GA–A22446

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This is a preprint of a paper to be presented at the 19th Symposium on Fusion Technology September 16–20, 1996, Lisbon, Portugal and to be published in the *proceedings*.

Work supported by
General Atomics IR&D Funds

GA PROJECT 4437
OCTOBER 1996

Design, Fabrication and Testing of Helium-Cooled Vanadium Module for Fusion Applications*

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Vanadium alloys are attractive materials for fusion applications due to their low neutron activation and rapid decay of radioactivity with time. Design of high heat flux components with vanadium as the structural material is difficult due to its low thermal conductivity relative to copper and the lack of practical experience with fabrication of vanadium components. Similarly, helium is an attractive coolant for fusion power plants due to its chemical inertness, its transparency to neutrons, and stable heat transfer. However, there is a perceived difficulty that the use of helium as a coolant will limit the maximum heat flux on components. Reference 1 discusses the principle that heat transfer enhancement techniques reduce the pumping power for helium cooling, making it practical for cooling plasma facing components and General Atomics (GA) has demonstrated cooling of high heat flux components with helium coolant. A copper module designed by GA was successfully tested to a steady state heat flux level of 3200 W/cm^2 over small area and 1000 W/cm^2 over the entire 20 cm^2 area. As a continued effort to demonstrate practical application of fusion science, GA undertook the present effort to fabricate a vanadium module cooled with helium. Due to lower thermal conductivity of vanadium (6% of copper), this module will withstand about 300 W/cm^2 heat flux over the entire length. The module was fabricated from V-4Cr-4Ti alloy and is 228 mm long and 22.1 mm in diameter. The thickness of the vanadium tube is 1.76 mm. The internal flow path has been designed to enhance the heat transfer coefficient to a value of about 1 W/cm^2-°C at a helium flow rate of 20 g/s. A thermal stress analysis of the design was performed to ensure that the stresses are within limits at a heat flux level of 300 W/cm^2 and a helium pressure of 4 MPa. The test module has been hydrostatically tested to 7 MPa pressure and helium leak checked. The module is ready to be tested at the helium loop (4 MPa pressure 20 g/s flow) at Sandia National Laboratory, Albuquerque. Future high heat flux testing is planned.

1. DESIGN AND ANALYSIS

Thermal conductivity of vanadium is about 6% of copper. Hence, the methods previously used for designing the helium cooled copper module [1] are not attractive for this material. For example, the fin efficiency (ratio of actual heat transfer to heat transfer if entire fin was at the root temperature) for the GA copper module is about 0.5. For vanadium the fin efficiency will be less than 0.2. If the heat transfer area is increased by a factor of 10 using extended surfaces, no enhancement will be obtained.

First, an analysis was performed to find the required effective heat transfer coefficient (HTC). Then, we looked at methods which do not depend on thermal conductivity of the material to increase the heat transfer coefficient.

A finite element (FE) analysis was performed for a vanadium tube of 22.1 mm o.d. and 1.76 mm wall thickness, subjected to heat flux on one side using ANSYS [2]. The results of many analysesare summarized in Fig. 1. With a heat transfer coefficient of 1 W/cm^2-°C for a heat flux of 300 W/cm^2, the peak surface temperature is about 600°C.

We wanted to design our module such that it could be tested at Sandia National Laboratory, Albuquerque (SNLA). The helium loop and beam parameters at SNLA are: e-beam power of 30 kW, flow of 20 g/s, loop pressure 4 MPa, and maximum pressure drop 0.1 MPa.

The design shown in Fig. 2, using the full capacity of SNLA loop, will withstand a steady state heat flux of more than 300 W/cm^2.

The design consists of a vanadium tube of 22.1 mm o.d. and 18.3 mm i.d. with an insert of 18.1 mm o.d. The insert was made from stainless steel. The inside wall of the vanadium tube was

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*Work supported by General Atomics IR&D funds.

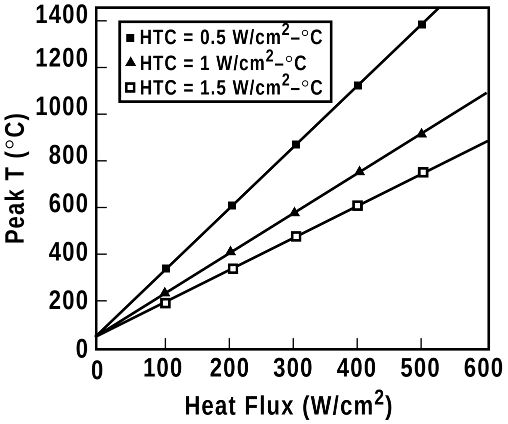

Fig. 1. Peak surface temperature for a vanadium tube of Do = 22.1 mm, Di = 18.3 mm and coolant temperature of 50°C.

roughened with axial ribs shown in Fig. 3 to increase the heat transfer coefficient. The gap between the tube and the insert is maintained by a spiral fin of1 mm height and 100 mm pitch on the stainless steel rod (Fig. 4). This geometry enhances the heat trasfer coefficient by 1) increasing the flow velocity, 2) reducing the hydraulic diameter, 3) increasing top to bottom flow mixing and 4) breaking up the laminar boundary layer at the wall with the ribs.

