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FAST-RESPONSE CRYOGENIC CALORIMETER CONTAINING A 52-KG RADIATION ABSORBER*

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An isothermal liquid helium boiloff calorimeter containing a 52-kg copper radiation absorber, and having a time constant < 1 s, was built to measure fission product beta and gamma radiation from 60-mg ^{235}U foils irradiated in a nuclear reactor. The short response time was achieved by the large reduction in heat capacity of solids at 4 K, and by nearly isothermal operation. Though the initial power level was ~ 5 W, the maximum thermal energy storage was ~ 1 joule.

The Al clad foils were transported in ~ 1 s, and cooled to liquid helium temperature in ~ 3 s. Boil-off helium gas was warmed to room temperature in a controlled manner, and measured with a hot-film anemometer flowmeter, which was calibrated by comparison with a dry-test volume flowmeter, and by electric heating of the radiation absorber. The correction for gamma leakage from the absorber was ≤ 3%, and the correction at short cooling times for sample cool-down, 2.24-m activity of the Al cladding, and system response time, amounted to 3.4% at 10 s. The overall accuracy (1 σ) of the radiation measurements is ≤ 2%, except at the shortest cooling time (10 s), where it rises to 4%.

*Work performed under the auspices of the U. S. Nuc. Reg. Comm.

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INTRODUCTION

We describe an isothermal liquid helium boil-off calorimeter which was used to measure fission product beta and gamma radiation following exposure of 60-mg ^{235}U foils to the thermal neutron flux in the Los Alamos Omega West Reactor. This work is part of a program sponsored by the U.S. Nuclear Regulatory Commission to provide better values of the fission product decay heat following reactor shutdown, for use in reactor safety evaluations. Particular effort was directed at reducing the uncertainty during early cooling times (10 to 1000 s), where the present ANS 5.1 Decay Heat Standard[1] is assigned an uncertainty of + 20%, - 40%.

The calorimeter had a thermal time constant of < 1 s, even though it contained a copper radiation absorber weighing 52 kg. The short response time was achieved by operating the calorimeter nearly isothermally, and by taking advantage of the large reduction in the heat capacity of solids at 4 K. For comparison, the time constant of the radiation absorber at room temperature is > 400 s.

LAYOUT OF THE EXPERIMENT

The ^{235}U foils were placed in 8-mm x 39-mm envelopes of 0.127-mm thick Al, which were sealed by electron-beam welding. A dart was used to transport the samples from the reactor to the sample release chamber above the calorimeter

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(see Fig. 1). At the start of irradiation, the dart was pushed into position in the reactor with a long, flexible plastic rod. Following an irradiation of 20,000 s, the dart was ejected by 30-psi helium gas, and took a fraction of a second to strike and stick in a wooden target in the sample release chamber. The dart traveled ~ 5 meters, and the outer sleeve of the dart was stripped away when the dart entered the release chamber.

The hinged halves of the dart separated upon impact on the wooden target, and the sample then fell under gravity into a funnel and was guided into a tube which led to the liquid helium reservoir in the calorimeter. The same tube was used to fill the helium reservoir, and to conduct the boil-off helium gas to the flowmeter. The sample took ~ 1 s to drop, and ~ 3 s to cool from ~ 400 K to 4 K, during which time the burst of boil-off gas escaped through the ball valve above the calorimeter. Four seconds after the sample was ejected from the reactor, the ball valve was closed, and boil-off gas then passed through the room temperature heat exchanger and hot-film anemometer flowmeter.[2] Since the flowmeter makes use of the thermal conductivity of helium gas, accurate measurements require that air be kept out of the system.

At cooling times > 30,000 s, when the absorbed radiation is $\leq$ 70 mW, the anemometer flowmeter is no longer accurate, and a calibrated dry-test volume flowmeter was used to make integral measurements of the slowly varying gas flow. In this mode of operation, the sweep gas was turned off, and the dry-test meter was attached to the helium exhaust line.

DESIGN OF THE CALORIMETER

The uranium sample fell to a position centrally located in the 52-kg copper radiation absorber, which was a cylinder 178-mm diam and 298-mm high (see Fig. 2). The reservoir at the top was 3/4 filled with 1.2 liters of liquid helium. A 196-ohm manganin coil was imbedded in Stycast 2850FT epoxy in a groove near the bottom of the cylinder, and was used for electric-heating calibration of the flowmeter. The reservoir also contained a liquid level sensor and germanium resistance thermometer (GeRT), and three GeRTs were attached to the absorber. A copper vacuum jacket surrounded the radiation absorber, and the entire assembly was immersed in a liquid helium bath contained in a commercial dewar. All electrical leads passed through the outer helium bath. The calorimeter was assembled by successive high-temperature brazing in a hydrogen furnace.

