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CONCEPTUAL DESIGN OF THE HIGH-FLUX VTA-2 TEST ASSEMBLY FOR FMIT

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Hanford Engineering Development Laboratory

M.A. Vogel
August 1983

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CONCEPTUAL DESIGN OF THE HIGH-FLUX
VTA-2 TEST ASSEMBLY FOR FMIT

M. A. Vogel

ABSTRACT

This report describes the conceptual design of the test module for the high neutron flux vertical test assembly (VTA-2). The description emphasizes the thermal control systems available for monitoring test specimen temperatures at any desired temperature within the range of 1000-650°C. VTA-2 will be located in the Fusion Materials Irradiation Test Facility (FMIT) test cell directly behind VTA-1.

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CONCEPTUAL DESIGN OF THE HIGH-FLUX
VTA-2 TEST ASSEMBLY FOR FMIT

1.0 SUMMARY AND CONCLUSIONS

1.1 SUMMARY

This report describes the conceptual design of Vertical Test Assembly 2 (VTA-2) with emphasis on the thermal design of the test system. VTA-2 is similar in structure to VTA-1 and is composed of a test module, a test stalk, and a shield plug with positioner. VTA-2 is designed for irradiation of fusion material specimens at any desired temperature within the range of 100° to 650°C. It will be located directly behind the VTA-1, which is positioned directly in front of the Fusion Materials Irradiation Test (FMIT) Facility's lithium target. A positioner concept is also presented but is not dimensionally defined.

An overall description of the VTA-1 and VTA-2, including nuclear characteristics within these modules and their interface requirements with the FMIT Facility, is given in Reference 1. Mechanical design details of the module, the test stalk or the shield plug with positioner are not included in this report.

1.2 CONCLUSIONS

1.2.1 Design Options

The design concept provides several options for achieving the required test temperatures of 100°C to 650°C. These options are:

NaK-Bonded Chambers:

- Temperatures below 460°C can be achieved by controlled gas gaps that conduct heat to an open- or closed-loop coolant system (nitrogen, helium or water).
- Temperatures above 460°C require in addition to the gas gaps:
 - Heating of the NaK bond for the open-loop coolant system (nitrogen)
 - Heating of the NaK bond or the loop coolant (or a combination of both) for the closed-loop coolant system (nitrogen or helium)

Weeper Chambers:

- Temperatures of 100°C can be achieved with an open-loop nitrogen coolant system or with a closed-loop water coolant system.
- Any desired temperature between 100°C and 650°C can be achieved by external heating of a closed-loop coolant system (nitrogen or helium); but, this temperature then represents the minimum temperature at which a companion NaK-bonded test can be operated in the same test module.

1.2.2 Temperature Control

The setpoint control accuracy and the temperature variation within chambers have not been determined; however, experience with similar designs suggests that the required temperature control accuracy can be attained.

The proposed test module concept consists of a rectangular box-like structure with a capacity to accept three test chambers. These test chambers are surrounded by a flowing coolant that serves as a heat sink. Two types of chambers filled with fusion materials test specimens can be inserted into the test module. The first type, referred to as a NaK-bonded chamber, will contain specimens immersed in a NaK alloy. The NaK will serve as the thermal conducting media between the specimens and the chamber walls. The chamber walls are separated from the flowing coolant by a gas gap. The second type, referred to as a "weeper" chamber, will be provided with holes so that the specimens contained in it will be directly cooled by flowing coolant.

This flowing coolant can be an open- or closed-loop system. The open loop draws nitrogen from the test cell, blows it through the test module, and returns it to the test cell. The closed loop provides a completely independent coolant circuit.

