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EXPECTED MEASUREMENT ACCURACIES AND LIMITS OF ERROR IN A FABRICATION PLANT FOR HIGH ENRICHED URANIUM [x)]

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Zusammenfassung

Im vorliegenden Bericht wird eine typische Fabrikationsanlage zur Verarbeitung von hochangereichertem Uran (HEU) hinsichtlich der Spaltstoffflußkontrolle im Rahmen der Verpflichtungen des Kernwaffensperrvertrages (NPT) untersucht.

Im Vordergrund der Untersuchung stehen die notwendigen Bilanzierungsmaßnahmen mit der Einrichtung von geeigneten Materialbilanzzonen (MBA) und Schlüsselmeßpunkten (KMP). Insbesondere wird das Problem der realen Bestandsaufnahme von spaltbarem Material behandelt und Abschätzungen der gegenwärtig erreichbaren Meßgenauigkeiten statistischer und systematischer Art an den entsprechenden KMP's gegeben. Mit Hilfe einer Referenzkampagne wird die Gesamtunsicherheit einer Spaltmaterialbilanz berechnet, die bei ca. 0,5 % relative Standardabweichung (RSA) des verarbeiteten Materials liegt.

Abstract

In the present paper a typical fabrication plant for high enriched Uranium (HEU) is investigated concerning safeguards of nuclear material under conditions of the Non-Proliferation Treaty (NPT) with respect to accountability of nuclear material.

For this purpose a hypothetical material balance area (MBA) plan with some corresponding KMP's is assumed. Particular attention is paid on the estimation of attainable measurement accuracies at the KMP's and the problem of physical inventory taking. With the help of a reference campaign the total uncertainty of the material balance including flow and inventory measurements is investigated resulting in a standard deviation of 0.5 % relative to the processed material.

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Expected Measurement Accuracies and Limits of Error in a Fabrication Plant for High Enriched Uranium [1)]

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Introduction

In the peaceful nuclear sector high enriched uranium (HEU) with 90-93 % U-235 enrichment is mostly used for different types of MTR and High Flux Reactor (RHF) fuel elements and their components. Another large scale application may lie in the area of gas cooled U-Th reactors (THTR). A further use of such materials lies naturally in different research activities.

In the Federal Republic of Germany, all the industrial activities in this field are carried out in the fabrication plant NUKEM, Hanau. A plant of this type is expected to have a yearly throughput of around 400-700 kgs U with 90-93 % U-235 concentration. The total plant inventory at any time may lie somewhere between 300-500 kgs U although the process bound inventory may be only around 50-70 kgs of U.

Because of the high value and high purity of the material, coupled with the fact that a major part of the process steps involve Uranium metal, the measurement accuracies for different safeguards relevant streams are expected to be fairly high (excepting of course the discard streams).

[1)] Paper presented at the IAFA Working Group Meeting on 'Accuracy of Nuclear Material Accountancy and Technical Effectiveness of Safeguards', Vienna, 28.8.-1.9.1972

In the present paper a NUKEM type HEU fabrication plant has been investigated with particular attention to attainablemeasurement accuracies at some key measurement points (KMP) and to the problem of inventory taking. For this purpose a hypothetical material balance area (MBA) plan has been assumed with some corresponding KMP's. The attainable measurement errors (both systematic and random) have been estimated on the basis of actual measurement data (whenever available). The problems associated with the inventory taking and the error propagation with the expected measurement accuracies have been investigated for a reference campaign. It is to be noted that the data and results discussed in this paper are preliminary in nature and do not in any way prejudice the layout for or methods used in a future plant of this type.

2. Material Balance Areas and Key Measurement Points

A possible arrangement of MBA's with safeguards relevant KMP's both for throughput and inventory taking for a HEU fabrication plant is shown in Fig. 1. The NUKEM type plant under consideration is expected to be a multiple production facility. With high enriched uranium (90-93 %) in the form of UF_6 as feed it is expected to produce uranium oxide, U-metal platelets, cermet and alloy pictures, finished MTR and RHF elements. A single MBA is suggested for this tpye of facility with 3 KMP's (1,2,3) for feed, product and waste streams and 2 (I_I, II_I) for inventory measurements.

2.1 Material Balance Area

A NUKEM type plant may be taken to consist of a storage and a process area. At a first glance it might appear to be worthwhile to divide the plant into two MBA's namely one storage and one process. However, because of expected operation practices a fairly heavy volume of back and forth flow is expected to exist between the storage and the process areas. This is mainly because of the fact that intermediate products from a number of process steps are stored temporarily in the storage area before they are sent to the next process step. The storage time for such items may vary between some hours and days. A separate MBA for the storage area would involve enormous volume of reporting of temporary material movements which would not be pertinent to safeguards.

For safeguards purposes, the shippers batch data at the input of the storage area can be used as input to the process, since the same data are used by the operator for this purpose. Only some of the shippers data (weight, isotopic U-235 concentration etc.) are checked roughly by the operator for internal verification purposes.

For these reasons only one MBA appears sufficient for the NUKEM type plant under consideration.

2.2 Key Measurement Points

At the KMP-1 (Fig. 1) the batch data for UF_6 consisting of cylinder number, amount, U-factor and the U-235 enrichment are expected to be taken over from the shipper, i.e. at present the USAEC. The KMP-2 symbolically represent the measurement points for different types of products. It should be noted that:

a) A part of the source data for the KMP-2 may be generated somewhere else (central laboratory, γ-spectroscopy stand etc.).

b) For the MTR type fuel elements (stream no. 2.4) the plant operator generates the batch data at the process step where pictures are made (see Fig. 7), whereas, it has been assumed in this paper that the relevant batch data for this stream are generated at the final step i.e. after the assembly has been completed. This is done on an experimental basis by the EURATOM safeguards organization in the present NUKEM plant /2/ it may be changed or remain as it is at a later date.

c) For the RHF fuel elements, no measurement method exists today for the assay of uranium. Therefore, the last point of the process at which uranium is measured for this stream is at the picture stage. Hence this is the stage at which source data are generated for the purposes of safeguards. A number of process steps (plating, rolling, assembling, welding, quality control etc.) follow this stage.

d) The KMP's I_I and II_I are meant for inventory taking. It is to be noted in this connection that a particular feature of this type of facility is

that all the nuclear material present in the storage or process areas, can be brought into itemised forms during a physical inventory. As a result the main activities at these KMP's consist of tag-inventory, the amount stated in the tag having been measured at some other time. A small part of inspection activities will consist of random sampling and analysis of U content in measuring units to verify the tag value.

3. Measurement Accuracies at KMP's

A reference campaign has been constructed to assess the influence of the measurement errors on the material balance as well as to investigate the problem of inventory taking. The throughput and the inventory data are summarized in table 1. A 6 months throughput has been assumed with 195 kgs of 90/93 % enriched uranium as feed. Six categories of products are assumed to be produced. The measured discards of 0.9 kgs of high enriched uranium correspond to approximately 0.5 % of feed. The beginning and the end inventories each of 495 kgs of high enriched uranium appear to be high compared to the throughput. This is mainly dictated by operation and commercial conditions. The large number of products require relatively large amounts of material as intermediate buffer volumes. Also the procurement of the material for the whole campaign causes the inventory to go up.

