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STUDY OF THE ADVANTAGES TO BE DERIVED FROM MIXING URANIUM COMPOUNDS AT VARIOUS DEGREES OF ENRICHMENT

by

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[* Euratom]

MARCH 1962

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URANIUM COMPOUNDS AT VARIOUS DEGREES OF ENRICHMENT

SUMMARY

This study investigates the possibility of obtaining on an economic basis uranium compounds of a given enrichment by mixing compounds having different enrichments.

The various possibilities for the economic application of this method were demonstrated together with the advantages it offers from the standpoint of flexibility and relative independence of production.

INTRODUCTION

1 - DEFINITION AND AIMS OF THE STUDY

Examination of the relevant official USAEC tables, to which the study refers for purposes of comparison, reveals not only that the unit cost of enriched uranium increases in direct proportion to the degree of U-235 enrichment, but also that the unit cost of this isotope increases in direct proportion to the degree of enrichment of the uranium which contains it.

It follows from this that the mixture of uranium compounds of varying degrees of enrichment to obtain a final product having an intermediate degree of enrichment constitutes a priori a wasteful process in as much as the loss in value of the most expensive component is not offset by a corresponding increase in the value of the poorer component.

In fact, however, there are certain other factors by which this conclusion, which is a first approximation, may be modified.

Among these factors, we should mention the fact that the isotope separation process can operate only on one particular compound of uranium, i.e. uranium hexafluoride, and therefore involves an additional cost relating to the fabrication of this compound and to its reconversion at the end of the process.

In the case of the mixing process, this additional cost does not apply, at least for the poorer component. In actual fact, the above-mentioned mixing must be carried out, in order to obtain a homogeneous mixture, in liquid phase, for which purpose we can make use of an aqueous solution of uranyl nitrate, a stage which is already reached in the normal technique employed for processing natural uranium concentrates and in the processing of irradiated fuels after the extraction of plutonium and fission products.

Table 1

Enrichment %	Cost of UF_6 $/kg	Enrichment %	Cost of UF_6 $/kg
0.0040	3.00	0.018	136.60
0.0042	3.75	0.019	148.20
0.0044	4.70	0.020	160.00
0.0046	5.75	0.022	183.60
0.0048	6.85	0.024	207.60
0.0050	8.05	0.026	232.00
0.0052	9.30	0.028	256.40
0.0054	10.60	0.030	281.20
0.0056	11.95	0.032	306.00
0.0058	13.35	0.034	331.00
0.0060	14.80	0.036	356.20
0.0065	18.60	0.038	381.60
0.0070	22.60	0.040	407.60
0.007115	23.50	0.045	471.00
0.0075	26.70	0.050	535.50
0.0080	31.70	0.055	600.50
0.0085	35.60	0.060	665.50
0.0090	40.30	0.07	797.00
0.0095	45.00	0.08	929.00
0.0100	49.90	0.09	1 062.00
0.011	59.90	0.10	1 195.50
0.012	70.20	0.12	1 464.00
0.013	80.80	0.14	1 733.00
0.014	91.60	0.16	2 044.00
0.015	102.60	0.18	2 275.00
0.016	113.80	0.20	2 547.00
0.017	125.20		

It therefore follows that if the variation in richness between the two components to be mixed is not very great, the saving thus achieved can be greater than the wastage entailed by having to mix components of two different degrees of enrichment.

It will be possible to ascertain the respective advantages afforded by each process by comparing case by case, the unit costs of uranium oxide enriched by the mixing of components of different contents with the corresponding cost of UO_2 obtained from UF_6 enriched by isotope separation.

In general, it may be said that the mixing of natural and enriched uranium, for example, is of value when the final enrichment required is not very great, in which case the savings made in the conversion to uranium hexafluoride will be considerable in respect to the actual cost of enrichment. This situation could arise in reactors designed to operate on natural uranium, for example, but in

which a slight enrichment of the fuel would afford considerable advantages.

The mixing process would also be of value in the utilization of enriched uranium produced by fuel processing plants for other reactors requiring an enrichment varying slightly from that mentioned above. The mixing process might be suitable for utilising uranium which is slightly depleted in relation to natural uranium (e. g. , uranium produced by plutonium-breeding reactors) and for obtaining new natural uranium or slightly enriched uranium.

