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Safeguards System Studies and Fuel Cycle Analysis

W. Häfele, W. Gmelin, D. Gupta, J. Larisse, H. Winter

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SAFEGUARDS SYSTEM STUDIES AND FUEL CYCLE ANALYSIS [x])

by

W. Häfele, W. Gmelin, D. Gupta, J. Larisse[xx]), H. Winter

Gesellschaft für Kernforschung m.b.H., Karlsruhe

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[xx]) On delegation from EURATOM

SAFEGUARDS SYSTEM STUDIES AND FUEL CYCLE ANALYSIS

W. Häfele, W. Gmelin, D. Gupta, J. Larisse[1], H. Winter

Institut für Angewandte Reaktorphysik
Kernforschungszentrum Karlsruhe

Abstract

In the early days of safeguarding, isolated nuclear facilities like research reactors and the nuclear material in them, were the subject of safeguard. In the present and future era of commercial nuclear power generation, it is the nuclear material flow through the various nuclear facilities in a fuel cycle, and the principle of safeguarding effectively the flow of fissile material by use of instruments and other techniques at certain strategic points appears to be well suited for this purpose.

In order to assess the requirements of such a safeguards system, a detailed systemsanalysis is necessary. Besides establishing quantifiable criteria for a safeguards system, such an analysis enables one to set the target values of instruments and methods as well as, other objectives of development. Extensive experiments in industrial scale facilities are also required to demonstrate the feasibility of such a safeguards system.

The present paper describes the various phases of activities carried out in this area at the Karlsruhe Research Center, and deals at some length, with the system analytical approach followed, to establish a safeguards system based on the above mentioned principle. The paper also describes in detail the safeguards exercise carried out in the plutonium fabrication plant ALKEM at Karlsruhe. The method of assessing the relative importance of the chosen strategic points, preparation of material balance and establishment of different types of statements which can be made by an inspection authority, have been discussed. The possibility of estimating the dynamic behaviour of the process inventory for a given plant lay-out has been indicated. It has been shown that this principle can be effectively realized also in existing plants of the ALKEM type.

[1] On delegation from EURATOM

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Kernforschungszentrum Karlsruhe

1. HISTORICAL BACKGROUND

If one casts a glance over the past two and a half decades of nuclear energy development, one can distinguish between three different phases [1,2]. The first phase which lasted from 1942 to 1953, was mostly a military oriented phase. The reactors installed during this phase, for example at Hanford and Windscale, were mainly plutonium producing reactors. Although fabrication and reprocessing facilities were available for these reactors, they did not operate under commercial aspects. The development of nuclear energy during this phase took place under the shadow of atomic explosions at Nagasaki and Hiroshima. All the major activities in this field were governed by the assumption that a 100 percent effective and technically feasible control system for the peaceful sector had to be in existence before the nuclear energy could be used for civilian purposes. The Baruch plan or the Atomic Energy Act of 1946 in the USA, which prevented dissemination of any nuclear information or supply of nuclear materials to other countries, were the out-come of this era.

The second phase was initiated by the "Atom for Peace" program of President Eisenhower in 1953 and related to that the passing of the Atomic Energy Act of 1954 [3]. This phase was characterized by a worldwide exchange of nuclear information in the peaceful sector, supply of limited amounts of nuclear materials and research reactors to different countries and the establishment of the International Atomic Energy Agency (IAEA). The European Atomic Energy Community (EURATOM) was also established during this phase. The internationally

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known safeguard systems of the IAEA and EURATOM were worked out during this period and reflect strongly the characteristic features of the nuclear energy development during this period.

The third phase began in 1963 with the Oyster Creek event. This phase is the phase of large scale commercial use of nuclear energy including full scale industrial competition. It is also during this phase that the commercial use of all the steps of a nuclear fuel cycle, namely, reprocessing, refabricating, and possibly isotope separation becomes essential, so that the nuclear power stations can produce power economically. The third phase is rapidly expanding to many countries of the world, and the amount of fissionable material which is expected to be required and produced in the civilian sector will be higher by several orders of magnitude than that in the second phase. Any safeguard system which has to be applied during this phase, has to be oriented to the conditions pertinent to this phase.

2. THE PRINCIPLE OF MODERN SAFEGUARDS IN THE FIELD OF PEACEFUL APPLICATION OF NUCLEAR ENERGY [4]

2.1. It is vital to ensure that the peaceful nuclear energy does not proliferate into the domain of nuclear weapons and that it is solely used for fulfilling man's hope for peace and progress. If one can ensure that all fissionable material, required and produced in the peaceful sector, also remains in this sector, such proliferation cannot take place. Therefore, the only and specific objective of a modern and properly designed safeguard system, is to ensure that virtually all fissionable material, which is used in the civilian domain, remains there. Logically, it cannot be the objective of a modern and properly designed safeguard system to control the peaceful application of nuclear energy as such.

2.2. If the flow of fissionable material in the civil domain could be entirely and effectively contained in this domain this would be the only required safeguards measure. In such a case it would be irrelevant to know the amount and the quantity of the fissile material. Therefore, it must be the first safeguards measure of a modern safeguards system to ensure that such a containment measure is realized wherever that is possible. It is important to

realize that most of the nuclear facilities require in any way containments of different types, because of the requirements inherent in the handling of nuclear material. The reactor vessel of a nuclear power station, the hot-cells in a reprocessing plant, the glove-boxes in a fabrication facility, are typical examples of such containments.

2.3. In practice it might not always be possible to realize a fully effective containment. It is therefore necessary to introduce a second safeguards measure. This measure consists of safeguarding the flow of fissionable material throughout the whole fuel cycle. This can best be executed at certain strategic points. The first safeguards measure namely, the containment, provides for a kind of conservation of mass flow and it is not necessary to follow the flow everywhere inside a facility. Although a detailed systems analysis is required to determine the location and the number of such strategic points, the entrance and the exits of all nuclear facilities appear to be the more important of these strategic points. If all the safeguards activities are confined to these points, it will suit the commercial nature of the competitive nuclear industry of the third phase in an ideal manner, as under such a condition, the industrially sensitive parts of a nuclear facility would then remain untouched.

2.4. In any commercial scale nuclear facility a process inventory of fissile material is always required to enable the plant to operate under equilibrium conditions. This process inventory cannot be measured directly by measuring the throughput of the fissile material alone, and can only be calculated from the difference between the input and the output flows. If the process inventory would have been negligible compared to the throughput over a given period of time, the first two safeguards measures would have been sufficient. However, this condition is normally not fulfilled in large, industrial scale nuclear plants and can only be approximately met with a very large number of strategic points inside a facility. Therefore, to establish a complete material balance, a third safeguards measure has to be introduced, namely the inventory taking. As will be shown in chapter 4, the process inventory can be estimated and established independently of throughput measurement in several ways. One of the ways is washing out the plant. In such a case the

process inventory is temporarily transformed into a flow and measured at one of the strategic points. Such an inventory procedure should however, to the greatest possible extend, coincide with one of the operational washouts of a plant to make this measure as unintrusive as possible. Normally inventory taking, once or twice a year, appears feasible.

2.5. The above considerations lead to the following scheme for a modern safeguards system:

a) The objective of a modern safeguards system is to reduce significantly the possibility of diversion of fissionable material from the domain of peaceful use of nuclear energy.

b) It is the fissionable material in the domain of peaceful use of nuclear energy and not the peaceful use of atomic energy as such that must be subject to safeguard, which is in view of the ultimate purpose of such safeguard, namely to prevent the illegal manufacturing of nuclear weapons, an indirect approach.

c) The design of a modern safeguards system is governed by a quantified criterion of the following type:

"The requirements of safeguards are met, if with x o/o confidence level the material balance is closed within y o/o".

Such a criterion can be established with the help of an extended systems analysis and cuts the open endedness.

d) The first safeguards measure is to materialize the principle of containing the fissionable material to the greatest possible extent. Therefore this first safeguards measure covers among other things: real containments (buildings) of principal nuclear facilities, gate controls, waste control, safing and sealing, in particular in the case of transportation.

e) The second safeguards measure is to measure the flow of fissionable material at a finite number of strategic points. The assessment of strategic points, their distance and therefore the hold up between two of these strategic points and their required accuracy of flow

measurement shall be such, that the quantified criterion c) is met. In particular it will be the amount and the constancy of the hold up between two strategic points which has to be taken into account when this assessment is made.

f) The third safeguards measure is inventory taking, intentionally a rare event, which should coincide to the largest possible extent with the anyway expected regular wash-outs. The type of inventory taking shall be at the discretion of the operator of a principal nuclear facility, provided that the accuracy of the chosen type of inventory taking is in conformity with the purpose of that inventory taking.

g) Inspectors shall not interfere with the operation of a principal nuclear facility and shall have access only to the strategic points.

If in the course of safeguards experience it can be demonstrated that also another area of a principal nuclear facility has to be touched, this other area shall be identified as another strategic point by proper agreements between the involved parties or authorities.

h) Design details of a principal nuclear facility are of relevance for safeguards purposes only insofar, as certain ground rules for the general lay out of the building must be implemented. These ground rules are there to make the containment function of the building obvious and to identify in advance the strategic points and enhance their efficiency.

i) On a somewhat larger time scale tamper-proof instruments for measuring the flow of fissionable material at the strategic points shall be developed and their readings shall be processed by a suitable automatic data processing system. As these instruments come up, they shall gradually replace the safeguard inspectors.

3. IMPLEMENTATION OF THE PRINCIPLE

Work in three major areas is required to implement the principle of the proposed safeguards system in commercially operating nuclear facilities.

These areas are

3.1 Systems analysis

3.2 Containment studies

3.3 Development of instruments

A detailed research and development program has been worked out at Karlsruhe [5] in which the different types of activities being performed under the three major areas have been detailed. These activities and their timescales are indicated in tables I, II and III.

3.1 Systems analysis (Table I)

Emphasis has been laid on model simulation, development of statements and cost-effectiveness-study. The results of the first two areas of activities are expected to be available by the middle of 1969. Some more time would be required to obtain the results of the cost-effectiveness-studies, however, they should be available not later than the end of 1971.

3.2 Containment (Table II)

The role of the first measure of safeguards, i.e. containment, in the proposed scheme of safeguards cannot be over-emphasized. A close collaboration with the operators of different nuclear facilities in the fuel cycle, is required to determine the optimum way of laying out a plant so that the containment requirements can be fulfilled to the maximum possible extent without affecting significantly the economics of the plant. The first concrete results of these studies should be available by the end of 1969. The development work on sealing and identification of fuel subassemblies should yield definite results by the middle of 1970. The ultimate goal of the containment measure as well as the use of instruments is the tamper-proof storage and transmission of the information obtained from these measures. However, this goal is not expected to be reached before 1971.

3.3 Development of instruments (Table III)

Development of instruments is required mainly to implement the second and the third safeguards measures namely, the measurement of the fissile material throughput and the process inventory at the strategic points. In following the flow of fissile material in a fuel cycle (Fig. 1) it

becomes evident that two different types of measuring methods are required. After the fissile material is filled in the fuel pins at the final stage of a fabrication plant, it is no longer available in a directly accessible form and remains in this inaccessible and quantified form during its passage through the reactor and until the irradiated subassemblies containing the pins are destroyed in the dissolver stage of a reprocessing plant. At the strategic points in this part of the fuel cycle, indirect, non-destructive methods are required to determine the fissile material flow. On the other hand, direct methods of measurements can be used at strategic points in the rest of the fuel cycle. Some of the indirect and direct methods for example calorimetry for Pu-containing pins and X-ray fluorescence for the dissolver solution in a reprocessing plant, in their final industrial form should be available by the end of 1969. Others are expected to be available during the period 1970 - 1972.

