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IN-PILE TEST OF A THERMIONIC CONVERTER

by

C.A. BUSSE, R. CARON (EURATOM)
and E.W. SALMI (Los Alamos Scientific Laboratory)

1963

Joint Nuclear Research Center
Ispra Establishment - Italy

Direct Conversion Service

Text presented at the
Thermionic Converter Specialist Conference,
Gatlinburg (Tenn.) USA October 7-9, 1963

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IN-PILE TEST OF A THERMIONIC CONVERTER

Abstract

A test with a nuclear heated thermionic converter was performed in July 1963 at Ispra. The main object of this experiment was to study the temperature distribution in the converter under different operating conditions. The converter was principally constructed of Niobium and Alumina, with a cylindrical Molybdenum emitter which was radiation heated from a (UZr)C fuel pin. The vacuum-contained converter was in thermal contact with the cooling water through three bridges. Measuring the temperature drop along these bridges allowed direct determination of the emitter lead losses and the converter efficiency. No currents very much higher than the vacuum saturation emission current were obtained since the Cesium heater failed in the check-out before the test.

Introduction

A test with a nuclear heated thermionic converter was performed in July 1963 at Ispra. The tested cell has three characteristic features in which it differs from other in-pile cells known from literature [1-5] :

1. The refractory metal emitter is separated from the fuel pin by a gap and heated by thermal radiation.
2. The vacuum-contained thermionic converter is in thermal contact with the cooling water through three bridges.
3. Measuring the temperature drop along these bridges allows one to determine the emitter lead losses and the converter efficiency.

The main object of the experiment was to study the temperature distribution in the converter under different operating conditions in order to firmly establish some of the design values for future tests. Furthermore, the test served to check the construction in general as well as a number of special fabrication techniques.

Design of test rig

The test rig consisted of an irradiation capsule which was suspended by three tubes from a plug in the Helium filled central thimble of the reactor Ispra I (CP 5 type), offering a neutron flux of $4x10^{13}cm^{-2}sec^{-1}$ (empty thimble) at full reactor power of 5 MW.

Fig. 1 shows a simplified design of the irradiation capsule. Principally it consists of a water cooled vacuum container which surrounds a sealed thermionic converter. The main components are a Molybdenum emitter, a (UZr)C radiation heater, a Niobium collector, a Cesium reservoir, and a water cooling jacket formed by two stainless steel tubes.

All parts of the thermionic converter are made of Niobium, except the Molybdenum emitter, the (UZr)C heater, and the high purity alumina insulator. Niobium was chosen because it matches very well the thermal expansion coefficient of the alumina ring, and because it also has a very high melting point ($\sim 2500^{\circ}$C) and a rather low neutron absorption cross section ($\Sigma_a = 0.060$ cm^{-1}). The Molybdenum emitter of 10 mm outer diameter and 27 mm length is radiation heated by an $(UC)_{0.2}(ZrC)_{0.8}$ fuel pin of 6 mm diameter $^{+}$, separated from the emitter by a gap of 1 mm. The lower part of the heater (24 mm long) is 93 % enriched; its depleted upper part (9 mm long) is loosely fixed to a holder by means of a pin. A hole in the bottom of the emitter connects the volumes inside and outside the emitter.

The emitter and the pin holder are supported by the emitter base, isolated from the collector by an alumina ring. The collector surrounds the emitter with a gap of 0.5 mm. A tubular extension at the top of the collector protects the alumina ring against heat radiation. Another extension at the bottom of the collector prevents liquid Cesium from coming into contact with the fuel pin whenever the converter is tilted over. The Cesium reservoir surface is protected against heat radiation from the fuel by a shield.

Two demineralized H_20 circuits cool the irradiation capsule. These are the collector and the emitter cooling circuits. The emitter cooling circuit removes heat which arrives at the emitter base. The collector cooling system cools the remain part of the capsule including heat flowing across the thermal bridge from the collector and also heat from the cesium reservoir.

The Copper cooling tubes and all other Copper parts coming in contact with the demineralized degassed water are Nickel plated in order to prevent corrosion.

The plug, serving as a radiation shield, has the necessary feed-throughs for control of the irradiation capsule and also supports the capsule. By means of an O-ring seal the plug is a vacuum tight closure of the thimble of the reactor, which is filled with Helium.

General instrumentation

The general instrumentation of the test rig consists of the instrumentation directly concerned with the performance of the thermionic converter, the instrumentation of the two water cooling circuit and the system for establishing and controlling the Helium atmosphere inside the thimble.

Fig. 2 shows schematically the electrical instrumentation used to control and investigate the performance of the thermionic converter contained in the irradiation capsule.

$^{+}$ Supplied by General Atomic, San Diego

Six Chromel-Alumel thermocouples with ceramic insulation and stainless steel canning are attached to the wall of the converter. These are : One thermocouple at the emitter base (this thermocouple serves at the same time as probe to measure the electrical potential of the emitter), three thermocouples along the collector (the lower one serves as a probe for the collector potential), one thermocouple at the outside end of the collector bridge and one thermocouple at the Cesium reservoir. The thermocouple voltages are registered on two multi-track recorders, one for the high temperatures, and one for the low temperatures.

