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Construction and Experimental Equipment of the Karlsruhe Fast Critical Facility, SNEAK*)

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*) Work performed within the association in the field of fast reactors between the European Atomic Energy Community and Gesellschaft für Kernforschung mbH., Karlsruhe

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Summary

Construction of the Karlsruhe Fast Critical Facility, SNEAK, was completed in the summer of 1966. A brief description of its main design features, its experimental equipment, and the methods used for precise reactivity measurements are given.

SNEAK is a fixed vertical assembly with fuel elements suspended from a top grid. Horizontal and vertical channels may be formed in the reactor. The two horizontal channels will be used for a material replacement drawer with automatic sample changer, a detector or material traverse device, and a pulsed neutron source. Four vertical channels close to the core center are available for installation of a pile-oscillator. A gas-heated loop is being constructed for Doppler experiments.

Four methods used in SNEAK for precise reactivity measurements are compared: the asymptotic period method, the pile oscillator method, the inverse kinetics method, and the autorod method. Some details are given about the equipment and data treatment, in particular about measurements in the presence of a spontaneous neutron source. Signals from linear pulse or ionization chamber channels may be collected either by a four channel data acquisition system or a 256 channel analyzer. A special technique for storing periodic signals enables elimination of linear drift.

1. Introduction

The first ideas for a fast critical facility in Germany date back to the end of 1961. At that time, substantial uncertainties existed in basic nuclear data. Many design parameters of large fast power reactors, such as critical mass, breeding ratio, and the Doppler reactivity coefficient could not be predicted with sufficient accuracy. It was felt that a fast zero power reactor could provide appreciable support for the fast power reactor development work in Germany.

In 1962 the basic design objectives of SNEAK were fixed: SNEAK should allow the investigation of large dilute fast systems with Pu fuel; it should provide accessibility for experiments inside and outside of core and blanket; reactor safeguards should be stressed because SNEAK would be Germany's first fast reactor with Pu fuel. In order to provide adequate safety, any possibility of large accidental reactivity additions and fast uncontrolled reactivity additions had to be excluded. The reactor containment should protect the surrounding area even in the unlikely case of a large fire inside the building.

The design began in 1963. Siemens (SSW) was chosen as architect engineer and primary contractor. Construction at the site started by the end of 1963. The buildings were basically completed by the end of 1965 and in 1965 the major reactor parts were supplied. Installation and functional tests continued during 1966.

SNEAK was constructed and will be operated as part of the association EURATOM-GfK in the field of fast reactors.

In part 2 of this paper a brief description of the facility will be given. Part 3 describes the experimental equipment which is directly associated with the reactor. Part 4 deals with reactivity measurement techniques.

2. Description of SNEAK

2.1 General Arrangement of Buildings

The general arrangement of SNEAK is shown in Figs.1,2, and 3. The reactor is housed in an airtight and pressure resistant building. In order to withstand even a very severe metal fire, the design pressure was chosen as 2 atmospheres gauge. Two steel shells, each with a leak rate smaller than 1% per day, guarantee an extremely small overall leakage. By pressure regulation in the interspace, the leakage can be controlled so that all air leaving the reactor building is given to the atmosphere through filters.

The reactor building is connected with the operations and storage building by a personnel air lock and with the loading area by the fuel element transit lock.

2.2 Reactor Construction

SNEAK is a fixed vertical assembly with fuel elements suspended from a grid. A major point in selecting this type was that the large reactivity addition in closing the halves of a split-table machine could be avoided. The loading is performed from below in order to exclude fuel rod drop accidents. The fixed vertical assembly type furthermore has the advantage of smaller void and steel fractions (6.5% and 7.5% respectively) as well as convenient cooling and loop installation. These advantages and the increased safety had to be paid for by a rather high building and by the need for a number of transport and loading devices.

The reactor has a maximum diameter of 3.2 m and a max. height of 2.7 m. It is assembled out of square elements which are suspended from a top grid plate, and, after completion of loading operations, are fixed in their positions by clamping devices at the bottom. There are two loading machines: a lower loading machine which transports elements between the reactor and the fuel element transit lock; an upper loading machine which hoists the elements into the reactor.

The fuel elements in the core section are square stainless steel tubes of 51 x 51 mm inner dimensions, the elements in the blanket section are square tubes of 153 x 153 mm inner dimensions. The lattice pitch is 54.4 mm in the core and 163.2 mm in the blanket. At present, the core section contains a 24 x 24 array of elements (fig. 4), it can later be extended by replacing blanket elements with bundles of 9 fuel elements.