Calculations were made using a flow of 20 g/s, an inlet pressure of 4 MPa, an inlet temperature of 20°C, and a heat flux of 300 W/cm^2 on the vanadium module. The results showed a maximum surface temperature of 600°C, a pressure drop of 0.6 bar (9 psi), and a pumping power of 200 W, about 3% of the power removed.

This design has potential of operating near 500 W/cm^2 heat flux by:

1. Reducing the wall thickness to 1 mm.
2. Allowing higher wall temperatures up to 750°C.
3. Using higher flow rates and pressures than currently available at SNLA.

The stresses in the vanadium tube at the maximum pressure (7 MPa) were acceptable (41.3 MPa) for the material (allowable = 124 MPa). This is the pressure at which the module was tested hydrostatically at room temperature to fulfill SNLA requirements. Additionally, the deflections of the tube due to bowing, caused by the temperature gradient of 300°C, were calculated to be small (0.43 mm max). Also, the calculated thermal stress was less than 50% of the allowable.

2. TEMPERATURE LIMITS ON VANADIUM

An assessment was made of the maximum temperature limits for the V-4Cr-4Ti alloy components of the module using Argonne National Laboratory (ANL) and Oak Ridge National laboratory oxidation data for vanadium alloys in air and low partial pressure oxygen environments. Calculations/extrapolations based on tensile properties (ductility) of V-alloys exposed in air at

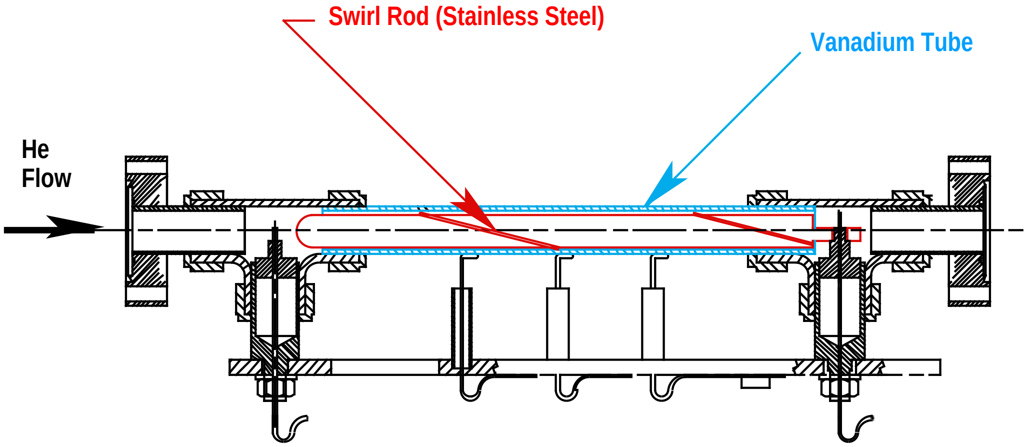

Fig. 2. He cooled Vanadium Module.