The expected measurement accuracies at the KMP's 1, 2 and 3 for the feed, product and waste streams, i.e. the throughput of the plant, are presented in table 2 along with some other relevant data for material balance. A number of points are worth noting:

a) Very high overall accuracies are attainable for the KMP-1 under the present day industrial operating conditions (weighing $\leq$ 0.01 %; U-factor 0.05 %; mass spectrometry 0.05 %, all values in the table 2 on measurement errors are for 1σ value unless otherwise specified). As has been mentioned earlier this may be because of the fact that UF_6 is available in gas form for measurement and that it is obtained in a highly pure form because of low acceptable impurity limits.

b) The systematic and random errors of measurement for the U-oxide product are in the same range (0.2 %). Although in such cases the influence of the random error or error propagation reduces considerably for large numberof batches, in this particular case, the influence may not be negligible (2 batches/6 months).

c) All the pictures (cermet and ceramic) and the MTR elements are measured by γ-spectroscopy (absorption and passive γ) for their total uranium content. The random errors lie in the same range of 0.4 %. The systematic errors consisting of the calibration errors and the errors for standards have been found to be ≈ 0.3 % for the two types of pictures (stream nos. 2.3, 2.6). The systematic error for γ-spectroscopy for the MTR elements have not been estimated. For the error propagation calculations it has been taken to be ≈ 0.3 %, i.e. same as in the case of the pictures.

d) The random and systematic errors for THTR particles (stream no.2.5) of 0.1 % each, appear to be extremely good. Some check of these values, particularly the systematic part on an interlab scale might be worthwhile.

e) The discards, also assayed γ- spectroscopically, are measured with random and systematic error components of 15 % each. The fairly high percentage of systematic error is caused by the presence of Thorium. It might be possible to reduce this particular value.

f) The precision for U-235 enrichment for the feed stream (KMP-1) has been taken to be 0.05 % from Ref. /1/ and also used for error propagation calculations. The input values and also the enrichment in THTR coated particles are expected to be checked in a mass spectrometer at the plant. Typical results of calibration of such a mass spectrometer with NBS standards for 90 % and 93 % U-235 enrichment, are shown in Table 3. It is to be noted that the results show a reproducibility of 0.01 % and virtually no systematic error. The latter however, requires further checking.

An interesting check on the U-factor for the high enriched feed to the plant is obtained by plotting the U-factors as a function of enrichment, as shown in Fig. 2. The theoretical U-factors for stoichiometric UF_6 are given by the upper curve. The lower curve (dotted) is obtained by joining the mean values of the U-factors for a given enrichment obtained from the USAEC certificates. For a given enrichment a lower value than stoichiometric indicates the presence of gaseous impurities.

4. Reference Campaign

The more important data for the reference campaign are presented in table 1. In this section the main characteristics of the process scheme are analysed with particular emphasis on the inventory situation. The important steps for the multiple production scheme are shown in Fig. 3. Besides the feed and the product storage, four other areas are to be discerned. They are, a) chemistry, consisting of conversion and scrap recovery sections, the latter giving rise to a final product (UO_2 powder), b) kernel production with THTR coated particles as the final product, c) metallurgy, giving rise to three final products, i.e. BR2 cermet pictures, SNEAK metal platelets and MTR fuel elements, and finally, d) the assembly area for the RHF fuel element. It is recalled that the RHF fuel element being fairly bulky (Fig. 8) and containing 9.25 kgs of U of 93 % enrichment, cannot be measured for its U-content in an integrated manner. The cermet pictures used for these elements leaving the metallurgy area are therefore, measured γ-spectroscopically (Fig. 1 stream 2.6) for their U-content, and no further U-measurements are made for this stream.

Some typical views of the ceramic and cermet pictures are shown in Figs. 5 and 6 respectively. A schematic diagram on the different steps for the fabrication of a plate type MTR fuel element is given in Fig. 7.

4.1 Inventory of Nuclear Material

Fairly large amounts of nuclear material are required as inventory for the operation of the various process streams. A number of reasons were given under chapter 3 for the high amount of the inventory. Another characteristic of this type of facility which increases the inventory is the heavy recycle rate. In

some of the process steps this may be 2-3 times the production rate.

An analysis of the inventory situtation in the main process steps indicates that excepting for the materials in the chemistry section (conversion and scrap recovery), inventories in all the other steps can be converted into itemisable form with little or no difficulty. For example, the melting ovens for Al-U alloy in the metallurgy section or the co-precipitation and the homogenising units in the kernel production step, contain bulk material which cannot be itemised or measured easily. However, all these units operate in batches and the number of batches handled over a given period of time is considerably larger than that handled in the conversion or the scrap recovery section for the same period of time. The finished material coming out of these units can be brought into itemisable forms or transferred into weighable or measurable containers. Therefore, if the time for the physical inventory taking is so chosen that the conversion and the scrap recovery sections are empty, the inventory material in the rest of the plant can be itemised and tagged. Such an operating condition can be purposely induced at least twice a year in the reference plant under consideration. A typical inventory diagram over a six months period for a number of relevant process units is shown in Fig. 4. At the end of this period all the major units containing bulk material are emptied, transferred into itemised forms and a physical inventory is taken.The amount and categories of material which may be expected to be present during such an inventory is shown in table 4. Several points require further elaboration:

a) Out of a total of 495 kgs of U, 425 kgs are present in the storage and 70 kgs in the process area, during a physical inventory taking. Therefore, by choosing the time of inventory properly, more than 85 % of the nuclear material can be inventorised in the storage area alone. This fact reduces significantly the difficulties normally associated with inventory taking of large amounts of material in process areas for safeguards purposes.

b) The nuclear materials in the process area are all available in discrete, well defined, itemised batches at a relatively small number of points.

c) All the categories of material are tagged with important batch data and number of measuring units. Since these units have been measured by the operator (mostly at an earlier point of time) with the same accuracies

as those obtained at the corresponding KMP's for throughput measurements (table 2), the tag inventory taking will theoretically correspond to these accuracies. (In practice, an inspection organisation can make a full tag inventory with random sampling of a few measurement units for direct measurement; if the measurement values correspond to the tagged values within a certain preset confidence interval, the organisation can then accept all the values measured by the operator with the corresponding measurement accuracies).

d) Although the total amount of inventory before and after the reference campaign is the same, because of the high recycle rate, the different categories in the process are renewed completely after the campaign. Therefore, two inventories have to be taken. Only the sealed UF_6 cylinders (category 4) need not be measured since the shippers data remain unchanged during the operation.

e) The last category (heterogeneous scrap) poses a problem. Although the containers with these materials may be kept sealed, no measurement method exists at present to assay the uranium content in these materials. The amounts of U in these materials become known only after they have been treated in the scrap recovery section at a later date than that at which the physical inventory has been taken. Therefore, the balance can be struck only after they have been measured. It appears highly desirable to intensify efforts for the development of a suitable measurement method for these materials.

5. Error Propagation in the Reference Campaign

The limits of error for the reference campaign have been calculated on the basis of data given in tables 2 and 4. The results with the relevant input data are summarized in table 5. Before an analysis of the results can be attempted, some initial comments are required which pose limitations on the interpretation of these results.

a) The random errors δ_R's, as given in this table, are the resulting values for a given stream after taking into consideration the actual number of measurements (i.e. no. of batches, and analysis per batch where appropriate). For this reason the δ_R's for the stream 2.2 and

the inventory categories 1 and 3 are negligible compared to the corresponding δ_S's. Similarly, the systematic errors δ_S correspond to the resulting values after taking into consideration (whenever possible) the systematic errors in the different measurement steps for a given stream.

b) The reported δ_R value of 0.4 % /3/ in table 2 (U-factor) and the resulting value of 0.25 % for the KMP-1 has not been considered for the error propagation calculations since more than an order of magnitude lower value of δ_R is obtained from the data shown in table 2 (about 0.03 % instead of 0.4 %). The systematic error for the measurement of U-factor, if any has also not been considered. In Ref. /3/ no values for systematic error for this measurement has been given although in other literatures (for example in the IAEA Working Paper to the present Working Group) a fairly wide range of systematic errors can be found. The weighing error for this KMP (0.01 %) has been considered to consist of systematic errors only.

c) The LE calculations have been done for total uranium and not for U-235 since a major part of the output streams is not assayed directly for U-235 concentration. However, since the total uranium contains 90-93 % U-235, the LE for U-235 will be about 7-10 % less than that for total uranium, i.e. 0.82-0.85 kgs of U-235. These values will not be changed much by taking into consideration the mass spectrometric measurement errors.

d) The category 6 of inventory material in table 4 (heterogeneous scrap) with 15 kgs, has not been considered for the LE calculations. It has been assumed that at the time of balancing, the amount will be kept in sealed form without direct measurement since no measurement methods are available at present. After purification in the scrap recovery sections sometimes later, the material becomes measurable with the accuracies of the oxide stream (stream 2.1 table 2). This would mean an additional LE contribution to the physical inventory taking of around 0.04 kgs U by this category.

