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First Annual Progress Report on United States-Japan Collaborative Testing in the High Flux Isotope Reactor and the Oak Ridge Research Reactor for the Period Ending September 30, 1984

J. L. Scott
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S. Jitsukaw
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METALS AND CERAMICS DIVISION

FIRST ANNUAL PROGRESS REPORT ON UNITED STATES-JAPAN COLLABORATIVE TESTING IN THE HIGH FLUX ISOTOPE REACTOR AND THE OAK RIDGE RESEARCH REACTOR FOR THE PERIOD ENDING SEPTEMBER 30, 1984

J. L. Scott, M. L. Grossbeck, S. Jitsukaw, A. F. Rowcliffe,
M. P. Tanaka, Colin D. West, T. Kondo, and A. Hishinuma

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T. Kondo,‡ and A. Hishinuma‡

ABSTRACT

The first year of the Program of U.S.-Japan Collaborative Testing in HFIR and ORR has been completed. The program consists of eight Phase-I HFIR Target Capsules and two ORR Spectral-Tailoring Capsules equally shared. At the end of the first year, all eight HFIR capsules were completed and six were being irradiated in HFIR. Designs of both ORR capsules were completed, and a thermal mock-up of the 60/200°C capsule was successfully operated. Preparations were made for the installation of a new JEOL JEM-2000FX Microscope to be supplied by JAERI to ORNL for the collaboration. All work was completed on schedule and within costs.

1.0 INTRODUCTION

1.1 BACKGROUND

There exists an international consensus that the fusion materials test matrix of candidate materials, microstructural condition, temperature, stress state, and response is too large for any one country to accomplish alone, especially in the alloy-scoping stage. For this reason,

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†Japan Atomic Energy Research Institute, Tokai-mura, Japan, assigned to ORNL.

‡Japan Atomic Energy Research Institute, Tokai-mura.

international collaboration is viewed generally to be highly desirable. There are, however, many barriers to be overcome, including language, distance, institutions, and financing. All of these barriers were overcome for the program described in this report.

The Japanese have recognized the value of irradiations in HFIR (High Flux Isotope Reactor) and ORR (Oak Ridge Research Reactor) for a long time. These reactors are very useful for irradiation of nickel-containing steels such that both high levels of atomic displacements measured in displacements per atom (dpa) from fast neutrons and high helium contents via the two-step reaction, $^{58}Ni + 2n \rightarrow {}^{56}Fe + He$, are achieved simultaneously. For many austenitic and ferritic steels, irradiation of alloys in these mixed-spectrum fission reactors provides a useful simulation of a fusion-reactor irradiation, where high-energy neutrons produce displacements, helium, and hydrogen.

There is no mixed-spectrum fission reactor in Japan with the total flux of HFIR (peak 5×10^{19} neutrons/$m^2 \cdot s$), and the availability of other thermal reactors is such that the "spectral tailoring," as is done in ORR, is also not practical. In August 1978, Dr. J. Shimokawa, then Head of the Department of Fuels and Materials Research at JAERI (Japan Atomic Energy Research Institute), wrote to E. E. Bloom, ORNL (Oak Ridge National Laboratory), indicating that JAERI wished to irradiate capsules in HFIR and requesting information about costs and schedules. This letter initiated a series of discussions leading to the present collaboration. The major agreements leading to the collaboration are listed below. It should not be inferred that all agreements came about as a result of HFIR-ORR discussions, but each agreement was an essential step.

May 2, 1979 — Agreement between the government of Japan and the government of the United States of America on cooperation in research and development in energy and related fields.

August 24, 1979 — Exchange of notes between the two governments that established a coordinating committee on fusion and provided cooperative activities in (a) exchange programs, (b) a joint research project using Doublet III, (c) joint research for plasma physics, and (d) promotion of joint planning.

January 23, 1983 — Exchange of notes on the cooperation in fusion research and development among U.S. DOE (United States Department of Energy) and the Japanese Ministry of Science, Technology and Culture, the Ministry of International Trade and Industry, and the Japanese Science and Technology Agency. The cooperation may take the following forms:

1. Exchange of scientific and technical information;
2. Seminars and other meetings;
3. Short-term visits of scientists, engineers, and other experts to the facilities of the implementing agencies or of their designees;
4. Exchange or loan of equipment, instruments, and materials for testing;
5. Exchange of scientists, engineers, and other experts for participation in research, development, analysis, design, planning, and experimental activities conducted at the facilities of the implementing agencies or of the designees; and
6. Other cooperative activities as may be mutually agreed.

November 8, 1983 — Implementing arrangement between JAERI and DOE on cooperation in fusion research and development.

November 8, 1983 — Annex I to implementing arrangement between JAERI and DOE on cooperation in fusion research and development — U.S.-Japan collaborative testing of first wall and blanket structural materials with mixed spectrum fission reactors.

March 16, 1984 — Personnel assignment agreement between JAERI and ORNL on collaborative testing of first wall and blanket structural materials with mixed spectrum fission reactors.

Actual work on the collaboration began November 8, 1983.

1.2 OBJECTIVE

The objective of this collaborative program is to design, conduct, and evaluate joint irradiation experiments in HFIR and ORR for the purpose of investigating the irradiation response of Japanese and U.S. structural alloys to high levels of atomic displacement and helium content in order to establish the properties and behavior of such alloys and to evaluate their use for first wall and blanket structural applications in future fusion reactors.

1.3 SCOPE

This experimental program consists of eight HFIR capsules and two ORR spectral-tailoring capsules with space equally shared between the U.S. and Japanese programs. Four HFIR capsules will be irradiated to average exposures of 30 dpa, while the remaining four capsules will be irradiated to 50 dpa. In one capsule the specimens will be exposed to HFIR cooling water at about 60°C. The other seven capsules are designed so that specimen temperatures will be in the range 300 to 600°C. Tensile, fatigue, and transmission-electron-microscopy (TEM) specimens will be evaluated.

The two spectral-tailoring capsules will be irradiated in ORR to exposures of 30 dpa with interim examinations at 10 and 20 dpa. Each capsule will provide two different irradiation temperatures, so that specimens will be irradiated at 60, 200, 330, and 400°C. Approximately 650 specimens will be irradiated at each temperature. Data will be obtained on swelling, creep, tensile, fatigue crack-growth rate, and microstructural evolution.

1.4 MANAGEMENT

The management of the collaboration is carried out by a Steering Committee composed of four members, two each assigned by DOE and JAERI. All decisions are unanimous. The functions of the Steering Committee, which meets at least annually, are to:

1. Plan the collaborative program and develop the annual work plan and annual budget;
2. Review the implementation of the collaborative program;
3. Decide the experiments to be started, completed, or continued during the year;
4. Review the cost and projection of expenditures;
5. Review plans for joint paper publication;
6. Discuss personnel assignments;
7. Recommend the annual program of work, budget, and personnel assignments, and other such matters to DOE and JAERI for approval;
8. Report annually to the U.S.-Japan Coordinating Committee on Fusion Energy;

9. Select the time and place for the next Steering Committee meeting;
10. Discuss other matters as mutually agreed.

1.5 SCHEDULE AND COSTS

The costs for the collaborative program are shared equally between JAERI and DOE as are the individual capsules. The initial five-year plan of schedule and costs is shown in Table 1.5.1.

This report contains details of the first year's work on the collaborative program. For convenience, the work on HFIR and ORR will be discussed separately.

2.0 HFIR CAPSULES

2.1 DESCRIPTION OF FACILITY

The HFIR is a 100-MW beryllium-reflected, light-water-cooled-and-moderated, flux-trap reactor which uses a highly enriched cermet fuel. The reactor core, viewed from above (Fig. 2.1.1) (ref. 1), consists of a series of concentric annular regions, each about 0.6-m (2-ft) high. A 0.127-m-diam (5-in.) hole, referred to as the "flux trap," forms the center of the core. Into the flux trap are placed up to 30 "target" rods and 6 "peripheral-target-position" (PTP) rods for isotope production and irradiation testing. The target holder is shown in Fig. 2.1.2 (ref. 1). The fuel element, shown in Fig. 2.1.3 (ref. 1), consists of a single element with annular sections containing aluminum-clad U_3O_8-Al cermet fuel plates. Control plates, in the form of two poison-bearing concentric cylinders, are located just outside the fuel element.

The fuel element and control plates are surrounded by a beryllium reflector about 0.3-m (1-ft) thick. This reflector is divided into three regions (1) the removable reflector, (2) the semipermanent reflector, and (3) the permanent reflector. The beryllium is surrounded by a water reflector of effectively infinite thickness. The core operates at a pressure of 4 MPa (750 psi) and a coolant temperature between 50 and 73°C.

The radial flux distribution across the HFIR core is shown in Fig. 2.1.4 (ref. 1). The thermal flux has a peak value in the flux trap of about 3×10^{19} neutrons/m^2. The nonthermal flux peaks in the fuel

Table 1.5.1. Schedule and costs for U.S./Japan collaboration in HFIR and ORR

REACTOR	TASK	U.S. FISCAL YEAR 84	85	86	87	88
HFIR	CAPSULE ASSEMBLY					
	TEMPERATURE EXPERIMENT IRRADIATION					
	POSTIRRADIATION EXAMINATION					
ORR	60/200 DESIGN					
	60/200 ASSEMBLY AND CONNECTION					
	60/200 IRRADIATION					
	60/200 REINCAPSULATION					
	300/400 ASSEMBLY AND CONNECTION					
	300/400 IRRADIATION					
	300/400 REINCAPSULATION					
	FACILITY PREPARATION NO. 1					
	FACILITY PREPARATION NO. 2					
	POSTIRRADIATION EXAMINATION					
	COSTS (FY 1984 DOLLARS IN THOUSANDS)	1177.2	2065	2113.1	2064.5	2560.3

