Calibration of the Failed-Fuel-Element Detection Systems in the Ågesta Reactor

O. Strinshag
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ABSTRACT

Results from a calibration of the systems for detection of fuel element ruptures in the Ågesta reactor are presented. The calibration was carried out by means of foils of zirconium-uranium alloy which were placed in a special fuel assembly. The release of fission products from these foils is due mainly to recoil and can be accurately calculated. Before the foils were used in the reactor their corrosion behaviour in high temperature water was investigated.

The results obtained with the precipitator systems for bulk detection and localization are in good agreement with the expected performance. The sensitivity of these systems was found to be high enough for detection and localization of small defects of pin-hole type ($\nu = 10^{-8} \text{s}^{-1}$). The general performance of the systems was satisfactory during the calibration tests, although a few adjustments are desirable.

A bulk detecting system for monitoring of activities in the moderator, in which the $\gamma$-radiation from coolant samples is measured directly after an ion exchanger, showed lower sensitivity than expected from calculations. It seems that the sensitivity of the latter system has to be improved to admit the detection of small defects. In the ion exchanger system, and to some extent in the precipitator systems, the background from $^{41}$Am in the coolant limits the sensitivity.

The calibration technique utilized seems to be of great advantage when investigating the performance of failed-fuel-element detection systems.

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1. INTRODUCTION

The estimation of sensitivity and general performance of failed-fuel-element detection systems is often an involved procedure both theoretically and experimentally. This is due to the many different factors which influence the performance and to the great number of isotopes which have to be taken into consideration.

Among the important factors which determine the sensitivity are efficiency of sampling, sample transport time, leakage and mixing in tube systems, deposition of fission products in tubes and containers, efficiency of detector arrangement and the influence of background. When electrostatic precipitators together with gas scrubbers are used, for detection in water-cooled reactors, the efficiencies of these units have to be considered as well as, for instance, the vapour content in the gas entering the precipitator. Although the influence of most of the mentioned factors, separately, can be determined quite accurately, the need for an experimental investigation of the total efficiency of a failed-fuel-element detection system under actual working conditions is obvious. However, it is felt that the sensitivity of such systems in many cases is known only very roughly, as hardly any simple method of carrying out a calibration is available.

The detection systems in the Ågesta reactor respond to the activity from the fission gases krypton and xenon and their daughter products. That means that, for a calibration, known quantities of these gases have to be introduced into the coolant. The method chosen for the Ågesta reactor systems implies that foils of zirconium-uranium alloy are inserted between the rods of a special fuel assembly. The foils come into direct contact with the coolant water and the fission products are released to the water mainly through recoil. By comparing the calculated and measured count rates due to the release from these foils the total efficiencies of the detection systems can be found. The response to various types of cladding defects and to uranium surface contamination can then be estimated. The calibration method in question also has the advantage of allowing a functional analysis of the system for localization of ruptures. It is, for instance, possible to investigate the mixing of samples in that system.
A sensitive system for failed-fuel-element detection is important if the system is going to be used for studies of the release from small defects or for determination of surface contamination. The system then serves as a complement to radiochemical analysis of the fission product concentration in the coolant. For these analytical purposes it is desirable to have a failed-fuel-element detection system with accurately known sensitivity. On the other hand a knowledge of the total sensitivity within a factor of two might be satisfactory if only the setting of alarm levels is concerned.

2. CALIBRATION TECHNIQUE

The sensitivity of a system for failed-fuel-element detection is preferably referred to the count rate increase obtained for the activity release from a cladding defect of specified size. The detection systems could therefore be tested by means of fuel rods with defects, for instance in the form of drilled holes. The release from defective $\text{UO}_2$ elements depends on several parameters such as fuel temperature, fuel density and dimensions of pellets and rods. As the influence of all these parameters on the release of fission products is not very accurately known, a defective fuel rod is unsuitable for calibration of a detection system. If, instead, thin uranium foils, or foils of some material containing uranium, are used for the calibration, the release of fission products can be estimated with satisfactory accuracy, as recoil ranges are well established for several materials.

When selecting a foil material for the calibration in the Ågesta reactor, the corrosion behaviour of the material in high-temperature water has to be regarded. The erosion of uranium from the foil to the coolant water has also to be low to avoid uranium contamination of the primary circuit. The mechanical properties of the material should, of course, be good enough to allow the foils to be placed in the coolant stream. Taking also availability into consideration foils of zirconium-uranium alloy containing 10% by weight of natural uranium were chosen. This alloy was delivered by the American company Metals and Control Inc.
2.1 Design of foil holder

In a special fuel assembly, called FII assembly, it is possible to place up to eight foil holders in slits in the shroud tube (two slits in each section). The FII assembly has previously been utilized for reactor physics experiments. The foil holders used for the physics experiments were made of two Zircaloy-2 plates of thickness 0.7 mm. A similar design was chosen in our case, i.e. two zirconium-uranium plates of thickness 0.7 mm bolted together and to a holder of Zircaloy-2 constitute the calibration foil (Fig. 1). Thus the existing manipulator for loading and unloading of foil holders could be used. Fig. 2 shows a calibration foil in position in the FII assembly.

The total area of the Zr/U foils in contact with the coolant is 137 cm$^2$. According to preliminary calculations it was expected that at least two such calibration foils would be needed to get satisfactory count rates. Four calibration foils were therefore produced and tested in a pressurized water loop at a temperature of 250 °C and a water flow of 4.5 kg/s, the same flow as in peripheral fuel assemblies in the reactor. Three of the calibration foils were tested in 10 days, one in 30 days. (The latter foil was not used in the reactor experiments.) No mechanical defects could be seen on the foils after these loop tests.

2.2 Corrosion of Zr/U foils

The corrosion behaviour of zirconium-uranium alloys in high-temperature water has been extensively studied by several authors [1, 2]. Results at different water and steam temperatures for alloys containing up to 60 weight percent uranium have been reported. As known, these alloys represent an important fuel material in water-cooled reactors.

For the calibration purpose in question the corrosion behaviour of the foils is of interest for two reasons. Firstly the oxide film produced should be adherent. If the film flakes off, this certainly means that some quantity of uranium will be released to the coolant. Secondly the growth of an oxide film influences the recoil of fission fragments from the foil surface. Due to the uranium content of this film
**Fig. 1** Calibration foil with holder.

**Fig. 2** Cross section of FII assembly with calibration foil.
the emission of fission fragments from the foils can either be increased or decreased.

Several autoclave tests were carried out to investigate the corrosion resistance of the zirconium-uranium foils. For the corrosion tests small pieces (about 4 cm$^2$) of the 0.7 mm thick foil were used. It has been reported that a suitable heat treatment can improve the corrosion resistance of zirconium-uranium alloys considerably [2]. Such a tendency was also found in one of our experiments carried out at 400 °C steam temperature. Two plates which were heat-treated at 850 °C in helium atmosphere and oil-quenched showed after 12 hours weight increases of 36 and 62 mg/dm$^2$, respectively. A non-heat-treated plate showed after the same time at 400 °C a weight decrease of 35 mg/dm$^2$. A weight decrease is, for the application in question, more disadvantageous than a weight increase. Autoclave tests at 250 °C, however, showed weight gains both for heat-treated and non-heat-treated plates. It was therefore decided to omit the heat treatment of the final calibration foils, particularly as the mechanical properties of the foils could be expected to be unfavourably influenced by a heat treatment.

The weight gain of the calibration foils together with the holders was investigated during the loop test mentioned in Sec. 2.1. In Tab. 1 the weight gain and original total weight of the calibration foils with holders are given. As follows from this table, the four calibration foils show up about the same behaviour and the corrosion resistance can be regarded as satisfactory. The underlined values are the most accurate ones, as these values refer to weighings carried out after the foils had been dried for 20 h at 150 °C. (The water content between the riveted pieces ought then to be negligible.)
Tab. 1 Weight changes of the calibration foils with holders during a loop test at 250 °C water temperature. Underlined values refer to weightings after drying (20 h at 150 °C).