In addition to the above-mentioned purely technical and economic considerations, there are others of a commercial nature, since that the USAEC tables are based on a particular price for natural uranium, while the market price of such materials can vary considerably. However, the purchaser of USAEC enriched uranium buys a certain quantity of natural uranium (necessary for the fabrication of enriched uranium) at a special arbitrary price which in some cases may not be realistic.

The mixing process provides such a purchaser with a further degree of freedom in that it offers him the advantage of being able to acquire a fraction of this natural uranium at the market price from the supplier of his choice.

Obviously, the greater the divergence between the reference cost given in the USAEC tables and the market price of natural uranium, the greater are the advantages of the mixing process and the more extensive is the field in which such processes can be used to advantage.

The aim of this study is to investigate, on the basis of various theoretical cases, the limitations of this mixing process compared to the conventional method and the conditions under which it could be applied.

The nature of the study and of the material treated is such that the following findings are to a certain degree approximations and their value is therefore more indicative than absolute. In this study an attempt has in fact been made not so much to provide final data for immediate use as to throw light on certain technical and economic aspects of the problem and to single out certain methods for investigating them.

2 - COST ESTIMATES FOR COMPONENT MATERIALS

2.1 URANIUM HEXAFLUORIDE

The USAEC table quotes the price of uranium (in the form of UF_6, referring to the uranium content) enriched and depleted in relation to natural uranium for various values of the isotopic content ranging from 0.4 % to 20 %. This table is the latest one officially published by the USAEC and supersedes a previous one which quoted considerably higher prices. The present prices are based on a price of 23.5 $ /kg for natural uranium in the form of hexafluoride. Since the cost of converting the uranium concentrates into hexafluoride can be estimated at 8 $ /kg, the reference price of natural uranium in concentrate form may be put at 15.5 $ /kg.

2.2. ENRICHED URANIUM OXIDE PRODUCED FROM UF_6

Let us now examine the cost of uranium oxide produced in Europe, taking enriched UF_6 as the source material, on the basis of the prices given in the above-mentioned Table 1 for materials in the USA. It may be considered that the price of UO_2 can be calculated from the equation :

$$C_{UO_2} = 1.015 \ C_{UF_6} + 6.80 \ \$ \ /kg$$

where the coefficient 1.015 takes into account the wastage due to processing (in our case assumed to be equal to 0.5 %), loss of interest during processing (presumed to be 0.66 %), cost of insurance during transportation (0.35 %), while the figure of 6.80 $ is made up of the transportation costs (estimated at 5 $ /kg) and the cost of converting UF_6 to UO_2, which for a plant with a capacity of 50 tons/year we have taken as being 1.80 $ /kg.

The figures given in Table 1 for the cost of the hexafluoride enable Table 2 to be compiled , which quotes the cost of enriched UO_2 produced form UF_6.

Table 2

Enrichment %	Cost of UO_2 $/kg	Enrichment %	Cost of UO_2 $/kg
0.7115	30.65	2.0	169.20
0.75	34.90	2.2	193.15
0.8	38.97	2.4	217.51
0.85	42.93	2.6	242.28
0.90	47.70	2.8	267.05
0.95	52.47	3.0	292.22
1.00	57.45	3.1	317.39
1.1	67.60	3.4	342.76
1.2	78.05	3.6	368.39
1.3	88.81	3.8	390.12
1.4	99.77	4.0	419.90
1.5	110.94	4.5	484.86
1.6	122.31	5.0	550.33
1.7	133.88	10.0	1 220.23
1.8	145.45	20.0	2 592.20
1.9	157.82		

2.3 PRODUCTION OF NATURAL URANIUM OXIDE FROM PRE-CONCENTRATES

The cost of producing natural uranium oxide from pre-concentrates in Europe is made up of the cost of the source material plus the conversion costs, which also include wastage and interest payable to creditors. The source material is a 60-70 % uranium concentrate, the cost of which varies within a fairly wide range according to the state of the market. Let us assume the prices per kg of contained U_3O_8 to vary from 9.94 $ (4.5 $ /lb.) to 17.61 $ (8 $ /lb.).Two plants have been taken as the basis for calculating the conversion costs, one with a capacity of 50 tons/year and the other with an output of 350 tons/year.

