ENGINEERING DEVELOPMENT OF FUSION-2 EXPERIMENT FOR IRRADIATION TESTING OF VANADIUM ALLOYS IN A LITHIUM ENVIRONMENT AT 450-750°C IN THE BOR-60 REACTOR[1] – V. Kazakov, V. Chakin, V. Efimov, A. Tuktabiev, P. Gabiev (Research Institute of Atomic Reactors), H. Tsai, T. S. Bray, D. L. Smith (Argonne National Laboratory); and A. Rowcliffe (Oak Ridge National Laboratory)

OBJECTIVE

BOR-60 is a sodium-cooled fast reactor in Russia with a coolant inlet temperature of 300-330°C. Previous irradiation experiments conducted in the BOR-60, EBR-II, HFIR, ATR, and SM reactors indicate that the threshold for low-temperature embrittlement of vanadium-base alloys is ≈400°C. The purpose of the proposed Fusion-2 experiment in BOR-60 is to study the effects of neutron damage in vanadium-base alloys at temperatures above this threshold, up to ≈700°C. The objective of the present task is to develop the engineering design of the experimental assembly based on the functional requirements of the experiment. Engineering development focuses on construction of the experimental assembly including test volumes and specimens, methods of temperature control and measurement that are especially important for creep tube specimens, and thermal performance of the assembly in the Research Institute of Atomic Reactors (RIAR), where BOR-60 is located.

SUMMARY

The requirements of this task are to complete the engineering designs of irradiation capsules in BOR-60. The specimen matrix will include sheet tensile specimens, Charpy impact specimens, TEM disks, and pressurized creep tubes. This experiment will not include DHCE samples. To better utilize the test volume and provide additional temperature options, it was decided to modify the experiment from a two-capsule to a three-capsule design. All capsules will be liquid-metal-bonded for temperature uniformity. The top two capsules with be fitted with thermocouples for temperature measurement in early stages of the irradiation. Goal temperatures for the three capsules will be 450, 600, and 700-750°C, with an emphasis on 600°C. A key objective of the experiment will be to generate irradiation creep data for vanadium-base alloys, especially at the emphasized temperature of 600°C, where thermal creep may not be dominant. To ensure correct generation of irradiation creep data, knowledge of the temperature profile and minimal temperature fluctuations during irradiation are important.

PROGRESS

The three capsule design for Fusion-2 is shown in Fig. 1. A three-capsule design would permit better utilization of the high-flux space at the core midplane and, because each capsule can operate at a different temperature, a more diverse study of temperature effects on irradiation. By adopting three shorter capsules, there would also be less axial power/temperature variation in each capsule.

The proposed materials of construction for the Fusion-2 experiment are shown in Table 1. The double-wall capsule (Item 3) would be made of austenitic stainless steel or Inconel for compatibility with the bond sodium at elevated temperature. The subcapsules (Items 4 and 5) containing the test specimens would be made of TZM (a Mo-base alloy) for impurity control and compatibility with the specimen lithium bond. There would be two sizes of subcapsules; those of smaller diameter (Item 5) are sized to accommodate pressurized creep tubes.

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Thermal analysis has been conducted to determine the construction of capsules for the desired temperatures. For performance assessment of the vanadium-base alloy for fusion applications, we decided that the most important test temperature at this time would be 600°C. Accordingly, the high-flux middle capsule would be allocated for this temperature. Because the lengths of the three capsules need not be the same, the middle capsule would be slightly elongated to provide a ≥40% total test volume. The top and bottom capsules would be designed for 700-750 and 450°C, respectively, and would have a smaller test volume than that of the middle capsule.