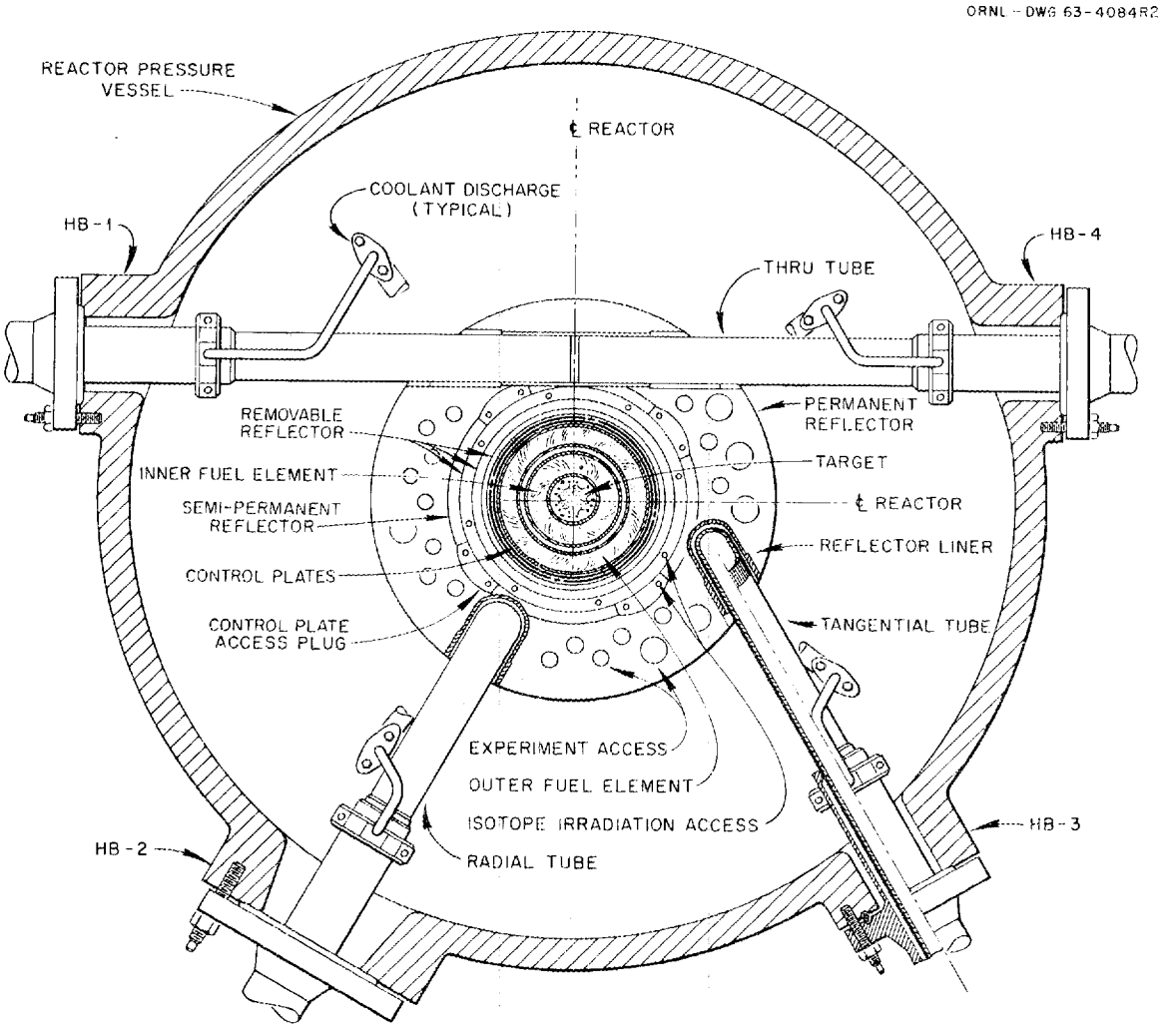
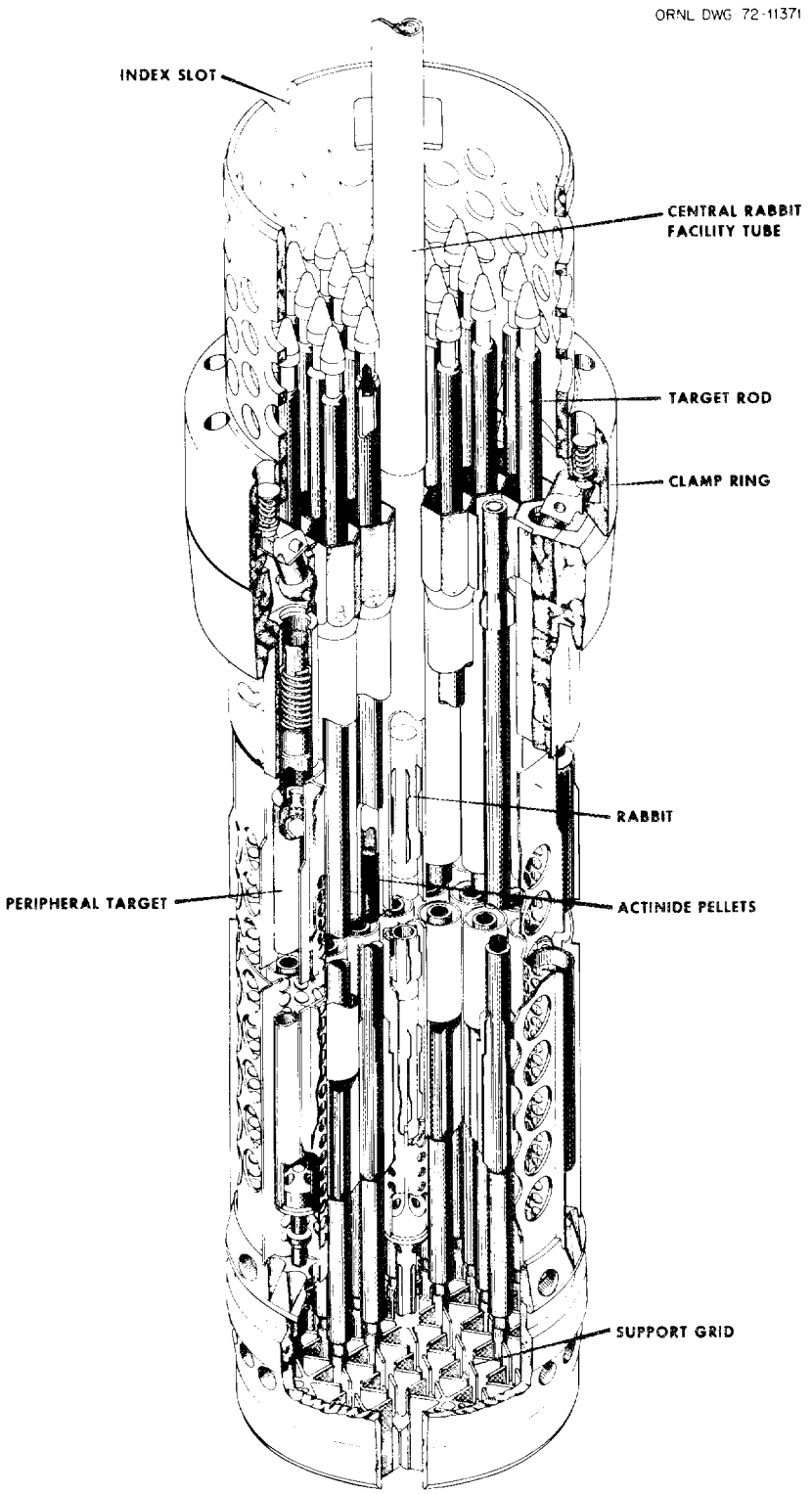


Fig. 2.1.1. Series of concentric annular regions, each about 0.6-m (2-ft) high.



TARGET HOLDER ASSEMBLY

Fig. 2.1.2. Target holder assembly.

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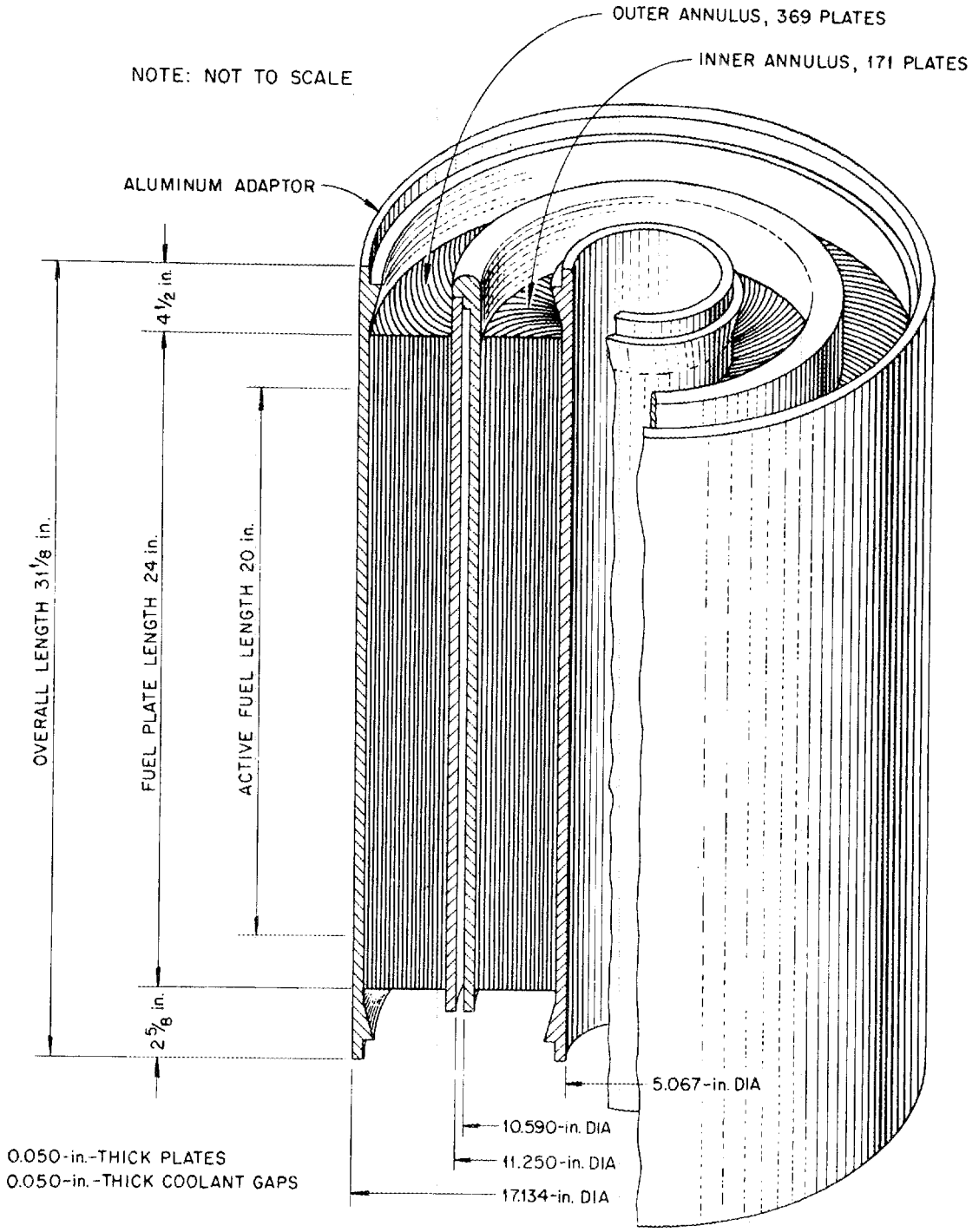

Fig. 2.1.3. HFIR fuel element.