In addition to the thermocouples the irradiation capsule contains an electric trimmer heater which is embedded in the wall of the cesium reservoir. The heater consists of a ceramic insulated Ni-Cr wire with Inconel canning.

The emitter and the collector are electrically connected to an outer measuring system by means of the Copper tubes of the two cooling circuits. This measuring system consists essentially of a battery, a voltage divider (using a water cooled stainless steel strip resistance of 0,12 ohms) and a x-y-recorder for registration of the emitter-collector current as a function of the applied voltage.

Fig. 3 is a schematic diagram, showing on the right hand side the two water cooling circuits and the instrumentation which consists of a manometer and two flow meters with regulating valves. On the left is shown the layout of the Helium circuit.

Leak detectors

The test rig contains leak detectors for checking the vacuum tightness of the converter and the wall of the irradiation capsule, and for indicating water leaks in the thimble.

Fig. 4 shows the system for the measurement of the leak tightness of the converter and the wall of the irradiation capsule which serves as secondary containment of the fuel. The leak detector consists of a Tungsten filament which is mounted into the evacuated space between the converter and the capsule, and which is flashed at intervals of 5 minutes to a temperature of about 1900°K in order to measure its saturation electron emission current. A leak in the capsule wall will allow Helium to enter the evacuated space between converter and capsule. The emission current from the tungsten filament will then drop to practically zero in the pressure region above 1 Torr since the Helium cools down the filament. A leak in the converter wall will allow Cesium to enter the space between converter and capsule. The emission current will then increase because of Cesium adsorption on the filament during the cold periods. This Cesium detection is very sensitive.

Experimental operations

The rig was inserted into the reactor the 24. 7. 1963. After making the reactor critical, the power was levelled off at 50 kW. All thermocouples showed response, except the thermocouple in the outer side of the collector bridge.

The reactor power was then increased stepwise to 1 MW. After a stepwise power decrease and a total operating time of 3 hours, the reactor was shut down. At each power level a sufficient time was waited to allow the temperature to come to equilibrium. Temperature data and characteristics of the converter were taken at the different power levels. Fig. 5 shows the current-voltage characteristics at the highest used reactor power of 1 MW.

The test went very smoothly. The only irregularities observed were some short circuit current oscillations with a frequency in the order of 1 c/s when the reactor power was increased from 0. 5 to 0. 72 MW.

Data analysis

The thermal analysis of the observed temperatures was based on the equivalent circuit shown in fig. 6 : The total heat developed in the fuel pin (ϕ_T) is partially transfered to the collector (ϕ_C). In case of an open electrical converter circuit, the rest of the heat goes to the emitter base plate (ϕ_E). Part of ϕ_E flows over the metal ceramic joint to the collector (ϕ_4), the rest goes down to the emitter cooling circuit (ϕ_3). The heat, arriving at the collector flows down across the collector bridge (ϕ_1) or to the Cesium reservoir (ϕ_2) and then to the collector cooling circuit.

Calculating the different thermal resistances of the circuit and correcting for gamma heating (which is supposed to be proportional to the reactor power N, with a value of 1 W/g at N=5 MW) one finds

$$\phi_1 = 0.91 \quad (\mathrm{W/^oC})(T_{CM} - T_{H_2O}) - 11.83 \times 10^{-6} N \qquad (1)$$

$$\phi_2 = 0.085 \quad (\mathrm{W/^oC})(T_{CL} - T_{Cs}) - 1.56 \times 10^{-6} N \qquad (2)$$

$$\phi_3 = 0.22 \quad (\mathrm{W/^oC})(T_{EB} - T_{H_2O}) - 8.53 \times 10^{-6} N \qquad (3)$$

$$\phi_4 = 0.078 \quad (\mathrm{W/^oC})(T_{EB} - T_{CU}) \qquad (4)$$

The different temperatures T_{EB} (emitter base), T_{CU} (collector, upper side), T_{CM} (collector middle), T_{CL} (collector, lower side) and T_{Cs} (Cesium reservoir), which were measured by the thermocouples, are plotted against the reactor power in fig. 7.

Then according to fig. 6

$$\phi_C = \phi_1 + \phi_2 - \phi_4 \qquad (5)$$

$$\phi_E = \phi_3 + \phi_4 \qquad (6)$$

$$\phi_T = \phi_C + \phi_E \qquad (7)$$

Using the temperatures from fig. 7, one can calculate ϕ_C, ϕ_E and ϕ_T. These values are shown in fig. 8 as functions of reactor power.

The average open circuit emitter temperature T_E can be determined from ϕ_C, supposing that only the thick walled part of the emitter radiates, and neglecting heat conduction through the Cesium vapour. Then

$$T_E = \left[\phi_C \frac{1 + \frac{r_E}{r_C} \epsilon_E \left(\frac{1}{\epsilon_C} - 1\right)}{F \epsilon_E \sigma} + T_C^4 \right]^{1/4} \qquad (8)$$

where r_E = outer radius of emitter, r_C = inner radius of collector, ϵ_E and ϵ_C = total thermal emissivity of emitter and collector, F = radiating emitter surface, σ = Stefan-Boltzmann constant and T_C = average collector temperature. The ϕ_C can be taken from fig. 8. Neglecting T_C^4 and taking for ϵ_E and ϵ_C the total emissivities of clean Molybdenum and Niobium at the temperature T_E [6] one obtains the emitter temperature which has been plotted in fig. 8 versus the reactor power.

