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by

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SAFEGUARDS MEASURES AND EFFORTS IN CONCEPTUAL FABRICATION PLANTS FOR URANIUM AND PLUTONIUM CONTAINING FUEL ELEMENTS

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1. Introduction

Fabrication plants occupy a key position in any nuclear fuel cycle. From the point of view of fuel cycle optimisation, the fabrication costs require attention, as they influence significantly the fuel cycle costs of any power reactor. In connection with safeguards, particular attention has to be paid to fabrication plants, as both uranium and plutonium are present in a fairly inactive and accessible form through all the process steps in such plants.

In the present paper, some estimates have been made on the growth of fabrication demands in Germany in the coming years. Some measuring methods which could be of interest for fabrication plants, have been discussed. Some conceptual designs of fabrication plants have also been presented which have been specially prepared to analyse and incorporate various safeguards requirements based on the principle of controlling the flow of fissile material at strategic points. Finally, the total efforts required in implementing all the safeguards measures at these strategic points have been estimated for these plants.

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2. Fabrication Requirements in a Country

The fissile material throughputs in a fabrication plant influence the safeguards measures in a significant manner. The uncertainties with which the fissile material amounts can be determined at a particular strategic point, are a direct measure of the accuracy with which statements on the diverted material can be made. And for a given measuring accuracy, the larger the throughput of fissile material in a plant, the larger is the uncertainty with which they can be determined. It is therefore, important to know the throughputs which are to be expected for fabrication plants in the coming decades in a country. However, the total required throughput in a given year will not necessarily be covered by a single plant but will have to be covered by several plants.

The fabrication requirements for fissile materials in any country are determined mainly by the rate of penetration of nuclear energy and the types of reactors used to produce this energy. Analytical and numerical methods which can be used to estimate this requirement have been discussed in great detail elsewhere /1,2/. These analyses show that the throughput in a fabrication plant in a given year depends ultimately on two reactor parameters. The burn-up determines the running requirement of the reactors already installed and the rating determines the requirement of the reactors to be installed in that year. It is also interesting to note in this connection, that for a given year and a given nuclear system, the fabrication requirement will always be greater, in the seventies even by a factor of two, than the reprocessing requirement.

The estimated fabrication capacities in the next two decades for Germany, for a light water reactor - fast breeder combination, have been shown in Table II. The capacities for a given year have been broken down for enriched uranium (LWR), depleted uranium (radial blanket for fast breeders) and plutonium uranium mixtures (core and axial blanket for fast breeders). Table I gives the data which were used in estimating these capacities. Table II shows that fabrication requirements for light water type reactors would be around 550 t/a in 1970 going up to about 1300 t/a in 1980. The fabrication capacity for plutonium containing fuel is expected to be around 10 t/a in 1975 and 100 t/a around 1982.

3. Measuring Methods in a Fabrication Plant

Any measuring method to be applicable for safeguards purposes should fulfil a number of basic conditions /‾3_7. The more significant of these conditions are summarised in Table III. These conditions are particularly applicable to indirect methods for pins and subassemblies at the process end of a fabrication plant. A large number of such methods receiving active attention of different research groups, have already been discussed in detail /‾4-9_7. Therefore, only a short description of a few measuring systems which are being investigated at Karlsruhe Research Center, are summarised in this paper.

3.1 Calorimeter

The radio calorimetry, which utilizes the α-decay heat of the plutonium isotopes for estimating the plutonium content in a given amount of nuclear fuel, is a fairly known method. The heat outputs from a typical mixture of plutonium isotopes are shown in Table IV. A prototype calorimeter was built by the Firm ALKEM in collaboration with the Karlsruhe Research Center, in which plutonium containing fuel pins can be measured. This calorimeter was tested for accuracy during the framework of a safeguards experiment in a fabrication plant /‾10,11_7. The total measuring error (coefficient of variation of 1-σ value) in a calorimeter of this type, consists of three different types of errors, namely (a) reproducibility of the results (which is a function of the calorimeter set-up), (b) errors in the determination of Pu isotopes and, (c) error in the determination of the age of Am-241 produced initially from Pu-241. The over all error in this calorimeter was found to vary between 0.8 - 1.2 %. The contribution of errors from the different sources is also indicated in Table IV. An analysis of these errors and the present calorimeter set-up indicate, that the contribution of reproducibility can be reduced to around 0.1 % and that of the isotopes to around 0.35 % so that an overall error of $\pm$ 0.4 % appears to be attainable in a commercial calorimeter of this type. In collaboration with the Karlsruhe Research Center, the firm ALKEM is now engaged in designing calorimeters for industrial scale production. In the final design, the neutron generated by spontaneous fission of Pu-240 and by α-n reaction will also be measured, to make the system as tamperproof as practicable. The calorimeter is expected to be located permanently at the process end of the plant and to be used both by the plant operators and the safeguards personnel.

3.2 Slowing Down Time Spectrometer [4, 9]

The heat release due to α-decay in uranium is 5 to 10 orders of magnitude lower than that in plutonium. As a result radio calorimetry cannot be used for uranium with the presently known sensitivity of the system. A slowing down time spectrometer is under development, in which typical fuel pins for light water reactors, containing upto 5 % U-235 (rest U-238), can be interrogated for their U-235 content. This method is based on the fact that short periodic neutron pulses from a neutron generator will sustain a relatively narrow energy distribution while slowing down in a lead pile. There exists a simple relation between the mean neutron energy of the distribution and the slowing down time as shown in Fig. 1. If the fuel pin to be investigated, is introduced in the lead pile, in the path of the neutron beam, fission of U-235 and Pu-239 is initiated by the impinging neutrons, provided they have energies in one of the resonance regions. The time dependent fission rate, which may be measured by accounting the induced fission neutrons with proton recoil counters, is proportional to the fuel content of the pin.

Although this method can be used to estimate both U-235 and plutonium, the industrial instrument is being developed by the firm INTERATOM, Bensberg Germany (in collaboration with the Karlsruhe Research Center) mainly for the estimation of U-235 content in fuel pins for light water reactors. Research work to determine accurately U-235 and Pu in the presence of each other, is being continued at the Karlsruhe Research Center.

Some important data on the spectrometer are presented in Table VI. The whole system is expected to be ready by the end of 1970. Because of the heavy bulk of the apparatus and the fact that it would be useful to the plant operators also, it is expected to be permanently installed at the fabrication plant.

3.3 n,γ Process [4, 8]

The measuring method, based on n,γ reaction, which is also being investigated at Karlsruhe, is in its initial phase of development. In this method, the fissile material under investigation is exposed to neutrons of energy high enough to avoid destortion due to resonance self shielding. When the incident neutron hits the target nucleus, a compound nucleus results. Because of the binding energy ofa neutron(5 to 8 MeV) and its kinetic energy, this nucleus will necessarily be in an excited state. This excitation energy is dissipated by emission of γ-rays. It is expected that the fissile material isotopes of interest (e.g. U-235, Pu-239, Pu-240), will show some isotope specific γ lines in the capture γ-ray spectrum. These specific γ-lines can then be utilized in estimating the isotopes in a quantitative non-destructive and indirect manner. This method has been tested successfully for some low molecular isotopes. Detailed investigations are being carried out for the fissile and the fertile isotopes.

3.4 Methods for Feed and Waste-Streams

The methods discussed above are mainly for fissile material assay in completed pins or subassemblies, although the calorimetric method can be used to determine plutonium content in bird cages at the feed point of a fabrication plant also. Other, fairly accurate direct methods are available for determining the fissile material content in the feed streams. Besides this, in practice, the shipper's data on the fissile material content in the feed stream of a fabrication plant will also be available for establishing the material balance. Therefore, the measuring methods at the feed point have not been discussed here.

Two methods are under active investigation for estimating fissile material content of the solid and heterogeneous wastes from a fabrication plant. They are,(a) neutron counting for plutonium containing wastes and, (b) measurement of delayed neutron for wastes containing uranium and plutonium. The neutron counting method was used for the waste streams in the control experiment mentioned earlier [10, 11]. The accuracy for this method, averaged over the whole experiment was found to be around $\pm$ 8 %. The neutron counting method is not tamperproof in its present form and further work is being carried out to improve it. The method using delayed neutron is still at the initial stage of its development.

4. Conceptual Designs

Three conceptual designs for fabrication plants were prepared in which the major requirements of a safeguards system, based on the principle of fissile material control at strategic points, were incorporated. One of the reference plants is for LWR fuel elements with low enriched U-235, and the other two are for fast breeder fuel elements with plutonium, for two different yearly throughputs. The characteristics of these plants are summarised in Table VI. Their simplified layouts are shown in Figs. 2, 3 and 4 respectively.