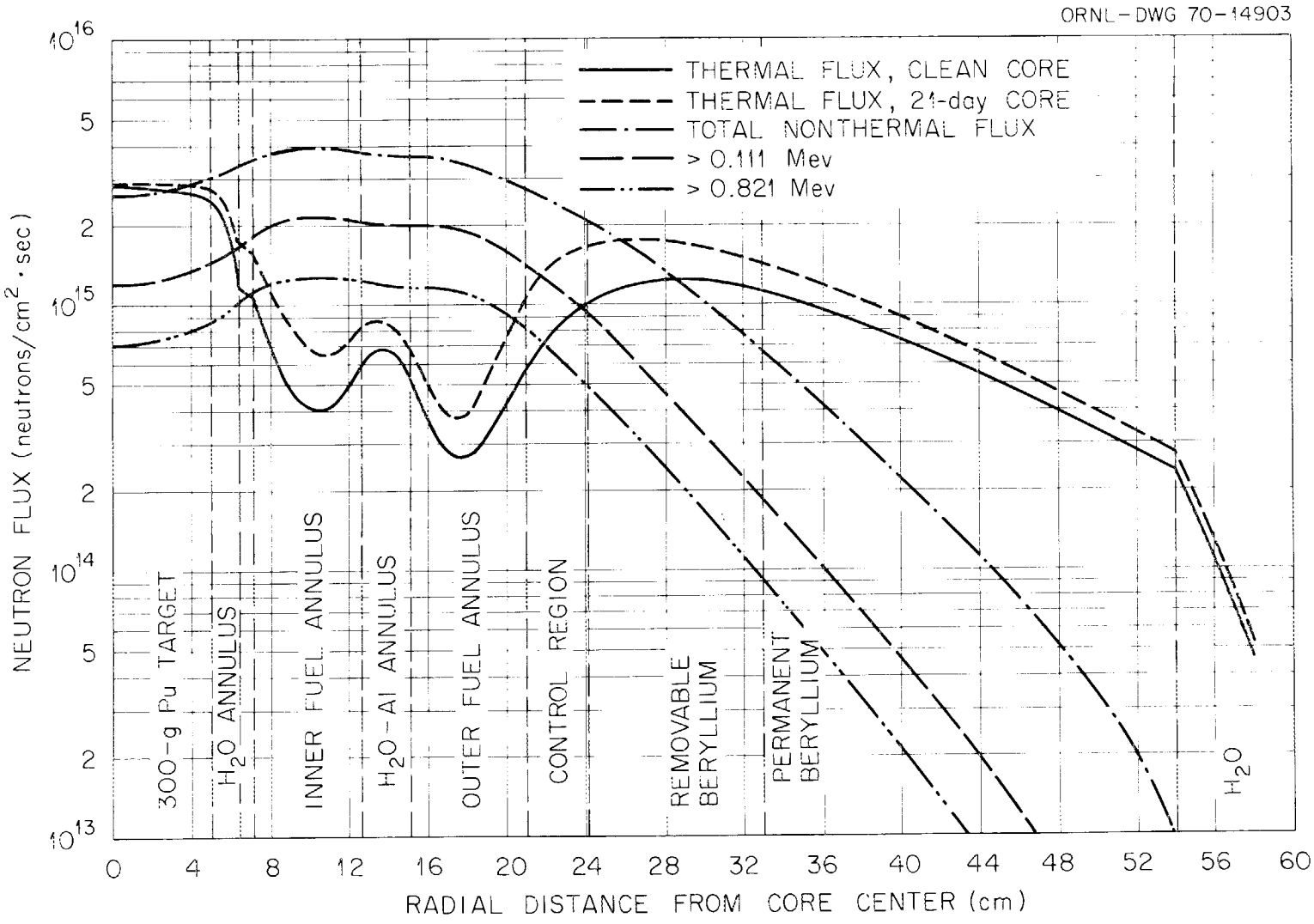

Fig. 2.1.4. Radial flux distribution across the HFIR core.

element itself and has a value of about 3×10^{19} neutrons/m^2 in the target region adjacent to the fuel element. The U.S.-Japan HFIR capsules are placed in target rods nearest the fuel elements to obtain the maximum fast/thermal-flux ratio.

2.2 CAPSULE DESCRIPTION

The capsule design for the U.S.-Japan HFIR experiments is similar to that used for the U.S. Alloy Development Program.[2] The specimens, which consist of rod tensile bars, fatigue bars, or tubes containing TEM disks, are placed in carefully machined aluminum specimen holders. During irradiation the specimens are heated by gamma heat. A helium gap between the specimens and the carefully contoured holders provides the thermal resistance to obtain desired temperatures. Previous calibrations are used to determine the correct gamma heating rates and helium gaps. Molybdenum TEM disks are also used as temperature monitors to check previous calibration curves. Specimen-holder assemblies for tensile specimens, fatigue specimens, and TEM disks are shown in Figs. 2.2.1, 2.2.2, and 2.2.3. An array of specimens is shown in Fig. 2.2.4, and a sealed tube is shown in Fig. 2.2.5 (ref. 3).

2.3 HFIR TEST MATRIX

The HFIR test matrix consists of 810 specimens designed to provide information on swelling, tensile, fatigue, and microstructural changes in the temperature range 55 to 600°C at fluences of 30 and 50 dpa. Design-type data will be obtained on 20% cold-worked type 316 stainless steel, on prime-candidate austenitic fusion alloys, and on the ferritic steels HT9 and modified 9 Cr-1 Mo. Data on swelling and microstructural evolution will be obtained on these alloys and on various exploratory alloys. The distribution of specimens is given in Table 2.3.1. Detailed loading lists for capsules HFIR JP1 to JP8 are given in Tables 2.3.2, 2.3.3, 2.3.4, 2.3.5, 2.3.6, and 2.3.7. Alloy compositions for U.S. disk specimens are given in Tables 2.3.8 and 2.3.9; those for Japanese disk specimens are given in Table 2.3.10. Alloy chemistries for tensile and fatigue specimens are given in Table 2.3.11 and thermomechanical treatments are in Table 2.3.12.

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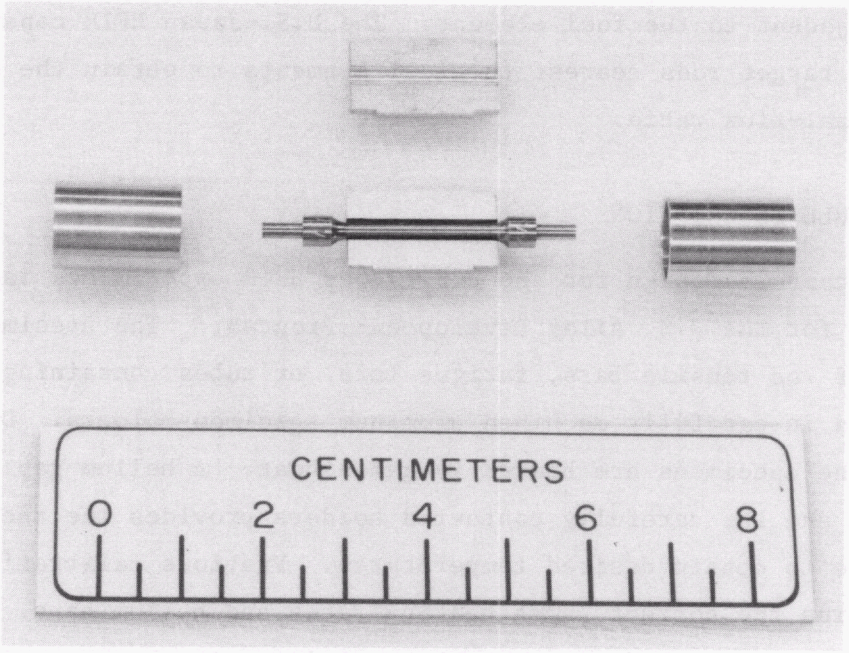

Fig. 2.2.1. Tensile specimen-holder assembly.

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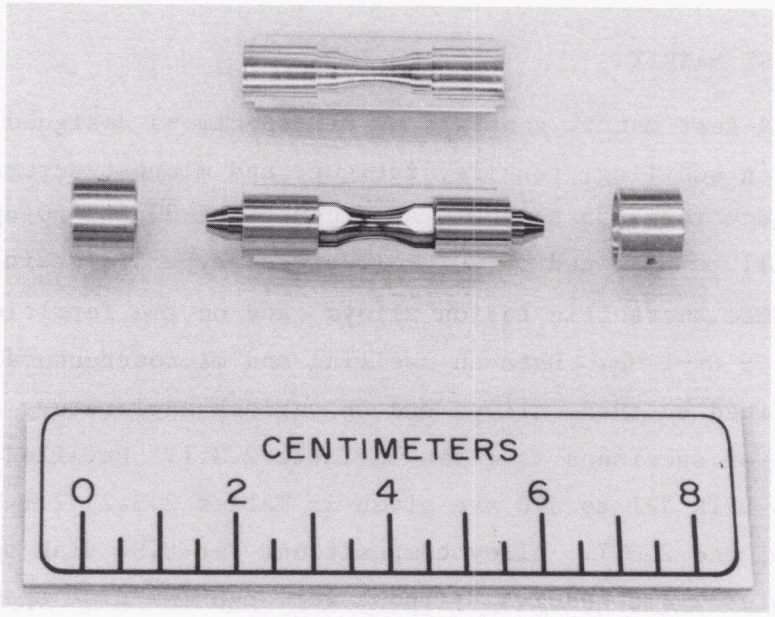

Fig. 2.2.2. Fatigue specimen-holder assembly.

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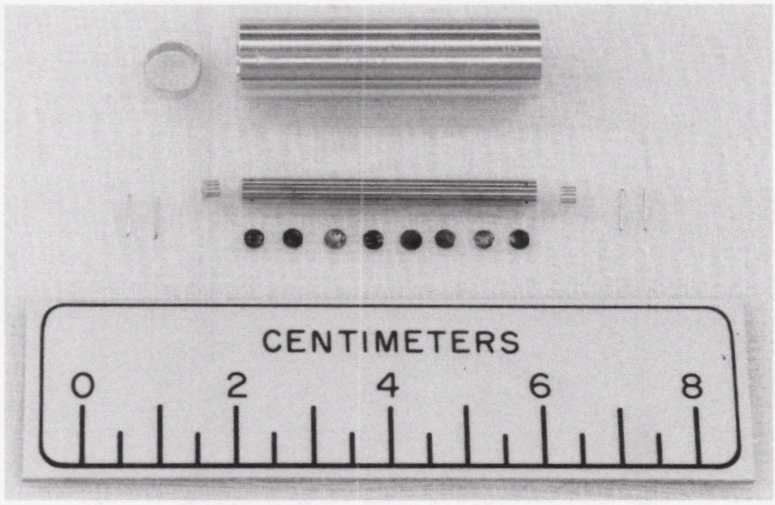

Fig. 2.2.3. TEM specimen-holder assembly.

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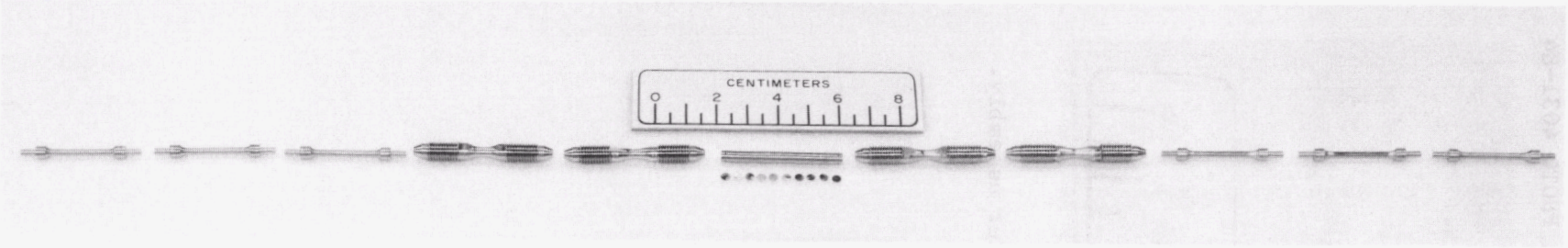

Fig. 2.2.4. Array of specimens.

