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Department of Reactor Physics

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Foreword:

This is the second Progress Report from the Department for Reactor Physics of Aktiebolaget Atomenergi, which is issued for the information of institutions and persons interested in the progress of the work. In this report the activities of the General Physics Section have been included, since this section nowadays belongs to the department.

This is merely an informal progress report, and the results and data presented must be taken as preliminary. Final results will be submitted for publication either in the regular technical journals or as monographs in the series AE-reports.

B Tell
Editor

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Rotating plasma

1) The measurements of the interaction between a neutral gas and a plasma moving relatively to each other have been continued and completed for the time being. The investigations have included experiments on the influence of impurities which are evaporated from the electrodes during the discharges. The impurities were found to have a great influence only for discharges with heavy gases. For hydrogen the influence on the voltage across the discharge was smaller than the experimental errors.

The velocity of the plasma has been measured spectroscopically by means of Doppler shift measurements. The results were found to be in agreement with the velocities derived from the electrical data.

A detailed report on these measurements was presented at the IAEA-conference in Salzburg, Sept. 4 - 9, 1961. The proceedings of this conference will be published in Nuclear Fusion 1962.

2) The measurements with the inhomogeneous magnetic field have been continued. Only one single turn coil was used. Two coils had been used earlier but they exposed too large a surface to the plasma. This had a cooling effect which partly counteracted the magnetic heating.

To begin with, the single turn coil was enclosed in a spherical shell which was covered with fluorescent material. In this way it is possible to study the formation of forbidden regions around the coil. These forbidden regions are necessary to prevent the plasma from hitting the surface of the coil. When this study has been finished we will remove the shell and allow the plasma into the interior of the coil where the hot region will occur.
The construction of the new large iron-free coils is almost completed. They will produce up to 10 kgauss in approximately 0.04 m$^3$ and 20 kgauss in the mirrors. According to the schedule they will be completed in February 1962. (L Block)

**Plasma acceleration**

1) The performance of a coaxial plasma gun mentioned in the report for 1960 has been studied further. Thus study was completed, and some of the results have been published in the abstracts to the IAEA-conference in Salzburg, Sept. 4 - 9, 1961.

2) In connection with Block’s investigations of the interaction of plasma moving through a neutral gas it became of interest to study this motion in more detail. A new plasma acceleration device was constructed by Dattner in cooperation with J Wilcox, a visiting scientist from University of California, Berkeley. The acceleration mechanism is the same as in Block’s experiment, but the geometry of the device is different so as to give a rectilinear motion instead of a rotation. This allows the use of more direct methods of diagnostics. The experiment has been in operation since Dec. 1961 and there is hope that it will throw some light on the limitation of the velocity of plasma moving through a neutral gas, as found by Block. (A Dattner)

**Plasma resonance**

The study of resonance phenomena arising when a high frequency wave interacts with a cylinder of plasma were continued during 1961. The resonance spectra were found to depend on the diameter of the plasma cylinder, a linear proportionality was established between resonance frequency and plasma frequency and the limits of spectral series were found and investigated. The results were presented at Fifth International Conference on Ionization Phenomena in Gases, Munich 28/8 - 1/9, 1961. The proceedings of this conference are published by North Holland Publishing Company. (A Dattner)
Theoretical plasma physics

1) The study of the motion of a plasma in crossed electric and magnetic fields was continued. If the plasma is forced to move into a region with a strong magnetic field, the density and the temperature of the plasma will increase. As the drift velocities of the ions and of the electrons are not equal, space charges will arise, which modify the electric field, and thus strongly influence the motion. The motion of the particles was studied, in a two-dimensional case, with the influence of the space charges taken into account. The results are that the particle trajectories are considerably changed, but the increase in temperature and density given by the one-particle density is very nearly correct.

Preliminary results have been published in the abstracts of the IAEA-conference in Salzburg, Sept. 4 - 9, 1961. The complete results are given in a paper "Motion of charged particles in an inhomogeneous magnetic field", which has been accepted for publication in The Physics of Fluids.

2) If the inhomogeneity is strong enough, "forbidden regions", i.e. regions which cannot be reached by particles coming from outside, will arise. The calculations mentioned above are not valid in this case. As the intention is to use a very strong magnetic field, a study of the motion in this case was started. This investigation is now nearly completed. It has been found that the forbidden region is smaller than in the one-particle case. Otherwise, the results are very similar to those cited above. This investigation is of interest not only for controlled thermonuclear research, but it also gives a somewhat firmer foundation to Alfvén's electric field theory of magnetic storms and the aurora, (E Karlson)
PROJECT CALCULATIONS

R3 - Ågesta

This 65 MWth reactor for combined heat and electricity (12 MW) production will be put into operation in 1963. The reactor has natural uranium oxide clusters as fuel and pressurized heavy water as moderator and coolant.

New calculations have been made in order to establish the reactivity balance for fresh fuel and to predict the burnup. Account has been taken of the results from critical and exponential experiments on realistic fuel elements. Measurements on R3 fuel were made both in the R0 critical facility and at the Savannah River Laboratory. The measurements included determination of the material buckling as a function of lattice pitch, rod spacing, void and temperature. Although current lattice recipes cannot satisfactorily account for all the experimental information, the agreement at the design point is considered acceptable.

A number of criticality calculations with conventional as well as heterogeneous methods have been made for different initial core configurations.

1) From August 14, 1961
2) From March 13, 1961
loadings leading to a suggested start-up procedure for the reactor. The effect on reactivity and burnup of spiking the core with slightly enriched fuel elements has been investigated. Transient effects due to xenon and temperature changes during start-up and shut-down have been studied.

R4 - Marviken

The R4 design is for a 100 MWe heavy water moderated pressure vessel reactor scheduled to go critical in 1967. It has been optimized for the use of natural uranium oxide clusters as fuel and for on-power refuelling. The design calculations have been made by the ASEA Company, a private industrial firm, using reactor physics methods developed at AB Atomenergi.

Specific calculations of reactivity coefficients, power distributions and hot spot factors, attainable burnup for different fuelling schemes, and of spatial xenon and temperature feed-back stability have been made partly in collaboration with the Swedish State Power Board. The lattice calculations have been tested by buckling measurements in R0 of representative clustered oxide lattices. The predicted cold, clean buckling for the chosen 27 rod 13.5 mm dia fuel element was in good agreement with the measurements over a large range of lattice spacings.

The effect of slight enrichment on fuel costs and on the possibility of reducing the reflected core volume has been investigated. It has been shown that the use of slightly enriched fuel leads to savings in fuel costs but that no significant reduction of the core volume is possible if full power operation with natural uranium is to be guaranteed.

A study has been made of the economic implications of on-power refuelling as compared to refuelling at shut-down. The results indicate a significant advantage of on-power refuelling for natural uranium
operation of the R4 reactor type.

**PHWR**

During 1961 a design study of the PHWR-type of reactor was made. This reactor uses a wide, uniformly spaced lattice of uranium oxide fuel rods in heavy water. The work was performed at the Westinghouse Electric Corporation and at the Bechtel Corporation in the United States with participation of Swedish physicists and engineers.

The reactor physics work included development of computer codes for uniform lattices and correlation with buckling measurements performed in R0. Parametric studies led to a reference design for a 265 MWe reactor with slightly enriched fuel which yields a burnup of 20 000 MWD/tonne based on a 3-region core and 7 - 8 month interval between refuellings. Preliminary analysis indicated that a partial power of about 40 per cent could be obtained from a natural uranium oxide core.

**Boiling and superheating reactor design study**

A design study for a 400 MWe heavy water moderated and cooled boiling and superheating reactor with slightly enriched uranium oxide fuel has been performed. Parametric studies were carried out to determine fuel elements dimensions, lattice spacing, degree of enrichment, distribution of boiling and superheating fuel channels, effect of subcooling, temperature and void coefficients, and number and location of control rods.

Stability studies were made by analysis of the transfer functions associated with a simplified representation of the system. Preliminary results indicate that a reactor of this type would operate in a stable manner, although further studies using more refined calculational
models and experimentally determined void coefficients are necessary for a more accurate appraisal of the system.

RESEARCH AND DEVELOPMENT

Lattice calculation methods

A series of computer codes have been developed for the calculation of lattice parameters for uniform and clustered natural uranium metal and oxide, heavy water moderated lattices as a function of irradiation. In general, the codes are based on conventional two-group four-factor formalism although some refinements have been introduced. A comparison of measured and calculated bucklings showed a good overall agreement but significant discrepancies still exist especially for low moderator to fuel volume ratios and for moderator temperatures larger than 100°C.