The core elements have a specially shaped cross section so that cooling channels are created between adjacent elements. Air taken from the reactor hall flows downward through these channels at a flow rate sufficient to hold material temperatures close to ambient. As the coolant air flows outside the fuel element tubes, there is no direct contact between it and fuel pieces and the air can not be contaminated.

2.3 Safety System and Instrumentation

The inherent safety of a flexible system such as SNEAK is relatively poor. Calculations show /1/ that only 0.3 to 0.4% $\frac{\Delta k}{k}$ can be compensated by the negative temperature coefficients before dangerous temperatures are reached. Therefore the safety system must be very reliable. Neutron flux, core temperature, γ-flux, U- and Pu-concentration, ß-activity, and air pressure inside the reactor building are controlled by fixed instrumentation. Reactor power is controlled from the beginning of fuel loading by means of a logarithmic BF_3-counter channel. At higher power a logarithmic ionization chamber channel takes over automatically. The safety channels are built in 3 parallel units, working for greater reliability in a 2 out of 3 system. Incorporated in the control system is a circuit which checks the digital part of the system by periodically supplying test pulses. Thus, the maximum time interval of undetected failures in this part of the instrumentation is kept very small ($<$ 2 sec). The analog part of the system is checked by comparing the output signals of any 2 parallel units. Upon a failure in one unit, the 2 out of 3 system is automatically switched to a 1 out of 2 system.

At scram the safety rods are released from their holding magnets and accelerated downward by an electromagnetic impulse generated by discharging a high voltage capacitor (3000 V, 500 μf) through a coil. The rods reach a speed of 1 m/sec within 1 msec after the scram signal.

There are up to 20 shim rods and up to 10 safety rods. All control rods may be used either as fuel or as fuel-poison rods, thus providing sufficient shut down reactivity even in very large assemblies. Control rods may be placed at any 9th core element position (fig. 4). All parts of the rods, including the drives of the shim rods, are contained within a guide tube of normal fuel element cross section.

The moveable parts are tubes of somewhat smaller cross section (47 x 47 mm square). Shim and safety rods add reactivity in moving upward, therefore the motor speeds are restricted in order to keep reactivity insertion rates below 0.1 $/sec. After a scram all shim rods are driven out of the core. During loading operations the safety rods are in and the shim rods are out.

2.4 Core and Blanket Materials

The core materials have been fabricated into square 50.75 x 50.75 mm plates, varying in thickness between 1.57 mm and 25.37 mm. Most pieces are 3.15 mm thick; the steel canned Na and PuO_2-UO_2 plates are 6.30 mm thick. The metallic uranium plates are nickel plated to prevent corrosion. At present, about 530 kg of U235 are available, most of it in 20% or 35% enrichment. 175 kg of Pu are being fabricated into PuO_2-UO_2 pellets with a Pu:U ratio of 1:3 and will be available early next year. This ratio was chosen in order to provide a negative Doppler coefficient in the assemblies. Each fuel plate contains 9 PuO_2-UO_2 pellets in a stainless steel can.

Materials for blanket and reflector simulation, i.e., depleted uranium, steel, aluminium, and graphite, are also available as rods of 17 x 17 x 305 mm (fig. 5). Bundles of 9 of these rods fit in a core element, 81 in a blanket element.

The materials are stored in a series of cells in the storage building. The fissile material containers are mounted in bird-cages in order to prevent accidental criticality during storage and handling.

2.5 Loading of Elements

Normally core elements are loaded and unloaded by ZEBRA-type automatic loading and unloading machines. The machines can identify the various types of plates by means of two identification slots located at one edge of the plate. The loading machine fills the core tubes automatically with a stack of plates in a sequence programmed on tape. The unloading machine takes the plates out of the core elements and sorts them back into their storage containers. The machines guarantee correct loading and reduce manual handling and the radiation exposure of the loading personnel. The loading operations are made under a hood whose exhaust air is monitored for U and Pu α-activity and then fed through filters into the exhaust system.

For the loading of special elements there is a hand loading station. A special device exists for the loading of the heavy blanket tubes

Filled elements are either stored in a storage area in the loading room, or they are taken to the element transit lock through which they are brought into the reactor building, taken over by the lower loading machine and hoisted into the reactor by the upper loading machine (Figs. 2 and 3).

