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**EXPERIMENTAL PLAN TO DETERMINE THE PERFORMANCE
OF THE OAK RIDGE NATIONAL LABORATORY
COLD NEUTRON MODERATOR**

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Experimental Plan to Determine the Performance of the Oak Ridge National Laboratory Cold Neutron Moderator

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Abstract

This paper outlines an experimental plan to test the thermohydraulic concept of the proposed Oak Ridge National Laboratory Cold Neutron Moderator. The goals, approach, description of the experimental apparatus, and proposed budget and duration are presented.

Introduction/Goals

ORNL plans to construct an Advanced Neutron Source (ANS) for scientific research where subcooled liquid deuterium is circulated through a spherical aluminum vessel to remove heat and moderate the neutron beam. As part of the plan, ORNL requested that NIST conduct a preliminary study for a research program to provide data and/or models to determine the heat transfer mechanisms and predict the thermal-hydraulic performance of the ANS cold neutron moderator cooling system. Based on preliminary discussions with ORNL technical leader of the cold source development program, three research efforts were defined:

1. Measure and characterize the forced convection local heat transfer to sub-cooled liquid deuterium over a flat plate for the conditions of the ANS Cold Source. (Hydrogen may be substituted for deuterium for some of the tests)
2. Perform a numerical modeling effort (to be done elsewhere) to map the flow patterns in the spherical moderator. If deemed necessary from the results of the model and the results of the heat transfer experiments in 1, above, perform an experimental flow visualization study of the flow in the moderator.
3. Simulate by mock-up of the ORNL final design for the moderator, the conditions of the ANS Cold Source flow loop, perhaps employing the actual ORNL pump in the experiments. Establish the stability and functionality of the design.

Approach to Problem

The complex spherical geometry, including an internal cavity and perhaps additional baffling, of the proposed ANS moderator makes prediction of the thermal-hydraulic performance of the device difficult. Efficient removal of heat, generated by the absorption of radiation in the bulk fluid and the moderator wall, and minimum generation of vapor volume in the moderator is required for stability of operation and sufficient moderation of the neutron beam. Accurate predictive models and experimental data for LD₂ forced convection, subcooled boiling heat transfer coefficients will be necessary for the numerical thermal-hydraulic modelling effort that is underway. We shall measure heat transfer coefficients as indicated in the Introduction, and provide correlations that can be used in the thermal-hydraulic models.

The first phase of the research program (1. above) will provide the fundamental heat transfer data, especially investigating the influence of velocity and degree of subcooling on the heat transfer coefficient, critical heat flux, and void fraction for LD₂. Wall heat flux, wall temperatures, and bulk fluid temperatures will be measured for a range of velocities and subcooling. A flat plate geometry will be employed. Provision will be made to observe vapor accumulation in the test section to obtain qualitative information regarding vapor formation and accumulation.

The second phase of the program, (3 above) following the numerical thermal-hydraulic modeling completion, will simulate the final design of the ANS moderator in a flow-loop that will incorporate a ANS circulating pump, if feasible, and will establish the stability and heat removal capability of the neutron moderator. Power inputs, bulk fluid temperatures, and flowrates will be measured. Provision for observation of vapor accumulation and or possible surging in the exit line will provided.

Literature Search

We conducted a literature search for relevant forced convection subcooled boiling heat transfer data and models or correlations. We found no publications specific to forced convection subcooled boiling of deuterium. We included other cryogenic liquids in the search and found only one relevant study of subcooled boiling hydrogen; the bibliography contains the references reviewed and those used in the calculations described below.