The emitter temperature T_E increases at first sharply with reactor power and flattens then off, as soon as radiative cooling becomes significant. At a reactor power of 1 MW the emitter temperature reached 2025°C. This value corresponds well to the emitter temperature which can be calculated from the observed open circuit voltage (2.9 V) of the converter [7] . The observed emission current at 1 MW (see fig. 5), however, is about a factor of 10 higher than the saturation current of pure Molybdenum. It is supposed that the emitter was covered with Oxygen so that in spite of the low Cesium pressure some Cesium adsorption took place, which would have been impossible on pure Molybdenum under these conditions [8] .

The total heat generation ϕ_T varies fairly linear with the reactor power, as one should suppose it to do. At low reactor power the emitter temperature T_E is too low for radiative heat transfer to the collector. Nearly all the heat therefore flows down to the emitter base (ϕ_E), causing there the observed rapid temperature increase (curve T_{EB} in fig. 7). At higher reactor powers the greater proportion of the generated heat is radiated to the collector (ϕ_C).

It is remarkable that the heat loss to the emitter base (ϕ_E) - which is difficult to calculate - increases much slower than the temperature difference between emitter (T_E) and emitter base (T_{EB}). At low emitter temperatures the heat loss corresponds to what one would expect from calculation of the thermal resistances between the emitter base on one side and the emitter and the fuel pin on the other side [+]. At high emitter temperatures, however, the heat current to the emitter base is much smaller than one would expect from such a calculation. This is probably due to the fact that an important amount of heat is lost from the emitter stem by radiation to the collector.

At 1 MW reactor power the total heat generation was 265 W. Due to the failure of the Cesium heater and the resulting too low Cesium temperatures no high electrical output could be obtained.

Conclusions

The construction in general seems well suited to the needs of an experimental thermionic converter. It permits a rather detailed thermal analysis of the converter and direct determination of its efficiency without post-irradiation examination or flux measurements. Furthermore, the double containment with the possibility of checking the vacuum tightness of the walls separately during operation offers a high degree of safety.

The high temperature resistant all-Niobium-Alumina construction of the converter wall made it necessary to develop appropriate high vacuum assembly techniques. The smooth run of the test speaks well for the methods employed, though, however, only life tests will give a final answer to this point.

Aknowledgements

This work was performed in the Direct Conversion Group of Ispra which is under the direction of Dr. H. Neu. The assistance of all concerned in the project is gratefully acknowledged. The authors are specially indepted to Mr. C. Cappelletti and Mr. J.M. Bouillet, who assembled the rig, and to Mr. F. Geiger, who cared for the electrical instrumentation.

The authors furthermore wish to express their gratitude to the people of the Central Workshop of the Ispra center for their precise and fast machining job, and to the helpful staff of the reactor Ispra I, which was open minded to all wishes.

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[+] A major uncertainty in this calculation is the loose fit of the fuel pin in its holder.