Special effort was put into the estimation of coolant reactivity worths and void coefficients. A recipe was developed which includes a $P_3$ spherical harmonics calculation of flux disadvantage factors, transport theory corrections for streaming effects and a two-dimensional diffusion theory calculation of leakage. Calculated coolant worths show satisfactory agreement with measured values.

Fast neutron spectrum and group constants

A method for calculating fast neutron spectra in infinite homogeneous media has been developed and coded for the Ferranti MERCURY computer. The method uses direct numerical integration of the Boltzmann equation with constant lethargy intervals. Arbitrary cross sections including anisotropic and inelastic scattering can be taken into account. Calculated spectra for $H_2O$ and $D_2O$ show characteristic peaks in the keV-MeV region. For an Al-$H_2O$ mixture good agreement was obtained with measurements in the Swedish light water-moderated
A programme for calculating fast and resonance fluxes and group constants has been coded for the MERCURY computer. The programme solves the energy-dependent transport equation in a homogeneous medium according to the MUFT scheme. The number of energy intervals is limited to 256 and the size of the inelastic scattering matrix to $128 \times 128$. Different approximations for treatment of the slowing-down flux and current can be handled and output options for condensation of the results into data for a few groups are available.

**Heterogeneous methods**

A series of computer programmes based on source and sink theory have been developed. The standard programme uses two-group, two-dimensional diffusion theory for calculating the criticality constant, thermal utilization and relative number of thermal absorptions in fuel elements and control rods for a finite cylindrical reactor. The programme has been used for studying non-uniform lattices, control rod effects and reactivity variations with burnup.

A special programme has been made for the analysis of exponential measurements. In experiments of this kind the number of fuel rods is usually rather small which makes conventional analysis with homogenized methods uncertain. Application of the method to experiments in the Zebra exponential facility has, however, not yet been entirely successful, probably due to the difficulty of defining a correct extrapolated radius for the exponential tank.

Preliminary investigations have shown that extension of the heterogeneous method to three dimensions is feasible with the MERCURY computer. A three-dimensional programme for treatment of partially inserted control rods in a homogeneous medium has been completed,
**Fuel cycle code**

A two-group, two-dimensional fuel cycle programme has been developed for the MERCURY computer. The programme uses conventional lattice theory for calculating lattice parameters and group constants as a function of irradiation in combination with two-dimensional two-group diffusion theory and calculates power distributions and burnup for specified fuel loading schemes. Several schemes of practical interest can be treated, such as batch loading, region-wise out-in and in-out and axial inversion. The computing time in a test run for the Marviken reactor using 16 core zones, 19 x 19 mesh points and 7 flux calculations was of the order of 2 hrs.

**Control rod theory**

The effect of control rods is usually calculated by representing the region occupied by control rods by a homogeneous medium with equivalent parameters. A Mercury autocode programme has been developed for calculating current-equivalent parameters. The original cell consists of a control rod in a homogeneous medium described by the usual two-group parameters. The equivalent cell consists of a homogeneous medium with two-group parameters which give the same fast and thermal currents into the cell.

**Reactor kinetics and stability**

A Mercury autocode programme has been developed for the investigation of spatial xenon stability in slab geometry. The stability of small oscillations is studied by modal expansion of the reactor variables with all coupling between modes represented. The resulting matrix eigenvalue problem is solved from the characteristic equation which is calculated from the unsymmetric real matrix by a new method, developed by O Norinder.
A transfer function model for investigating the stability of heavy water moderated boiling reactors has been worked out and coded for Mercury. The essential part of the model relates to the feedback from nuclear power to void reactivity and is to a large extent based on work by Beckjord and Akcasu for light water reactors, although modifications have been introduced due to the presence of heavy water with boiling confined to coolant channels. The characteristic equation of the system is solved by the above-mentioned general root-locus programme.

Theoretical studies of non-stationary two-phase flow have been initiated as a complement to the experiments under way at Studsvik. The system of partial differential equations derived from the conservation laws of mass, momentum and energy is solved numerically on the Mercury computer by a difference approximation and an iterative method. Preliminary results from a one-dimensional model for an electrically heated channel with given driving pressure have been encouraging.

**Fast reactor physics**

For the zero-energy fast reactor FR-0 which is under construction at Studsvik studies have been made of the reactivity effect of the transverse air gap that divides the reactor in two halves. Higher approximations to a transport theory perturbation method due to Friedman have been derived and a variational method which is valid also for large gap widths has been developed. Work on a numerical method for direct integration of the integral transport equation where the effect of the reflector may be taken into account has been started.

A computer program for the calculation of fast microscopic cross-sections has been developed. The program uses the optical model for neutron-nucleus interaction and the interaction potential has been chosen as an arbitrary combination of the Wood-Saxon type with an absorption potential of the Gaussian type. Spin-orbit coupling has been neglected.
Calculations have been performed with parameters chosen to fit experimental values of U-238 cross-sections. Good agreement has been obtained with earlier results with similar methods.

**Neutron slowing-down and thermalization**

An investigation of the space and energy distribution of neutrons from a point source of fission neutrons in light and heavy water has been performed using Monte Carlo technique. Cross-section variations and anisotropic effects have been taken into account. An attempt was made to fit the calculated slowing-down distributions by a combination of age and diffusion kernels. A good fit was obtained over a large range of energies and distances from the source by using three age kernels and one diffusion kernel. Deviations occur close to the source and at very large distances and for energies higher than 0.1 MeV.

A similar Monte Carlo programme was written for studying slowing down in cylindrical geometry consisting of a uranium rod in heavy water. Production runs have been performed with this code and the results are being analyzed.

The Monte Carlo code for studying space-dependent thermal spectra in slab geometry is being extended to cover cylindrical geometry. This code uses the gas model for neutron-moderator interaction. A new collision routine has been developed which works directly in the laboratory system of coordinates leading to savings in machine time.

Studies of the multi-phonon model for neutron-moderator interaction in the thermal energy region have been initiated. A Monte Carlo sampling technique for selecting scattering angle and energy gain from the multi-phonon probabilities in the incoherent approximation has been developed.

An analytic study of velocity dependent transport theory has been
performed. The thermal neutron distribution was determined in a $P_1$-approximation for a monatomic gas moderator containing a constant source of high energy neutrons using the method of the variation of constants. Application was made to a slab of finite thickness. The results indicate that the method can give accurate analytic expressions for the distribution.

The space-, time-, and energy-distribution of neutrons from a pulsed, plane, high energy has been determined in a diffusion approximation. For simplicity the moderator was first assumed to be hydrogen gas but it was also shown that the method could be used for a moderator of arbitrary mass.

Reports

Some reports published during the year are given below. The availability of RFR-reports, which are internal working reports and printed only in a small number of copies, cannot be guaranteed.

MARGEN, P, AHLSTRÖM, P E, PERSHAGEN, B, Pressure tube and pressure vessels reactors; certain comparisons. (AE-49)

JONSSON, A, NÄSLUND, G, Heterogeneous two-group diffusion theory for a finite cylindrical reactor. (AE-57)

HÖGBERG, T, A Monte Carlo sampling technique for multi-phonon processes. (AE-62)

HÅKANSSON, R, Numerical integration of the transport equation for infinite homogeneous media. (AE-63)

NORINDER, O, Inherent stability of circulating moderator reactors with negative moderator coefficient. (RFR-107)

NILSSON, T, AHLSTRÖM, P E, Correlation of the Burnup-programme to experiments on irradiated natural uranium fuel. (RFR-129)
HÄGGBLOM, H, The reactivity of a central air gap in a bare reactor. (RFR-138)

CARLVIK, I, On the reactivity effect of a transverse gap in a reactor, higher approximation to the transport perturbation formula by Friedman. (RFR-139)

McDANIEL, C T, SCAT, A fuel cycle code for continuous plutonium recycling. (RFR-149)

CLAESSON, A, Velocity dependent neutron transport theory with high energy sources. (RFR-150)

AHLSTRÖM, P E, Calculations of lattice parameters as a function of the irradiation. Presented to the EAES-symposium on "measurements and calculations of the influence of burnup on reactivity", 20 - 23 Sept., 1961, at Risø. (RFR-151)

CARLVIK, I, A remark on the eigenvalue of the adjoint equations in diffusion theory. (RFR-152)

JAHNBERG, S, A one-dimensional model for non-stationary two-phase flow. (RFR-156)

CLAESSON, A, A diffusion equation solution for the space-, time-, energy-distribution of neutrons from a pulsed plane source. (RFR-159)

NORINDER, O & NYMAN, K, Two-group current-equivalent parameters for control rod cells. Autocode programme CRCC. (RFR-160)

NORINDER, O, Two-group analysis of xenon stability in slab geometry by modal expansion. (RFR-167)
1. Experimental Facilities

The critical assembly R0 (height 3.2 m, diam. 2.25 m) was operated without a graphite reflector, and the incomplete radiation shield limited the activation possibilities to mainly thermal neutrons. However, the main purpose of the bare assembly was to obtain a facility suitable for buckling measurements and therefore most of the running time, two shifts a day, has been devoted to such experiments.

