CONCEPTUAL DEVELOPMENT OF THE FUSION-2 EXPERIMENT FOR IRRADIATION TESTING OF VANADIUM ALLOYS IN A LITHIUM ENVIRONMENT AT 500-700°C IN THE BOR-60 REACTOR[1] – V. Kazakov, V. Chakin, V. Efimov, V. Petukhov, 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 vanadium alloy 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 in a lithium environment at the high-temperature end, i.e., 500-750°C. The objective of the present task is to develop the conceptual design of the experimental assembly based on the functional requirements of the experiment. The conceptual development focuses on the construction of the experimental assembly, methods of temperature control and measurement, thermal performance of the assembly, and the feasibility of conducting assembly and disassembly in the Research Institute of Atomic Reactors (RIAR) where BOR-60 is located.

SUMMARY

The specific requirements of this task were to complete the conceptual designs of irradiation capsules to a neutron dose of approximately 20 dpa in BOR-60. The specimen matrix will include sheet tensile, compact tension, bend bars, irradiation creep tubes, and TEM disks. The irradiation temperatures will be approximately 500, 550, 600, and 650°C; the temperature changes related to changes in reactor operating conditions are to be minimized; and all specimens are to be encapsulated in lithium. In addition, the possibility of a multi-temperature assembly and reconstitution of assemblies was assessed.

PROGRESS

Task Formulation

The Fusion-2 conceptual design effort concentrated on defining the capabilities and limitations of the experimental irradiation facility. The conclusions of the conceptual design can then be used as the basis for the detailed engineering design of the Fusion-2 experiment. The task formulation consisted of defining the requirements of the conceptual design. The requirements are outlined as follows:

- Determine the maximum irradiation temperature achievable in the BOR-60 reactor with specimens in a lithium environment. (The desired range is 450-750°C.)
- Determine the methods for specimen temperature control and measurement.
- Design a capsule assembly that allows two irradiation temperatures.
- Design a capsule with the possibility of reconstitution for achieving top radiation damage doses of ~100 dpa.
- Determine the feasibility of assembly, disassembly, and reloading of capsules in RIAR.

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Capsule Construction

A conceptual design has been established and the schematic of this design is presented in Figure 1. Table 1 presents the materials of construction for the capsule; item numbers refer to components as identified in Figure 1.

