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EXPERIMENTAL METHODS AND EQUIPMENT FOR DIFFUSION MEASUREMENTS OF RADIOACTIVE RARE - GASES IN SOLIDS

(Rare - Gas Diffusion in Solids 7)

by

F. FELIX and P. SCHMELING

1962

JOINT EURATOM/UNITED STATES PROGRAM

Topical Report established by
Hahn-Meitner - Institut für Kernforschung Berlin
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Experimental Methods and Equipment for Diffusion Measurements of Radioactive Rare-Gases in Solids (Rare-Gas Diffusion in Solids 7*)

Summary

A literature survey is given on the methods and equipment used for the measurement of release of radioactive rare-gases in solids, with a discussion of advantages or disadvantages. Continuous methods with sweepgas or circulation and various discontinuous methods are discussed and apparatus used for Hahn emanation-, DAD- or PAD-experiments are described. In addition references are given concerning sampling purifying and measuring of radioactive rare-gases as well as materials to be used for measuring rare-gas diffusion at high temperatures in oxygen sensible systems.

Introduction

The results of diffusion studies in solids are often influenced by surface reactions of the specimens and misleading conclusions concerning the diffusion coefficients may result. This fact has been stressed by others, e.g. by Gray [7] for the work on uranium metal. Other sources of error in diffusion experiments with radioactive rare-gases are numerous. In connection with the work of our group [1-6] on rare-gas diffusion in solids, a great deal of effort has been exerted in designing suitable apparatus and techniques. This report describes some of the equipment used and has been extended to a review of some experimental techniques used elsewhere for diffusion studies of radioactive rare-gases.

In the following the abbreviation PAD is used for post-activation diffusion and DAD for dum-activation diffusion or in-pile measurements (cf. [5]).

This work was carried out under the EURATOM research and development contract Nr. 064-61-8 RDD.

* Earlier publications cf. references 1-6

1 CONTINUOUS METHODS

The advantage of a continuous method is that a fast release of fission gases may be recorded and the kinetics may in this way be studied. The main drawback with a sweep gas method is connected with the difficulties in producing a pure enough gas, as even carefully treated gas can corrode a sample in a short time. In order to avoid the difficulties of purifying the continuous feed of incoming sweep gas, a forced circulation method may be used. Thereby the purified carrier gas is pumped back to the specimen and the accumulated activity is recorded.

1.1 Sweep gas method

A principle lay-out of the apparatus is given in Figure 1a. Helium is preferred as sweep gas as it facilitates the removal of krypton and xenon with the aid of cooled charcoal traps. The helium passes a purification system to remove corroding impurities and enters the furnace with the specimen from where the released gases are carried through a second purification system in order to remove all components save rare-gases. The stream then passes a monitoring and measuring device where the radioactivity is continuously recorded. For detailed analysis, gas samples are collected for subsequent measurement.

A sweep gas method may be used for Hahn emanation as well as for DAD and PAD experiments; the equipment used is in principle the same as described in Figure 1a.

1.1.1 Hahn emanation techniques

Simple sweep gas apparatus used for measuring the emanating power were early developed [8]. More sophisticated designs including automatic registration of temperature and rate of release have been described in great detail by Zimen [9,10], and Figure 2 shows a typical setup. As the measured gas in these experiments was an alpha emitter, electrometers were suitable detectors and were also developed to a high state of perfection. Gregory [11,12] later described a similar flow system for measuring thoron emanation from $-180^{\circ}C$ to $1650^{\circ}C$. Bevan [13]

used a scintillation counter instead of an electrometer and Skladzien [14] developed a cylindrical geometry proportional spectrometer for the counting.

1.1.2 DAD experiments

The first detailed description of a dum-activation apparatus is given by Markowitz [15]. Later a number of in-pile experiments were performed in Harwell by Stubbs, Walton and co-workers [16-21]. The technique used is nearly identical in all the experiments [16, 17, 22] and permits measurement of rare-gas release up to 1000°C. The upper temperature limit is due to the fact that the specimen is contained in a quartz tube which is electrically heated. By using ceramic material, higher temperatures could be reached if the safety of the reactor so permits. Details of the apparatus used, especially of the specimen capsule design are given in ref. [17, 22].

Stubbs and Walton have investigated the influence of the sweep gas velocity on the composition of the radioactive gas reaching the counting chamber. If the velocity of the gas is so adjusted that the fission gases reach the detector in the order of minutes, a number of nuclides with short half-lives are registered. The resulting gamma spectrum consists largely of superimposed peaks and is furthermore too complicated to be analyzed. If the gas velocity is lowered until the radioactive gases take hours to reach the detector, the short-lived isotopes have decayed away, leaving the gamma peaks from Xe-133, Xe-135 and Kr-85m to be registered.

A similar technique has recently been used in Oak Ridge by Carroll and Baumann [23], Figure 3. With a suitably designed charcoal trap krypton has a hold-up time of five minutes while xenon is delayed for two hours. This enables krypton to be measured separately until xenon breaks through. However, they also found that solid daughters of krypton and xenon contaminate the walls of the counting chamber, amounting to about one third of the total activity.

As distinguished from the heating technique previously described, the

uranium specimens investigated contained fissile material in such a quantity that they were heated by their own fission heat. However, in this case only thin specimens may be used if diffusion coefficients are to be measured, as otherwise too high a temperature difference between the surface and the centre of the specimen makes a calculation of diffusion coefficients impossible.

The difficulties of determining the short-lived fission gases have been overcome by measuring their daughter products [17] which, as mentioned above, tend to contaminate the gas line. The technique has been thoroughly investigated by Townley et al. [24] and is described later (see 2.1.1 and 3.1). The fission products released from defective fuel elements during their use in a reactor have been determined using sweep gas. As such investigations do not permit a calculation of diffusion coefficients, the technique used is not covered here. The registered radioactivity originates from a number of nuclides with short and long half-life, and good results are hard to get even with the best gamma-spectrometer.

1.1.3 PAD experiments

Flow systems using helium and nitrogen as sweep gases have been used for some time [25]. Cubiciotti [26] has thoroughly described an argon flow system in which the specimen is heated in a furnace and the evolved radioactive fission gases are carried through a train of traps in order to remove all nuclides save the rare-gases. The radioactivity was measured with an ionization chamber. The amount of rare-gases left in the specimen after heating in argon was determined by burning it in oxygen. A similar system using argon is described by Bates and Clark [27].

An apparatus used at the Battelle Memorial Institute for continuous measurement of the cumulative amount of fission rare-gases is described by Rosenberg et al. [28], Figure 4. The sweep gas passes through a charcoal trap within a scintillation crystal where the radioactive xenon is absorbed and continuously recorded together with the temperature of the specimen.

A similar technique is used by Barnes and Sunderman [29], Figure 5. In this case the helium used is first continuously analyzed before entering the furnace, and the radioactivity of the gas is thus continuously recorded together with furnace temperature, helium flow rate and pressure, and oxygen and moisture concentrations. The accumulated amount of fission gas is also measured, as the sweep gas passes charcoal traps cooled with liquid nitrogen. The successful use of an apparatus of similar design is reported by Berry and Darras [30] and by Parker and co-workers [153].

1.2 Forced circulation method

The main components of a forced circulation system are shown in Figure 1b, a detailed example is shown in Figure 6. The method has been used [31, 32], though difficulties seem to be connected with the pump, which has to be completely leak tight (see 3.5). Normally the accumulated activity is recorded, but also rates of release may be observed. In the latter case, the system is preferably filled with helium, and the evolved radioactive gases continuously removed with a cooled charcoal trap before the gas stream returns to the specimen.

1.3 Natural circulation method

In the case of relatively slow diffusion processes the released radioactive gases have plenty of time to spread evenly to all parts of a closed system, and the method can be regarded as reliable and requires only simple apparatus. Reynolds [33] used an evacuated closed system for the postirradiation heating of uranium metal. The evolved Kr-85 was measured with a double walled GM counter which was attached to the system. The activity was continuously recorded and assumed to be proportional to the fraction of the total krypton leaving the sample.