The conversion costs in the first instance have been estimated at 3.50 $ and in the second at 2.80 $ per kg of contained uranium. To these figures must be added wastage and interest. Possible inaccuracies in the calculation of the above-mentioned costs are not of any great importance for the purposes of this study, since the cost of conversion is in every case small in relation to the cost of the source material and the price variations. In view of the foregoing considerations, the cost of natural uranium oxide per kg of contained uranium can vary between a minimum of around 15 $ /kg and a peak level of about 25 $ /kg. In view of this degree of variation, it will be useful for the purposes of this study to consider various UO_2 price levels.

The figures 15, 17 and 19.5 have been selected for this, 19.5 being important for the reasons given below.

2.4 DEPLETED AND ENRICHED URANYL NITRATE

The value for uranyl nitrate produced by European processing plants can be calculated as a function of its enrichment (whenever the USAEC) should be willing to acquire such material) by subtracting from the corresponding values in Table 1 :

a) the cost of converting uranyl nitrate into uranium hexafluoride (estimated at 5.6 $ /kg);

b) transportation costs (estimated at 5 $ /kg);

c) wastage and insurance costs, estimated at 1 % of the cost of the material processed.

In order to calculate the cost of the contained uranium oxide in the above-mentioned nitrate, we must add to the previously obtained uranyl nitrate value :

a) the nitrate-to-oxide conversion cost (estimated at 1.2 $ /kg for a plant with an output of 350 tons/year);

b) interest payable to creditors (0.7 %) during processing;

c) wastage (0.5 %).

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The relative data are given in Table 3.

Table 3

Enrich. %	Cost UF6 $/kg	Cost UF6 cost transfer and transportation $/kg	Nitrate value $/kg	Cost of conversion into UO2, including losses and interest $/kg	Cost UO2 $/kg
0.56	11.95	1.35	1.35	1.23	2.57
0.58	13.35	2.75	2.73	1.25	3.98
0.60	14.80	4.20	5.17	1.29	6.46
0.65	18.60	8.00	7.94	1.31	9.25
0.70	22.60	12.00	11.90	1.35	13.25
1.0	49.90	39.30	39.00	1.60	40.60
1.8	136.60	126.00	125.00	2.80	127.80

3 - MIXING PROCESS

As has already been stated, the mixing of compounds of different degrees of enrichment must be carried out in liquid phase if an absolutely homogeneous final product is to be obtained.

Aqueous solutions of uranyl nitrate are ideally suited to this, since uranyl nitrate is a compound which arises at a particular stage of the processes employed for converting hexafluoride into oxide and pre-concentrated minerals into oxide and which can also be the final stage of irradiated fuel processing.

The economic comparisons could be drawn on the basis of uranyl nitrate, but instead it is preferred, for practical reasons, to carry out all the comparisons on the basis of uranium oxide, which is the final compound of a well-defined series of processes and which in turn forms the starting point for the fabrication of ceramic and metallic fuels.

If the initial compound is UF_6 or a mineral pre-concentrate, the respective processes for obtaining the nitrate are different, while the processes for converting nitrate into oxide are, of course, the same. In our opinion, however, it is reasonably accurate to assume that the cost of uranium oxide manufactured by mixing two nitrates which are of different degrees of enrichment and have been obtained by different processes is equal to the average cost of the two oxides obtained by the respective processes.

If, therefore, we make :

- C_r the unit cost (calculated on the basis of the uranium content in the form of oxide) of the component with an isotopic enrichment of X_r (richer);

- C_p similarly, the cost of the component with an isotopic enrichment of X_p (poorer);

- C_f similarly, the cost of the final mixing product with the desired enrichment of X_f;

- α the weight of the component with the X_p enrichment expressed as a percentage of the weight of final product, so that by being mixed with the fraction $(1-\alpha)$ of the component X_r, the mixed product finally obtained has an enrichment of X_f, the following relations are valid :

$$\alpha = \frac{X_r - X_f}{X_r - X_p}$$

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$$C_f = \alpha \ C_p + (1 - \alpha) \ C_r$$

hence

$$C_f = \frac{X_r \ C_p - X_p \ C_r}{X_r - X_p} + \frac{(C_r - C_p)}{X_r - X_p} \ X_f$$