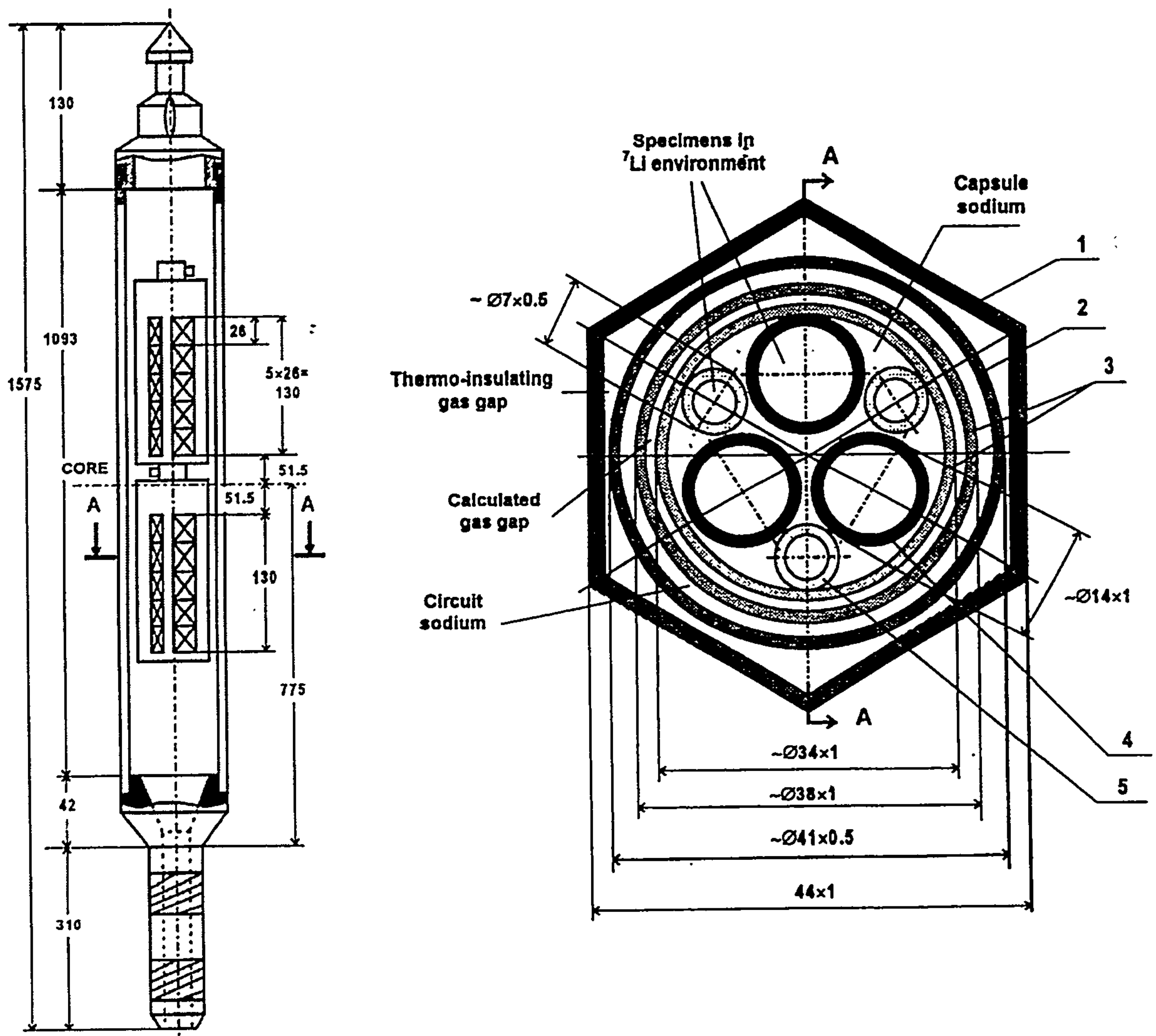

Figure 1: Two-temperature Fusion-2 capsule assembly (left) and cross-section of the capsule (right).

Table 1: Materials of construction for the Fusion-2 test assembly

Item No.	Test Temperature = 500, 550, 600°C	Test Temperature = 700°C	Fill
1	Hex Can	Hex Can	He
2	SS	SS	Sodium
3	304 SS	Inconel	He (outer) Sodium (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

Thermal Calculations

Thermal calculations were performed assuming one and two 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 results of the calculations are presented in Tables 2 and 3 for a one and two capsule assembly, respectively, for capsules at temperatures of 500, 550, 600, and 700°C.

Table 2. Results of Fusion-2 basic variant thermal calculations for one capsule in the capsule assembly

Parameter	Capsule Assembly Variation			
	A	B	C	D
Capsule Temperature (°C)	500	550	600	700
Calculated Gas Gap (mm)	0.25	0.34	0.41	0.62
Axial Temperature Variation from the average (°C)*	±20	±26	±28	±42

*The axial temperature variation can be significantly reduced with the addition of masses (e.g., tungsten) at the upper and lower locations of the capsule.

Table 3. Results of Fusion-2 basic variant thermal calculations for two capsules in the capsule assembly

Parameter	Capsule Assembly Variation			
	A		B	
	Lower Capsule	Upper Capsule	Lower Capsule	Upper Capsule
Capsule Temperature (°C)	500	600	550	700
Calculated Gas Gap (mm)	0.31	0.41	0.43	0.62
Axial Temperature Variation from the Average (°C)	±36	±45	±42	±63
Axial Temperature Variation from the average after smoothing attempts (°C)*	±20	±15	±25	±25

*The axial temperature variation can be significantly reduced with the addition of masses (e.g., tungsten) at optimum locations within the capsules.

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.

The one capsule assembly has two drawbacks. First, only a single test temperature would be achieved in a single capsule; therefore, in order to irradiate specimens at multiple temperatures, multiple capsules would need to be constructed. If a single assembly were used, and only one capsule was irradiated at a time, the irradiation time increases. The combination of constructing multiple capsules and increased irradiation time increases the total cost of the study. The assembly irradiation time could be decreased by means of a parallel irradiation of a few capsule assemblies in analogous cells of the fifth row of the BOR-60 reactor; however, this option also has increased costs.

The two capsule assembly also has disadvantages. First, the central part of the core is unused; this does not take advantage of the temperature profile in this area. Second, the lower capsule specimens are in the lower part of the core where radiation heating uncertainty increases, and the axial temperature variation throughout the capsule is quite high.

Temperature Control

The specimen temperature will not be actively controlled. Rather, it will be determined by the preset width of the gas gap. Errors 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 thermohydraulic process inside of the capsule. The uncertainty is approximately 30-40°C for a test temperature of 700°C and ~25°C for a test temperature of 500°C.

Reductions in the temperature uncertainty can be achieved through the use of a methodical capsule in an instrumented D-23 cell of the BOR-60 reactor. The methodical capsule assembly contains thermocouples in the capsule sodium (see Fig. 1), thereby allowing for the measurement of the temperature in the capsule. In addition, the D-23 cell has neutronics and temperatures similar to those found in the E-23 cell. If the D-23 reactor location is available for the entire irradiation time and the costs are not prohibitive, the capsule could remain in this location for the entire irradiation period up to a damage dose of 20 dpa. If the core location is not used throughout the irradiation period, after a short (i.e., weeks) irradiation in the D-23 cell, the assembly would be discharged and the themocouples disconnected at the top of the assembly. If possible, the assembly would then be inserted into the analogous E-23 cell to continue the irradiation. A potential complication of this approach is that if the disconnection of the thermocouples and subsequent insertion of the assembly into the E-23 location fails, the capsules would need to be removed from the D-23 assembly, the subcapsules would need to be opened, and the capsules would have to be reconstructed and placed into a new assembly.