Some other instruments, which are not directly required for the fissile material flow measurement but for implementing the containment measure, are listed under point III of table III. All these instruments are expected to be available by the end of 1969.

3.4 Experimental work

In the R+D program at Karlsruhe, one of the important phases of activities is the experimental testing of system analytical results and instruments in industrial scale nuclear facilities. The main objectives of such testing are summarized below:

Objectives of experimental testing

To test:

1. The proposed safeguards system in existing plants.
2. The validity of system analytical results.
3. The measuring and containment methods as and when they are developed.
4. The final safeguards system with instruments and other techniques in individual nuclear facilities and in the whole fuel cycle.

3.5 Implementation at the Karlsruhe Research Center

The principle of the safeguards system as elaborated in chapter 2 can be realized in an effective manner and within reasonable time scales only if the required research, development and testing program can be carried out and coordinated in an optimum manner. The basic conditions required for the fulfillment of such an objective are present at the Karlsruhe Research Center. Besides the fact that sufficient experience and research facilities in the required fields are available at the center, a complete, industrial scale fuel cycle is also present there, in which the research and system analytical results can be tested without any serious time lag. A rapid flow, exchange and feed back of information is therefore possible to attain the objectives within a preset time schedule. Also a close collaboration exists between the center and international control organizations which is essential for the actual implementation of any safeguards system.

4. RESULTS OF RESEARCH, DEVELOPMENT AND TESTING

Active work in the frame work of the fissile material control project was started at Karlsruhe in August 1967. Some interesting results, which were obtained during the last one year have been discussed in this chapter.

4.1 Systems analysis

4.1.1 Criteria for measuring methods

During the course of the system analytical investigation it became evident that intensive effort would be required to develop indirect methods for determining fissile material content in fresh and unirradiated fuel pins and subassemblies at the exit of a fabrication plant or at the entrance of a reactor. In case it would have been absolutely essential to measure the fissile material content in irradiated subassemblies, much larger effort would be required. Fortunately, irradiated subassemblies from most of the presently known reactors are reprocessed so that the fissionable material content of these subassemblies can be directly measured there. The direct methods which are already known have fairly high accuracies. Therefore,

indirect methods for irradiated subassemblies have been allocated a low priority in the Karlsruhe program and criteria for only freshly fabricated fuel pins or subassemblies have been established. The more important criteria have been shown in table IV. According to this the overall measuring accuracy for plutonium containing fuel pins should be better than ± 0.4 % and that for uranium better than ± 1.6 % [6]. These accuracies are based on throughputs in fabrication plants during the early seventies in Germany [13, 14, 15]. The accuracies are so chosen that with such throughputs, the integrated uncertainties in the throughputs reach a value of 10 effective [18] kgs of Pu in one year's time.

4.1.2 Relative importance of strategic points

A number of nuclear facilities like reprocessing plants with different capacities [7], ~~and fabrication plants with plutonium containing fuel,~~ were simulated to assess the relative importance of the strategic points. The range of uncertainties in the integrated amount of fissionable material, which is obtained at each of these strategic points, after a given amount of fuel has been processed, was taken for the time being as an index for assessing the relative importance of these points. The randomness of the measured results was simulated by using a random number generator. The location and number of the strategic points in the reprocessing plant are shown in Fig. 2, and the results on uncertainties are summarized in table V [7]. The range of uncertainties at a strategic point is a function of the integrated amount passing through this point, the accuracy of measurement and the number of samples taken for analysis. For the accuracies considered in this simulation, the feed point shows the highest range of uncertainties. This means that in a reprocessing plant, of all the strategic points considered, highest priority has to be given to the improvement of the measuring methods used at the feed point.

4.1.3 Statements

It has been shown [4] that with the information obtained from the second and the third safeguards measures (Throughput measurement and inventory taking), three different categories of statements can be made:

a) Probability of diversion (P_D). This is a statement by the safeguards authority. On the basis of the two series of measurements,

the safeguarding authority can determine the probability with which a minimum amount of fissionable material has been diverted from the plant.

b) Risk of the operator (R_D): This is a statement of the operator. In case an operator plans to divert a certain amount of fissionable material, and knows the accuracies with which the safeguards authority has carried out the two safeguards measures, he can calculate the risk (which can also be expressed as a probability) that the safeguards authority would find out with the probability P_D that he has diverted a minimum amount of fissionable material.

c) Proofing probability (P_B): This is a statement of the safeguards system designer. With this probability he can determine the quality of a particular safeguards system. For this purpose, he assumes that a certain amount of fissionable material has been diverted by the operator. He can then calculate the chance (which is also a probability) which the safeguards authority will have, in proving that a fraction of the diverted amount (with a corresponding probability P_D) has actually been diverted by the operator. This particular statement can be extended to determine the effectiveness of a safeguards system.

Because of the inaccuracies inherently associated with the measurement of throughputs and inventory, it is not possible for a safeguards authority to find out with a 100 % probability, that is with certainty, the total amount of fissionable material diverted by the operator.

4.1.4 Process-inventory functions

In chapter 2 it was indicated, that several possibilities exist in determining the process-inventory independently in nuclear facilities to exercise the third safeguards measure. These possibilities are:

a) Physical measurement of fissionable material inventory in each and every part of the plant during (or after) the process operation.

b) Inventory taking by washing out the fissile material content from the internal parts of a plant to one or more of the strategic points.

c) Determination of the process inventory from the known operational and inventory characteristics of each part of a plant.

d) Measurement of the plant inventory with the help of tracer techniques.

ad a) The first possibility requires a complete penetration into the plant by the safeguards authority and therefore should be regarded as a rare event and should be carried out only if the operator of a plant explicitly agrees to it. Besides, physical inventory is not sufficently accurate as it is very seldom that all the internal parts are calibrated or that the volumes of the interconnecting pipelines are known with a high degree of accuracy.

ad b) The second possibility, i.e. washout, was given as an example for exercising the third safeguards measure to emphasize the non-intrusiveness of this measure. If the inventory washouts are allowed to coincide with the operational washouts of a plant and are undertaken once or twice a year, it means that six to twelve months would have passed before a diversion by the operator can be detected by the safeguards authority. It is one of the objectives of the proposed safeguards system to reduce the time lag between a diversion and its detection, and the third and the fourth possibilities are being investigated intensively for this purpose [9]. The methods have been analysed with the fabrication plant, in which the control experiment (see below) has been carried out, as an example, but they are similar for a reprocessing plant also.

ad c) A fabrication plant can be divided into a number of unit fabrication cells. These cells can further be divided into a storage part and a machine part. The flow of the fissionable material through such a cell can be uniquely described with the help of three characteristic functions of time. They are, i) the inventory function h (t), which gives the mass of fissionable material present at time t in the fabrication cell [in kg e.g.]; ii) the output function k (t), which gives the rate of mass flow leaving the fabrication cell at the time t [in kg/h e.g.]; and iii) the residence time function, T (t), which indicates how long the fissionable material,

entering the fabrication cell at the time t remains in this cell /in h e.g./. If there is recirculation of fissionable material between some of the cells, the fraction or recirculation $\kappa(t)$ should also be known.

The plutonium fabrication plant ALKEM at which the control experiment was carried out, was divided into 5 such fabrication units as shown in Fig. 3. The hold-up and output functions for all these cells as well as the fractions recirculated at different points for the experimental campaign were collected and suitable analytical expressions were developed to fit into the actual data. Typical results of these analytical approximations are shown in Figs. 4 and 5 (output functions) and 6 and 7 (hold-up functions). The total hold-up in the plant during the campaign was then calculated with the analytical expressions and compared with the actual data obtained. The fitting of the analytical results with the actual values appears to be fairly satisfactory as shown in Fig. 8.

The results of this method indicate that it is possible to determine the hold-up in a plant at any time if the characteristics of the unit cells are known. However, this method does not appear to be very effective from the point of view of safeguards. As was seen at ALKEM, the hold-up functions can vary within fairly wide range for the same throughput, so that the operator can manipulate with his hold-up and the manipulation cannot be found out with this method. Besides that, the plant characteristics will vary from plant to plant and the safeguards authority has to have an intimate knowledge of the plant to establish the analytical expressions required. This may not be possible in a large number of cases and is contrary to the here proposed safeguard approach.

ad a) If fissile material is introduced at the feed point of an operating fabrication plant having a process inventory of h (t), at the rate of k (t), at the time t_o, the same material will appear at the exit of the plant after the whole of the process inventory h (t_o) has been processed out of it, if no internal mixing takes place. Therefore, the residence time T of the fissile material, which enters the fabrication plant at the time t_o, is given by

$$\int_{t_o}^{t_o+T(t_o)} k\,(t)\,dt = h\,(t_o)$$

In the case of a steady state operation $[k(t) = k_o]$ this equ. reduces to

$$T(t_o) = h(t_o)/k_o \ .$$

If the fissile material introduced in the plant at t_o be tagged with a certain amount of tracer isotope and the time T (residence time) be noted which the tracer takes to appear at the exit of the plant, the inventory $h(t_o)$ of the plant can be found out by knowing the throughput rate k_o. This is an indirect measure of determining the inventory as it is calculated from T and k_o. The hold-up can also be determined directly with the help of a traced material. For this purpose, the traced material is fed continuously from the time t_o onwards into the plant. The untraced material which was still inside the plant, is measured at the exit from the same time t_o onwards till the traced material starts coming out at the exit. The integrated amount of untraced material between these two time limits is the process inventory of the plant $h(t_o)$.

The ACDA proposed MIST program [19] follows a similar line.

By the extension of the indirect tracer method, for example, by repeating the delta type signal in a randomly periodic fashion, the rate of change of the process inventory can probably also be determined.

The tracer technique if properly developed, can be a highly efficient method of non-intrusively determining the inventory, during the operation, and the time lag between a diversion and its detection can be reduced significantly. Further and intensive efforts are however required for the development of this method.

4.1.5 Control exercise at the fabrication plant ALKEM

By far the most significant result obtained sofar in the framework of the fissile material control project at Karlsruhe, is the completion of the first safeguard exercise at the fabrication plant of the firm ALKEM. Observers from IAEA, EURATOM, USAEC and the German Ministry of Scientific Research have been present there. A detailed report on this exercise will be published shortly [10]. Only the important features of the exercise are presented here.

This fabrication plant is located at the Karlsruhe research center but operates under fully commercial conditions. The plant can handle about 200 kgs of Pu/yr.

and the fabrication of roughly 1 t of UO_2/PuO_2 platelets for the SNEAK has been carried out there.

a) Objectives of the exercise

The main objectives of the exercise can be formulated as follows:

1. To determine whether the principle of fissile material flow control at a certain number of strategic points can be realized in an existing plant, in which the strategic points cannot probably be selected in an optimum manner because of the already existing plant layout.
2. To find out whether the different types of statements developed on the basis of system analysis (chapter 4.1.3) can be made on the basis of the material balance established at the strategic points. For this purpose the owners of the fabrication plant were requested to withdraw a certain amount of Pu (known only to them) from the process stream. The objective was to demonstrate the applicability of the above mentioned statements.
3. To use mostly the measuring methods already available, but also to use the methods which are being developed and establish their suitabilities and weaknesses.
4. To prepare an estimate of the total amount of effort required to exercise different safeguards measures.
5. To determine the drawbacks of the existing layout from the point of view of safeguards.

b) Plant layout and location of strategic points

The plant layout and the location of the strategic points are shown in Fig. 9. The first strategic point was the Pu and the product storage. Since there was no possibility of weighing and sample taking in the storage and the only weighing and sampling possibility was in the glove-box no. 1/85 in the ceramic section, a part of the safeguards activity for the strategic point 1 had to be carried out at this box. At this point the input of the plant was measured. The layout of the plant is such that plutonium cannot be introduced into the plant excepting through this point.