3. Experimental Equipment

3.1 Linear Neutron Flux Channels

In addition to the logarithmic channels, which are connected to the reactor safety system, two linear ionization chamber channels are installed for experimental purposes. Various BF_3 and He^3 filled ion chambers of high neutron sensitivity serve as detectors for the linear channels. Two kinds of amplifiers are used: the electrometer type and that based on voltage dependent capacities. A deviation meter with display on the control desk facilitates accurate reactor operation. It shows the deviation of reactor power from a set point in percent. For easy data acquisition the signals are digitized by voltage to frequency conversion. Several BF_3 and He^3 filled proportional counters are available for linear pulse channels. Small U235, U238, and Pu239 fission chambers will be used for power calibrations of the SNEAK assemblies.

3.2 Autorod (/2/, /3/)

In addition to the standard control rods, a high precision automatic rod has been built which accurately compensates reactor perturbations and measures their magnitude in terms of rod travel. The rod is moved automatically until the output of a linear channel equals a highly stabilized reference voltage. The reactor power is thus kept constant, and a change in rod position is a direct measure of the reactivity worth of the perturbation in the reactor. The autorod assembly is mounted on the topgrid plate and can be located above any fuel element position. It is driven by a printed circuit motor because of its favorable torque-inertia ratio. The vertical stroke of the rod is limited to 300 mm. The time constant of the rod is smaller than 0.1 sec and its maximum velocity is approximately 75 mm/sec. Digital position indication is obtained by optical decoding of the angular position of two discs, one of which is directly fixed to the lead screw of the autorod. The resolution of this system is one part in 10^5. The part of the rod which travels in the reactor core contains natural boron carbide in a tube. Other loadings are prepared in identical tubes so that the boron carbide can easily be replaced by a different material.

3.3 Reactivity Meter

It is possible to obtain continuous reactivity information with the aid of a small on-line analog computer that solves the inverse reactor kinetic equations /4/, /5/. Although very high precision cannot be expected, the fact that the information is instantaneous facilitates experimental reactor operation. For this reason a reactivity meter has been incorporated into the SNEAK instrumentation. Its output is displayed on a recorder at the control console and on one in the experiment control room. Four operational amplifiers and one servo-multiplier are incorporated in the fixed wired circuit of the meter; the delayed neutron terms are generated by passive networks. Automatic switching of the source term simulator occurs simultaneously with range switching of the linear amplifier in the ionization chamber channel.

3.4 Vertical and Horizontal Core Channels (Fig. 4)

The SNEAK design with fuel elements suspended from a top grid makes it relatively easy to generate vertical channels at any desired location. A number of fuel and blanket elements can be equipped with a hollow suspension rod with an inside diameter of 18 mm. This rod is followed by a tube with equal inside diameter protruding through the fuel element. The vertical channel which is formed in this way from the top of the reactor allows the insertion of a neutron source, detectors, or material samples. The space between the cylindrical tube and the sides of the fuel element can be filled with core materials.

Larger vertical channels can be formed at four locations near the core center where the top grid has square holes with sides of 55 mm. These large channels will, e.g., be utilized for pile-oscillator experiments.

A horizontal channel in SNEAK has to penetrate a row of core and blanket elements. To allow this, these elements are provided with windows which give access to a rectangular tube with sides of 31 and 58 mm. One horizontal channel can be inserted at midcore level in the north-south direction, another one 30 cm lower in the east-west direction. The horizontal channels will be used for detector and material traverses and for insertion of a pulsed neutron source. A pneumatic system enables rapid transport of activated foils with short halflife from the reactor core to a counting device /6/.

3.5 Horizontal Drawer with Sample Changer

As the reactor hall is not accessible during operation, a mechanism is constructed which can move and exchange various sample materials in a special drawer through a horizontal reactor channel. The drawer is subdivided into 30 compartments of 54.4 mm length. Each of them can hold a container with a sample of dimensions 25.5 x 51 x 51 mm. A sample may consist of a stack of standard SNEAK material plates. A sample container can be inserted manually or by an automatic sample changer which has storage capacity for 24 samples. The reactor does not have to be shut down between measurements if the sample changer is used. The sample drawer can be moved with speeds of 1,3 or 10 m/sec by a high precision lead screw. Digital position indication with a resolution of one part in 10^5 is obtained from a coded disc which rotates when the drawer moves along its 2 meter travel path.

An electronic control unit enables automatic operation of sample changer and drawer. Entire sequences of operations consisting of repeated sample changing, positioning to an accuracy of 0.2 mm, and removal of the sample after a certain time interval, may be read into the electronic control unit from punched paper tape. The automatic operation can be interrupted at any time and continued by manual instructions to the electronic unit which is located in the experiment control room. The mechanism can also be used for detector traverses.