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 averages 30-35 MW in the summer and ~45 MW in the winter. For a 10-MW change in the reactor power, the corresponding change in the specimen temperature is estimated to be 65-70°C for a test temperature of 700°C and 30-35°C for a test temperature of 500°C. Additionally, the reactor power fluctuates ±10-15% during normal operations. Therefore, an acceptable test temperature range must be developed.

One possible way to achieve a more steady temperature for the specimens during the entire irradiation is to irradiate the assembly only in winter campaigns. Two winters would be necessary to achieve the desired damage dose of ~20 dpa. There is, however, a potentially significant drawback of staying out of the reactor during the summer. In addition to the prolonged irradiation time, such action could potentially jeopardize the conduct of a dynamic helium charging experiment (DHCE) which may be included in Fusion-2. (In a DHCE, tritium is implanted in the capsule. During the irradiation, some of the tritium would diffuse into the specimen and decay in-situ into ^{3}He, thereby yielding the concurrent effects of helium generation and neutron damage. If, however, the assembly is out of the core during the summer, excessive helium may build up in the specimens without the concurrent neutron damage, thus degrading the experiment.) These drawbacks could be eliminated by moving the assembly to a more central core location for the summer to compensate for the lower reactor power in the summer campaign.

Reconstituted Capsule

A dose-dependent radiation creep model can be developed by collecting geometric data on specimens at varying doses. The BOR-60 reactor and associated facilities do not allow for the removal, measurement, and reinsertion of the specimens. Thus, Tables 4 and 5 propose an irradiation scheme for multiple capsules that allows for the collection of the geometric data on samples removed and replaced with fresh specimens. Table 4 allows for three capsules in the assembly; Table 5 allows for four capsules in the assembly. The maximum dose accumulation for any one capsule is 100 dpa.

Table 4: Dose Accumulation for a Reconstituted Capsule Assembly with Three Capsules.

Irradiation Time (Years)	Accumulated Dose (dpa)			
	Capsule Position 1	Capsule Position 2	Capsule Position 3	Removed Capsule
1	20*	20	20	20
2	20	40*	40	40
3	40	20	60*	60
4	60	40	20	-
5	80*	60	40	80
6	20	80	60	-
7	40*	100*	80*	100, 80, 40

*Accumulated dose of capsule removed at the end of the year

Table 5: Dose Accumulation for a Reconstituted Capsule Assembly with Four Capsules.

Irradiation Time (years)	Accumulated dose (dpa)				
	Capsule Position 1	Capsule Position 2	Capsule Position 3	Capsule Position 4	Removed capsule
1	20*	20	20	20	20
2	20	40*	40	40	40
3	40	20	60*	60	60
4	60	40	20	80*	80
5	80	60	40	20	100
6	100*	80*	60*	40*	100, 80, 60, 40

*Accumulated dose of capsule removed at the end of the year

The irradiation schemes presented in Tables 4 and 5 assume that the assemblies are at a single irradiation temperature. However, because some data points will be duplicated with the above schemes, one could insert the fresh capsules at a second temperature, thereby allowing for the collection of dose dependent data at two temperatures.

Table 6 presents the thermal calculations for a four capsule assembly assuming a two-temperature irradiation scheme. The first four capsules, variations 1 through 4, are at an assumed 700°C. The last three capsules, inserted after the removal of an original capsule, variations 5 through 7, are assumed to be inserted at 650°C.

Table 6: Thermal calculation results for a four-capsule assembly that involves the removal of one capsule per year and replacing the removed capsule with a fresh capsule.

Parameter	Capsule Variation						
	1	2	3	4	5*	6*	7*
Capsule Temperature (°C)	700	700	700	700	650	650	650
Calculated Gas Gap (mm)	0.77	0.59	0.56	0.36	0.64	0.49	0.53
Axial Temperature Variation from the average (°C)**	±32	±5	±20	±65	±35	±5	±20

*Fresh capsules reinserted after the removal of an original capsule (i.e., capsule 5 replaces capsule 1 after year one, etc.).
** The axial temperature variation can be significantly reduced with the addition of masses (e.g., tungsten) at the upper and lower locations of the capsule.

From the table, it can be seen that the highest axial temperature variation occurs in capsule 4, or bottom-most, capsule. The addition of tungsten rods does not acceptably smooth the temperature profile; therefore, a slight shift of the capsules upwards in the core should alleviate this high axial temperature variation.

CONCLUSION

The Fusion-2 conceptual design effort concentrated on defining the capabilities and limitations of the experimental irradiation facility. The conclusions of the conceptual design can be used in the engineering design of the Fusion-2 experiment. During the conceptual design effort, irradiation temperatures and corresponding thermal gas gaps for multiple capsule assemblies were determined. Calculations also showed that the test temperatures can be maintained to provide the desired irradiation damage doses up to 100 dpa; higher doses can be achieved through increased irradiation time.

REFERENCE

V. Kazakov et. al., "Conceptual Development of Fusion-2 Experiment for Radiation Test of Vanadium Alloys in BOR-60 Reactor at 500-700°C in Lithium Environment," Report on Milestone 1 of the Subcontract 28X-SZ738V of 06/08/98 with Lockheed Martin Energy Systems, Inc., USA, 1998.