COLD SOURCE MODERATOR VESSEL DEVELOPMENT FOR THE HIGH FLUX ISOTOPE REACTOR: THERMAL-HYDRAULIC STUDIES[a]

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ABSTRACT

A project is underway at Oak Ridge National Laboratory (ORNL) to design, test, and install a cold neutron source facility in the High Flux Isotope Reactor (HFIR). This new cold source employs supercritical hydrogen at cryogenic temperatures both as the medium for neutron moderation and as the working fluid for removal of internally-generated nuclear heating. The competing design goals of minimizing moderator vessel mass and providing adequate structural integrity for the vessel motivated the requirement of detailed multidimensional thermal-hydraulic analyses of the moderator vessel as a critical design subtask. This paper provides a summary review of the HFIR cold source moderator vessel design and a description of the thermal-hydraulic studies that were carried out to support the vessel development.

I. INTRODUCTION

In 1995, a project was initiated to design, test, and install a cold neutron source facility in the High Flux Isotope Reactor (HFIR) located at Oak Ridge National Laboratory (ORNL). Initial feasibility studies[1] demonstrated that a cold source could be retrofitted into an existing HFIR beam tube providing a small but very bright cold neutron beam. It was determined that this cold neutron beam would be comparable, in cold neutron brightness, to the best facilities in the world.

A versatile isotope production and research reactor with the capability and facilities for performing a wide variety of irradiation experiments, the HFIR (see Fig. 1) is a beryllium-reflected, light-water-cooled and -moderated, flux-trap type reactor that uses highly-enriched ^{235}U as its fuel. The neutron-scattering instruments installed on its horizontal beam tubes are used in fundamental studies of materials of interest to solid-state physicists, chemists, biologists, polymer scientists, metallurgists, and colloid scientists.

The purpose of the proposed HFIR cold source is to increase the available neutron flux delivered to instruments at wavelengths from 4 to 12 Å. Design optimization is based on neutron brightness (/s/cm ^{2}/steradian/Å) where the gain factor on brightness should be of the order of ~ 10 to 20 at 7 Å which is comparable to existing cold sources of similar geometry.

The HFIR is equipped with three horizontal beam tubes, extending outward from the reactor core midplane. The HB-2 and HB-3 beam tubes extend radially and tangentially, respectively, from the reactor center line with their inner ends penetrating the permanent reflector. The remaining beam tube is positioned on a tangential line with both ends, designated as HB-1 and HB-4, extending outward from the reactor. The proposed cold source will be positioned in the HB-4 beam tube.

The scope of the HFIR cold source project includes the development, design, procurement/fabrication, testing, and installation of all of the components necessary to produce a working cold source within an existing HFIR beam tube.[2] All aspects of the cold source design will be based on demonstrated technology adapted to the HFIR design and operating conditions. The competing design goals of minimizing moderator vessel mass and providing adequate structural integrity for the vessel indicated the need for detailed multidimensional thermal-hydraulic

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analyses of the moderator vessel as a critical design subtask. Similar studies are also planned for the cold source in ORNL's Spallation Neutron Source currently being designed by five U.S. Department of Energy national laboratories. This paper provides a summary review of the HFIR cold source moderator vessel design and a description of the thermal-hydraulic studies that were carried out to support the vessel development.

II. COLD SOURCE CONCEPTUAL DESIGN

In the cold source conceptual design, hydrogen circulates in a closed loop at a supercritical pressure of nominally 15 bar absolute at all temperatures. The major advantage of operating with supercritical hydrogen is the freedom it offers from potential problems associated with a two-phase fluid during cool-down, warm-up, transitioning to a standby state, or other possible operational transients. Two steady-state operating conditions are a part of the reference design: (1) *normal operation* where 1 L/s of supercritical hydrogen enters the moderator vessel at 18 K and leaves at approximately 22 K, and (2) *standby operation* with 2.25 L/s of 14 bar hydrogen entering the moderator vessel at 90 K and leaving at approximately 106 K.

Designed on a modular basis, the cold source system consists of eleven basic elements:

(1) moderator plug assembly,
(2) hydrogen circulators,
(3) heat exchangers,
(4) gas-handling system,
(5) cryogenic refrigerator,
(6) transfer lines,
(7) insulating vacuum systems,
(8) inert blanket system,
(9) instrumentation and control,
(10) equipment enclosures and safe room, and
(11) dedicated vent system.