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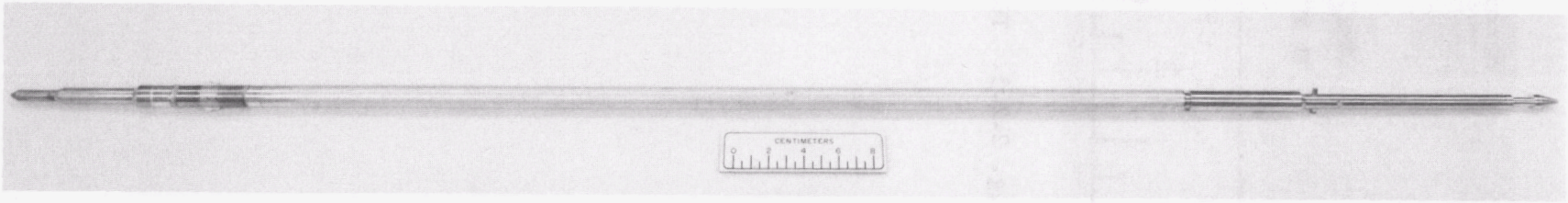

Fig. 2.2.5. Sealed tube.

Table 2.3.1. Distribution of HFIR specimens

Irradiation temperature (°C)	30 dpa			50 dpa		
	Tensile[a]	Fatigue[a]	Disk packet	Tensile[a]	Fatigue[a]	Disk packet
Specimens for United States						
55	0	0	0	20[b]	0	6[c]
300	2	0	0.5[d]	2	0	0.5[d]
400	3	0	0.5	2	0	0.5
430	0	6	0	0	6	0
500	3	0	1.5	3	0	0.5
550	0	2	0	0	0	0
600	3	0	0.5	2	0	0
TOTALS	11	8	3.0	29	6	1.5
Specimens for Japan						
55	0	0	0	20[b]	0	8[c]
300	4	0	0.5[d]	3	0	0.5[d]
400	4	0	0.5	3	0	0.5
430	0	6	0	1	4	0
500	4	0	0.5	3	0	0.5
550	0	0	0	0	0	0
600	2	0	0.5	1	0	0
TOTALS	14	6	2.0	31	4	1.5

[a]Rod specimens, identical to those used in previous HFIR experiments, except as noted.

[b]Sheet tensile specimens (SS-1).

[c]Rectangular strips, 42 × 1.5 × 0.25 mm for TEM disks.

[d]Disk size, 3 mm diameter × 0.25 mm thick; each packet contains at least 100 disks.

Table 2.3.2. Loading list for capsules HFIR-JP1, -JP2, and -JP3

Level	Specimen type	Temperature (°C)	Alloy	Condition	Identification		
					HFIR-JP1[a]	HFIR-JP2[b]	HFIR-JP3[a]
1	Tensile	300	PCA	B3	EL15	EL36	EL30
2	Tensile	400	PCA	B3	EL21	EL37	EL34
3	Tensile	500	PCA	B3	EL28	EL39	EC29
4	Fatigue	430	PCA[c]	A3[c]	AA1	EC157	EC152
5	Fatigue	430	Ref. 316	20% cold-worked	AA2	AA3	AA8
6	TEM	*d*	*d*	*d*	*d*	*d*	*d*
7	Fatigue	430	JPCA	PC2	FE1	FE3	FE5
8	Fatigue	430	JPCA	PC2	FE2	FE4	FE6
9	Tensile	500	JPCA	PS2	TB1	TB4	TB7
10	Tensile	400	JPCA	PS2	TB2	TB5	TB8
11	Tensile	300	JPCA	PS2	TE1	TB6	TB9

[a]Capsules HFIR-JP1 and -JP3 irradiated to 30 dpa.

[b]HFIR-JP2 irradiated to 50 dpa.

[c]Reference heat type 316 20%-cold-worked in HFIR-JP1.

[d]Capsules HFIR-JP1 and JP2 at 300°C; HFIR-JP3 at 400°C.

Table 2.3.3. Loading list for capsule HFIR-JP4 (50 dpa)

Level	Specimen	Temperature (°C)	Alloy	Condition	Identification
1	SS-1 Tensile	55	Ref. 316	20% CW	AB-41, -42, -45
			EP-838	20% CW	EP05
2	SS-1 Tensile	55	EP-838	20% CW	EP06, EP10
			PCA	B3	EL0, EL2
3	SS-1 Tensile	55	PCA	A3	EC284
			PCA20	25% CW	HV01
			PCA13	25% CW	HA1
			PCA19	25% CW	HT01
4	SS-1 Tensile	55	T9 Mod-2 Ni	NT4	TB01
			T9 Mod-2 Ni	NT4	TB02
			HT9	NT1	SB2
			HT9	NT1	SB3
5	SS-1 Tensile	55	HT9-2 Ni	NT2	SD01
			HT9-2 Ni	NT2	SD02
			T9 Mod	NT3	TA01
			T9 Mod	NT3	TA04
6	[a]	55	(Various)		
7	SS-1 Tensile	55	J316	15% CW	D-46, -47, -48
			J316	SA weld	D-16
8	SS-1 Tensile	55	J316	SA weld	D-17, -18
			JPCA	SA weld	CLW-1, -2
9	SS-1 Tensile	55	JPCA	SA weld	CLW-3
			JPCA	CW weld	DLW-1, -2, -3
10	SS-1 Tensile	55	J316	SA	D-1, -2
			J316	CW	D-31, -32
11	SS-1 Tensile	55	JPCA	SA	CL-1, -2
			JPCA	CW	DL-1, -2

[a]Fourteen strip specimens 42 × 4.6 × 0.25 mm.

Table 2.3.4. Loading list for capsule HFIR-JP5 (50 dpa)

Level	Specimen type	Temperature (°C)	Alloy	Condition	Identity
1	Tensile	300	PCA	A3	EC34
2	Tensile	400	PCA	A3	EC31
3	Tensile	500	PCA	A3	EC32
4	Fatigue	430	PCA	A3	EC153
5	Fatigue	430	Ref. 316	20% CW	AA27
6	TEM	400	[a]	[a]	[a]
7	Fatigue	430	JPCA	PC2	FE10
8	Fatigue	430	JPCA	PC2	FE11
9	Tensile	500	JPCA	PC2	TE7
10	Tensile	400	JPCA	PC2	TE8
11	Tensile	300	JPCA	PC2	TE9

[a]One hundred disks shared between U.S. and Japan.

Table 2.3.5. Loading list for capsule HFIR-JP6 (30 dpa)

Level	Specimen type	Temperature (°C)	Alloy	Condition	Identity
1	Tensile	600	PCA	B3	EL24
2	TEM	500	*a*	*a*	*a*
3	Tensile	500	Ref. 316	20% CW	AA42
4	Fatigue	430	PCA	A3	EC156
5	Fatigue	430	PCA	A3	EC161
6	TEM	600	*b*	*b*	*b*
7	Fatigue	430	JPCA	PC2	FE12
8	Fatigue	430	JPCA	PC2	FE13
9	Tensile	500	JPCA	PC2	TE10
10	Tensile	400	JPCA	PC2	TE11
11	Tensile	300	JPCA	PC2	TE12

[a]One hundred disks for U.S. program for subsequent irradiation in FFTF (Fast-Flux Test Facility).

[b]One hundred disks shared between U.S. and Japan.

Table 2.3.6. Loading list for capsule HFIR-JP7 (30 dpa)

Level	Specimen type	Temperature (°C)	Alloy	Condition	Identity
1	Tensile	600	PCA	A3	EC36
2	Tensile	600	PCA	B3	EL29
3	Tensile	500	PCA	B3	EL31
4	Fatigue	550	Ref. 316	20% CW	AA54
5	Fatigue	550	PCA	B2	EF5
6	TEM	500	*a*	*a*	*a*
7	Tensile	600	JPCA	PC2	TE16
8	Tensile	600	JPCA	PC2	TE17
9	Tensile	500	JPCA	PC2	TE18
10	Tensile	400	JPCA	PC2	TE19
11	Tensile	300	JPCA	PC2	TE20

[a]One hundred disks shared between U.S. and Japan.

Table 2.3.7. Loading list for capsule HFIR-JP8 (50 dpa)

Level	Specimen type	Temperature (°C)	Alloy	Condition	Identity
1	Tensile	600	PCA	B3	EL26
2	Tensile	600	PCA	B3	EL35
3	Tensile	500	PCA	B3	EL25
4	Fatigue	430	PCA	A3	EC163
5	Fatigue	430	Ref. 316	20% CW	AA53
6	TEM	500	*a*	*a*	*a*
7	Tensile	600	JPCA	PC2	TE21
8	Tensile	500	JPCA	PC2	TE22
9	Tensile	430	JPCA	PS2	TB12
10	Tensile	400	JPCA	PC2	TE23
11	Tensile	300	JPCA	PC2	TE24

[a]One hundred disks shared between U.S. and Japan.

Table 2.3.8. Alloy chemistries for U.S. Alloy Development Program disk specimens

Alloy	Content, wt %[a]														
	Cr	Ni	Mo	Mn	Si	Ti	Nb	V	C	N	P	Co	Cu	B	S
PCA	14.0	16.2	2.3	1.8	0.4	0.24			0.05	0.01	0.01			0.001	0.003
PCA-1	14.0	16.0	2.5	2.1	<0.01	0.13	0.12	<0.01	0.04	0.003	<0.001	<0.01	0.02	<0.001	0.008
PCA-3	14.3	15.8	2.5	2.0	0.4	0.13	0.11	<0.01	0.056	0.005	<0.001	<0.01	0.02	<0.001	0.007
PCA-6	14.0	16.0	2.4	1.9	0.4	0.23	0.01	<0.01	0.083	0.004	<0.001	<0.01	0.02	<0.001	0.007
PCA-8	13.9	16.0	2.7	2.1	<0.01	0.17	0.14	<0.01	0.081	0.007	<0.001	<0.01	0.02	<0.001	0.008
PCA-9	13.8	16.0	2.5	2.0	0.4	0.25	<0.01	<0.01	0.073	0.005	0.03	<0.01	0.02	<0.001	0.007
PCA-10	13.8	15.9	2.5	1.9	0.4	0.3	0.1	0.02	0.04	0.002	0.002	<0.01	0.02	<0.001	0.009
PCA-11	13.8	16.0	2.5	1.9	0.4	0.3	0.1	0.5	0.04	0.002	0.002	<0.01	0.03	<0.001	0.008
PCA-12	13.8	15.9	2.4	1.9	0.4	<0.01	0.47	0.01	0.044	0.004	0.002	0.01	0.02	<0.001	0.008
PCA-13	13.8	15.9	2.5	1.9	0.4	0.3	0.1	0.5	0.063	0.002	0.002	<0.01	0.02	<0.001	0.009
PCA-16	15.9	14.1	2.5	1.9	0.4	0.27	<0.01	0.02	0.051	0.002	0.002	<0.01	0.02	<0.001	0.009
PCA-17	15.8	16.0	2.5	1.9	0.4	0.3	<0.001	0.03	0.047	0.002	0.002	<0.01	0.02	<0.001	0.009
PCA-18	17.6	16.1	2.5	1.9	0.4	0.27	<0.01	0.02	0.044	0.002	0.002	<0.01	0.02	<0.001	0.009
PCA-00	14.0	16.0	2.46	2.0	0.4	0.24	<0.01	0.02	0.056	0.001	0.002	0.01	0.02	<0.001	0.008
PCA-19	13.8	19.9	2.44	2.1	0.44	0.28	0.1	0.5	0.076	0.002	0.030	0.01	0.01	<0.001	0.006
PCA-20	13.8	16.1	2.5	2.1	0.42	0.28	0.1	0.5	0.083	0.006	0.07	0.01	0.01	0.001	0.007
PCA-21	15.8	15.8	2.44	3.4	0.4	0.27	0.1	0.5	0.077	0.006	0.06	<0.01	0.05	0.001	0.007
PCA-22	13.8	15.9	2.4	2.5	0.4	0.28	0.1	0.5	0.078	0.004	0.03	<0.01	0.05	0.003	0.007
EP-838[b]	11–13	4.4–4.8	0.3–0.6	12–14	0.6				0.02	0.05–0.09	0.4			0.0005	0.4
N-lot 316	16.5	13.5	2.5	1.6	0.5				0.05	0.006	0.013			0.0008	0.006
Ref. 316	17.3	12.4	2.1	1.7	0.7		0.08		0.05		0.04	0.35		0.0004	0.015
DO-316	18.0	13.0	2.6	1.9	0.8	0.05			0.05	0.05	0.01	0.004		0.0005	0.016
D9-699	14.2	15.2	1.95	2.1	0.5	0.23	0.01	0.02	0.033	0.004	0.005	0.02	0.02	<0.001	0.001
D9-697	14.4	16.2	1.5	1.9	0.5	0.25	<0.01	0.02	0.035	0.009	0.003	0.03	0.02	0.0001	0.002
D9-A7	13.7	16.3	2.5	2.0	1.42	0.18	0.01	0.023	0.045	0.011	0.075	0.06	0.03	0.0005	0.017

[a]Balance iron.