<table>
<thead>
<tr>
<th>Cal. foil No.</th>
<th>Original weight with holder (g)</th>
<th>Weight gain (mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1d</td>
</tr>
<tr>
<td>1</td>
<td>70.2898</td>
<td>35.4</td>
</tr>
<tr>
<td>2</td>
<td>69.2452</td>
<td>41.1</td>
</tr>
<tr>
<td>3</td>
<td>70.1597</td>
<td>60.0</td>
</tr>
<tr>
<td>4</td>
<td>70.2198</td>
<td>56.5</td>
</tr>
</tbody>
</table>

During the loop test of the foils the amount of uranium in the water was also investigated. The values were in general very low (≤ 0.5 μg uranium per litre).

When placing the calibration foils inside a reactor the corrosion resistance is strongly affected by the neutron and fission fragment bombardment of the foil surface. As no data of the corrosion of zirconium-uranium alloys during irradiation were available, the influence of irradiation had to be estimated from data valid for Zircaloy-2. At full reactor power (65 MW) an increase of the corrosion rate of about 15 times can be estimated from these data [3]. However, the whole calibration experiment was expected to be performed at an irradiation dose corresponding to less than 2 h at 65 MW. Thus the high corrosion rate during irradiation was not regarded as serious.

2.3 Fission product release from Zr/U foils

The reason for choosing thin foils containing uranium as the "fission product source" is that the release might be assumed to arise from a single and accurately known process, i.e. recoil. Other mechanisms by which fission products can be released from such a foil are erosion of the foil material, release through pores and
cracks, knockout of fission products at rest and diffusion. Release by recoil and diffusion will be discussed below. The other release mechanisms are difficult to estimate but are expected to be negligible. As a matter of fact experimental recoil ranges in zirconium have been determined under the same assumption [4].

It is convenient to compare the release of fission products from the calibration foils with the release from uranium surface contamination in the reactor. At steady state conditions the rate of release of a fission product, \( r_s \), due to surface contamination can be written

\[
r_s = \frac{1}{2} F m_c y_i
\]

where \( F \) = number of fissions/s per gram uranium, \( m_c \) = surface contamination (gram uranium) and \( y_i \) fission yield of isotope \( i \).

From a foil with thickness much greater than the recoil range, the release rate follows from

\[
r_f = \frac{1}{4} C_f S R y_i
\]

where \( C_f \) = concentration of uranium, \( S \) = total foil surface and \( R \) = range of fission fragments in the material. The release from the calibration foil therefore corresponds to an equivalent surface contamination, \( m_f \), given by

\[
m_f = \frac{1}{2} C_f S R
\]

The recoil range of fission fragments has been experimentally determined for zirconium as well as for many other materials [4]. Ranges vary with the mass of the fragment and have to be given separately for the group of light fragments and the group of heavy fragments. In our case mass numbers 87 - 92 and 137 - 140 are of interest. The range of a fragment with initial energy \( E \) (MeV) can be calculated by means of the empirical equation

\[
R/E^{2/3} = 0.0391 + 0.0202 A/Z^{1/2}
\]
where the range is given in mg/cm$^2$ [5]. ($A =$ atomic weight and $Z =$ atomic number of the foil material.) The ranges in zirconium found experimentally are in good agreement with Eq. (4). According to this equation the recoil ranges in the Zr/U foil are 7.26 mg/cm$^2$ for light fragments ($A = 89$) and 5.68 mg/cm$^2$ for heavy fragments ($A = 138$). The value of $A/Z^{1/2}$ has then been calculated according to the rule given in Ref. [5]. Using this range values it is found that the calibration foil, which has a total surface area of 137 cm$^2$, corresponds to 49.8 mg of natural uranium in the form of surface contamination when light fragments are concerned, and to 39.0 mg when heavy fragments are concerned.

The relative release of fission products by diffusion is largest in the case of long-lived isotopes. The most long-lived isotope to be considered here is Kr$^{88}$. The concentration in the coolant of this isotope due to recoil and due to diffusion will therefore be estimated. According to Eq. (2) and Ref. [6] the ratio between the concentration from diffusion, $C_d$, to that from recoil, $C_r$, can be written

$$\frac{C_d}{C_r} = \frac{4 \rho}{R(1-e^{-\lambda t})} \left( \frac{D}{\lambda} \right)^{1/2} F(A, \lambda, t)$$

where

$$F(A, \lambda, t) = (1-e^{-\lambda t}) \tanh \frac{A}{2} - 2A^3e^{-\lambda t} \sum_{n=1}^{\infty} \frac{1}{n^2} \frac{\cos n\lambda}{\lambda^n} \left( 1 - e^{-\frac{n^2 \pi^2 \lambda t}{A^2}} \right)$$

$A = a(D)^{1/2}$

$a =$ thickness of foil
$\lambda =$ decay constant,
$D =$ diffusion coefficient
$\rho =$ density of the material
$t =$ time of irradiation

The ratio between the concentrations of Kr$^{88}$ after one hour of irradiation is found to be $1.88 \cdot 10^{-4}$ using a diffusion coefficient of $10^{-18}$ cm$^2$/s at the temperature 220 °C (temperature of reactor coolant). This diffusion coefficient is valid for uranium and the coefficient
for the Zr/U foil might be considerably higher. Anyhow the contribution from diffusion can be regarded as negligible when calculating the release from the foils.

The influence of corrosion on the release of fission products from the calibration foils was studied by means of a fission chamber. Small pieces (about 4 cm²) of the Zr/U foil were measured before and after autoclave tests. Tab. 2 shows the relative release from the Zr/U plates compared to a thin uranium standard (0.1099 mg nat. uranium). The autoclave tests were carried out at a water temperature of 250 °C and went on for 10, 15 and 20 days, respectively. It is obvious that the corrosion of the foils decreases the release of fission products considerably.

During the two calibration tests the calibration foils were in contact with the reactor coolant for 2 - 4 days before the calibration started. Taking also the loop test (10 days at a water temperature of 250 °C) into consideration, the release from the calibration foils can from the values given in Tab. 2 be estimated to have decreased to about 82 % of the original. This means that for the light fragments the calibration foils correspond to 40.8 mg natural uranium in the form of surface contamination, and for the heavy fragments to 32.0 mg.

<table>
<thead>
<tr>
<th>Foil No.</th>
<th>Release compared to standard (rel. value)</th>
<th>Release in per cent of original</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before autoclave test</td>
<td>After autoclave test</td>
</tr>
<tr>
<td>3²</td>
<td>3.95</td>
<td>3.35 (10 days)</td>
</tr>
<tr>
<td>3³</td>
<td>4.01</td>
<td>3.29 (15 days)</td>
</tr>
<tr>
<td>3⁴</td>
<td>4.31</td>
<td>2.90 (20 days)</td>
</tr>
</tbody>
</table>

Tab. 2 Influence of corrosion on release of fission products from Zr/U foils according to fission chamber measurements. Water temperature = 250 °C.
The emission of fission fragments from the Zr/U plates is, compared to the emission from the standard, considerably lower than expected from Eq. (3). This deviation is probably instrumental and due to the fact that the average energy of fragments from the Zr/U plates is lower than that of fragments from the standard. In a later experiment a platinum foil was used for catching the fragments [4]. The emission from the Zr/U foil was then in good agreement with the expected value. (Collected activity of La$^{140}$ was measured.)

3. SHORT DESCRIPTION OF THE DETECTION SYSTEMS

For detection and localization of failed-fuel-elements in the Ågesta reactor five channels with electrostatic precipitators are used, three for detection and two for localization. During the construction and installation of the precipitator systems several reports were written about the design and expected performance of these systems [7,8]. The precipitator systems will therefore be described only very briefly in this report.