3.6 Vertical Traverse Mechanism

Traverses in vertical direction in any one vertical channel can be made by a mechanism that can be operated automatically from the experiment control room. For example a set of fission chambers can be moved stepwise into the reactor core by means of a program punched on paper tape. Although the mechanism is primarily intended for detector traverses, light weight samples may also be traversed. Exchange of samples must be done manually in the reactor hall. The traverse mechanism has been developed at STARK by D. Stegemann /7/.

3.7 Pile-Oscillator

A pneumatic pile-oscillator has been built for measurement of very small reactivity effects. Two specific examples are the effect of temperature rise in a sample and that of voiding a core material sample of sodium.

The part of the oscillator which moves through the reactor core is a square tube with the same cross section as a control rod. In addition to holding samples, the tube can be filled with material plates over its full length. The tube is much longer than a normal fuel element, so that, even in the extreme oscillating positions, the part of the oscillator channel which is located in the reactor core is filled with material. If the oscillator is filled with core material, the reactor core is perturbed by the sample only. The tube is oscillated pneumatically with a stroke of 80 cm and a transition time of less than 2 sec. The whole mechanism is mounted on a motor driven carriage so that the oscillator can be remotely repositioned vertically over a length of 70 cm. This is of interest when space-dependent sample worths are measured: If the oscillator could not be repositioned, it would be necessary to relocate the sample inside the oscillator tube several times in order to measure space-dependent worths. Exchange of samples is done manually because the oscillator is not meant for routine measurements of large series of samples.

The oscillator will be utilized for Doppler reactivity measurements by oscillation of a heated fuel sample. The sample is electrically heated up to 1000°C in an oven which is insulated from the reactor by a thermal shield and a vacuum. The cylindrical fuel samples have a diameter of 3.5 cm and lengths of 9 and 15 cm.

Pile-oscillator and Doppler-furnace have been developed at STARK by L. Barleon /7/.

3.8 Doppler-Loop

The Doppler effect will be measured not only by exchange of hot and cold fuel samples, but also by periodic heating of a geometrically fixed amount of fuel /8/. This Doppler sample consists of pins which are located in the core center in special fuel elements. The size of the samples can be varied up to 4.5 l by addition or removal of these special elements. The composition of the sample can be altered by mixing pins of PuO_2-UO_2, pure UO_2, a Na alloy, zirconium hydride and various structural materials. Except for a narrow gas flow channel, the unheated volume of the Doppler elements is completely filled with standard SNEAK material plates.

The sample is periodically heated and cooled by a stream of CO_2 through a temperature interval between $50^{\circ}C$ and $350^{\circ}C$. In order to avoid thermal instabilities two separate loops are used for cooling and heating. In each of these loops the gas flows continuously either through the sample or through a dummy which has equal heat capacity and flow resistance. The sample is thermally insulated from the reactor core by double walls and a flow of air.

4. Reactivity Measurement Techniques

4.1 Methods for Precise Reactivity Measurements

Among the methods to determine reactivity there are some which enable the measurement of very small effects with high accuracy. Each of the methods has its specific merits, and therefore several will be applied at SNEAK, the choice depending on the requirements for various experiments. The methods differ in their sensitivity to noise, drift, and transients, and in the amount of equipment needed for control of the experiment and analysis of the data. Furthermore the length of time required for a measurement and for its analysis varies widely.

Measurement of asymptotic periods certainly is the most popular method to determine reactivities. It has the advantage of simplicity and therefore of reliability. Special equipment is not required, neither for the measurement nor for its analysis, although digital output of the varying neutron flux over a selected time interval and subsequent treatment of the data by a digital computer considerably facilitates the experiment. Disadvantages of the method are: 1) an asymptotic period is established only after transients have died out; 2) it is difficult to eliminate the influence of reactor drift. In a plutonium reactor the presence of a large spontaneous neutron source prevents the establishment of an asymptotic period at low power. A computer program that follows the procedure of the commonly used graphical analysis of asymptotic periods would be of little use at SNEAK. Therefore two other methods of analysis which take the influence of a source into account were programmed. Each method calculates in a different way the magnitude of the spontaneous neutron source and extrapolates the measured reactor periods to an asymptotic one. The first method was developed at the Swiss reactor SAPHIR /9/ as a graphical extrapolation procedure by which the stable reactor period can be found from measured positive or negative reactor periods. The reciprocal values of instantaneous reactor periods are plotted as a function of the reciprocal of reactor power. The points lie on a straight line which intersects the ordinate at the reciprocal stable reactor period. A different graphical method was used at the Halden Boiling Water Reactor in Norway /10/. The influence of a photoneutron source on period measurements was reduced by an iterative procedure. We have programmed this method in order to allow more iterative cycles /11/. For a supercritical reactor a logarithmic plot of count rates versus time deviates from a straight line if a spontaneous neutron source is present. The deviation disappears if a constant source term is added to each count rate. In order to determine the value of this source term, a straight line is fitted to the last part of the data where high count rates occur and the source term has little influence. The source term is subsequently obtained from the first part of the data by determining the difference between the fitted line and these data. With this term added to the measured count rates, a logarithmic plot now approaches the expected straight line more closely than the original data points. The procedure is repeated with larger portions of the data. Iteration continues until all experimental data are utilized and the slope of a fitted straight line does not deviate significantly from the previous one. This slope gives the reciprocal asymptotic period. It can be shown that this procedure leads to a higher accuracy than the Swiss method.

