAL	BAL	BAL	BAL	BAL	BAL	BAL	BAL	BAL	BAL

1. TEM disks from five heats of 316 SS will be irradiated. The compositon shown is typical of all five; the other heats show only minor variation from the compositon shown.
2. The standard compositon is that of the conventional 9Cr-1MoVNb and 12 Cr-1MoVW steels.

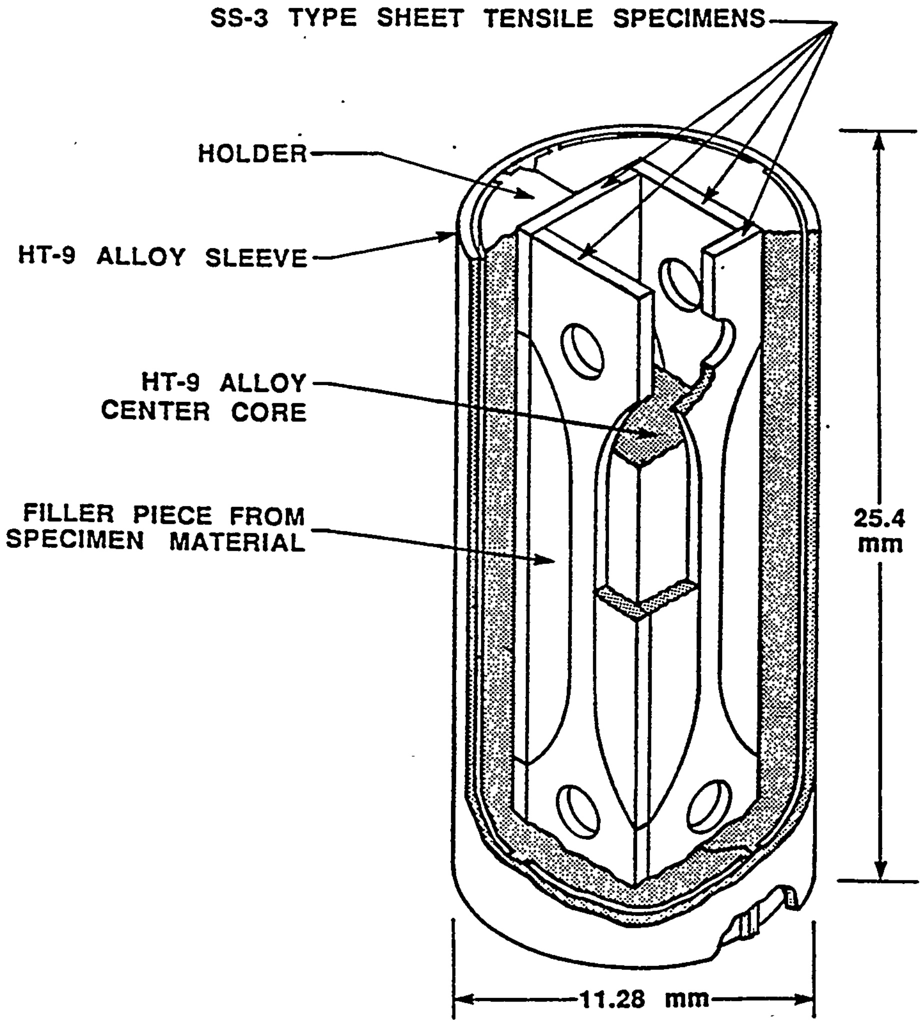

Fig. 3. Tensile specimen holder used in HFIR-CTR-63.