A fission product monitoring system utilizing an ion exchanger was later installed (autumn 1964). The activity in this system is measured by means of three scintillation counters.

3.1 Precipitator systems

Water samples to the precipitator systems are taken from each of the 140 fuel assemblies. Samples of about 70 cm$^3$/s from the coolant outlet at the top of assemblies are distributed to the two localizing systems and the three bulk detection systems (Fig. 3).

One of the localization systems, the L1 system, is sequentially connected to each of the sample lines by means of solenoid valves. The other localization system, the L6 system, gets water samples from a group of six primary lines. The bulk detecting systems T1, T2 and T3 get water samples from 47, 46 and 47 primary sample lines, respectively. Four lines, one from the T1, two from the T2 and one from the T3 system are connected to the L1 system (not shown in Fig. 3). The L1 system accordingly has 144 inlet tubes. The L6 system is sequentially connected to 24 six-line groups.
Fig. 3 Block diagram of precipitator systems.
After cooling and pressure reduction the water samples in the various systems pass a scrubber where fission gases are removed from the water stream. Nitrogen stored in the expansion tanks is used as scrubber gas. The gas flow passing the scrubber (about 35 cm$^3$/s) is mixed with dry nitrogen and the total gas flow (about 900 cm$^3$/s) goes to the precipitators. The precipitators have a chamber volume of 4000 cm$^3$ and are of the tape type, delivered by the English company Salford Electrical Instruments Ltd. In the precipitator chamber the solid daughters of the fission gases are electrostatically collected on the metal tape which moves stepwise to a scintillation detector. Both the precipitator chamber and the scintillator are placed inside a pressure vessel and, to prevent active gases reaching the detector directly, a small purge gas flow enters near the detector position. The detector pulses in the various systems are counted by means of integrating rate meters connected to recorders. The L1 system has digital print-out.

The programming unit controls valve operation, tape transport, precipitator voltage and the rate meter operation (start, stop, read-out and reset). Water samples are taken every 30 seconds in each of the systems. The total measuring cycle in the L1 system is then 72 minutes. In the T system the connections between sampling lines and measuring channels are automatically permuted and the rate meter outputs are coupled to difference discriminators. If the difference in count rates between two channels exceeds the alarm level, a signal is given to one of the memory units. The reactor is shut down if two such signals are obtained in one of the memories within three measuring periods (one measuring period = 30 s).

3.2 Ion exchanger system

The ion exchanger system is used for bulk monitoring in the main coolant flow. A sampling flow of about 20 kg/h is taken from the purification system after the main ion exchangers (Fig. 4). The fission product monitor consists of a small ion exchanger and three $\gamma$-sensitive scintillation counters viewing a sample container with a volume of 100 cm$^3$. The mixed bed ion exchanger collects most of the activities in the water and, as the transport time from reactor
Fig. 4 Block diagram of ion exchanger system. Only one of the three scintillation counters is shown.
to monitor is about 10 minutes, only relatively long-lived background isotopes have to be considered.

The main background contribution is from $^{41}A$ with a $\gamma$-energy of 1.3 MeV. As the single channel analysers only count gammas in the energy region 1.9 - 2.5 MeV, the contribution from $^{41}A$ is eliminated provided that pile-up effects are negligible. Of the fission products only the long-lived gases reach the detector. In the energy region 1.9 - 2.5 MeV only the krypton isotopes $^{87}Kr$, $^{88}Kr$, and $^{89}Kr$ have to be taken into account. (Some of the fission gas daughter products also have $\gamma$-energies in the energy region in question, but their count rate contribution is small.)

The single channel analysers are connected to trip units which are coupled in a two-out-of-three connection. Too high activity in this system results in shut-down of the reactor. The ion exchanger system is in this report referred to as the T0 system.

4. EXPECTED PERFORMANCE

As mentioned, the purpose of calibrating the detection systems was to determine the total efficiencies and to control the function of the systems in general. By comparing the calculated response to that measured, in channels with and without calibration foils, most details concerning the performance of the various systems are found. Although the relative amounts of short-lived and long-lived fission gases, released from the foils and from defects, are different, the calibration test gives the desired information for estimation of the response of the systems to cladding defects. The expected response to defects of pin-hole type is calculated here, whereas also other types of defects were regarded in previous reports [7, 8].

4.1 Calculation of count rates

For the precipitator systems the count rates are related to the concentration of fission gases at the outlet from fuel assemblies. The krypton and xenon isotopes which have to be taken into account are $^{87}Kr$, $^{89}Kr$, $^{90}Kr$, $^{91}Kr$, $^{92}Kr$, $^{137}Xe$, $^{138}Xe$, $^{139}Xe$, and $^{140}Xe$. The count rates in the ion exchanger system are related to the concentration of the krypton isotopes $^{87}Kr$, $^{88}Kr$, and $^{89}Kr$ in the moderator.
The concentration of the fission gases mentioned is calculated for three cases, i.e. normal conditions, during calibration and for one pin-hole present. During normal conditions the count rate is due both to background (background radiation and non-fission products in the water) and to uranium surface contamination. The factor which determines the relation between concentration and count rate, or number of counts per measuring period, has to be calculated separately for each of the fission gases.

a) Normal conditions

The concentration of a fission product in the moderator, \( C_o \), and at the outlet from a fuel assembly, \( C_e \), can at equilibrium be written

\[
C_o = \frac{1}{2} \bar{F} m_c \gamma_i / \lambda_i \nu
\]

and

\[
C_e = C_o + \frac{1}{2} \bar{F} m_c \gamma_i / n w_e
\]

where

- \( \bar{F} \) = number of fissions/s per gram uranium (\( F = \bar{F} \) at average neutron flux \( \bar{\phi} \))
- \( m_c \) = surface contamination in grams
- \( \lambda_i \) = decay constant of isotope i (fission gas)
- \( \gamma_i \) = fission yield of isotope i (cumulative)
- \( \nu \) = total circulating water volume
- \( w_e \) = coolant flow through assemblies
- \( n \) = number of assemblies in the reactor.

It is then assumed that the fission products are perfectly mixed in the moderator and that they do not escape from the primary coolant. The decay during the transport in the fuel assembly is neglected. The concentration \( C_e \) is given for an assembly with average neutron flux and coolant flow.
b) During calibration

If a calibration foil, equivalent to a surface contamination \( m_f \), is placed in a fuel assembly with neutron flux \( \Phi \) and water flow \( w_e \), the concentrations at equilibrium follow from

\[
C_o = \frac{1}{2} F y_i \left( m_c + m_f \frac{\Phi}{\Phi} \right) / (\lambda_i V)
\]

and

\[
C_e = C_o + \frac{1}{2} F m y_i / (n \overline{w_e}) \quad \text{(channel without foil)}
\]

\[
= C_o + \frac{1}{2} F (m_c / n + m_f) y_i \frac{\Phi}{(\overline{\Phi} w_e)} \quad \text{(channel with foil)}
\]

\[ (8) \]

\[ (9) \]

c) One pin-hole

The release from defects of pin-hole type is usually assumed to be determined by an escape rate coefficient \( \nu \), which either is a constant or proportional to the square root of the decay constant \([9, 10]\). A better description of the release mechanism ought to be attained by combining these two processes.

The assumption made in our case is that the escape rate coefficient is constant and equal to \( 10^{-8} \text{s}^{-1} \). The number of released atoms/s, \( N_i \), of an isotope \( i \) can then, at equilibrium, be written

\[
N_i = \frac{\nu}{\nu + \lambda_i} F m_r y_i
\]

\[ (10) \]

where \( m_r \) = quantity of uranium in one rod (gram).