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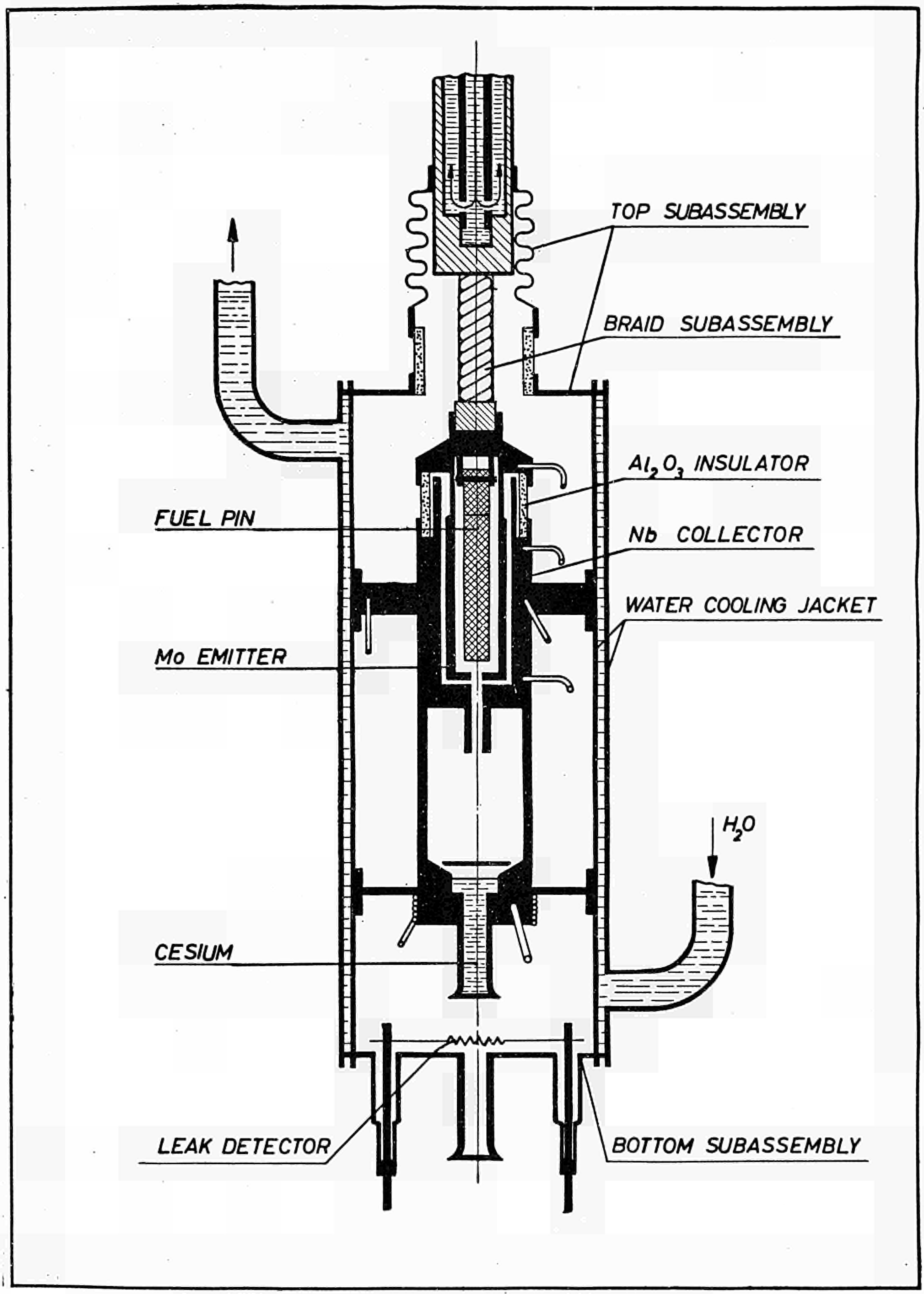

FIG. 1. IRRADIATION CAPSULE (simplified)