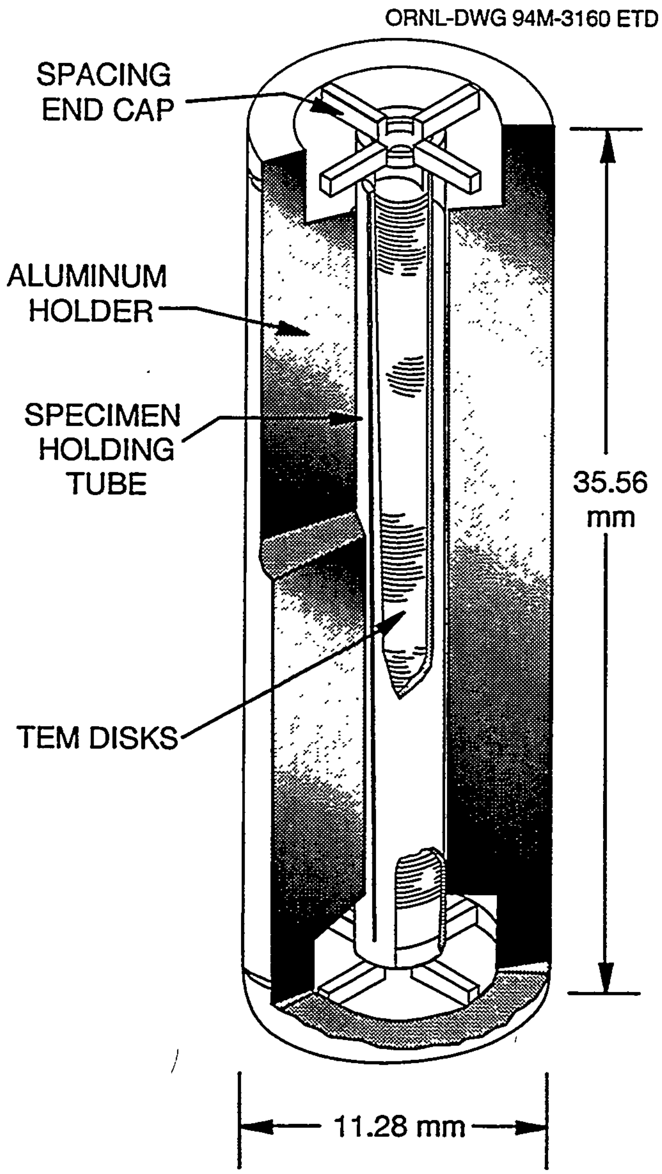

Fig. 4. TEM specimen holder used in HFIR-CTR-63.

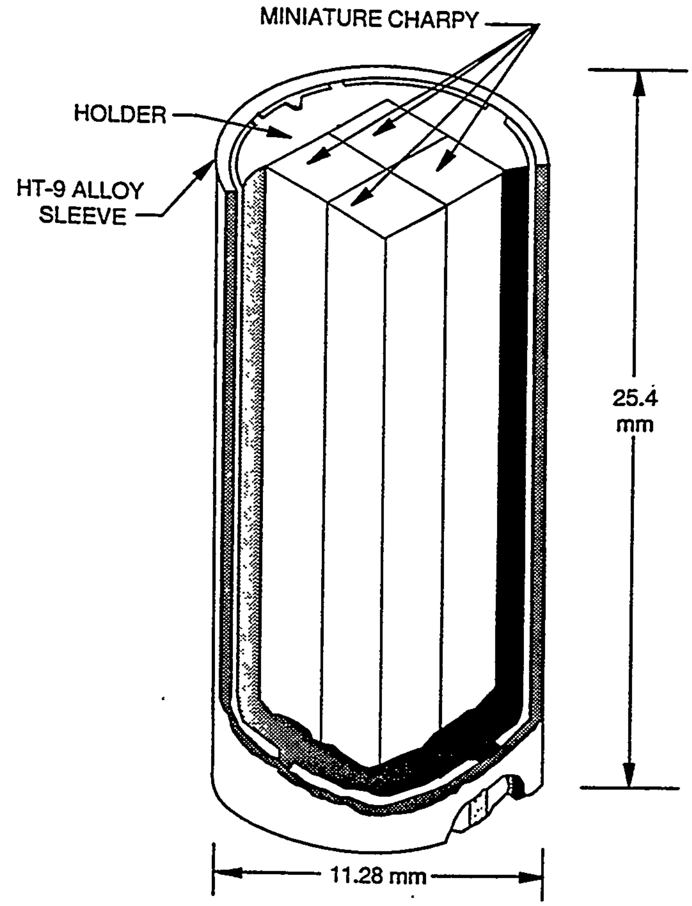

Fig. 5. Charpy specimen holder used in HFIR-CTR-62 and -63.