It is clear from Eq. (10) that the release from pin-holes is dominated by long-lived isotopes. For most of the fission gases of interest \( \lambda_i \gg \nu \) and therefore \( N_i \) becomes proportional to \( 1/\lambda \).

The concentrations at equilibrium in the case of one defect of pin-hole type, in a fuel assembly with neutron flux \( \overline{\Phi} \) and water flow \( \overline{w_e} \), then follow from

\[
C_o = F y_i \left( m_c / 2 + \frac{\nu}{\nu + \lambda_i} m_r \right) / (\lambda_i V)
\]

\[ (11) \]
and
\[ C_e = C_o + \frac{1}{2} \bar{F} m_C y_i/(n w_e) \text{ (channel without pin-hole)} \]
\[ = C_o + \frac{1}{2} \bar{F} y_i (m_C/n + \frac{v}{v + \lambda_i} m_p)/w_e \text{ (channel with pin-hole)} \]  \hspace{1cm} (12)

The factor which gives the count rate as a function of \( C_o \) or \( C_e \) will now be calculated. In the following this factor will be referred to as the \( f(\lambda) \) factor. For the precipitator channels the number of counts, \( S_c \), during the measuring time is given by
\[ S_c = \sum_{i=1}^{g} (C_{e_i}) f_1(\lambda_{i}) \]  \hspace{1cm} (13)

The following notations are used when deriving the \( f(\lambda) \) factor:
- \( \lambda_k \) = decay constant of a fission gas daughter isotope \( k \)
- \( t_d \) = total transport time between fuel assembly and precipitator
- \( t_p \) = precipitation time
- \( t_w \) = delay time between the end of precipitation and start of counting
- \( t_m \) = measuring time (counting time)
- \( t_g = V_g/w_g \)
- \( w_s \) = water flow to scrubber
- \( w_g \) = gas flow to precipitator
- \( V_p \) = precipitator volume.

The number of atoms, \( N_w \), on the metal tape at the end of precipitation follows from
\[ N_w = \frac{\lambda}{\lambda_k} w_s C_e \frac{t_g}{\lambda_i t_g + 1} (1 - e^{-\lambda_k t_p}) e^{-\lambda_i t_d} \]  \hspace{1cm} (14)

The efficiency of scrubber and precipitator are then assumed to be 100%. The total transport time is made up of several transport times, which are all regarded as pure delay times (no mixing). Also
the transport through the scrubber is taken into account as a pure de-
lay process. Anyhow the transport time through the scrubber is short
compared to other transport times.

In the derivation of Eq. (14) it was assumed that the concentra-
tion of daughter products is zero at the start of precipitation. If this
concentration is not negligible, a correction term has to be applied
according to

$$\Delta N_w = C_p(o)e^{-\lambda t_p}$$  \hspace{1cm} (15)

where $C_p(o)$ is the concentration of daughter products in the pre-
cipitator gas volume at the start of precipitation. At first this cor-
rection will be disregarded (compare Sec. 5.1). The assumption is
also made that the second daughters, Sr and Ba, collected on the
tape give a negligible count rate.

By integration over the measuring time $t_m$ and assuming that
the counting is started a time $t_w$ after stopping the precipitation,
the factor $f_1(\lambda_i)$ becomes

$$f_1(\lambda_i) = \eta_t w_s \frac{\lambda_i}{\lambda_k} \frac{t_g}{\lambda_i t_g + 1} \left(1 - e^{-\lambda p t} \right) \left(1 - e^{-\lambda m t} \right) e^{-\lambda d t + \lambda w t}$$  \hspace{1cm} (16)

where $\eta_t$ = total efficiency (efficiency of scrubber, precipitator and
detector).

The factor $f_1(\lambda_i)$ is given in Appendix II for the following val-
ues: $t_g = 4.45$ s, $t_p = 17.5$ s, $t_m = 25$ s, $t_w = 12.9$ s, $t_d = 10$, 25
and 50 s, $\eta_t = 100 \%$ and $w_s = 19 \text{ cm}^3/\text{s}$ (average water flow during
the calibration tests). In Appendix II also the concentrations $C_e$ are
given. The data used for the calculation of these concentrations follow
from Sec. 4.2, 4.3 and 4.4. In previous calculations the total effi-
ciency $\eta_t$ was estimated at 25 \% \hspace{1cm} (8). It was then assumed that scrub-
ber, precipitator and detector have the efficiencies 70, 75 and 50 \%,
respectively. Particularly the efficiency of the scrubber seems to be
somewhat underestimated. The calibration tests also indicate that the
total efficiency is somewhat higher than 25 \%. However, the value
25 \% will be used in calculations throughout this report.
If the tape transport is stopped, it is possible to measure the
decay of the collected activities and thereby to investigate whether
the detected fission products have the assumed half-life distribution
or not. The distribution of half-lives is strongly dependent on the
transport time. By studying the shape of the decay curve the trans-
port time can therefore be estimated. The general performance of
the precipitator systems can also be checked by investigating the de-
cay of collected activities. The calculated decay curves are given in
Appendix III for normal conditions, during calibration (Test No. I)
and for the case of one pin-hole.

In the ion exchanger system the number of counts, during a
measuring time $t_m$, follows from the relation

$$S_c = \sum_{i=1}^{3} (C_i \cdot f_i)^2 \cdot \int_{0}^{\infty} \frac{e^{-\lambda_i t_d}}{1 + \lambda_i V_i/w_d} \, dt_m$$

where

- $\eta_d =$ detector efficiency
- $e_i =$ number of $\gamma$-quanta/disintegration with $E_\gamma > 2$ MeV
- $t_d =$ total transport time (from moderator to detector)
- $w_d =$ water flow to monitor
- $V_d =$ volume of sample container.

In Appendix II the calculated concentrations and $f(\lambda)$ factors
are given for $\eta_d = 100\%$. The calculated efficiency of the scintilla-
tion detectors is $0.8\%$ for gammas of $2.24$ MeV energy.

### 4.2 Background

For calculation of the count rates under normal conditions i.e.
without cladding defects, it is necessary to estimate the contribution
from background radiation and from non-fission products in the wa-
ter.

In the precipitator channels the contribution from background
radiation is very small, less than $5$ counts for a counting time of
$25$ s. Several background measurements were performed before the
two calibration tests (Test No. I, June 16, 1965 and Test No. II,
Oct. 7, 1965). These measurements showed that most of the background counts are due to $^{41}A$. Over 2000 counts/25 s were sometimes recorded.

Argon activity can come into the precipitators in three ways, by the scrubber gas flow, by the dry gas flow or by the purge flow. The two latter flows are taken from the gas stored in the expansion tanks and can contain a certain amount of $^{41}A$. The activity registered by the detector is either $\gamma$-radiation from argon in the precipitator chamber or $\beta$- and $\gamma$-radiation from argon leaking to the vicinity of the detector. The purge gas flow ought to prevent this leakage. A separate test showed that an increase of the purge gas flow to about $5 \text{ cm}^3/s$ gave a decrease of the background counts, whereas higher purge gas flows did not give any further reduction. It is therefore most probable that the background contribution from $^{41}A$ originates from direct radiation from argon in the precipitator chamber. (By using inactive purge and dry gas flows the various contributions can be investigated more accurately.) The argon concentration in the coolant during the background measurements was very high, up to $5 \cdot 10^4 \text{ dps/cm}^3$ in May 1965. During the calibration tests the argon concentration was considerably lower. In the T3 system a background of only 170 c/25 s was recorded during Test No. I at 50 MW. (The background was measured by switching off the tape transport of the precipitator.) It is hoped to keep down the concentration of argon in the primary coolant in the future, as the amount of nitrogen added to the water is going to be reduced. The nitrogen normally added contains a certain amount of argon.