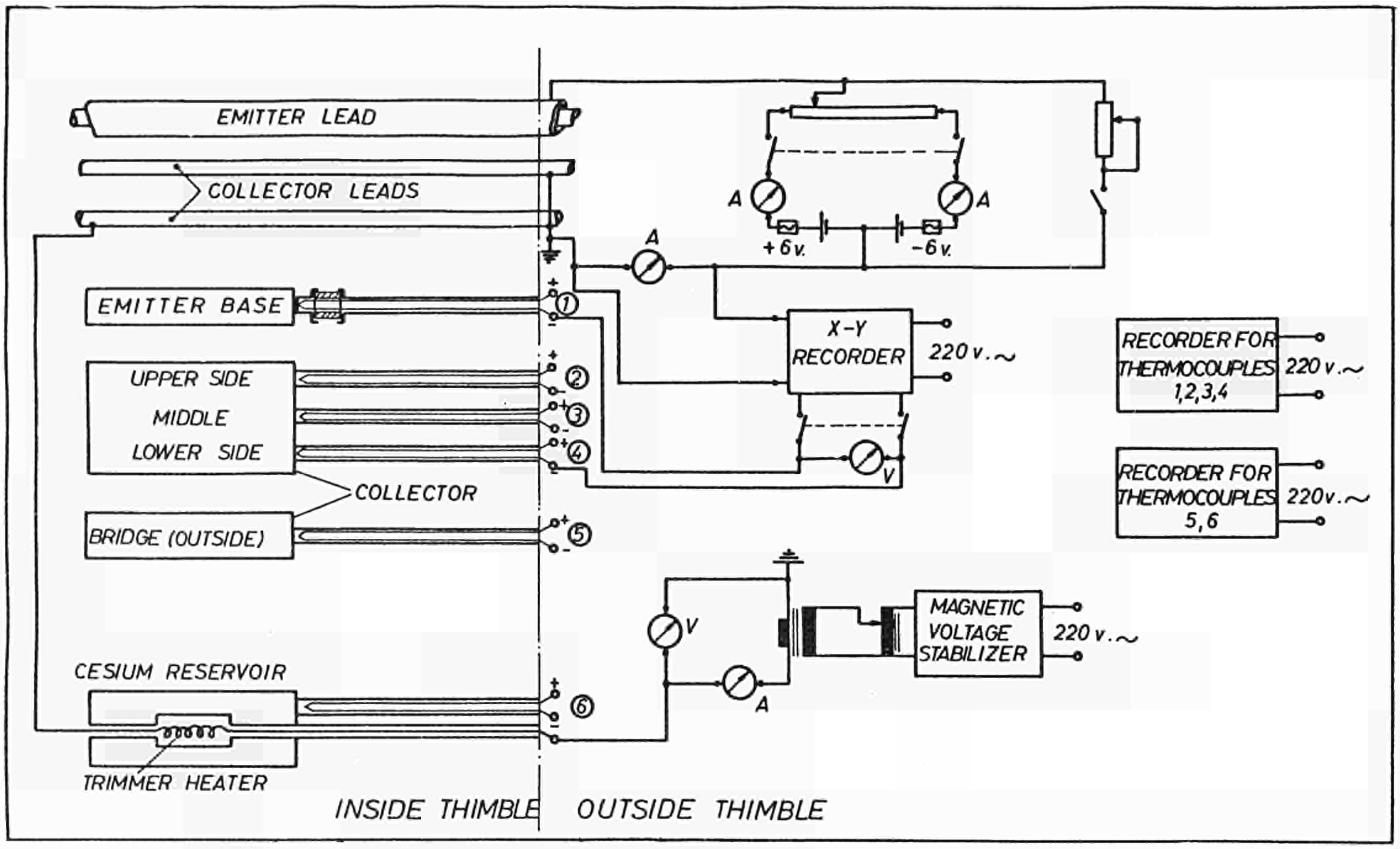

FIG. 2. CONVERTER INSTRUMENTATION

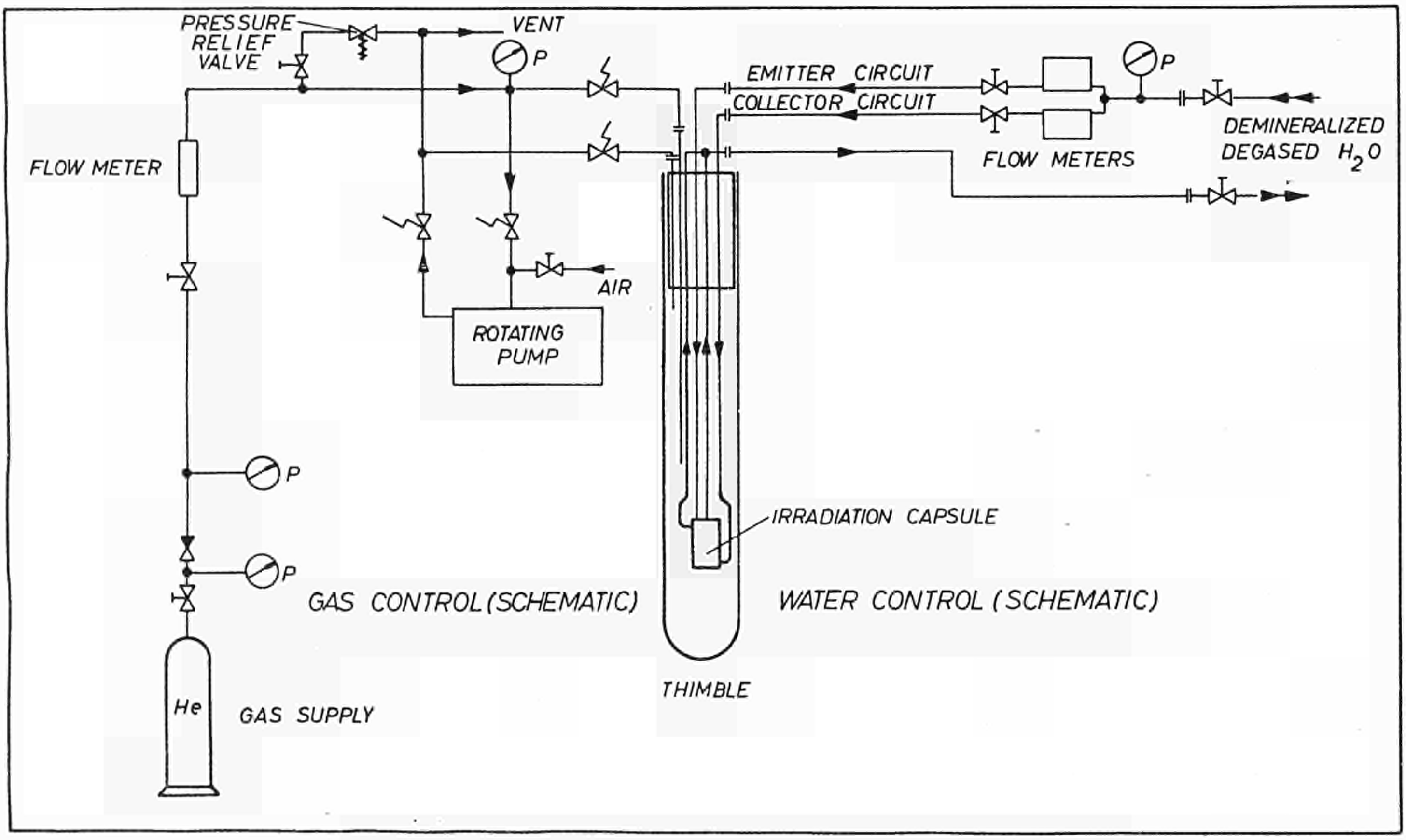

FIG. 3. WATER AND GAS CONTROL SYSTEM

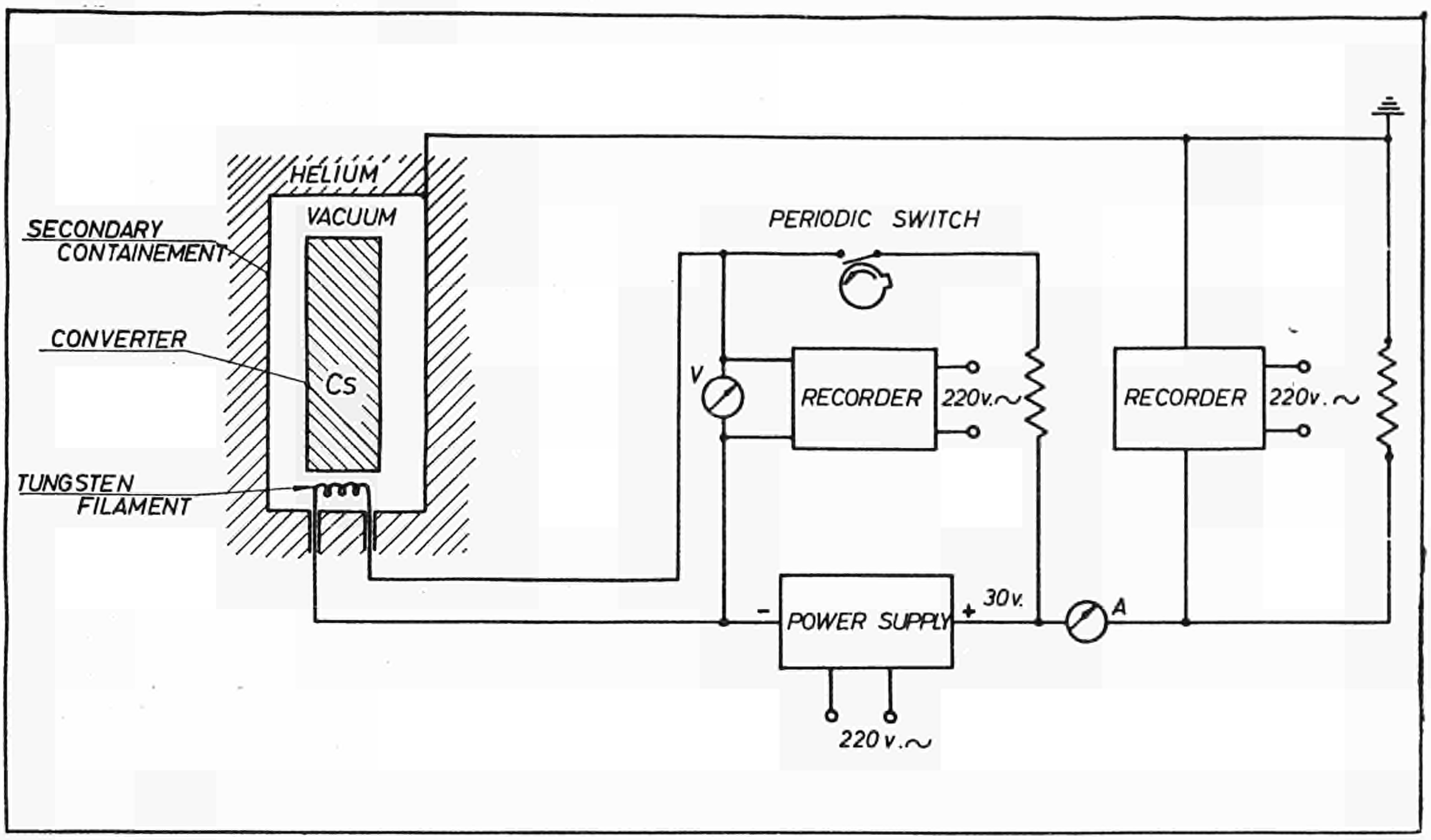