Test Section Scaling and Experimental Parameters

The ORNL design parameters that are the basis for our experimental design and operating conditions are:

- 410 mm diameter spherical moderator constructed of 6061 Aluminum
- Heat Load 16kW in LD₂, 16kW in shell (approx. 2.5-3.5 W/cm²)
- Operating pressure 0.4 MPa(4 atm)
- Volume flowrate of D₂, 6.5 l/s
- 9 K inlet subcooling (T_{inlet} = 20 K, T_{sat} = 29.4 K)

The proposed NIST test section is a flat plate but as a practical matter, to force the heat transfer fluid past the plate it must be enclosed by walls. Therefore the test section is a rectangular flow channel heated on one side. We sized the channel to maintain thermal and hydrodynamic similarity with the ORNL moderator, to the extent possible.

It was desired to maintain the same degree of subcooling and the same heat flux at the wall. An energy balance applied to both systems with the above requirement leads to the following ratios:

$$\begin{aligned} A_{\text{surf nist}}/A_{\text{surf ornl}} &= V_{\text{nist}}/V_{\text{ornl}} \\ A_{\text{surf ornl}} &= 0.6 \text{ m}^2 \\ V_{\text{ornl}} &= 6.5 \text{ l/s} = 6.5 \times 10^{-3} \text{ m}^3/\text{s} \\ A_{\text{surf nist}} &= 92.3(V_{\text{nist}}) \end{aligned} \quad (1)$$

We also desired to maintain the same velocity (although that does not provide for true hydrodynamic similarity). As noted in the introduction, numerical modeling is necessary to determine the velocity distribution in the ORNL spherical moderator. We think an important experimental goal will be to investigate the effect of velocity on subcooled boiling heat transfer since parts of the ORNL sphere walls will experience much lower velocities than other parts. In view of the fact that the final configuration of the sphere is not decided, and the hydrodynamic modeling is not complete, we simply took the velocity to be the ORNL design volume flow rate divided by the cross section area of a 410 mm dia sphere.

$$v_{\text{ornl}} = (V/A_{\text{cs}})_{\text{ornl}} = v_{\text{nist}} = (V/A_{\text{cs}})_{\text{nist}} = 0.05 \text{ m/s} \quad (2)$$

Solving for V_{nist} and substituting in (1) above,

$$A_{\text{surf nist}} = 4.62 A_{\text{cs nist}}$$

$$L \times W = 4.62 H \times W.$$

If we choose $H = 5 \text{ cm}$, then $L = 23.1 \text{ cm}$.

For $V_{\text{nist}} = 0.1 \times 10^{-3} \text{ m}^3/\text{s}$ (We have this cryogenic pump available at NIST), we solve for W from equation (1).

$$W = 4.01 \text{ cm}.$$

Hence, we have provisionally sized the NIST flow channel as 4 cm x 5 cm x 23 cm.

The required power input is 230 watts, easily attainable, to give 2.5 W/cm^2 heat flux at the heated wall. We can easily achieve a heat flux of 10 W/cm^2 , the approximate critical heat flux for nucleate boiling of liquid deuterium (leading to surface dry-out or "film boiling").

A detailed description of the test section will follow in a later section.

Thermophysical Properties

All thermodynamic properties of deuterium used in the heat transfer correlations described below were obtained from GASPAK [1], an integrated computer code of thermodynamic properties. This code may be linked to a spreadsheet and provides for convenient calculation of properties for heat transfer correlations, as was done below. The transport properties, thermal conductivity and viscosity were not available in this code. The liquid thermal conductivity and liquid viscosity were required for the heat transfer correlations. The viscosity data used were those of Konareva and Rudenko reported in [2] and the thermal conductivity values were taken as 94% of liquid hydrogen values, as suggested in [2]. Liquid hydrogen values are available in GASPAK.

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Predictions from Heat Transfer Correlations

Subcooled boiling is a non-equilibrium process. This is so because vapor may be present in a heated vessel even though the average bulk fluid temperature is below the saturation temperature corresponding to the system pressure. Collier [3] describes conceptually the various regions of subcooled boiling along the length of a uniformly heated flow channel. Figure A1 (Appendix) is taken from that reference and displays the surface and bulk fluid temperature distribution along the heated length. The figure illustrates that fully developed subcooled boiling may occur even though the bulk fluid temperature is below the saturation temperature. This is characterized by the presence of vapor bubbles in the bulk fluid, not confined to the wall where the temperature is above the equilibrium saturation value. It is not clear that similar regions will occur in the proposed spherical moderator geometry. However, we considered it worthwhile to perform calculations to determine if the proposed design conditions minimize the probability for fully developed boiling in ANS moderator. This condition is to be avoided to insure stability of operation, as well as moderation of the neutron beam.