4.1 General Remarks

As can be surmised from Table II, the throughputs of these plants correspond to the fabrication requirements in Germany, covering the period mid seventy to early eighty. All operational and process improvements (automation, rationalisation of process steps and data processing,reduction of fissile material wastes etc.), which appear feasible during this period have been incorporated in these plants. Besides this, the guiding principle for these conceptual designs, has always been to arrange the layout in such a way that all the fissile material in input and output streams and in inventories could be conveniently safeguarded at a very limited number of strategic points, and that the areas in between these points could be effectively contained. A detailed analysis of the layouts shows fairly conclusively that safeguards (according to the concept of strategic point control) and plant rationalisation requirements are highly correlated . Both the safeguarding authority and the plant operators are interested in:

a) The establishment of an accurate material balance with as little time lag as practicable.

b) A reduction in the recoverable and irrecoverable losses.

c) A reduction in the material unaccounted for (MUF)

d) A rational data processing system for the establishment of material balance.

e) A reduction in the total efforts (time, personnel and investment) in obtaining information for the preparation of material balance.

f) An efficient containment system for the whole plant.

Therefore, a fabrication plant can always be laid out in such a way as to optimize the effectiveness of both the safeguards measures and the plant operation.

4.1.1 Scraps and Wastes

Present day experience on fabrication scraps and wastes has been somewhat discouraging. From the point of view of safeguards, three basic problems appear to be associated with them. Firstly, they may form a fairly large fraction of the total input; secondly, they are quite often obtained in forms which cannot be measured conveniently and accurately; and thirdly, they are normally collected over several fabrication campaigns and recovered at a much later date, so that a closure of material balance after a single campaign becomes difficult. These problems were analysed in some detail while preparing the conceptual design of these plants.

a) Scraps: Scrap material has been defined in this paper as that part of fissile material from a process stream which is chemically pure but because of some physical shortcomings (geometry, density, etc.), cannot be used in the subsequent process steps in a production line. For ceramic fuel pellets, considered for all the three reference plants, the major part of the scraps is obtained during or after the sintering step, in the form of low-density or geometrically defective pellets, which are not according to the specifications. Fabrication experience, particularly with plutonium containing pellets, has shown that upto about 5 % of the input streams, such scraps can be recirculated back to some previous process steps, without any special treatment. If the fraction be higher, it has to be treated in a scrap recovery process before a recirculation. Upto about 20 % of the feed stream, such sintered scrap can be dry oxidised (in air at around $800^{o}C$) and fed back to the homogenizing step. In both these cases, these scraps do not appear as a separate stream for the material balance and therefore, need not be separately accounted for for safeguards purposes. They would just increase the internal hold-up of the plant.

If these scraps are not recirculated continuously and immediately or if a part of the scrap is kept over after a campaign, they can be homogenised quite easily and brought in batches to a strategic point where their plutonium content can be determined accurately.

It is important to note that recirculation of 20 % of the feed material in the form of scrap, is extremely undesirable from operational aspects as it reduces the actual throughput of the plant in the same proportion and therefore, affects the overall economics of the plant in an adverse manner. In commercially operating plants, the percentage of scrap formation under normal operating conditions is expected to be well below 20 %. If necessary, it can always be estimated at strategic points with the same accuracy as that at the feed point.

b) Wastes: The waste stream has been defined as that part of the fissile material flow in a plant, in which the chemical purity or concentration of the fissile material has been degraded to such an extent that it has either to be discarded or can be recovered only by complicated, fairly expensive process steps. Waste streams may be both heterogeneous and homogeneous. Normally, fissile material is recovered from waste streams only if the attainable price is expected to be higher than the cost of recovery. Fissile material dust from absolute filters, scrapings from glove boxes, grinding slime (if grinding is used) are typical examples of heterogeneous, recoverable wastes; plastic sacks, gloves, cleaning papers etc. can normally be taken as irrecoverable heterogeneous wastes; chemical solutions produced from sample analyses are typical recoverable homogeneous wastes whereas, mother liquor from a wet recovery plant is regarded as irrecoverable homogeneous wastes.

In normal practice, the recoverable wastes are stored over a long period before treating them in a waste recovery plant as, such a plant operates economically over a certain capacity. The measuring methods known at present, to not permit an accurate estimate of fissile material content in any of these wastes.

At present it is quite common to obtain around 1 % of the feed stream as irrecoverable wastes. A fairly detailed research and development activity has been initiated at Karlsruhe Center to analyse the various sources of waste materials and the means of reducing them in commercially operating fabrication plants. Preliminary results indicate that these losses can be reduced drastically with increasing size and increasing automation of the plant.

Typical values of fissile material concentrations in waste streams which are expected in the reference plants and which form the basis for the subsequent effort analysis, have been presented in Table VII. The reduction of fissile material amounts in the different irrecoverable waste streams as compared to the present day values, has been possible because of the following improvements:

(a) Automation of process steps which reduces the number of transfers from outside areas to the glove boxes, and reduces the use of cleaning papers and the number of plastic sacks. The number of gloves to be discarded does not increase proportionately with increasing size of the plant so that its contribution to the total amount decreases. All these factors cause a reduction in the fissile material concentration in heterogeneous waste streams from plutonium fabrication plants.

(b) Reduction in the number of samples to be chemically analysed. For the reference plant III (large Pu-plant), a further reduction in the number of samples to be taken from the process streams by increasing the hight to diameter ratio of the pellets to two. This causes a reduction in the total number of pellets in this plant by a factor of two.

The recoverable and irrecoverable wastes in homogeneous form are obtained from analytical solutions containing fissile material, mother liquor from a waste recovery unit and from fissile dust from filters and glove box scrapings, which are recovered chemically.

By a rigid quality control and automatic operation, the number of samples to be taken from different process steps for chemical analysis can be reduced. Besides, a part of the chemical analyses can be replaced with non-destructive analytical methods. As in the case of gloves, the amount of fissile material dust and the glove box scrapings do not increase liniarly with increasing capacity of the plant.

4.2 Layout of LWR Fuel Plant, Ref. Case I (Tables VI, VII, Fig. 2)

4.2.1 Process Description

The fabrication plant has a capacity of 230 t/a of 3 % enriched uranium. It is estimated that in Germany two such plants would be required in the early seventies.

The feed material is obtained in the form of enriched UF_6 in cylinders,and stored in a compartmentalised large storage area located in the cellar of the plant (Fig. 2). From this storage area the flow of uranium through the various process steps in the plant is arranged in the form of an inverted U. The completed subassemblies, which are the final product from this plant, are also stored in the same storage area. The space between the parallel arms of the flow is used for a wet waste recovery unit, to which all the recoverable waste streams from the different process steps are fed. This unit operates continuously and the recovered uranium is fed back to the homogenizing step. The scraps, as defined in this paper, are not expected to exceed 10 % of the feed and are fed back directly and continuously to a suitable process step. The waste stream from the scrap recovery unit, in the form of liquid solution with traces of uranium, is stored temporarily in a 10 m^3 tank which is also located in the same general storage area. It is to be noted that in this plant, this is the only waste stream containing fissile material which leaves the plant. The recoverable waste streams are fed directly to the waste recovery unit.

The operation and maintenance personnel can enter or leave the process area only through the personnel lock under normal condition. The emergency exits are normally sealed with an electrical alarm signal system.

The walls of the plant enclosing the various process and auxiliary steps can be regarded as the containment for the process uranium. The continuity of the containment is guaranteed with the help of an electromagnetic signal system.

4.2.2 Strategic Points

Because of the particular way the plant has been laid out, all the ingoing and outgoing streams containing uranium, pass through the general storage area. This area has therefore been laid out as a strategic point. Since for this plant, the completed pins and not the subassemblies, will be measured, the pin measuring station has also been included in this strategic point. All the measuring units (namely, a weighing machine and a sampling point for the UF_6 stream, a lead pile spectrometer for the pins and a storage tank with sampling point and a chemical analysis unit for the waste stream), which are required by the safeguards system to establish an independent material balance, are located in this area. The electrical signals showing the continuity of the containment and the operation of the personnel lock, are also brought to this area. This means that this plant has only one strategic point at which all the safeguards activities can be carried out. The service of a single safeguards personnel is required to execute these safeguards measures for the plant.

4.3 Layout of FBR Fuel Plant, Ref. Case II (Tables VI, VII, Fig. 3)

4.3.1 Process Description

This plant is capable of producing fast breeder fuel pins for the core and the axial zone of a reactor. The capacity is around 8.8 kg of Pu and 35 kg of depleted uranium per day and corresponds to the requirement in Germany during the early seventies. The plant has been designed by the firm Alkem and is at present under construction in Hanau, Germany. It has been laid out to fabricate converted fuel pins containing recycled plutonium as well. The following description is for the fast breeder fuel, as it corresponds to the maximum throughput of plutonium for the plant.

The fissile material is received at the plant in the form of powders of plutonium and uranium oxide. The plutonium is supplied in standard bird cages and is stored at first in the general storage area. The depleted uranium is received at the plant in special sealed containers and is transfered pneumatically to a silo inside the plant. Because of the extremely low value of depleted uranium, its flow will not be safeguarded independently in this plant.

The final product from this plant is in the form of fuel pins containing pellets of a mixture of uranium and plutonium oxide in the middle part (core zone) and similar type of pellets with only depleted uranium oxide in the top and bottom part of the pin for the axial blanket zone. Assembling of these pins will be carried out by the reactor vendor. The completed pins are stored in the same storage area before transport.

The ceramic scraps obtained from different process steps will be recovered internally. In case it has to be stored for a longer period or sent to some other recovering facility outside the plant, it will be homogenized and brought to the same fissile material storage area.