With the above mentioned limitations as well as the process conditions in view,a number of points are worth mentioning:

i) The LE for the total material balance is influenced significantly by the errors in inventory taking (total LE of MB - 0.91 kgs U; LE of inventory - 0.858 kgs U). This is mainly because of the large LE for the category 1 material of the inventory (δ_S 0.3 %). compared to the feed material (δ_S 0.01 %) for approximately the same amount as also, because of the larger amount of inventory material compared to the throughput (960 kgs inventory against 390 kgs throughput).

ii) In all the streams and categories,the systematic errors control the LE's. The weighted systematic error corresponding to the LE for the throughput amounts to 0.08 % of the total throughput (2 times 195 kgs = 390 kgs U) or 0.16 % of the input. The corresponding value of the systematic error for the inventory is 0.09 % (2 times 480 = 960 kgs U ; 15 kgs are not measured). The total LE for the material balance correspond to 0.47 % of the input or 0.91 kgs U. If the total amount U be considered which has been measured during the balancing period, it amounts to 1350 kgs U (390 kgs throughput, 960 kgs measured inventory). The absolute value of the LE if expressed as a percentage of this total amount, corresponds to 0.07 % which may also be considered to be a systematic error, since all the sources of the LE are virtually from systematic errors as mentioned earlier. These low values of systematic errors reflect the care with which high enriched uranium is expected to be handled under present day industrial conditions. However, some of the measurement error values may require rechecking under interlaboratorium test conditions.

iii) The ratio of the LE's for the inventory and the throughput amounts is approximately the same as that for the two amounts themselves (2.8 to 2.5). This indicates the predominance of the linearity in error propagation.

iv) An analysis of the LE's for the different streams and categories show that the main contributions come from category 1 (plates, platelets, elements) of the inventory followed by feed (stream 1) and oxide category (inventory, category 2) and finally by the THTR particles (stream,2.5) and measured discards (stream, 3). Important point to note is the fact that the measured discards being only 0.5 % of the input, contributes significantly to the total LE, obviously because of the very high systematic error component of the measurement (15 %). Still, the actual amount of 0.91 kgs uranium is low compared to LE's in other nuclear facilities with equivalent amounts of inventory and throughput.

6. Concluding Remarks

The main purpose of the present paper is to analyse the existing measurement accuracies in a HEU fabrication plant which could be of relevance for safeguards, and also to investigate their influences on the limits of error for a material balance. The conclusions which can be drawn from this analysis are of a preliminary nature and their validity are within the limitations set forth in this paper. With this in view, following remarks are made.

6.1 The measurement accuracies (both systematic and random) attainable under industrial conditions in a HEU fabrication plant of the NUKEM type for the feed and product stream are very high. Some of them, for example the mass spectrometric analysis and the Redox analysis for the THTR particles may need checking on an interlaboratorium scale to verify the given values. On the other hand, the very high systematic error of around 15 % expected in the γ-spectrosopic measurements used for measured discards also requires a careful checking. High priority R+D-work is needed for a nondestructive, and quick measurement method for heterogeneous scraps available in itemised containers during a physical inventory taking.

6.2 Although the amount of inventory material in a HEU fabrication plant may be high compared to the throughput (≈ 500 kgs high enriched U compared to 400-700 kgs throughput/yr), because of a high degree of itemisation a tag inventory can be carried out relatively easily.

6.3 The limits of errors for a material balance are controlled almost exclusively by the systematic errors of measurement for different streams and categories and are influenced significantly by the LE's of the inventories. The absolute value of LE's obtained for a material balance period of six months for a fabrication plant of the NUKEM type is in the range of 1 kg U and well below those obtained in other nuclear facilities with equivalent throughputs and inventories.

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Table 1 Throughput and Inventory Data for a Reference Campaign in the HEU Fab. Plant.

I Throughput Data			
1.	Total time of campaign	[months]	6
2.	Feed		
2.1	Total U (as UF_6)	[kg U]	195
	U-235-Concn.	[%]	90/93
3.	Product		
3.1	Oxide	[kg U]	20
	U-235-Concn.	[%]	90
3.2	Metal Platelets	[kg U]	5.1
	U-235-Concn.	[%]	90
3.3	Cermet Pictures	[kg U]	20
	U-235-Concn.	[%]	90
3.4	MTR-Elements	[kg U]	30.5
	U-235-Concn.	[%]	90
3.5	THTR-Particles	[kg U]	100
	U-235-Concn.	[%]	90
3.6	RHF-Elements	[kg U]	18.5
	U-235-Concn.	[%]	93
4.	Measured Discards		
	Filtrates, sludges etc.	[kg U]	0.9
II Inventory Data			
1.	Total inventory		
1.1	Beginning	[kg U]	495
1.2	End	[kg U]	495

Table 2 Measurement Accuracies and Other Relevant Data for the KMP's for Feed (1), Product (2) and Waste (3) Streams in the Ref. HEU Fab. Plant.

1. KMP category	1	2						3
		2.1	2.2	2.3	2.4	2.5	2.6	
2. material	UF_6	Oxide	met. plat. (SNEAK)	cerm. pict. (BR2)	MTR-elem.	THTR-particles	cerm. pict. (RHF)	meas. discards
3. kgU/batch	15	10	5.1	0.025	0.277	1(+10Th)	0.033	0.010
4. kgU/6 month	195	20	5.1	20	30.5	100	18.5	0.9
5. No. of batchs/6 month	13	2	1	800	110	100	560	90
6. meas. of total quant.	weighing	weighing	weighing	passiv-γ	γ-meas.[5]	weighing	passiv-γ	volume meas.
6.1 mean./batch	22,3 kg	11.5	5.1	22.5 gr U-235	250 gr U-235	11.76 kg	30 gr U-235	500 l
6.2 random error[1]	0.01%[2] RSD	0.1% RSD	0.1% RSD	0.4% RSD	0.3%	0.1% RSD	0.4% RSD	5% RSD
6.3 system. error				0.3% RSD	not reported		0.3% RSD	3% RSD
7. U-factor	3)	gravimetry	stoichiometric			redox titration		γ-meas.
7.1 mean./batch	0.6735	88.0 W/o				8.5 W/o		≤ 20 mg U/l
7.2 random error[1]	0.4% RSD[8]	0.2% RSD				0.1% RSD		15% RSD
7.3 system. error	not considered	0.2% RSD				0.1% RSD		15% RSD
7.4 No. of samples/batch	0.2 á 400gr UF_6[4]	1				0.1[7]		1
7.5 No. of anal./samples	not reported	2				2à 7000 particles		1 x 1 min.
8. U-235 conc.	mass. spec.	mass. spec.	6)	6)	6)	mass. spec.	6)	6)
8.1 mean./batch	90/93%	90/93%	90/93%	90%	90%	90%	93%	90/93%
8.2 random error	0.05% (2σ)[3]	0.05% RSD				0.05% RSD		
8.3 system. error	not reported	0.01% RSD				0.01% RSD		
8.4 No. of samples/batch	not reported	1				0.1		
8.5 No. of anal./sample	not reported	1				1		