We calculated the forced convection boiling curve (q vs ΔT) for deuterium for a range of velocities, and inlet subcooling. We used the common superposition correlation [3],

$$q_{\text{superposition}} = q_{\text{scb}} + q_{\text{fc}} \quad (3)$$

where q_{scb} is the subcooled nucleate pool boiling contribution and q_{fc} is the forced convection single phase heat transfer contribution. In particular we chose the Kutateladze correlation [4] for q_{scb} , and flat plate laminar, or turbulent as appropriate for the particular velocity, single-phase forced convection heat transfer correlations [5] for q_{fc} .

$$q_{\text{fc}} = h_{\text{fc}}(T_{\text{wall}} - T_{\text{bulk}}), \quad (4)$$

$$h_{\text{fc}} = \text{Re}^{(1/2)} \text{Pr}^{(1/3)} (k_{\text{liq}}/D_{\text{sphere}}) \text{ for laminar flow } \text{Re} < 2000, \quad (5)$$

$$h_{\text{fc}} = \text{St} \rho_{\text{liq}} C_{\text{pl}} v \text{ for turbulent flow } \text{Re} \geq 2000, \quad (6)$$

where

$$\text{St} = (1/2) C_f \text{Pr}^{(-2/3)}, \quad (7)$$

$$C_f = 0.37 [\log_{10}(v D_{\text{sphere}}/\nu)]^{(-2.584)}, \quad (8)$$

$$\text{Re} = \rho_1 v D_{\text{sphere}}/\mu.$$

Figures 1-6 show the results of the calculations at 4 bar. Three curves are shown in the figures, representing the single phase forced convection contribution to total heat transfer, q_{fc} , the nucleate pooling boiling contribution, q_{scb} , and the summation of the two contributions, $q_{\text{superposition}}$. At low wall superheats, where the $q_{\text{superposition}}$ curve is indistinguishable from q_{fc} , the mechanism of heat transfer is single phase forced convection. This is depicted by region A in figure A1. Region B in figure A1, the onset of boiling where bubbles begin to form but remain attached to the wall, is represented in Figures 1-6 where the curve $q_{\text{superposition}}$ first begins to deviate from the q_{fc} curve. Fully developed boiling, characterized by the bubble departure from the heated wall into the bulk fluid and illustrated by Region C in Figure A1, exists for wall superheats where the superposition curve blends with the nucleate pool boiling curve.

As seen in the figures 1-6, for fixed velocity and a given wall superheat, before fully developed boiling occurs, the heat transfer improves with subcooling. This situation persists until wall superheat is $\geq$ approximately 1 K where fully developed boiling has commenced; then the heat transfer is independent of subcooling and velocity. For fixed subcooling and a given wall superheat, the heat transfer improves with velocity until wall superheat $\geq$ 1 K where once again, when fully developed boiling commences, heat transfer is independent of subcooling and velocity. We note that for the range of conditions shown, and for the ORNL ANS design heat flux of 2.5-3.5

W/cm², deuterium may be in fully developed subcooled boiling, according to these correlations. This is a condition one would prefer to avoid for the ANS cold source design because significant vapor may be generated and persist for some time in the bulk liquid.