3.0 DESIGN CONCEPT

3.1 DESIGN REQUIREMENTS

The following fusion materials test program design requirements were used as a basis for development of the test module concept:

- VTA-2 shall provide for simultaneous irradiation of three chambers with each chamber having nominal dimensions of:
 - 5 cm wide horizontal (X)
 - 15 cm deep along beam axis (Z)
 - 20 cm high vertical (Y)
- Each chamber shall have independent temperature control with a temperature range within each chamber of 100° to 650°C.
 - Setpoint control accuracy $\pm 10^{\circ}\text{C}$
 - Calculated temperature variation within chamber $\leq 10^{\circ}$
- VTA-2 shall have a minimum design lifetime under in-cell operating conditions of 1 full-power year.
- VTA-2 shall be capable of undergoing reconstitution with previously irradiated specimens.
- VTA-2 shall be capable of being positioned behind VTA-1 to within ± 2 mm in the X and Y directions and to within ± 1 mm in the Z direction.

3.2 TEST MODULE CONCEPT

The test module concept shown in Figure 1 consists of a rectangular stainless steel container divided by four walls into three test chambers. Rapid assembly, disassembly, and versatility are emphasized to accommodate a wide range of structural alloy specimens as well as special-purpose fusion materials such as ceramics. Test chamber pockets are sized to accept a 5-cm wide x 15-cm long x 20-cm high test chamber. Test chambers are fastened to a common test module flange that seals the test pockets when the test chambers are inserted into the test module. The removable seal flange arrangement also provides for efficient test specimen removal and reconstitution after irradiation. Coolant inlet and outlet pipes and lower and upper coolant plenums serve to direct bulk coolant through the walls separating the pockets and/or through the bottom and top of each pocket. This coolant system provides a common heat sink for all three test chambers. This design allows the experimenter considerable versatility in the means of attaining the required test temperature.

Two basic types of test chambers (see Figure 1) are interchangeable and can be used in any of the three pockets. The first type will contain specimens immersed in NaK and will be used for high-temperature isothermal testing. NaK was chosen because it has high-thermal conductance and is liquid at ambient laboratory temperatures. Sodium can also be used as a heat transfer media. However, sodium changes phase and volume at 98°C, and this must be considered in design and operation.

All outside chamber walls will be thermally insulated except for the side walls, which will be designed to provide a predetermined static gas gap between it and the cooled pocket wall. In the center position, both side walls will be gas gapped; in an outer position only the inward facing side wall will be gas gapped. This type of capsule will provide primary temperature control by adjustment of gas gap size and gas composition to balance heat removal with neutron heat generation. Additional specimen temperature control can be provided for the highest temperatures by

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FIGURE 1. VTA-2 Test Module.

immersion heaters located inside the NaK-filled test chamber and/or by heating the bulk coolant systems.

The second type, called a weeper test chamber, will be provided with holes so that the specimens will be directly cooled by the flowing coolant. These chambers will be designed to support specimens in an easily accessible open cage. In these chambers, the specimen temperature will be controlled by the temperature of the coolant. This coolant may be inert gas or water that is limited to low-temperature operation. Bulk temperature may be externally controlled by a heater in the common coolant loop.

Both types of test chambers are instrumented with thermocouples to provide on-line test specimen temperature measuring capability.

4.0 THERMAL CONTROL SYSTEMS

At the outset it was decided that thermal control must be achieved in a reliable, straightforward way compatible with the current test cell/service cell and the VTA-1 designs.

The temperature control system must be capable of independently regulating the temperature of each test chamber within the range of 100° to 650°C. In order to minimize heat transfer and thermal stresses, it was assumed that maximum temperature differences between adjacent test chambers will be limited to 150°C. For example, a module could operate with test chambers at 600°C, 450°C, and 300°C. It was also assumed, based upon fabrication and operating experience, that the minimum practical gas gap width is 0.005 inches, and the maximum gas gap width is 0.050 inches.

The proposed thermal control concepts involve one or a combination of the following: a temperature-controlled flowing coolant to remove neutron-deposited heat, static gas gaps to control individual test chamber temperatures, and heaters to adjust the internal test chamber power generation level.