The outer helium bath was operated at 15 torr above atmospheric pressure by venting it through a bubbler. This raised its temperature by 25 mK above the boiling point of the liquid in the reservoir, and prevented condensation of the boil-off gas on the tube walls.

A significant precaution about warming the boil-off helium gas was to minimize the changes in temperature gradients, since this caused changes in gas storage along the tube, and thereby distorted the time profile of the gas flow rate. This was especially important at low temperatures, where the gas density was high. We therefore minimized the volume of tubing between fixed temperatures. After leaving the absorber, the boil-off vapor flowed through tubing in thermal contact with the outer helium reservoir; it then passed through a short length of thin-wall tubing in vacuum, and through a long tube in thermal contact with a liquid nitrogen bath. Above the calorimeter, the boil-off gas flowed through a horizontal heat exchanger. Water at 27°C flowed through the outer jacket of the heat exchanger.

PERFORMANCE OF THE CALORIMETER

Since we had a two-phase system, the temperature of the liquid helium depended on the pressure in the reservoir. With maximum gas flow, the pressure drop along the transport tube and across the flowmeter was not more than one torr, and the liquid helium temperature did not rise more than 1.7 mK, according to the saturated vapor pressure curve.[3] The heat capacity of the 1.2 liters of liquid helium in the reservoir was ~ 550 joules/K, so the maximum energy storage in the liquid helium was ~ 1 joule. The heat capacity of the radiation absorber was only 4.4 joules/K, and since the maximum temperature rise (measured with a GeRT) was 40 mK, energy storage in the block was < 0.2 joule. The heat leak into the absorber was proportional to the temperature difference between the absorber and the outer helium bath, and was 800 μW/K. The maximum heat leak was 20 μW, which was neglected.

The 40-mK temperature rise of the absorber is the ΔT necessary to transfer ~ 3 watts across the copper-liquid interface in the reservoir. Convection currents in the liquid helium, initiated by thermal cooling of the irradiated sample, provided rapid heat transport to the liquid-vapor interface. We observed superheating of the liquid helium only when the liquid was quiescent.

The time constant of the calorimeter was measured by making step changes in electrical power to the heater in the absorber. For changes between power levels that were both above 70 mW, the response was well represented by a single exponential. The time constant was 0.85 ± 0.09 s, based on 10 measurements including both increases and decreases in power. Since the thermal time constant of the absorber was estimated to be ≤ 0.16 s, the response of the calorimeter was dominated by the time constant of the helium gas transport and measurement system. An important contribution was the time required to build up pressure across the flowmeter.

CALIBRATION AND DATA RECORDING

Approximately 10% of the helium evaporated from the liquid in the reservoir did not pass through the flowmeter, but remained in the volume formerly occupied by liquid. In order to convert liters/s of helium gas flow into mW of heat deposited by beta and gamma radiation, it is necessary to know the "apparent" heat of vaporization[4] of liquid helium at saturated vapor pressure equal to atmospheric pressure.[5] Room temperature gas flow calibration measurements of the anemometer flowmeter were made by comparison with a calibrated dry-test volume flowmeter. In addition, the anemometer flowmeter was calibrated by joule heat deposited in the absorber, by measuring both voltage and current supplied to the electric heater, and correcting for the resistance of the lead wires.

The gamma leakage out of the radiation absorber was $\leq 3\%$. A correction for this was obtained from Monte Carlo calculations based on experimentally determined gamma spectra. Additional corrections had to be made at short times for the 2.24-minute ^{28}Al activity produced by neutron capture in the Al cladding of the sample, and for the initial disturbance caused by dropping the irradiated sample into the liquid helium reservoir. To correct for these effects, the average signal for three irradiated dummy Al samples was subtracted from the calorimeter power recorded when a uranium-loaded sample was measured. We also corrected for the 0.85-s response time of the system These corrections amounted to 3.4% at 10 s, and were $< 0.1\%$ for cooling times > 400 s.

The data were recorded by converting the anemometer flowmeter bridge voltage (dc output) to a pulse train with a voltage-to-frequency converter, and counting pulses in 1-s and 10-s intervals in a 4,096-channel pulse-height

analyzer used in the multiscaling mode. The contents of the pulse height analyzer were transferred to magnetic tape for computor analysis. The calorimeter measurements were normalized by the number of fissions in the sample, which was determined by radiochemistry. Our error analysis showed the overall uncertainty (1 σ) of the experimental data is ≤ 2% except at the shortest cooling time (10 s), where it rises to 4%.