The moderator plug assembly consists of a cylindrical vacuum chamber that is bolted and sealed into the forward end of one of the existing horizontal HFIR beam tubes, specifically HB-4. The assembly (see Fig. 2) includes a vacuum tube that contains the cold source moderator vessel and associated hydrogen transfer lines. A vacuum envelope, split into two sections, insulates all cold components of the cold source loop. The entire hydrogen system is further enclosed by a continuous inert blanket that uses either helium or nitrogen depending on location. This inert blanket provides double isolation of the hydrogen from atmospheric air and also prevents air from entering the insulating vacuum spaces where it could cryopump onto cold surfaces. In areas of high radiation, such frozen air could break down to form hazardous unstable free radicals.

III. THERMAL-HYDRAULIC MODEL DESCRIPTION

The numerical studies described in this paper were carried out using the commercial computational fluid dynamics (CFD) computer code CFX-4.[3] In addition to convective heat transfer within fluids, CFX-4 can also be used to simulate conjugate heat conduction within solid structures bounding and/or within the flow field. Internal heat generation can be accommodated through user-supplied subroutines.

A. Conservation Law System

The turbulent flow of the cryogen is governed by the physical principles of conservation of mass, momentum, and energy. An appropriate mathematical form for this conservation law system is the coupled set of nonlinear partial differential equations called the Reynolds-averaged Navier-Stokes equations for an incompressible (constant density) fluid. Using index notation, steady-state forms for the conservation of mass, momentum, and energy are

$$\frac{\partial U_j}{\partial x_j} = 0 \quad , \qquad \textbf{(1)}$$

$$\frac{\partial}{\partial x_j}\left[\rho U_i U_j - \mu\left(\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i}\right) + \rho\overline{u_i' u_j'}\right] + \frac{\partial P}{\partial x_i} = 0 \,, \qquad \textbf{(2)}$$

$$\frac{\partial}{\partial x_j}\left(\rho U_j H - \rho\,\alpha\frac{\partial H}{\partial x_j} + \rho\overline{u_j' h'}\right) - S_H = 0 \quad , \qquad \textbf{(3)}$$

respectively, where ρ, μ, and α are the density, dynamic viscosity, and thermal diffusivity, respectively, of the fluid; U_i is the time-averaged velocity vector; H is the time-averaged static enthalpy; P is the *motion* pressure (equal to the thermostatic pressure minus the hydrostatic pressure), and S_H represents any distributed volumetric heat sources. In CFX-4, Eqs. (1)-(3) are discretized using generalized coordinates with a nonstaggered finite volume mesh. Steady-state solutions for the discrete equation set are calculated using the SIMPLEC algorithm.[4]

B. Turbulence Modeling

Arising from the time-averaging of the convection terms in the original instantaneous conservation law system, statistical double correlations appear in Eqs. (2) and (3) that characterize the effects of turbulence on the transport of momentum (Reynolds stresses, $\rho u_i' u_j'$), and thermal energy (turbulent heat fluxes, $\rho u_i' h'$) in the mean flow field. Turbulence models are required to provide estimates for these terms. For engineering calculations, the two-equation k-ε (where k is the turbulence kinetic energy, and ε is the isotropic turbulence dissipation rate) turbulence model is appropriate for a wide range of applications. In the standard high-Reynolds number k-ε model, the computational domain does not extend all the way to solid walls. So-called *wall functions*, derived from the logarithmic "law-of-the-wall" velocity profile, are employed to simulate the effect of the no-slip wall boundary condition on the flow field adjacent to the wall. Related *heat flux wall functions* are also available for the energy equation to calculate the heat transfer between the flow domain and solid boundaries.[5]

C. Nuclear Heating

Nuclear heating, resulting from neutron and gamma bombardment of the aluminum walls of the cold source moderator vessel and the hydrogen flowing through the cold source, is simulated in the moderator vessel model as internally-distributed heat sources that are added to the energy equation, Eq. (3). Look-up tables of nuclear heating values in terms of W/g of material were developed from data in ref. 6. These data are presented as a function of position along the beam tube as measured from the midpoint of the HB-1/4 beam tubes. Near the reactor, the data are also divided into reactor-side and far-side heating values. Representative nuclear heating data for the reactor-side of the moderator vessel are shown in Fig. 3. A schematic drawing of the moderator vessel is also shown in Fig. 3 depicting the position of the vessel relative to the midpoint of the beam tube. The hydrogen cryogen has a maximum nuclear heating rate of 20.2 W/g with a rapid decline moving away from the reactor core. Both the aluminum moderator vessel and vacuum tube have a maximum nuclear heating value of 5.75 W/g at positions nearest the core with a more gradual rate of decrease of heating (relative to the hydrogen) moving down the beam tube and away from the reactor core.

