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MASTER

EXPERIMENTAL EQUIPMENT ASSOCIATED WITH THE UNITED KINGDOM HIGH FLUX RESEARCH REACTORS

By

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Introduction

The United Kingdom has three general purpose high flux research reactors DIDO, PLUTO and DMTR. All are very similar, using enriched uranium-aluminium-alloy plate fuel elements, with heavy water serving as the coolant, moderator and reflector. They operate at a maximum power of 15MW producing a maximum thermal flux of $\sim 2 \times 10^{14}$n cm^{-2}s^{-1} and a maximum fast (fission) flux of 0.7 x 10^{14}n cm^{-2}s^{-1}. Some of the more interesting of the wide variety of designs of in-pile experiments have been chosen to illustrate the experimental equipment associated with these reactors. The use of the reactors and our experience with them is described in another paper [1].

Non-Fissile Materials Irradiation Rig

This is one of the most successful types of rigs to be developed and used in the United Kingdom. It was conceived in 1958 to study the variation of stored energy, conductivity and growth of graphite as a function of fast neutron dose in the temperature range 150°C - 350°C and was designed for the 2 in. diameter experimental holes in the centre of the fuel elements, where the γ-ray heating is about 4 W/g. The rig, see Fig. 1, consists of a shield plug from which are suspended three magazine drums, one above the other in a vertical articulated array. Each drum accommodates nine specimens, one cobalt and one nickel flux monitor, and three thermocouples. A heater is wound on a layer of alumina cement inside each drum and its leads with those of the thermocouple pass through the central tube via a seal to a terminal block at the top of the rig.

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The performance of the rig depends on the balance between heat loss from the drum to the experiment thimble and the heat generation by γ-ray and electrical heating. The heat loss is determined by a gas filled annulus between the specimen drums and the thimble, which varies, depending on the specimen temperatures required, from 0.007 in. to 0.070 in. Accuracy and constancy of the gap is achieved by precision machining of the drum, by grinding locating spigots on each drum and by honing the inner surface of the thimble. The electrical heating is about 25% of the total heat generation and provides accurate temperature control of the drums in the presence of local variations in γ-ray heating due to changing flux patterns in the reactor. The gross temperature can be controlled by varying the gas filling; helium and neon, or mixtures of both are used to obtain the correct heat loss from the can.

In the early rigs, failures of the heater supply leads occurred due to hydrogen embrittlement. This problem has been overcome and a nimonic alloy is used in the latest high temperature (900°C) rigs. The position of the heaters in the drums has been varied. Initially, they were positioned between the specimens and the axis of the drum, whilst some later rigs have the heaters outside the specimens near the periphery of the drum. The latter position provides the optimum irradiation conditions but access is difficult for changing specimens.

More than 200 rigs of the above design have already been built and have been most successfully used in the United Kingdom for irradiating graphite, stainless and mild steel, beryllium and beryllia.

From the above design, by several substantial modifications, has evolved a rig for irradiating specimens at temperatures in the range 1200°C - 1400°C. In this rig no electrical heating is provided, the desired operating temperature being obtained with nuclear heating only and by the use of neon gas and polished low-absorptivity surfaces. Control of the temperature is achieved by vertically adjusting the position of the specimen capsule within the thimble. At present only graphite specimens have been used. They are held in a graphite drum inside a niobium capsule. The capsule and specimen temperatures are monitored by four Pt - 13% Rh/Pt thermocouples with four chromel/alumel, thermocouples in a cooler location as alternatives. After one cycle of operation of the reactor (~ 4 weeks) the rig is controlled on these latter thermocouples to avoid errors due to irradiation effects on the Pt-Rh thermocouples. Five of these rigs have been successfully operated during the last year.

Fissile Materials Rig

The first fissile irradiations in DIDO and PLUTO were extensions of experimental designs used for the Windscale production reactors [2]. Although capable of fulfilling a wide range of experimental requirements these rigs suffered from a disadvantage that the separate light water cooling circuits made them costly to manufacture and test.

With experience in the use of the reactors and in the design of rigs the technique used for the non-fissile materials rigs of rejecting heat directly to the D_2O moderator was employed. This, coupled with an increase of the permitted heat fluxes into the moderator, led to the elimination of the water-jacket. This development has resulted in the so-called Unit Irradiation Rig, the detail of which is shown in Fig. 2. Adaptor shield plugs allow rigs to be installed in 2 in. or 4 in. experimental holes and other special adaptors allow 3 rigs in a 6 in. hole, each rig accommodating up to five specimen cans of average complexity. The specimens are immersed in liquid sodium, which is maintained at a steady temperature with electrical heaters. Heat loss as with the non-fissile rig is through a helium gas gap to a thimble in the heavy water. The rig leads to a better usage of the reactors; in a 6 in. hole the failure of one rig means removing five capsules only, the other ten in the two other rigs remain. Considerable development work has been put into the grooved former, in which the service leads run, and its surrounding envelope, the heat-transfer characteristics of the rig, and the possible effect of vibration due to the turbulence of the D_2O.