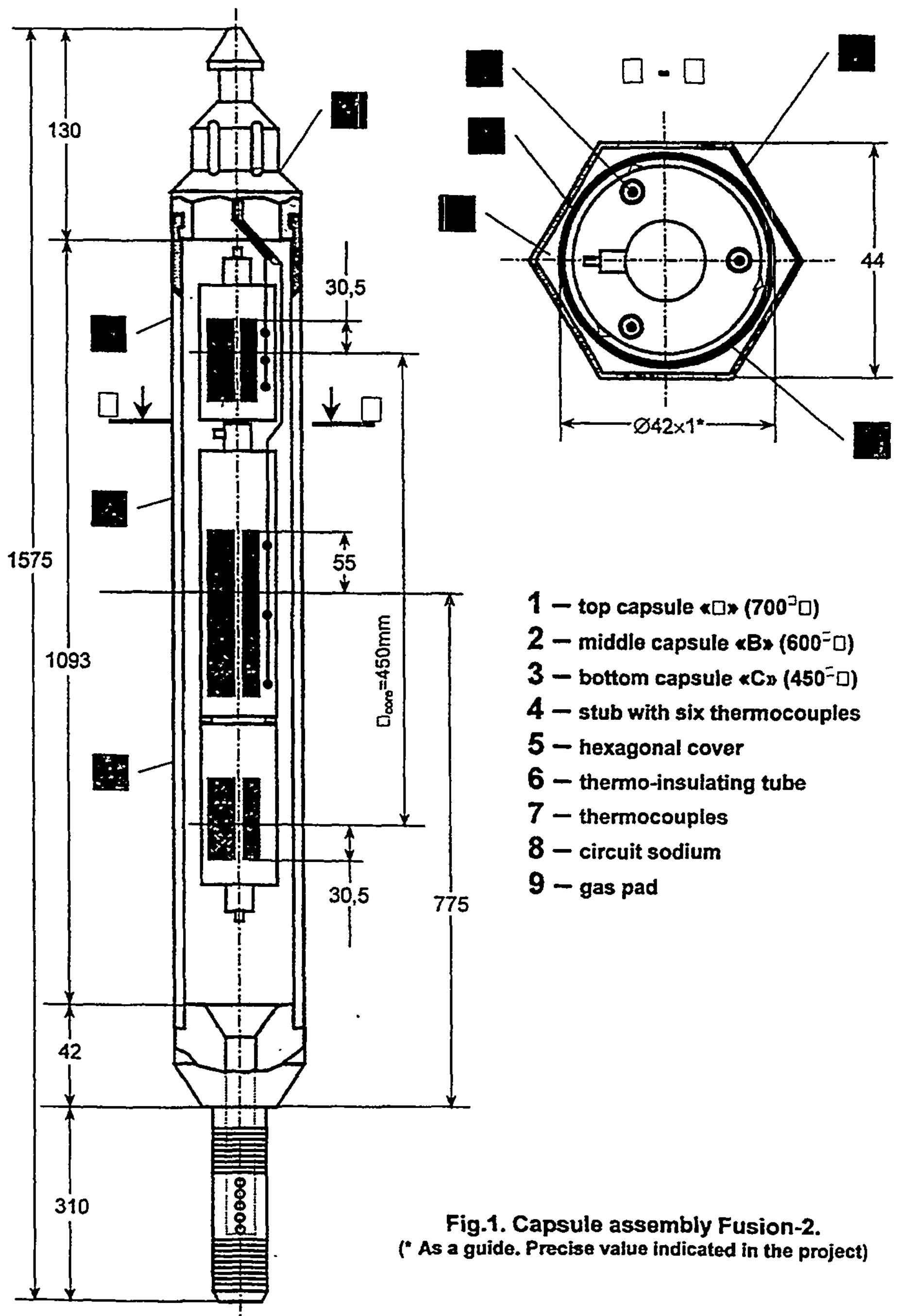

Fig.1. Capsule assembly Fusion-2.
(* As a guide. Precise value indicated in the project)

Table 1. Materials of construction for Fusion-2 test assembly

Item No.	Test Temperature = 450, 550, 600°C	Test Temperature = 700°C	Fill Medium
1	Hex Can	Hex Can	He
2	SS	SS	Na
3	304 SS	Inconel	He (outer) Na(inner)
4	Mo alloy of TZM or VM-1A type	Mo alloy of TZM or VM-1A type	Li-7, specimens
5	Mo alloy of TZM or VM-1A type	Mo alloy of TZM or VM-1A type	Li-7, specimens

To monitor the specimen temperature, thermocouples will be incorporated in the top and middle capsules in the Fusion-2 vehicle. Because only one core location (D-23) in BOR-60 permits deployment of thermocouples, the Fusion-2 experiment would be irradiated at this location for approximately two weeks at the onset of the experiment to establish the thermal baseline.