D. Moderator Vessel Geometry

The moderator vessel is constructed of Al 6061-T6 alloy with wall thicknesses varying from 1 to 4 mm. The competing design requirements of maintaining the structural integrity of the vessel under pressure and thermal stress loads and minimizing the mass of aluminum to keep the total nuclear heating rate as low as possible produced the varying wall thicknesses. The overall length of the vessel is 153 mm with an inner radius at the hemispherical endcap of 47 mm. Both inlet and outlet nozzles have an inner diameter of 9.5 mm.

The CFD model, constructed with 94,880 finite volumes, consisted of the aluminum walls (with varying thickness) of the moderator vessel and the volume displaced by the hydrogen moderator. In all cases, the hydrogen was assumed to be incompressible, and a standard two-equation k-ε turbulence model was employed to determine the effects of turbulence on the flow field and heat transfer due to turbulent mixing within the hydrogen.

E. Boundary Conditions

Applied as spatially-distributed internal heat generation sources, nuclear heating of both the aluminum and hydrogen was included in the model. A fixed uniform velocity boundary condition was applied at the inlet. When integrated over the inlet cross-sectional area, this boundary condition results in the required total volumetric flowrate. For an incompressible fluid, the absolute pressure is not used explicitly in the calculations (only the pressure gradient); therefore, a relative reference pressure of 0.0 was applied to the outflow plane. This boundary condition results in a "continuative" or "vanishing normal velocity derivative" outflow boundary. All external aluminum surfaces had radiative boundary conditions applied assuming the moderator vessel has a complete view of its containment vessel (the vacuum tube set at a constant 373 K) with blackbody radiative properties. This assumption is conservative in that it overstates the amount of heat gain by thermal radiation from the surrounding environment.

F. Thermophysical Properties

Thermal conductivity data[7,8,9] for the aluminum alloy Al 6061-T6 was obtained from the literature for a range of temperatures and compared to the thermal conductivities of pure aluminum and the alloy Al 2024-T4.[10] The latter two materials were used in sensitivity studies assessing the effects of uncertainties in the conductivity of Al 6061-T6. Pure aluminum at cryogenic temperatures has a very high thermal conductivity that increases with decreasing temperature. The presence of even a small amount of alloying material or contaminant, however, reverses this trend with a decreasing conductivity for a decreasing temperature. In addition, some reduction in the thermal conductivity is expected due to radiation-induced effects; however, the degree of change for Al 6061 is not known.[11] Since both electrical and thermal conduction are determined primarily by the free electrons, an increase in electrical resistivity implies a decrease in thermal conductivity. Resistivity measurements in irradiated copper have shown increases as large as about 30% for doses above 1 dpa. Calculations, to be reported in the next section, were carried out to determine the sensitivity of the results to uncertainties in the assumed aluminum thermal conductivity. At 20 K, Al 2024-T4 has a thermal conductivity that is approximately 45% below that of Al 6061-T6. The density of aluminum is 2.7 g/cm^3 (2700 kg/m^3).

At room temperature, the equilibrium mixture of "normal" hydrogen is fixed at 25% para and 75% ortho; however, for the temperature range of 20 to 250 K, the percentages of para and orthohydrogen vary appreciably at equilibrium.[12] Below 20 K, hydrogen is essentially all parahydrogen in the absence of irradiation. Under irradiation conditions, some amount of orthohydrogen is produced even at 20 K and below. Except for small differences in specific heat, however, the thermodynamic and transport properties of para and normal hydrogen are effectively the same. The property data for parahydrogen used in these calculations were obtained from the NIST Standard Reference Database for Pure Fluids.[13]