This rig has also been used for non-fissile specimens and has certain advantages over the non-fissile materials rig previously mentioned in that specimens are irradiated with smaller temperature gradients. The rig is also very robust and can withstand rougher handling, but the serious disadvantage is that it cannot be used for repetitive irradiations.

An extension of the principle of the previous rig has been used for testing fissile specimens at fast-reactor ratings (up to 400 W/cm^2) by nucleate boiling of D_2O in a thimble with double thermal convective heat transfer to the D_2O in the reactor tank through the thimble wall.

Figure 3 shows the principle of the capsules used. Up to six containers, each with a specimen can be accommodated in a 7 in. vertical experimental hole position. A further development is envisaged to allow internal nucleate boiling of the liquid sodium to be used to control the surface temperature of the specimen and hence ensure that the specimen is in a near isothermal zone in spite of possible neutron flux variations.

High Pressure Water Loop in DIDO

The High Pressure Water Loop in DIDO was installed in 1957/58 to enable irradiation experiments to be carried out in support of the U.K.A.E.A. water programme. When it became operational in late 1959 it served one 6 in. vertical experimental hole. The loop normally operates at 2000 p.s.i., 300°C and pH 10.5 with a heat removal capacity of 100 kW, however, changes in these parameters can be made at the request of experimentalists.

The loop is made mainly of mild steel with selected items in stainless steel. Its basis is a unit containing the pumps, heaters, cooler and surge tank, which is contained within a ventilated shielded room with 2 ft. thick concrete walls, roof and floor. Circulation is by two canned rotor pumps connected in series. Bulk-water temperature is controlled by electric loop heaters and a water-cooled heat exchanger. Dump valves and quench and catch tanks empty the loop safely and quickly if this is required under serious fault conditions, and following a dump emergency water cooling automatically comes into operation to cool all the fissile rigs. Chemical purity of the water is controlled by mixed-bed ion exchangers in a bypass circuit and the correct pH is maintained by the addition of ammonia.

Recently the loop has been modified to serve up to four parallel circuits from inlet and outlet manifolds. With the pumps in series, the high pressure difference across the manifolds enables two or more experiments to be connected in series in each parallel circuit. Fine control of temperature in each circuit is achieved by heaters and coolers. Difficulties can occur with this shared system in that the presence of gross fission products in one circuit, either from specially defected fuel elements or from an unplanned fuel-element rupture, can completely upset experiments in other circuits. Such situations have to be carefully considered, but usually with the addition of extra instrumentation and some compromise a working arrangement is possible.

The use of the loop is summarised in Table (1). In the first series of experiments the pressure vessel was directly welded to the loop unit, but this caused substantial delays to the reactor operating cycles when a vessel was changed, owing to the number of welds and the inspection required. Demountable couplings are now used enabling pressure vessel changes to be made easily during the normal reactor shutdown period of four days.

The work that has been done with the loop can be divided into the following categories:-

1. Experiments which rely on post-irradiation studies. Examples are shown in Table (1) (1964 b, c, d, e, f). The main requirement is for steady operation under known conditions. A number of such experiments can be carried out simultaneously.

2. Experiments which involve sampling from the loop outside the reactor. This type of experiment has been carried out extensively in the loop (Table 1, 1959-1962) with the object of studying (a) the distribution of activated corrosion products throughout the system [3,4] (b) the rate of emission of fission products from defected fuel (c) distribution of fission products in this system. Only one programme of this type can be carried out at a time.

3. Experiments which involve observing the behaviour of specimens during the course of irradiation. Experiments of this kind are in Table (1) under 1963 and 1964(a). There are two alternatives; either the samples can repeatedly be removed, have measurements made on them, and then be replaced, or a large number of samples can be used and a few at a time unloaded for measurements. The latter method is preferred if all the samples can be exposed to comparable conditions, as the former method can create considerable active-handling difficulties.