Table 4. Specimen layout and thermal characteristics for HFIR-CTR-62.

POS. NO.	DISTANCE SPEC. C/L FROM Rx C/L, inches	GAMMA HEAT-SST W/g	GAMMA HEAT-AL W/g	SPECIMEN TYPE	DESIGN SPECIMEN TEMP. C	COLD GAS GAP in.	Ave Temp (C)	Peak Temp (C)	SPECIMEN MATERIAL *	SPECIMEN DENSITY, g/cc (AVG. FOR MIX) g/cc	THERMAL CONDUCTIVITY (AVG. FOR MIX) BTU/h ft F	MEAN LINEAR COEFF. THER. EXP. MICRO(1/F)
1	9.00	17.85	11.25	4 CHARPY	300	0.0075	304	313	12Cr-1MoVW-2Ni	7.688	14.90	6.30
2	7.80	24.63	15.52	4 CHARPY	300	0.0050	306	318	Mix (1, 3, 15, 16)	7.669	16.07	6.36
3	6.60	30.50	19.21	4 CHARPY	300	0.0035	309	295	9Cr-1MoVNb	7.650	17.24	6.42
4	5.40	35.44	22.33	4 CHARPY	400	0.0055	400	416	10Cr-0.5MoVNb	7.610	17.30	6.60
5	4.20	39.46	24.86	4 CHARPY	400	0.0050	408	425	Mix (4, 6, 12, 13)	7.610	17.30	6.60
6	3.00	42.57	26.82	4 CHARPY	400	0.0045	408	427	9Cr-2WVTa-2Ni	7.610	17.30	6.60
7	1.80	44.75	28.19	4 CHARPY	400	0.0040	403	426	12Cr-1MoVW-2Ni	7.656	15.20	6.58
8	0.60	46.01	28.99	4 CHARPY	400	0.0040	410	434	12Cr-1MoVW	7.656	15.20	6.58
9	0.60	46.01	28.99	4 CHARPY	400	0.0040	404	425	9Cr-1MoVNb	7.610	17.30	6.60
10	1.80	44.75	28.19	4 CHARPY	400	0.0040	398	419	Mix (7, 8, 9, 11)	7.633	16.25	6.59
11	3.00	42.57	26.82	4 CHARPY	400	0.0045	408	427	9Cr-1MoVNb-2Ni	7.610	17.30	6.60
12	4.20	39.46	24.86	4 CHARPY	400	0.0050	408	425	9Cr-2WVTa	7.610	17.30	6.60
13	5.40	35.44	22.33	4 CHARPY	400	0.0055	400	416	8Cr-2WVTa	7.610	17.30	6.60
14	6.60	30.50	19.21	4 CHARPY	400	0.0065	397	411	Mix (4, 6, 12, 13)	7.610	17.30	6.60
15	7.80	24.63	15.52	4 CHARPY	300	0.0050	307	320	12Cr-1MoVW	7.688	14.90	6.30
16	9.00	17.85	11.25	4 CHARPY	300	0.0075	302	310	9Cr-1MoVNb-2Ni	7.650	17.24	6.42

Rx C/L (between positions 8 and 9)

* Pos.	Temp. (C)	Alloy Mix
2	300	12Cr-1MoVW-2Ni, 9Cr-1MoVNb, 12Cr-1MoVW, 9Cr-1MoVNb-2Ni
5	400	10Cr-0.5MoVNb, 9Cr-2WVTa-2Ni, 9Cr-2WVTa, 8Cr-2WVTa
10	400	12Cr-1MoVW-2Ni, 9Cr-1MoVNb, 12Cr-1MoVW, 9Cr-1MoVNb-2Ni
14	400	10Cr-0.5MoVNb, 9Cr-2WVTa-2Ni, 9Cr-2WVTa, 8Cr-2WVTa

Table 5. Specimen layout and thermal characteristics of HFIR-CTR-63.