[b]This alloy also contains approximately 1% Al.

Table 2.3.9. Compositions of Damage Analysis and Fundamental Studies Program alloys[a]

Alloy designation	Concentration, wt %						
	Fe	Ni	Cr	Mn	C	N	Si
AMCR	Bal	0.5	18.0	18.0	0.1	0.4	0.6
AE37	Bal	35.0	7.5	-	-	-	-
CE37	Bal	35.0	7.5	-	-	-	-
R77	Bal	0.5	2.0	30.0	0.40	0.15	0.4
A5	Bal	14.0	16.0	2.0	0.04	-	1.5
R111	Bal	14.0	10.0	2.0	0.04	-	1.5
A61	Bal	14.0	16.0	2.0	0.04	-	0.8
R100	Bal	18.0	16.0	2.0	0.04	-	1.5
R103	Bal	18.0	10.0	2.0	0.04	-	1.5
R106	Bal	18.0	10.0	2.0	0.04	-	0.8
R107	Bal	18.0	10.0	2.0	0.04	-	1.5
R92	Bal	40.0	7.5	2.0	0.08	-	0.1
R94	Bal	40.0	7.5	2.0	0.02	-	0.1
R27	Bal	40.0	7.5	2.0	0.08	-	0.1
316	Bal	14.0	17.0	1.7	0.05	-	0.6

[a]All materials in 20%-cold-worked condition except AE37 which is solution annealed 1/2 h at 1030°C.

Table 2.3.10. Alloy chemistries for Japanese disk specimens in HFIR-JP1 through -JP4 capsules

Alloy	Content, wt %												
	C	Si	Mn	P	S	Ni	Cr	Mo	Ti	Nb	B	N	Co
JPCA	0.06	0.50	1.77	0.027	0.005	15.60	14.22	2.28	0.24		0.0031	0.0039	0.002
JPCA(QS)	0.06	0.53	1.79	0.027	0.009	16.22	14.51	2.37	0.20		0.0035	0.009	0.025
C	0.02	0.51	1.56	0.017	0.007	15.6	15.4	2.4	0.25	0.08		0.0018	
K	0.02	0.48	1.46	0.015	0.005	17.56	17.99	2.6	0.29			0.004	
Type 316	0.058	0.61	1.80	0.028	0.003	13.52	16.75	2.46	0.005	<0.1			<0.1
Ferritic steel[a]	0.056	0.74	0.70	0.008	0.0059	1.37	8.86	2.46		0.06		0.0069	

[a]Also Al, 0.04; V, 0.11; Cu, 0.02; W, 0.01.

Table 2.3.11. Alloy chemistries for tensile and fatigue specimens in HFIR-JP1 through -JP8 capsules

Alloy	Heat	Content, wt %[a]																
		Cr	Ni	Mo	Mn	Si	Ti	Nb	V	C	N	P	Co	Cu	B	S	Al	W
U.S. PCA	K-280	14.0	16.2	2.3	1.8	0.4	0.24			0.05	0.01	0.01			0.001	0.003		
JPCA		14.22	15.60	2.28	1.77	0.50	0.24			0.06	0.004	0.027	0.002		0.003	0.005		
Ref. 316	X15893	17.3	12.4	2.1	1.7	0.70		0.08		0.05		0.04	0.35		0.004	0.015		
J316		16.75	13.52	2.46	1.80	0.61	0.005			0.058		0.028	<0.1			0.003		
EP-838 (USSR)		12.0	4.6	0.4	13.0	0.6				0.02	0.08	0.4			0.0005	0.4	1.0	
HT9	XAA3587	11.99	0.43	0.93	0.50	0.18	0.003	0.018	0.27	0.21	0.020	0.011	0.017	0.05	<0.001	0.004	0.030	0.54
HT9—2 Ni	XAA3589	11.71	2.27	1.02	0.49	0.14	0.003	0.015	0.31	0.20	0.017	0.011	0.021	0.05	<0.001	0.004	0.028	0.54
T9 Mod	XA3590	8.62	0.11	0.98	0.36	0.08	0.002	0.063	0.21	0.09	0.050	0.008	0.013	0.03	<0.001	0.004	0.013	0.01
T9 Mod—2 Ni	XA3591	8.57	2.17	0.98	0.36	0.08	0.002	0.066	0.22	0.064	0.053	0.008	0.015	0.04	<0.001	0.004	0.015	0.01

[a]Balance iron.

Table 2.3.12. Thermomechanical treatment codes

Code	Alloy	Final alloy condition
PS-1	JPCA	Solution-annealed (1175°C/1 h)
PS-2	JPCA	Solution-annealed (1100°C/1 h)
PS-3	JPCA	Solution-annealed (1050°C/1 h)
PC-1	JPCA	Solution-annealed (1100°C/1 h) + 10% cold-worked
PC-2	JPCA	Solution-annealed (1100°C/1 h) + 15% cold-worked
PC-3	JPCA	Solution-annealed (1100°C/1 h) + 20% cold-worked
A0	U.S. PCA	Solution-annealed (1050°C/1 h)
A1	U.S. PCA	Solution-annealed (1100°C/0.5 h)
A3	U.S. PCA	A1 treatment + 25% cold-worked
B3	U.S. PCA	A1 treatment + 800°C/8 h + 25% cold-worked
NT-1	U.S. ferritic alloys	Normalized (1050°C/0.5 h/AC[a]); tempered (780°C/2.5 h)
NT-2	U.S. ferritic alloys	Normalized (1050°C/0.5 h/AC); tempered (700°C/5 h)
NT-3	U.S. ferritic alloys	Normalized (1040°C/0.5 h/AC); tempered (760°C/1 h)
NT-4	U.S. ferritic alloys	Normalized (1040°C/0.5 h/AC); tempered (700°C/5 h)

[a]AC = Air-cooled.

2.4 SCHEDULE AND STATUS

The schedule for design, fabrication, and irradiation of the ORNL-JAERI HFIR capsules is shown in Figs. 2.4.1 and 2.4.2. The explanation of milestones is given in Fig. 2.4.3. The HFIR thermal-analysis experiment and the ORR experiment are described in later sections of this report. The status of the eight HFIR capsules at the end of the reporting period is shown in Table 2.4.1.

2.5 HFIR TEMPERATURE EXPERIMENT

As discussed earlier, the HFIR-JP capsules are uninstrumented so that specimen operating temperatures are determined by calculation. Although the calculations have been verified by melt wire and passive thermal monitors, such as the lattice expansion of SiC, a temperature-measurement experiment using thermocouples would provide a direct verification of the calculated values. Such an experiment is to be designed in the latter part of FY 1985; therefore, detailed discussions must be deferred.

3.0 ORR SPECTRAL-TAILORING EXPERIMENTS

In a fusion reactor, high-energy neutrons (up to 14 MeV) generate hydrogen and helium in a metal lattice via nuclear transformations. At operating temperatures, the hydrogen normally diffuses rapidly out of the steel with no permanent effects anticipated. However, helium is highly insoluble, becomes trapped at various lattice defects, and can have large effects on swelling, microstructural evolution, and mechanical properties.[4,5]

To study the response of alloys to the fusion environment, one needs a high-flux, high-fluence source of 14-MeV neutrons. Since a source of this type does not exist, various simulation techniques must be used. As mentioned earlier, for alloys containing nickel irradiated in a mixed-spectrum reactor, one can use the two-step thermal reaction to produce helium while simultaneously producing displacements via fast-neutron atom collisions. For alloys such as austenitic stainless steels, which contain 14-16% Ni, these reactions lead to a helium production rate on the order

ORNL DWG 83-16470

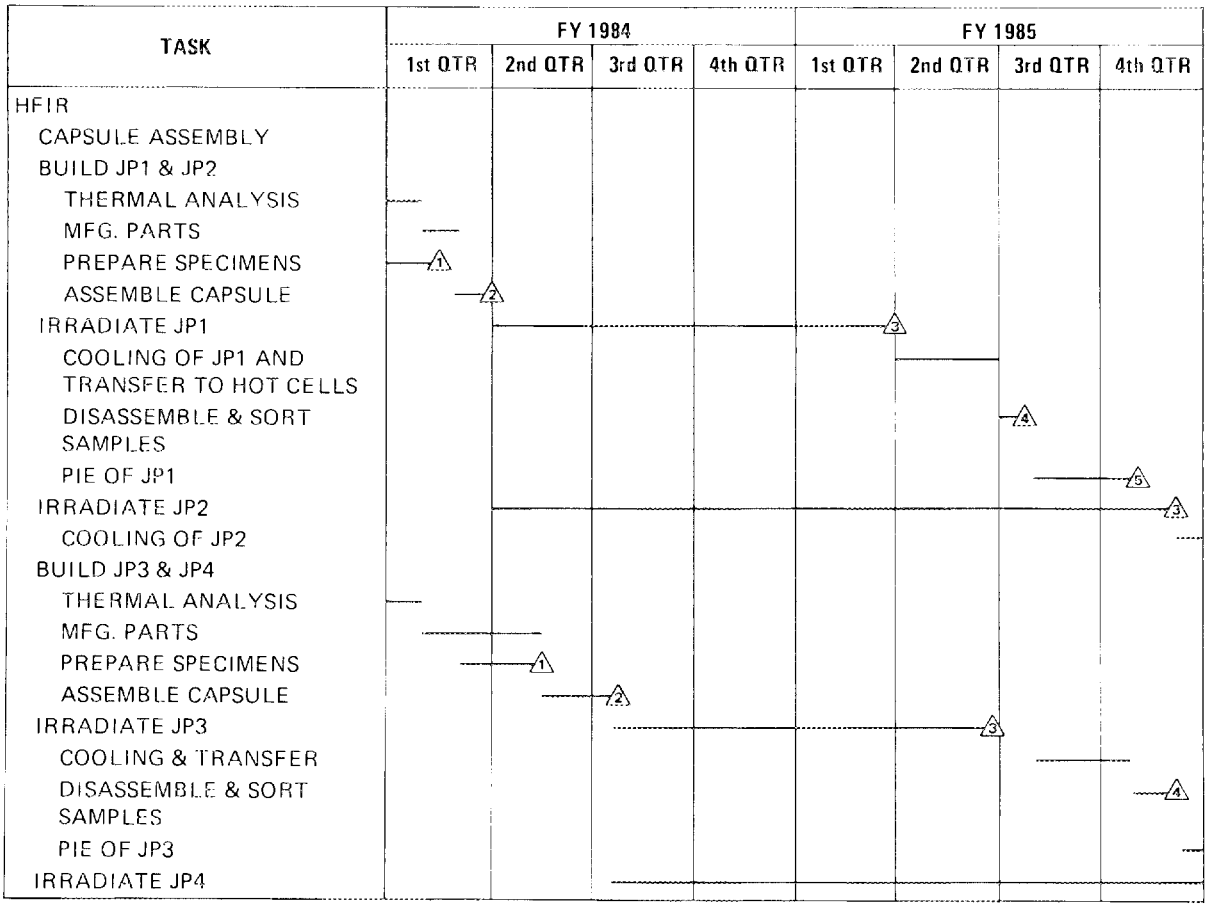

Fig. 2.4.1. Schedule for design, fabrication, and irradiation of U.S.-Japan HFIR capsules.