H.T.G.C. Loop in PLUTO

This loop was conceived in the early days of the pre-DRAGON, High-Temperature Reactor Project as a means of testing near-full-size core units suitable for the Reactor Experiment. Heavy emphasis was placed on the control of emitted fission products, since there was at that time no guarantee that fission-product-retaining fuels were practicable. The design was for a three foot long fuel specimen to be subject to an effective thermal-neutron flux of about $3.10^{13} n\ cm^{-2} s^{-1}$ and to dissipate into a helium coolant stream about 30 kW of nuclear heat. A separate purging stream is drawn off from the interior of the graphite tube containing the fuel so that emitted fission gases and vapours are swept away to a clean-up section, in which also chemical impurities are removed, and a stream of cleaned helium is returned to the heat-removal circuit. Figure 4 illustrates the main features of the loop.

To facilitate post-irradiation examination, the whole specimen together with its shielding and termination arrangements was designed as a demountable and expendable capsule enclosed in its own high-pressure tube. The tube is joined during irradiation to the heat-removal equipment, which is wheel-mounted so that it moves the specimen at will into or out of the neutron flux, thus achieving the required degree of separation between the reactor and loop faults and failures.

The possibility of high gas activity and circuit contamination poses serious safety problems. The entire circuit, with a few limited exceptions is formed of welded stainless steel tubes and a very high standard of leak tightness is set (less than .01% of the contents per day). In addition the components are divided into units, each of which is surrounded by an air tight lead-shielded containment box. Finally, all equipment is housed in two shielded and ventilated rooms to which entry is not normally allowed during operation.

Coolant clean-up is performed in several stages, consisting of in-pile and out-of-pile charcoal traps and a liquid-nitrogen cold trap. After passing through these traps a stream of clean helium is returned to the main circuit.

Measurements are made throughout the loop of pressure, flow and temperature, and there are a very large number of instruments measuring ancillary quantities connected with loop operation, but not of direct scientific interest.

A series of built-in γ-ray scintillation crystal heads is provided at various points in the loop so that fission-product activity can be monitored, but the main measurements of radioactivity are performed on samples extracted from the loop in special shielded probes.

Seven fuel charges for DRAGON have been irradiated in the loop since it became operational in December 1961. The first two charges were early concepts of fuel copiously emitting gaseous fission products at working temperatures. They gave useful experience in sampling and other operations on a highly radioactive circuit and data on the efficiency of the clean-up circuits. The following two charges were some of the first of the fission-product-retaining fuels with of course relatively low fission-product emission, and the methods of analysis were adequate to measure it. The fifth and six charges used low-permeability graphite, a "sweep-back" purging stream being drawn through the fuel-tube walls. The final specimen in the DRAGON programme was a string of compacts of coated particles without any enclosure in a special graphite tube and with a separate purging stream. The maximum operating temperatures varied from 1150°C in the first irradiation to 1400°C in the final experiment with the mean burn-up in one specimen reaching 10%.

In general the loop has been very successful in achieving its main objectives of irradiating high-temperature gas-cooled fuel units under reactor conditions, and in assessing the behaviour and fate of fission products under these conditions. A wealth of data has emerged in particular from post-irradiation radiochemical analysis of samples from the dismantled fuel elements but the extraction of data from the loop during running suffers a little from the early design philosophy of coping with large releases.

Building and commissioning the loop from nominally-finished components took some nine months, a great deal of time being consumed by installation and testing of electrical circuits (mainly safety circuits). By use of pre-tested components and sub-assembly, in-situ welding was reduced to a minimum and few leaks were discovered on proof testing. Since then, the circuit has shown no tendency to develop leaks.

The loop has caused remarkably little interference with the normal working of the reactor over and above those detailed working demands which any large experiment is entitled to make. Early difficulties in the first few days of operation were due entirely to inadequate instruments in a part of the ancillary circuits; the effects on the reactor of the inevitable initial faults and troubles in the loop during operation have been almost completely eliminated by the ability to move the specimen rapidly in and out of the reactor.

'Cold' and 'Hot' Neutron Sources and Neutron Beams

Beams of 'cold' (~30°K) and 'hot' (~ 1600°K) neutrons are required for studying the solid and liquid states of matter, and the problem of producing such beams has been considered at Harwell for several years. To produce neutrons in a given energy range probably the best technique is to allow them to come into thermal equilibrium with a moderator at a temperature close to that corresponding to the required neutron energy. For beams of neutrons with an energy of 4 meV a moderator at a temperature about that of liquid hydrogen is therefore required. Liquid hydrogen is also one of the most suitable moderators and it has been successfully employed in the BEPO and DIDO reactors for several years[5].