Figure 4 shows the relationship between the reference supercritical hydrogen normal operating mode and a liquid hydrogen system on a plot of pressure vs enthalpy. For the high pressure and standby modes between 14 and 15 bar absolute, the hydrogen is a supercritical fluid, but for the low pressure 4 bar state, the hydrogen is in the compressed liquid phase. In a plot of temperature vs entropy, Fig. 5 depicts a zone of thermodynamic states called the "near-critical" region[11] which for hydrogen is approximately bounded by the reduced pressures $0.8 \le P/P_c \le 3$ and the temperatures of T_{sat} at the reduced pressure $P/P_c = 0.8$ and the transposed critical temperature, T^*, which is defined as the temperature where the specific heat c_p attains a maximum for a given supercritical pressure. For hydrogen at 15 bar absolute, $T^* \approx 34\text{K}$. The difficulties with operating within this near-critical region are due to the uncertainties associated with accurately predicting transport properties and convective heat transfer.[12] The operating states proposed for the cold source lie well outside of the near-critical region; however, certain operational transients (such as high pressure cool down) will pass through this region.

IV. RESULTS AND DISCUSSION

A 3-dimensional thermal-hydraulic analysis was carried out on the moderator vessel for a range of operating conditions. The normal steady-state operating condition is based on a supercritical hydrogen pressure of 15 bar absolute with a supply temperature from the refrigeration system of 18 K and an average flowrate through the vessel of 1 L/s. It was also desirable to obtain performance predictions for the lower subcritical pressure of 4 bar absolute. A standby operating mode is also envisioned which requires the moderator to run at a steady-state condition of 14 bar absolute with a supply temperature of 90 K and a flowrate of 2.25 L/s.

Steady-state results for 15 cases are summarized in Table 2. The hydrogen flow field is characterized by an expanding jet, formed at the inlet, that flows up the wall of the hemispherical endcap, see Fig. 6. The jet then bifurcates as it rolls over, forming a recirculating cell that provides a downwash across the face of the ellipsoidal interior wall. Flow reversals are observed in both the inlet and outlet transition regions. For all cases, the integrated nuclear heat load on the vacuum vessel is 1.49 kW. An additional 0.04 kW has been added to the vessel heat load due to thermal radiation interchange between the vacuum vessel and the moderator vessel. Nuclear heating of the cryogen within the moderator varies with the density of the hydrogen. For the two low pressure cases at 8 bar absolute and 4 bar absolute, the hydrogen bulk temperature remains subcooled throughout the moderator vessel. For all cases at the design flowrate of 1 L/s, the hydrogen pressure drop from inlet to outlet ranges from 0.129 to 0.135 bar.

Maximum vessel wall temperatures are presented in Table 1. The first three cases investigated the sensitivity of the results to ± 20% variations in flowrate at a hydrogen pressure of 15 bar absolute. Subsequent cases checked the sensitivity of the maximum wall temperature results to uncertainties in the thermal conductivity of the walls and changes in operating pressure. Using thermal conductivity data for Al 2024-T4 results in a decrease in wall heat conduction of approximately 45%. As an upper bound on the most optimistic estimate for wall conduction, property data for pure aluminum was applied. For the low temperature cases, the wall temperatures remain below 47 K. A 20% reduction in flowrate raises the peak wall temperature by 3 K; however, increasing the flowrate by 20% only lowers the wall temperature by 0.9 K. The most optimistic prediction for peak wall temperature is 28.7 K for pure aluminum.

The moderator vessel material is Al 6061-T6; however, the results with Al 2024-T4 properties provide conservatively high estimates of wall superheat and maximum wall temperatures. At a subcritical pressure of 8 bar, the maximum vessel wall temperature is 44.6 K or 14.8 K above the saturation temperature of 29.84 K. Upon lowering the pressure to 4 bar, a portion of the vessel wall near the outlet reaches a temperature of 45.2 K or 19.2 K above the saturation temperature of 25.96 K. Due to this superheating of the walls, there is a potential for localized subcooled nucleate boiling at 4 and 8 bar. These results were among the factors that motivated the decision to move to a supercritical operational mode. By adopting 15 bar absolute as the design pressure, the uncertainties associated with operating the cold source in a two-phase flow regime were removed.

In its standby mode of operation at 14 bar absolute, the hydrogen temperature could rise to a supply inlet temperature of 90 K with an increased flowrate of 2.25 L/s. Corresponding to a reduced hydrogen density at this temperature, the nuclear heating of the hydrogen is also reduced from a nominal 0.63 kW at 18 K to 0.03 kW at 90 K. The maximum wall temperature for this case is 144.7 K.