All the irrecoverable heterogenous and homogeneous wastes will be brought to this storage area also before disposal.

Because of the extreme danger associated with the handling and disposal of plutonium, very strict health physics and criticality controls are imposed by the plant operators themselves on all the process steps in the plant. This implies that all the input and output streams to and from the plant have to be controlled by the operators also.

As in the case of uranium plant, the walls enclosing the process steps forms the containment for the fissile material inside the plant. The emergency exits are normally sealed with an electrical signal system which also shows the continuity of the containment.

The offices, personnel locks laundries etc. are located in a separate building which is connected to the process area with a passage way. A personnel lock has been installed in this passage way. All the operation and maintenance personnel can enter the process area only through this personnel lock.

4.3.2 Strategic Points

All the materials leaving and entering the plant, have to pass through the general storage area. Therefore, this has been laid out as the first strategic point. The measuring instruments, the safing and sealing units and other items required for executing all the safeguards measures for the plant, are located in this area.

The personnel lock represents the second strategic point. A specially developed γ-lock has been installed here which can detect less than 1 gm of plutonium carried by a person going through the personnel lock, The γ-lock gives an alarm and bars the passage in case a person tries to carry this amount of plutonium with him across the γ-lock.

Since the signals for testing the continuity of the containment and the alarm signal from the γ-lock can be brought to the first strategic point, all the safeguards activities can be carried out in this area. It is estimated that a single safeguards personnel can safeguard the whole plant.

4.4 Layout of FBR Fuel Plant, Ref. Case III (Tables VI, VII, Fig. 4)

4.4.1 Process Description

The layout of this plant has been discussed in detail /‾10, 12_7. This plant corresponds to the plutonium fabrication requirement in Germany during the early eighties. It is laid out to fabricate only fast reactor fuel subassemblies containing core and axial fuel. This plant has been designed in collaboration with the Transuranium Institute, Euratom, and incorporates to a high degree conceivable automation and rationalisation techniques.

The plutonium input is in the form of plutonium oxide powder. Depleted uranium for the core zone is also received as oxide powder. However, as opposed to the Ref. case II, the uranium for the axial blanket is obtained in the form of sintered oxide pellets, which can be filled directly into the pins without any further processing.

The final product is in the form of completed fuel subassemblies, each containing about 330 pins with core and axial fuel.

The scraps from the different process steps are continuously recovered in a dry oxidising unit and recirculated back to an appropriate process step. A wet waste recovery unit recovers plutonium from homogeneous wastes and discards irrecoverable wastes in liquid form. Heterogeneous wastes are obtained only with irrecoverable amounts of plutonium and discarded directly.

The pellets have a height to diameter ratio of 2 as opposed to around 1.2 in the Ref. plant II. This causes a reduction in the number of pellets and hence the number of chemical analysis to control them. The grinding step after sintering has also been eliminated in this plant, as it is expected that by the time the plant goes into operation, direct sintering giving specified diamensions of pellets will be feasible. This causes a reduction in the amount of chemically recoverable plutonium wastes.

The containment of fissile material is realised in the same manner as in the Ref. plant I and II.

4.4.2 Strategic Points

The fabrication process has been laid out in two parallel lines mainly because of the fact that the core of a fast breeder has normally two zones with two different plutonium concentrations. Because of this particular layout, two strategic points are required for the input and output streams. The feed and the waste streams pass through the first strategic point which is located in the cellar of the plant and the product stream leaves the plant through the second strategic point. The personnel lock forms the third strategic point. All the measuring instruments required to establish an independent material balance and to execute other safeguards measures are all located at these strategic points. Since the containment and personnel lock signals can be brought to either of the first two strategic points, all the safeguards activities can be restricted to these two points.

Because of a considerably higher safeguards work load in this plant, 2-3 safeguards personnel would be required to perform all the safeguards duties.

5. Safeguards Measures and Efforts

In this chapter, an effort has been made to lay down all the safeguards measures to be carried out by the safeguards personnel at the strategic points. These measures involve firstly, the establishment of an independent material balance and secondly, testing of the integrity of containment for the plant and the containers (bird cages, fuel pins and subassemblies) containing fissile materials. The total expenditures per year involved in executing these measures have then been estimated for each of the reference plants. An evaluation index has been defined, based on the specific safeguards expenditures (DM/kg fissile material safeguarded in a particular stream) and the standard deviation of measurement at a given strategic point, to show the relative importance of the individual strategic points.

5.1 Safeguards Measures

All the safeguards measures to be carried out for establishing a material balance and testing the containment of plants and containers have been indicated in Tables IX, X and XI for the three reference plants I, II and III respectively. The independent material balance for the uranium plant (Ref. I) is established by weighing the UF_6 cylinders and mass spectrometrically analysing the U-235 content at the feed point, by measuring the U-235 concentration in completed pins by a lead-pile spectrometer at the product end and by chemically analysing the U-235 concentration in liquid waste streams. For the plutonium reference plants II and III, it is established either by measuring the plutonium content in the incoming bird cages with a colorimeter (defined as the upper limit in the respective tables) or by accepting the data from the shipper plant (defined as the lower limit in the respective tables),by measuring calorimetrically the plutonium in the completed pins (Ref. II) or in subassemblies (Ref.III) at the product point, and measuring the plutonium content in the waste stream by neutron counters.

It is to be noted that the process inventory in all the three plants can be temporarily converted into one of the output streams and measured with the respective instruments.

The containment measures are similar for all the three plants. They include, identification and destruction of seals at the feed point (UF_6 cylinders for plant I, plutonium bird cages for plants II and III), sealing at product point (subassemblies for plants I and III, pins for plant II), and sealing of waste containers (only for plants II and III). Observation of all containment signals for the emergency exits, containment walls and personnel locks at the strategic points also fall under this catagory.

A certain amount of computer work has been included in the safeguards activities for all the three plants. It is expected that the establishment of material balance will be facilitated considerably with the use of computers, particularly for the plant I and III.

The time required to execute the safeguards measures has also been estimated for the upper and the lower limit for the three plants. In all these plants, the reduction in time for the lower limit is mainly due to the elimination of the flow measurement at the feed point. For plant III a further reduction has been shown for the waste stream (Table XI). It is possible to reduce the measuring time of neutron counting for the barrels and the bottles by a factor of two.

The number of inspection personnel for each of the plants has been calculated on the basis of the time required. For the reference plant II, the estimate for the lower limit gives only 722 hrs/a. Since this corresponds to less than 50 % load factor for a single person (normal working hours of an inspection personnel 8 • 200 = 1600 hrs/a), an inspector has been allocated only 50 % of the total time in a year for this case.

5.2 Standard Deviations at Strategic Points

In Table VIII, the total standard deviations for the feed, product and waste streams (in $kg_{fissile}/a$) have been shown for the three plants. These streams have been defined as the strategic points, although they have been combined at one or two strategic areas in the reference plants as indicated earlier. As can be seen, the standard deviations (i.e. the uncertainty with which the fissile material amounts passing through a strategic point, can be determined) are surprisingly low. For example in reference plant I, the standard deviation in a year is only ± 0.36 kg of U-235 for a total of 6900 kg U-235 in the product stream. For reference plant II it is ± 0.35 kg for a total of 1750 kg plutonium, and for plant III it is ± 1.46 kg for a total of 11 600 kg of plutonium. The main reason is the large number of measurements made in a year.

5.3 Efforts in executing Safeguards Measures

The total amount of efforts is composed of the time spent by the personnel in executing the safeguards measures, the capital investments for material balance and containment measures, and running expenditures for operation and maintenance. All these efforts can be reduced to the common denominator of a monitary unit. In other words, the expenditures involved in these efforts which would be incured by a safeguards authority in a year, can be estimated, provided the specific costs for these efforts are known.

The yearly expenditures for each of these strategic points have been estimated for the three reference plants and shown in Tables XII, XIII and XIV respectively. These expenditures can be regarded as conservative as the capital investments and the operation costs for all the measuring instruments and sealing units have been charged to the inspection system, although the plant operators could use them and would even benefit from them. Only the computer costs have been halved between the plant operators and inspection authority for the plants I and III. The yearly personnel costs have been distributed among the strategic points according to the percentage of time spent by the inspection personnel for a given strategic point.

Point 7 in these tables gives an idea on the effort spent for a kg of fissile material safeguarded at a strategic point. The maximum specific amount spent is always for the waste stream, although less than 0.5 % of the total material is safeguarded in this stream. The same point shows that the total effort at the feed point, can be reduced significantly if throughput messurements at this point are eliminated and inspectors data from the shipping plant are used instead.

5.4 Evaluation Index for Strategic Points

The importance of a strategic point in any nuclear facility may be considered to be a function of the standard deviation (i.e. the range of uncertainty in estimating the amount flowing through the plant) and the total effort spent at the strategic point. The first factor indicates the difficulty with which a diversion can be identified as a diversion. The larger the standard deviation, the larger is the difficulty. The second term gives an indication of the magnitude of the effort spent in generating the standard deviation. If the effort is disproportionately high, different means have to be investigated to reduce it. A combination of these two terms should therefore give an idea on the importance of a strategic point from the point of view of safeguards. A high value of this combination for a strategic point would mean that more attention has to be paid to this point, either to reduce the standard deviation or to reduce the effort.