Another precise method for measurement of reactivities which has been in use for many years is the pile-oscillator method. Advantages over the asymptotic period method are: 1) the influence of reactor drift can be effectively eliminated and 2) data can be collected continuously during an arbitrary length of time. This is accomplished at the cost of a relatively complicated mechanism that accurately oscillates the sample. Also required is computing equipment that calculates the amplitude of the fundamental harmonic of the reactor power signal. At SNEAK this is done with a digital computer. The program is based on cross correlation of a cosine and the experimental signal; it removes the influence of linear drift. The periodic reactivity signal is not necessarily generated by a moving sample; e.g., in the SNEAK Doppler loop, periodic heating and cooling of a sample causes a reactivity signal.

A third method of determining reactivity is to solve the inverse reactor kinetic equations with the aid of an analog or digital computer /4/, /12/. The input is a signal proportional to the time varying neutron flux of the reactor; output is the reactivity as a function of time. In addition to the effective delayed neutron constants the effective strength of a spontaneous neutron source is needed as a constant in the equations. The source term can be determined by solving the equations without this term after a step change in reactivity at low reactor power. The main advantage of the method is the time saving resulting from the fact that one does not have to discard the data taken during flux transients, since their effect is taken into account properly in the reactor kinetic equations. A disadvantage is its sensitivity to noise and reactor drift. It is possible, however, to reduce their influence by repeating the measurements. Data collection need not be interrupted between measurements. The inverse kinetics method is applied at SNEAK by off-line digital analysis for precision measurements and by on-line analog computing (reactivity meter) for ease of reactor operation. The digital code will be used for rapid rod calibrations and sample reactivity measurements.

The fourth method utilizes an automatic regulating rod /2/, /3/. Each reactor perturbation is immediately compensated by this rod and no transients of reactor power occur (only the spatial distribution fluctuates slightly). Reactivity is derived from differences in control rod position, which makes a separate rod calibration necessary. In contrast to the other methods, this method makes only relative reactivity measurements. The influence of drift and noise can be reduced by careful planning of measurement and analysis. Very good results with the autorod method have been reported at the ARMF /13/.

4.2 Data Acquisition from Periodic and Non-Periodic Signals

A four channel data acquisition system is available for general use, in particular for collecting non-periodic signals. The system consists of a timer, four counters, a printer, and a punch unit. The eight-channel paper tape can be manually or automatically prepared for computer input. Both alternating or continuous modes of operation are possible. In the alternating mode two of the counters are read out while the other two collect counts. In the continuous mode all four count independently, so that four signals can be accepted.

A 256 channel analyzer will be utilized for data collection of periodic signals from one of the linear channels. The analyzer has been modified slightly to permit direct access to any one channel. This has been done for use with a special method for elimination of linear drift; this method is as follows. Assume that 4n counts have to be collected during each period. The first n counts, which are collected during the first quarter period, are stored in a separate set of analyzer channels 5n+1 through 6n. The remaining 3n counts of the first period are stored in the channels n+1 through 4n. The 4n counts of each following period are stored in the channels 1 through 4n, which results in a great reduction of data. If the measurement must be interrupted due to drifting of the signal out of the linear amplifier range, the data storage is not simply stopped at the end of a full period, but the counts arriving during the first quarter of the next period are also stored separately in the channels 4n+1 through 5n. This storage method offers the usual periodical data storage with arbitrary intial phase, with the added possibility of shifting this phase up to a quarter period. The correlation function of the signal with a cosine can now be calculated with a correlation time varying between zero and a quarter of an oscillation period. It should be noted that a signal drift which is linear during each single period does not contribute to this function. The amplitude of the fundamental harmonic of the signal is determined by means of two cosine cross correlations with correlation times zero and a quarter period respectively.