1) per single measurement
2) scale precision ± 0.1 grams, weights are reported to nearest gram by USAEC /1/
3) see table IV and V of /1/
4) composite sample of max. 6 cylinder /1/
5) reported in /2/
6) based on previous measurements
7) sampling from homogenisation lot = 10 batches
8) reported in /3/

Table 3 Recalibration data for 2 NBS-Standards in a Mass Spectrometer in the HEU-Fab. Plant

NBS U-900

Date	U-234	U-235	U-236	U-238	at %
31.7.1970	0.768	90.195	0.341	8.696	
31.7.1970	0.772	90.188	0.343	8.698	
30.10.1970	0.769	90.190	0.337	8.705	
18.6.1971	0.762	90.196	0.337	8.705	
7.10.1971	0.769	90.205	0.331	8.696	
10.1.1972	0.764	90.173	0.338	8.725	
25.2.1972	0.756	90.203	0.338	8.694	
23.3.1972	0.765	90.206	0.333	8.705	
21.7.1972	0.756	90.203	0.333	8.708	
Mean	0.7646	90.1954	0.3368	8.7036	
RSD %	0.746	0.0118	1.157	0.109	
NBS U-900	0.7779	90.1955	0.3329	8.6937	
(1-Mean/NBS)%	+1.71	0.00	-1.17	-0.11	

NBS U-930

Date	U-234	U-235	U-236	U-238
31.7.1970	1.077	93.336	0.210	5.377
31.7.1970	1.080	93.328	0.208	5.384
24.3.1971	1.067	93.354	0.205	5.374
11.5.1971	1.067	93.351	0.208	5.374
18.6.1971	1.073	93.337	0.207	5.383
25.2.1972	1.038	93.349	0.211	5.402
23.3.1972	1.064	93.355	0.204	5.377
21.7.1972	1.052	93.356	0.205	5.387
Mean	1.0648	93.3458	0.2073	5.3823
RSD %	1.30	0.0113	1.20	0.17
NBS U-930	1.0806	93.3368	0.2027	5.3799
(1-Mean/NBS)%	+1.46	-0.01	-2.27	-0.045

Reference data in the paper are refered to U-235.

TABLE 4 CATEGORIES OF NUCLEAR MATERIAL DURING A PHYSICAL INVENTORY FOR THE REF.CAMPAIGN IN THE HEU FAB. PLANT

NO.	CATEGORIES	AMOUNT /KG U/ STORAGE	PROCESS	NO. OF TAGS/ MEAS.UNITS	EXP.MEAS.ERRORS RANDOM %RSD	SYST. %RSD	MEAS.METHODS
1.	PICTURES, PLATELETS, ELEMENTS	160	30	350/6000	0.4	0.3	γ-SPECTROSCOPY/ DENSITY
2.	UF_4, UAL_3, UO_2	80	20	20/20	0.2	0.2	WEIGHING AND/OR CHEM.-ANALYSIS
3.	U-METAL REGULUS	50	-	10/10	-	0.1	"
4.	UF_6-CONTAINER (SEALED)	100	-	NOT NECESSARY AS SEALED	-	-	-
5.	THTR-PARTICLES	20	20	40/40	0.1	0.1	WEIGHING AND CHEM.ANALYSIS
6.	HETEROGENEOUS, IMPURE SCRAPS (CRUCIBLES, SLAG, OXIDE DUST ETC.)	15	-	-	-	-	NOT MEASUREABLE BEFORE RECOVERY
	TOTAL	425	70				

TABLE 5 LIMITS OF ERROR (LE) OF MATERIAL BALANCE (MB) FOR THE REFERENCE CAMPAIGN IN THE HEU-FAB.-PLANT

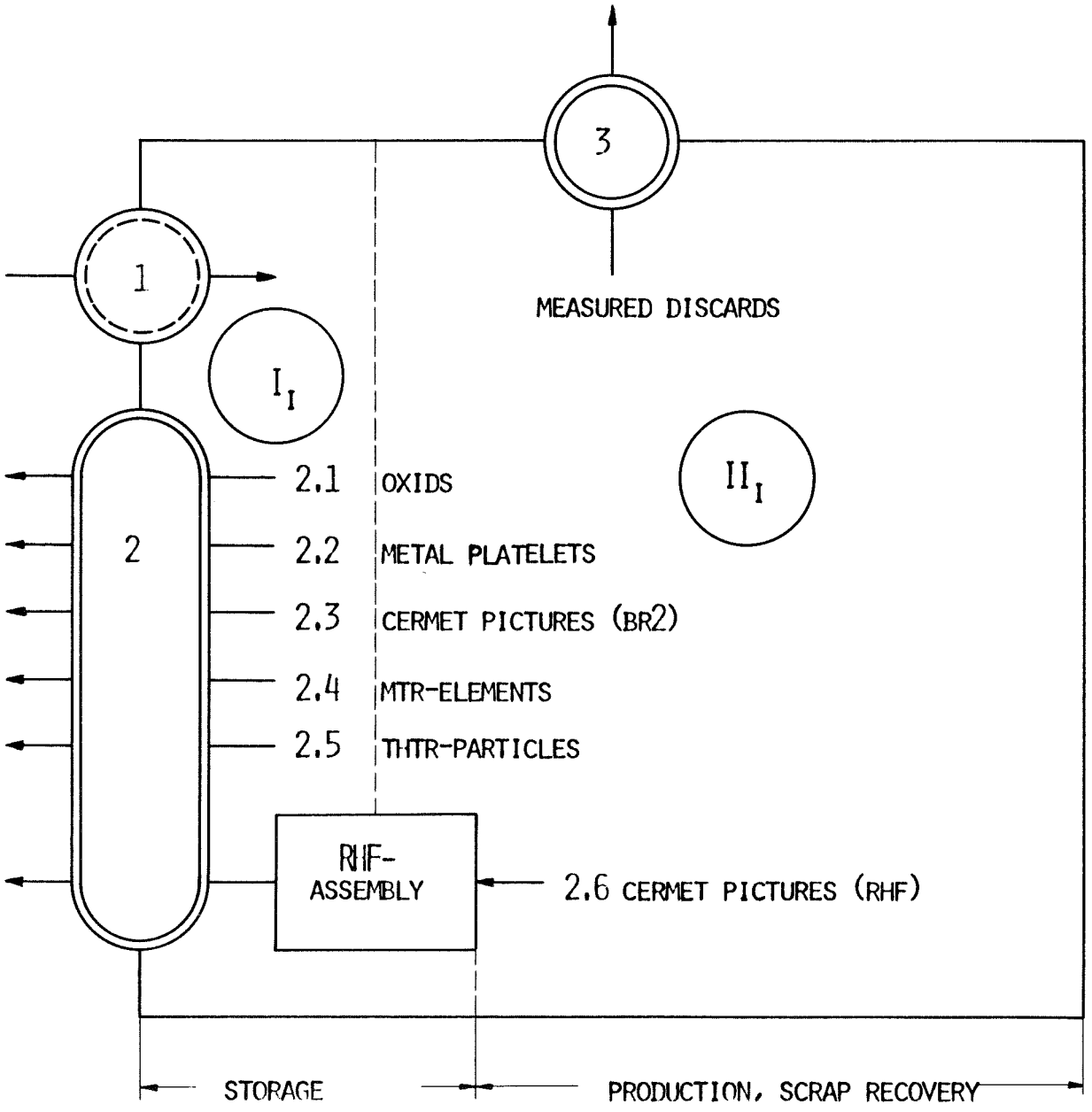
1. KMP	1	2						3	PHYSICAL INVENTORY[2] (I_I+I_{II})				
STREAM/CATEGORY		2.1	2.2	2.3	2.4	2.5	2.6		1	2	3	5	6
2. TOTAL QUANTITY /KG U/	195	20	5.1	20	30.5	100	18.5	0.9	190	100	50	40	15
3. δ_R % RSD	(0.25)[1]	0.14	-	0.01	0.03	0.03	0.02	1.7	-	0.04	-	0.02	
4. δ_S % RSD	0.01	0.22	0.1	0.3	0.3	0.14	0.3	15.	0.3	0.2	0.1	0.1	
5. TOTAL UNCERTAINTY													
% OF 2.	0.01	0.26	0.1	0.3	0.3	0.14	0.3	15.1	0.3	0.2	0.1	0.1	-
KG U	0.195	0.050	0.005	0.060	0.092	0.14	0.056	0.136	0.570	0.200	0.050	0.040	-
6. SUBTOTAL /KG U/	0.306								$\sqrt{2}$[3] x 0.607 = 0.858				
LIMITS OF ERROR (LE) OF TOTAL MB:	0.910 KG U 0.47 % OF INPUT												