The method has also been used by Felix [34] to study slow release of fission gases over longer periods of time. The heated part of the system, as well as all connecting tubes, has a small volume and the main volume consists of a counting chamber which is located at such a distance from

the radioactive specimen that the background activity is low.

2 DISCONTINUOUS METHODS

Many of the apparatus described above for continuous registration of the released fission gas may be used for discontinuous measurements. One is forced to measure discontinuously as soon as the released gases consist of a mixture of many radioactive species. Sampling and analysis of the gas is thus necessary, and specially designed apparatus are preferable in many cases.

2.1 Sweep gas method with discontinuous sampling

2.1.1 DAD experiments

Sweep gas methods with discontinuous sampling applied to Xe-133 have been used [35] but the apparatus is the same as described 1.1.2 . The discontinuous sampling is in this case a complement to the continuous measurement and may possibly also be needed if the registered gamma spectrum is complicated. At Harwell [36] this procedure has often been needed; gas collected in the counting chamber (see 1.1.2) was sampled and measured from time to time, thus making an analysis of the gamma spectrum possible.

Investigators at Battelle Memorial Institute [24] have determined the released rare-gases with short half-lives using an in-pile loop, Figure 7. Sweep helium passes the sample and enters a trap filled with steel-wool. The mean passing time for the gas through the trap is 90-125 seconds and most of the Xe-140 (16 sec) and Xe-141 (1.7 sec) present decays within the trap. The radioactive daughters are absorbed on the steel-wool. After removal of the trap the daughters Ba-140 and Ce-141 are extracted by chemical treatment and measured . Kr-89 (3.2 min) and Xe-137 (3.9 min) may also be determined in this way. The method is usable, however, only if the daughters are not released directly from the fuel together with the rare-gases, which does not apply at high fuel temperatures.

2.1.2 PAD experiments

A discontinuous apparatus for postirradiation experiments using helium as carrier gas is described by Booth and Rymer [37], Figure 8. The specimen is placed in a furnace, through which the purified helium in order to sweep out the evolved rare-gases. The krypton and xenon are trapped by means of activated charcoal cooled with liquid nitrogen. During the experiment the carrier gas alternates between two parallel trap lines for a period of 3 to 6 hours. The charcoal trap is fused off and placed in a fixed geometry over a spectrometer crystal for measurement of the activity.

A similar apparatus is used at the Oak Ridge National Laboratory [38], Figure 9. The helium sweep gas carries the rare fission gases into a train of collection bulb containing activated charcoal at $-190^{\circ}C$. Parallel trains are incorporated in the system so that up to 12 samples of fission gas may be collected from a single specimen. The bulbs are sealed off and krypton and xenon are measured by means of a gamma spectrometer.

2.2 Closed systems with discontinuous sampling

Heating a sample in a closed system after irradiation and collection of the released gases is an often used and reliable method for the calculation of diffusion coefficients.

The most simple procedure is to heat the specimen in a closed tube in vacuum or indifferent atmosphere. After the heat treatment the evolved rare gases are sucked into evacuated counting chambers [3, 40] and the radioactivity is measured. The tube with the specimen may also contain charcoal, and after heating , this part of the tube is cooled with liquid air and sealed off [35, 39]. By this method a maximum temperature of only $1100^{\circ}C$ can be reached, and possibly less than that considering the permeability of quartz glass at high temperatures (see 3.6).

The following procedures allow heating of the specimen under controlled vacuum conditions. Figure 10 shows the annealing system

by Auskern and co-workers [41]. In the evacuated, closed system the sample is lowered into the hot zone. During heating there is enough degassing of the furnace material to raise the pressure to about 0.5 torr. After annealing the sample is raised from the hot zone and the gases evolved are collected on activated charcoal at $-190^{o}C$. When the pressure of the system is low enough, the charcoal trap is sealed off and the sample may again be lowered into the furnace for further heat treatment.

A similar procedure is used by Schmeling [42], Figure 11. A double-walled quartz tube is heated in a furnace in high vacuum. During this degassing period the specimen is located at position 1 until the quartz is completely baked. The specimen is then placed in position 2 in the hot zone for a certain period of time. After cooling, spectral pure krypton and xenon is added as carrier; the line is connected to a charcoal trap cooled with liquid air, and the radioactive gases evolved during heating are collected.

The procedure described permits a clean treatment of the sample. In order to completely avoid corroding influence of the gases evolved when heating the furnace material, a method has been developed to heat the sample in high vacuum [42] to high temperatures. Figure 12 shows the arrangement . The sample is placed in a cool part of the system during the initial degassing of the furnace material and is later brought into the hot zone. The furnace is connected to a high vacuum glass pump via an activated charcoal trap. The evolved gases are continuously pumped into the cooled trap where they are collected. An extra trap situated after the high vacuum pump ensures quantitative collection of the gases evolved, and it has been found that this second trap contains less than 1 % of the gases collected in the first one. The sample is thus annealed in high vacuum, and the addition of small amounts of spectral pure rare gas carrier from time to time ensures a complete transfer of the evolved gases.

The method of evacuation through an activated charcoal trap has also been used by investigators at Chalk River [43], whereby the trap is continuously monitored with a gamma-ray-spectrometer.

Other investigators use Toepler pumps as a collecting device or for intermittent circulation of the gases. In the latter case they may easily be made to work automatically (see 3.5). Toepler pumps are complety leak proof and therefore suitable for use in a closed system.

With an apparatus used at Bettis Plant [44], a capsule containing the irradiated specimen may be remotely punctured, and the gases are released into an evacuated system. The gases are pumped trough cooled charcoal traps with the aid of a Toepler pump. Felix [3] used a valveless pump in order to distribute the radioactive gases evenly in the system, as shown in Figure 1c and Figure 14.

Other investigators [27, 31, 33, 46, 47] also report the beneficial use of a Toepler pump, as exemplified by the apparatus used by Walker [47], Figure 13. Belle and co-workers [152] used a closed system filled with helium, whereby a Toepler pump circulates the gas through charcoals traps which were sealed off at various times.

2.3 Irradiation capsule studies

A technique to yield valuable information about the quality of a reactor fuel element is the method to irradiate capsules. A specimen is irradiated in a closed capsule under simulated reactor conditions and under rigorous atmosphere control.

By puncturing the capsule the fission gases released can be collected and measured. However, due to the temperature gradient in the sample and to the fact that a sample allows just one single measurement of the quantity of gases released though knowledge of release as a function of time is desirable, such studies are of little value for the calculation of diffusion coefficients. Therefore, this technique is not fully covered here, but some interesting studies may be mentioned. An excellent review is given by Plail [48]. Equipment used [48-54] and details of the postirradiation examination [44, 51, 53, 55-57] are described by many authors. The postirradiation examination can be extended to determine not only the radioactive fission gases evolved but also the stable ones [55, 56, 58].

3 AUXILIARY EQUIPMENT

3.1 Notes on counting and sampling techniques

A review on the counting of rare gas activity is given by Momyer Jr. [59] . Early investigators describe the use of electrometers [8-11,26] and GM tubes [25, 60] . With the development of the gamma-scintillations-spectrometer this instrument is the one most frequently used today [15, 16, 23, 28, 29, 37, 61] and it may even be used for determining short lived rare gases by measuring their longer living daughters [17, 24] .
A "pair production" spectrometer has been used by Stubbs et al. [17] .

The collection of rare-gases on activated charcoal at low temperatures is a much used method. Adams and Browning [62-66] have measured the hold-up of krypton and xenon by charcoal traps and Cannon et al. [67] report adsorption isotherms for xenon and argon. An excellent work is reported by Peters and Weil [68], and a good review is given by Momyer Jr. [59].. The use of charcoal traps for the separation of xenon and krypton with subsequent measurement of only krypton is also possible [23] . The collected activity in a dry ice cooled trap may be measured continuously with a well scintillation crystal [28] .
In this case one has to consider the fact that the incoming rare-gas may be adsorbed in different parts of the charcoal column, thereby affecting the counting geometry [30, 150] . Mostly the traps are arranged in a train and individually sealed off and measured. The procedure preferred in this laboratory is to transfer the gases from the trap into a standardized gas counting chamber which has a thin aluminium window. These chambers may be stored and measured by a GM-counter or a scintillation crystal until the contents are assuredly known. Samples of the gas may also be collected directly without charcoal trap with the aid of a medical syringe and evacuated serum bottles as standard counting chambers [69] .