The present liquid-hydrogen loop and moderator chamber has been in DIDO for 2 years and it now operates continuously for the usual 4 weekly cycle of the reactor. It is shown in outline in Figure 5. The 200 c.c. of hydrogen in the moderator chamber is condensed by a separate liquid-hydrogen coolant circuit. Except for the moderator chamber and its feed pipes, which are made from magnesium alloy the liquid-hydrogen circuit is constructed in copper and there is a mechanical joint between the copper and alloy outside the reactor. The cryogenic compressor has an output of 150 watts and the total heat generation in the moderator chamber is about 60 watts. Apart from occasional random faults, operation of the loop is limited by the life of the valves and diaphragm of the compressor.

The in-pile section contains separate vacuum systems for the liquid-nitrogen-cooled beryllium filter, through which the neutrons pass before they are used in the beam experiment, and for the moderator chamber. This is desirable to prevent any leakage of commercial-grade nitrogen from the filter into the source volume; if this occurred the gas would condense on the cold source and cause a potential explosion hazard due to the build up of ozone. The in-pile elements are surrounded by a magnesium alloy pressure vessel, which can safely contain pressures up to 2000 p.s.i. and should prevent any failure of the loop from damaging the reactor core.

Different problems exist for producing beams of 'hot' neutrons. A 'hot' source is being constructed for DIDO[6] consisting of a cylinder 5 in. diameter and 4 in. long, which will be heated by the absorption of incident γ-rays from the reactor. Surrounding the source block are molybdenum heat shields and the temperature ($\sim 1600^{\circ}K$) is regulated by varying the composition of an atmosphere of helium and argon. Beryllium and beryllia have been considered for the source block and tests have been started on some beryllia blocks.

Both DIDO and PLUTO are used for neutron-beam experiments. On PLUTO the beam holes pass completely through the reactor and are tangential to the core. The neutrons for the experiments are scattered out to the instruments from a small "source block" of light water placed in the central high-flux region of each hole. Such an arrangement has the property of providing a thermal-to-fast neutron ratio higher than that in the reflector itself. The source block is a flat aluminium box, through which the light water is circulated to provide cooling. The optimum size and shape of such source blocks has been experimentally investigated and found to be a thin slab placed in a slanting position across the hole[7].

In order to extend the range of the crystallographic investigations that can be carried out with neutrons, automatic diffractometers intended for the examination of single crystal specimens have been developed. An automatic instrument[8] has been in continuous operation since mid-1963, and four more flexible instruments[9] are to be installed in 1964. These machines are controlled by instructions punched by a computer on paper tape and the results are recorded in the same medium ready for computer analysis. The specimen orientation is adjustable by rotation about three separate axes. A high accuracy of angular setting is achieved ($\pm$ 0.01°) with the use of a moiré fringe system of sensing. The flux of 1 Å neutrons at the sample is about 3×10^6 n $cm^{-2} s^{-1}$, and the time taken to measure a typical reflection is one hour; thus some 500 reflections (a typical number required for a 3-dimensional analysis) can be measured in a reactor cycle of one month.

All time-of-flight inelastic-scattering experiments at Harwell utilise a basic chopper unit which incorporates a magnetically lifted rotor spinning in vacuum about a vertical axis. Angular velocities of 600 c/s are satisfactorily achieved and a pair of rotors may be synchronized at these speeds to relative angular displacements of within $\pm$ 0.2°[10,11].

Present Developments and Discussion

The user requirements for the research reactors depend much upon future power-reactor projects and there has been a constant demand for rigs to operate at higher temperatures and a build-up of interest in high-pressure water systems. A unit type of water loop designed to be installed in any suitable vertical experiment hole is being considered. The specimens, circulating water and pump are contained in a pressure vessel coupled by a small-bore pipe to an external pressurising system, the principle again being one of rejecting heat to the reactor D_2O. Such units could be simple and quickly built, and should make reactor utilisation more flexible.

In DIDO a rig has recently been commissioned for operation at 1900°C to study fission-product gas release. The design embodies three furnaces, only one of which will be operated at a time, the others being available when failures occur due to the limited heater life at this high temperature. Each furnace is constructed around a central molybdenum tube which contains the specimen (~1g. uranium oxide) and consists of a tungsten heater surrounded by molybdenum radiation shields. The specimen temperature is measured and controlled by a tungsten/tungsten 26% rhenium thermocouple whilst helium gas is used as the carrier for the gaseous fission products released.

The rigs described in this paper, with many others, have been developed over the years. The accumulated experience has resulted in rigs reaching the high standard of reliability required for an important research programme. By collecting together the design resources and research requirements it has been possible to produce the minimum number of really reliable types of rigs and is an argument in favour of such an organisation.