Since the neutron beam is insufficiently moderated in vapor, we thought it would be of interest to estimate void fraction during subcooled boiling. We used the method of Levy[6] which postulates a relation between the thermal equilibrium value, obtained from an energy balance, and the true local vapor weight fraction. The relationship is,

$$x' = x - x_d \exp(x/x_d - 1), \quad (9)$$

where

$$x_d = -C_{pl} \Delta T_d / \lambda = \text{the vapor weight fraction at bubble departure,}$$

$$\Delta T_d = \text{Wall superheat at bubble departure.}$$

ΔT_d was determined by inspection from the spreadsheet calculations where $q_{\text{superposition}}$ first approaches q_{scb} , curve, i.e. at onset of fully developed nucleate boiling. Finally, x' is related to void fraction, α , according to Levy by

$$\alpha = x' / \rho_v \{ 1.13 [x' / \rho_v + (1 - x') / \rho_l] + 1.18 / G [\sigma g (\rho_l - \rho_v) / \rho_l^2]^{1/4} \}^{-1}. \quad (10)$$

Figures 7 through 9 show the results of the calculations for two velocities at each of three inlet subcooling values. The results indicate that at low velocities for the ORNL ANS design heat flux of 2.5-3.5 W/cm², the void fraction may reach significant levels. We expect the NIST experiments to elucidate this issue. If NIST experimental observations in the test section indicate significant vapor formation and persistence, even in the subcooled bulk fluid, this information would be a warning to the ANS modelers and designers that provision must be made for effective removal of vapor from the moderator. The use of beryllium or another suitable material leading to lower heat fluxes at the moderator wall may be necessary.

Figure 1.

D₂ Subcooled Boiling, P=4 Bar, Subcooling=9K, Vel=0.5m/s

Figure 2.

D₂ Subcooled Boiling, P=4 Bar, Subcooling=6K, Vel=0.5m/s

Figure 3.

D₂ Subcooled Boiling, P=4 Bar, Subcooling=0.05K, Vel=0.5m/s

Figure 4.

D₂ Subcooled Boiling, P=4 Bar, Subcooling=9K, Vel=0.05m/s

Figure 5.

D₂ Subcooled Boiling, P=4 Bar, Subcooling=6K, Vel=0.05m/s

Figure 6.

D₂ Subcooled Boiling, P=4 Bar, Subcooling=0.06K, Vel=0.05m/s

Figure 7.

D2, P=4 bar, 9 K subcooling

Figure 8.

D2, P=4 bar, 6 K subcooling

Figure 9.

Experimental Apparatus

The design of the experiment was guided by the desire to (1) simulate the ANS operating conditions of pressure, temperature, velocity, applied heat flux, and degree of subcooling, (2) provide flexibility and ease of operation, (3) minimize the volume of liquid required in the test loop, since D₂ is an expensive commodity, (4) provide sufficient instrumentation to obtain the measurements required, (5) provide for uniform application of heat flux at the test section wall and at the same time minimize extraneous heat flow, and (6) utilize existing NIST equipment where possible. The outputs of the experiments will be a series of graphs representing heat flux vs wall superheat ($T_{\text{wall}} - T_{\text{sat}}$) for the range of velocities and subcooling levels covered in the experiments. Radiation heating in the bulk fluid will be simulated by reduced subcooling. These data may be utilized in the numerical models that are to be developed.

Test Section

Figure 10 shows a possible test cell for measuring the heat transfer from a surface, simulating the cold neutron moderator chamber walls, to LD₂ at the conditions representative of the Advanced Neutron Source (ANS). Liquid deuterium will be pumped through a 4 cm X 5 cm rectangular channel 24 cm long. The channel is shown in cross section in figure 11, looking upstream toward the exit end. Three walls of this channel will be stainless steel. The fourth channel wall will consist of the faces of 6 aluminum blocks about 40 mm square by 6 mm thick. A face view of the heated blocks is shown in figure 11. These blocks are set flush in thermally insulating material such as fiberglass epoxy or a phenolic plastic to insulate all but the face forming the channel wall. The blocks will be separated by about 2 mm of insulating material. The heaters will be cast into these blocks if possible. Drilled holes allow placing a thermocouple junction in the aluminum block near the heat transfer surface. Thermometers in the liquid stream at the inlet and outlet of the test section, figure 10, will measure the liquid temperature. Because of the short length of each aluminum section, the aluminum section should be nearly isothermal while the temperature change of the liquid upon passing one plate should be about one sixth the total temperature change of the liquid over the test cell length.