In the case of Doppler loop experiments, not only the periodic neutron flux signal but also temperature signals have to be stored. Up to four signals may be stored on a time sharing basis in the multichannel analyzer. Because temperature signals have a very large signal to noise ratio they can be recorded with sufficient accuracy in a short time. Therefore most of the analyzer time is available for the collection of the neutron flux signal.

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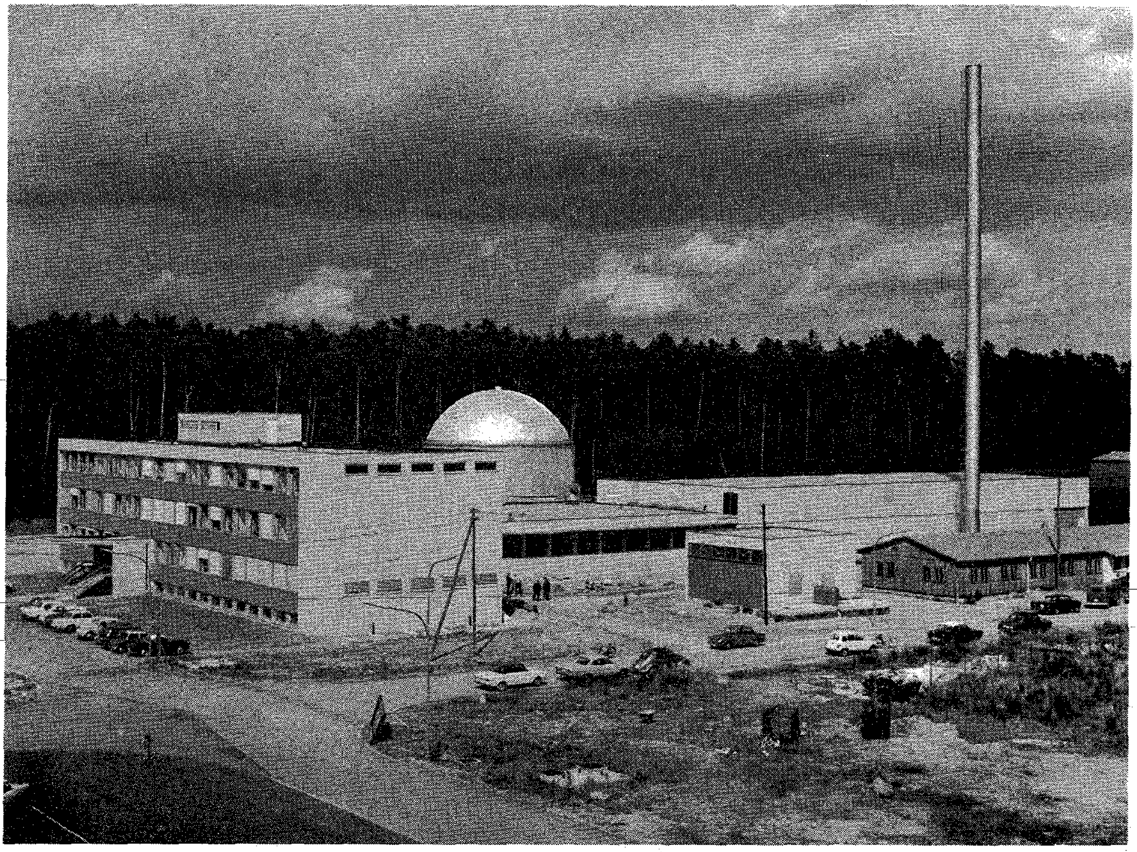