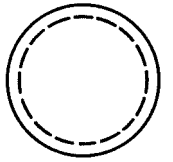
[1] not considered because of small range of variation as shown in Fig. 2

[2] see table 4

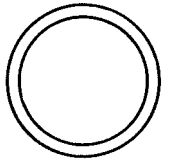
[3] beginning and ending physical inventory considered here

4) resulting value after considering involved measurement

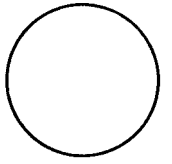




BATCH DATA GENERATED AT OTHER MBA

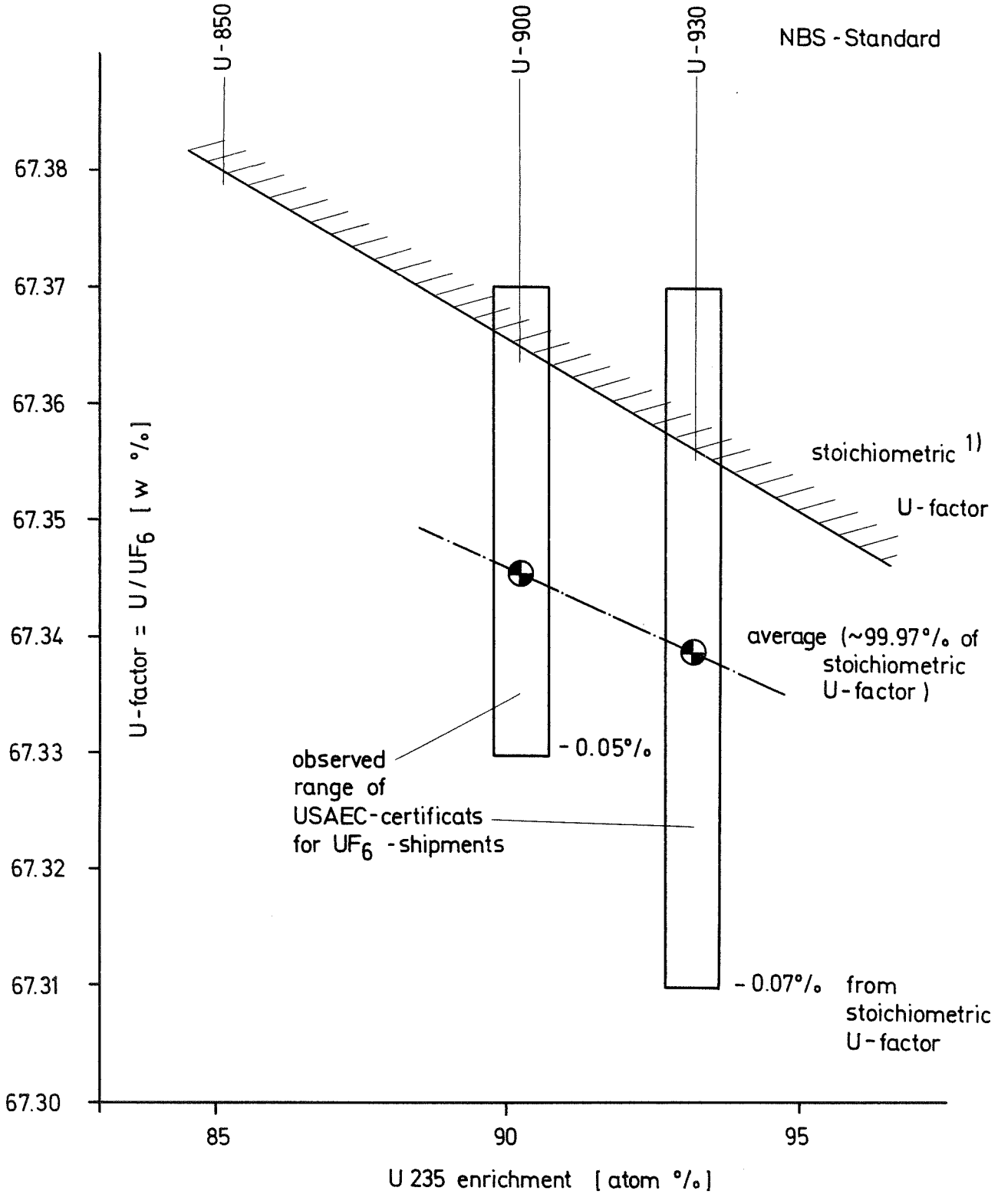


BATCH DATA BASED ON MEASUREMENTS AT KMP