3.2 Determination of the total amount of rare-gas present

The determination of the total amount of rare-gas present in the specimen may be made by calculation or by using a suitable dosimeter

to be irradiated together with the specimen [28, 49, 70, 71] . The determination of U-235 depletion and the ratio of cesium/uranium or plutonium/uranium [70] is more cumbersome and is not needed in most cases.

Many investigators determine the total activity by dissolving the specimen in acid [44, 41, 72] or potassium pyrosulphate [30, 37, 73] . In order not to destroy the sample, a second piece of the sample material may be irradiated together with the specimen and separately dissolved.

In some cases the total activity is determined by burning the specimen in oxygen [26] . However, the method cannot be recommended as the rare-gases are not completely released. It is inefficient for the complete release of krypton and xenon [74, 153] , and metallic uranium is not liberated from its rare-gas contents when treated in air at temperatures above its melting point [75, 76].

3.3 Purification of sweep gases and inert atmosphere

Inert atmosphere in general and sweep gases in particular have to be very pure if corrosion of the specimen is to be avoided. Corrosion is accompanied by a release of rare-gases, and may be mistaken for diffusion, a fact which is recognized [7] and which necessitates rigorous purification [23, 29] . Corrosion of the specimen as a result of impure gases has been noted during experiments for the study of diffusion of rare-gases in metallic uranium [16, 46, 47] , uranium dioxide [34] and uranium carbide [77]. The effect of oxidation on the gas release from uranium and uranium dioxide has also been reported [74-76, 78, 79] . A number of methods are used to purify rare-gases [80-84, 86]. Metallic uranium is known to be a good getter for oxygen and nitrogen [80, 81] and has been used for the purification of sweep gases [16, 17] . Calcium has been frequently used [23, 55, 56, 80, 82, 83] as well as copper [15, 25, 29, 30, 80, 84, 85], titanium [80, 82, 83] , zirconium [15, 29, 80], magnesium [83], molecular sieve [30], and activated charcoal [38, 55] at the temperatures of liquid air. In order

to remove the last traces of oxygen, hydrogen may be added, catalyzing the reaction between the oxygen and hydrogen present [23, 86]. Traces of gas may be adsorbed at the walls of the apparatus and released when the system is heated. In order to eliminate corrosion as far as possible it is advisable to place the sample in a cold part of the closed system, where it is kept during an initial degassing heating period. It is then transferred to the hot zone with a suitable device, i.e. magnetically operated [29], with winch and chain [38], or simply by dropping the specimen [42], cf. Figure 12.

3.4 Purification of released fission gases

The gases released from an irradiated specimen at temperatures of about 1000°C in most cases consist exclusively of krypton and xenon. At higher temperatures a number of other elements are vaporized which makes the measurement of the rare-gases more difficult. The main contaminating species is iodine but a whole range of isotopes may be released at very high temperatures [87-89].

A simple filter [16, 23, 75, 89] may be used for the condensation and trapping of radioactive species other than the rare-gases, while a charged wire technique is preferred by other investigators [26, 61, 90, 91]. The removal of iodine from gas streams has been thoroughly studied [92], and a number of trapping materials have been investigated, such as activated charcoal [75, 93-99], Linde Molecular Sieve Material [94, 97], silvered copper [95, 97, 98], copper [25, 26, 30, 95 98], silver [4, 29, 31], sodium thiosulphate [97], potassium iodine [99], and potassium hydroxide [37, 75, 76, 91, 93]. Many of the cited materials have to operate at elevated temperatures. However, the most efficient of all seems to be activated charcoal [95, 97, 98] which can operate at room temperature.

3.5 Pumps

For the circulation of radioactive gases through filters and counting chambers, a leak proof pump is needed. Few pumps fulfil this

requirement, and all pumps based on rubber or plastic tubing [100, 101] and diaphragms must be discarded as air easily leaks through the tube walls [102] .

3.5.1 Mercury displacement pumps

Displacement pumps using mercury are reliable and are very suitable for circulation if mercury vapors can be tolerated in the system. The Toepler pump is widely used and can be made to work automatically [203 - 205] The pumping however is discontinuous.
A mercury displacement pump designed to give a constant rate of flow is described by Shapiro and Landesman [106].

3.5.2 Magnetically operated pumps

A magnetically operated pump consists of an accurately fitting barrel and piston coupled to a pair of valves. The piston has a core of soft iron and is moving in an electromagnetic field. The pump is completely sealed and therefore leak proof. It performes well also at pressures as low as 300 torr [107-110, 149].

3.5.3 Bellows pumps

A metallic bellow coupled to a pair of valves may be used as a pump [111]. A cheap and efficient pump of this type is available commercially [112].

3.5.4 Blowers

Fans have been used to circulate gases. However, the fan must not be connected to a motor by a shaft passing through a seal, as such seals tend to leak. A completely built-in blower is described by Foresti [113].

3.6 Materials

Many authors have reported the corrosion of a specimen during heat treatment [46, 47, 77] due to the pick up of trace impurities from the surrounding atmosphere, and the effect on the determination of diffusion

coefficients has been pointed out by Gray [7] in the case of metallic uranium. The mounting of the specimens is also of great importance, as well as the behaviour of materials present during the heat treatment. The extreme difficulties to be overcome when heating metallic uranium are well known, as uranium is an effective getter and readily reacts with air in trace amounts. The mounting of uranium does not seem to be a problem, as relatively moderate temperatures are used [114, 115]. Quartz glass has often been used in connection with heat treatment of metallic uranium, which however leads to corrosion at temperatures above 800°C [116]. Quartz is slightly permeable for gases already at 700°C [45, 151] and special precautions must be taken to inhibit permeation at higher temperatures. Furthermore, the quartz must be baked in high vacuum in order to remove not only adsorbed gases but also gases which seem to be solved in the glass [117, 118]. The compatibility of uranium dioxide at temperatures above 2000°C with various materials has been reported [119, 120]. Tantalum, tungsten, molybdenum and rhenium seem to be suitable materials in combination with uranium dioxide.

The uranium carbides are more reactive than uranium dioxide and caution must be taken when mounting a specimen for high temperature treatment. Tungsten, tantalum, zirconium carbide and niobium carbide seem to be suitable mounting materials. Thoria and pure zirconia seem to be inert against uranium carbide to at least 2000°C [121-126]. Uranium carbide reacts with platinum [30] and iridium [127].

Details regarding high temperature metals and oxides can be found in handbooks as well as reports [128-136].

3.7 Furnaces

The literature contains many furnace designs which are quite suitable for heating a radioactive specimen in vacuum or in a controlled atmosphere above 1500°C, and the references given below may be useful.

3.7.1 Resistance furnaces

Wire-wound furnaces are seldom capable of reaching temperatures above 1500°C. However, with rhodium wire 1800°C may be reached [29]. The metallic resistor furnaces can be brought to temperatures in the neighbourhood of 3000°C and are suitable for work in vacuum or inert atmosphere. They consist of a tube or a coil made of molybdenum, tantalum or tungsten which is directly heated with a high current (low voltage) power supply [119, 130, 137-144].

Graphite resistors have also been used for many years [145]. Adsorbed gases are however difficult to remove from graphite, and gaseous products may also contaminate the furnace atmosphere and react with the specimen.

3.7.2 Induction heated furnaces

In induction heating a current-carrying conductor operates at high frequency and induces an eddy current in a susceptor made from graphite, iridium, tantalum, molybdenum, or tungsten. The susceptor may be heated very rapidly, in a couple of minutes the temperature reaches 1500°C. Temperatures of about 2400°C may be achieved [38, 120, 130, 146-148].