The gases considered were either nitrogen or helium. Nitrogen is inexpensive, has low-neutron activation, and is the reference FMIT test cell atmosphere. The VTA-2 test module is located in the test cell and is, therefore, surrounded by a nitrogen atmosphere. The cell nitrogen can be diverted into the VTA-2 tubing to form an open-loop bulk coolant system. Figure 2 is a simplified schematic of the open system. In this system, nitrogen is drawn by a centrifugal blower from the test cell and is blown through the VTA-2 piping in the shield plug. This blower, located above the shield plug under the service dome (see Figure 3 of Reference 1), forces nitrogen down through a return pipe in the shield plug which, is connected to the VTA-2 test module. The nitrogen cools the test module side walls and/or the pocket for weeper tests and exits the test module at the top. Nitrogen then returns to the test cell.

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FIGURE 2. VTA-2 Schematic of Open-Loop Thermal Control System.

Advantages of this system are:

- It does not require a separate heat exchanger to cool the nitrogen (cooling provided by test cell cooling system).
- It is a low-pressure system requiring only a low head (ΔP) blower.

Disadvantages of this system are:

- It limits the weeper test chamber temperature to the maximum test cell gas temperature of approximately 100°C.*
- It will be shown later that the upper temperature limit of a NaK-bonded center test chamber without additional electrical heating, using a 0.050 in. maximum gas gap, is approximately 460°C.
- The 650°C test temperature can be attained by adding approximately 500 watts of electric heat to the NaK-bonded test chamber.

The closed-loop coolant system can be designed to attain the 650°C without requiring heaters in the test chamber. A schematic of a closed-loop system with independent external temperature control is shown in Figure 3. The closed loop has the advantage of controlling the temperature of the circulating gas independent of the test cell environment. The coolant can be water, helium, or nitrogen. Water and helium have the advantage of better thermal heat transport properties than nitrogen, and hence smaller mass flow rates are required. However, a larger volumetric flow rate of helium is required than nitrogen because of its lower density. In the case of water, the upper temperature limit without significant pressurization is 100°C. This represents approximately the same bulk coolant temperature as for the open nitrogen system. Therefore, for a water heat sink, heaters are also required inside the NaK-bonded test chamber to attain the 650° test specimen temperature.

*This represents 75°C cell temperature plus 25°C temperature rise through the test module.

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FIGURE 3. VTA-2 Schematic of Closed-Loop Thermal Control System.

Helium or nitrogen can be maintained at any desired temperature required to attain test temperature. For a 650°C NaK-bonded test chamber temperature, the helium or nitrogen bulk temperature must be approximately 300°C. Weeper test chamber temperatures up to 650°C are obtained by adjusting the bulk gas coolant loop temperature to the desired test temperature.

5.0 RESULTS OF THERMAL ANALYSIS

5.1 THERMAL CALCULATIONS

The following data were used in the calculations:

- Neutron heating data calculated for VTA-2 (see Appendix A and Reference 3)
 - Heating in each outside chamber 590 watts
 - Heating in center chamber 844 watts
 - TOTAL ($2 \times 598 + 844$) 2040 watts
- Bulk coolant calculations assume no heat loss or gain except at desired heat transfer surfaces
- Conduction calculations are one dimensional; they assume that all surfaces except those selected for heat transfer are perfectly insulated
- Heat transport properties for helium, nitrogen, and water are from Reference 2

5.2 BULK COOLANT CALCULATIONS

Table 1 presents the assumptions and results of the bulk coolant system flow rate and pipe size calculations. Results show that the pressurized closed-loop system requires a smaller pipe size than the open-loop system. It also indicates that helium requires larger coolant lines than nitrogen, and water requires the smallest pipe size.