V. FUTURE STUDIES

An integrated thermal analysis of the cold source moderator vessel combined with the vacuum tube, beam tube, and reactor cooling water on the outside of the beam tube is planned to assess the safety of the system under both steady and transient conditions. These analyses involve computational fluid dynamics, conduction heat transfer in the aluminum, and radiation heat transfer within two enclosures: the moderator vessel itself and the vacuum between the moderator and vacuum tube. Steady-state simulations will be performed for full power normal operation. The most limiting transient to be simulated involves the total loss of coolant flow to the moderator vessel coincident with a reactor trip. Because the moderator is so well insulated from the vacuum tube, the decay heat in the moderator vessel walls may elevate the temperatures near the melting point, thus violating the containment boundary. To mitigate these consequences, an option is being considered to perform an emergency helium fill of the vacuum region once the loss-of-flow situation is detected.

VI. CONCLUSIONS

Multi-dimensional thermal-hydraulic analyses have been carried out for the proposed HFIR cold source moderator vessel. The hydrogen flow field in the moderator vessel consists of a number of complicated 3-dimensional flow structures, characterized by an expanding jet, formed at the inlet, that flows up the wall of the hemispherical endcap. The jet then bifurcates as it rolls over, forming a recirculating cell that provides a downwash across the face of the ellipsoidal interior wall. Flow reversals are observed in both the inlet and outlet transition regions. It is within these separation regions that the peak wall temperatures occur. For the supercritical normal and standby operating modes, the temperature gradients are acceptable from a thermal-hydraulic point of view. Additional thermal stress calculations will address any issues concerning the mechanical design and structural integrity of the vessel. At the two subcritical pressures investigated, 4 and 8 bar absolute, significant wall superheat was predicted within the transition regions of the moderator vessel. At these levels of superheat there is a potential for localized subcooled nucleate boiling of the hydrogen. Uncertainties associated with operating the cold source in a two-phase flow regime motivated the design to adopt the supercritical operating mode.

Future studies will address the integrated performance of the moderator vessel and surrounding components, both under steady-state and transient conditions.

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REFERENCES

1. D. L. Selby, A. T. Lucas et al., *High Flux Isotope Reactor Cold Source Preconceptual Design Study Report,* ORNL/TM-13136, Lockheed Martin Energy Systems, Inc., Oak Ridge Natl. Lab. (1995).

2. D. L. Selby, A. T. Lucas et al., *High Flux Isotope Reactor Cold Neutron Source Reference Design Concept*, ORNL/TM-13498, Lockheed Martin Energy Research Corp., Oak Ridge Natl. Lab. (1998).

3. *CFX 4.1 Flow Solver User Guide*, Computational Fluid Dynamics Services, Harwell Laboratory, Oxfordshire, UK, October 1995.

4. J. P. van Doormaal and G. D. Raithby, "Enhancements of the SIMPLE Method for Predicting Incompressible Fluid Flows," *Numerical Heat Transfer* 7, 147-163 (1984).

5. B. E. Launder and D. B. Spaulding, "The Numerical Computation of Turbulent Flows," *Computer Methods in Applied Mechanics and Engineering* 3, 269-289 (1974).

6. J. A. Bucholz, "Discussion of New Calculations for the July 1996 Conceptual Design: MCNP Results from Run HF072," Internal Correspondence to D. L. Selby, Oak Ridge National Laboratory, Oak Ridge, TN, August 16, 1996.

7. M. F. Marchbanks, *Aluminum Alloys Properties Databook*, Savannah River Laboratory, May 1988.

8. U.S. Dept. of Defense, "Metallic Materials and Elements for Aerospace Vehicle Structures," MIL-HDBK-5E, June 1, 1987.

9. *Structural Alloys Handbook, Vol. 3,* Battelle's Columbus Division, Metals and Ceramics Information Center, 1986 Edition.

10. Y. S. Touloukian, et al., *Thermophysical Properties of Matter, Vol. I: Thermal Conductivity of Metallic Elements and Alloys*, IFI/Plenum, New York, 1970.

11. Personal communication with Dr. K. Farrell, Oak Ridge National Laboratory, Oak Ridge, TN, July 30, 1997.

12. W. Frost, *Heat Transfer at Low Temperatures*, Plenum Press, New York, 1975.

13. D. G. Friend, *NIST Standard Reference Database 12, NIST Thermophysical Properties of Pure Fluids, Version 3.1*, National Institute of Standards and Technology, Gaithersburg, MD, 1992.