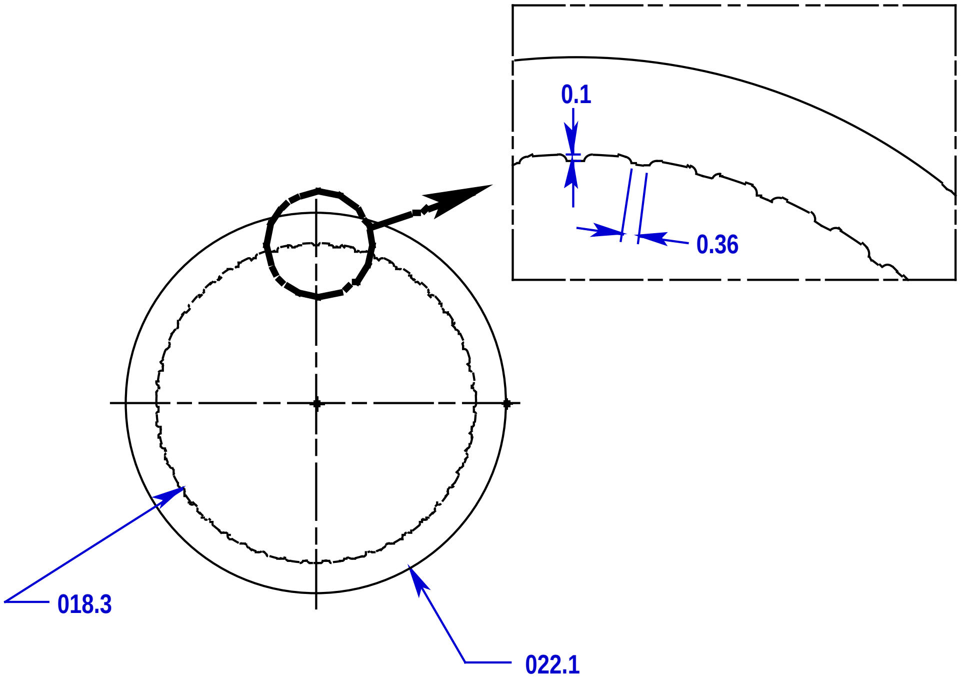

Fig. 3. Vanadium tube cross section and magnification of axial grooves (dimensions in mm).

temperatures of 400 and 500°C yielded a conservative temperature limit of ~750°C for a 1 hour exposure during the high heat flux testing.

3. FABRICATION

The vanadium tube for this module was some of the first tubing made. It was fabricated starting with 29 mm thick plate material produced by Teledyne Wah Chang in Albany, Oregon for ANL. The vanadium was then cold drawn by Century Tubes of San Diego, California. The drawing was done in a series of cycles separated by annealswith the cold work between anneals limited to 30% reduction with 10%–12% per pass. Electric discharge machining was used to make the axial ribs. A vacuum bake was used to degas the hydrogen from the material.

The stainless steel Spiral Rod Insert (SRI) was made from 304 stainless steel rod stock on a four axis lathe by Qualtech Manufacturing in San Diego, California. The rod is rounded at the inlet end to reduce the pressure drop. It is fixed at the exit end to prevent the rotation of the rod.

The vanadium tube is connected to the inlet and exit flanges by standard Swagelock compression fittings. This allowed us to make the assembly without any brazing or welding of the vanadium tube.

The module was equipped with five k type thermocouples. Two thermocouples measure the inlet and outlet temperatures of the helium. The other three measure the vanadium tube temperature and will be used for calibration of the infra-red (IR) camera and two color pyrometer.

The module was assembled, pressure tested to 7 MPa pressure, and leak checked at GA. The helium leak rate was less than 10^{-7} Pa m^3/s.

4. TESTING PLANS

The testing is planned to occur in September 1996.

The test plan consists of three parts. During the first phase, a relation between flow and pressure drop will be established to insure that sufficient flow can be obtained. During the second phase, an IR camera and a two color pyrometer will be calibrated by heating the module slowly to about 300°C using the leakage current for the e-beam. During the final phase, the heat flux will be increased in steps until

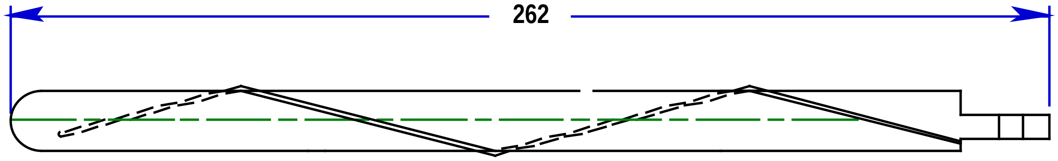

Fig. 4. Sketch of spiral rod insert.

the surface temperature limit of 700°C is reached. The surface temperature will be measured by a two color pyrometer and an IR camera. The heat flux will be calculated from calorimetry. Flow rate, inlet and outlet temperatures, and pressure drop will also be measured during the test.

CONCLUSIONS

We have demonstrated that vanadium components can be fabricated and vanadium can be used as a structural material with helium cooling to remove steady-state fluxes to a level of 300 to 500 W/cm^2.

ACKNOWLEDGMENTS

Authors want to thank K. Redler for help with finite elements analysis and J. Lindgren for material availability evaluation and ANL for supplying the vanadium.

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1. C.B. Baxi, “Evaluation of Helium Cooling for Fusion Divertors,” Fusion Engineering and Design, **25** (1994) 263–271.
2. ANSYS Finite Element code, Swanson Analysis System Inc., Houston, PA.