The exponential facility ZEBRA (diam. 1.00 m) was used for buckling measurements mostly at night. Since the working scheme of the travelling probes containing BF$_3$ counters is programmed, the measuring device could run without supervision.

The heavy water was degraded from 99.70 mol % D$_2$O (January 1961) down to 99.63 mol % D$_2$O (December 1961).

The hot pressurized exponential facility (TZ) that will permit investigation of D$_2$O/UC$_2$ lattices up to 250 °C has been in course of construction during the year. It will probably be completed in the beginning of 1963. The experimental procedures have been planned and analyzed in more detail. Buckling measurements with travelling pulse counters during a continuously rising temperature seem to have good possibilities of saving experimental time and still giving high accuracy.

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1) Since Oct. 1, 1961, Dr Pauli has been acting Department Manager for the Department of Reactor Physics and Dr Hellstrand acting Section Head.
2. The substitution technique

The substitution technique is used to obtain buckling values with a comparatively small amount of fuel material. The central part of a square reference lattice is replaced by a progressively increasing number (1, 2, 4, 6 etc.) of the fuel assemblies to be investigated. In the buckling measurements reported below the substitution technique has been the standard method used in RO, whereas the experiments in ZEBRA were ordinary exponential experiments, each loading containing only one type of elements.

The effect of eccentric test regions has been studied theoretically (see RFX-70) and compared with earlier experiments (see RFX-56). Correction formulas which allow for the perturbed radial bucklings of the different regions and for two-group effects have been worked out (to be reported).

A one-group perturbation treatment taking into account the effect of different diffusion coefficients, e.g. caused by voids, has been carried out (see RFX-74). Complementary experiments with single fuel assemblies are shown to give the information about the diffusion coefficients in the axial and radial directions.

Various experiments to verify the reliability of the substitution analyses have been performed and have shown good agreement between extrapolated and directly measured values. Such experiments were:

a) Fuel rods of a reference lattice were taken out successively in every fourth lattice position. The buckling difference $\Delta B^2$ was $-1.3 \text{ m}^{-2}$ (to be reported).

b) Reference rods with shrouds (U, diam. 30.5 mm, with Al, ID 63 mm, OD 65 mm) were used for complete substitution measurements with void. $\Delta B^2$ was $-0.27 \text{ m}^{-2}$ and the diffusion coefficients were changed 8 to 12 per cent (see RFX-74).

c) A uniform lattice (pitch 64 mm) of UO$_2$, diam. 13.5 mm, was substituted completely in a reference lattice of pitch 160 mm, $\Delta B^2$ being about $-1.6 \text{ m}^{-2}$ (to be reported).
3. R3 fuel assemblies

Test versions of the R3 fuel assemblies, 19-rod clusters, UO$_2$ diam. 17.0 mm, were partly investigated already during 1960. The experiments were finished during 1961 and were restricted to studies of

a) the buckling at room temperature over a wide range of lattice pitches (from 190 mm up to 320 mm corresponding to $7 < \frac{V_m}{V_f} < 22$)
b) the uniform temperature coefficient of the buckling
c) two different internal spacings (c-c: 21.1 and 22.1 mm)
d) the void effect (changes of diffusion coefficients and buckling).

Part of the experimental material was discussed in two preliminary reports RFX-66 and RFX-73. The final results were reported early in 1962 (see AE-66) and are to be published in Nukleonik.

Comparisons with theoretical predictions of the material buckling showed that there are rather large discrepancies in the extreme ranges of the moderator-to-fuel ratio. One may suspect that the theoretical treatment of fuel gaps may to some extent be responsible for the discrepancy in undermoderated lattices. Experiments to obtain the buckling effect of gaps in the fuel columns did not succeed because no fuel without gaps was available.

4. Fuel for the R4 project

Fuel clusters of 27 oxide rods, UO$_2$ diam. 13.5 mm, were investigated in ZEBRA. The square lattice pitch was varied between 190 mm and 380 mm with clusters having an internal c-c spacing of 21 mm. The temperature coefficient of the 270 mm lattice was found to be $-0.0087 \pm 0.0006$ m$^{-2}$/°C. Two lattices of clusters with c-c: 24 mm were also studied. A comparison with theoretical values shows that measurements on dilute lattices with only 6 and 8 fuel assemblies give reasonable buckling results (see RFX-84).

Critical substitution measurements with 27-rod clusters started in the end of 1961, and void effects are to be studied for various c-c spacings.
5. Uniform UO$_2$ lattices

Two different lattices of UO$_2$ rods, diam. 13.5 mm, have been studied both in R0 and in ZEBRA. The two square pitches were 32 $\sqrt{2}$ mm and 64 mm. In the latter case it was possible to perform measurements with a full critical loading, the buckling being about 5.8 m$^{-2}$, whereas the minimum geometric buckling of the system is 5.4 m$^{-2}$. The uniform temperature coefficient was studied up to 90°C. Part of the results were reported in RFX-75, but the final report will appear in 1962.


The 1.5% enriched second charge of the HBWR was manufactured by the company and as a quality check single fuel assemblies were inserted in a central position of a reference lattice in R0 and tested for reactivity worth. The fuel assemblies are 7-rod clusters of UO$_2$, diam. 1/2", clad in S.S. The buckling of various open hexagonal lattices were measured in ZEBRA. The interpretation of the measurements was complicated because of perturbations from fuel-free gaps. The results are to be reported by H Smidt-Olsen, Halden.

A total number of 84 of these enriched elements were used as an annular driving core in R0 for measurements of the slowing-down distribution in D$_2$O (to be reported).

7. Fuel exchanged with the SRL

As a part of the cooperation between the company and the Savannah River Laboratory tubular fuel assemblies of natural uranium metal from the SRL were measured in ZEBRA which has a rather small radius ($B_r^2 \approx 21$ m$^{-2}$) compared with other exponential assemblies. The purpose of the measurements was to investigate the effect of voids and compare with similar experiments in larger facilities ($B_r^2 \leq 8.5$ m$^{-2}$) at the SRL. Because of anisotropy in the neutron diffusion the interpretation of the experimental data is, however, not straightforward (to be reported).
8. Miscellaneous

Beside buckling differences obtained from substitution measurements we have also to know the bucklings of the reference lattices correctly. In order to get rid of systematic errors some investigations were carried out. The radial and axial components of the buckling were determined in detail by means of BF$_3$ counters, which reproduced the distributions very well and with high accuracy. Small but not negligible irregularities in the radial distribution were discovered. It is hoped that complementary experiments will provide an explanation of this phenomenon. Furthermore, the measurements revealed that the microstructure in the radial distribution is dependent on the over-all flux gradient as is expected from the simple diffusion theory. Such an effect can sometimes give systematic errors in radial buckling determinations with foils, so, on the basis of our experience, we regard travelling detectors as superior to foils when measuring over-all distributions. Azimuthal harmonics due to adjacent concrete blocks were found to be negligible. The effect of D$_2$O reflectors was studied by varying the number of fuel rods and keeping the lattice pitch constant.

The radial weight functions of a uranium metal rod and a stainless-steel rod were studied in a core with a central fuel-free column in R0. However, the form of the functions were too similar to make a separation of fission and absorption cross-sections possible.

The reactor noise in the R0 as seen by an ionization chamber has been registered by means of a tape recorder. The tape was then replayed 50 faster and the output was analyzed through electrical filters. However, if one wants to come down to frequencies lower than 1 cycle/sec, digital recording is probably necessary and such experiments have also been started. The datas are collected in a transistorized register (designed by J Björkman) and then transferred to a punched tape.