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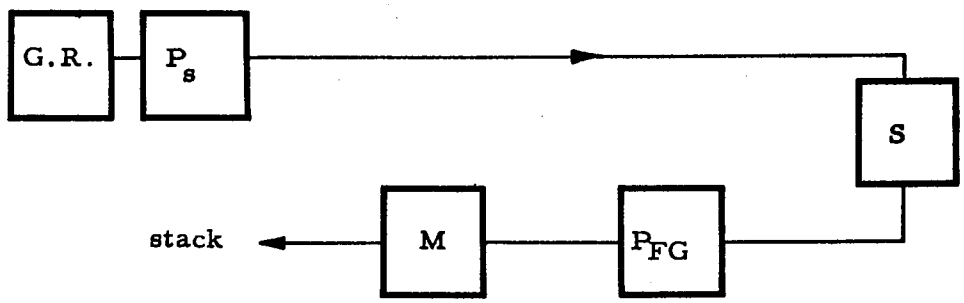
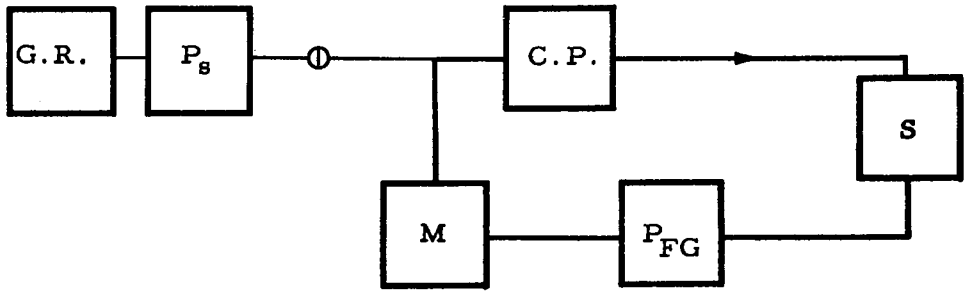
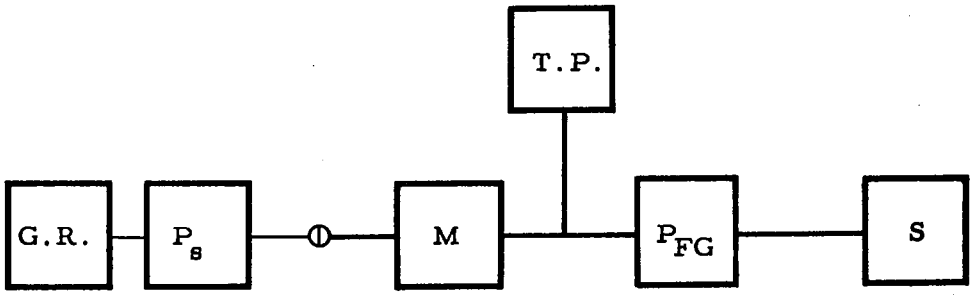


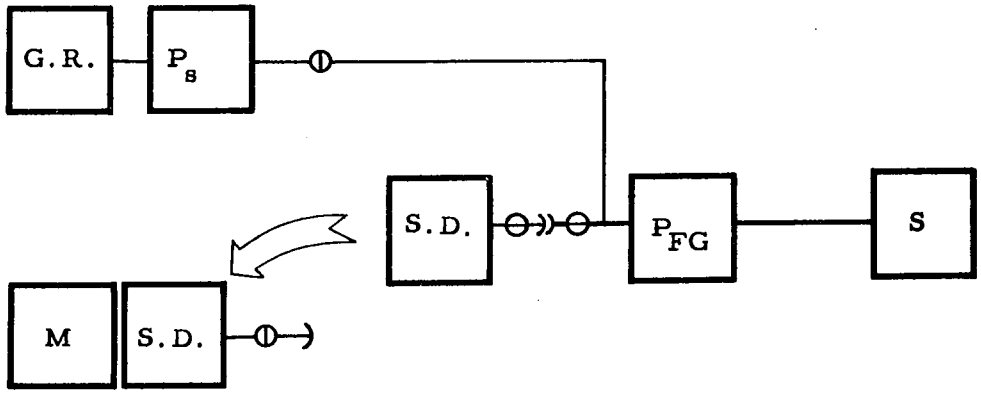
HMI-B19 Sweep gas method
Fig. 1a



HMI-B19 Forced circulation method
Fig. 1b



HMI-B19 Toepler pump mixing method
Fig. 1c



HMI-B19 Discontinuous sampling method
Fig. 1d

G.R.	gas reservoir	C.P.	circulation pump
P_s	purifier for carrier gas	M	measuring device
S	specimen in furnace	T.P.	Toepler pump
P_{FG}	purifier for released gas	S.D.	sampling device

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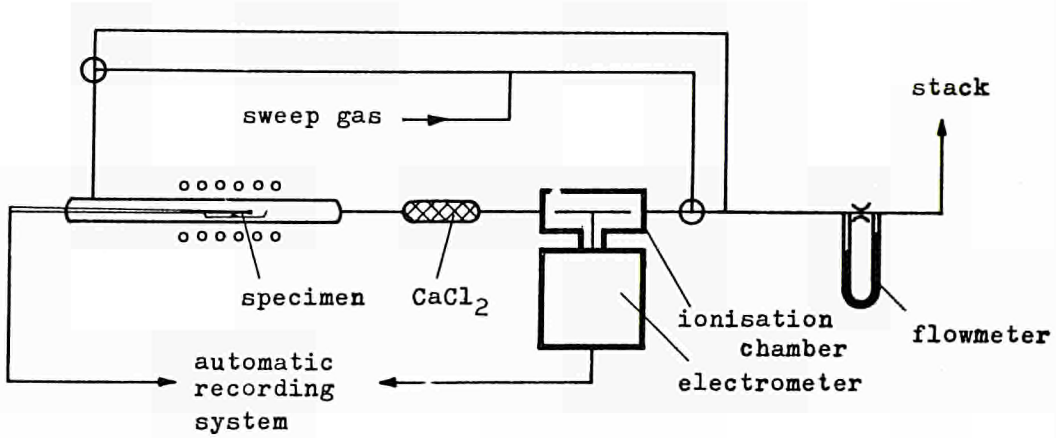
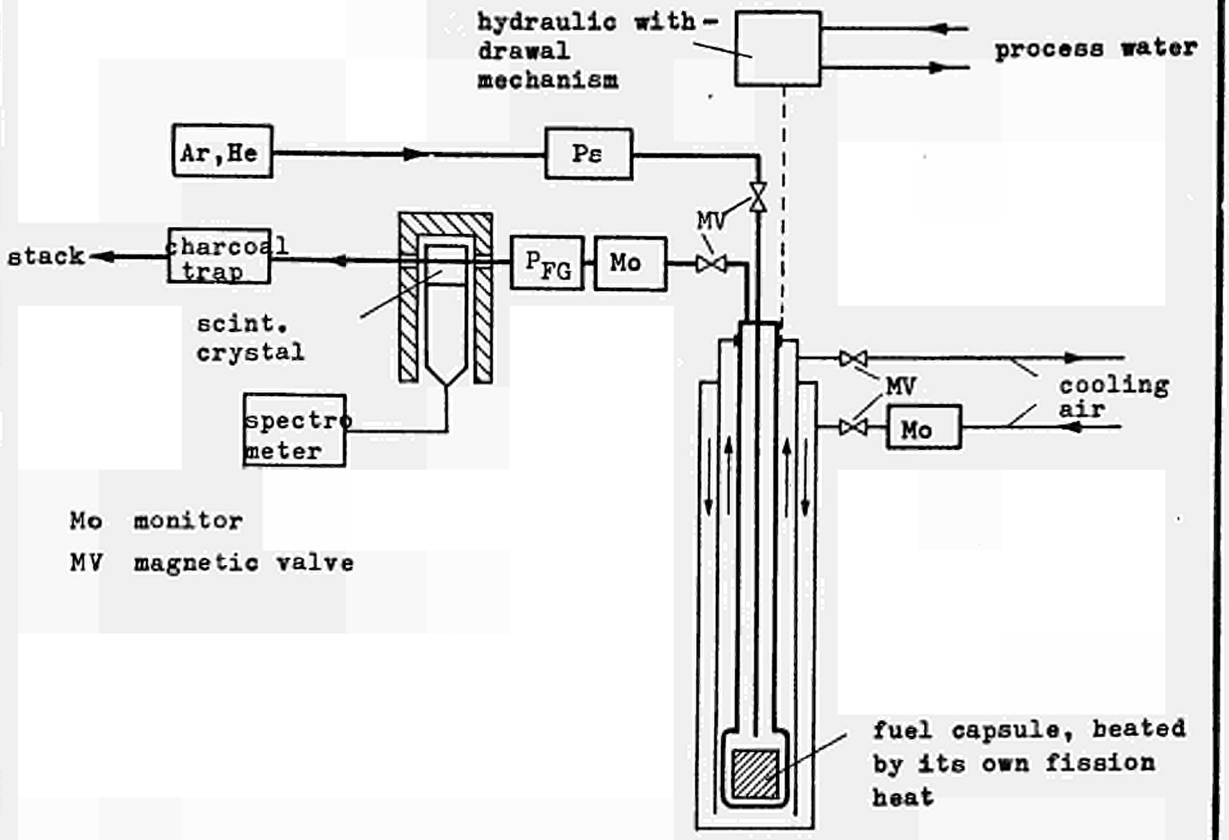
The following figures 2 - 14 are based on actual designs described in literature:

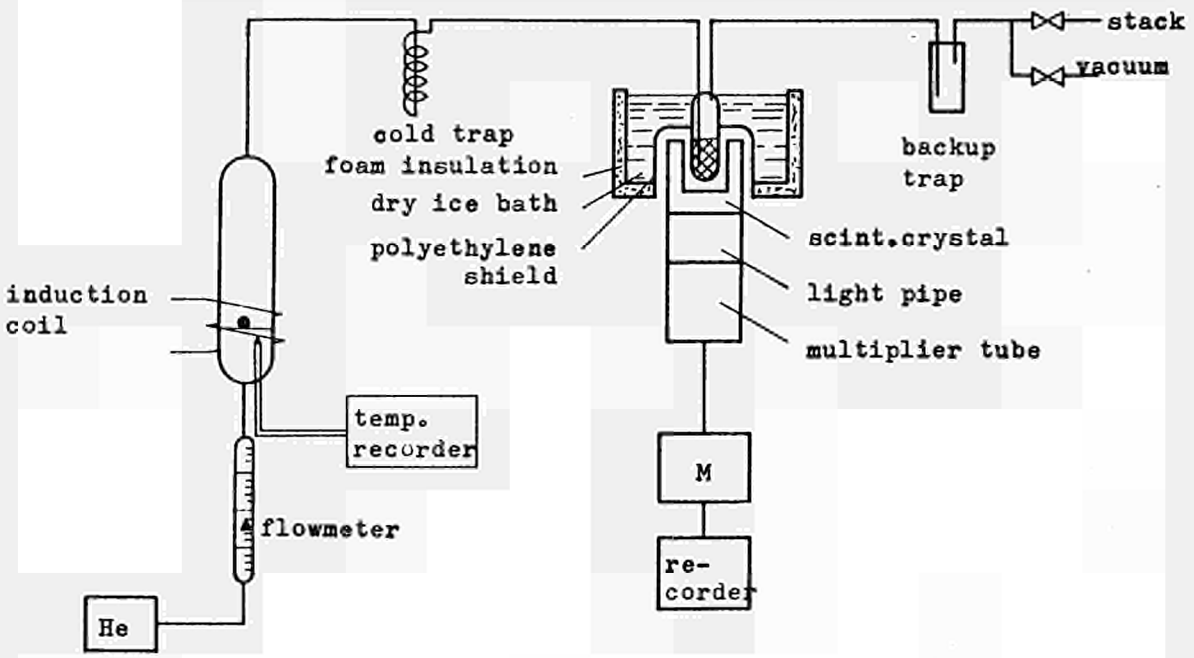
Fig. 2	Sweep gas apparatus for Hahn emanation studies
Fig. 3	Sweep gas apparatus for in pile use
Fig. 4	Sweep gas apparatus for post activation experiments (continuous measuring)
Fig. 5	Sweep gas apparatus for post activation experiments (continuous measuring and sampling)
Fig. 6	Continuous measurement with forced circulation
Fig. 7	Experiment with delay trap for the determination of short-lived fission gases
Fig. 8	Post activation experiment with sweep gas
Fig. 9	Post activation experiment with sweep gas
Fig. 10	Post activation experiment with closed circuit
Fig. 11	Closed circuit experiment
Fig. 12	Closed circuit experiment
Fig. 13	Toepler pump arrangement
Fig. 14	Continuous measurement by mixing with Toepler pump at atmospheric pressure



HMI-B19 Fig. 2 — Sweep gas apparatus for Hahn emanation studies — [Zimen, Z. phys.Chem.A 191 (1942)1]



HMI-B19 Fig. 3 Sweep gas apparatus for in pile use [Carrol, Baumann, ORNL-3050, 1961]



HMI-B19 Fig. 4 Sweep gas apparatus for post activation experiments (continuous measuring) [Rosenberg et al., BMI-1444, 1960]

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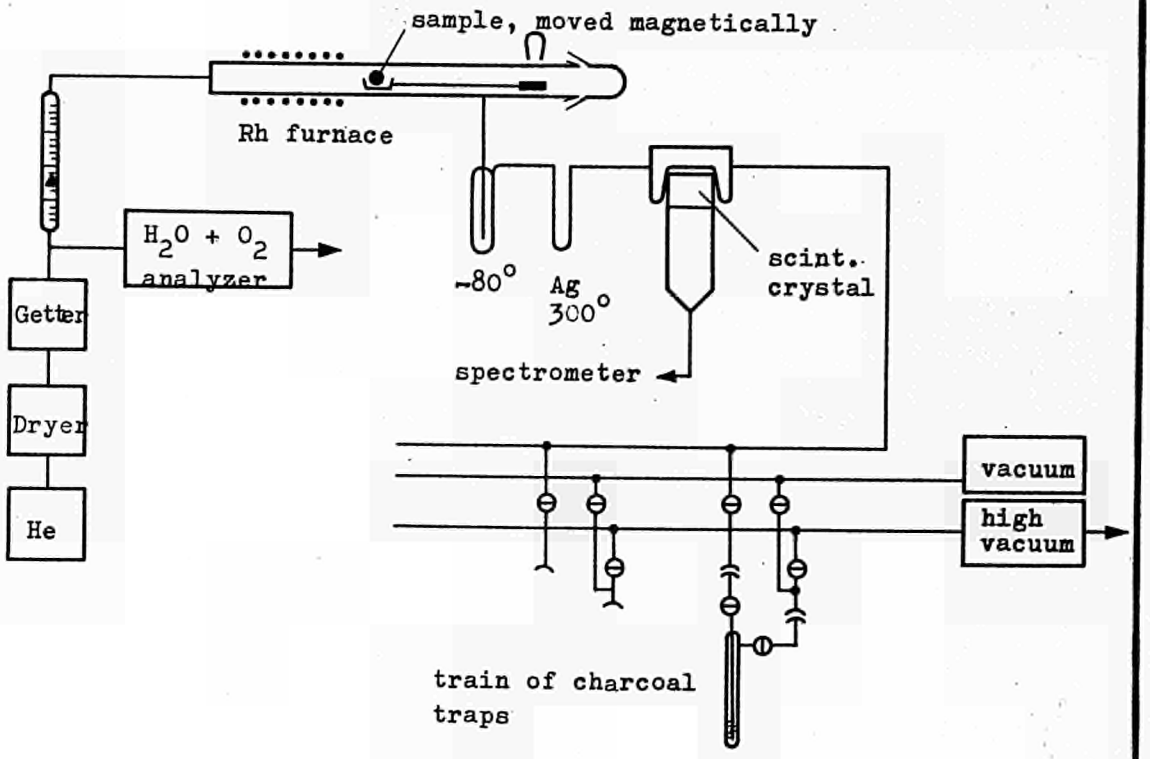
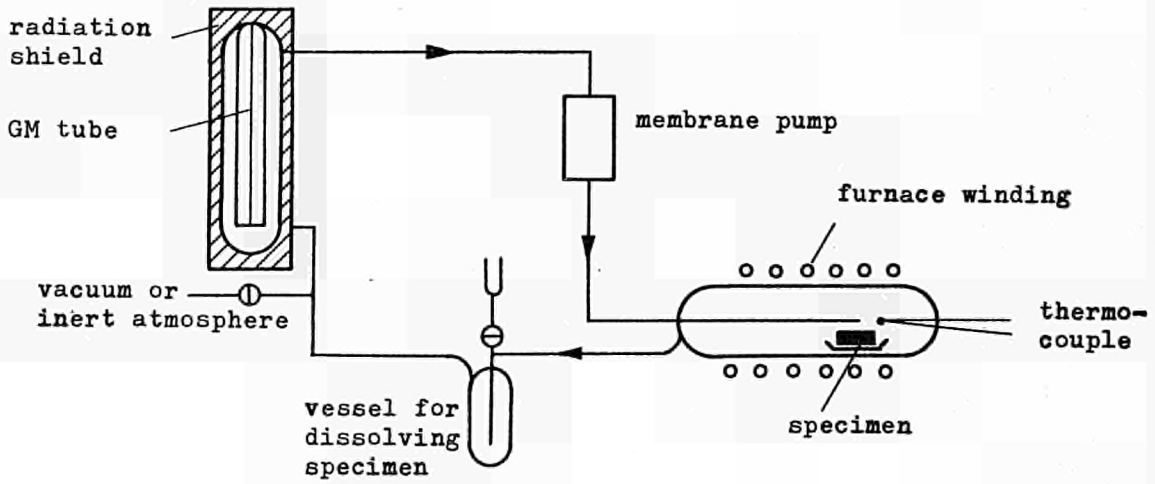