Steady irradiation temperature is important in testing structural materials samples. For pressurized creep specimens, this is particularly true, because temperature fluctuation affects not only creep properties but also internal gas pressure. Means to ensure steady irradiation temperatures were explored.

Thermal Calculations

Thermal calculations were performed assuming three capsules in the assembly. The thermal calculations were performed in consideration of the reactor power (55 MW), the distribution of radiation heating in the elements, specimens and the coolant at the specimen height, radial and axial heat transfer in the assembly, and convective heat transfer in the capsule. Thermal gas gaps and spatial distribution of temperature were determined using helium as the gap gas.

The calculations show that without extra measures, the axial temperature variation across the capsule can be large. With the addition of mass (tungsten) into the capsule, the temperature deviation can be significantly decreased; however, the temperature variation may still be somewhat unsatisfactory. Various internal wall geometries were evaluated—a multistep-shaped profiling, a conical-multistep-shaped profiling, and a conical-multistep-shaped profiling with additional masses. Figure 2 shows a three step profile for the top (700°C) and bottom (450°C) capsules and a six step profile for the middle (600°C) capsule.

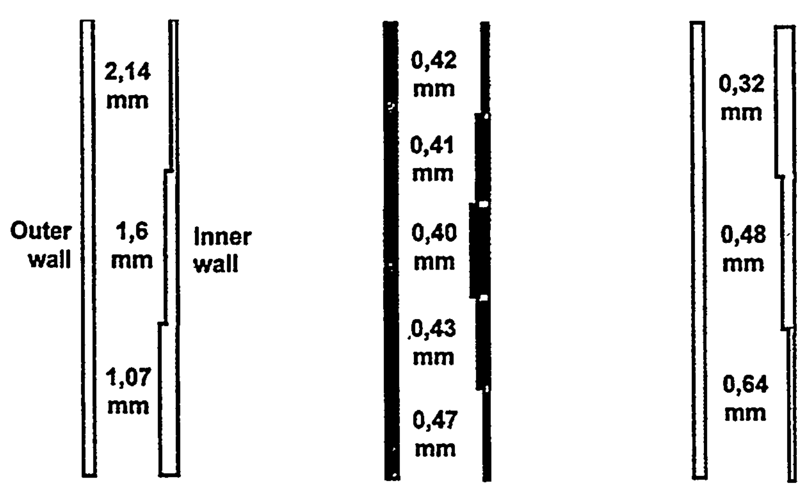

Figure 2. Multi-step Profile for Top (700°C), Middle (600°C), and Bottom (450°C) Capsules. Dimensions only approximate.

Tables 2, 3, and 4 outline the thermal calculations and the impact of the geometry variations on axial temperature variation and uncertainty. The calculations show that a conical-step-shaped profile with additional masses provides the best results in minimizing axial temperature variation and uncertainty.

Table 2: Thermal Calculations for Upper Capsule (700°C)

Variation	Gas Gap (mm)		Additional Mass (g)		Temperature (°C)**	
No Additional Measures	1.45		--		S1*	630±30
					S2*	705±35
					S3*	765±25
Gas Gap Plus Additional Masses	1.28		S1*	44.14	S1*	680±30
			S2*	16.19	S2*	700±45
			S3*	--	S3*	725±20
Step-Shaped Gas Gap	S1*	1.78	--		S1*	700±40
	S2*	1.42			S2*	700±46
	S3*	1.18			S3*	700±20
Conical-step-shaped gas gap	S1*	2.02-1.62	--		S1*	700±7
	S2*	1.62-1.26			S2*	700±5
	S3*	1.26-1.13			S3*	700±8
Conical-step-shaped gas gap plus additional masses	S1*	1.40-1.14	S1*	44.14	S1*	700±6
	S2*	1.14-0.92	S2*	44.14	S2*	700±5
	S3*	0.92-0.90	S3*	44.14	S3*	700±7

*S1 = Top (First) Step of Capsule, M = Middle (Second) Step of Capsule, B = Bottom (Third) Step of Capsule.
**Temperature reported is at the center of the step.