The second strategic point was installed at the final pellet control stage. At the beginning of the experiment it was not clear whether the calorimeter which was supposed to be used to measure indirectly the plutonium content of the fabricated fuel pins (which were the final product), would be ready for operation. The final pellet control stage was the last step at which the product stream could be measured for its plutonium content with the already available method of γ-spectorscopy.

Since the calorimeter became ready during the exercise , it was taken into operation and installed in a corner of the metallurgy room which is air conditioned, and the area around the calorimeter was declared as the third strategic point, although logically, the calorimeter belongs to the room for pin fabrication, there was no space available there and there was no air conditioning, which is essential for the operation of a calorimeter. The completed pins were measured for their plutonium content in the calorimeter during the end phase of the campaign.

The fourth strategic point was located at the waste analysis room, in which all the waste streams from the different parts of the plant were collected and the plutonium contents of the waste were measured by a neutron counter. The neutron counter is permanently located in this room and is used regularly during plant operation.

The safeguards measures and acitivities at these strategic points are shown in table VI. Some additional safeguards activities were required on account of the prevailing conditions in the plant. They are summarized in table VII. Because of the campaign type of operation during the safeguards exercise the beginning and the end of the exercise were well defined for the establishment of the material balance. The chemical and isotope analysis required for the material balance calculations, were carried out in independent laboratories at the center and only these results were used for the exercise

c) The production campaign

The specification of the production campaign which was safeguarded, is given in table VIII. About 200 kgs of U+Pu mixed oxide were used to produce 186 fuel pins. The plutonium concentration was 2.3 %. The total amount of plutonium supplied to the plant was 4909 gms. Only the flow of Pu was safeguarded.

d) Results of the exercise

i) Material balance: The material balance for the safeguarded campaign was obtained by summing up the output and the input streams. The output streams consisted of the product stream (measured as pellets by the γ-spectroscopy and as pins by the calorimeter), the waste streams, and the scrap stream (the scrap is obtained as PuO_2 mixture from different process steps, it is normally recovered and re-used in one of the next campaigns or returned to the owner of the material), and the scrapings from the boxes at the end of the campaign. The amounts measured, the range of uncertainty for each of these amounts and the resulting difference are shown in table IX. The difference between the input and the output stream was found to be 48.38 gms of Pu with a 1-σ-range of uncertainty of ± 8.095 gms. No significant difference between the main values of calorimetry and γ-spectroscopy was obtained. This means, that all the pellets measured by the γ-spectroscopy were also introduced into the pins which were then measured by the calorimetry. However, the difference was calculated with the results of the γ-spectroscopy as it was found to be more accurate (table IX). In this exercise, the calorimetry was used mainly as a containment measure.

ii) The probability of diversion (P_D): The probabilities of diversion for different amounts of Pu were calculated according to the principle statements in [4] and are shown in table X. The actual amount of Pu withdrawn by the ALKEM authority during the exercise was 42 gms of Pu. It was possible to state for example, that with 95 % probability $\geq$ 35.06 gms of Pu had been diverted from the process stream.

iii) Risk of the operator (R_D): The risks of the operator for different amounts of plutonium and the corresponding probabilities of diversion have also been indicated in table X. It was shown in [4] that, for a given fraction of the diverted amount, which can be declared with P_D as diverted, the risk of the operator is mainly a function of the ratio of the plutonium amount which he plans to divert, to the total range of uncertainty in the measurement. Since this

ratio was fairly high in case of the safeguards exercise (amount withdrawn = 42 gms; 1-σ-range of uncertainty 8.09 gms), his risk was also high. For example, as the table X indicates, he stood a risk of 98.9 % that 10 gms, from a total of 42 gms, would be declared with a P_D of 95 % as diverted. In actual case, ≥35 gms (i.e. 83.2 % of the diverted amount) were declared with a probability of diversion of 95 %. For this statement, the operator stood a risk of only 22 %. This shows clearly that even with a low risk, the probability of diversion can be very high.

iv) Effort of safeguards: The man-hours for different safeguards activities have been summarized in table XI. and the chemical and mass-spectrometrical analyses in table XII. The largest fraction of man-hours was required by the γ-spectroscopy mainly because two persons were required at this point. A large saving in man-hours will be caused by the elimination of this point and using only the calorimeter at the final stage of pin production. A fairly large fraction of the chemical and mass-spectrometrical analysis was also required for the γ-spectroscopy.

v) Relative importance of the strategic points: It was indicated in 4.1.2 that the range of uncertainties can be regarded as an index for the relative importance of the strategic points. For a first approximation this can be characterized for a strategic point i by a number Z_i which is a product of the range of uncertainty σ_i and the square-root of the total effort A_i spent at that strategic point. For the ALKEM experiment, the total effort is given by the sum of the man-hours, chemical and mass-spectrometrical analyses. The number Z_i and the relative weightage of Z_i have been calculated for all the strategic points as shown in table XIII. The highest number is given by the calorimeter because of the highest range of uncertainties. However, this is not contradictory to former statement of ours as it was this particular and first device in which the full potential of the method has not been realized.

vi) Drawbacks of the instruments and layout: Because of the use of γ- spectroscopy and physical separation of the strategic points 1a and 1b three safeguards personnel were continuously required during

the exercise. Besides, the safeguards personnel had to enter the ceramic and the pellet production area. Absence of adequate space and air conditioning in the pin fabrication room, necessitated the location of the calorimeter in the waste reprocessing room. None of the measuring methods used at the plant, namely the γ-spectroscopy, the calorimeter, and the neutron counter are tamperproof in their present form. However, the calorimeter and the neutron counter can be made tamperproof with further effort.

e) Conclusion

The results of the exercise have shown, that the principle of fissile material control can be realized in the existing plant of the ALKEM type, with reasonable efforts. Because of the fairly high measuring accuracies obtainable, diversion of relatively small amounts can be detected with a fairly high degree of probability. Valuable experience was gained which can be used in setting the priorities of different development work and system analytical investigations.

4.2 Containment studies

4.2.1 Nuclear power stations

A recent study [11] undertaken to determine the optimum and effective safeguards measures for nuclear power reactors has shown that nuclear power stations of the presently known heavy water natural uranium and light water slightly enriched uranium types, can be safeguarded mainly with the help of containment measures. A nuclear reactor is the only step in the whole fuel cycle in which fissionable material remains contained in fuel subassemblies during its entire residence time. During normal operation of such a reactor, the fuel subassemblies move through three well defined containment areas namely, the dry storage area for fresh fuel subassemblies, the reactor vessel, and the wet storage area for irradiated subassemblies. Three measures are required to safeguard the movement and account for the subassemblies.

a) Sealing and identification of the subassemblies at the dry storage and the wet storage area.

b) Registration of movement and loading of the main cranes and the refuelling machines.

c) Measurement of the activity over the reactor bay area.

A combination of these measures can determine the movement and the number of subassemblies in a reactor as a function of time.

4.2.2 Fabrication plant [12]

A typical layout of a 100 t/a of PuO_2+UO_2 fuel for fast breeders is shown in Figs. 10a and 10b. The experience gained from the ALKEM experiment and the trend of the fabrication industries for automation, have been incorporated in this reference layout. Fig. 10a gives the layout of the cellar and the ground floor at which all the fabrication steps are located. Fig. 10b gives the front view of the fabrication building. The plant is laid out in such a way that the movement of fissile material is fully contained inside the plant and the fissile material can enter or leave the plant only through strategic points. The first of these strategic points is in the cellar for the fissile material entrance and for the waste material which leaves the plant. It is possible to weigh and take samples at this point. The second strategic point is directly on top of the first strategic point on the ground floor and is used for the personnel check. The third strategic point is at the product end. At this point there are possibilities for both pin measurement and sealing of subassemblies. The containment of the fissile material is shown by the dotted line.

In laying out this particular plant it has been assumed that the fuel for the core part of the subassembly will be received in the form of sinterable UO_2 and PuO_2 powder, whereas, that for the axial blanket (which is normally depleted uranium) will be obtained as completed pellets. All these materials will be received at the first strategic point, located in the cellar. The sealing of the bird cages will be checked at this point and if necessary samples can be taken on the basis of random statistical methods. Simple chemical analyses, if necessary can also be carried out by the safeguards personnel at this point, but samples for independent mass-spectrometric analyses, will have to be sent to some other laboratories. After identification and sampling, the fissile material will be stored in the respective storage areas.

The material from these areas is transfered to the ground floor with the help

of lifts provided for this purpose. All the operational personnel can enter or leave the fabrication area through the personnel lock only, which functions as the second strategic point. The fabrication area has been divided into two parallel lines to fabricate fuel for the two core-zones of a fast breeder separately, each of which has a different plutonium concentration. The two lines join again at the third strategic point. At this point the finished pins or the subassemblies can be tested for their plutonium content. If necessary, sealing of the pins and subassemblies by the safeguards authority, can also be carried out here. The completed subassemblies can leave the plant only at the third strategic point. This point is used also for the supply of structure and canning materials and other inactive materials required for the plant.

The scraps and analytical wastes are reworked and the scrap recovers the plant continuously and the reworked plutonium is sent back to the first stage of the fabrication. Only the waste from this stage is sent to the waste storage-cellar with the material lift. The waste can leave the plant only through the first strategic point.

The fabrication area is flanked by two wings of the building in which the technical offices, storage for inactive materials etc. are located. All the areas surrounded by the dotted line are contained. Different measures can be taken for ensuring this containment.

On the first floor, assembly and testing of the canning material are carried out. The tested and partly assembled canning materials are sent to the pin fabrication station with the lift located at the third strategic point. The inactive workshop is also located on the first floor.

Several of such layouts and their drawbacks and advantages have been discussed in detail in [12].

4.3 Instruments

Important progress has been made on slowing down spectrometer, on the basic research on n, γ-reactions, and on the calorimeter. Work on the first method is being refered to by Stegemann and on the second method by Michaelis at this conference [16, 17].

4.3.1 Calorimeter

The radio-metric calorimeter is a well known device for determining the heat generated by the α-decay of Pu in Pu-containing fuel. If the isotope composition of Pu is known, the total amount of Pu present in the fuel can be calculated from the heat generated by the different isotopes of Pu and by the Am-241 which is present in the fuel at the time of measuring the heat.

The principle of the calorimeter is shown in Fig. 11. Fuel pins with unknown Pu content are introduced into the α-calorimeter which is surrounded with thermocouples. The heat flux obtained by α-decay of Pu and Am-241 in the pin, generates the potential difference in the thermocouples and can be measured accurately by a micro-voltmeter. This calorimeter is immersed in a constant temperature water bath. A second identical reference calorimeter connected to the α-calorimeter is also immersed in the same bath. The reference calorimeter contains an electrical resistance which is heated up simultaneously with the heating of the α-calorimeter and the heat input registered. The voltage of the two calorimeters is balanced in a wheatstone-bridge. From the accurately measured voltage supplied to the reference unit, the heat production rate of the α-calorimeter and therefore, the amount of Pu inside the pins can be calculated, once the potential difference and the heat flux relation has been standardized.

The main advantage of a calorimeter of this type lies in the fact that the method is simple, reliable and easily automatizable. In principle it is possible to estimate the plutonium content in fuel subassemblies also. It is not fully tamperproof, as plutonium in the fuel pins could be replaced by some other α-producing element. However, the method can be made tamperproof if the neutrons produced by the isotopes, on account of spontaneous fission are also measured simultaneously and the ratio neutrons/watt is determined.