TABLE 1
BULK COOLANT REQUIREMENTS

<u>Assumptions:</u>	Temperature (outlet):	100°C
	Temperature (inlet):	75°C
	ΔT :	25°C
	Pressure (open N ₂ systems):	1 atm
	Pressure (closed systems):	3 atm
	Velocity in Piping (gas):	100 ft/s
	(water):	10 ft/s

Results:

<u>Coolant</u>	<u>Flow Rate (ft³/min)*</u>	<u>Pipe Size (in.)</u>
N ₂ (open system)	166.0 (1 atm)	2-1/4
N ₂ (closed system)	55.3 (3 atm)	1-1/4
Helium (closed system)	79.4 (3 atm)	1-1/2
Water (closed system)	0.308 (gpm)	1/4

*Volumetric rate at pressure and temperature conditions of flowing gas.

5.3 THERMAL CONTROL GAS GAP SIZES

Table 2 presents the assumptions and results of the thermal control gas gap sizes and compositions required to attain various temperature ranges inside NaK-bonded test chambers. Appendix B shows the effects of the simplifying assumptions on predicted test temperatures.

Values are first presented for the center and outside test chambers without supplemental electrical heating. Next, the increase in temperature range resulting from the addition of 500 watts of electrical heating to the inside of the center test chamber is shown. The outside test chamber requires approximately 50 watts of electrical heating to attain a 650°C temperature with a 50-mil nitrogen gas gap.

5.4 TEST TEMPERATURE VERSUS GAS GAP SIZE

Figure 4 shows the test temperatures attained for various gas gap sizes inside a NaK-bonded center chamber and an outside test chamber without supplemental electrical heating. The difference in temperature between using helium and nitrogen in the gas gap is indicated. Figure 4 is an open-loop nitrogen bulk coolant system (nitrogen taken from and returned to the test cell).

Figure 5 shows the test temperatures attained for various gap sizes inside a NaK-bonded center test chamber. It shows the effect on temperature of externally heating the bulk nitrogen coolant system to 300°C or of supplying 500 watts of electrical heat to the test chamber.

Figures 4 and 5 show that a proper combination of gas gap size and composition, bulk coolant, or internal test chamber heating will provide the required test temperature range of 100°C to 650°C inside NaK-bonded test chambers.

The required test temperature range of 100 to 650°C can be attained inside weeper test chambers by adjusting the bulk coolant temperature of a closed-loop system to the desired temperature level.

TABLE 2
THERMAL CONTROL GAS GAP SIZE REQUIREMENTS

Assumptions:

- Bulk coolant outlet temperature: 100°C
- Center test chamber: top and bottom, front and back are perfectly insulated; both sides are cooled.
- Outer test chambers: top and bottom, front and back, and outboard side are perfectly insulated; inboard side is cooled.
- Allowable gap size: 5-50 mil*
- Gap gas: 1 atm at 400°C
- ΔT s due to gas film, chamber walls on NaK bond are neglected.

Gas Gap ΔT (°C/mil)

Gas	Center Chamber		Outside Chamber
	(844 W)	(1344 W)	(598 W)
Helium	1.344	2.13	1.883
Nitrogen	7.28	11.58	10.17

Attainable Range of Temperatures (°C) Without Additional Heating

Gas	Center Chamber		Outside Chamber	
	Gap Range (mil)	Temperature (°C)	Gap Range (mil)	Temperature (°C)
Helium	5-50	107-167	5-48	109-190
Nitrogen	9-50	168-464	9-50	191-609

Attainable Range of Temperatures (°C) with 500-W Electrical Heating

Gas	Center Chamber	
	Gap Range (mil)	Temperature (°C)
Helium	5-50	111-207
Nitrogen	9-50	204-679

*1 mil = 0.001 inches.

FIGURE 4. Gap Size Versus Test Temperature Inside NaK-Bonded Test Chambers for Open Nitrogen Bulk Coolant System.

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FIGURE 5. Gap Size Versus Test Temperature Inside NaK-Bonded Center Test Chamber for Closed Nitrogen Bulk Coolant System.