When strongly $\gamma$-radioactive samples (e.g. burnt fuel) are oscillated in R0 one has to correct for the photo-neutron source. If the source is not too strong it is possible to separate this source term with adequate accuracy by varying the power of the reactor, at present maximized to about 5 W.
Experiments with a Ra-Be source (300 mC) were carried out and measurements on burnt fuel are planned.

The analysis of oscillator experiments was simplified by using a voltage-to-frequency converter and by integrating over successive quarters of each oscillating period. The higher harmonics could easily be eliminated by adjusting the phase angle (to be reported).

Experiments in ZEBRA showed that the temperature coefficient of the buckling could be measured with good accuracy when the temperature varies linearly with time. During the heating-up period the travelling detector, a BF$_3$ counter, is moved upwards and downwards over a distance of about 0.5 to 1.0 m and the counting-rate is integrated over distances of about 5 cm. It is planned to use the same technique in the hot exponential assembly, TZ.

**PLANNING OF START-UP EXPERIMENTS IN R3 (P E Blomberg)**

The starting-up program has been worked out in detail and rather extensive calculations have been carried out, as regards control rods, reflector savings, critical levels and various reactivity coefficients.

Special experimental equipment has been designed, ordered and partly delivered, e.g.

(a) a level meter (+3 mm) to be used also at elevated temperature ($\sim 220^\circ$C).

(b) four start-up detectors, fission counters, to be placed in pockets into the core.

(c) devices (pockets and semaphores) necessary for measurements of axial and radial over-all flux distributions.

(d) three one-inch-tube channels placed axially outside on the reactor tank.

(e) arrangements with cooling so that a neutron pulse generator
(Kaman) can be introduced into the core.

(f) one fuel cluster with removable single rods in representative positions to be used for intracell studies.

(g) two special fuel clusters to be used in burn-up experiments.

(h) device for remote exchange of detector foils in spent fuel.

Various experimental techniques and methods have been tested at the Studsvik site.

At R0 investigations of the pulsed neutron technique for reactivity measurements in a subcritical assembly were started. This method is very suitable for measurements of the reactivity worth of control rods (see (e) above).

Pile-oscillator measurements in R0 with a Ra-Be source have shown that, when burnt fuel is to be oscillated, the photo-neutron effect in D₂O probably can be eliminated by varying the power level.

Studies of the reactor noise is also going on at R0.

At R2-0 (a swimming-pool reactor) preliminary static experiments were performed to get suitable methods for burn-up studies. Reactivity coefficients and neutron spectra were investigated in three different geometrical arrangements. The preliminary results indicate that in R2-0 it would be possible to measure changes of neutron cross-sections in single rods of a R3 cluster. A pneumatic oscillator equipment has been designed for such experiments and it will be ready in 1962.
REACTOR PHYSICS II (E Hellstrand)

Most of the activity within the group has concerned measurements of resonance integrals for different materials and configurations. In addition, the group is responsible for the planning of and preparation for the experimental work at a zero power fast critical assembly, FR0.

1. Measurement of the resonance integral of zirconium and niobium

The effective cross sections for zircaloy plates ranging in thickness from 0.2 to 6.4 mm has been determined using pileoscillator technique. Boron was used as a cross-section standard. The factor $r \sqrt{\frac{T}{T_0}}$ for the neutron spectrum was determined with the aid of the cadmium ratio for thin gold foils. The zircaloy values were transformed to be valid for pure zirconium with the aid of the chemical analysis of the alloy. For the subtraction of the thermal absorption a 2200 m/s cross-section of 183 mb was used for zirconium.

From the plot of the effective resonance integral as a function of effective plate thickness a crude extrapolation to zero thickness has been made. A value of $0.85 \pm 0.15$ b was in this way obtained for the dilute resonance integral of zirconium. The measurements have been published in Arkiv för Fysik 20, no. 41, 1962.

The resonance integral for niobium has been studied with pile oscillator as well as activation technique. The activity measurements were made on the 0.9 MeV $\gamma$-line following the $\beta$-decay of the Nb$^{94m}$ isomeric state. The pile oscillator measurements were made to check that this decay was quantitatively representative for the total absorption in niobium. The accuracy of the measurements is therefore limited to that obtained for the pile oscillator results.

A value of $8.15 \pm 0.65$ b has been obtained for the dilute resonance integral. Studies of the variation of RI with foil thickness is under way.
The half life of the isomeric state has been determined to 6.30 ± 0.03 m (old value 6.6 m).

2. The resonance integral for thorium oxide

The measurements on thorium oxide could not be completed during the year because of lack of material. New slugs of thorium oxide have been ordered and were delivered in December 1961. New sets of measurements have started.

3. Resonance integrals for clusters of rods

Extensive measurements of the resonance integrals for clusters of rods have been performed in the central channel of the R1 reactor. The clusters were about 40 cm long and completely covered with cadmium. Because of the limited reactivity margin of the reactor the clusters could not be lowered further than just below the heavy water level. Measurements have been made on two different 19 rod clusters (rod diam. 17 mm) with air and D2O as coolants and on four 27 rod clusters with the same coolants. Some measurements were also made on light water cooled clusters. The large degradation of the neutron spectrum, however, makes these measurements less reliable. A final report is under way.

4. The resonance integral for uranium metal and oxide

A minor set of measurements has been made to determine the resonance integral for uranium metal and oxide. In connection with these experiments a measurement has been made of the ratio of the resonance absorption for a R1 fuel rod in a lattice position and that for a cadmium covered rod in a cell boundary flux.

For a 1/E flux the following results were obtained
Metal: \( R_1 = 2.95 + 25.8 \sqrt{\frac{S}{M}} \)

Oxide: \( R_1 = 4.15 + 26.6 \sqrt{\frac{S}{M}} \)

The oxide results agree with those from our earlier measurements. The metal values, however, are 4.5% higher. No reason has been discovered which can explain the difference. For the new measurements gold was used as a cross-section standard.

The comparison between the resonance absorption in different neutron spectra was not completed during the year. The work will be reported in AE-77.

5. Purity control of reactor material

Purity control of uranium oxide and zircaloy has been performed to about the same extent as in 1960. Pile oscillator technique is used and the method is sensitive to \( \pm 0.2 \) ppm of boron for the oxide samples (weight about 3 kg) and to about \( \pm 2.5 \) % of the absorption cross-section for the zircaloy.

6. Planning of the experimental work at the zero power fast critical assembly, FR0

A general survey of possible and desirable experiments on FR0 has been made. The preparations for the experiments have just started. The technique for obtaining neutron spectra from photographic emulsions has been worked out. Preliminary measurements have been made on mono-energetic neutrons from a neutron generator as well as on a beam from the central channel of the reactor R1. The scanning of the emulsions is made in cooperation with The Physics Department of Stockholm University.
Scattering of slow neutrons from $\text{D}_2\text{O}$, $\text{H}_2\text{O}$ and other hydrogenous substances

During the year 1960 the cold neutron technique was applied to the atomic motions in light and heavy water. It was shown that the atoms in water behave much as the atoms in a solid. The general ideas developed during this preliminary work were tested in experiments carried out during 1961.

The discussion of atomic motions in liquids as seen by neutron scattering may conveniently be divided in two parts:

I. Diffusive motions and small energy transfers. This part corresponds to a quasi-elastic scattering of neutrons.

II. Vibrational and rotational motions and large energy transfers. This part corresponds to a broad inelastically scattered neutron spectrum.

The measurements performed at the reactor, R1, on light and heavy water deal mainly with the detailed study of the vibrational and rotational motions. Scattering measurements were performed on light water from $-8^\circ\text{C}$ to $+95^\circ\text{C}$ and on heavy water from $-8^\circ\text{C}$ to $+350^\circ\text{C}$. Many interesting conclusions may be drawn from the experimental results. The most striking result is perhaps the exact similarity between the neutron spectra observed just below and just above the melting point of the two liquids. As it is known that a true frequency spectrum must exist for the vibrational and rotational motions in the solid phase, it is reasonable to assume that a similar frequency spectrum exists in the liquid phase. This assumption receives strong support from the observation of the diffusive quasi-elastic part of the neutron spectra. The careful analysis of these quasi-elastic spectra reveals, that probably the atoms reside for a time $\tau_0$ considerably longer than the period $\frac{1}{\nu}$ for the vibrational and rotational motions in
a sort of quasi-equilibrium positions. $\tau_o$ might be of the order of a few times $10^{-12}$ seconds, while $\frac{1}{\nu}$ ranges from $10^{-12}$ down to $10^{-14}$ seconds.