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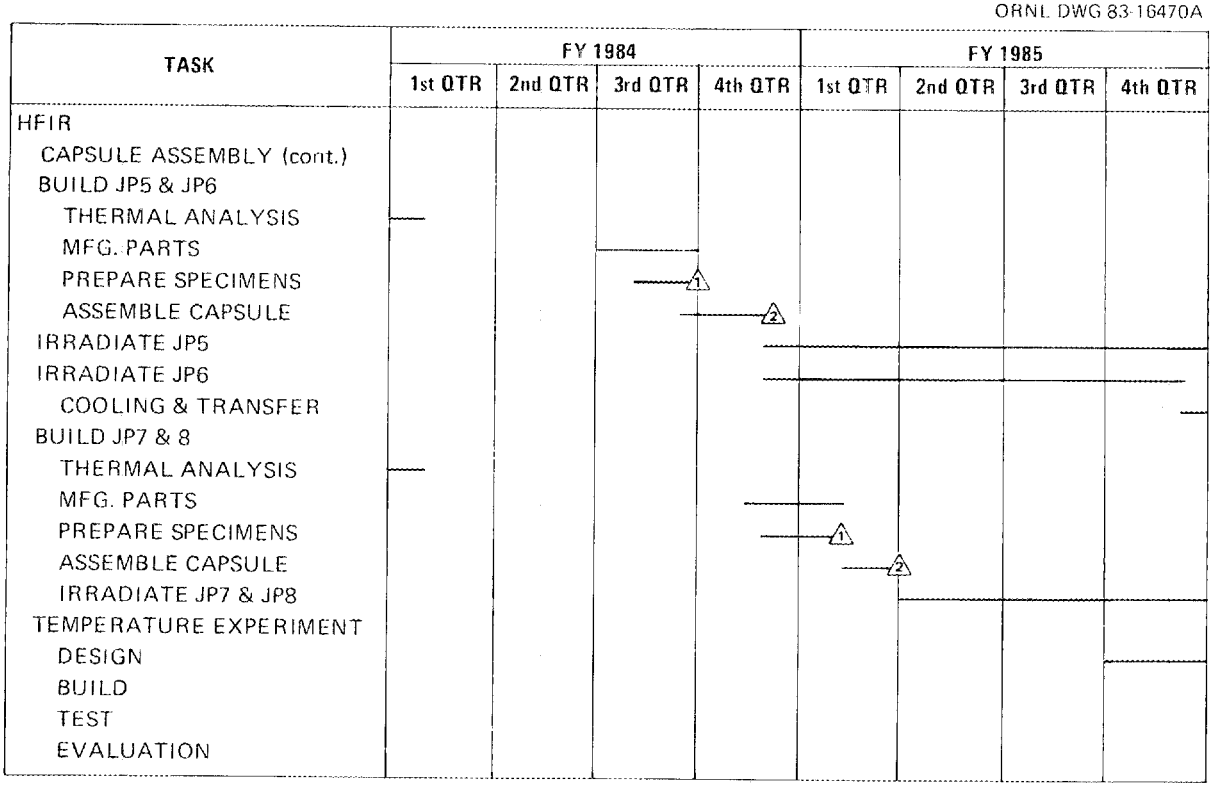

Fig. 2.4.2. Schedule for design, fabrication, and irradiation of U.S.-Japan HFIR capsules (continued).

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EXPLANATION OF MILESTONES

1. DELIVER SPECIMENS TO ORNL
2. INSERT JP CAPSULE IN HFIR
3. REMOVE JP CAPSULE FROM HFIR
4. BEGIN PIE OF JP CAPSULE
5. COMPLETE PIE OF JP CAPSULE
6. SELECT ORR DESIGN CONCEPT
7. VERIFY ORR DESIGN CONCEPT
8. INSERT SPECTRAL-TAILORING CAPSULE IN ORR

Fig. 2.4.3. Explanation of milestones.

Table 2.4.1. Status of U.S./Japan HFIR capsules

Capsule	Reactor[a,b] exposure (MWd)	Present[c] dpa level	Goal dpa level
JP1	22 855	22	30
JP2	22 855	22	50
JP3	12 467	12	30
JP4	12 467	12	50
JP5	2 108	2	50
JP6	2 108	2	30
JP7	0	0	30
JP8	0	0	50

[a]Date: October 2, 1984.

[b]HFIR power level: 100 MW.

[c]Type 316 stainless steel.

of 50 ppm/dpa. The helium generation rate in austenitic stainless steels can be reduced to the range expected in a fusion environment (10-15 ppm/dpa) by using the spectral-tailoring method. The principle of this method is shown in Fig. 3.0.1. Initially, the specimen-containing capsule is surrounded with water to thermalize as many neutrons as possible. The thermal neutrons react with Ni to form He. Later a solid aluminum core piece is placed around the capsule, making the flux harder. Finally, in the third phase, a Hf sleeve is placed around the capsule to absorb thermal neutrons. The effects of spectral tailoring in ORR on type 316 stainless steel are shown in Fig. 3.0.2. In a fusion reactor the He appm/dpa ratio has constant value of about 14, depending upon the blanket design. In a fast reactor, such as EBR-II, very little helium is produced; and, in a mixed spectrum reactor like HFIR when no spectral tailoring is employed, too much He is produced after about 3 dpa. In a mixed-spectrum fission reactor like the ORR, for example, with U.S.-Japan capsule MFE-7J, a close approximation to the correct He/dpa ratio can be achieved by spectral tailoring.

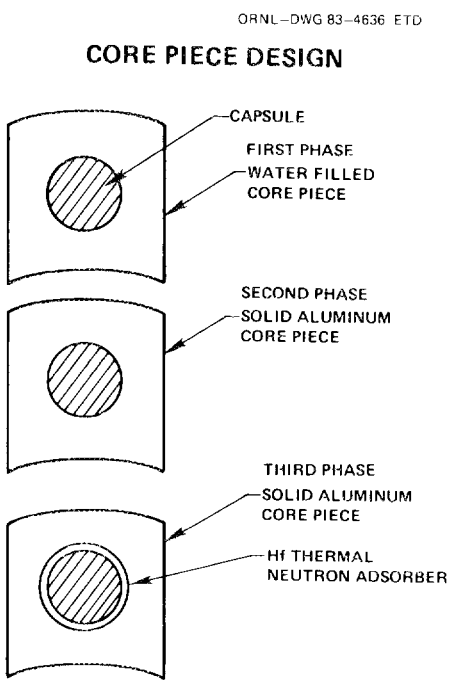

Fig. 3.0.1. Spectral-tailoring method.

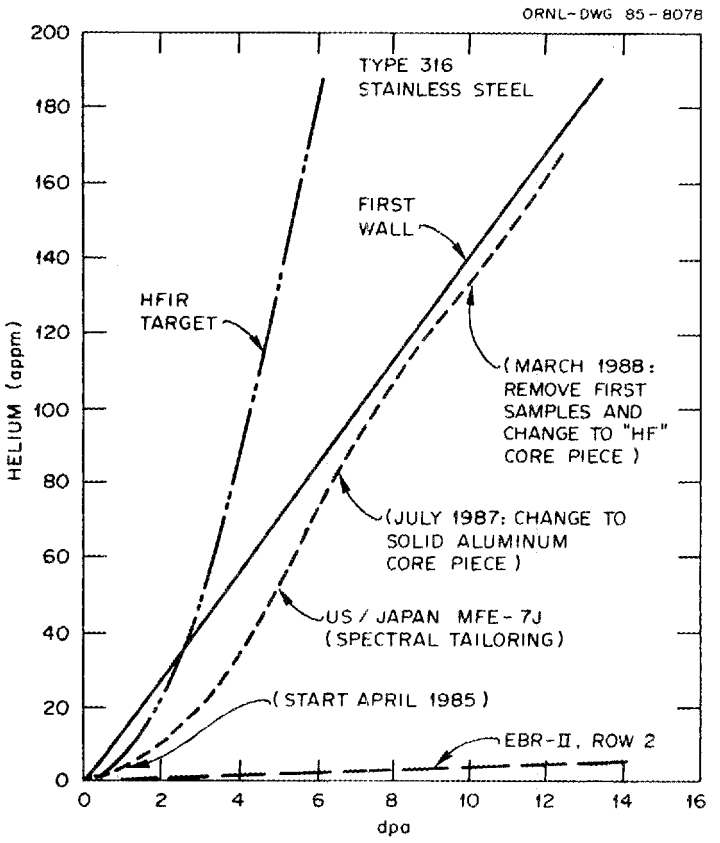

Fig. 3.0.2. Effects of spectral tailoring in ORR on type 316 stainless steel.