As a first trial, the contribution $\sigma . \sqrt{DM/kg_{fiss}}$ has been used for this purpose and defined as the "Evaluation Index". σ is the standard deviation in kg/a (Table VIII) and the term under the square root is the specific safeguards costs at a given strategic point. Point 8 in Tables XII, XIII and XIV gives the different values of the evaluation index for the different strategic points in the three reference plants. Point 9 of the same tables gives the relative importance of the strategic points which is the percentage contribution of an evaluation index for a strategic point to the sum of the evaluation indices for all the strategic points.

For plant I the relative importances of the strategic points are almost equally distributed. For plant II the relative importance of the product end and the waste point is almost equally high, the former on account of high standard deviation, the latter because of the high specific safeguards costs. In plant III, the relative importance of the waste stream has been reduced to the level of the feed stream, mainly because the percentage of fissile material in the waste stream has been reduced compared to that for the plant II.

5.5 Specific Safeguards Costs for Reference Plants

The yearly estimated costs for safeguards as well as the specific safeguards costs for the the three reference plants have been shown in Table XV. It becomes once more apparent that elimination of flow measurements at the feed point causes a significant reduction in the total costs. The reduction in specific safeguards costs with increasing size of the plant is also quite evident (from 30 DM/kg to 14 DM/kg for a plutonium plant).

The specific safeguards costs appear to be quite low particularly in view of the fact that all the capital and operation costs for the instruments at the strategic points have been charged to the safeguards system. On the other hand, these costs represent only the field costs for safeguards. Central organization charges have to be added to these costs to obtain the total expenditure.

5.6 Safeguards costs in relation to fabrication costs

The high cost effectiveness of such a safeguards system as has been discussed in this paper, can be illustrated in a fairly convincing manner, by setting the safeguards costs in relation to the specific fabrication costs (DM/kg heavy metal). The fabrication costs for light water fuel elements in reference plant I,would normally range between 250-300 DM/kg heavy metal (U-235 + U-238). The safeguards costs as estimated here turn out to be only around 1.3 DM/kg heavy metal. This is less than 0.5 % of the total fabrication costs or, less than 1/1000 Dpf/kWh if expressed in terms of specific energy generation costs. Similar relations are obtained for the plutonium fabrication plants. The averaged fabrication costs for the core and the axial blanket fuel would be around 800 DM/kg heavy metal in reference plant II, and around 500 DM/kg heavy metal in reference plant III. The safeguards costs expressed in the same units would be approximately 4-7 DM/kg heavy metal and 1.0 - 1.5 DM/kg heavy metal respectively. These values correspond to 0.5 - 0.9 % of the fabrication costs for reference plant II and 0.2 - 0.3 % for reference plant III.

Although the safeguards cost figures are rather approximate, an increase in these costs even by a factor of 2 or 3 would not change the above mentioned trend appreciably.

6. Conclusions

A number of generalized conclusions can be drawn on the basis of the analysis presented in the paper. They are summarized below:

6.1 The fabrication requirements in Germany are expected to increase rapidly in the coming years. However, a number of parallel units will be installed to meet the total yearly requirement. Therefore, a 230 t/a plant for LWR fuel elements and a 10 t/a and a 100 t/a plant respectively, for fast breeder fuel elements represent the wide spectrum of the plant sizes to be expected in the coming decade.

6.2 The measuring instruments under development at Karlsruhe appear adequate for such plants. The lead pile spectrometer with a coefficient of variation of ± 2 % per pin, gives an overall standard deviation of only ± 0.35 kg U-235/a for a total of 6900 kg U-235/a. With a calorimeter coefficient of variation of ± 0.4 %, an overall standard deviation of ± 1.46 kg Pu/a for a total of 11600 kg Pu/a is obtained. These low ranges are mainly obtained because of the large number of measurements carried out in a year.

6.3 Any fabrication plant can be laid out in such a manner as to optimize the effectiveness of both the safeguards measures and plant operation, provided the present trends of automation and rationalization possibilities are fully utilized.

6.4 The problem of scraps can be completely eliminated in such layouts. They can be circulated internally in a continuous manner or brought out to one of the strategic points in homogenized batches and measured with the same accuracy as that for the feed or the product stream.

6.5 The percentage of irrecoverable fissile material wastes can be reduced by almost an order of magnitude (0.1 % instead of 1 % in present day plants) in the reference plants, mainly because of automation and rationalization of process steps.

6.6 In all these plants, the fissile material storage areas can be laid out as strategic areas to which all the safeguards activities can be restricted.

6.7 A significant reduction in safeguards activities and costs can be achieved if fissile material flow measurements at the feed point are eliminated and the inspectors data for the shipper plant are used for material balance. The personnel requirement in that case will be around 1 or 2 (2 only for the large Pu-plant in the eighties) per plant.

6.8 The specific field safeguards costs in DM/kg fissile material safeguarded are estimated to vary between 40 DM/kg uranium and 14 DM/kg plutonium. They can be considerably reduced if a part or the whole of the measuring instruments costs are taken over by the plant operators, as they have to measure the flow in any case.

6.9 The high cost effectiveness of a safeguards system based on fissile material control at strategic points, as discussed in this paper, can be convincingly illustrated by the fact that the total safeguards costs for the three reference plants make out only 0.2 - 0.5 % of the fabrication costs respectively, in DM/kg of heavy metal fabricated.

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TABLE I. REACTOR DATA FOR ESTIMATING THROUGHPUTS IN FABRICATION PLANTS

	Dimensions	LWR	Plutonium Fast Breeder
Net electrical power	[GWe]	1	1
Thermal efficiency	[1]	0.35	0.43
Load factor		0.7	0.7
Average burnup	[$\frac{MWd}{t}$]	27000	25700+)
In-pile time	[a]	4.8	1.66
Inventory:			
U (tot)	[t/GWe]	130.	49.7
Pu (tot)	[t/GWe]	-	2.7
Radial blanket	[t/GWe]	-	27.9
Core + axial blanket	[t/GWe]	-	24.6
Running requirement:			
U (tot)	[t/GWe a]	40.	21.6
Pu (tot)	[t/GWe a]	-	1.6
Rad.blanket	[t/GWe a]	-	8.4
Core + Ax. blanket	[t/GWe a]	-	14.8
Pu-dischange factor	[t/GWe a]	0.150	0.155

+) Averaged over core, axial and half of the radial blanket.

TABLE II. ESTIMATED THROUGHPUT [t heavy metal/a] IN FABRICATION PLANTS IN GERMANY

Year		1970	1980	1990	2000
Estimated nuclear power demand	[GWe]	10	28	84	200
LWR	[GWe]	10	28	64	116
Breeder	[GWe]	0	2	20	84
U-throughput (LWR) (3% enriched)	[$\frac{t}{a}$]	556	1330	3180	5300
Radial blanket(FB) (depleted uranium)	[$\frac{t}{a}$]	0	20,0	320	1130
Pu-throughput (FB)	[$\frac{t}{a}$]	0	3,0	52	190
Core + ax.blanket (FB)	[$\frac{t}{a}$]	0	40,0	460	1700

TABLE III. CRITERIA FOR INDIRECT MEASURING METHODS OF FISSILE MATERIAL CONTENT IN FRESH, UNIRRADIATED FUEL PINS AND SUBASSEMBLIES

Criteria	Remarks
1. Tamperproofness	Against all conceivable measures, which can simulate the presence of the absence of one of the fissionable elements (inhomogenity, addition or removal of absorbers, reflectors, and foreign neutron and heat source)
2. Free from systematic errors	Any bias in the measurement should be identifiable and correctable
3. Capacity of discrimination	The method should be capable of discriminating between uranium and plutonium
4. Low measuring time	Depends on the throughput and the number of measuring units used in a plant. For 1 t heavy metal/d capacity fabrication plant and one measuring unit, the measuring time should not exceed 2-3 minutes/pin
5. Accurate	For the same throughput as in (4) the overall measuring accuracy for Pu should be greater than $\pm$ 0.4 % and that for U-235 $\pm$ 1.6 % (1-σ value)
6. Simple, reliable, easy to automatise and adaptable to continuous operation	
7. Economic	

TABLE IV. HEAT PRODUCTION AND OVERALL ERROR IN THE MEASUREMENT OF CALORIMETRY ON ACCOUNT OF VARIOUS SOURCES OF ERROR

Isotope	% Conc.	error % (1-σ value)	heat production w/g of isotope	watts
Pu_{38}	0.27099	1.3	0.569	0.001542
Pu_{39}	75.492	0.21	0.001923	0.0014517
Pu_{40}	17.9703	0.56	0.00703	0.0012633
Pu_{41}	4.8261	0.97	0.0045	0.0002172
Pu_{42}	1.0704	1.33	0.00012	$1.28 \quad 10^{-6}$
Am_{41}	0.3699	1.5	0.1084	0.000401
Total (on account of Pu-isotopes and Am_{241})		0.45		0.00488 w/g
Error on account of reproductibility		0.6 - 1.0		
Total error		0.8 - 1.2		

TABLE V. SPECIFICATION OF THE SLOWING DOWN TIME SPECTROMETER FOR U-235 ASSAY IN FUEL PINS FOR LWR TYPE BEING DEVELOPED BY FIRMA INTERATOM IN COLLABORATION WITH THE KARLSRUHE RESEARCH CENTER

Throughput	600 pins[1)]/day of 24 hrs. (measuring time of ≈3 min./pin corresponding to a 1 t/d fabrication plant)
U-235 concentration in a pin	upto ± 5 %
U-238 concentration	95-100 %
Accuracy of measurement (coefficient of variation 1-σ value)	<2 % / pin

The system will consist of automatic fuel pin feeding mechanism, neutron generator, lead pile, photon recoil counters, automatic data processing, recording and selecting a system and all the other necessary accessories.