ACKNOWLEDGMENTS

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REFERENCES

1. American Nuclear Society, Draft Standard ANS 5.1, approved by Subcommittee ANS-5 of the ANS Standards Committee, Oct. 1971 (revised 1973).
2. Manufactured by Thermal-Systems, Inc., St. Paul, MN. We used model 1054B Bridge and Amplifier, and model 1051-1 Monitor and Power Supply.
3. We used the 1958 Helium-4 Temp. Scale; see F. G. Brickwedde et al., J. Res. Natl. Bur. Std. 64 A, 1 (1960).
4. H. Ter Harmsel, H. Van Dijk, and M. Durieux, Physica 36, 620 (1967).
5. Atmospheric pressure was 595 ± 5 mm Hg at the elevation of the Omega West Reactor.

FIGURE CAPTIONS

Fig. 1. Layout of the experiment, showing the sample release chamber, the top of the calorimeter, and the helium boil-off gas tubing, which passes through the heat exchanger and the anemometer flowmeter.

Fig. 2. The active portion of the helium boil-off calorimeter. The radioactive sample falls to the bottom of a thimble in the liquid helium reservoir, where it is centrally located in the copper radiation absorber. The bottom of the liquid nitrogen reservoir and the outer liquid helium bath are also shown.

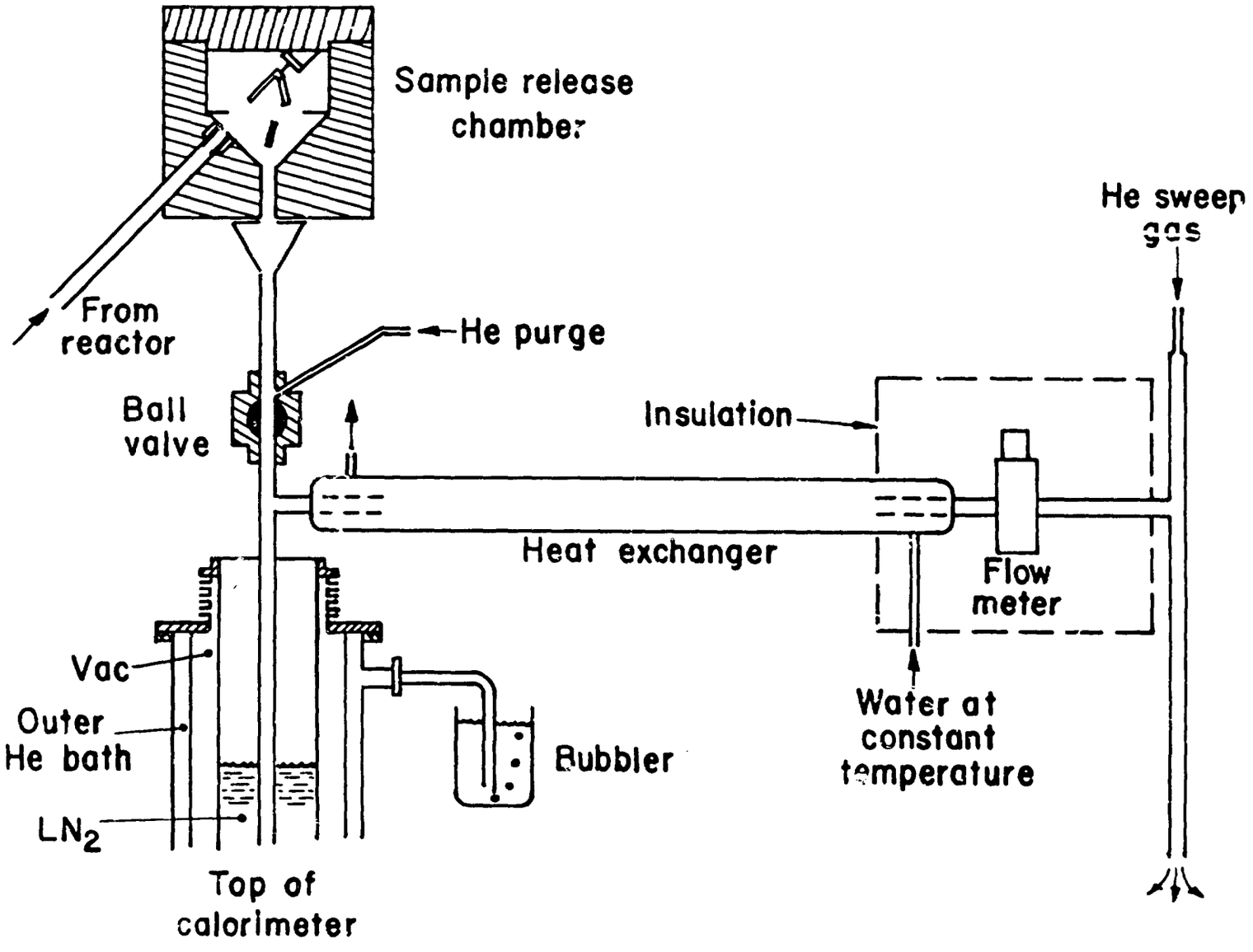
Sample release chamber
He sweep gas
From reactor
He purge
Ball valve
Insulation
Heat exchanger
Flow meter
Vac
Outer He bath
LN_2
Bubbler
Water at constant temperature
Top of calorimeter