A large loop because of its size and complexity cannot be developed in the same manner as a rig. It takes so long before it is operational that it is advisable for its design to precede the design of the reactor, whose development it will support. Nevertheless, coolant-technology loops, serving a wide sphere of interests have proved valuable in covering a range of problems.

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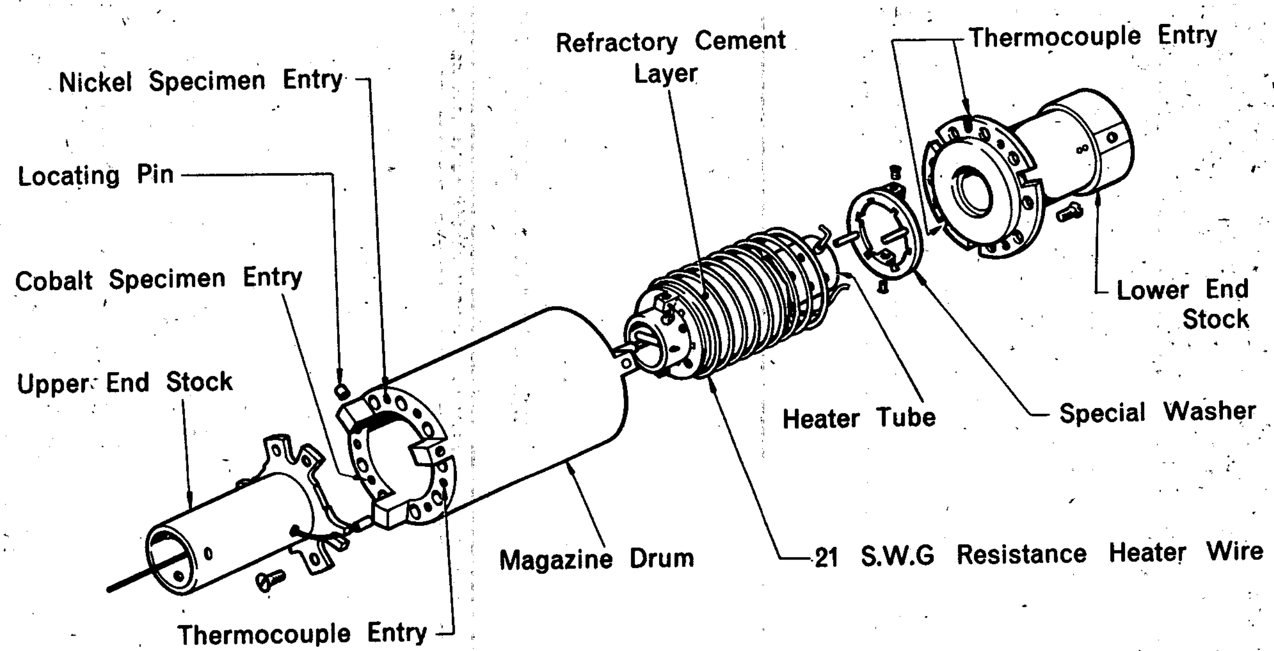