The background count rates in the ion exchanger system are also to a great extent due to $^{41}A$ in the coolant. Another isotope which sometimes contributes to the background is $^{24}Na$, due to unsatisfactory performance of the ion exchangers. The $\gamma$-radiation from $^{41}A$ of energy 1.3 MeV is registered mainly as double pulses. The number of double pulses can be estimated with a knowledge of the dead time, $\tau$, in the single channel analyser. For an argon concentration $C_A$ in the coolant the number of double pulses/s, $A_c$, can approximately be written
With $\eta_d = 1.1\%$ (for $E_Y = 1.3$ MeV), $V_d = 100 \text{ cm}^3$, $\tau = 5 \cdot 10^{-7}$ s and $\lambda_1 C_A = 9.0 \cdot 10^3 \text{ dps/cm}^3$ (the value measured on Oct. 4, 1965, at 62 MW) the count rate of double pulses becomes 49 cps. The measured background was about 8 cps, which indicates that the efficiency is lower than expected. The background registered is regarded as too high, and if the argon concentration in the coolant cannot be decreased, one has to improve the time resolution of the electronics.

### 4.3 Surface contamination

It has not been possible to measure accurately the count rate contribution from uranium surface contamination with any of the failed-fuel-element detection systems. The reason for this is that the contribution from contamination is small compared to the background values mentioned in the previous section. The estimated surface contamination on the cladding material, when designing the precipitator systems, was $10^{-8}$ g/cm$^2$ of natural uranium, which according to the measured count rates seems too high. Also the radio-chemical investigations of the coolant water indicate a surface contamination considerably less than $10^{-8}$ g/cm$^2$.

The fission product which in the radiochemical analysis gives the most consistent values seems to be $^{131}I$. The concentration in the coolant of this isotope is regularly measured. The activity concentration measured during the spring of 1965 has an average value of about $3.0 \cdot 10^{-2}$ dps/cm$^3$ at full reactor power. During this period the main ion exchangers were in operation. The cleaning flow varied between 2.0 - 3.5 kg/s. Measurements of the $^{131}I$ concentration in May 1964 with the ion exchanger shut-off gave an average value of 0.42 dps/cm$^3$. The relation between the total surface contamination and the concentration in the coolant can for an effective cleaning flow $w_r$ be written

$$m_c = 2 C_0 (\lambda_1 V + w_r) / (Fy_1)$$

$$A_c \approx (\eta_d \lambda_1 V_d C_A)^2 \tau$$ (18)
Assuming that $w_r = 0$ when the ion exchangers are shut-off, a surface contamination of $0.19 \times 10^{-8} \text{g/cm}^2$ is obtained (total cladding area $= 4.26 \times 10^6 \text{cm}^2$). Due to deposition on walls the effective cleaning flow can be regarded as only approximately zero when the ion exchangers are shut-off. The value $0.19 \times 10^{-8} \text{g/cm}^2$ should therefore be somewhat too low. The concentration when the ion exchangers are in operation is dependent on the efficiency of the ion exchangers. Assuming an efficiency of 50% for iodine and a cleaning flow of 2 kg/s, i.e. an effective flow of 1 kg/s, the concentration $3.0 \times 10^{-2} \text{dps/cm}^3$ points to a surface contamination of $0.23 \times 10^{-8} \text{g/cm}^2$. For calculation of the count rates due to surface contamination the value $0.2 \times 10^{-8} \text{g/cm}^2$ will be used. This is a comparatively low value, but it is not contradicted by the results obtained during the calibration tests.

The concentration of fission gases due to surface contamination follows from Appendix II. In Tab. 3 the calculated number of counts in the various systems are given. A total efficiency in the precipitator systems of 25% and a detector efficiency of 0.8% in the ion exchanger system is assumed. The number of counts as a function of transport time is shown in Fig. 6, curve 5, for the precipitator systems.

<table>
<thead>
<tr>
<th>System</th>
<th>$t_m$ (s)</th>
<th>Number of counts (counts/$t_m$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$t_d = 10$ s</td>
</tr>
<tr>
<td>T1-3 L1, L6</td>
<td>25</td>
<td>146</td>
</tr>
<tr>
<td>T0</td>
<td>1</td>
<td>0.36</td>
</tr>
</tbody>
</table>

Tab. 3 Calculated number of counts due to surface contamination under normal conditions. Reactor power = 65 MW, no background values added.
4.4 Calibration foils

During the two calibration tests the FII assembly containing the foils was in the positions G81 (Test No. I) and A56 (Test No. II), see Appendix I. Two foils were utilized in the first test and the neutron flux at the position of the foils was calculated to be \(8.78 \times 10^{12}\) n/cm\(^2\)s, using the computer program HETERO [11]. In Test No. II only one foil was used and the neutron flux was in this case calculated to be \(2.50 \times 10^{13}\) n/cm\(^2\)s. The concentration of fission gases during the calibration tests follows from Appendix II, assuming that one foil corresponds to 40.8 mg uranium in the form of surface contamination when light fragments are concerned and to 32.0 mg when heavy fragments are concerned. The coolant flow in the channels with foil is 4.47 kg/s. The calculated number of counts in the various systems follows from Tab. 4 at full reactor power. For the precipitator systems the number of counts as a function of delay time is shown in Fig. 5.
Fig. 5  Number of counts in the precipitator systems at calibration as a function of transport time. Reactor power = 65 MW.
<table>
<thead>
<tr>
<th>System</th>
<th>Channel with/without foil</th>
<th>Number of counts (counts/t&lt;sub&gt;m&lt;/sub&gt;)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Test No. I</td>
<td>Test No. II</td>
</tr>
<tr>
<td></td>
<td></td>
<td>t&lt;sub&gt;d&lt;/sub&gt;=10s</td>
<td>t&lt;sub&gt;d&lt;/sub&gt;=25s</td>
</tr>
<tr>
<td>T1-3</td>
<td>w</td>
<td>2100</td>
<td>1210</td>
</tr>
<tr>
<td></td>
<td>wo</td>
<td>372</td>
<td>244</td>
</tr>
<tr>
<td>L6</td>
<td>w</td>
<td>13600</td>
<td>7620</td>
</tr>
<tr>
<td></td>
<td>wo</td>
<td>372</td>
<td>244</td>
</tr>
<tr>
<td>L1</td>
<td>w</td>
<td>79600</td>
<td>44500</td>
</tr>
<tr>
<td></td>
<td>wo</td>
<td>372</td>
<td>244</td>
</tr>
<tr>
<td>T0</td>
<td></td>
<td>1.79</td>
<td></td>
</tr>
</tbody>
</table>

Tab. 4 Calculated number of counts during calibration. Reactor power = 65 MW, no background values added.

4.5 Pin-holes

The number of counts for the case of one pin-hole is calculated for a constant escape rate coefficient of 10<sup>-8</sup>s<sup>-1</sup>. The calculations concern pin-holes in a fuel assembly with average neutron flux (2.14×10<sup>13</sup>n/cm<sup>2</sup>s) and average coolant flow (8.65 kg/s). Calculated concentrations of fission gases follow from Appendix II and calculated number of counts in the various systems from Tab. 5. For the precipitator systems the number of counts as a function of transport time is plotted in Fig. 6.
Fig. 6 Number of counts in the precipitator systems under normal conditions and for the case of one pin-hole as a function of transport time. Reactor power = 65 MW.
Tab. 5 Calculated number of counts with one pin-hole in a fuel assembly with average neutron flux and average coolant flow. Reactor power = 65 MW, no background values added.

5. TEST RESULTS

The calibration tests started by warming up the reactor station to operating temperature. The reactor power was then increased in steps. During Test No. I (June 16, 1965) the power levels were 0.8, 15, 30 and 50 MW and during Test No. II (Oct. 7, 1965) 0.8, 12 and 40 MW. The transport time of water samples from position C81 (Test No. I) is one of the longest in the reactor, whereas the transport time from position A56 (Test No. II) is of medium length.