Table 1. Summary of Moderator Vessel Cases

Hydrogen Operating Conditions								
Press. (bar)	Inlet Temp. (K)	Outlet Temp. (K)	Flow Rate (L/s)	ΔP[c] (bar)	Al Type	k/k_{6061}[d]	Max. Wall Vessel (K)	Max. Wall Superheat[e] (K)
15	18	21.7	1.0	0.135	6061-T6	1.0	43.2	NA[f]
15	18	21.2	1.2	0.194	6061-T6	1.0	42.3	NA
15	18	22.6	0.8	0.086	6061-T6	1.0	46.2	NA
15	18	21.7	1.0	0.135	2024-T4	0.548	46.6	NA
15	18	21.7	1.0	0.135	pure Al	428	28.7	NA
8	18	21.6	1.0	0.133	6061-T6	1.0	37.6	+ 7.8
8	18	21.6	1.0	0.133	2024-T4	0.548	44.6	+14.8
8	18	21.6	1.0	0.133	pure Al	428	28.6	- 1.2
4	18	21.2	1.0	0.129	6061-T6	1.0	37.8	+11.8
4	18	21.2	1.0	0.129	2024-T4	0.548	45.2	+19.2
4	18	21.2	1.0	0.129	pure Al	428	27.7	+ 1.7
15	100	109.2	4.0	0.105	6061-T6	1.0	139.9	NA
15	100	109.2	4.0	0.105	2024-T4	0.548	144.5	NA
15	100	109.2	4.0	0.105	pure Al	428	135.4	NA
14	90	106.4	2.25	0.038	6061-T6	1.0	144.7	NA

[c]ΔP = pressure drop across moderator vessel
[d]Relative conductivity = thermal conductivity/thermal conductivity of 6061-T6 at inlet temperature.
[e]Superheat = $(T_{wall} - T_{sat})$ for H_2: T_{sat} = 29.84 K at 8 bar; T_{sat} = 25.96 K at 4 bar.
[f]NA = not applicable

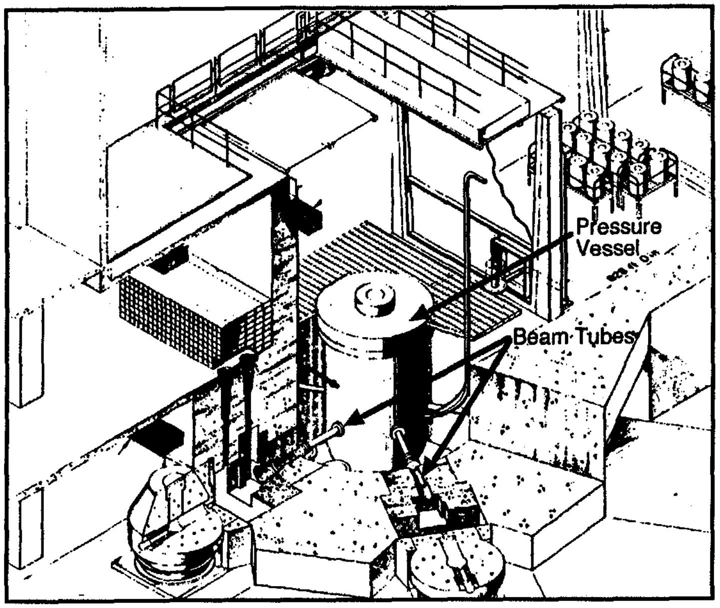

Fig. 1. High Flux Isotope Reactor (HFIR)