A positioner is required to accurately locate the VTA-2 module behind the VTA-1 test module in the optimum neutron flux field. VTA-2 positioning accuracy requirements are somewhat less than for VTA-1; however, additional complexity is introduced because the VTA-2 shield plug position is located approximately 14 inches from the center of the neutron beam Z-axis. (See Figure 4 of Reference 1.) The positioner requires a mechanism for translating the VTA-2 module sideways along the X-axis to the neutron beam centerline. In addition, it must move VTA-2 forward in the Z direction so it contacts* the back of VTA-1. It must also locate the center of the test module on the vertical Y-axis beam centerline.

A simplified diagram of a concept for accomplishing these requirements is shown in Figure 6. This concept utilizes a parallelogram support structure to articulate the test module in the horizontal X direction. The Z direction adjustment will be made by sliding the support structure towards VTA-1 using a sliding bushing (Thompson rails). The vertical Y position will be established by design so that the test module will be in the correct vertical position when the X and Z motions have been completed. The positioner requires flexible bulk coolant lines between the test module and the shield plug to provide for compliance during positioner adjustment.

*It may be designed to provide a slight amount of standoff from VTA-1.

FIGURE 6. VTA-2 Positioner Concept.

7.0

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A P P E N D I X A

NEUTRON HEATING DATA FOR
VTA-2 THERMAL CALCULATIONS

APPENDIX A

NEUTRON HEATING DATA FOR VTA-2 THERMAL CALCULATIONS

FIGURE A1. Location of VTA-2 Neutron Heating Zones.

TABLE A1

HEATING RATES* IN NEUTRON ZONES

Front to Back Location	Center Chamber			Outside Chamber		
	Level			Level		
	1	2	3	1	2	3
0-2	22	24 2/3	6 1/3	23	34 1/3	9 2/3
2-4	16 1/3	20 2/3	5 1/3	19 2/3	29 1/3	9 2/3
4-8	20 1/3	28 2/3	9 2/3	26 2/3	42 1/3	15 1/3
8-12	11 2/3	17 1/3	6 2/3	16 1/3	28 2/3	10 1/3
12-16	6 2/3	10 2/3	4	10 1/3	16 1/3	7
TOTAL	211 x 4 = 844 watts			299 x 2 = 598 watts		

*Heating rates are for one symmetric quadrant. Numbers must be multiplied by 4 for center chamber, by 2 for outside chamber.

A P P E N D I X B

EFFECTS OF SIMPLIFYING ASSUMPTIONS
ON TEST TEMPERATURES

APPENDIX B

EFFECTS OF SIMPLIFYING ASSUMPTIONS ON TEST TEMPERATURES

The following factors were omitted in the calculation of test temperatures. A summary of the factors that tend to increase (+) or decrease (-) test temperatures, including an estimate of the effect are given below:

Factor	Equation	Resulting Temperature (°C) Increase(+) or Decrease(-)	
		Center Chamber	Outside Chamber
Film drop (coolant gas)	$\Delta T = \frac{Q}{Ah_f}$	+25	+34
ΔT metal wall	$\Delta T = \frac{Q}{A} \left(\frac{L}{k} \right)$	+3	+4
ΔT NaK-filled chamber	$\Delta T = \frac{Qr\ell^{\star 2}}{2k}$	+4	+9
ΔT conduction heat loss from 0.25-in. NaK-insulated walls	$\Delta T \propto \frac{Q}{A} \left(\frac{L}{k} \right)$	-11 —	-107 —
Net change		+21°C	-60°C

Where:

$\ell^{\star} = 0.082$ ft for center chamber

0.164 ft for outside chamber

ΔT = Temperature difference (°C)

$\frac{Q}{A}$ = Heat flux (Btu/h·ft²)

h_f = Heat transfer coefficient (Btu/h·ft²·°F)

L = Thermal conduction length (thickness-ft)

k = Thermal conductance (Btu/h·ft²·°F)

Q_v = Volumetric heat generation (Btu/h·ft³)

Conclusions:

- Center test chamber will operate 21°C hotter than predicted by Figures 5 and 6.
- Outside chamber will operate 60°C cooler than predicted by Figure 5.
- Allowance for the above factors must be made by design and operation of the experiments.

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