The inaccuracies in this measurement result from two sources, a) the inaccuracies in the measurement of the isotopes and the Am-241 content and b) inaccuracies caused by the reproducibility of the measurement

error on account of the first source, obtained for the safeguards exercise, was found to be 0.45 % as shown in table XIV. The major part of the total error (found between 0.8 - 1.2 %, table IX) was from the reproducibility of measurement and varied between 0.6 % - 1.0 %. With further development, the total percentage error from all the sources is expected to be reduced to around 0.4 - 0.5 %.

4.3.2 Slowing down time spectrometer

The slowing down time spectrometer has also reached an advanced stage of development.

A pulse of fast neutrons is allowed to pass through a lead pile. Because of the slowing down process, the average energy of neutrons can be calculated as a function of time. If a fuel pin containing uranium or plutonium is placed in the lead pile in the path of these neutrons, fission of U-235 or Pu-239 is initiated by the impinging neutrons, provided they have energies in one of the resonance regions. Knowing the energy of the neutrons and the cross sections of the fissile material at this energy, the amount of fissile material can be determined by measuring the resulting fission neutrons. For the determination of U-235 alone, the resonance energy level of 0.28 keV may be chosen.

As indicated in chapter 3, an industrially finished instrument based on this principle is expected to be ready by the middle of 1970. This instrument will be in a position to measure the U-235 content in fuel pins for light water type reactors (appr. 3 % U-235 concentration) with an accuracy of < 2%. The capacity of this instrument will be around 600 pins/day. This corresponds to a fabrication plant of 1 t/d capacity.

Further details of this method are given in [16].

5. CONCLUDING REMARKS

The modern safeguards system involves a number of complex and interrelated problems. They range from the intangible political feelings, human relations and other apparently unquantifiable areas, to the development of highly sophisticated methods. Experience and results gathered during the past year indicate however, that most of these problems yield solutions if handled in a rational manner, that most of the areas, hitherto considered unquantifiable, can be quantified and, finally that the whole development of a modern safeguards system is a fully rational venture. These experiences and results also indicate that such a system is not a long term hope but a short time reality. It can be realized and implemented in existing plants in the near future.

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TABLE I. ACTIVITIES AND TIME SCALE FOR THE SYSTEMS ANALYSIS

Activities	Time scale
I. Model simulation	
a) Establishment of objectives for safeguards methods	Middle of 1969
b) Number, location and relative importance of strategic points	
c) Process inventory analysis	
d) Effective use of statistical, probabilistic and other similar methods	
II. Development of statements	
a) For the safeguard authority	
b) For the operators of nuclear facilities	
c) For safeguards systems designer	
d) On effectiveness of safeguard system	
III. Cost effectiveness	
a) Use of operators data	End of 1969
b) Cost functions for measuring accuracies, containment and other safeguards measures	End of 1971
c) Optimization of the whole safeguards system	

TABLE II. ACTIVITIES AND TIME SCALE FOR CONTAINMENT STUDIES

Activities	Time scale
I. Containment of nuclear facilities	
a) Nuclear reactors b) Fabrication plants c) Reprocessing plants	End of 1969
II. Containment of fissionable material	
a) Sealing and identification of fuel subassemblies b) Sealing of containers and transport casks	Middle of 1970
III. Tamperproof storage and transmission of safeguards information	End of 1971

TABLE III. DEVELOPMENT OF INSTRUMENTS AND THEIR TIME SCALE

Instruments	Time scale
I. Indirect methods	
a) Calorimeter (Pu-containing fuel pins)	End of 1969
b) Calorimeter (Pu-containing subassemblies)	End of 1970
c) Slowing down time spectrometer (U-235 containing fuel pins)	Middle of 1970
d) Slowing down time spectrometer (U and/or Pu-containing fuel pins)	Middle of 1972
e) Methods based on γ-spectroscopy with induced reactions (U and/or Pu-containing fuel pins)	Middle of 1972
f) Neutron dose measurement (Pu-containing wastes)	Middle of 1970
g) Delayed neutron (fissile material containing wastes)	Middle of 1970
II. Direct methods	
a) X-Ray fluorescence for β, γ-active samples (U+Pu)	End of 1969
b) Isotope dilution by mass-spectrometry (U+Pu isotopes)	Middle of 1970
c) α-spectroscopy (Pu-238)	End of 1969
d) Neutron activation of homogenuous waste solutions	Middle of 1969
e) Improvement of standard methods	Middle of 1970
III. Other methods	
a) Distance-cum-load measuring instruments for cranes, fuelling machines etc.	End of 1969
b) Activity measuring instruments for reactor bay, storage pond for active subassemblies etc.	End of 1969
c) Control of personnel and material for concealed fissionable material (Pu)	Middle of 1969

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

Criteria	Remarks
1. Tamperproofness	Against all conceivable measures, which can simulate the presence or 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 value)
6. Simple, reliable, easy to automatise and adaptable to continuous operation	
7. Economic	

TABLE V. RANGE OF UNCERTAINTIES IN PLUTONIUM AMOUNTS MEASURED AT STRATEGIC POINTS IN A REPROCESSING PLANT

	Low Pu-Content Fuel			High Pu-Content Fuel		
Amount of Pu Processed [kg]	132			1050		
Measuring Accuracies [1σ; %]						
Product		0.2 (2)				
Acid Recycle		3.0 (3)				
Waste		10.0 (6)		10.0(30)		
Feed	0.5 (3)	1.0 (3)	2.0(3)	0.5(15)	1.0(15)	2.0(15)
Range of Uncertainties [kg Pu]						
Feed	0.63	1.26	2.53	3.16	6.33	12.68
Acid Recycle	0.45			0.35		
Product	0.27	Same	Same	0.75	Same	Same
Waste	0.10			0.51		
Total	0.85	1.37	2.59	4.05	6.81	12.84

( ) Number of samples per day

TABLE VI. SAFEGUARDS MEASURES AND ACTIVITIES AT STRATEGIC POINTS FOR THE CONTROL EXPERIMENT AT ALKEM

Strategic point	Safeguards measures	Safeguards activities
1a	Containment	Sealing of the Pu storage to identify the in and outgoing Pu-containing boxes.
1b	Throughput measurement for feed and scraps	Weighing, sample-taking, chemical analysis. Known methods.
2	Throughput measurement product stream in the form of pellets	Measurement with the help of γ -spectroscopy. Known method but introduced for the experiment for the first time.
3	Throughput measurement product stream in the form of pins	Measurement with the help of calorimeter. New method introduced particularly for the experiment for the first time.
4	Throughput measurement waste streams	Measurement with the help of n-counter. Known method, standardized for the experiment

TABLE VII. ADDITIONAL SAFEGUARDS ACTIVITIES IN CONNECTION WITH THE SAFEGUARDS EXPERIMENT AT ALKEM

Safeguards activities	Purpose
Sealing of active waste storage drums	To prevent removal
Sealing of waste storage area	To ensure that no recirculation takes place
Accompaniment during transport of Pu from Pu-storage to weighing and sampling box and back (Str.Pt. 1a)	To prevent mixing and recirculation
Accompaniment during transport of pellets from final control stage to pin filling stage	To prevent mixing and recirculation
Identification of material under safeguards through mass-spectrometric analysis	To prevent mixing between safeguarded and unsafeguarded material which had different Pu-isotopic compositions
Marking of finished pins	To prevent recirculation in the calorimeter
Control of cleaning operation of the plant before and after the experiment	To establish well defined starting and end conditions for establishing material balance
Homogenization of scraps	To determine accurately the Pu-content in scraps

TABLE VIII. SPECIFICATION OF THE PRODUCTION CAMPAIGN SAFEGUARDED DURING THE EXPERIMENT

Amount of Pu supplied [gm]		4909.00, as PuO_2	
Amount of U supplied [kg]		250, as UO_2	
Total amount of ceramic processed [kg]		200, mixed U + Pu oxide	
Pu-concentration [%]		2.3	
Pellet specification			
Height	[mm]	15	
Diameter	[mm]	12.5	
Weight	[gm ceramic]	18.6	
Pin specification		Type I	Type II
Height	[mm]	1325	410
Diameter	[mm]	13.5	13.5
Weight	[gm]	1472	452
No. of pins		113	73

TABLE IX. RESULTS OF THE MATERIAL BALANCE

Point	Amount (gm Pu)	Range of uncertainties (1-σ value in gm Pu)
Input	5070.25	5.86
Output, Product; Pellets (γ-spectroscopy)	4209.57	4.91
Output, Product; Pins (Calorimetry)	4213.76	14.48
Output, Scrap	677.63	2.19
Output, Waste	127.95	1.49
Output, Waste (box scrapings)	6.50	0.06
Difference between input and output (based on the γ-spectroscopy)	48.38	8.09

Accuracies of measuring instruments used:

Feedpoint	0.4 %
γ-spectroscopy (pellets)	0.5 % per batch
Calorimeter	0.8 - 1.2 %
n-counter	8 %

TABLE X. PROBABILITIES OF DIVERSION (P_D) AND THE RISK OF THE OPERATOR (R_D) CALCULATED ON THE BASIS OF MATERIAL BALANCE

Actual amount diverted: 42 gms of Pu

Probability of diversion

	P_D [%]		
	90	95	99.0
Amount [gms Pu]	38.09	35.07	29.56
Percentage of the actual amount diverted	90.5	83.5	70.4

	P_D [%]		
	90	95	99.0
	Risk (R_D)		
For amounts declared as diverted [gms Pu]			
10	99.6	98.9	94.8
15	98.0	95.4	84.4
20	92.4	85.7	65.2
30	58.3	43.6	20.1
35	33.7	22.0	7

TABLE XI. MAN HOURS FOR DIFFERENT SAFEGUARDS ACTIVITIES DURING THE CONTROL EXPERIMENT AT ALKEM

Location	Man hours	% of total
Pu-storage	32	3.9
Box 1/85	62	6.9
Waste analysis (n-counter)	121	13.4
γ-spectroscopy	484	53.5
Calorimeter	70	7.7
Waiting time	80	8.8
Miscellaneous	56	6.2

TABLE XII. EFFORTS ON CHEMICAL AND MASS-SPECTROMETRICAL ANALYSIS

Purpose	No.	% of total
A. Chemical		
Input	8	20.5
γ-spectroscopy	26	16.7
Scrap + Waste	5	12.8
Calorimetry	0	0
Total	39	100
B. Mass-spectrometrical analysis		
Input	12	35.3
γ-spectroscopy	12	35.3
Scrap + Waste	5	14.7
Calorimetry	5	14.7
Total	34	100