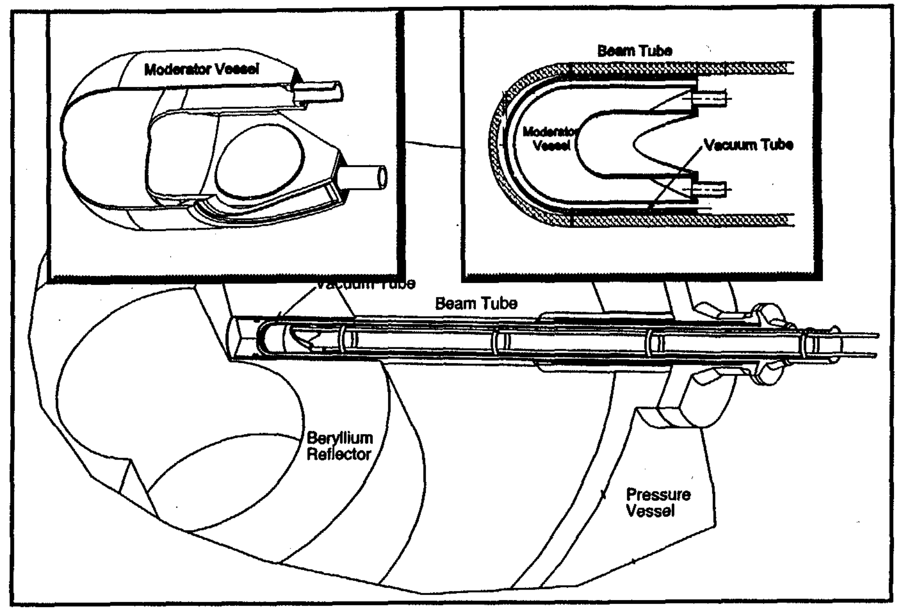

Fig. 2. Cold source moderator vessel and vacuum tube.

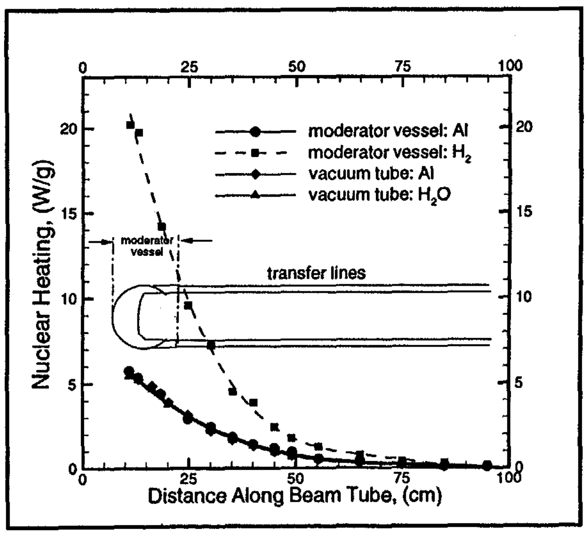

Fig. 3. Nuclear heating of cold source.

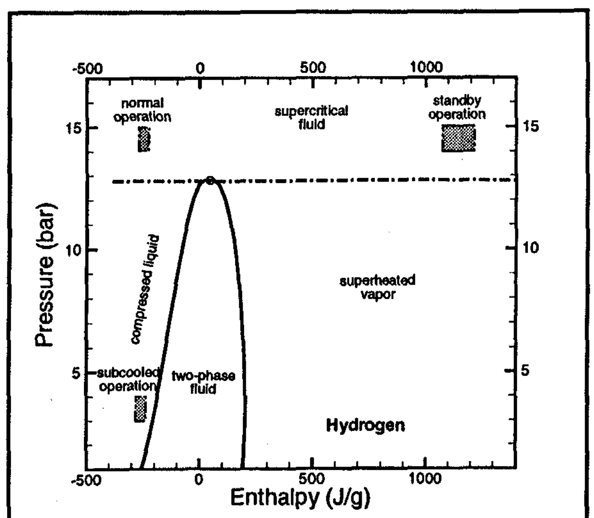

Fig. 4. Pressure vs enthalpy.

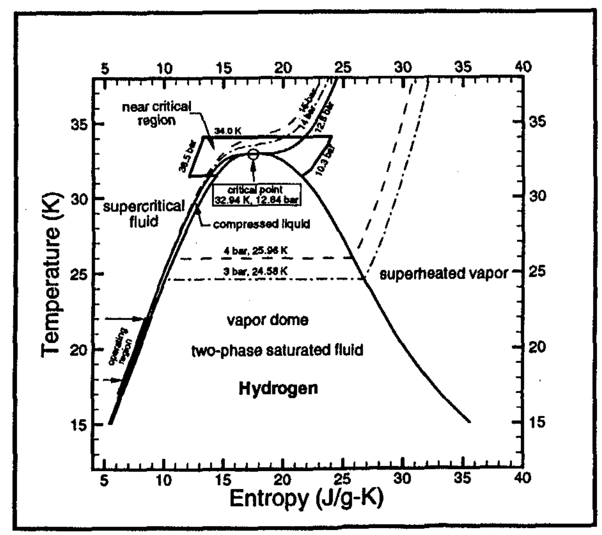

Fig. 5. Temperature vs entropy.