HMI-B19 Fig. 5 Sweep gas apparatus for post activation experiments (continuous measuring and sampling) [Barnes, Sunderman, BMI-1453, 1960]



HMI-B19 Fig. 6 Continuous measurement with forced circulation [HMI-EURATOM-program, quarterly report EU-B2, 1960]

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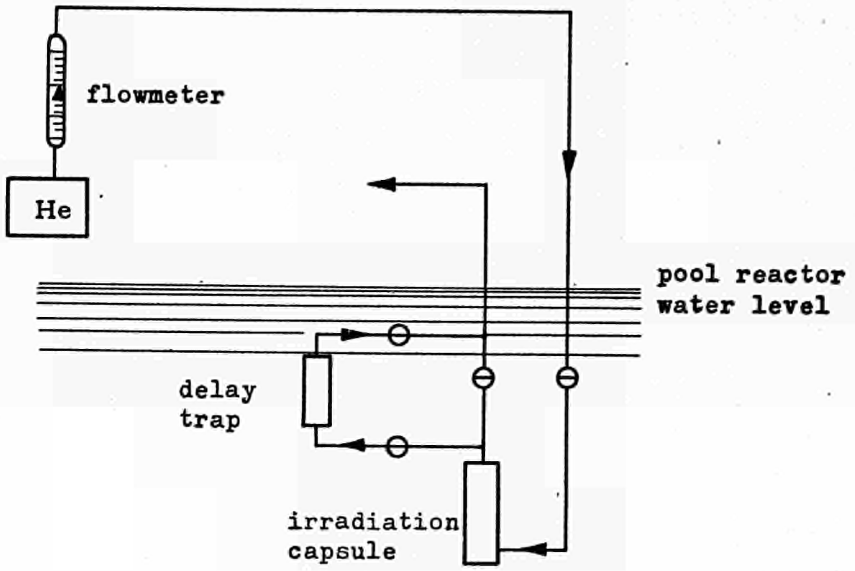
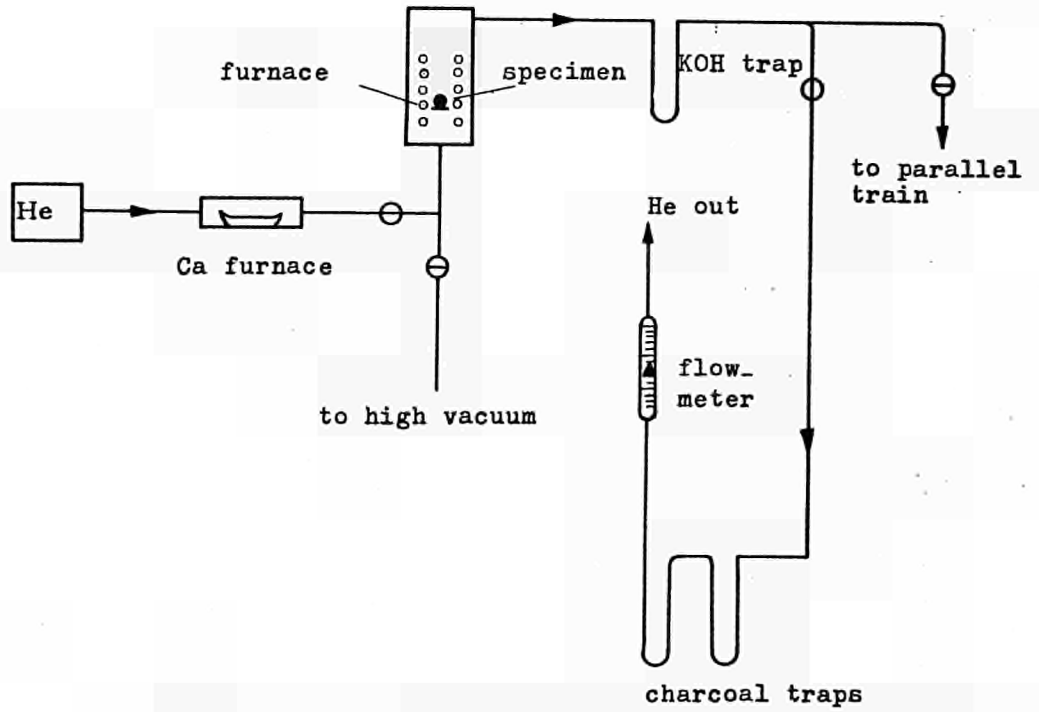


HMI-B19 Fig. 7 — Experiment with delay trap for the determination of short-lived fission gases [Townley, BMI-1466, 1960]



HMI-B19 Fig. 8 — Post activation experiment with sweep gas [Booth, Rymer, AECL-692, 1958]