POS. NO.	DISTANCE SPEC. C/L FROM Rx C/L, inches	GAMMA HEAT-SST W/g	GAMMA HEAT-AL W/g	SPECIMEN TYPE	DESIGN SPECIMEN TEMP. C	COLD GAS GAP IN.	AVE Temp (C)	Peak Temp (C)	SPECIMEN MATERIAL *	SPECIMEN DENSITY, g/cc (AVG. FOR MIX) g/cc	THERMAL CONDUCTIVITY (AVG. FOR MIX) BTU/h ft F	MEAN LINEAR COEFF. THERM.EXP. MICRO(1/F)
1	9.00	17.85	11.25	4TENSILE	300	0.0100	305	308	12Cr-1MoVW, 12Cr-1MoVW-2Ni	7.688	14.90	6.30
2	7.80	24.63	15.52	4TENSILE	300	0.0070	307	311	9Cr-1MoVNb, 9Cr-1MoVNb-2Ni	7.650	17.24	6.42
3	6.60	30.50	19.21	4 CHARPY	300	0.0035	295	309	8Cr-2WVTa	7.650	17.24	6.42
4	5.40	35.44	22.33	4 CHARPY	300	0.0030	303	319	8Cr-2WVTaB	7.650	17.24	6.42
5	4.20	39.46	24.86	4TENSILE	400	0.0070	413	419	10Cr-0.5MoVNb,8Cr-2WVTa	7.610	17.30	6.60
6	3.00	42.57	26.82	4TENSILE	400	0.0065	413	420	8Cr-2WVTaB, 12Cr-1MoVW-1Ni	7.633	16.25	6.59
7	1.80	44.75	28.19	4TENSILE	400	0.0060	410	418	12Cr-1MoVW, 12Cr-1MoVW-2Ni	7.656	15.20	6.58
8	0.60	46.01	28.99	TEM	400	0.0085	404	408	All Steels**	7.656	15.20	6.58
Rx C/L												
9	0.60	46.01	28.99	4 CHARPY	400	0.0040	404	425	8Cr-2WVTaB	7.610	17.30	6.60
10	1.80	44.75	28.19	4 CHARPY	400	0.0040	397	417	Mix (9, 9, 9, 13C)*	7.610	17.30	6.60
11	3.00	42.57	26.82	4TENSILE	400	0.0065	413	419	9Cr-1MoVNb, 9Cr-1MoVNb-2Ni	7.610	17.30	6.60
12	4.20	39.46	24.86	4TENSILE	400	0.0070	413	419	9Cr-2WVTa, 9Cr-2WVTa-2Ni	7.610	17.30	6.60
13	5.40	35.44	22.33	4 CHARPY	400	0.0055	401	418	Mix (7C, 8C, 9C, 11C)*	7.633	16.25	6.59
14	6.60	30.50	19.21	4TENSILE	300	0.0055	307	311	8Cr-2WVTaB, 8Cr-2WVTa	7.650	17.24	6.42
15	7.80	24.63	15.52	TEM	300	0.0105	297	299	All Steels**	7.688	14.90	6.30
16	9.00	17.85	11.25	4 CHARPY	300	0.0075	303	312	Mix (1C, 3C, 15C, 16C)*	7.669	16.07	6.36

* Pos.	Temp. (C)	Alloy Mix
10	400	8Cr-2WVTaB, 8Cr-2WVTaB, 8Cr-2WVTaB, 8Cr-2WVTa
13	400	12Cr-1MoVW-2Ni, 9Cr-1MoVNb, 12Cr-1MoVW, 9Cr-1MoVNb-2Ni
16	300	12Cr-1MoVW-2Ni, 9Cr-1MoVNb, 12Cr-1MoVW, 9Cr-1MoVNb-2Ni

**The all steels TEM materials were treated as HT-9 and the material properties were allowed to vary with temperature.