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1) Specification of fuel pin

Length	3000 mm
Diameter	upto 15 mm
Chemical form of fuel	UO_2 pellets
Canning material	Zircalloy
Amount of total uranium/pin	1.8 kg
Amount of U-235/pin	56 g

TABLE VI. CHARACTERISTICS OF THE THREE REFERENCE FABRICATION PLANTS

	I LWR-fuel elements (1972)	II Fast-Breeder fuel elements (core+ax.bl.) (1972)	III Fast-Breeder fuel elements (core+ax.bl.) (1980)
1. Type of material	U(enriched)	U(depl.), Pu	U(depl.), Pu
2. Pu(tot)-enrichment /%/	-	20	19,4; 24,6[1)]
3. U-235 enrichment /%/	3.0	0.2	0.2
4. Fuel composition:			
4.1. Feed-point	UF_6	UO_2, PuO_2	UO_2, PuO_2
4.2. Product	UO_2	UO_2, PuO_2	UO_2, PuO_2
5. Throughput /day:			
5.1. Feed-point kg Pu	-	8.8	50.0
5.1. Feed-point kg U	1000	35.2	390.0
5.2. Conversion	1480 kg UF_6	-	-
5.3. Ceramic /kg/	1137 kg UO_2	50 kg$(U+Pu)O_2$	500 kg $(U+Pu)O_2$
5.4. Pellets	170.000	34.000	150.000
5.5. Fuel pins	620	205	1430
5.6. Subassemblies	3 - 4	-[2)]	4 - 5
5.7. No.ofworking days/a	230	200	230
5.8. Throughput /t/a/	230(3%U)	1.76 (Pu)	11.6 (Pu)
6. Pin characteristics:			
6.1. Length /mm/	2917	3000	2672
6.2. Diameter /mm/	10.7	6.5	6.7
6.3. Fissile material /g/	48 (U235)	43 (Pu)	40 (Pu)
7. Number of strategic points			
7.1.Material	1	1	2
7.2.Personnel	1	1	1

[1)] Of core I and core II fuel respectively

[2)] No assembly station

TABLE VII. FISSILE MATERIAL CONCENTRATIONS IN VARIOUS WASTE STREAMS OF THE THREE REFERENCE FABRICATION PLANTS

	I LWR fuel element (1972)	II FBR fuel element (1972)	III FBR fuel element (1980)
1. Specific amount of irrecoverable wastes			
Heterogeneous			
150 l barrel/kg fissile	-	0.5	0.5
gm fissile/barrel	-	10	2 (Pu)
Homogeneous			
l/kg fissile	5	6	6
gm fissile/l	0.2 (U)	0.1 (Pu)	0.1 (Pu)
2. Total amount of irrecoverable wastes			
Heterogeneous			
150 l barrel/a	-	880	5800
kg fissile/a	-	8.8	12
Homogeneous			
l/a	$1150 \cdot 10^3$	$10.5 \cdot 10^3$	$69 \cdot 10^3$
kg/a	230 (3%U)	1.05	7
Total kg/a	230	9.85	19
3. Irrecoverable wastes % of input	0.10	0.56	0.15
4. Accuracy of measurement [%]	5	10	10
Unit amount for each measurement			
Heterogeneous [barrel]	-	1	1
Homogeneous [l]	10^4	50	50

TABLE VIII. RANGE OF UNCERTAINTIES (1 σ) AT STRATEGIC POINTS FOR THE THREE REFERENCE PLANTS

Strat.pt.	Data	I LWR (1972)		II FBR (1972)		III FBR (1980)	
		U-235	U(tot)	Shipper	Receiver	Shipper	Receiver
1. Input	Throughput /t/a/	6.9	230	1.76(Pu)		11.6(Pu)	
	Specific amount per meas. /kg/	45	1500	4(kgPu/Bc)	4(kgPu/Bc)	4(kgPu/Bc)	4(kgPu/Bc)
	Number of measurements/year /1/	154	15.4	440	440	2900	2900
	Coefficient of variation /%/	0.2	0.05	0.2	0.4	0.2	0.4
	Total stand.deviation /kg/a/	1.1	9.3	0.168	0.336	0.43	0.86
	Improved stand.deviation[1)] /kg/a/	0.79	6.6	0.15 (Pu)		0.384 (Pu)	
2. Product	Throughput /t/a/	6.9(U-235)		1.75 (Pu)		11.6(Pu)	
	Specific amount per meas. /kg/	0.049 (kgU5/pin)		4.28 (kgPu/1oo pins)		11.65 (kg Pu/SA)	
	Number of measurements/year /1/	142 000(pins)		410		990	
	Coefficient of variation /%/	2		0.4		0.4	
	Total stand.deviation /kg/a/	0.366(U-235)		0.347 (Pu)		1.46 (Pu)	
				barrels	bottles	barrels	bottles
3. Waste	Throughput /kg/a/	6.9 (U-235)		8.8 (Pu)	1.05 (Pu)	12 (Pu)	7 (Pu)
	Specific amount per meas. /kg/	0.06(kgU235)		10 gr.	5 gr.	2 gr.	5 gr.
	Number of measurements/year /1/	115		880	210	6000	14000
	Coefficient of variation /%/	5		10	10	10	10
	Total stand.deviation /kg/a/	0.032(U-235)		0.03	0.007	0.015	0.019
				0.031 (Pu)		0.024 (Pu)	
	Total stand.deviation for mat.bal.	1.16	0.87[1)]	0.387	0.380[1)]	1.52	1.50[1)]

[1)] By using shippers data in addition

TABLE IX. SAFEGUARDS MEASURES FOR INPUT AND OUTPUT STREAMS AND TIME REQUIRED FOR THEIR EXECUTION FOR REF.PLANT I

Stream	Safeguards measure	No.of measures/a	Time required per unit measure	Total No. of working hours/a Upper limit	lower limit
Feed	Weighing	154 cylinders à 1.5 t U 2 weighing/cylinder = 308	0.1 h/weighing	31	-
	Mass-spec.Anal.	1/cylinder = 153	1 h/anal.	153	-
	Sealing/identification	153	0.1 h/cylinder	15	15
	Maintenance			20	20
	Total			219	35
Product	Measurement in Lead-pile spectrometer	142,000 pins/a 100 pins/batch = 1420 batches/a	10 min./batch	230	230
	Sealing	760 subassemblies	0.5 hr/sub.	400	400
	Maintenance + Standardization			240	240
	Total			870	870
Waste	Chemical analysis	115 batches à 10 m^3	0.5 h/batch	60	60
	Sampling+measurement		0.2 h/batch	24	24
	Total			84	84
			Total	1173	989
			No. of safeguards personnel	1 Inspector	1 Inspector

Assumptions (valid for Tables IX to XIV

a) Working hours for a safeguards personnel/a = 1600
b) Expenditure for safeguards personnel
   Inspector = 50,000 DM/a
   Technician = 30,000 DM/a
c) Observation-time for containment and personnel lock signals are included in the total time.