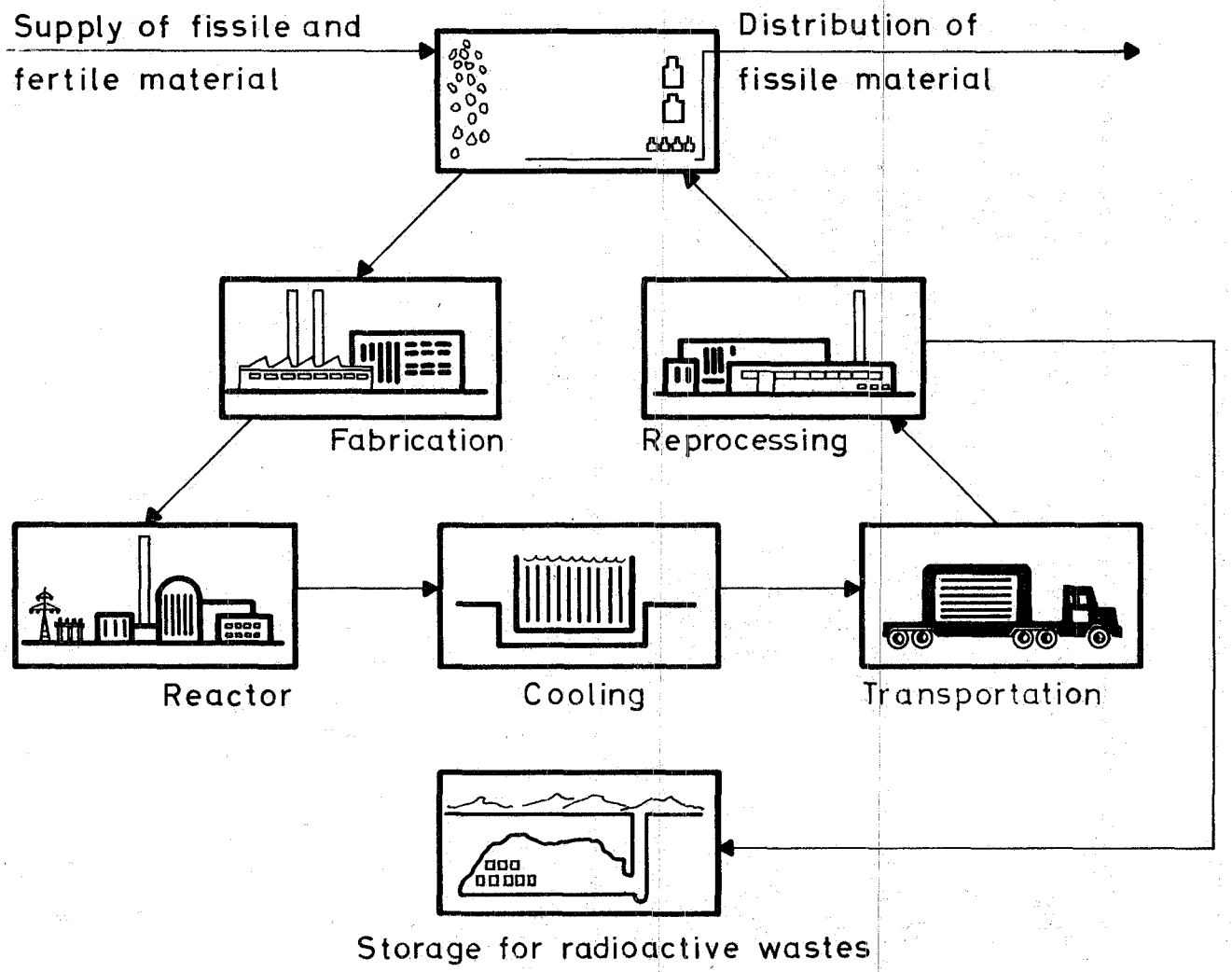
TABLE XIII. RELATIVE IMPORTANCE OF STRATEGIC POINTS

Strategic Point	Measurement of	Range of uncertainties [g Pu]	Man hours [h]	Chem. analyses [no.]	Mass-spectr. analyses [no.]	Costs [DM] A_i	Z_i	Z_i rel.%
1a 1b	Input + Scrap	6.256	94	13	17	7430	539.	27.0
2	Pellets (γ-spectr.)	4.91	484	26	12	15280	606.	30.6
3	Pins (calorimetry)	14.48	70	0	5	2650	744.	37.4
4	Waste	1.46	121	5	5	4710	100.	5.0

TABLE XIV. ERROR IN THE MEASUREMENT OF CALORIMETRY ON ACCOUNT OF ISOTOPE MEASUREMENT ERRORS

Isotop.	perc.	error	heat val. rel. w/g	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	$1.28\ 10^{-6}$
Am_{41}	0.3699	1.5	0.1084	0.000401
Total:		0.45		0.00487644 watt/gm of Pu safeguarded

Fig. 1 Fuel cycle industries for the production of nuclear power



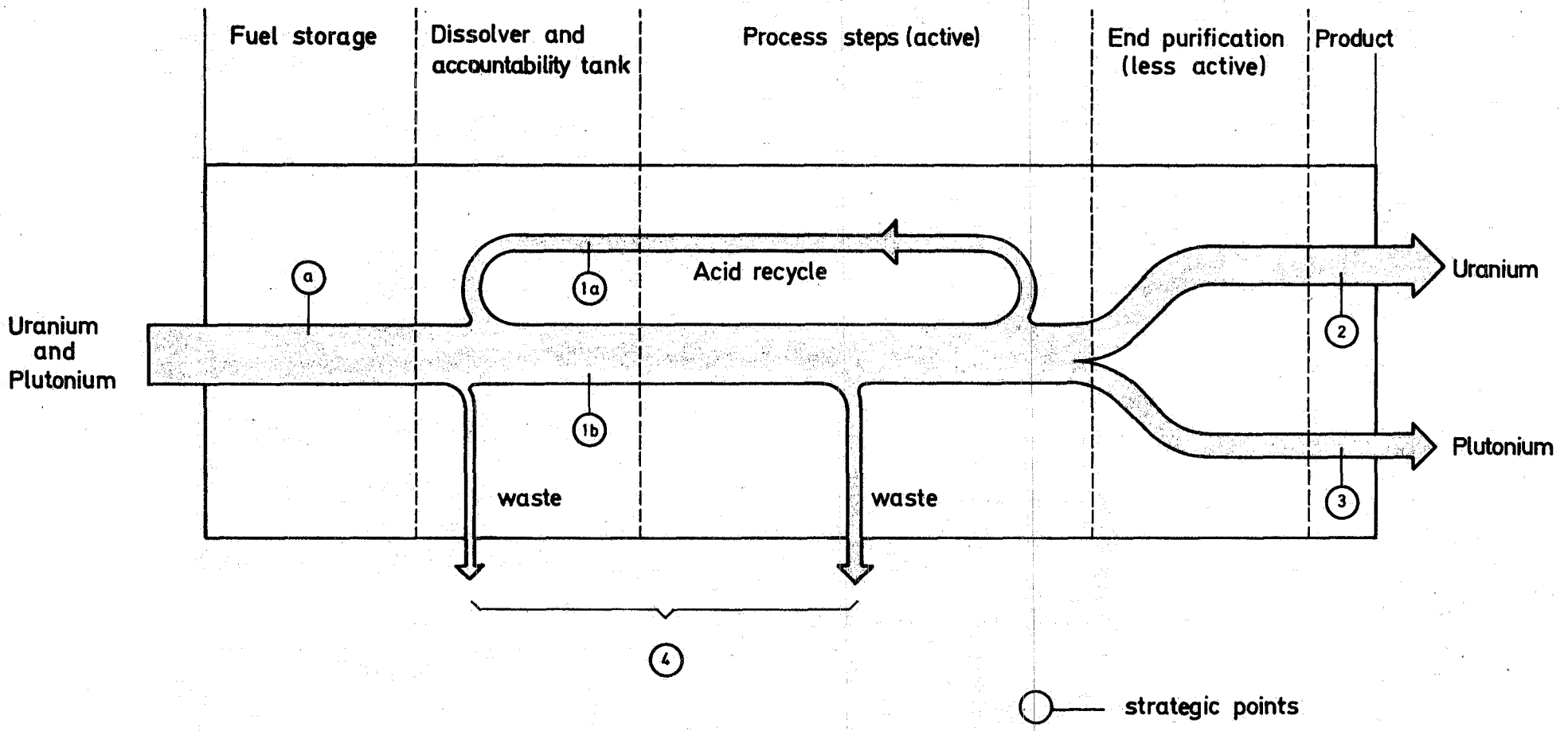
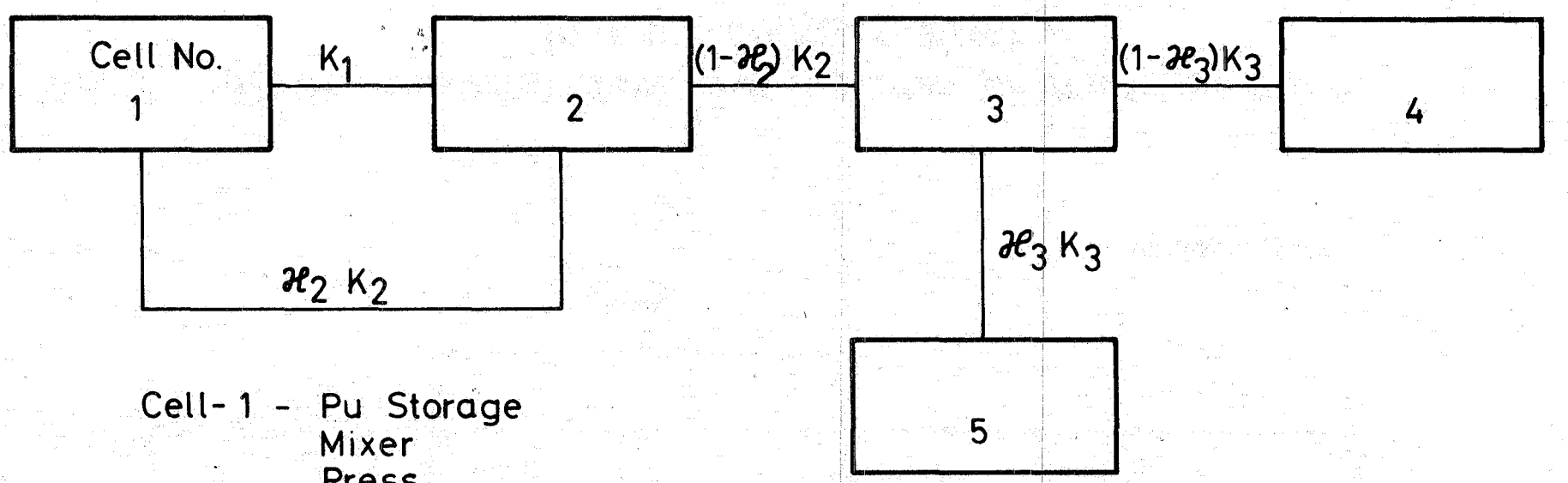


Fig. 2 Fissile material flow and location of strategic points in a reprocessing plant



Cell-1 - Pu Storage
Mixer
Press

Cell-2 - Sinter Oven

Cell-3 - Grinding
Washing
Drying
Final Control of Pellets

Cell-4 - Pin Fabrication
Final Storage

Cell 5 - Waste Storage

Fig. 3 Division of the fabrication plant Alkem into 5 unit fabrication cells.