The ORR is a 30-MW swimming-pool reactor containing highly enriched, aluminum-clad, UAL_3-Al, dispersion fuel elements. Each fuel element is ~7.0 cm square × 0.61 m long. Representative neutron fluxes in ORR are shown in Table 3.1.1 (ref. 6). A spectral-tailoring capsule occupies a fuel-element position in the core; a typical core configuration, as viewed from above, is shown in Fig. 3.0.3 (ref. 6). In particular, the U.S.-Japan Spectral-Tailoring capsules will occupy position C-3 and E-3. For spectral tailoring these positions will be surrounded with fuel elements to increase the local flux and reduce flux gradients. Spectral tailoring has been carried out previously as a part of the U.S. Alloy Development Program for fusion.[7]

Table 3.1.1. Representative peak neutron fluxes and gamma heating rates available in ORR experiment facilities

Facility	Thermal flux (neutrons/m^2/s)	Fast flux[a] (neutrons/m^2/s)	Gamma heating (W/g graphite)
Core position A-2	1.7×10^{18}	1.17×10^{18}	2.1
Core position A-7	1.1×10^{18}	1.6×10^{17} (>2.9 MeV)	
Core position A-9	9.5×10^{17}		
Core position B-3	1.65×10^{18}	2.7×10^{18}	
Core position B-8	2.5×10^{18}	1.4×10^{18}	
Core position B-9	1.7×10^{18}		1.5
Core position C-3	2.4×10^{18}	3.5×10^{18} (>0.18 MeV)	7.7
Core position C-5[b]	3.5×10^{18}	3.4×10^{18}	
Core position C-8	2.6×10^{18}		3.5
Core position D-1		1.53×10^{18}	3.0
Core position D-8[c]	2.25×10^{18}		
Core position E-3	2.2×10^{18}	2.9×10^{18} (>0.18 MeV)	7.9
Core position E-5	3.8×10^{18}		
Core position E-8		1.46×10^{18}	2.7
Core position E-9	1.4×10^{18}		
Core position F-1	1.65×10^{18}	1.13×10^{18}	2.1
Core position F-7		1.86×10^{18}	4.0
Core position F-8	2.1×10^{18}		
Core position G-1	1.2×10^{18}		
Core position G-2	1.7×10^{18}		
Core position G-4	2.1×10^{18}		
Core position G-5	2.2×10^{18}		
Poolside P-5	1.5×10^{18}	1.3×10^{18}	
Poolside P-9	8.3×10^{17}		
Beam tube HB-5	1×10^{18} (reactor end)		
Beam tube HB-5	2×10^{13} (collimator end)		
Beam tube HB-6	2.3×10^{12} (collimator end)		

[a] Except as noted: >0.1 MeV.
[b] In partial fuel element surrounded by 200-g elements.
[c] Hydraulic tube.

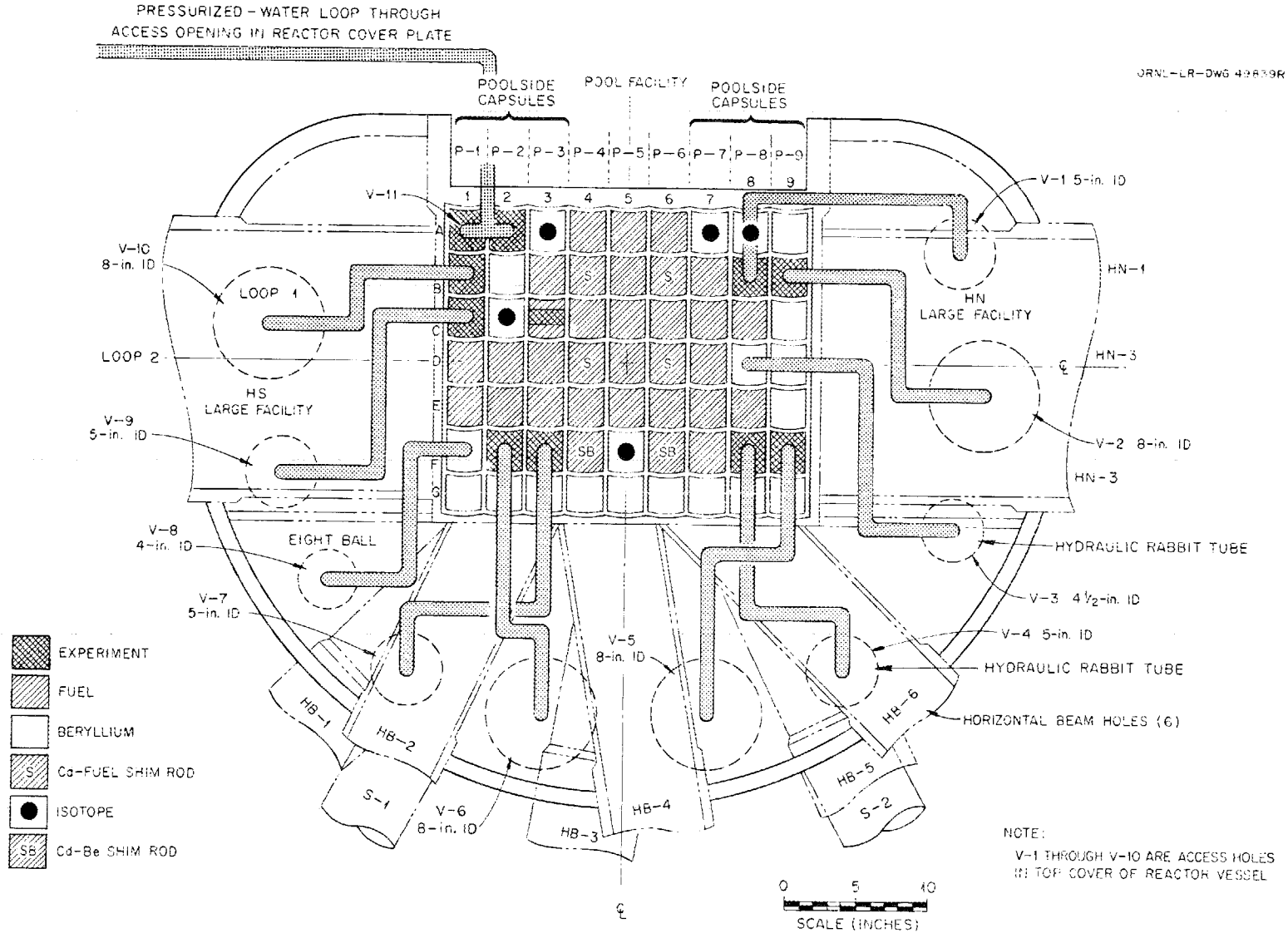

Fig. 3.0.3. Typical fuel-element core configuration, as viewed from above.

Each U.S. spectral-tailoring capsule had two independent temperature zones filled with sodium-potassium eutectic (NaK) for good heat transfer. Temperatures were measured with thermocouples placed down the central spine of the capsule and were controlled by adjusting the composition of a He-Ne mixture in an annulus between the primary and secondary containment. Flux monitors were placed in the central spine and in specimen positions. A schematic of the U.S. spectral-tailoring capsule is shown in Fig. 3.0.4 (ref. 7). The temperatures in MFE-4A were 330 and 400°C and in MFE-4B were 500 and 600°C.

3.1 U.S.-JAPAN ORR CAPSULE DESIGN

Under the collaboration two new spectral-tailoring capsules are being irradiated. Capsule MFE-7J will operate at 300 and 400°C and has the same basic design of MFE-4A. The only difference is that each temperature zone has been lengthened 4.4 cm to accommodate additional specimens. Capsule MFE-6J will operate at 60 and 200°C. The 60°C region is the reactor coolant temperature, and the specimens are in contact with the ORR cooling water.

The 200°C region is especially challenging. Since NaK does not wet stainless steel below 300°C, it would not be a good heat-transfer medium. The alternate-design approach selected was to use a solid piece of aluminum as the heat-transfer medium with carefully machined slots to contain flat tensile specimens and holes to contain pressurized tubes and TEM disk packets. It was also found convenient to put the 60°C region outside the 200°C zone instead of having one above the other. A schematic of MFE-6J is shown in Fig. 3.1.1.

3.2 ORR TEST MATRIX

The test matrix for the ORR capsules consists of a variety of types of specimens listed in Table 3.2.1. The number of specimens is limited at 300 and 400°C by the total mass of specimens of 250 g at each temperature. The specimens must be distributed uniformly along the length so that there is no more than 21.4 g per cm. These limits are set by the allowable

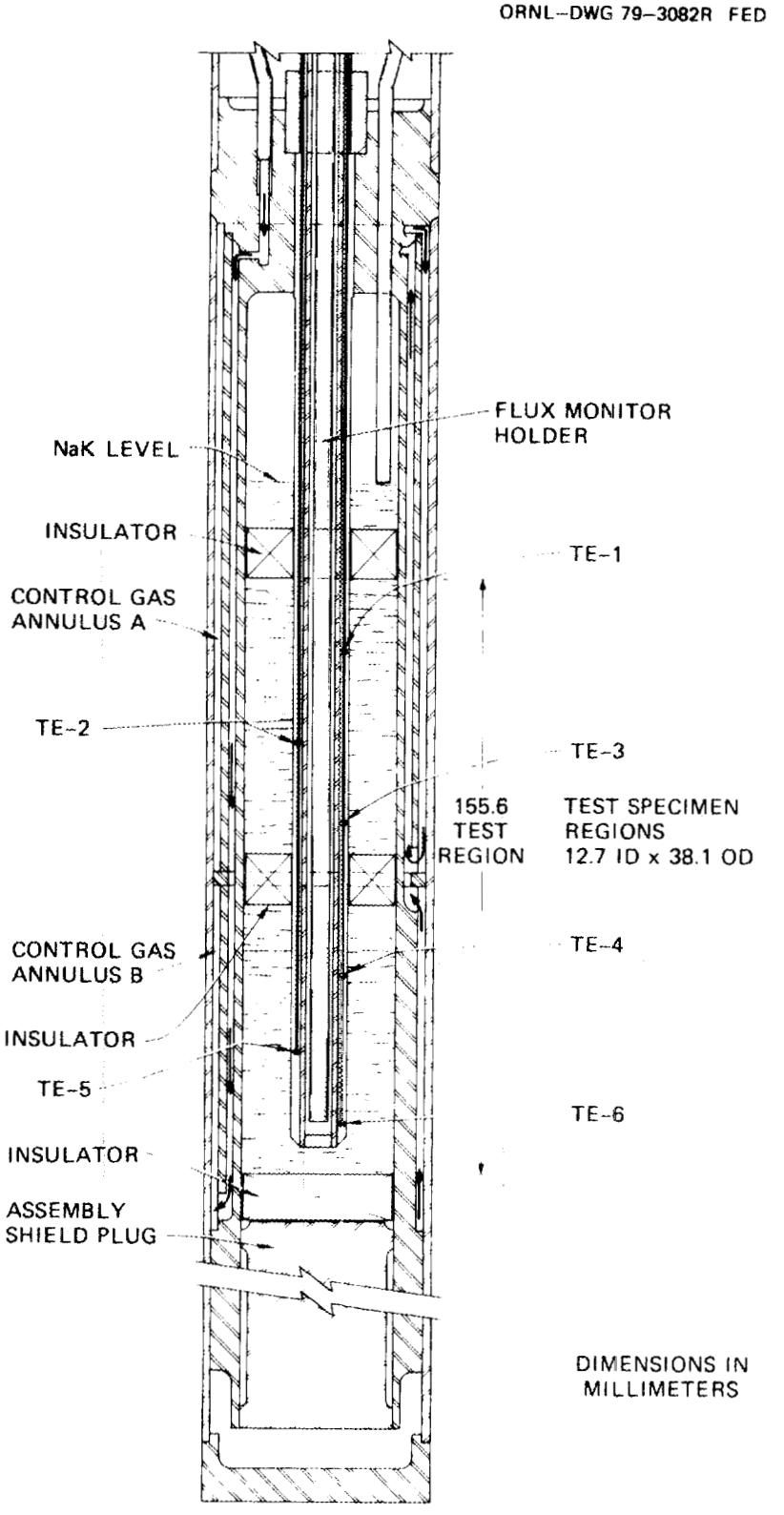

Fig. 3.0.4. Schematic of U.S. spectral-tailoring capsule.