TABLE X. SAFEGUARDS MEASURES FOR INPUT AND OUTPUT STREAMS AND TIME REQUIRED FOR THEIR EXECUTION FOR REF.PLANT II

Stream	Safeguards measure	No. of measures/a	Time required per unit measure	Total No. of working hours/a Upper limit	Lower limit
Feed	Calorimetry	440 Bird cages	3 hr/4 BC	330	-
	Sealing/identification	440 BC	0.1 hr/BC	44	44
	Maintenance			100	
	Total			474	44
Product	Calorimetry	41,000 pins/a; 100 pins/bundle 410 bundles/a for calorimetry	3 h/4 bundles	310	310
	Sealing/identification	169 pins/transport container 240 containers for sealing	0.1 h/container	24	24
	Maintenance, standard.			100	100
	Total			434	434
Waste	Neutron counting	880 barresl à 10 gm. Pu 210 bottles à 50 l 5 gm Pu/bottle	0.1 h/barrel 0.1 h/bottle	88 21	88 21
	Sealing	880 + 210	1 min/barrel 6 min/bottle	15 70	15 70
	Maintenance,standard.			50	50
	Total			244	244
			Total	1152	722
			No.of safeguards personnel	1 Inspector	0.5 Inspector

Assumptions see Table IX

TABLE XI. SAFEGUARDS MEASURES FOR INPUT AND OUTPUT STREAMS AND TIME REQUIRED FOR THEIR EXECUTION FOR REF. PLANT III

Stream	Safeguards measure	No. of measures/a	Time required per unit measure	Total No. of working hours/a Upper limit		Lower limit	
Feed	Calorimetry	2900 BC	3 h /8 BC	1089		-	
	Sealing/identification	2900 BC	5 min/BC	250		250	
	Maintenance/Standard.			100		50	
	Total				1439		300
Product	Calorimetry	990 subassemblies	3 h/4 SA	742		742	
	Sealing	990 subassemblies	0.5 h/SA	495		495	
	Maintenance/Standard.			100		100	
	Total				1337		1337
Waste	Neutron counting	5800 barrels/a à 2 g Pu 1400 bottles à 50 1;100 mg/1	0.1 h/2 barrels 0.1 h/2 bottles	290 70		145 35	
	Sealing	5800 barrels + 1400 bottles	1 min/unit	120		120	
	Maintenance/Standard.			100		100	
	Total				580		400
			Total		3356		2037
			No. of safeguards personnel		1 Inspector 2 Technicians		1 Inspector 1 Technician

Assumption: see Table IX

TABLE XII. ESTIMATES OF COSTS FOR SAFEGUARDS MEASURES PER STRATEGIC POINT IN REFERENCE PLANT I

U.L = upper limit
L.L = lower limit

Strategic Point	Feed				Product				Waste			
	UL		LL		UL		LL		UL		LL	
1. Capital investments [10^3 DM]												
Weighing	20.				1000		1000					
Lead Pile												
Spectrometer												
Sealing												
Identification	30.		30						20		20	
Storage												
Data processing	33		33		33		33		33		33	
Miscellaneous	8		6		8		8		5		5	
Total	91		69		1041		1041		58		58	
2. Annual capital Charges (14,2%) [10^3 DM/a]		12.9		9.8		147.8		147.8		8.2		8.2
3. Personnel [10^3 DM]		9.4		1.8		37.1		44.0		3.2		4.2
% of total personnel Costs (see Table IX)	18.7		3.5		14.2		88		7.1		8.5	
4. Other operation costs (maintenance,		17.1		1.4		24		24		7		7
utilities (2% of 1)	1.8		1.4		20		20		1.2		1.2	
analysis charges) (mass-spectrometric, chemical etc.)	15.3				4		4		5.8		5.8	
5. Miscellaneous (10 % of sum 2,3,4)		3.9		1.3		20.9		21.6		1.8		1.9
6. Total yearly charges (sum 2–5) [10^3 DM/a]		43.3		14.3		229.8		237.4		20.2		21.3
7a. Specific Safeguards charges [DM/kgU]	0.19		0.06		1.0		1.03		87.8		92.6	
7b. Specific Safeguards charges [DM/kgU-235]	6.27		2.1		33.3		34.4		2927		3087	
8. Evaluation Index σ [DM/kg_{fiss}]	1.97		1.59		2.11		2.14		1.73		1.78	
9. Relative Importance [%]	33.9		28.9		36.3		38.8		29.8		32.3	

TABLE XIII. ESTIMATES OF COSTS FOR SAFEGUARDS MEASURES PER STRATEGIC POINT IN REFERENCE PLANT II

U.L. = upper limit
L.L. = lower limit

Strategic Point	Feed				Product				Waste			
	UL		LL		UL		LL		UL		LL	
1. Capital investment [10^3 DM]												
Calorimeter	100		-		100		100		-		-	
Neutron counter	-		-		-		-		30		30	
Glove box complete	10		10		-		-		-		-	
Miscellaneous [10 % from Total investment]	11		1		10		10		3		3	
Total	<u>121</u>		<u>11</u>		<u>110</u>		<u>110</u>		<u>33</u>		<u>33</u>	
2. Annual capital charges [14.2 %/a] [10^3 DM/kg]		17.2		1.6		15.6		15.6		4.7		4.7
3. Personnel [10^3 DM/a]		20.6		1.5		18.8		15.0		10.6		8.5
% of total (see table X)	41.0		6.1		37.7		60.1		21.1		33.8	
4. Other operation costs [10^3 DM/a] Maintenance, utilities, Computer rental etc.		6.4		4.2		6.2		6.2		4.6		4.6
5. Miscellaneous (10 % of sum 2,3,4) [10^3 DM/a]		4.4		0.7		4.0		3.7		2.0		1.8
6. Total		<u>48.6</u>		<u>8.0</u>		<u>44.6</u>		<u>40.5</u>		<u>21.9</u>		<u>19.6</u>
7. Specific Safeguards Charges	27.6		4.5		25.5		23.1		2190		1960	
8. Evaluation Index $\sigma\sqrt{}$ DM/kg fissile	0.76		0.36		1.76		1.68		1.45		1.37	
9. Relative Importance [%]	19.1		10.6		44.3		49.3		36.6		40.1	

TABLE XIV. ESTIMATES OF COSTS FOR SAFEGUARDS MEASURES PER STRATEGIC POINT IN REFERENCE PLANT III

U.L = upper limit
L.L = lower limit

Strategic Point	Feed		Product		Waste	
	UL	LL	UL	LL	UL	LL
1. Capital investment /‾ 10^3 DM_7						
Calorimeter	160 (2 units)	-	100 (1 unit)	100 (1 unit)	-	-
Neutron counter	- -	-	-	-	40 (2 units)	40 (2 units)
Sealing and/or identification investment	30	30	30	30	10	10
Glove box complete	10	10	-	-	-	-
Automatic transport loading system	20	20	-	-	-	-
Data processing[3)]	33	33	33	33	33	33
Miscellaneous	3	3	3	3	3	3
Total	256	96	166	166	136	136
2. Annual capital charges /‾ 10^3 DM/a_7 (10 kg 7%; 14.7 %/a)	36.5	13.6	24.0	24.0	19.3	19.3
3. Personnel /‾ 10^3 DM/a_7	47.0	11.8	43.8	52.5	19.0	15.7
% of total personnel costs (see Table XI)	42.8	14.7	39.8	65.6	19.4	19.7
4. Other operation costs /‾ 10^3 DM/a_7 Maintenance, utilities, materials etc. (2 % of 1)	5.0	2.0	3.5	3.5	2.7	2.7
5. Miscellaneous (10 % of sum 2,3,4) /‾ 10^3 DM/a_7	8.8	2.7	7.3	8.0	4.1	3.7
6. Total yearly charges (sum 2-5) /‾ 10^3 DM/a_7	97.3	30.1	78.6	88.0	45.1	41.4
7. Specific Safeguards charges /‾ DM/kg fissile_7	8.5	2.6	6.8	7.7	2360	2190
8. Evaluation Index $\sigma \sqrt{DM/kg_{fiss}}$	1.12	0.69	3.81	4.10	1.17	1.12
9. Relative Importance /‾ % _7	18.4	11.6	62.5	69.4	19.2	19.0

TABLE XV. SPECIFIC COSTS FOR SAFEGUARDS MEASURES FOR THE THREE REFERENCE PLANTS

	Ref. I		Ref. II		Ref. III	
	UL	LL	UL	LL	UL	LL
Total safeguards costs /‾ 10^3 DM/a _7	293.3	273.0	115	68.1	221	159
Total throughput of fissile material /‾ t/a _7	6.9	6.9	1.76	1.76	11.5	11.5
Specific safeguards costs /‾ DM/kg fissile _7	42.5	39.6	65.4	38.7	19.2	13.9