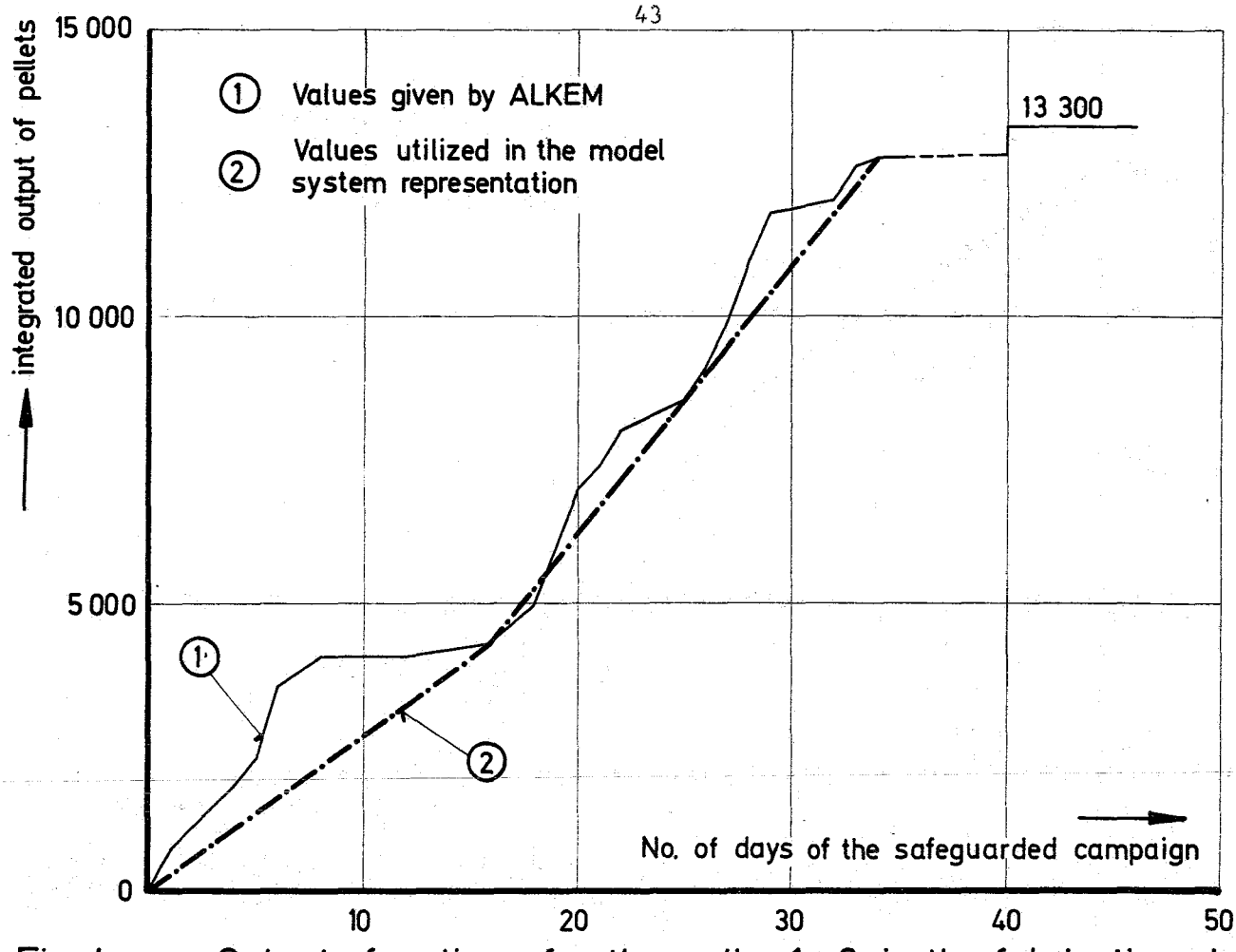


Fig. 4 Output functions for the cells 1 - 2 in the fabrication plant

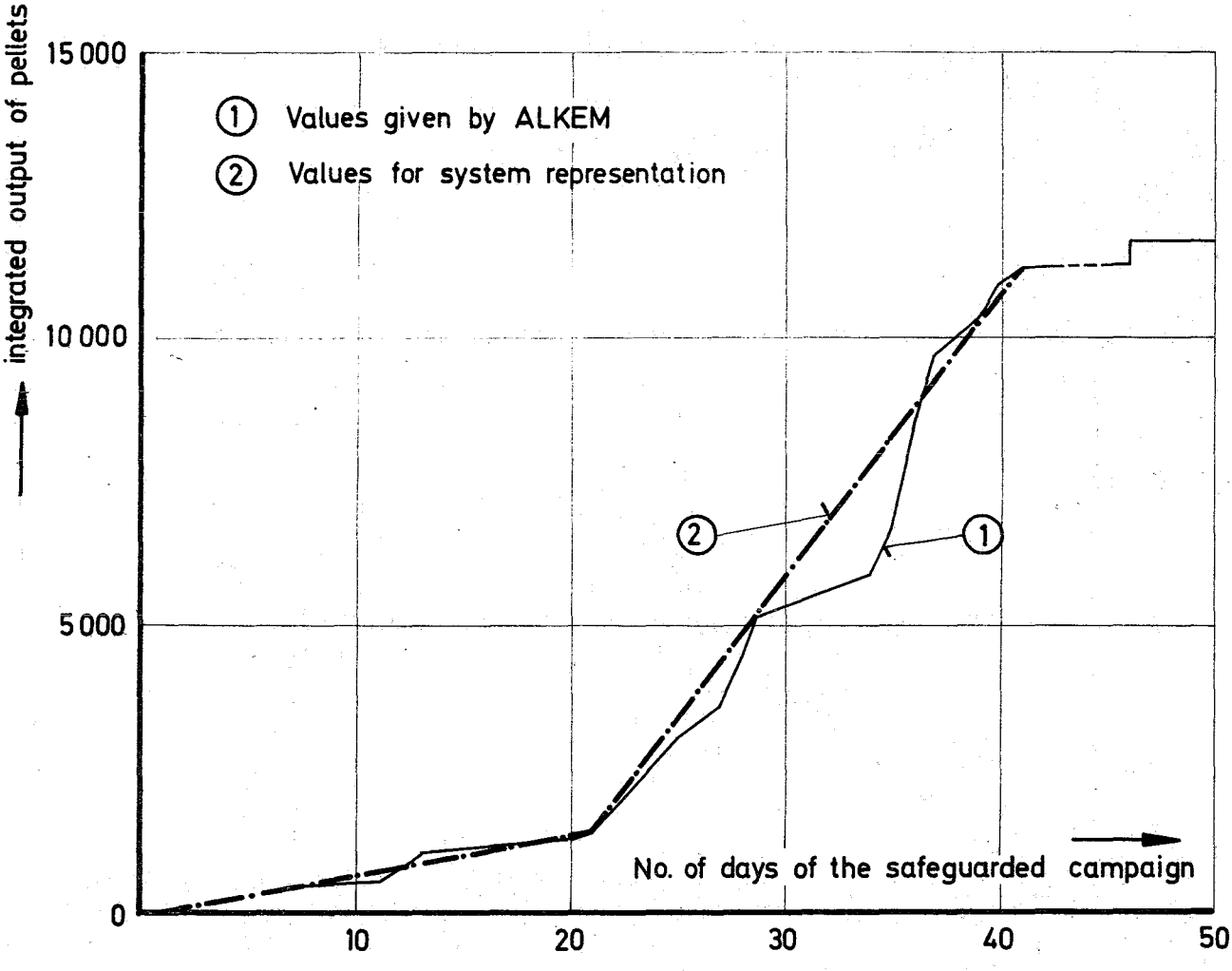


Fig. 5 Output functions for the cells 3-4 in the fabrication plant

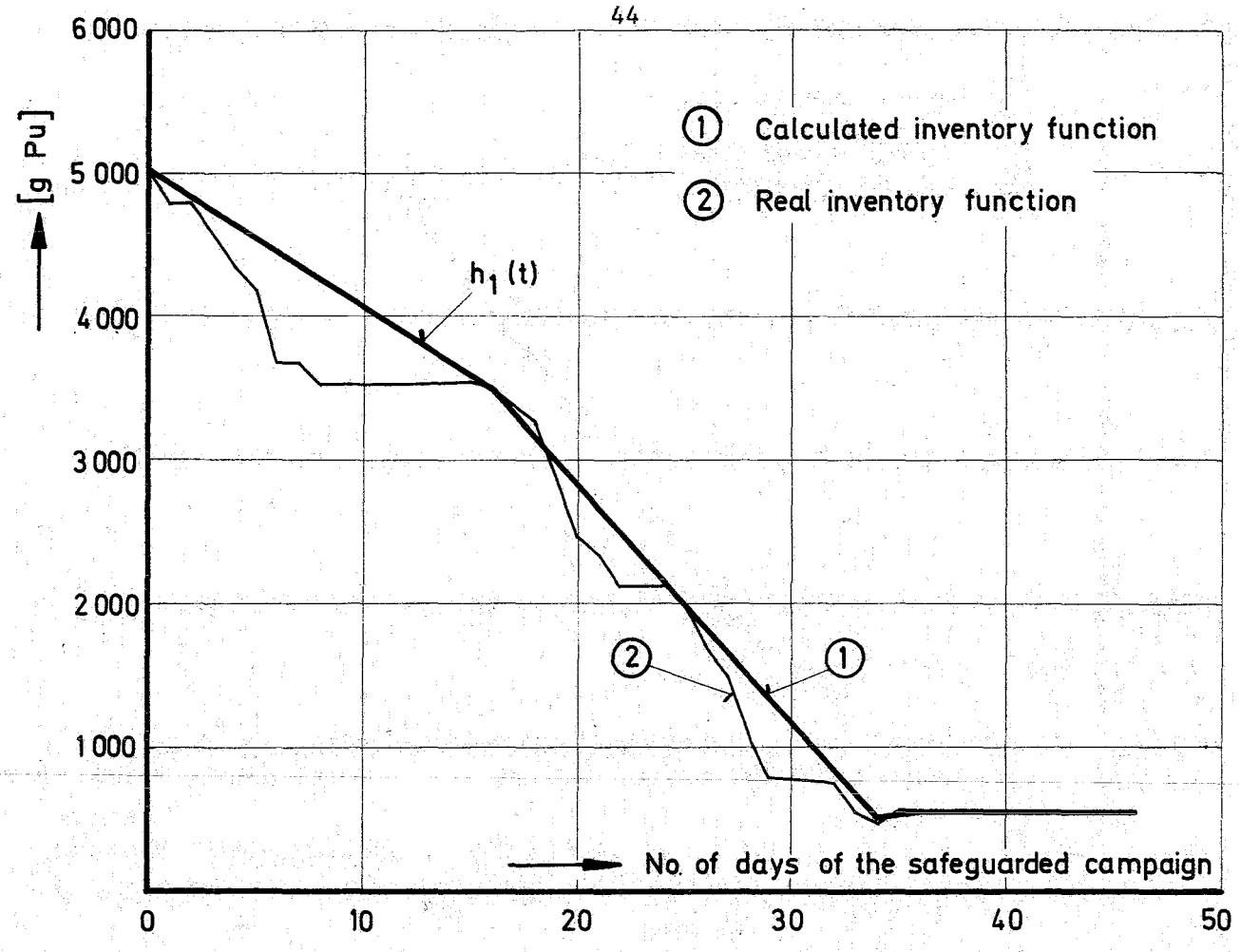