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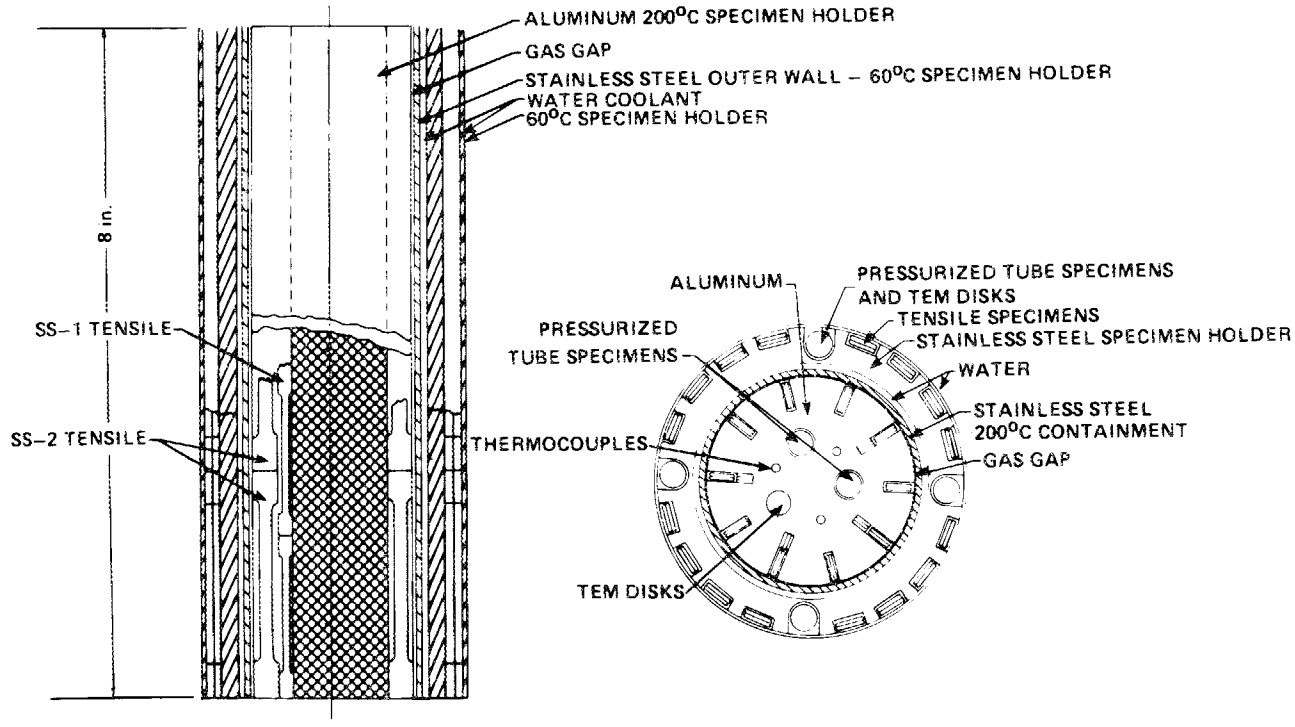

Fig. 3.1.1. Schematic of MFE-6J.

Table 3.2.1. Description of specimens

Type	Length (mm)	Width (mm)	Thickness (mm)	Test section Width (mm)	Test section Thickness (mm)	Test section Diameter (mm)	Weight (g)
SS 1 Tensile	44.4	4.95	0.74	1.52	0.74	-	0.71
SS 3 Tensile	25.4	4.95	0.74	1.52	0.74	-	0.50
Grodzinski fatigue	44.4	4.95	0.74	2.03	0.74	-	0.89
Hourglass fatigue	45.2	-	-	-	-	3.17	7.13
HFIR tensile	39.4	-	-	-	-	2.00	1.58
One-third-size Charpy	25.4	3.33	3.33	3.33	3.33	-	2.18
Pressurized tubes	25.4	-	-	-	-	4.60	0.93
Crack growth	25.4	12.7[a]	0.74	25.4	12.7	-	1.80
TEM disks	-	-	-	-	0.25	3.0	0.01

[a]Width, 10.2 mm at 200°C.

gamma heat in the test section. If the test magazines were more heavily loaded, it would not be possible to keep the temperature down to the desired value, especially at 300°C.

In the 60 and 200°C capsule, the specimen loading is controlled by the number and type of holes and slots machined into the specimen holders. The test matrix has been developed with equal sharing of volume at 60 and 200°C and with equal allocation of masses of specimens at the high temperature. The present test matrix is shown in Table 3.2.2. Specimens will be delivered and capsules will be assembled next fiscal year (FY 1985).

Table 3.2.2. Test matrix for U.S./Japan capsules

Source	Type										
	SS 1	Grod.	SS3	CG	PT	TEM (pkg.)	Ceramic TEM (pkg.)	HFIR-T	HFIR-F	Charpy	Tube blanks
						60°C					
JAERI	70	56	0	18	6	5[a]	0	0	0	0	3
HEDL	0	0	35	18	0	0	0	0	0	0	0
ORNL	32	0	44	0	34	3[b]	1[c]	0	0	0	6
						200°C					
JAERI	59	24	0	18	10	7[a]	0	0	0	0	3
HEDL	0	0	35	18	0	0	0	0	0	0	0
ORNL	34	0	44	0	15	3[b]	1[c]	0	0	6	6
						300°C					
JAERI	72	56	0	10	6	6[a]	0	4	0	0	3
HEDL	0	0	30	0	0	4[d]	0	0	0	0	0
ORNL	11	0	16	0	39	7[d]	1[c]	0	0	6	6
						400°C					
JAERI	64	40	0	10	0	6[a]	0	0	5	0	3
HEDL	0	0	30	0	0	4[d]	0	0	0	0	0
ORNL	13	0	25	0	33	7[d]	1[c]	0	0	6	6

[a]Length, 1 in. — 60 disks.

[b]Length, 0.65 in. — 40 disks.

[c]Length, 0.50 in. — 40 disks.

[d]Length, 0.75 in. — 50 disks.

3.3 FACILITY PREPARATION

The experimental facility in ORR for experiment MFE-6J (60 and 200°C) was prepared during this fiscal year. This facility had to be available for the calibration test of the MFE-6J prototype capsule.

3.4 TESTING OF MFE-6J PROTOTYPE

During the period July 1 through September 30, 1984, the fabrication, assembly, and flow and check-out tests for the prototype MFE-6J capsule were completed; the experiment was installed and operated in the ORR. The last of the fabricated parts were delivered on August 7.

Water flow tests to establish the orificing required for proper coolant water flow distribution were carried out concurrently with capsule assembly and were completed on August 16.

The assembly of the lower in-core portion of the capsule was completed on August 29 (the upper portion had been assembled during the second and third quarters of the year). The capsule checkout in the ORR mock-up was completed on September 3, and the capsule was inserted in the ORR on September 5. The reactor was at 30 MW by September 6, 1984.

The primary purpose of the operation of a prototype capsule was to verify the thermal design. The prototype capsule contains two instrumented dummy tensile specimens, which operate within a 2 to 5°C temperature difference. One can control the specimen temperature from 140 to 305°C and can maintain the mean temperature within ±2°C.

There is an acceptable axial temperature difference in the specimen holder from that at midplane — compared with the midplane, the holder is 10°C lower at the top and 30°C lower at the bottom. This small difference is believed to be due to heat losses at the ends and will be reduced by minor design changes in the capsule that will contain the actual test specimens.

3.5 AEM INSTALLATION

A room that was suitable for the analytical electron microscope to be supplied by JAERI (JEOL-2000FX) was identified in Building 5500 and

checked for the required low vibration level of the floor. After environmental testing showed that the room was suitable, preparation for the microscope was started. It is anticipated that the room will be ready when the microscope arrives in February 1985.

3.6 SCHEDULING FOR ORR TESTING

The schedule for the work in ORR and for AEM installation is shown in Fig. 3.6.1.

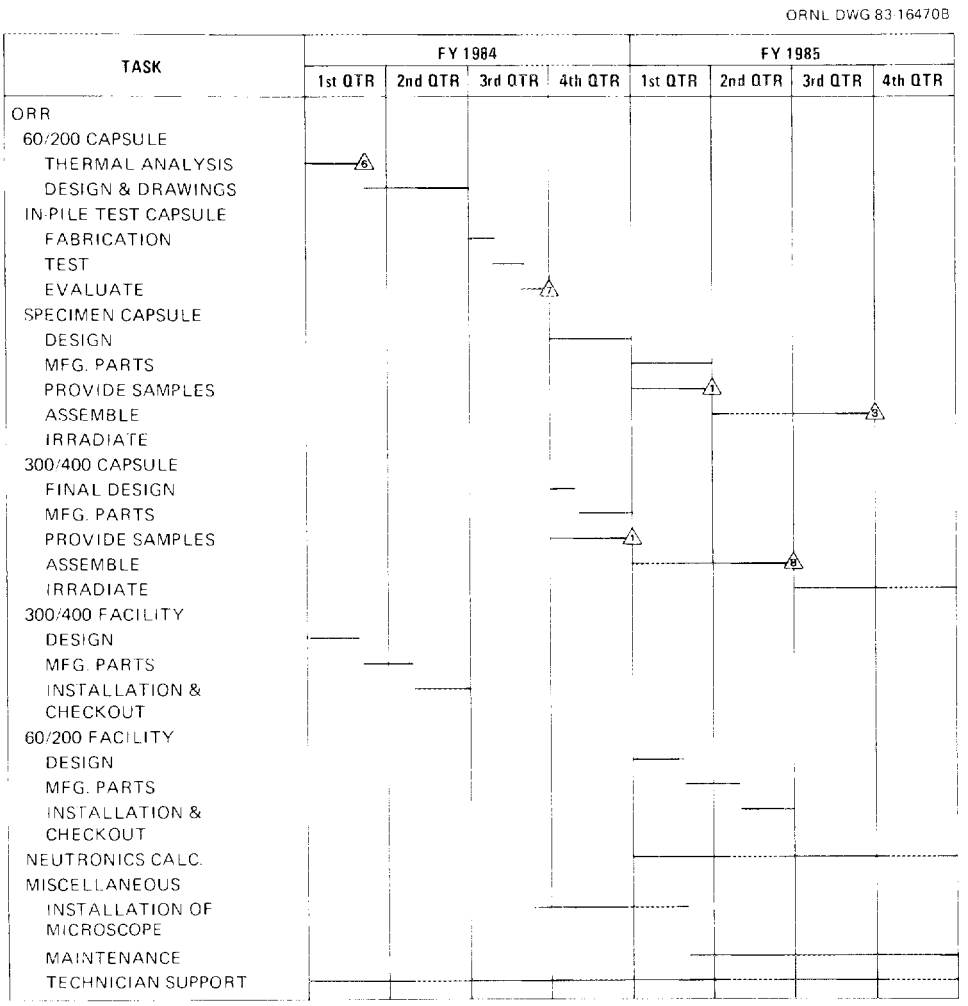

Fig. 3.6.1. Schedule for work in ORR and for AEM.

4.0 CONCLUSIONS

The first year of the ORNL-JAERI Collaborative Testing in ORR has been successfully concluded on schedule and within budget, even though there was a slight delay in starting the program.

Eight HFIR capsules were fabricated, and six were installed in the reactor target region. The facility for the first ORNL-JAERI spectral-tailoring capsule was completed, and a thermal mock-up of the newly designed 60/200 capsule was successfully operated. An excellent working relationship was established between ORNL and JAERI that will serve both sides well in future years.

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