Insulation of all but the heat transfer surface of the individual blocks is required when the tests are done with the heat transfer surface horizontal (simulating heat transfer from the bottom or top surfaces of the moderator chamber). For experiments simulating heat transfer from vertical walls of the moderator chamber, however, insulation could be eliminated and the heater surfaces suspended in the center of the channel. In this configuration all applied heat flux will go into the fluid, with small end effects corrections required. A cross section of the uninsulated vertical test configuration is illustrated in figure 12.

A window will be included to view the boiling phenomena in the test cell. The window will be placed either to look across the heated surface as shown in figure 10 or at the heated surface as shown in figure 11.

The seals for the window and the lead feed-through ring will be either thin Teflon sheet or Gortex packing string. This sealing technique has been quite successful for metal flanges made of the same materials. Whether the differential contraction of the glass relative to the stainless steel flange will cause a leak must be determined. Windows fused to stainless steel flanges that can be used to cryogenic temperatures are commercially available. These windows may be machined to fit the viewports thereby placing material with the same thermal expansion on each side of the seal.

Flow Loop for Heat Transfer Studies

Figure 13 shows a diagram of the proposed complete test facility. The test cell is contained in a cooled windowed chamber within an existing 50 cm diameter windowed vacuum jacket. The primary function of the cooled windowed chamber is to eliminate adverse effects due to window leaks. The chamber will be pressurized with GHe up to 4 bar absolute to inhibit the leakage of D_2 from the window. The chamber also serves as a radiation shield. This chamber will be eliminated if the window seals are reliable. The chamber can vent through relief valves on the He fill-tube during warm up of the system. The electrical leads from the test section will exit through the GHe fill-tube to an ambient temperature vacuum feed through.

The liquid hydrogen to be used in a test is placed in an existing 200 l Dewar. The pressure in this dewar will be held at pressures between 0.1 and 3.2 bar gage by a back pressure regulator. A stirrer and, if necessary for speed, an electrical heater (neither shown) will bring the liquid in the Dewar to equilibrium at whatever pressure is desired. By changing the Dewar vapor pressure, the degree of sub-cooling of the liquid in the test loop can be varied since the pressure in this loop will be maintained at 4 bar absolute. For a chamber without flow directing baffles, the heating of the liquid within the moderator chamber by radiation will be simulated by reducing the subcooling. When baffles are included that direct the liquid flow to the moderator chamber walls, reduced subcooling probably will not satisfactorily simulate bulk liquid heating. Distributed internal heaters be necessary to supply radiation heating in that case.

The pump shown in the bottom of the 200 l Dewar will circulate liquid deuterium through the test loop and the test section. This pump will, in fact need to be enclosed completely in the test loop source tank because it is not leak tight and requires that LD_2 circulate through the motor to cool it.

The inlet and return LD_2 lines between the Dewar and the test cell in the windowed vacuum vessel will be contained in a 152 mm diameter vacuum jacket. This vacuum jacket is independent of the Dewar jacket. A radiation shield, perhaps LH_2 cooled, will surround these LD_2 containing lines. A third LH_2 line is proposed to bring LH_2 from the bath to cool the secondary containment vessel surrounding the test cell. This line will also cool a radiation shield placed around the LD_2 lines to the test cell. This cooling line vents separately through an adjustable needle valve. These radiation shields serve to eliminate the need to correct the test results for radiation heat leak.

The leak tight test loop will have a small volume. Thus it will be economical to fill with LD_2 . The test system vent will be connected to a low pressure storage tank to recover the D_2 .