Fig. 6 Inventory function of the first fabrication unit

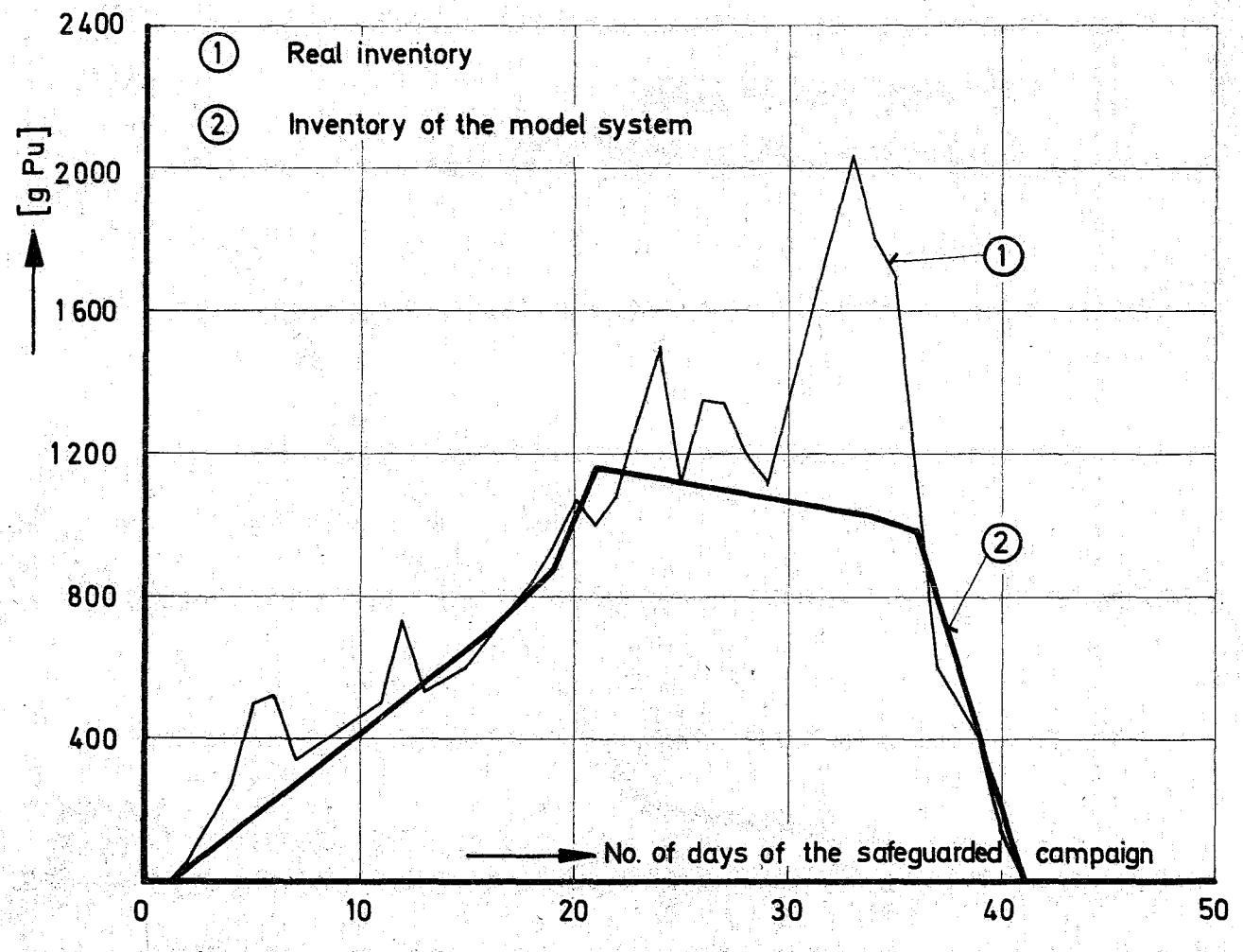


Fig. 7 Inventory function of the third fabrication unit

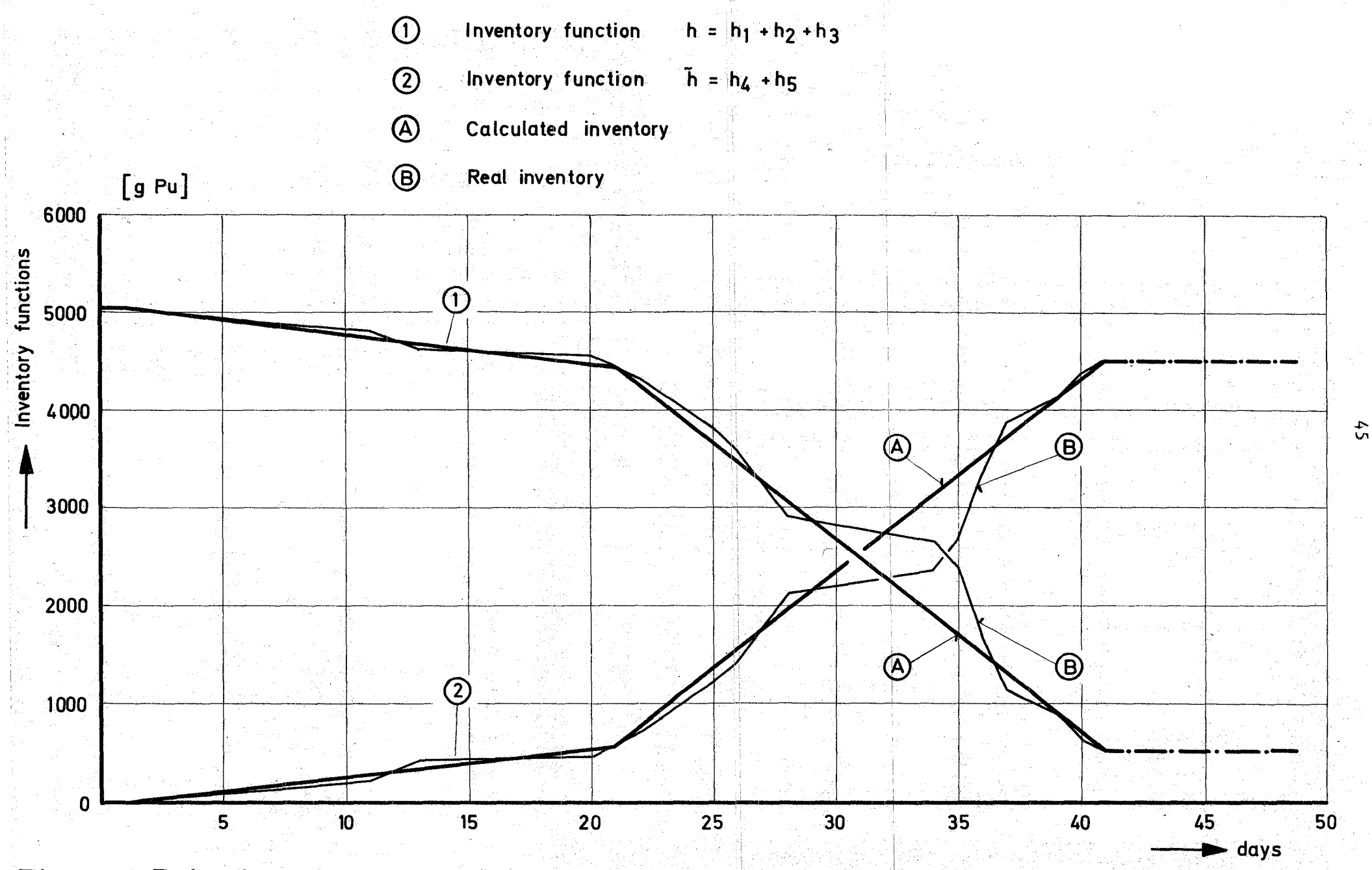
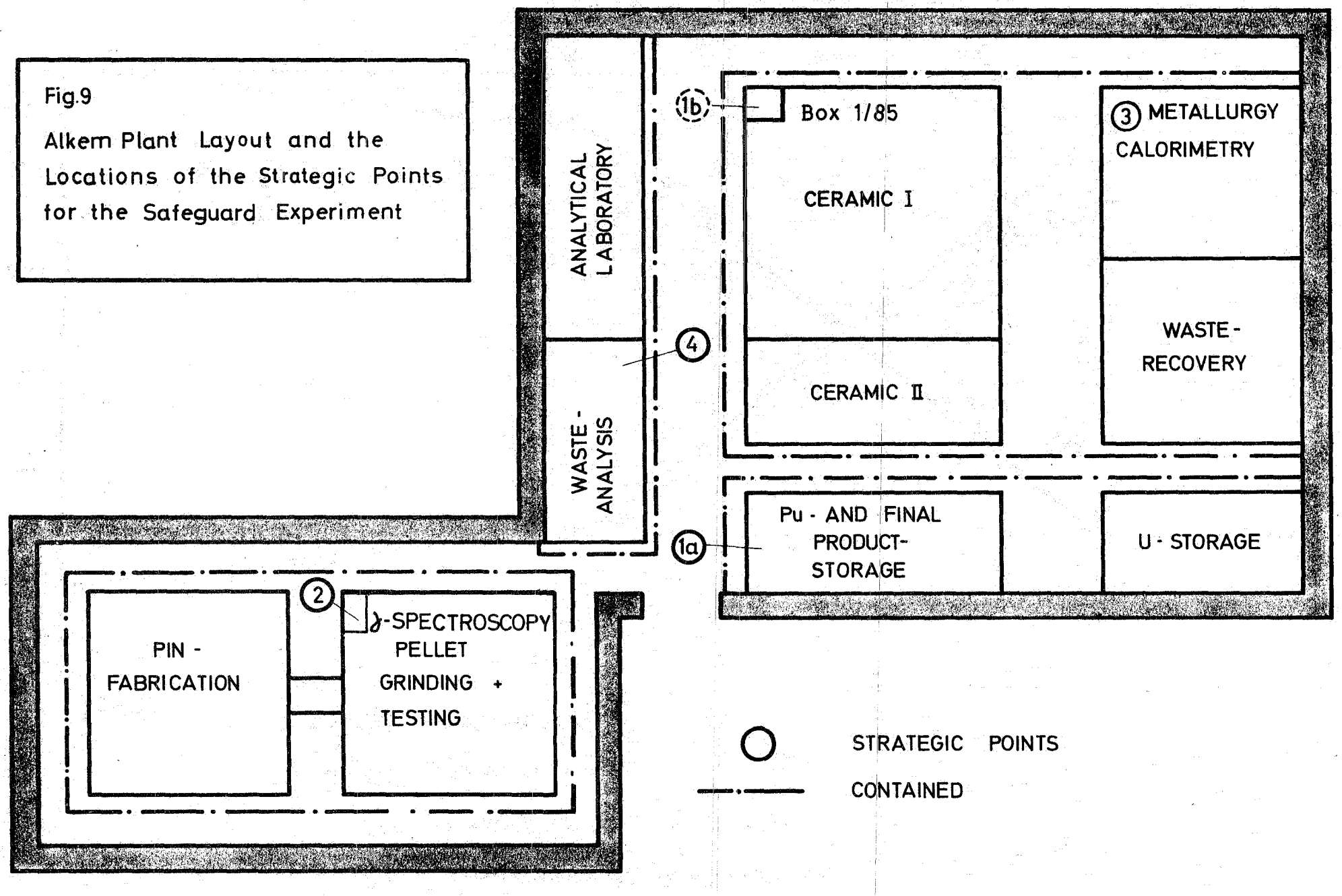
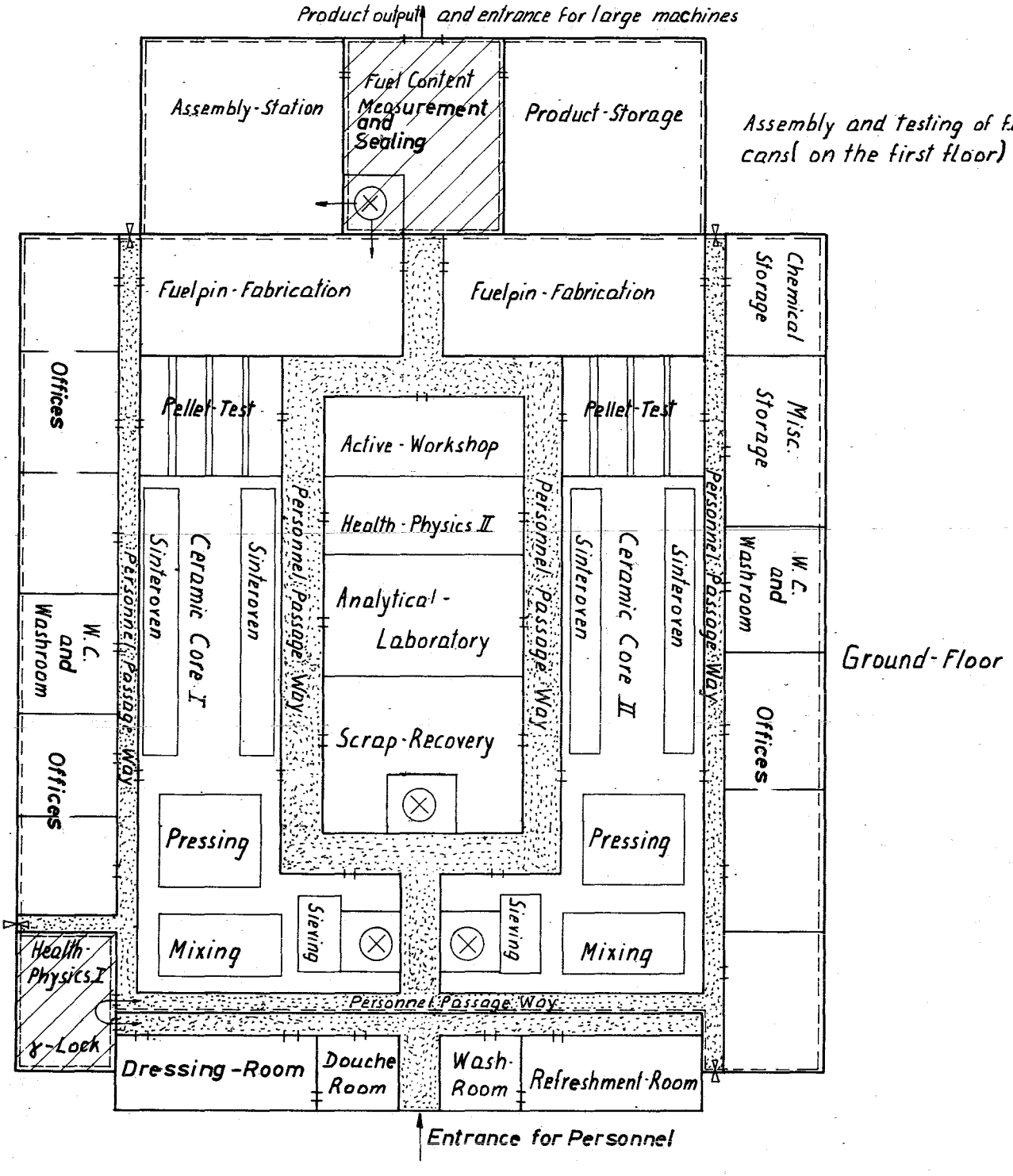