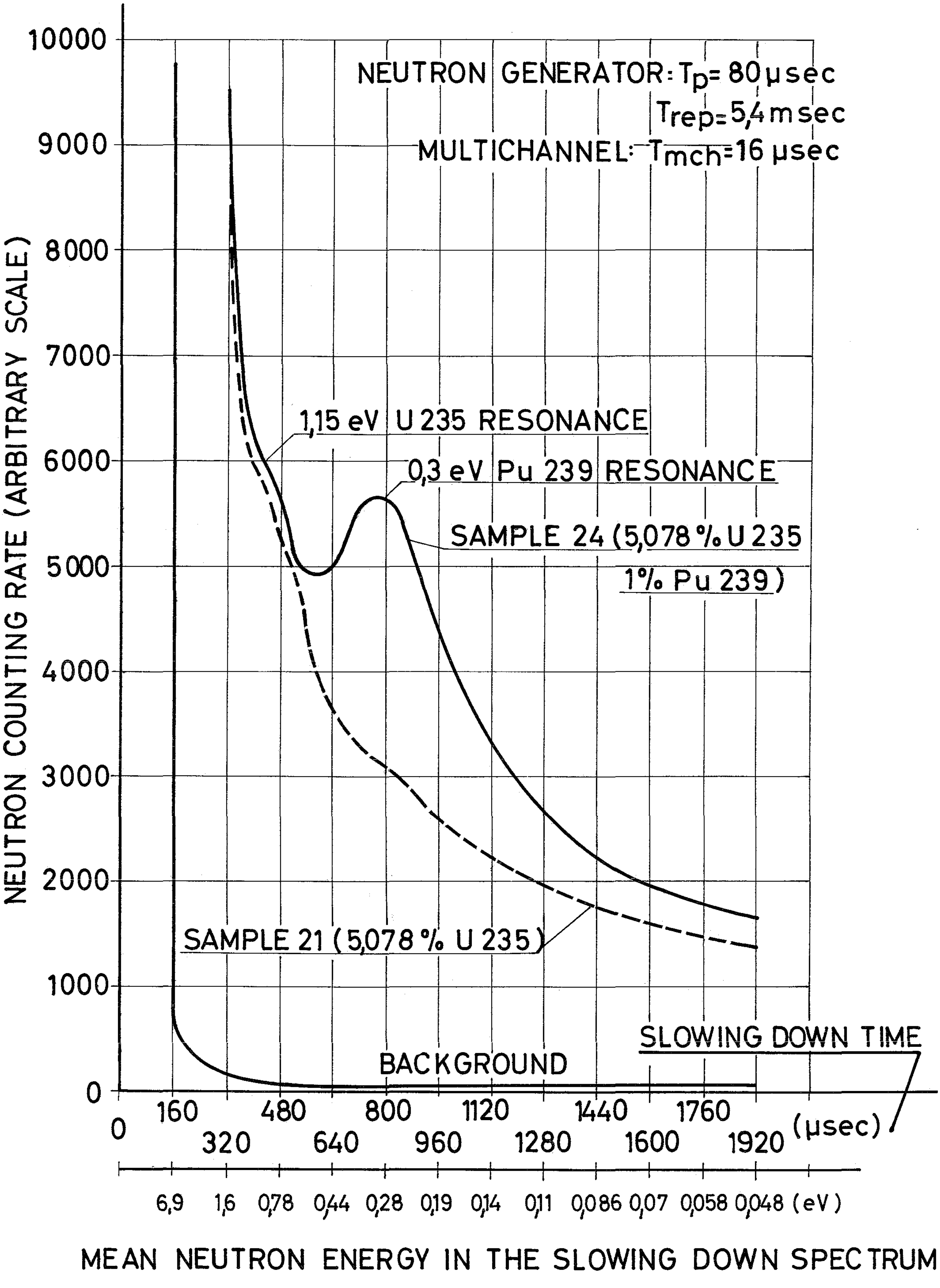
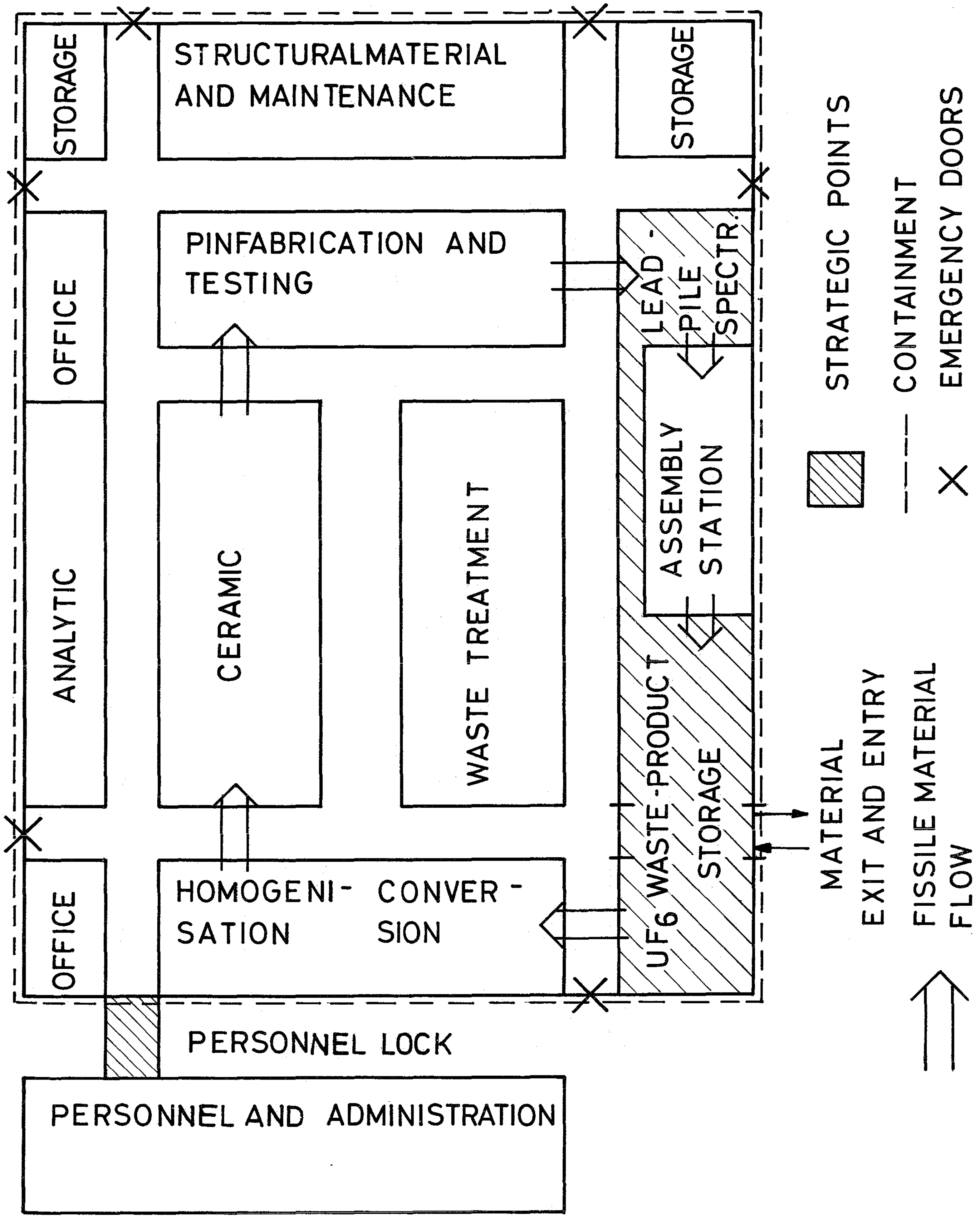


FIG. 1 NEUTRON COUNTING RATE VS SLOWING DOWN TIME (Measured by Fa. Interatom)

FIG. 2 LAYOUT OF THE FABRICATION PLANT FOR LWR FUEL SUBASSEMBLIES.

(Reference Plant I)