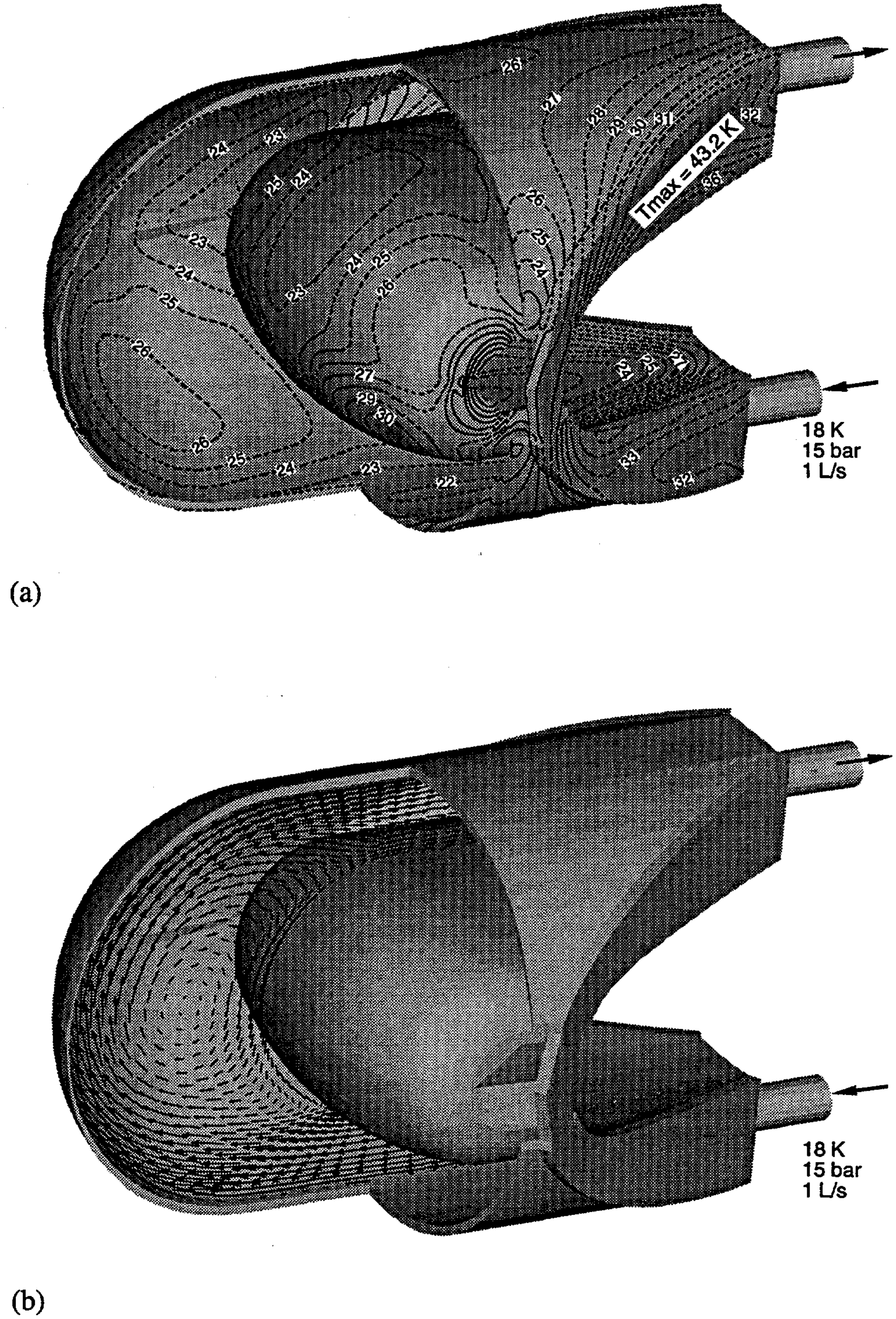

Fig. 6. Cold source moderator vessel (with cutaway) under normal operation: (a) temperature distribution of vessel walls and (b) velocity vector distribution on midplane.