The frequency spectra thus derived using a solid state model for water shows remarkable agreement with calculations of dispersion relations for ice based on the measured elastic constants for ice and carried out by Dr Forslind at the Institute of Chemical Physics of the Royal Institute of Technology. This statement is valid for the low energy part of the spectrum, in the range $0 < E < 0.045$ eV, corresponding to accoustical and optical modes of vibration. These parts of the spectrum change relatively little when the temperature is raised, the only change being a broadening of the low energy spectrum peak. The high energy part of the frequency spectrum, in the range $0.045 < E < 0.14$ eV may be interpreted as a vibrational part (hindered rotations). The energy range covered by this spectrum part agrees well with observations in Raman spectroscopy. When the temperature is raised this spectrum part is also broadened and its peak is shifted down towards lower energy corresponding to the onset of anharmonic effects (expansion) as the amplitudes of vibration get very high. Similar effects have been observed in crystals. A remarkable fact is that the general shape of these spectra prevails even up to temperatures near the critical.

The main part of the scattering of neutrons is contained in a region near the incoming primary neutron energy, the so-called quasi-elastic scattering, corresponding to the diffusive motions. A study of this part is thus very important for example in order to apply the results to neutron thermalization problems. The effects which reveal the details of the diffusive motion are, however, very small. The energy transfers in this region are in the range $0 - 10^{-3}$ eV.

As classically there is a simple connection between viscosity and self-diffusion properties of a liquid it was thought interesting to study a hydrogenous liquid with a wide variation of viscosity with temperature. Such a liquid is glycerine with viscosity values of 15 poise at $20^\circ$C and
about 1000 times lower at a temperature 100° higher. Scattering experiments were performed on glycerine which, however, showed that the approximate values of the measured diffusion constant varied only by a factor of 10, while the expected variation should have been a factor of 1000 when the temperature was varied from 20°C to 130°C. Moreover, the value of the diffusion constants derived, as well as of the possible residence times, $\tau_0$, are of the same order as for water. This seems to indicate the same type of motion and scattering mechanism in glycerine and water. A hypothesis might be that the neutrons are scattered from protons vibrating and moving relatively freely in a lattice of heavier atoms (oxygen, carbon). These latter atoms should then be considered as having longer residence times than the protons. Work is going on to find the general pattern of motions in hydrogenous liquids.

**Construction and fabrication of apparatuses for the reactor R2**

During 1961 the work on construction of the time-of-flight spectrometer and the triple-axes crystal spectrometer for the high flux reactor R2 has been almost completed.

A very difficult problem in connection with the beam experiments at the material testing reactor, R2, is the high flux of fast neutrons. In order to get rid of these fast neutrons suitable filters have to be used. Quartz crystal filters are supposed to be used at the crystal spectrometer. If this is not sufficient filters of single bismuth crystals are considered. Experiments are performed to make single crystals of large sizes of materials such as bismuth and lead. One oven constructed for this purpose is also intended to be used for the preparation of single crystals for use as monochromator and analyzer crystals in the triple-axes-instrument. A considerable effort also has gone into the construction and selection of suitable equipment for automation and data registering in the two new spectrometers. Both of these spectrometers are intended to come into operation during 1962.
NEUTRON PHYSICS II (NG Sjöstrand, E Johansson and E Möller)

1. Studies of neutron spectra with the fast chopper

The earlier measurements of the neutron spectrum in a beam extracted from the central channel of R1 have been supplemented with a more detailed study especially of the epithermal range. The upper energy limit has been increased to about 10 keV.

By the use of more efficient detectors it has been possible to discover a fine structure in the neutron spectrum at the three lowest resonances of the reactor fuel. Steps in the neutron flux expressed in lethargi units have thus been observed. The results are in agreement with calculations made in Canada and the USA.

The new measurements in the thermal region confirm the temperature difference of $29^\circ C - 10^\circ C$ between neutron and moderator temperature found in the old measurements.

The work with the fast chopper will continue with two types of experiments. In the first one the chopper will be used to measure the neutron spectrum transmitted through different absorbers such as gadolinium and boron (these measurements have actually already started). These spectra will be used for calibration of foil detectors of different energy sensitivity to be used for spectrum studies in the R3 reactor.

The second measurement is a series of measurements of the neutron energy distribution in a beam scattered out from the interior of a uranium tube. The spectral hardening effect in the thermal and near thermal region will be studied for various wall thicknesses of the uranium tube.

Two members of the group have participated in an international team organized by EANDC with the aim to analyse the possibilities of
making spectrum measurements on subcritical configurations at the Danish DR2 reactor. A report, EANDC 15 A, has been issued and distributed to the member countries for comments.

2. Pulsed experiments

The measurements of the slowing down time in light water for monoenergetic neutrons that started late last year have continued during the year. The efficient running time has been low because much time has been devoted to general improvement of the Van de Graaff machine (see below under Neutron Physics III).

The neutrons are generated in burst by the Li \((p, n)\) reaction in a target inserted in a large volume of water \((1 \text{ m}^3)\). A small amount of neutron absorber can be placed at a chosen position in the moderator. The rate of neutron capture in the absorber is registered by detecting the capture \(\gamma\) rays from the absorber. A fast scintillation counter is used, the pulses from which are fed to a multichannel time analyser. As neutron detectors dilute solutions of cadmium and gadolinium have been used.

The slowing down time to the cadmium resonance is found to be about 3.8 \(\mu\) sec. After about 7 \(\mu\) sec the neutron decay can be described as a sum of two exponentials with time constants of about 4 \(\mu\) sec and 200 \(\mu\) sec. The first one may be ascribed to the thermalization process and the second to the absorption in the water.

Further studies will concern among other things the space dependence of the time behaviour.
Most of the work in the two groups has concerned the completion of the installation of the Van de Graaff machine, construction and manufacturing of experimental equipment and trimming of the electronic circuits for the experiments planned. A continuous ion source was first installed in the machine and from April to August some experimental work could be done. From about September 1 to mid December the machine has been out of operation because of necessary trimming work in connection with the installation of a pulsed ion source. The machine is now furnished with a high frequency ion source yielding 10 nsec pulses, peak current 500 - 1000 μA.

1. (p,n) reactions

A minor set of measurements of (p,n) reactions has been started. The Co^{59}(p,n)Ni^{59} reaction has been studied by observing the γ-lines from excited levels in Ni^{59}. The angular distribution for neutrons emitted from the Be^{9}(p,n)B^{9} reaction has been measured for different proton energies. Studies of (p,n) reactions in manganese are under way.

2. (n,n) and (n,n') reactions

Measurements of elastic and inelastic cross-sections are planned but could not be started before the pulsed ion source was installed. All the experimental equipment is available and measurements will start in spring 1962.

3. Polarization experiments

Polarized neutrons from the Li(p,n) reaction have been used to study the asymmetry of neutron scattering against copper. A magnet
has been constructed which can flip the neutrons through $180^\circ$, whereby measurements for a certain angle can be made without moving the detectors. A neutron-$\gamma$ pulse discriminator has been developed in order to reduce the $\gamma$ background. A further reduction of the $\gamma$ background can be obtained with time of flight technique. This technique will be used for the measurements starting in spring 1962.
A large part of the group's work during the year has consisted of the building of electronic equipment for the Van de Graaff laboratory.

An electronic regulator has been designed and constructed for the beam distribution magnet in the Van de Graaff hall. After passing the distribution magnet the beam goes through a slit between two electrodes. The difference in beam current to these electrodes is amplified and taken to a special winding on the magnet so that the beam is held in the centre of the slit. An electronic difference galvanometer designed and constructed by Section RSI is used as input stage to the regulator.

Certain work has been done for R0 on the digital period meter to make it usable as time analyser in pulsed reactor experiments. Work has started on a circuit for compensation of the dead time losses in a pulse detector. The main object of the circuit is to increase the range of the digital period meter, but it should also be usable for similar applications where the accuracy of measurement is limited by the dead time of the detector.

The apparatus for automatic collection and recording of data (RAMSES) has been further improved. In accordance with the original idea it still consists of a ring circuit which scans a number of positions and from them transmits binary-coded decimal digits or other information to an output device. One position consists of a holder for a plug-in board. The boards containing either decade pulse counters or permanent symbols ("Space", "Carriage Return", "+", "-", etc.) can be inserted in the various positions as desired.