The increase in number of counts in the precipitator systems when going up in power is shown in Figs. 7 and 8. The count rates represent channels with foils. As can be seen, stable conditions are reached after about one hour. This means that the relative count rate contribution from Kr$^{88}$, with a half-life of 2.77 h, is small. According to the calculations the relative number of counts due to Kr$^{88}$ is almost negligible. The spread in the measured values is mainly caused by the fluctuations in the sample flow to scrubbers. The sample flows were adjusted to about 20 cm$^3$/s but decreased several times down to...
Fig. 7  Measured number of counts in L1, L6 and T2 systems at Test No. I in channels with foils. The values of the L1 and L6 systems are corrected according to Eqs. 20 and 21.
Measured number of counts in L1, L6 and T1 systems at Test No. II in channels with foils. The values of the L1 and L6 systems are corrected according to Eqs. 20 and 21.
about 15 cm$^3$/s. However, most of the important values were recorded when the sample flows to scrubbers were about 19 cm$^3$/s.

The number of counts in the precipitator channels is due both to fission products and background. The background during Test No. I was found by measurement to be 170 c/25 s at 50 MW. No separate background measurements were made during Test No. II, but from the recorded total number of counts, i.e. signal + background, in the various systems the background seems to be somewhat higher than in the first test.

As the sample flows to scrubbers were about 19 cm$^3$/s, instead of the design value 25 cm$^3$/s, the transport times become a few seconds too long. In the L1 and L6 systems this means that the count rate in the channel with foil is lower, and the count rate in the channel measured after the one with foil is higher, than expected. In Sec. 5.2 a method of correcting for "overlapping" between channels is discussed. The count rates given in Figs. 7 and 8 for the L1 and L6 systems are corrected according to this method.

The number of counts as a function of reactor power is plotted in Figs. 9 and 10. As can be seen, the linearity is good except for the L6 system during Test No. I.

In the following sections the performance of the various systems will be discussed separately.

5.1 Precipitator T system

The FII assembly with the calibration foils was in a position monitored by the T2 system during Test No. I and in a position monitored by the T1 system during Test No. II. The automatic permutation of measuring and sampling channels was not utilized during the tests, but in a few cases manual permutation was carried out to investigate whether the three precipitator channels in the T system had equal sensitivity. No significant difference in sensitivity was, however, found by such a permutation. As the automatic permutation was switched off, one of the solenoid valves was always open and the sample flow continuously flowing to the scrubbers in the T system. At the first calibration the tape transport of the T3 precipitator was shut-off which, as mentioned, allowed the background in that channel to be measured.
Fig. 9 Measured number of counts versus reactor power in channels with foils in Test No. I. The values of the L1 and L6 systems are corrected according to Eqs. 20 and 21. (Background subtracted.)

Fig. 10 Measured number of counts versus reactor power in channels with foil in Test No. II. The values of the L1 and L6 systems are corrected according to Eqs. 20 and 21. (Background subtracted.)
The total transport time from fuel assemblies to precipitator can, for the T systems, be estimated at on the average 23.1 s, and maximally at 24.6 s, when using the flow values from Test No. II (flows to manifold = 70 cm$^3$/s, flow to scrubber = 19 cm$^3$/s and bypass flow = 3340 cm$^3$/s).

The transport times during Test No. I are difficult to estimate due to the flow variations during this test. In the calculations the same transport times for Test No. I and Test No. II are assumed.

In Tab. 6 the measured number of counts is compared with that calculated for a transport time of 25 s. The comparison is made at 40 and 50 MW, respectively, the highest power levels used at the two calibrations. A background of 170 c/25 s is added to the calculated number of counts in all channels. (Tab. 4 gives the calculated number of counts at 65 MW without background.)

<table>
<thead>
<tr>
<th>Test No. I (50 MW)</th>
<th>Test No. II (40 MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>System</strong></td>
<td><strong>Counts/25 s</strong></td>
</tr>
<tr>
<td></td>
<td>calculated</td>
</tr>
<tr>
<td>T2 (with foil)</td>
<td>1001</td>
</tr>
<tr>
<td>T1 (without f.)</td>
<td>358</td>
</tr>
</tbody>
</table>

Tab. 6 Calculated and measured number of counts in precipitator T system at calibration. A background of 170 c/25 s is assumed for the calculated values.

According to Tab. 6 the measured count rates in channels with foils are higher than those calculated. It ought then to be noticed that the calculated values relate to a transport time of 25 s. It is possible that the actual transport time is a few seconds shorter. If a transport time of 20 s is assumed, the calculated count rate becomes about 20% higher than those given in Tab. 6 (see Fig. 5). The T system was working continuously during the calibrations, which means that the concentration of daughter products in the precipitator chamber is
not zero at the start of precipitation. The collected number of daugh-
ter products has therefore to be corrected according to Eq. (15).
This correction is estimated to be of the order of 10 %. Also a small
contribution from more short-lived fission gases than those consider-
ed in the calculations might be expected. Anyhow the results in the
T system indicate that the assumed total efficiency of 25 % is some-
what underestimated. A value in the range 30 - 35 % seems more re-
alistic. (The total efficiency of 25 % was estimated on the assump-
tion that the scrubber, precipitator and detector efficiencies were
70, 75 and 50 %, respectively. Particularly the scrubber efficiency
can be higher, possibly up to about 90 %.)

A higher count rate than expected could also be explained by
an overrepresentation of samples from the part of the fuel assembly
in which the foils were situated. According to loop tests, however,
the sampling should be satisfactorily uniform.

The high number of counts in the T2 system during Test No. I
is difficult to explain, especially as the transport time was in this
case about 1.5 s longer than the average. The longer transport time
ought to have resulted in a comparatively lower count rate during
Test No. I than during Test No. II. In fact a low count rate was re-
corded in the L1 system during Test No. I (see Sec. 5.3).

The decay of the activities collected on precipitator tape was
measured in the T2 system during Test No. I. The normalized de-
cay curve is plotted in Fig. 11, in which also the calculated decay
curve assuming 25 s transport time is given (compare Appendix III).
It follows from Fig. 11 that the collected activities decay more rap-
idly than calculated. This faster decay can be explained by a shorter
transport time than expected, a higher sample flow from the channel
with foils than from other channels, or by the fact that the amount of
short-lived fission gases is higher than expected. All these factors
give a higher number of counts than calculated for the T2 system,
i.e. in agreement with the measured values according to Tab. 6.

The possibility of using the T system for localization of a faulty
element was investigated by moving control rods in the neighbourhood
of the FII assembly. In Test No. I one of the fine control rods (posi-
tion B62) was moved from top to bottom, and in Test No II one coarse
Fig. 11 Calculated and measured decay of activities on precipitator tape in T2 system in Test No. I.
control rod (position A44) from top to half-way down. In both cases the decrease in number of counts in the channel containing the FII assembly was about 15 - 20 %. By means of this "shadowing" technique it is thus possible to localize defects which give about the same number of counts as the calibration foils. According to Tabs. 4 and 5 this corresponds to a defect with a release a few times larger than that from a pin-hole (with \( v = 10^{-8} \, \text{s}^{-1} \)). Anyhow localization of defects by means of shadowing is a very time-consuming procedure.

5.2 Precipitator L6 system

When the precipitator systems were designed, scrubber flows of 25 cm\(^3\)/s were presumed whereas the average flows at calibration were about 19 cm\(^3\)/s. For this reason the transport times were increased, which in the L6 and L1 systems resulted in a high number of counts, not only in the channel containing the foil(s), but also in the channel measured directly after.