Figure I. Non-Fissile Materials Irradiation Rig - Exploded view of Magazine Drum

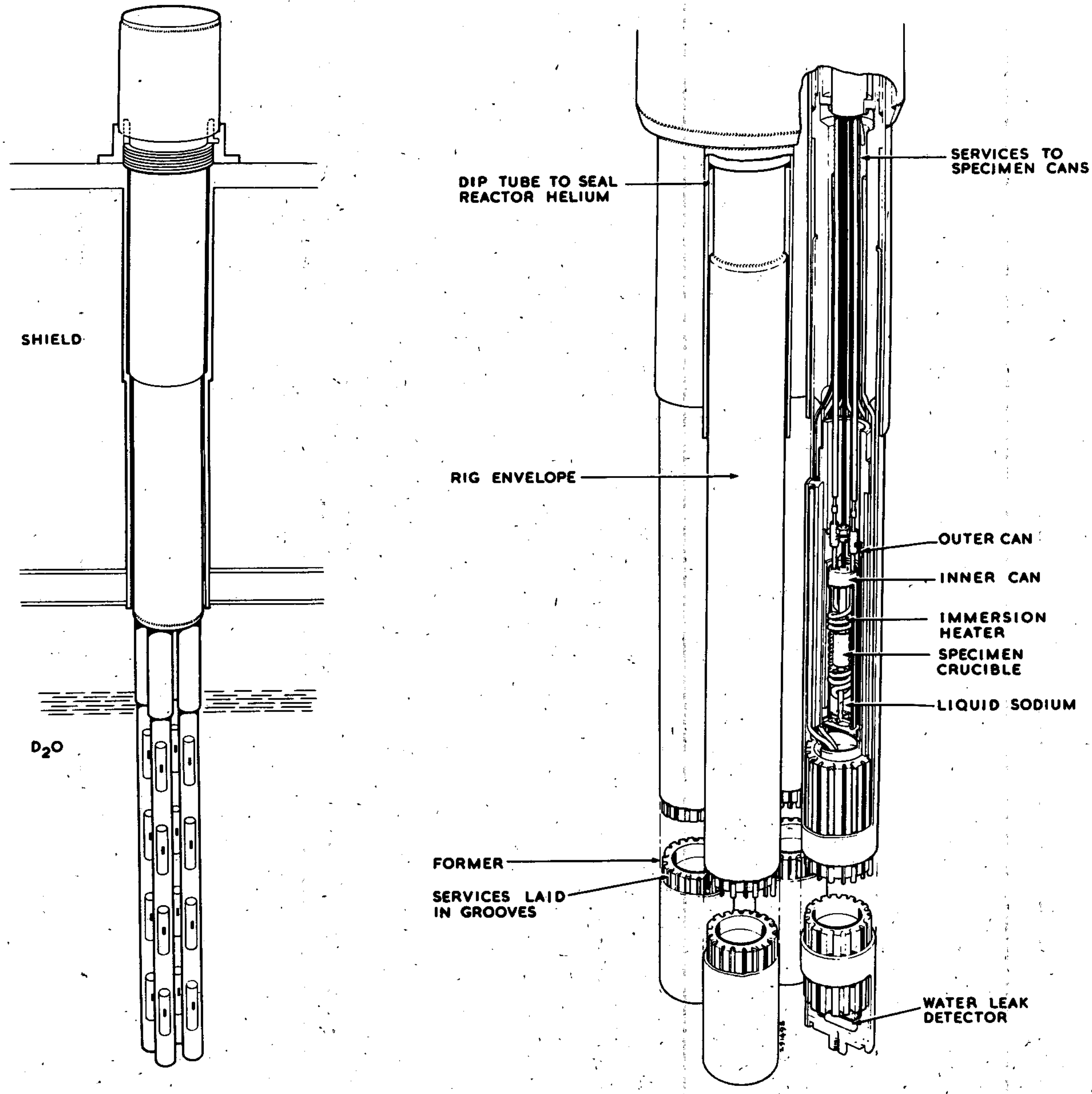


Figure 2. Unit Irradiation Rig

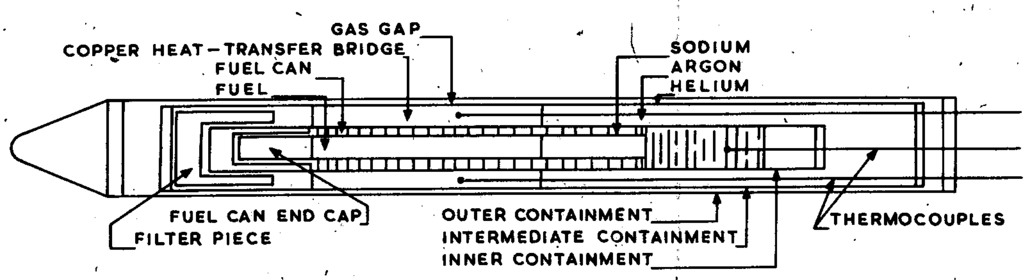


Figure 3. Typical Fuel Irradiation Capsule.