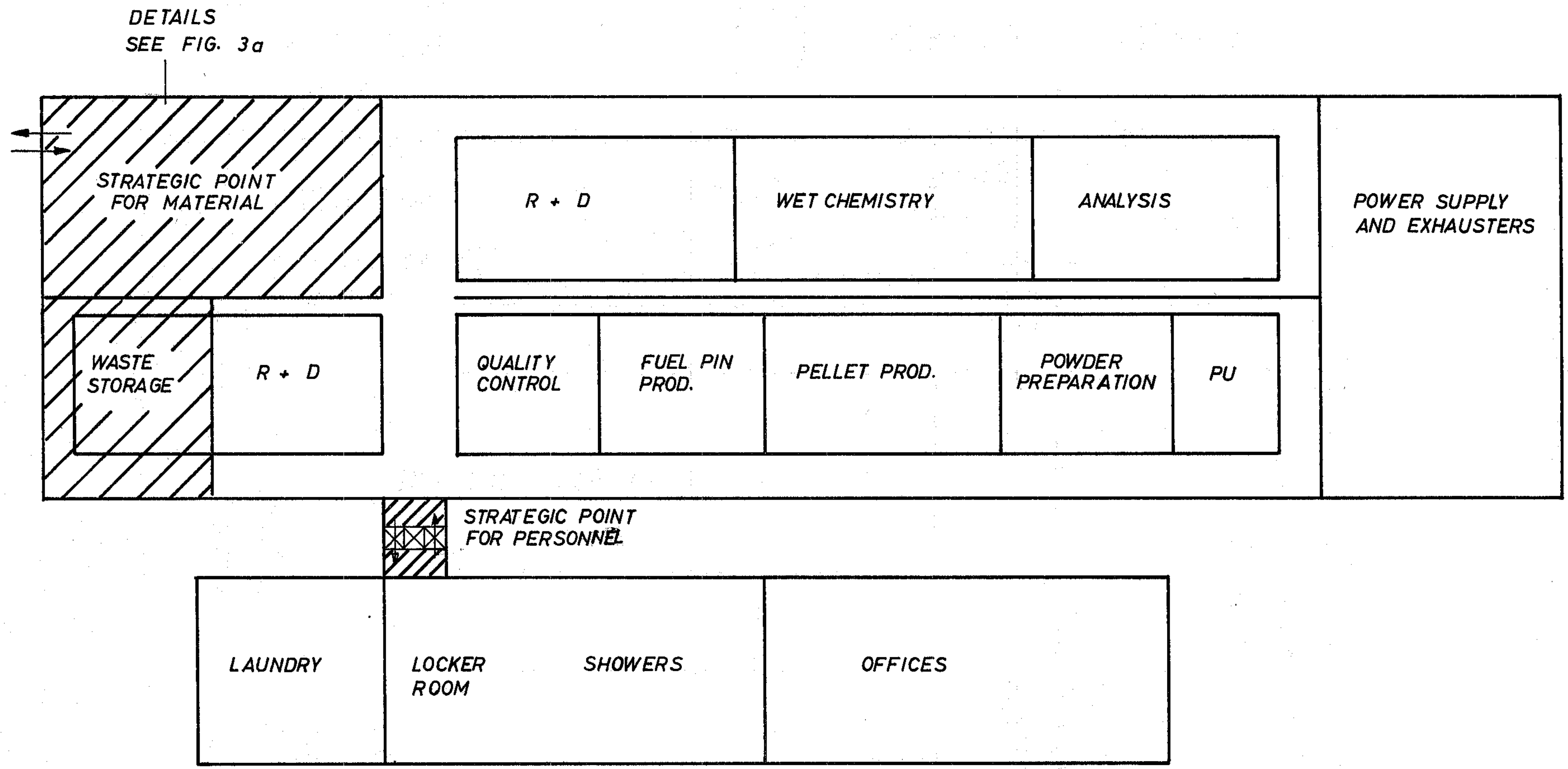


FIG. 3 LAYOUT OF THE FABRICATION PLANT FOR FAST BREEDER FUEL
REFERENCE PLANT II

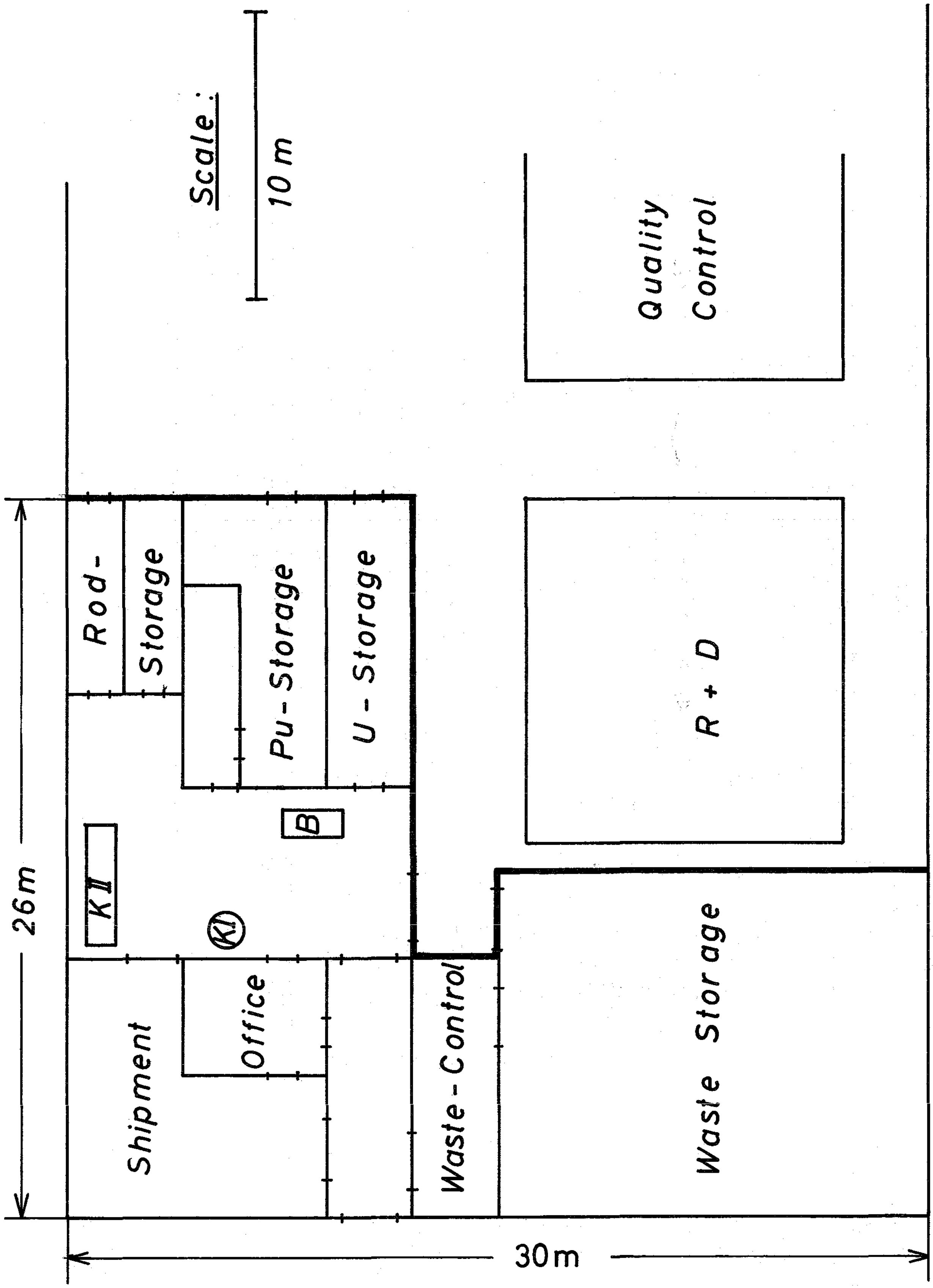


Fig. 3a Details of the strategic point

Reference plant II

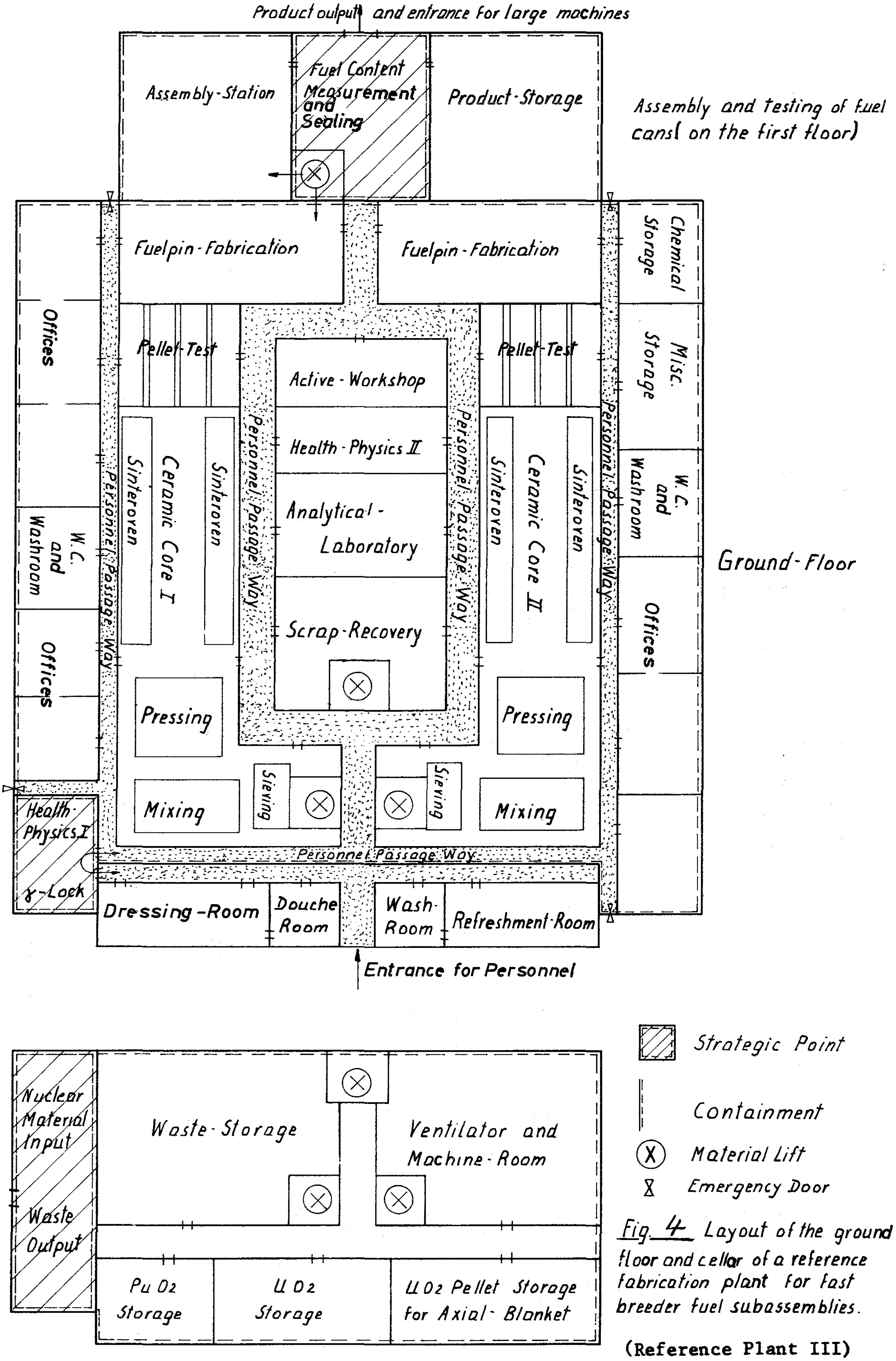


Fig. 4 Layout of the ground floor and cellar of a reference fabrication plant for fast breeder fuel subassemblies.

(Reference Plant III)