BATCH DATA BASED ON MEASUREMENTS MADE PREVIOUSLY

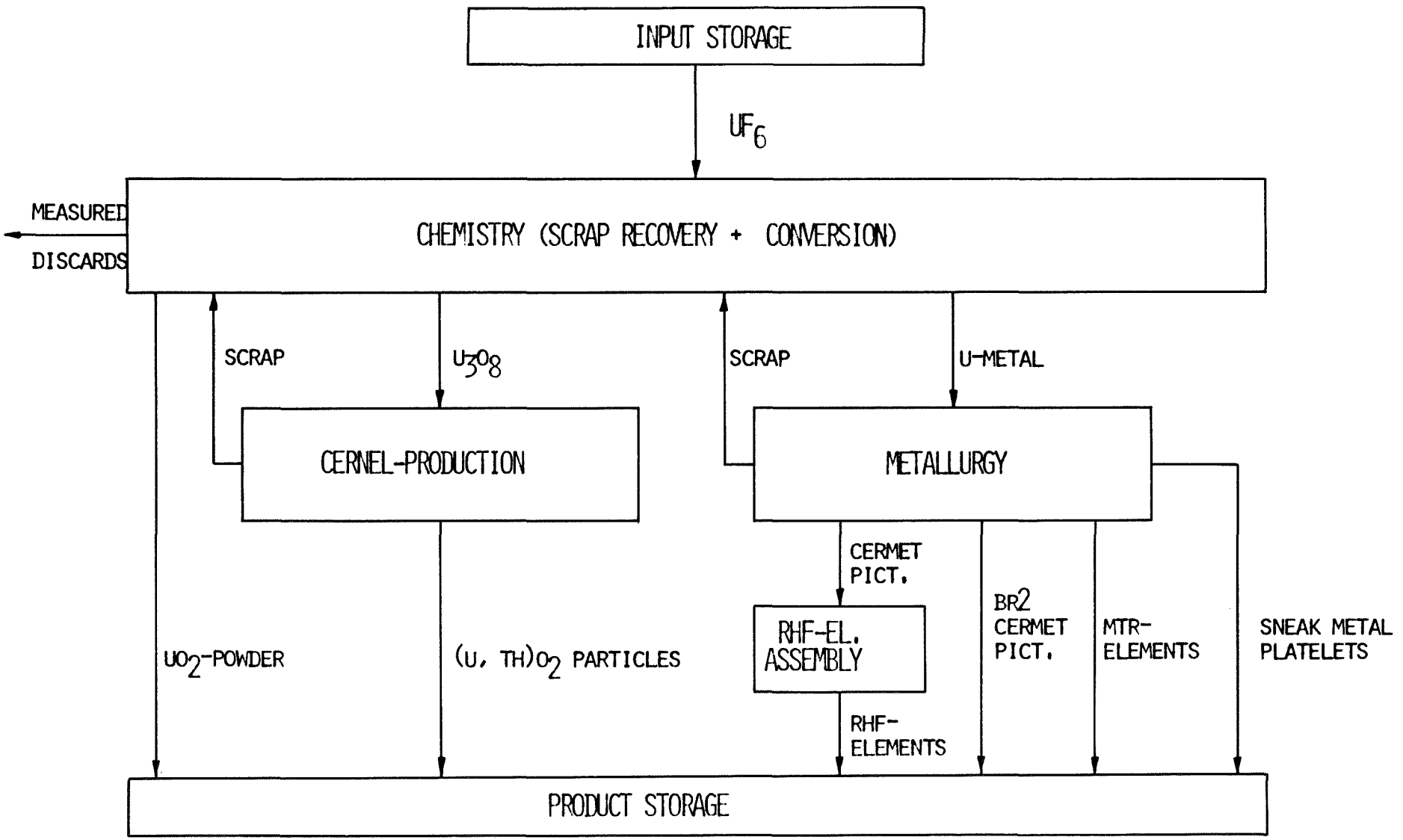
FIG. 1 POSSIBLE ARRANGEMENTS OF MBA AND KMP IN A HEU-FAB. PLANT



1) used isotopic composition from NBS-standards

Fig.2 U-factor vs U235-enrichment for UF_6

FIG. 3 PROCESS FLOW SCHEME OF THE REF. HEU-FAB. PLANT



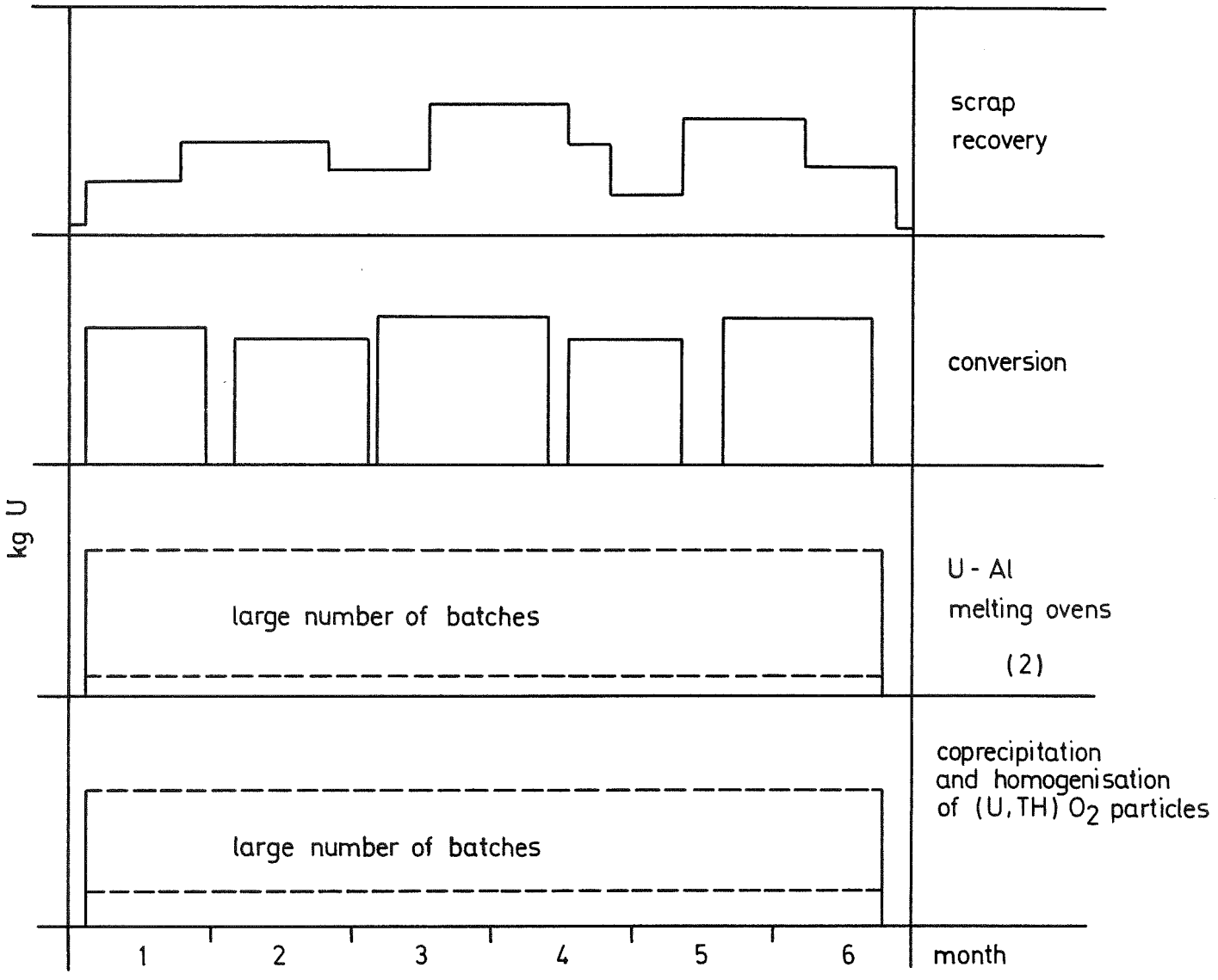


Fig.4 Inventory diagram for process steps with bulk material inventory over a 6 month period