The precipitator voltage is switched-on for 17.5 s and switched-off for 12.5 s, whereupon a new precipitation cycle starts. If the fission gas sample from the channel to be measured arrives at the precipitator after the start of precipitation the counts from the considered channel will be too low. If the channel in question is one containing a foil, or a defect, the true number of counts, \( S_c \), follows from the equations

\[
(1 - x) S_o + x S_c = S' \quad (20)
\]

\[
(1 - x) S_c + x S_o = S'' \quad (21)
\]

where

- \( S_o \) = number of counts in channels without foil
- \( S' \) = recorded number of counts in the channel with foil
- \( S'' \) = recorded number of counts in the channel measured after the one with foil
- \( x \) = fraction of precipitation time with true gas sample in precipitator.
The equations above can be used both for estimation of transport time and correction of measured count rates. From determinations of the factor $x$ a transport time from the position of the solenoid valves to the precipitator of, on the average, 20.1 s is found for the L6 system in Test No. II. From the flow values (flows to manifold = 36 cm$^3$/s, flow to scrubber = 19 cm$^3$/s and by-pass flow = 195 cm$^3$/s) an average total transport time of 24.4 s and a transport time from valve to precipitator of 15.5 s is obtained. The maximal total transport time is about 1.3 s longer than the average. (When calculating the transport times it was assumed that the fission gas concentration builds up exponentially in the precipitator, which can approximately be taken into account by adding a transport time in the precipitator of $V_p \ln \frac{2}{w_g}$, i.e. about 3.1 s.)

<table>
<thead>
<tr>
<th>Channel</th>
<th>Counts/25 s</th>
<th></th>
<th>Channel</th>
<th>Counts/25 s</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>calculated</td>
<td>measured</td>
<td></td>
<td>calculated</td>
<td>measured</td>
</tr>
<tr>
<td>with foils</td>
<td>6030</td>
<td>7100</td>
<td>with foil</td>
<td>6760</td>
<td>4430</td>
</tr>
<tr>
<td>without foils</td>
<td>358</td>
<td>223</td>
<td>without foil</td>
<td>361</td>
<td>256</td>
</tr>
</tbody>
</table>

Tab. 7 Calculated and measured number of counts in the L6 system at calibration. A background of 170 c/25 s is added to the calculated values.

In Tab. 7 the measured number of counts are compared with the calculated values for a transport time of 25 s. In all channels the background is assumed to be 170 c/25 s. The measured values are in satisfactory agreement with the calculations, although the count rates in the channel with foil in Test No. II are markedly low. In general the count rates in channels without foils are somewhat lower in the L6 system than in the T and L1 systems.

When comparing the measured and calculated response of the L6 system, as well as the L1 system, it has to be noticed that the corrections applied according to Eqs. (20) and (21) are rather approximate.
5.3 Precipitator L1 system

The total transport time in the L1 system in Test No. II was, according to the measured flows, on the average 24.2 s and maximally 25.4 s (flows to manifold = 50 cm$^3$/s, flow to scrubber = 19 cm$^3$/s and by-pass flow = 31 cm$^3$/s). For the same flow values the transport time from solenoid valves to precipitator may be estimated at 15.9 s (assuming an additional transport time of 3.1 s in the precipitator).

Because the transport time in the L1 system was found to be longer than expected, a too high number of counts was obtained in the channel measured directly after the one containing the foil(s). The correction of count rates according to Eqs. (20) and (21) was therefore applied also in the L1 system. From these equations and the count rates measured in Test No. II, the transport time from solenoid valves to precipitator becomes 22.1 s. As mentioned, a delay in start of precipitation of about 5 s is desirable to get satisfactory performance of the L1 and L6 systems unless the transport times can be decreased.

The calculated and measured numbers of counts at the highest power level used during the two calibration tests follow from Tab. 8. Calculated values refer to a transport time of 25 s. The agreement is good except for the channel containing the foils in Test No. I. The reason for the low count rate measured in Test No. I is not known, but it is supposed to be due to leakage in the closed solenoid valves, i.e. the flow through the 143 closed valves might not be negligible compared to the flow through the open valve. The leakage problems should be most serious when the open valve transmits samples from one of the fuel assembly positions with longest transport time, as from the F11 assembly position in Test No. I. Anyhow the results from the two calibration tests indicate that the sensitivity of the L1 system is satisfactory. For the channels near the one containing the foils no noticeable increase in count rates was recorded compared to channels far from the one with foils.
Tab. 8 Calculated and measured number of counts in the LI system at calibration. A background of 170 c/25 s is added to the calculated values.

When summarizing the results in all the precipitator systems, one finds that the count rates in channels with foils are higher than expected in the T system and equal or lower than expected in the L1 and L6 systems. A total efficiency of 25 % is then assumed in the calculations. The somewhat too low count rate in the L1 and L6 systems can be explained by the long transport time observed and, particularly in the L1 system, by valve leakage. It is therefore realistic to explain the high count rates in the T system partly by a higher total efficiency than originally assumed. As pointed out in Sec. 5.1 a total efficiency for all the precipitator systems of 30 - 35 % seems to give the best agreement with the calibration experiments.

5.4 Ion exchanger T system

The emission of fission products from the calibration foils gives theoretically only a small increase of the count rate in the ion exchanger T system (T0 system). According to Tab. 4 the calculated count rates at 50 MW during Test No. I are 1.38 cps and at 40 MW during Test No. II 1.47 cps. The calculation was carried out for a detector efficiency of 0.8 %.

The highest count rate registered in the T0 system was in Test No. I 1.1 cps and in Test No. II 2.2 cps. These count rates should to a great extent be due to the argon activity in the coolant, and the
low value found in Test No. I can be explained by the very low argon concentration in that test. The background count rate from $^{41}A$ increases as the square of the argon concentration (see Eq. (18)).

The pulse height spectrum from one of the scintillation counters in the T0 system was studied by means of a multichannel analyser both in Test No. II and under normal conditions (no foil). In Fig. 12 the low energy part of the spectra recorded on Oct. 4, 1965, at 62 MW and on Oct. 7, 1965, at 40 MW (Test No. II) are shown. The $^{41}A$ activity registered is proportional to the power levels in the two cases, and thus the argon concentration in the coolant ought to have been about the same in the two measurements. The high energy part of the spectra is plotted in Fig. 13. The energy region monitored by the single channel analysers, 1.9 - 2.5 MeV, is of particular interest. No additional contribution from the krypton isotopes $^{87}Kr$, $^{88}Kr$ and $^{89}Kr$ can be found in this energy region in Test No. II compared to the measurement without foil. The count rates registered by the single channel analysers in Test No. II seem therefore almost exclusively to be due to $^{41}A$.

According to Tabs. 4 and 5 one pin-hole gives 4 - 5 times higher count rate than the calibration foil during Test No. II. It is then possible that defects of pin-hole type can be detected by the T0 system. Anyhow it is desirable both to increase the detector sensitivity and to improve the time resolution of the single channel analysers. It is also important always to keep the argon concentration in the coolant as low as possible.

The low sensitivity of the T0 system might also be due partly to a loss of fission gases on the way to the detector. If the performance of the T0 system is improved by improving the electronics, it is therefore desirable to make new calibration experiments in this system.

5.5 Radiochemical analysis

The coolant water was analysed radiochemically at different power levels during the calibration tests to follow the build-up of fission products. Samples of 25 cm$^3$ were taken from the purification flow ahead of the main ion exchangers. The samples first passed
Fig. 12  Pulse height spectra, low energy part, measured in the TO system. Reactor power = 62 MW (Oct. 4, 1965) and 40 MW (Oct., 1965 in Test No. II).
Fig. 13  Pulse height spectra, high energy part, measured in the TO system. Reactor power = 62 MW (Oct. 4, 1965) and 40 MW (Oct. 7, 1965 in Test No. II).
a small container with cation bed and then a container with anion bed. The $\gamma$-spectra from the activity collected on the cation and anion beds, as well as the spectra from water samples which had passed both ion exchangers, were studied.