FIG. 4. CESIUM-HELIUM LEAK DETECTOR

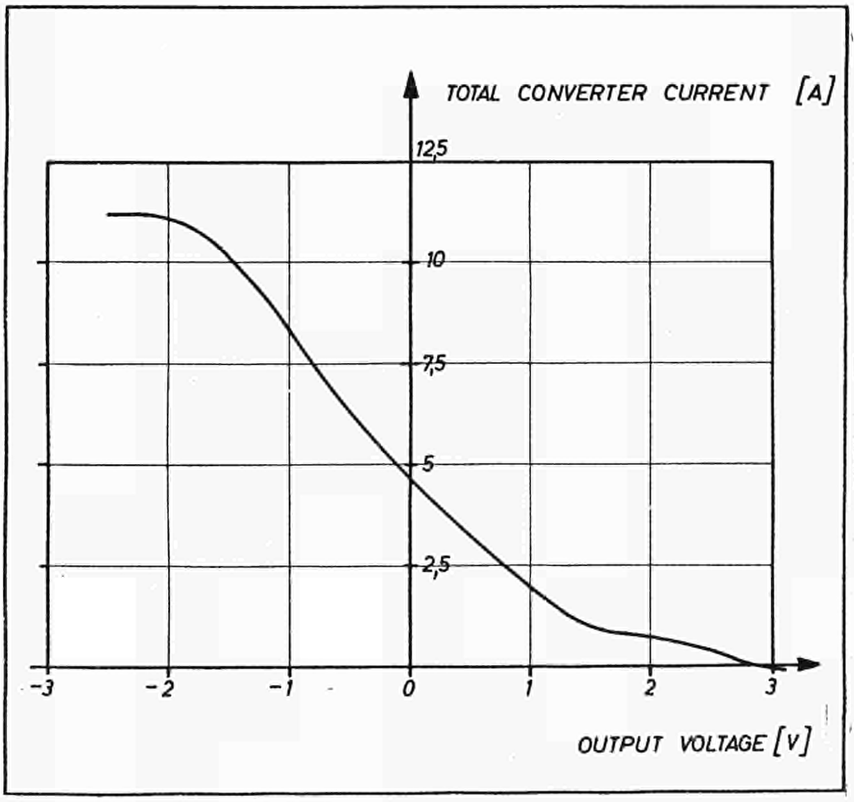

FIG. 5. VOLTAGE CURRENT CHARACTERISTIC (reactor power 1 MW, Cesium temperature 177°C)