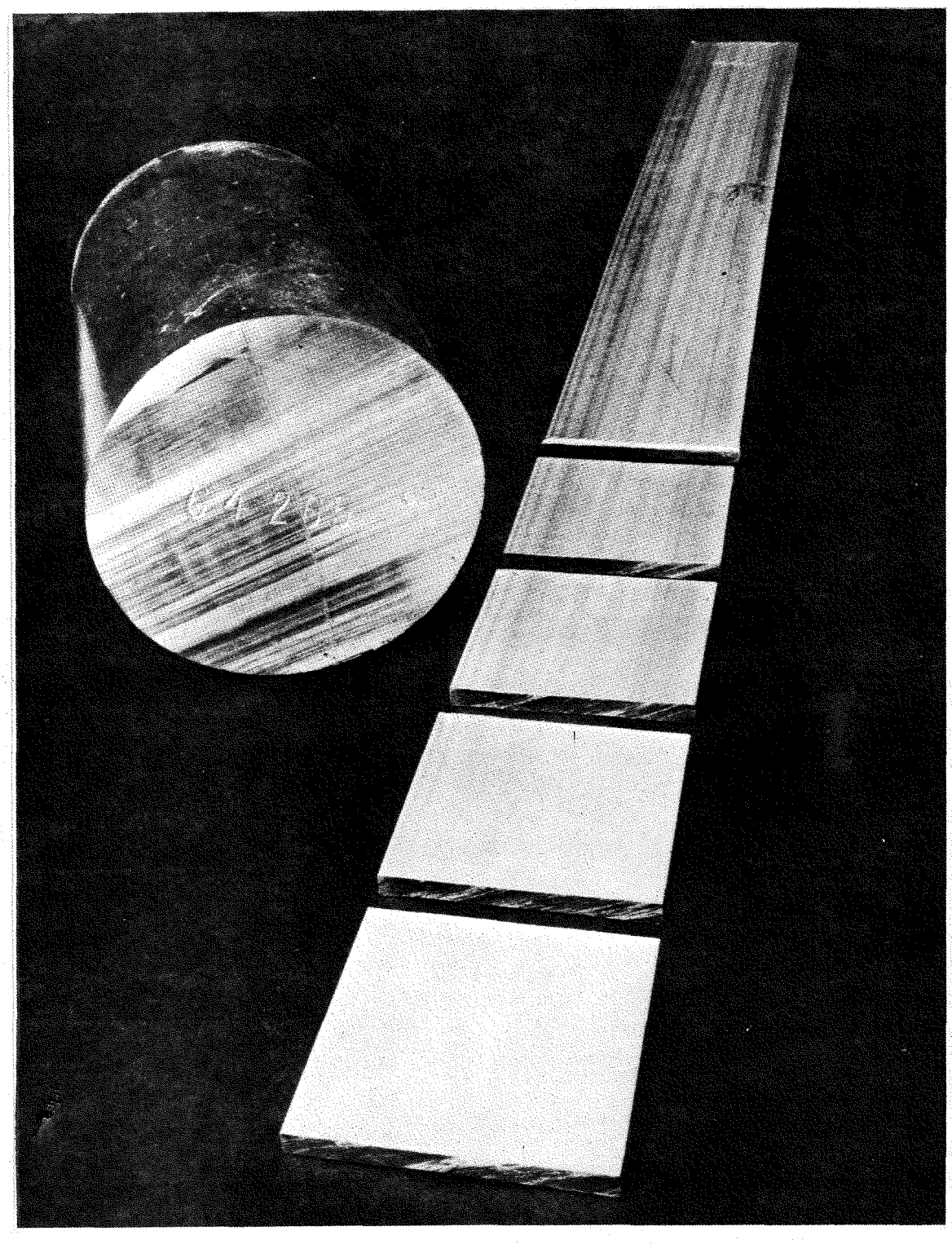
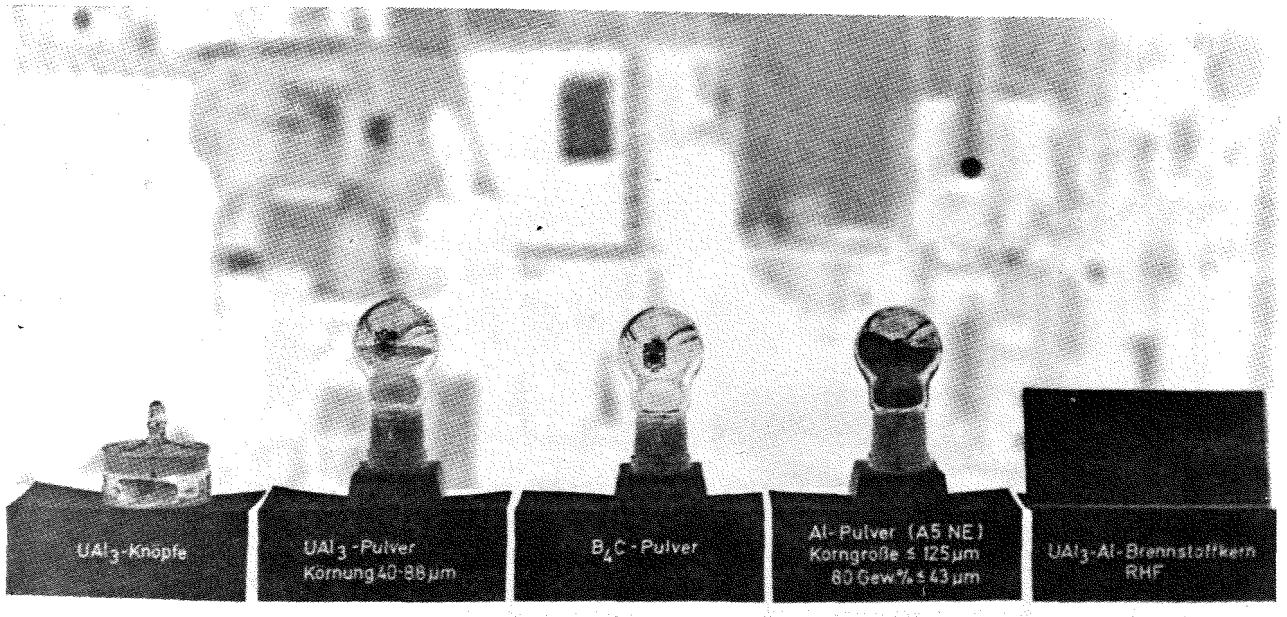


Fig. 5: U-Al-platelet shaped parts (pictures)