Fig. 1 SNEAK and Institut für Angewandte Reaktorphysik

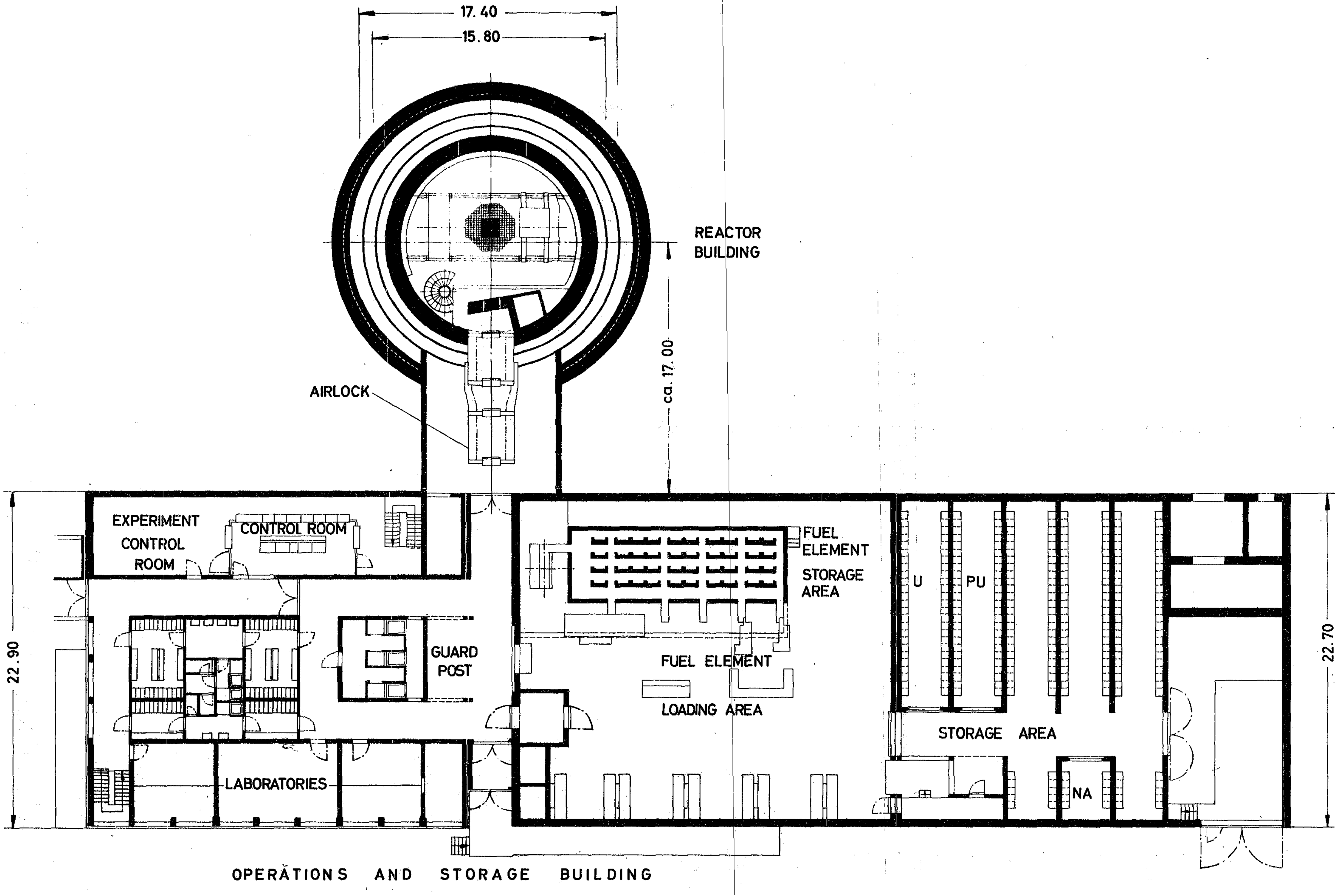

FIG. 3 FLOOR PLAN OF BUILDING