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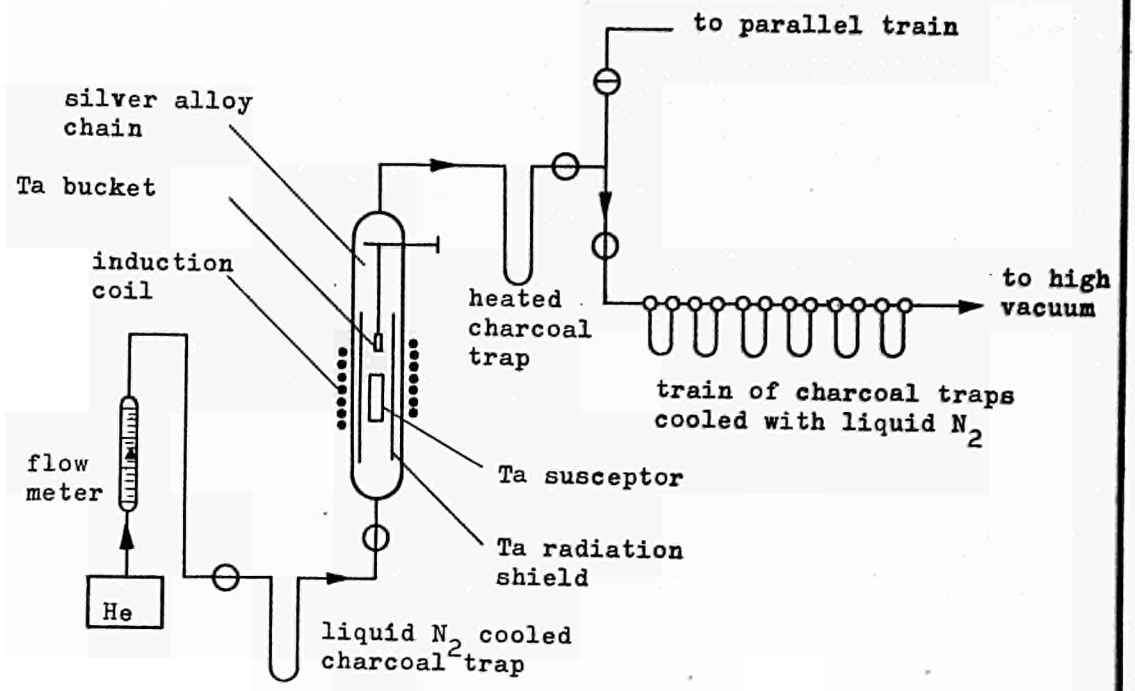
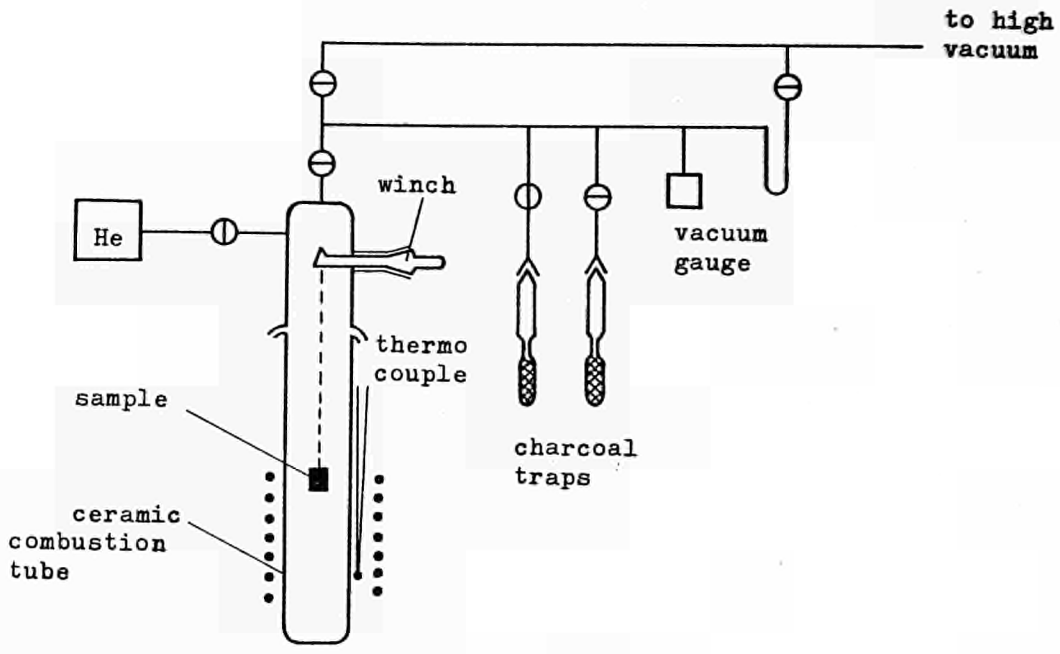
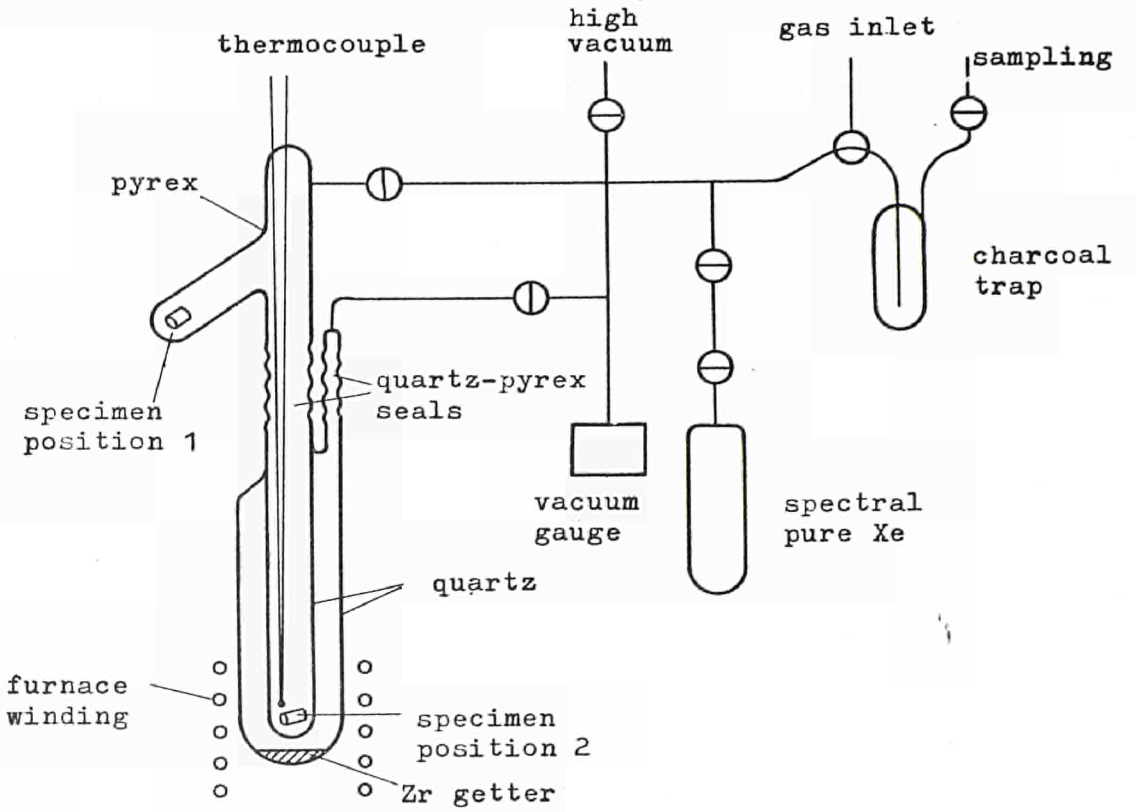


HMI-B19 Fig. 9 Post activation experiment with sweep gas [Scott ORNL-CF-60-8-15, 1960]