Fig. 1

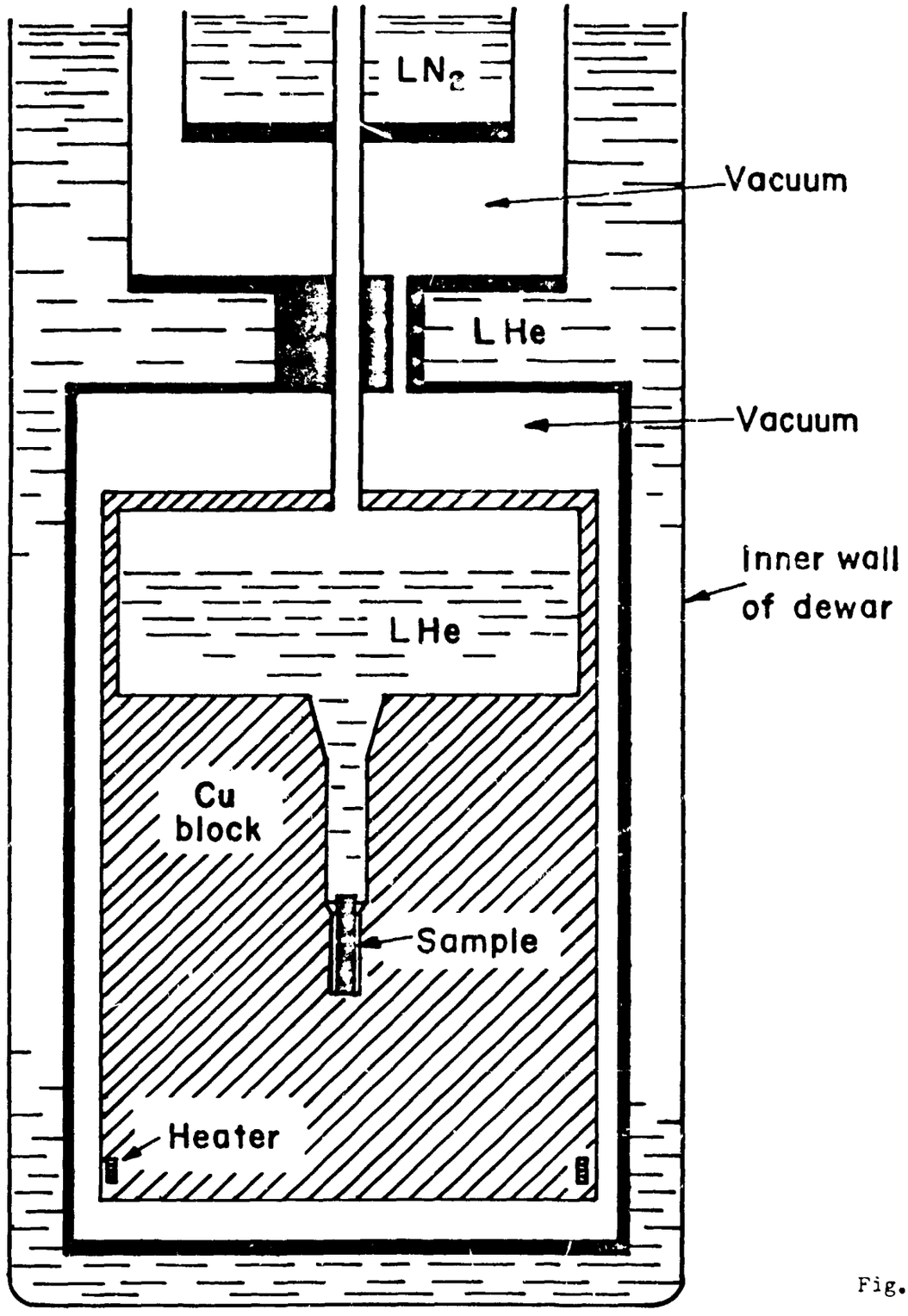
LN2
Vacuum
L He
Vacuum
Inner wall
of dewar
L He
Cu
block
Sample
Heater

Fig. 2