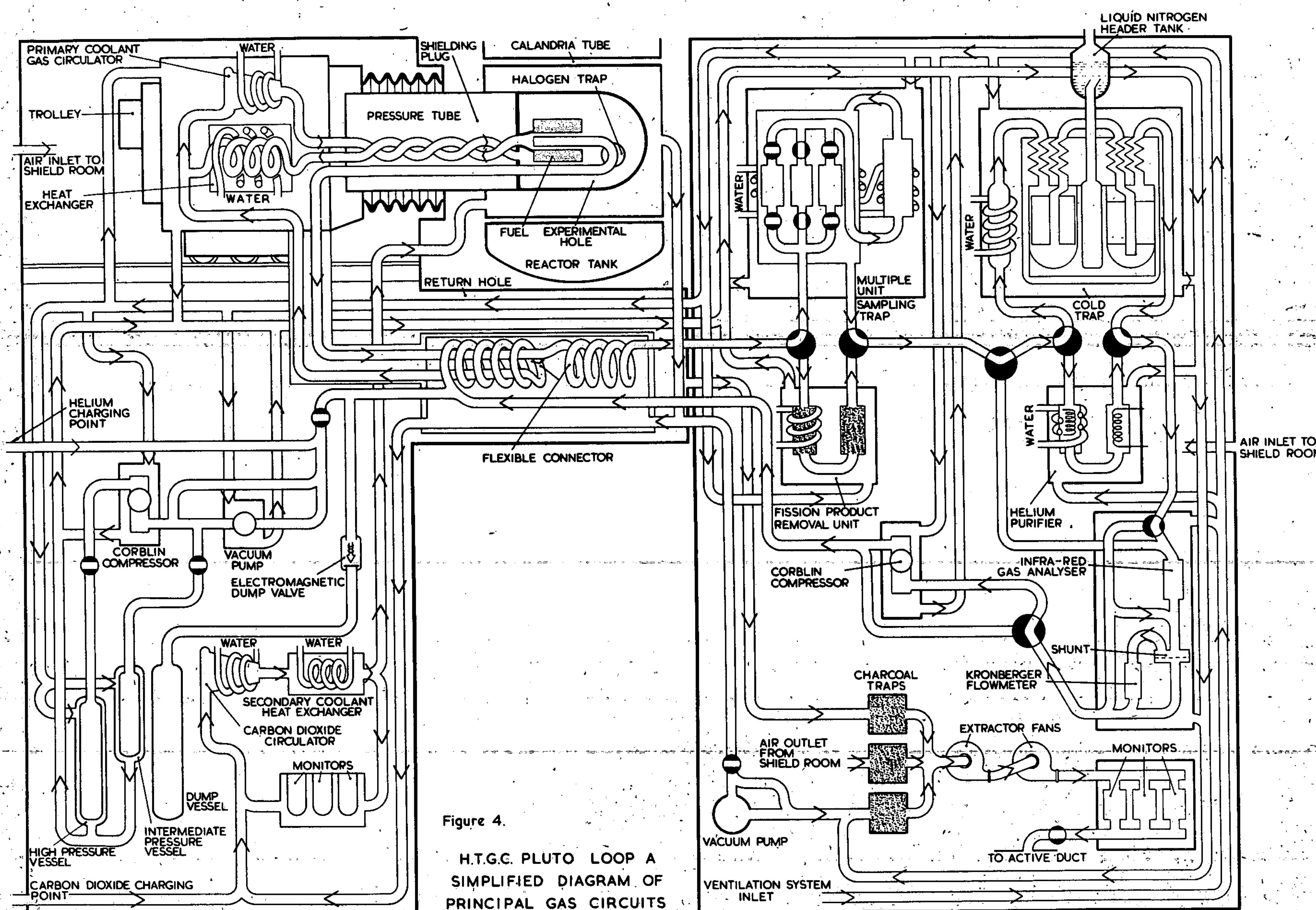
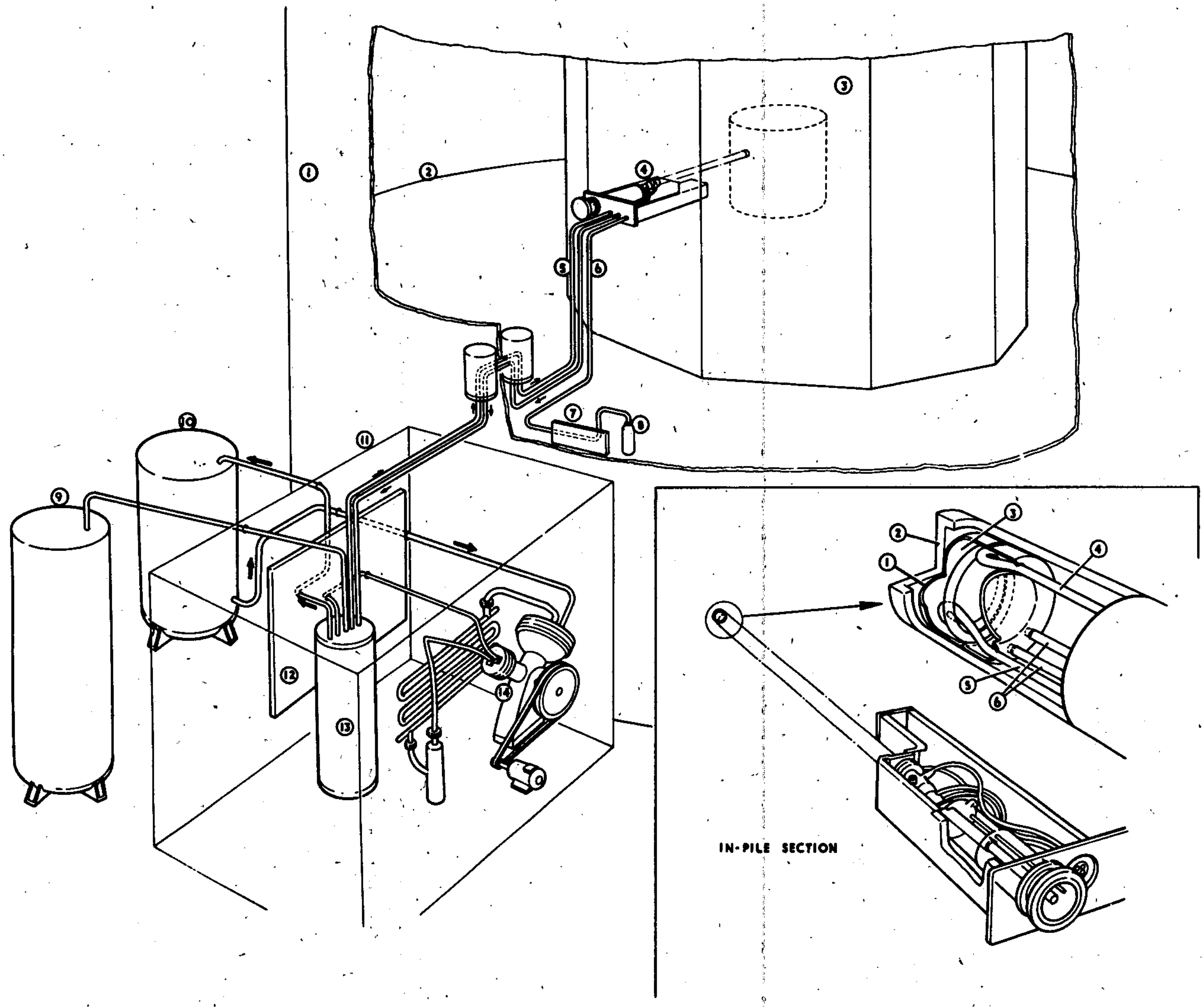