Several corrosion products could be identified in the $\gamma$-spectrum of the activity collected on the cation bed. The activity collected on the anion bed should to a great extent be due to fission products, and it was hoped that it would be possible to identify several isotopes, for instance several iodine isotopes. It was also hoped that it would be possible to determine the concentration of some of these isotopes with such an accuracy that the release of fission products from the foils could be verified. However, the spectra recorded did only allow for identification of $^{132}$I and the measured concentration of this isotope did not increase with reactor power as expected. Thus the radiochemical analyses did not permit any accurate determination of the release from the foils.

5.6 Inspection of the Zr/U foils

A few months after the calibration experiments the foils were inspected in a microscope and photographed. When investigating the whole foils with holder at low enlargement, the only damage found was some abrasion at the points which had been in contact with the fuel rods.

The influence of irradiation on the corrosion behaviour of the foils is of particular interest. Therefore one of the foils from Test No. 1 (foil No. 2) was compared with a small piece of foil (foil No. $3^3$) autoclave-tested for 15 days at 250 $^\circ$C water temperature. Foil No. 2 was first loop-tested for 10 days at 250 $^\circ$C and then exposed in the reactor for about 3 days at zero power, 4 hours at 0.8 - 50 MW (Fig. 7) and 17 hours at 50 MW. Fig. 14 shows the photographs of foils Nos. 2 and $3^3$ enlarged 14 and 105 times. Polarized light was used in the second case. No real difference between the two foils can be seen at the lower enlargement, but from Fig. 14 d it is clear that the foil exposed in the reactor has a much rougher surface, indicating that part of the oxide film has flaked off. (Whether the flaking off has any substantial influence on the release of fission products can probably only be found by further experiments.)
Fig. 14. Photomicrographs of foils Nos. 2 and 3.

a) Foil No. 2, nonpolarized light, 14 x
b) Foil No. 3, nonpolarized light, 14 x
c) Foil No. 2, polarized light, 105 x
d) Foil No. 3, polarized light, 105 x
By weighing the whole foil with holder it was also found that part of the corrosion film flaked off during the calibration. The weight losses of the foils used in Test No. I were 29.1 and 53.9 mg and the weight loss of the foil used in Test No. II was 46.3 mg. If it is assumed that 10% of the material flaking off from the foil is uranium, about 13 mg of natural uranium was added to the primary circuit of the reactor during the calibrations. (Probably the corrosion film contains less than 10% of uranium, but on the other hand the erosion may be somewhat higher than indicated by the weight losses, as some parts of the foils certainly show weight gains.) The adding of 13 mg uranium to the coolant cannot be expected to give any substantial background increase as only a small fraction of the uranium is supposed to be deposited on surfaces in high-flux position. In fact no significant background increase has been recorded after the calibration tests.

6. DISCUSSION

The calibration technique utilized in the Ågesta reactor seems to be very useful when investigating the sensitivity and general performance of failed-fuel-element detection systems. The experiments show that bulk detecting systems as well as localization systems can preferably be calibrated by means of thin uranium-alloyed foils. Due to the corrosion behaviour of the Zr/U foils used, both exposure time and coolant temperature have to be limited.

The sensitivity of the precipitator systems in the Ågesta reactor was found to be satisfactory. The results obtained with the bulk detecting T system points to a total efficiency of the precipitator systems of 30%, or somewhat higher. In the localization systems the measured count rates were in some cases lower than calculated, which was due to unexpectedly long transport times and probably to leakage in valves. To compensate for the too long transport times, originating from limitations of the sampling flows, it is desirable to delay the start of precipitation for about 5 s. The general performance of the precipitator systems during the calibration tests was good except for the fluctuation of the sampling flows. To take full advantage of the systems, improved methods of controlling these flows have to be
found. It is also important to keep down the argon concentration in the coolant to get a low background. Such a high argon concentration as measured in the spring of 1965 seriously reduces the sensitivity of the precipitator systems.

The sensitivity of the ion exchanger bulk detecting system was not high enough to allow a calibration. The calculated response of that system to defects of pin-hole type is several times higher than the calculated response to the calibration foils. Anyhow it seems necessary to improve the sensitivity of the ion exchanger system by increasing detector efficiency and improving the time resolution of the single channel analysers. It would then be desirable to make a new calibration of that system.

7. ACKNOWLEDGEMENTS

The author wishes to thank Mr. I. Myrén and Mr. M. Arnold for bringing the detection systems into operation, as well as for invaluable assistance during the calibration experiments. Thanks are also due to several members of the RMA, RMB, RKK, RTR and SSI sections of AB Atomenergi for performing various types of investigations and analyses. The assistance of the operating staff at the Ågesta reactor is gratefully acknowledged.
APPENDIX I
Reactor data and lattice

Some of the principal data of the Ågesta reactor are listed below.* Fuel assembly and control rod positions are shown in Fig. AI:1.

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<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Thermal power</td>
<td>65 MW</td>
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<tr>
<td>Electrical power</td>
<td>10 MW</td>
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<tr>
<td>Heat delivered to the district heating system</td>
<td>55 MW</td>
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<tr>
<td>Primary system operating pressure</td>
<td>33.3 bar</td>
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<td>Core height</td>
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<td>Lattice pitch</td>
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<tr>
<td>Core volume, unreflected</td>
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<tr>
<td>Number of rods per assembly</td>
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<tr>
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<td>Zircaloy-2</td>
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<td>Canning thickness</td>
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<td>Outlet temperature from fuel assembly</td>
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<tr>
<td>Average moderator temperature</td>
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<td>Coolant flow through central assemblies</td>
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<tr>
<td>middle</td>
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<tr>
<td>outer</td>
<td>8.35 kg/s</td>
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<td></td>
<td>4.47 kg/s</td>
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<tr>
<td>Purification system flow</td>
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<tr>
<td>Total mass of heavy water</td>
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<tr>
<td>Average flux in fuel</td>
<td>$2.14 \times 10^{13} \text{n/cm}^2$</td>
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* A description of the Ågesta reactor is given in the internal AE report R3-100 (1958): "R3-A Natural Uranium Fuel Heavy Water Moderated Reactor for Combined Electricity Production and District Heating", by P.H. Margen et al.
Fig. AI:1 Lattice
<table>
<thead>
<tr>
<th>System</th>
<th>Isotope</th>
<th>Concentration under normal conditions (atoms/cm³)</th>
<th>Concentration at calibration (atoms/cm³)</th>
<th>Concentration for one pin-hole (atoms/cm³)</th>
<th>f(λ) factor</th>
<th>Remarks</th>
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<thead>
<tr>
<th>Concentration at calibration (atoms/cm³)</th>
<th>Concentration for one pin-hole (atoms/cm³)</th>
<th>f(λ) factor</th>
<th>Remarks</th>
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<td>ch.w.o.foil</td>
<td>tₙ=50s</td>
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<th>Remarks</th>
<th>Conc.=Cₑ f(λ)=f₁(λ₁)</th>
<th>ηₑ=100%</th>
<th>wₑ=19cm³/s</th>
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<tr>
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<th>Conc.=C₀ f(λ)=f₂(λ₂)</th>
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**Used values**

- General: \( P=65 \text{ MW}, \phi=2.14 \times 10^{13} \text{n/cm}^2 \text{s} \)
- Test No. I: \( \phi=8.78 \times 10^{12} \text{n/cm}^2 \text{s} \)
- Test No. II: \( \phi=2.50 \times 10^{13} \text{n/cm}^2 \text{s} \)
Fig. AIII:1 Decay of activity on precipitator tape under normal conditions.

Fig. AIII:2 Decay of activity on precipitator tape at calibration (Test No. 1).

Fig. AIII:3 Decay of activity on precipitator tape for the case of one pin-hole.
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