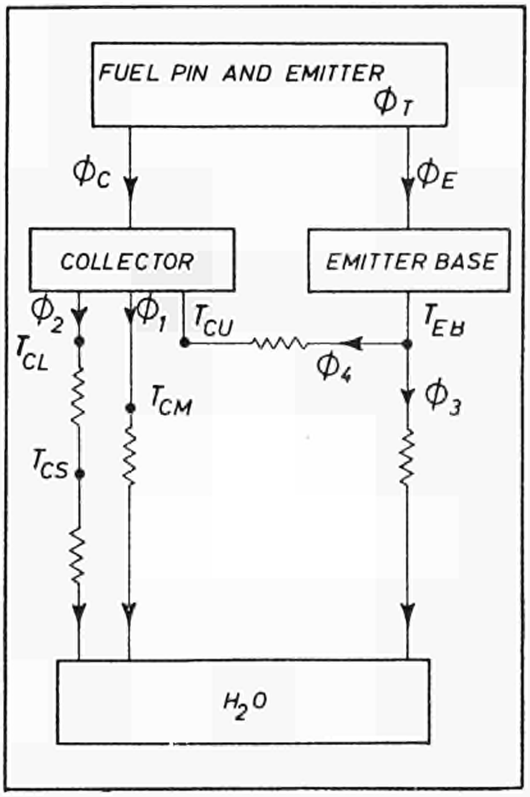

FIG. 6. THERMAL EQUIVALENT CIRCUIT OF THERMIONIC CONVERTER

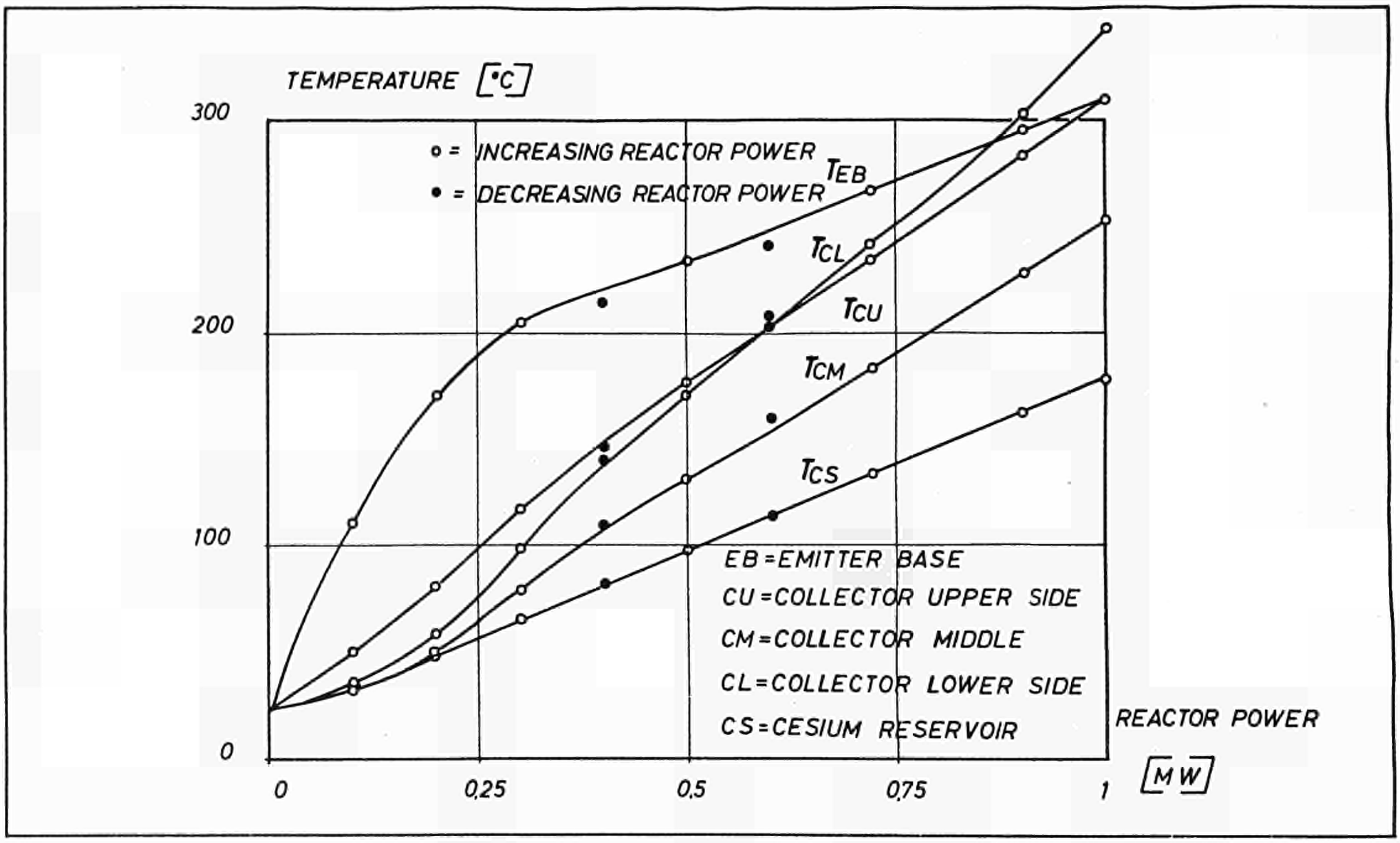