To render the apparatus as flexible as possible, the programme unit has been constructed on a similar plug-in board system. A preset scaler, a bistable trigger and the logic circuits "and", "or" and "nor".

1) This group was transferred to the Section for Instrumentation in October, 1961.
arc placed on boards which can be plugged into different holders. Via a terminal panel the inputs and outputs of the programme boards can be interconnected so as to provide the desired programme functions.

The output device may consist of practically any serial writing machine - a teleprinter, perforated tape punch, recording computer. Two (or more) machines, e.g. a punch and a typewriter, may also be operated in parallel.

A prototype, RAMSES I, is now complete and in operation for R0 and Zebra measurements. It has also been used (with different programmes) for reactor noise measurements and for writing out the contents of the core memory of a multichannel analyser.

As principal output device RAMSES I employs a perforated tape punch. The punched tapes are either directly printed out as tables on A4-size paper sheets or converted into data lists for the Ferranti Mercury computer in a Creed tape editing machine.

RAMSES I can also be connected to a recording addition and subtraction calculator. The latter responds to plus and minus signs from RAMSES so that, at the same time as it records, it can also carry out certain simple data processing operations such as the calculation of subtotals, differences between successive numbers, etc.

Two new RAMSES machines are under construction, one for the Van de Graaff laboratory and one for the crystal spectrometer at R2.

A magnetic tape recorder equipment is planned for the RAMSES system. It will record information from the data collection apparatus at high tape speed. The tape will then be played back at low speed, its contents being transferred to a punched tape. In this way it should be possible to record fairly rapidly varying processes such as high
frequencies of reactor noise.

Reports

WIKDAHL, C-E, The variation of the buckling with the $\text{H}_2\text{O}$-concentration of the moderator in R0. (RFX-68)

LARSSON, K-E, and DAHLBORG, U, Some vibrational properties of solid and liquid $\text{H}_2\text{C}$ and $\text{D}_2\text{O}$. (RFX-69)

PERSSON, R, Eccentric test region in substitution measurements. (RFX-70)

TRUMPY, G, A neutron-gamma discriminator. (RFX-71)

ASPELUND, O, and TRUMPY, G, Fast neutron polarization flip by a transverse magnetic field. (RFX-72)

PERSSON, R, Buckling measurements on homogenized (non-clustered) lattice of natural uranium dioxide, diameter 1.35 cm. (Preliminary results.) (RFX-75)

NYLUND, O, (ASEA), Measurements of the fast fission factor $\varepsilon$ in UO$_2$ elements. (AE-40)

HELLSTRAND, E, and WEITMAN, J, The resonance integral of thorium metal rods. (AE-48)

HELLSTRAND, E, LINDAHL, G, and LUNDGREN, G, Absorption cross sections for zirkaloy 2 and zirconium. (AE-59)
Computer service

The Ferranti Mercury computer of AB Atomenergi has been running in three shifts since 15th August 1961. Its backing store has been extended from 16384 to 32768 words. A new paper tape punch, a Creed 3000 with a capacity of 300 characters/sec, has been attached to the machine. The total useful computing time during 1961 was 2970 hours.

Heterogeneous reactor calculations

The method of individual source-sinks as given by Feinberg and Galanin has been applied to a cylindrical reactor of finite height. The formulation of the problem is based on two-group diffusion theory without fast absorption in the fuel elements. A computer programme calculating the criticality constant, the thermal utilization and the relative number of thermal absorptions in fuel rods, has been developed. The extension of the programme to handle three energy groups or a combination of age and diffusion theory has been discussed. (G Näslund)

The fine structure of the neutron flux

The fine structure of the flux distribution in a heterogeneous reactor has been studied. Programmes have been written assuming a given cosine-shaped source over a finite system or an external source of given strength outside an exponential assembly. (I Andersson, G Enger)
Flux integrals and shape factors

This programme has been developed to process the output from two-dimensional flux calculations. It takes its parameters and tables from the input and output tapes for a problem run by A Hassitt's multigroup programme (AERE T/R 2487) and computes shape factors and weighted integrals of the neutron fluxes and currents. (T Heyman)

Macroscopic reactor parameters

An auxiliary programme, similar to the MUFT code, has been written to calculate the macroscopic parameters required by diffusion programmes. The slowing-down spectrum is computed under simplifying assumptions. The microscopic cross-sections in the programme library are averaged over this spectrum and the parameters for the chosen few-group model are printed out. (K Nyman)

Two-group parameters for control rod cells

A reactor cell consisting of a control rod in a homogeneous medium is homogenized and equivalent two-group parameters are computed which for arbitrary fast and thermal flux on the cell boundary give the correct fast and thermal neutron currents into the cell. (K Nyman)

Burn-up calculations

Several versions of a programme "Burn-up" have been developed. They compute the fuel composition and the lattice parameters as functions of the fuel irradiation. In later versions improved methods have been used for calculating the fast fission factor, the U-238 effective resonance integral and the disadvantage factor. The calculation of geometrical quantities has been extended to handle different types of fuel rod clusters. (B Tolland)
Reactivity lifetime studies

A programme for investigating reactivity variations during the lifetime of a reactor has been obtained by combination of the "Burn-up" programme and the two-dimensional criticality programme written by A Hassitt. (G Eager)

Shielding programmes

A programme for computing the epithermal and thermal neutron radiation through a multilayer reactor shield has been written. It is based on multigroup diffusion theory and can handle up to 50 energy groups with an independent removal source in each. From each group scattering can take place to all groups of lower energy.

Several attempts have been made to compute the high energy radiation which forms the removal source in the shield by integrating a three-dimensional fission source function over the reactor core. The running time for such a programme is found to be prohibitive, however. A programme using simplified geometry and a one-dimensional source function is in preparation. (S Linde, Å Nordén)

Properties of heavy water

The thermodynamic properties of heavy water have been studied. Tables of saturated pressure and saturated volumes of liquid and of steam have been prepared. The pressure was calculated from an empirical formula. The saturated liquid volume has been computed to fit published measurements up to 300°C, and an extrapolation formula has been suggested for the range 300°C - 370°C. The saturated steam volume was calculated assuming the molecular volumes of D₂O and H₂O to be equal at equal pressures and reduced temperatures. (E Axblom)
Monte Carlo

Two programmes for calculating the slowing-down density distribution from a point source in $\text{H}_2\text{O}/\text{D}_2\text{O}$, when the scattering is regarded as anisotropic, have been coded: one for the distribution in space and energy, the other in time and energy. (P-E Persson)

The slowing-down of neutrons around a cylinder of uranium immersed in heavy water has been coded. Programmes for the study of reflection and penetration of neutrons and gamma in spherical and plane geometries have also been used. Studies have begun on using the transformation $\psi = \varphi \exp(-\alpha r)/r$ in cylindrical problems of deep penetration. (C Johansson)

Reports

TOLLANDER, B, 1961, Tables for some approximations used in the calculations of lattice parameters in burn up 1 and 2. (RFN-13)

NÄSLUND, G, and JONSSON, A, 1961, Heterogeneous two-group theory for a finite cylindrical reactor. (RFN-14)

TOLLANDER, B, and AHLSTRÖM, PE, 1961, Calculations of lattice parameters as a function of the irradiation for a heavy water moderated reactor with cylindrical fuel elements. (RFN-15, RFN-18)

ANDERSSON, I, and NILSSON, T, 1961, Programme for calculation of the decay constant from measurements using the pulsed neutron source method. (RFN-19) In Swedish only.

NYMAN, K, and NORINDER, O, 1961, Two-groups current-equivalent parameters for control rod cells autocode programme CRCC. (RFN-21)

PERSSON, P-E, and TELL, B, 1961, Programme producing lists of journals. (RFN-22) In Swedish only.
GENERAL PHYSICS SECTION

Section head: J Braun

THEORETICAL SHIELDING GROUP (M Leimdörfer)

PROJECT CALCULATIONS, POWER REACTORS

R3 - Ågesta (H Grönroos, H Malmberg)

The calculations of the biological shield were essentially completed in 1960. During 1961 the group was involved in this project to a limited extent. The following engagements may be noted: Control of various secondary shielding calculations performed by the contractor; design of transport containers for irradiated fuel elements and hot control rods; planning of experimental programme for testing of shielding calculations.