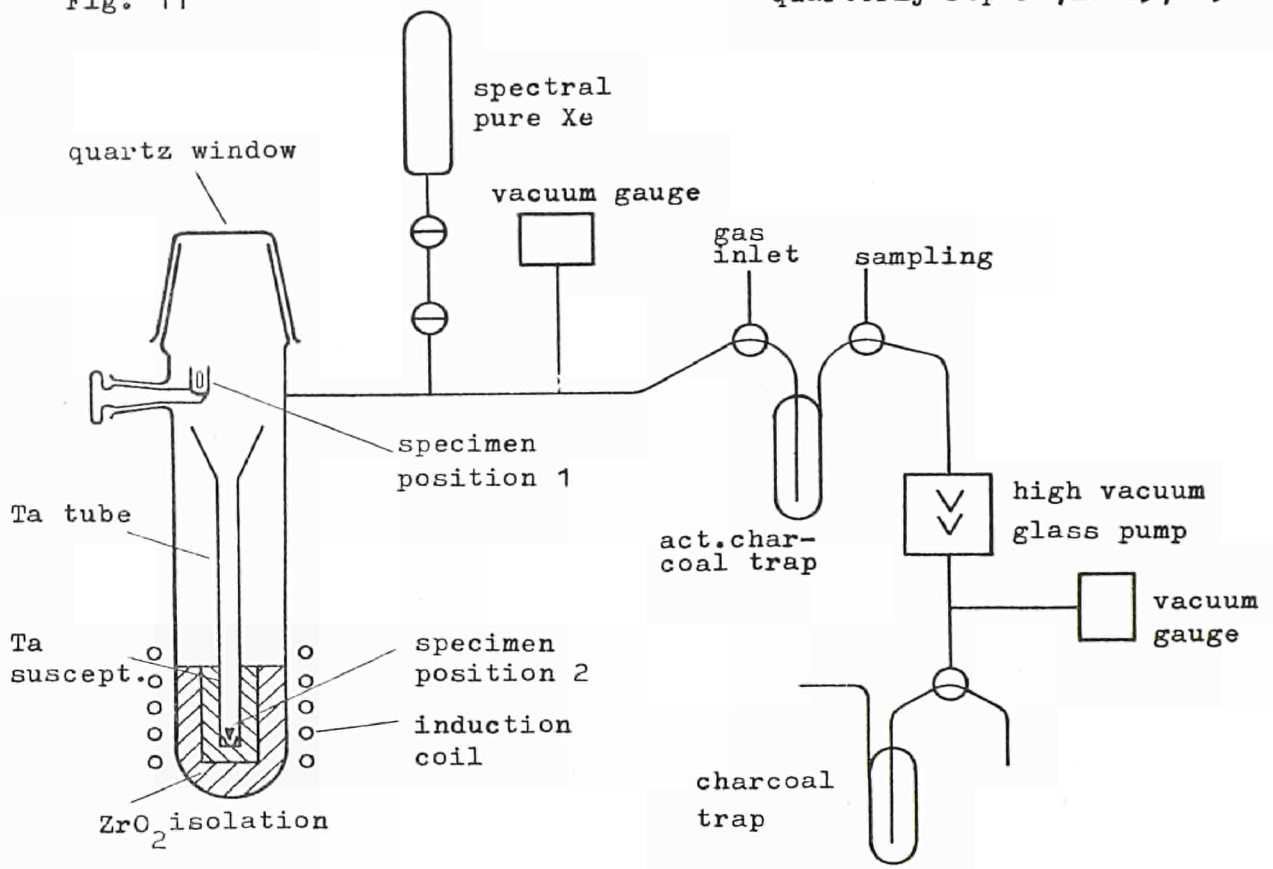


HMI-B19 Fig. 10 Post activation experiment with closed circuit [Auskern, WAPD-TM-185, 1960]

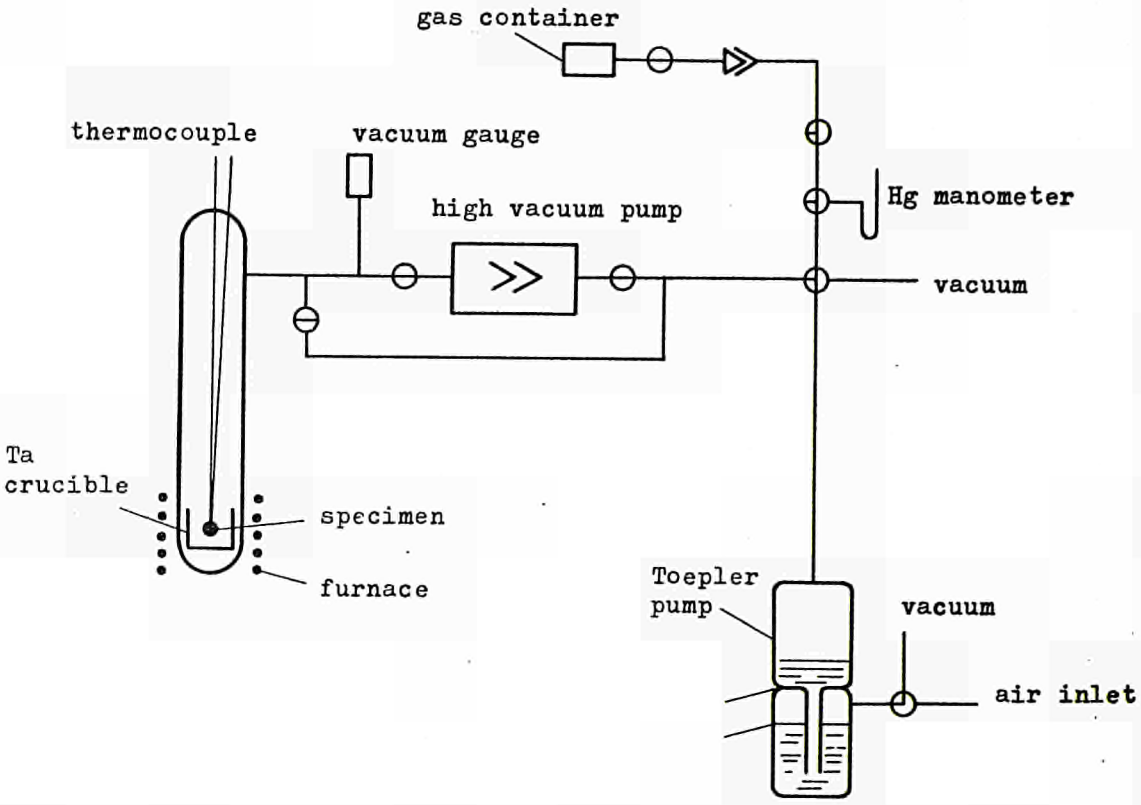
N-118/6/61



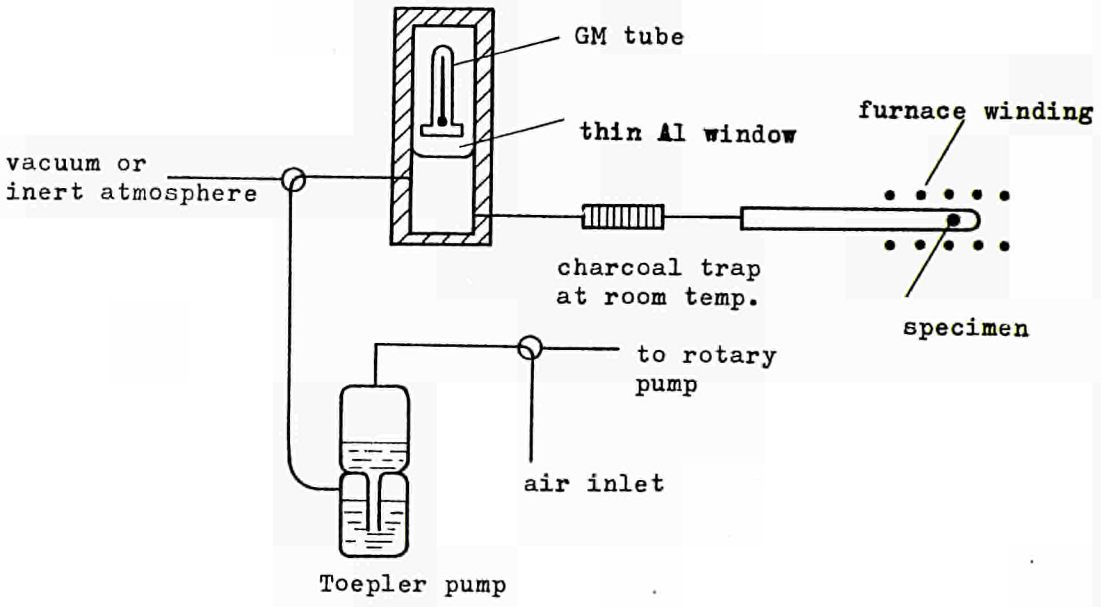
HMI-B19 Closed circuit experiment [HMI-EURATOM-program, quarterly report, EU-B5, 1961]
Fig. 11



HMI-B19 Closed circuit experiment [HMI-EURATOM-program, quarterly report EU-B5 (1961)]
Fig. 12



HMI-B19 Toepler pump arrangement [Walker, IGR-TN/W-1046, 1959]
Fig.13



HMI-B19 Continuous measurement by mixing with Toepler pump at atmospheric pressure [Felix,Nukleonik 1 (1958)66]
Fig. 14

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