Table 3: Thermal Calculations for Middle Capsule (600°C)

Variation	Gas Gap (mm)		Temperature (°C)**	
No Additional Measures	0.42		S1*	608±5
			S2*	618±5
			S3*	625±2
			S4*	619±3
			S5*	604±8
			S6*	585±11
Step-Shaped Gas Gap	S1*	0.41	S1*	600±5
	S2*	0.39	S2*	600±4
	S3*	0.38	S3*	600±2
	S4*	0.39	S4*	600±7
	S5*	0.41	S5*	600±7
	S6*	0.43	S6*	600±12
Conical-step-shaped gas gap	S1*	0.41-0.40	S1*	600±3
	S2*	0.40-0.39	S2*	600±4
	S3*	0.39-0.38	S3*	600±2
	S4*	0.38-0.40	S4*	600±4
	S5*	0.40-0.42	S5*	600±4
	S6*	0.42-0.46	S6*	600±5

*S1= Top (First) Step of Capsule, S2 = Second Step of Capsule, S3 = Third Step of Capsule, S4 = Fourth Step of Capsule, S5 = Fifth Step of Capsule, S6 = Bottom (Sixth) Step of Capsule.
**Temperature reported is at the center of the step.

Table 4: Thermal Calculations for Lower Capsule (450°C)

Variation	Gas Gap (mm)		Additional Mass (g)		Temperature (°C)**	
No Additional Measures	0.38		--		S1* S2* S3*	479±10 452±16 425±11
Gas Gap Plus Additional Masses	0.35		S1* S2* S3*	-- 22.07 44.14	S1* S2* S3*	459±15 450±10 450±8
Step-Shaped Gas Gap	S1* S2* S3*	0.31 0.37 0.48	--		S1* S2* S3*	450±14 450±16 450±8
Conical-step-shaped gas gap	S1* S2* S3*	0.29-0.33 0.33-0.43 0.43-0.54	--		S1* S2* S3*	450±4 450±5 450±6

*S1 = Top (First) Step of Capsule, M = Middle (Second) Step of Capsule, B = Bottom (Third) Step of Capsule.
**Temperature reported is at the center of the step.

Temperature Control

The specimen temperatures cannot be actively controlled in fusion-2. Rather, it will be determined by the preset width of the gas gap. Uncertainties in the radiation heating calculations are ±7% and determination of the reactor power is ±2.5%. There is also some uncertainty in the accuracy of the gas gap and associated with the thermal hydraulic process inside of the capsule. The installed thermocouples will provide information during the first two weeks of irradiation to reduce some of the uncertainties.

The reactor power over the course of a year can be described in two campaigns, winter and summer, divided by 45-day outages between each campaign. In addition, another 10 day refueling outage occurs in the winter campaign. The reactor power typically fluctuates from 35-48 MW in the summer and 45-56 MW in the winter. To attain the required test temperatures during the lower-power summer months, the subassembly will be moved to a more central core location. The typical reactor power fluctuation of ±10-15% during normal operations can be reduced to achieve more steady specimen temperatures; however, this will most likely result in higher experimental costs.

Sample Loading and Test Volume

Table 5 shows the sample loading and test volumes available for the Fusion-2 experiment. Test volume is defined as the space that can be used to load lithium or test specimens, i.e., excluding the plenum. A total of 108 mL of test volume is available for the Fusion-2 experiment. In comparison, the test volumes available in ATR-ITV, RB(10J), and ATR-A1 were 130 mL, 160 mL, and 47 mL, respectively. A total of approximately 95 tensile samples, 77 Charpy V-notch samples, and 69 creep tube samples could be irradiated in the Fusion-2 experiment.

Table 5: Sample Loading and Test Volumes for the Fusion-2 Experiment.

Item	Top Capsule (700°C)	Middle Capsule (600°C)	Bottom Capsule (450°C)
No. of Tensile Specimens	20	45	30
No. of Charpy V-Notch Specimens	20	45	12
No. of Creep Tubes	30	30	9
Small-Diameter Subcapsule Test Volume (mL)	6.6	13.2	6.6
Large Diameter Subcapsule Test Volume (mL)	18.4	36.7	26.5

REFERENCE

1. V. Kazakov et al., "Engineering Development of Fusion-2 Experiment for Radiation Test of Vanadium Alloys in BOR-60 Reactor at 450-700°C in Lithium Environment," Report on Milestone 2 of Subcontract 28X-SZ738V of 06/08/98 with Lockheed Martin Energy Systems, Inc., USA, 1998.