To perform heat transfer measurements to a horizontal surface, a 152 mm 90° elbow will be introduced into the vacuum jacket just ahead of the test section, figure 14. Elbows and extensions will be required to reconnect the inner lines. Changing the test cell heated surface from facing down to facing up is a relatively simple procedure of rotating the tank 180 degrees and reconnecting the inlet and outlet lines.

Test of ANS Cold Moderator System Design

In this phase of the program we will demonstrate with a half-scale mock-up of the ANS final moderator design and simulation of the flow and refrigeration system, the ability of the moderator to remove an applied heat load and operate in a stable manner. Preliminary testing will be done with LH_2 .

Figure 15 shows the proposed apparatus to test the moderator prototype. The test loop will consist of a simulated moderator chamber, a circulation pump and a heat exchanger cooled by an LH_2 bath. The LH_2 bath simulates the refrigerator of the ANS cold moderator design. The test loop will be closed and its volume kept small to permit economical testing with LD_2 . Electric resistance heaters will be used to simulate the radiation heating.

To reduce the cost of building and operating an electrically heated mockup of the cold source and associated refrigeration system, we suggest testing a one-half-scale size 205 mm diameter vessel. The heat generation required for the walls is decreased to one-fourth, and the heat generated in the bulk reduces to one-eighth if the heat flux at the wall and power input per unit volume of liquid is kept constant. Thus, assuming 32 kW of heating divided evenly between the liquid and container shell for the ANS moderator chamber, 6 kW of heat is needed for the half size model to achieve the same heat fluxes. Using LH_2 at atmospheric pressure as the refrigeration source, 445 J/g $\times$ 70.87 g/l or 31,537 J/l refrigeration is available. This corresponds to about 5 s of run time per liter or 37 minutes maximum of continuous run time for one 450 l transport Dewar.

The test moderator chamber shown in figure 15 will not be detailed here with the assumption that the ANS design will probably change before the test system is constructed. However, some general design considerations will apply to any design. These will be discussed below.

To minimize the cost of an electrically heated test vessel, it needs to be fabricated of something other than aluminum so it can be assembled by soft soldering. Fabricating the sphere of copper makes it relatively easy to solder while still providing a good wall conductivity. It is possible to add an aluminum coating to the inner wall to provide an aluminum heat transfer surface.

If baffling is included inside the vessel to force the flow preferentially to the walls, decreased subcooling may no longer be the best choice for simulating bulk heating of the liquid due to radiation. An internal distributed heater will have to be used to simulate the internal liquid heating should baffling be included.

Sheathed heaters will need to be soft soldered to the internal walls of the beam hole internal tank and to any internal baffling as required. The heat flux to the outer walls will be provided by sheathed heaters soft soldered in either a uniform distribution or in a front weighted uniform distribution to the outside walls of the moderator chamber. The copper walls should distribute the 6 kW of wall heat uniformly over the sphere.

A glass section is shown in the exit line. Inclusion of a glass section will be more complicated for coaxial inlet and outlet lines but should still be possible. This will allow visualization of any bubbles that might exit into the return stream because of the localization of heating in the walls. Any surging or non-steady state effects should be observable as fluctuations in the bubble behavior.

The existing NIST centrifugal pump for LD_2 used during the heat transfer measurements is too small to circulate the approximately $1\frac{1}{2}$ l/s of liquid needed to remove 6 kW of heat. If available, one of the ORNL circulation pumps running with the speed reduced sufficiently to limit the flow to 1.5 l/s will be used. A flowmeter will be required in the circulation loop to confirm this flow. The ANS circulator could be installed in the horizontal section of the moderator chamber inlet line as shown in figure 15. If NIST provides a centrifugal pump, one of sufficient capacity will need to be built by a qualified commercial supplier. It will probably be installed in a closed vessel inside the heat exchanger Dewar.

The Dewar simulating the ANS refrigerator cooling will need to be a bottom access Dewar especially if an ANS circulator is used. The heat exchanger, a gas/liquid separation vessel and perhaps the circulating pump is shown included in the Dewar. An existing NIST Dewar might be used for this though its 20 l capacity is probably too small. The transport Dewar will need to transfer LH_2 continuously to the bottom access Dewar.