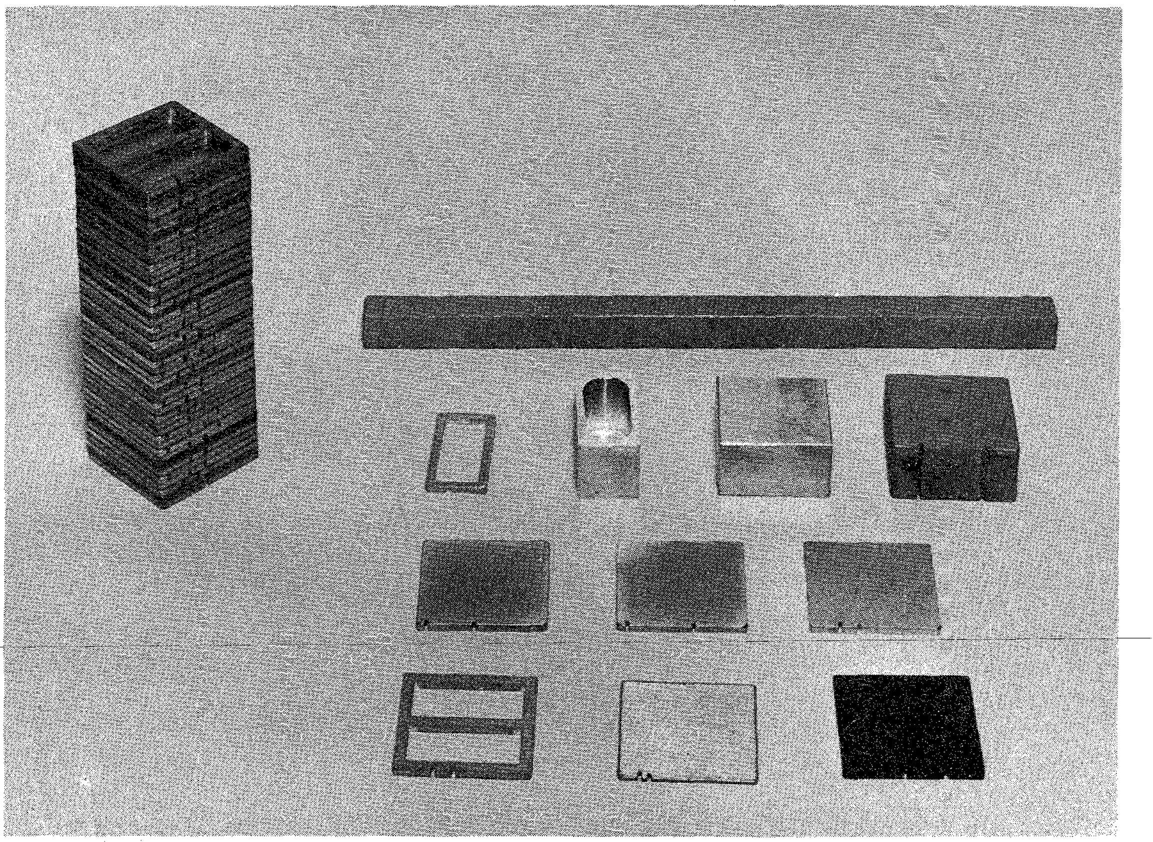

Fig. 5 Core and Blanket Materials

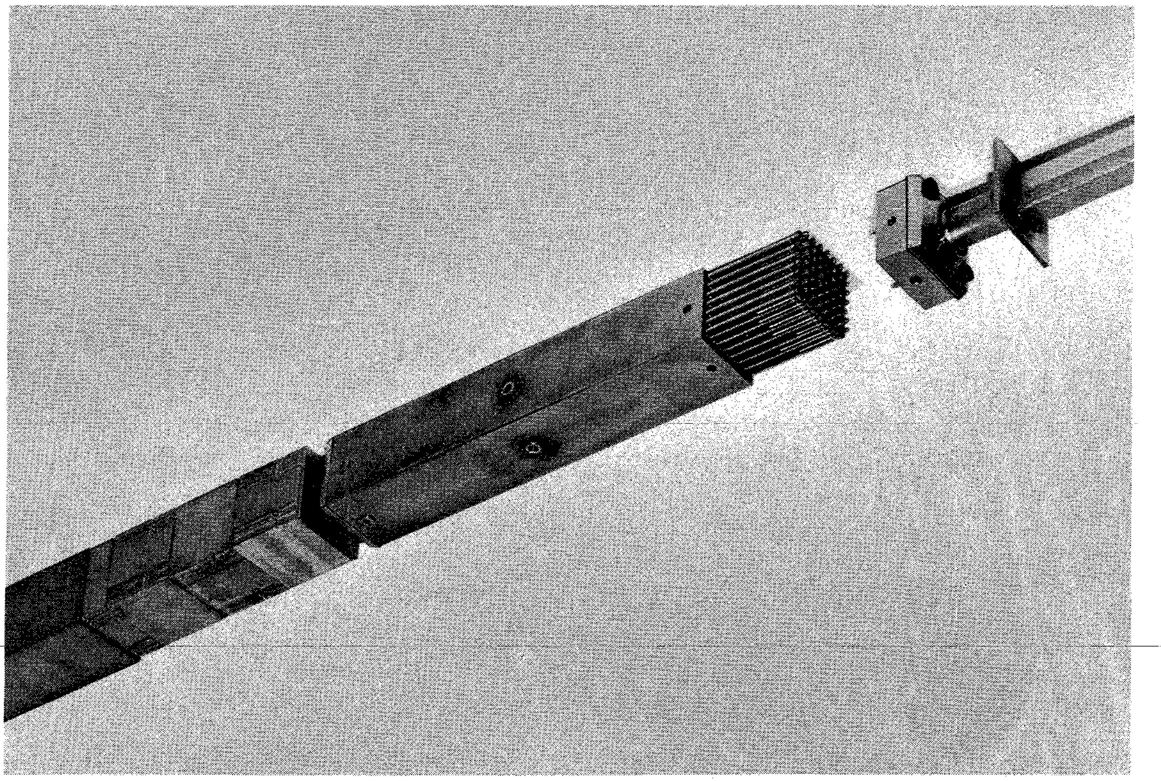

Fig. 7   Special Element with Doppler Sample