FIG. 7. OBSERVED TEMPERATURES VS. REACTOR POWER (open circuit)

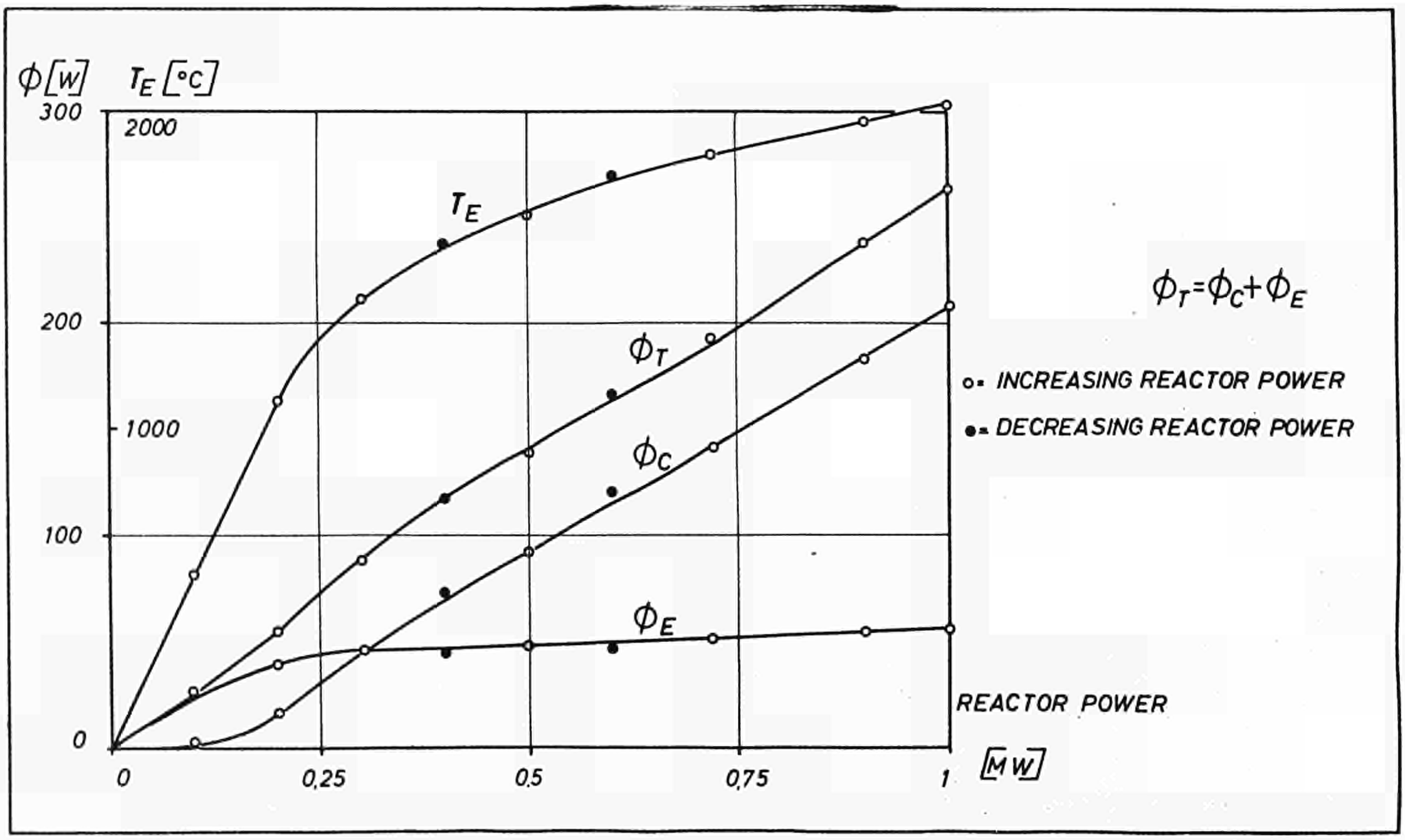

FIG. 8. HEAT FLOW AND EMITTER TEMPERATURE VS. REACTOR POWER (open circuit)