Large currents and relatively high voltages will be needed to supply the 6 kW. At 200 V, 30 A of current will be needed. A electrical lead heat sink may be required.

Thermometers are shown at the inlets and outlets of both the moderator chamber and the heat exchanger. The glass section allows view of the composition of the return stream. Thermometry installed in the interior of the moderator chamber would be heated to soft solder temperature during assembly. Most thermometers would not withstand that. If needed, rakes of thermometers therefore will be added through ports after assembly of the vessel is complete.

If large volumes of bubbles are observed in the glass section, a determination of the void fraction is possible by weighing the sphere while it is heated to various power levels. Flexible sections will have to be added in the fluid lines if a void measurement is to be made.

Nomenclature

A	Area, m^2
C _f	Drag coefficient
C _p	Specific heat, J/(kg-K)
D	Diameter, m
g	Gravitational constant, m/s^2
G	Mass velocity, $kg/(s-m^2)$
h	Heat transfer coefficient, W/m ²
H	Height of test section, m
k	Thermal conductivity, W/m-K
L	Length of test section, m
P	Pressure, Pa
Pr	Prandtl number
q	Heat flux, W/m ²
Re	Reynolds number
St	Stanton number
T	Temperature, K
v	Velocity, m/s
V	Volume flow rate, l/s
W	Width of test section, m
x	Vapor mass fraction (equilibrium value)
x'	True local non equilibrium vapor mass fraction

Greek symbols

α	Vapor void fraction
λ	Latent heat of vaporization, J/kg
ρ	Density, kg/m^3
ν	Dynamic viscosity, Pa-s
μ	Kinematic viscosity, m^2/s
σ	Surface tension, N/m

Subscripts

cs	cross section
d	at bubble departure
fc	forced convection
l	liquid
liq	liquid
ornl	Oak Ridge National Lab
scb	subcooled boiling
surf	surface
v	vapor

Budget/Duration

A two and one-half year effort is estimated to complete the work put forth in this plan. The first year and one-half effort would go toward the heat transfer measurements and the remaining time for the mock-up and testing of the ORNL final moderator design. A flow visualization study (item 2 of the three research efforts noted in the Introduction) is not included in the plan since the numerical modeling effort has not been completed and we believe the modeling should guide or have input to the experimental design.

The estimated costs are:

	Year 1 \$	Year 2 \$	Year 3 \$	Total \$
Phase 1 Heat Transfer Measurements				
Labor *1Full Time Senior Engineer	\$150K	\$75K		
1/2 time Technician	\$50K	\$25K		
Materials, Equipment, Cryogenic liquids	\$40 K	\$12		\$352K
Phase 2 Simulation of ANS System Design				
Labor*1Full Time Senior Engineer		\$75K	\$75K	
1/2 time Technician		\$25K	\$25K	
Materials, Equipment, Cryogenic liquids		\$70K	\$18	\$288K
Grand Total	240	282	118	\$640K

*Includes all incidental other objects, overhead, management, report writing, etc.

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Figure 10.

Proposed heat transfer coefficient measuring cell viewed from the back (insulated side).

Figure 11. Cross section of the heat transfer coefficient measurement cell at a window site. A single block of the heated section is shown in Section A-A. The thermometer well position is shown by the dotted lines.

Figure 12.

Alternative arrangement for the vertical heated surface measurements.

Figure 13.

Schematic of the heat transfer coefficient measuring system with the heat transfer surface vertical.

Figure 14.

Schematic of the heat transfer coefficient measuring system with the heat transfer surface horizontal.

Figure 15. A facility to test a half scale version of the ANS cold moderator design. The liquid deuterium will be circulated either by an ANS circulator outside or a centrifugal pump inside the Dewar.

Figure A1.

Wall temperature and bulk fluid temperature distribution in subcooled boiling.