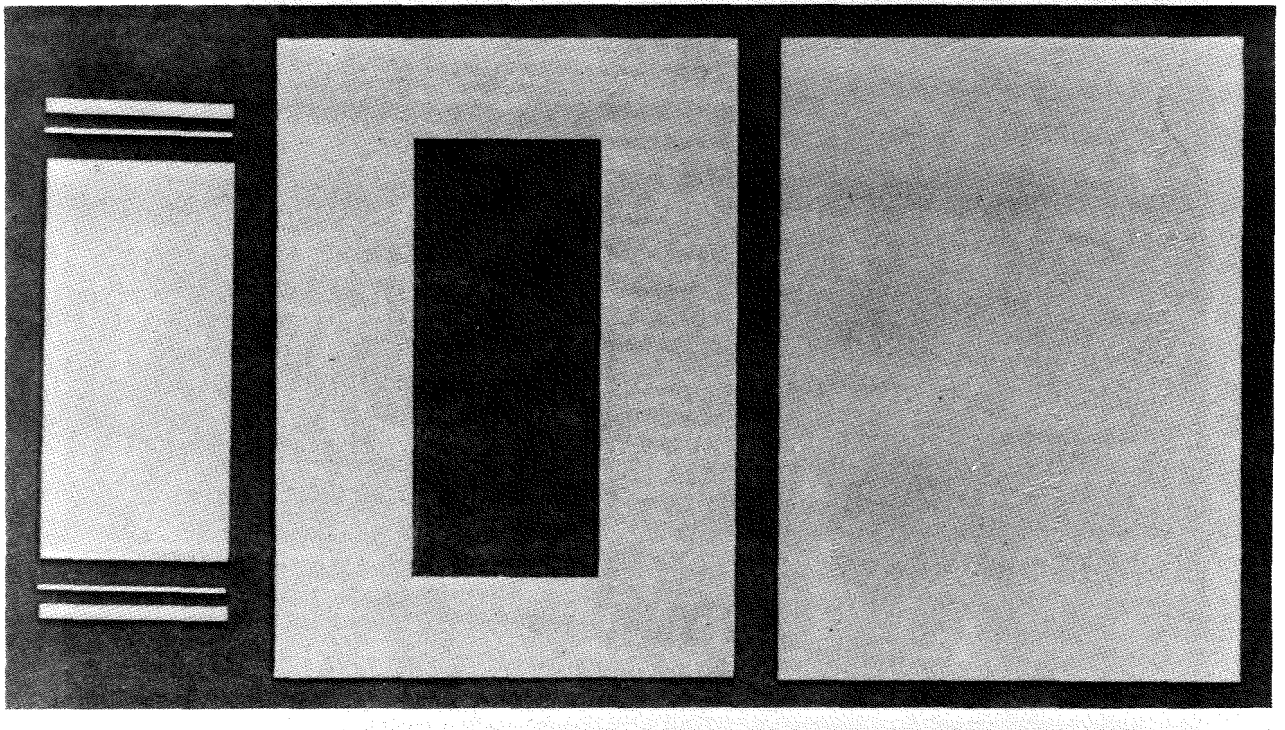
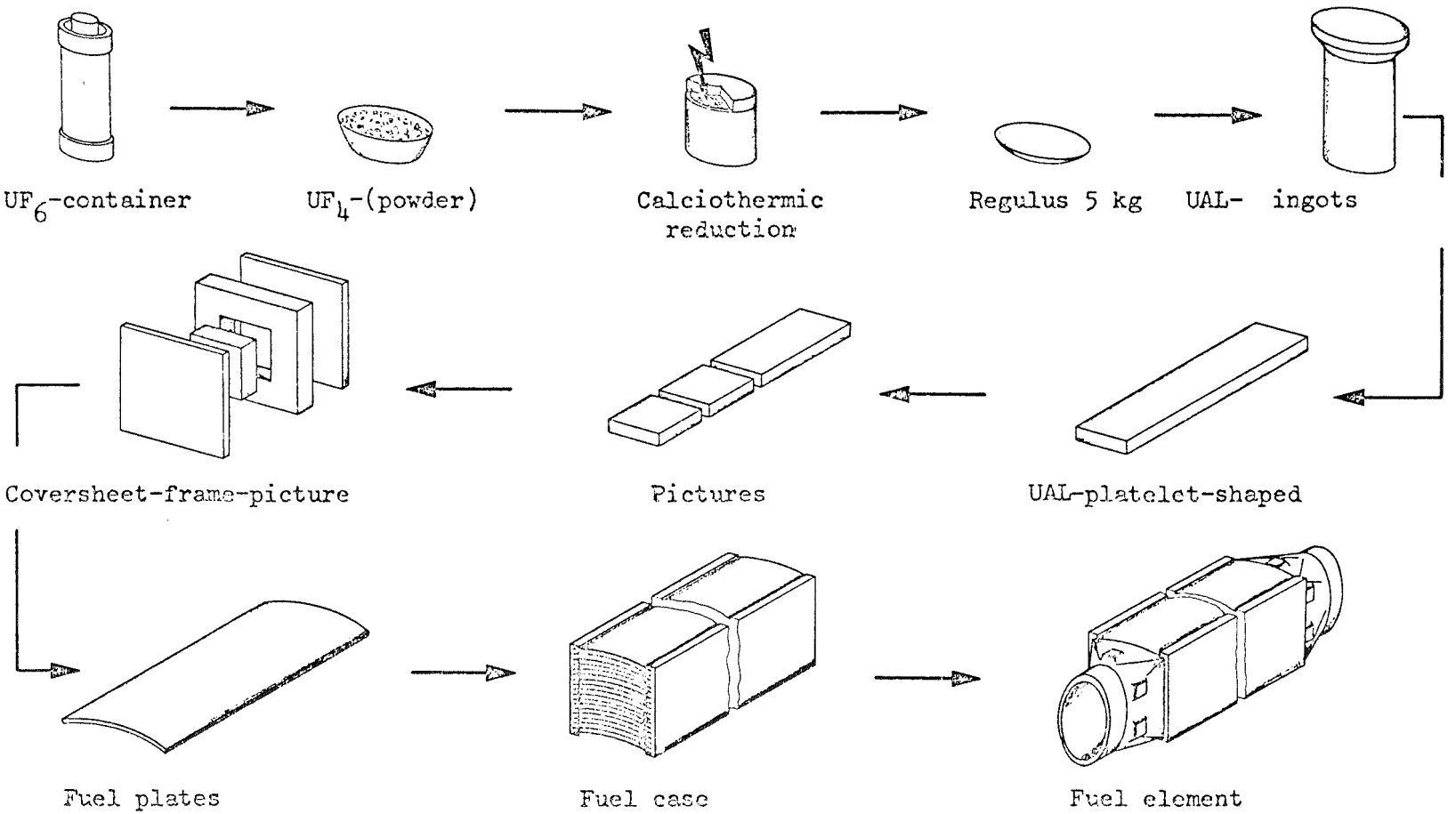


Fig. 6: Components of one cermet fuel plate

Fig. 7: Fabrication scheme of MTR-fuel elements



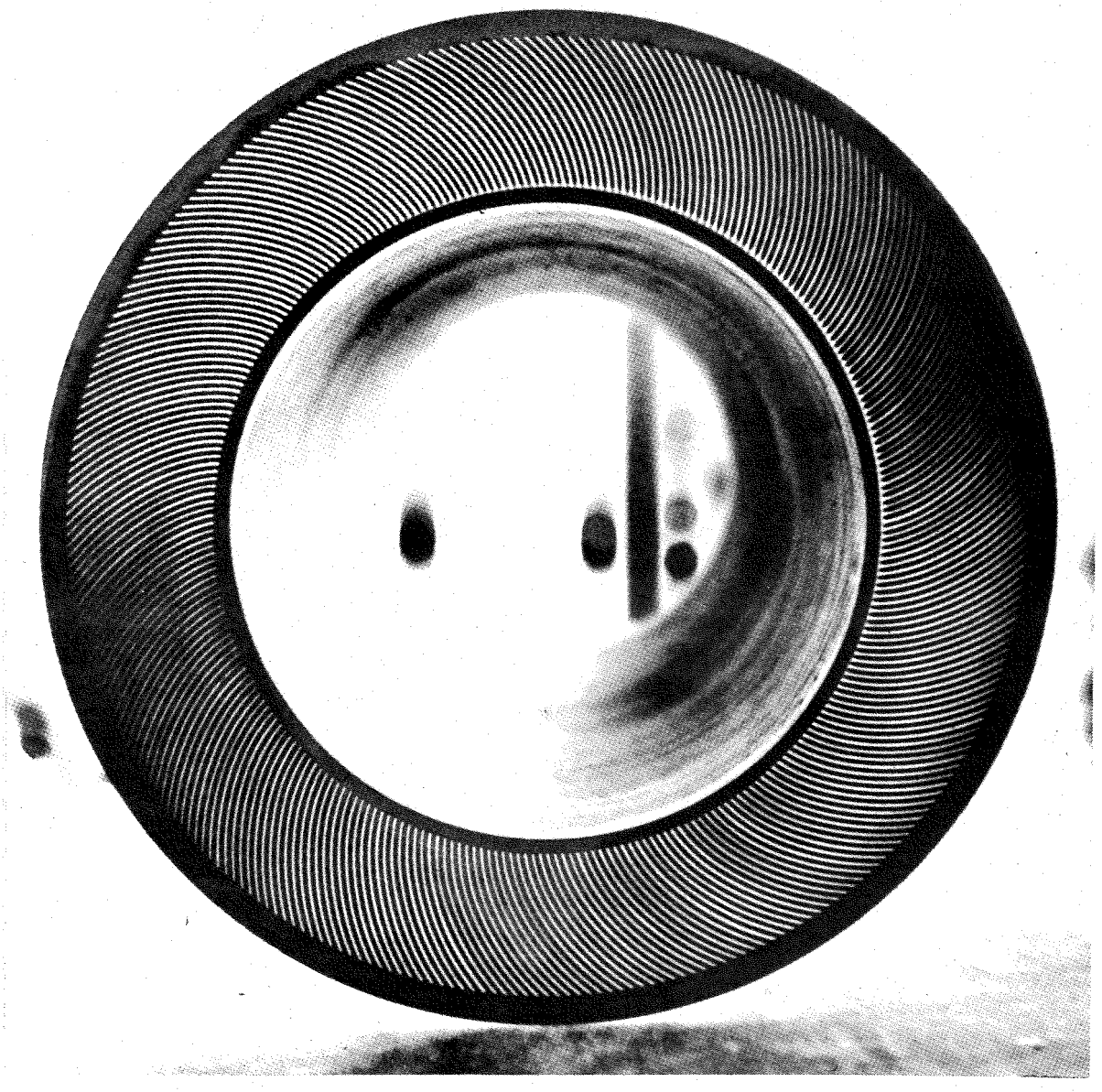


Fig. 8: Fuel part of the high flux fuel element (RHF) D = 414 mm