R4 - Marviken (H Grönroos, H Malmberg)

As this project is still in a preliminary stage no systematical calculations have yet been performed, but effort is being concentrated on various problems of shielding philosophy that occur during the study of different reactor alternatives. Among the problems treated we may enumerate: preliminary calculations on the top shield, control of contractors' calculations of the radial biological shield, investigation of the possibility of placing detectors in the concrete shield to register xenon oscillations. A special study was also made on the effect of neutron spectra upon radiation damage. This problem is of importance since the neutron spectrum in the R4 tank wall is expected to differ considerably from that present in materials testing reactors. The results obtained through the application of a simple cascade theory
Zero power pressurized heavy water reactor, TZ. (M Leimdörfer, C Jönemalm, R Fräki)

The necessary thickness of a magnetite concrete biological shield was determined in 1960. The radial shield has since been recalculated, now applying ordinary concrete, to investigate the economy of such a change. The test resulted in a recommendation to use ordinary concrete which was found to be economically superior to the magnetite concrete alternative, even though a supplementary 10 cm lead coat would have to be applied. Shielding problems in connection with the source loading machine were also treated. (TPM 179, 188, 203, 209, RFAT 22, 40, 41).

Fast zero power reactor, FRO. (M Leimdörfer)

The concrete walls of the reactor building were designed in 1960, and the only problems that remained in 1961 were those related to shielding of entrances and ventilation ducts. (RFAT 11, 20, 25)

Plutonium factory, project study (C Jönemalm, M Leimdörfer)

Calculations of concrete thicknesses in the factory building were started in 1961 and results have been issued in internal memoranda TPM 204, 211, 213.

Miscellaneous (C Jönemalm, R Fräki, H Malmberg, L Forsberg, M Leimdörfer)

The theoretical services of the group have been exploited for various problems in radiation physics and technology, such as designing an apparatus for detecting faults in irradiated fuel elements.
by a neutron transmission method, multiple gamma scattering in concrete-walled rooms (see below: Monte Carlo).

The energy dependence of the sensitivity of a polyethylene moderated boron counter has been investigated by diffusion theory in connection with experiments. The possibility of applying a poisoned moderator to attain tissue equivalence is being investigated.

METHODS FOR BULK SHIELDING CALCULATIONS (M Leimdörfer, L Forsberg)

A bulk shielding code for the Ferranti Mercury is being developed in cooperation with the Numerical Analysis Section. It is based on the principles outlined in report AERE-3216, and the main features of deviation are as follows; the removal source density is carried on to the diffusion calculation in parts, representing arbitrarily chosen energy groups. The multigroup diffusion part permits the use of energy group transfer between arbitrary groups, not only to the group next below as in age-diffusion calculations. These facilities, it is hoped, will improve the accuracy considerably, especially at the fast end of the spectrum and thus provide better predictions of neutron dose rates. The increased accuracy (over single-removal-group and age-diffusion) due to the improved model of treating slowing-down in hydrogen-rich media (by transfer to all lower groups) is evident, and inelastic scattering processes will also be treated more properly. The method has been tested with discrete-energy sources in the case of polyethylene clad boron counters (see above) and the comparisons with experiments are very promising. A programme for compiling the necessary neutron parameters is being coded. The fission, inelastic, and capture gamma penetration and heating will be treated by a Monte-Carlo programme which will take its neutron sources from the programme part described above. Details of the Monte Carlo code are given below. The calculation geometry is planned to be finite cylindrical, but if machine times prove to be prohibitively long a one-dimensional version will have to be used for routine calculations. The
whole bulk shielding programme is planned for completion in the spring of 1962.

NEUTRON DATA (M Leimdörfer, L Forsberg)

A continuous search for neutron data pertinent to shielding calculations is being performed. Unpublished data that are thought to be of interest to other parts of the company are issued as internal memoranda. A review of \((n, n')\) and \((n, 2n)\) data is being prepared in cooperation with the Technical Information Office and was issued in February 1962 (RFA 74).

MONTE CARLO (M Leimdörfer)

The gamma transport part of the bulk shielding code described above is being coded applying the Monte Carlo method. Special sampling procedures to decrease the variance at deep penetrations are being tested and results look very promising.

The problem of multiple scattering of gamma radiation in concrete-walled, spherical rooms with different source energies, detector positions, and wall thicknesses has been treated by the Monte Carlo method. The results have been collected and will be issued in the spring of 1962.

The energy and angular distributions of neutrons transmitted through and reflected from iron slabs have been calculated with plane sources of energies 3 MeV, 9 MeV, and fission and angular distributions of incident particles taken as isotropic, cosine, and parallel, all symmetrical about the plane normal. Energy distributions of collision densities are presented as well. A report of this work is planned to be issued in the spring of 1962. Preliminary results were given by M Leimdörfer at the EAES Shielding Conference at Studsvik in March 1961 and at the Physics Conference at Lund in June 1961.
RADIATION DAMAGE (H Grönroos)

In addition to what has been said under the R4 project the following information may be given: Several theoretical estimates have been made to obtain the influence of the neutron spectrum upon radiation damage. Results using simple cascade theories indicated that the fast neutron dose in the R4 tank wall produces twice as many displacements as the corresponding dose acting on a steel probe in the MTR reactor. Work is in progress, applying developments of modified cascade theory to the problem.
EXPERIMENTAL SHIELDING GROUP (R Nilsson)

Methods for neutron flux measurements

An integrated system for measurements of neutron flux and neutron spectra has been built. The system includes different kinds of thermal, resonance and threshold foils, a calibrated β-scintillation sample changer and computer programmes. (R Nilsson)

The sample changer has a capacity of 30 foils, is equipped with preset time and preset count, and prints out sample number, number of counts, sampling time and time at the measurement. (S Farvolden)

The Mercury computer programmes sort the data from different foil types and activations, calculate saturation activities and give ultimately the thermal, resonance and fast neutron fluxes with their errors. (S Svensson)

Calibration of R2-0

The power of the swimming-pool reactor R2-0 has been determined. The reactor has been used 32 days by the group, and a total power of 5940 kwh has been consumed. (K Randén)

Neutron and γ attenuation in concrete

Neutron and γ dose measurements are required in order to check the validity of shielding calculations. Comparisons between theory and experiment are especially valuable at great distances from the source. Measurements at distances up to 1.5 and 0.9 m have been made on magnetite and baryte concretes respectively. A paper, Aalto, E, and Nilsson, R: "Measurements of neutron and γ fluxes
through thick shields of magnetite and baryte concretes. A comparison with calculation, with some of the results was presented at the EAES conference at Studsvik on March 27 - 29, 1961. Systems with inserted lead-boron-plastic slabs between concrete blocks have also been investigated. Measurements on ordinary concrete have been started. (E Aalto, F Dutoit)

**Neutron attenuation in D\textsubscript{2}O-filled pipes**

A simplified model for calculating neutron streaming through pipes is being tested by experiments. A paper, Braun, J, and Randén, K: "Streaming in D\textsubscript{2}O-pipes", with some of the results was presented at the EAES conference at Studsvik on March 27 - 29, 1961.

**Neutron monitoring for radiation damage experiments**

Routines for determining large neutron doses (10\textsuperscript{17} - 10\textsuperscript{22} n \cdot cm\textsuperscript{-2}) are being worked out. Two new threshold detectors Cu\textsuperscript{63}(n, \alpha)Co\textsuperscript{60} and Ti\textsuperscript{46}(n, p)Sc\textsuperscript{46} have been used at several experiments together with the common Ni-detector. Experiments to determine cross-sections and effective threshold energies have been started. (R Nilsson, K Eriksson)

**Metrology of radioisotopes**

**Standardization**

For different purposes solutions or samples of the following isotopes have been standardized with an accuracy of ± 1 to ± 5 %, the source strength varying between 1 - 10000 dps:

α-emitting nuclides: Ra\textsuperscript{226}, Po\textsuperscript{210}, Pu\textsuperscript{239}, U\textsuperscript{238}
$\beta$-emitting nuclides: Na$^{22}$, Na$^{24}$, Si$^{31}$, P$^{32}$, Fe$^{59}$, Co$^{58}$, Co$^{60}$, Cu$^{64}$, Sr$^{89}$, Sr$^{90}$-Y$^{90}$, Y$^{91}$, Ru$^{106}$-Rh$^{106}$, I$^{131}$, Cs$^{137}$, La$^{140}$, Ce$^{144}$-Pr$^{144}$, Au$^{198}$, Hg$^{203}$, Tl$^{204}$.