Figure 4.

H.T.G.C. PLUTO LOOP A
SIMPLIFIED DIAGRAM OF
PRINCIPAL GAS CIRCUITS



1 DIDO SHELL
2 15' FLOOR LEVEL
3 REACTOR
4 IN PILE SECTION
5 REFRIGERANT LINES
6 CONDENSATE LINES
7 CONTROL PANEL

9 LIQUID NITROGEN STORAGE TANK
10 HYDROGEN GAS STORAGE TANK
11 BUILDING 469
12 CONTROL PANEL
13 LIQUEFIER
14 COMPRESSOR

1 MODERATOR CHAMBER
2 VACUUM CASE
3 CONDENSATE FILLING
4 REFRIGERANT
5 REFRIGERANT
6 CONDENSATE LINES

Figure 5. Liquid Hydrogen Loop in DIDO

Date	Description of Experiment	Specimens	Experiment Hole Used	In-pile vessel Material
1959	1. Irradiation-damage embrittlement 2. Corrosion of mild-steel system	Mild and low-alloy steel	6V-4	Low-alloy steel (CRN2)
1960	As above, but including corrosion of stainless steel and Zircaloy specimens.	As above with stainless steel and Zircaloy 2	6V-4	Stainless steel vessel
1962	1. As above. 2. Fission-product chemistry	Fissile stainless-steel-clad UO_2/iron cermet	6V-4	Stainless steel vessel
1963	1. Corrosion experiments on plate type elements. 2. Fission-product chemistry with defected fuel plates	Fuel plates	6V-4	Stainless steel vessel
1964(a)	1. Creep of Zr/Nb alloy 2. Fuel-plate corrosion 3. Control materials 4. Fission-product chemistry	As above	6V-4	Zr2$\frac{1}{2}$%Nb
1964(b)	Marine-reactor fuel pins	Marine-reactor fuel pins	2V-3	Immac 5
1964(c)	Fuel-plate irradiation	Fuel plates	2V-8	Immac 5
1964(d)	Control materials irradiation	Plates	2V-9	Immac 5
1964(e)	1. Creep of Zircaloy 2 2. Corrosion of Zircaloy 2 and Zr/Nb alloy	Zirc. 2 and Zr/Nb	Hollow fuel element	Zircaloy 2
1964(f)	1. Creep of Zirc/Nb alloy	As above	Hollow fuel element	Zirc/Nb alloy

Table (1) Use of DIDO High Pressure Water Loop