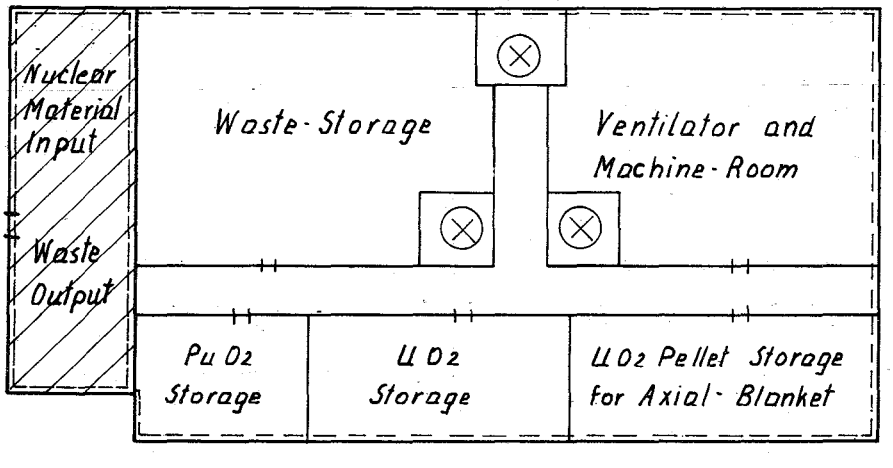
Fig. 8 Behaviour of the total inventory as a function of time.

Fig.9

Alkem Plant Layout and the Locations of the Strategic Points for the Safeguard Experiment







Strategic Point

Containment

Material Lift

Emergency Door

Fig. 10a. Layout of the ground floor and cellar of a reference fabrication plant for fast breeder fuel subassemblies.

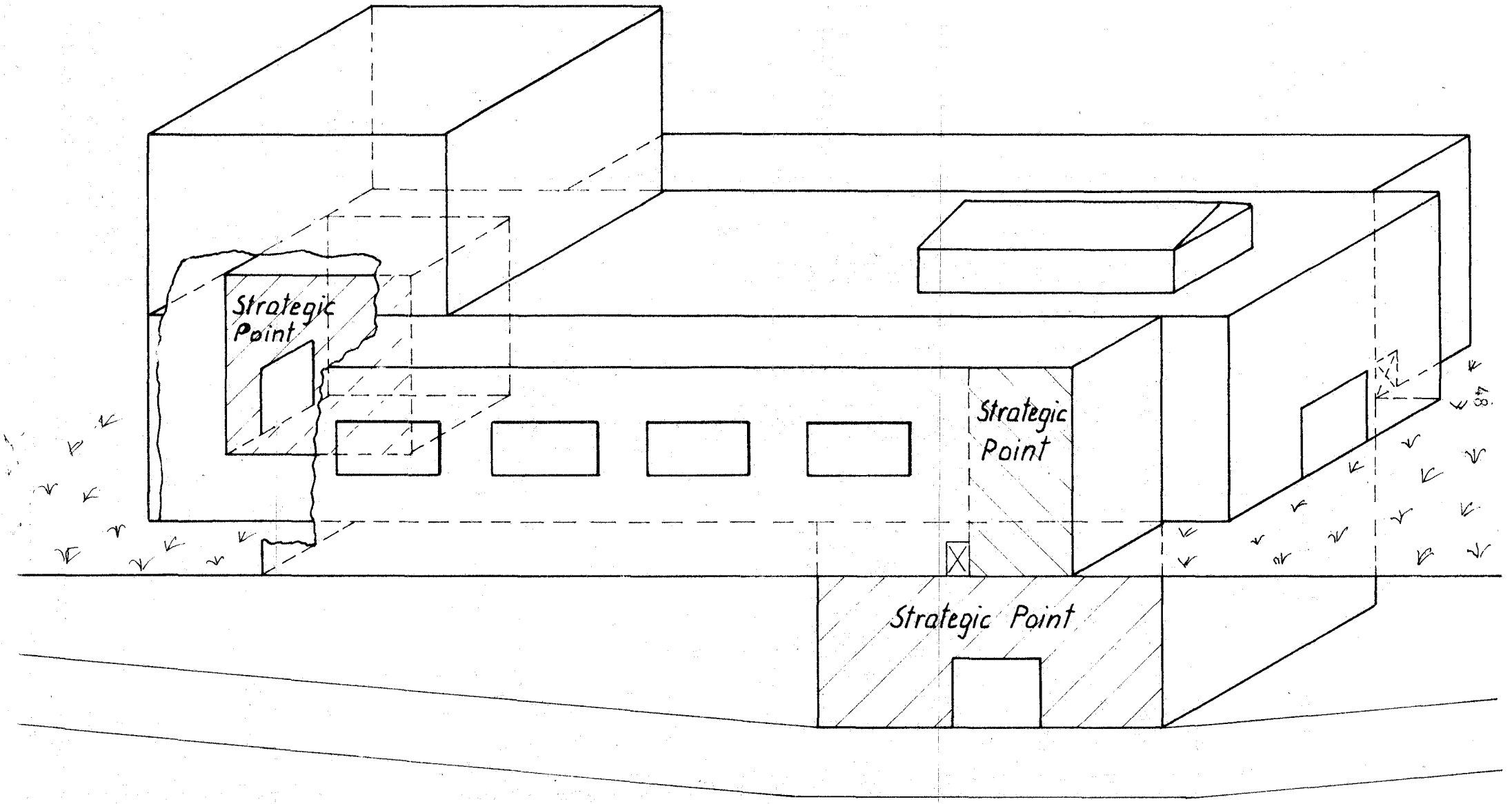


Fig. 10b Front view of the reference fabrication plant

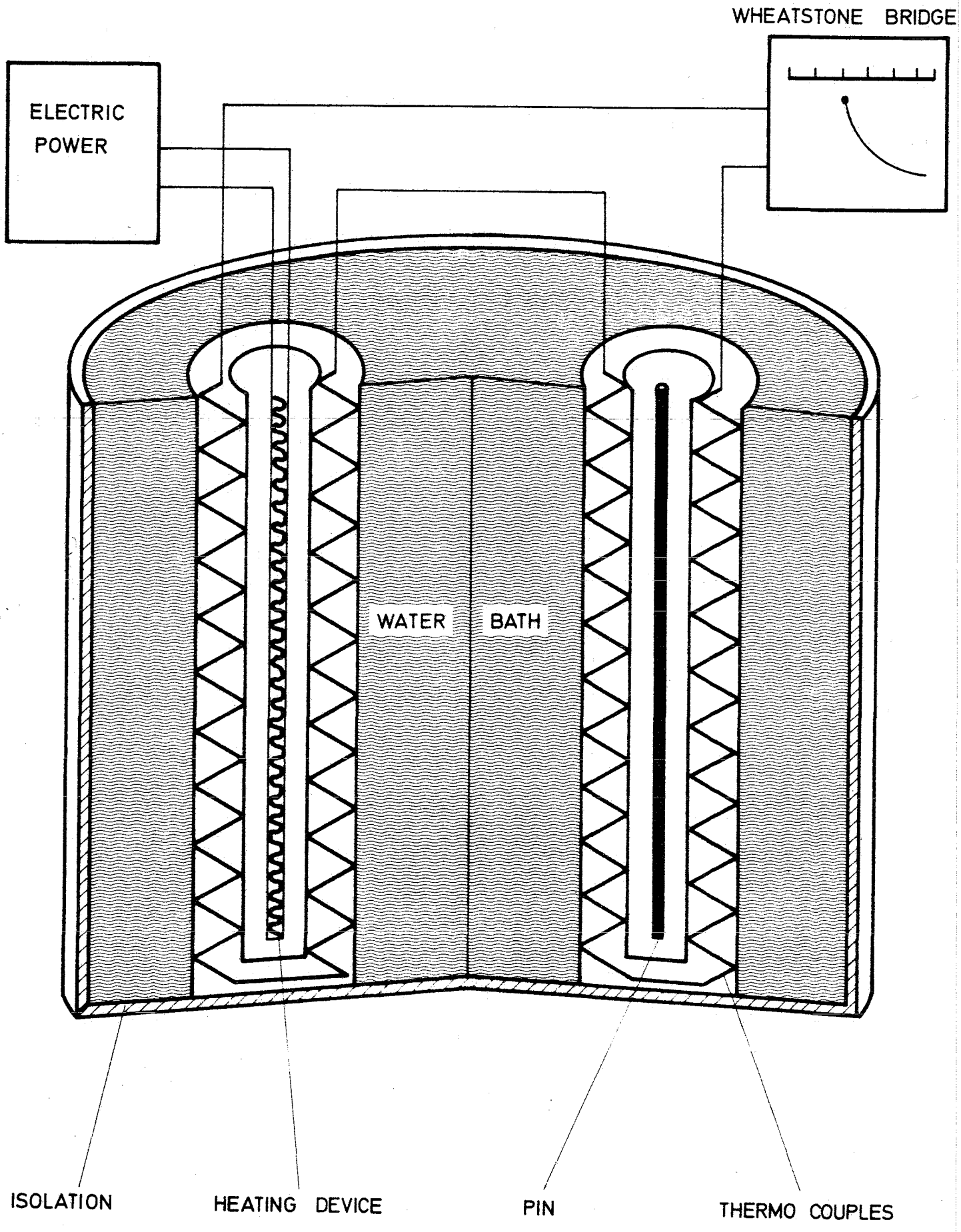


FIG. 11 PRINCIPLE OF THE CALORIMETER USED FOR THE SAFEGUARDS EXERCISE