**Development of methods**

A 4π$\beta$-γ coincidence set-up was built up offering or choice between a proportional counter and a liquid scintillation counter as $\beta$-detector. The instrument has linear amplifiers and single channel analyzers of high resolution in each channel, a coincidence unit with resolution variable from 0.1 to 4 μs and a variable dead time control.

A γ-spectrometer consisting of a 3/4" x 1" NaI(Tl)-detector associated with a multichannel analyzer was calibrated by means of absolutely counted sources. Preliminary measurements of the 1.52 MeV γ-emission rate from K$^{42}$-sources gave together with absolute $\beta$-counting a percentage of 17.7 ± 0.5 for the 1.52 MeV γ-branch.

The construction of a high-pressure chamber for the standardization of EC-nuclides was started.
Threshold and resonance detectors (J Konijn, B Fjällstam)

Investigations of possible detectors in the intermediate and fast neutron energy region have been carried out.

Resonance detectors

The resonance activation of fluorine was investigated. The reaction $^{19}\text{F}(n, \gamma)^{20}\text{F}$ has at least two strong resonances in the energy region 15 keV to 30 keV. In order to find out to what extent one can use teflon as an activation foil, a scintillation spectrometer equipment was built up, including a facility to measure short half-lives. The electronic equipment was built up during the first part of 1961 and was supplied by a fast-slow transistorized coincident equipment for measuring $\beta-\gamma$ and $\gamma-\gamma$ coincidences.

A pneumatic rabbit was constructed in order to shoot the teflon samples in and out of the reactor R2-0. At the sample activation position the Al-tube could be supplied by a 1 mm thick Cd-covering or a boral covering containing 360 mg B/cm$^2$. From the activation position the sample must pass through a helical bent tube, cast in a concrete plug, to reach the detector. The construction of the above was completed during the second quarter of the year.

The NaI(Tl)-scintillation spectrometer was calibrated for energy and intensity, using standardized isotopes obtained from the standardization group.

Experiments on the activation of teflon have been carried out and the occurring reactions $^{19}\text{F}(n, \gamma)^{20}\text{F}$, $^{19}\text{F}(n, \alpha)^{16}\text{N}$ and $^{19}\text{F}(n, p)^{19}\text{O}$ have been investigated. Activations with and without different kind of
coverings have been started. The construction of an enriched

\[ \text{B-covering} \text{ was started to study the influence of the neutron}
\]
\[ \text{energy spectrum on the activation. The experiments on studying}
\]
\[ \text{the \( \gamma \)-spectrum as well as the half-life measurements of the}
\]
\[ \text{different parts of the spectrum will be continued during 1962.}
\]

In connection with the above experimental a short survey
was made on possible resonance detectors and which \((n, \gamma)\)-cross-
sections are of importance to be measured. (RSA-TPM-180)

**Threshold detectors (J Konijn)**

A systematical investigation on threshold detectors has been
carried out.

Estimated average reaction cross-sections for pile neutrons
together with nuclear reaction Q-values, using the latest available
mass tables have been tabulated in AE-58 (RSA-58).

Threshold reactions having radioactive products with half-
lives longer than three years have been listed in RFA-71.

An investigation of threshold reactions induced by inelastic
neutron scattering on natural elements and leading to isomeric
states has been started.

**Cross-section measurements (J Konijn, B Fjällstam)**

The fast neutron flux of a reactor is frequently measured with
threshold detectors. When time-integral measurements are required
one has to choose reactions resulting in long-lived daughter activities.

To perform these time-integral measurements knowledge of the
reaction cross-section is required as a function of neutron energy.
For this reason cross-section measurements were started at the
Van de Graaff accelerator. The following reactions are planned to
be investigated: \( ^{63}\text{Cu}(n,\alpha)^{60}\text{Co} \), \( ^{58}\text{Ni}(n,\alpha)^{58}\text{Co} \), \( ^{54}\text{Fe}(n,\alpha)^{54}\text{Mn} \)
and \( ^{46}\text{Ti}(n,\alpha)^{46}\text{Se} \).

The cross-section measurements were carried out using a
new technique of detecting the charged particles, produced in the
reactions, with solid state detectors. These detectors are ob-
tained from the group for solid state detectors at the company.

Electronic equipment, a low noise charge sensitive amplifier
and the vacuum chamber were constructed and successfully tried.
The results of preliminary experiments on the \( ^{58}\text{Ni}(n,\alpha)^{58}\text{Co} \)
reaction are described in RFA-66.

Investigations on the background from the solid state detectors
(neutron induced reactions in Si) were started.

The reaction \( ^{31}\text{P}(n,\alpha)^{31}\text{Si} \) was chosen as standard reference
for the above cross-section measurements and an investigation
into this reaction has also been started.

Counters for neutron dosimetry (M Leimdörfer, S Malmskog, R Fräki)

We have earlier developed a proton recoil proportional counter
PC, which has a sensitivity which varies with energy in the region
0.3 - 15 MeV in such a way that the number of counts is proportional
to the rem dose rate. The PC-detector was presented at the Sympo-
sium on Selected Topics in Radiation Dosimetry in Vienna, 7 - 11 June,
1960. It was hoped to extend the lower limit of 0.3 MeV of the counter
down to thermal neutrons by surrounding it with suitable layers of
polyethylene, boron and cadmium. A theoretical investigation of the
possibility of this project is done by M Leimdörfer and R Fräki. To
check theoretical method used in these calculations an experimental
investigation has been performed by S Malmskog on the variation with
neutron energy of the sensitivity of a polyethene moderated boron counter for neutron energies of 2.3 MeV, 550 keV, 210 keV, 110 keV, 340 eV and 5 eV. The results have been compared with a theoretical treatment using the multigroup diffusion method.

(RFA-73)

Fast neutron detectors (S Malmskog, IÖ Andersson1), S Styrén)

A counter of stainless steel, containing field tubes and kovar-glass seals, has been constructed which can be outgassed at 500°C. All joints are welded. The sensitive volume is 503 cm³. To establish the counterproperties, the detector was first filled with ordinary krypton of 3 atm plus 30 mm CO₂. As an X-ray source Hg²⁰³ was used. The counter gave an acceptable resolution of 11.5% for the 72.9 keV Kα X-ray.

After this 668 mm Hg He-3 was added to the counter. The helium gas had a cleanliness of one tritium atom per 10⁸ He-3-atoms. This counter gave a resolution of 11.0% for thermal neutrons and 12.0% for neutrons of 1 MeV.

To improve the resolution a vacuum system has been built to remove tritium from the He-3-gas. The helium gas is forced to pass a trap cooled with liquid helium. When circulating the gas for 12 hours a cleanliness of one tritium atom per 5×10¹⁰ He-3-atoms was achieved. Unfortunately a better resolution did not show up. This must be due to the fact that electronegative gases enter the counter during the tedious filling process. The conclusion is drawn from the fact the X-ray resolution is destroyed after the He-3-filling. New attempts to get a better He-3-spectrometer will follow in the near future.

1) Since October 1, 1961, transferred to Electronics Section (SSI)
Slow neutron detectors. (S Malmskog, IÖ Andersson)

The pulse height distribution from BF$_3$-counters irradiated by thermal neutrons has been investigated. Special attention is given to the wall effect, the resolution and the branching ratio of the $^{10}$B$(n, \alpha)Li^7$ reaction. A comparison has been made with tubes delivered from 20th Century Ltd, England, and Nuclear Chicago Corp., USA, and those from our own production. (RFA-82)

Reports

A large number of internal reports were published during the year. Some of these written in English are listed below.

BRAUN, J, and RANDÉN, K, Streaming of neutrons in D$_2$O pipes.

FORSBERG, L, The $S_n$-method, a short introduction (RFA-61)

HELLSTRÖM, S, International intercalibration of $^{131}$I-solution. (RFA-60)

KONIJN, J, $Q$-values for $(n, p)$ and $(n, \alpha)$ reactions. (RFA-58; AE-58)

Preliminary experiments on the cross-section measurement of the $^{58}$Ni$(n, p)^{58}$Co reaction with a solid state detector. (RFA-66)

Threshold reactions having radioactive products with half-lives longer than 3 years. (RFA-71)

NILSSON, R

Half-live measurements of $^{204}\text{Tl}$ and $^{110}\text{mAg}$ (RFA-64)

RANDEN, K