If we now set up a graph (outlined in Fig. 1) having the unit costs as the ordinate and the enrichments as the abscissa, each compound of a given enrichment and cost is represented in such a diagram by a dot.
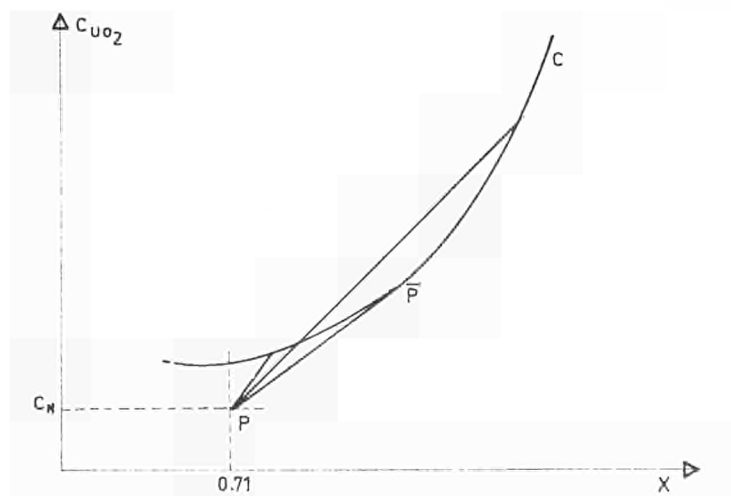
Fig. 1 - Qualitative diagram

If two compounds, the cost and enrichment of which are C_p and X_p and C_r and X_r respectively, are mixed in various proportions, the final products of the various costs and the various enrichments will be C_f and X_f respectively. These compounds will be represented in the above graph by the segment of a straight line having as its extremes the points of the coordinates C_r, X_r and C_p, X_p previously established as representing the two source components. For all values of the final enrichment X_p there will obviously be a particular value of alpha for the mixing ratios required.

Let us now insert in the above graph point P representing (in a particular situation) the natural uranium oxide obtained from pre-concentrates and then plot curve C on the basis of the data in Table 2, i.e., the cost of enriched UO_2 obtained from UF_6.

Let us suppose that we want to mix two such compounds in various proportions (thus obtaining various final enrichments). Each of the final products obtainable will be represented by dots on the segment of the straight line having as their extremes point P and the point on curve C representing the enrichment chosen for the richer component for use in mixing.

Of all the straight lines joining up point P with a point on curve C, that of the minimum inclination, i.e., the tangent to curve C from point P, represents, at the total distance between P and the tangent point, the minimum costs when the final enrichments are the same. Two important values can be established on the basis of the tangent point $\overline{P}$:

(a) the most suitable enrichment for the enriched component used in mixing;

(b) the enrichment limit of the final product for which the mixing process may be suitable from the UF_6 conversion standpoint.

It is also seen that if point P lies below curve C, the obvious interpretation of this is that the mixing process always has a practical field of application in relation to that of the pure conversion

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of UF$_6$.

Furthermore, this field will be all the more extensive and the mixing process all the more appropriate, the lower point P is in respect to curve C.

Our calculations hitherto have been based on a case in which the depleted component is natural uranium, but they are valid, of course, whatever the enrichment of the depleted component. In fact, it is sufficient, instead of point P, to take another point on the graph with the enrichment of such components as the abscissa and their cost as the ordinate.

4 – PRACTICAL LIMITATIONS AND OPTIMAL CONDITIONS IN THE PROCESS USED
      FOR MIXING NATURAL URANIUM AND ENRICHED URANIUM COMPOUNDS

By aplying the methods explained in the previous chapter, the costs of natural UO$_2$ obtained from pre-concentrates, already quoted, provide us with the values for X_f, which establish the most suitable enrichment of the component to be mixed with natural uranium as well as the final enrichment limit of the mixture beyond which the mixing process is no longer practical.

On the basis of the USAEC prices for UF$_6$, Fig. 2 contains a zigzag line which gives the values of the enrichment limit $\overline{X}_f$ for various values of the cost of UO$_2$ obtained from pre-concentrates.
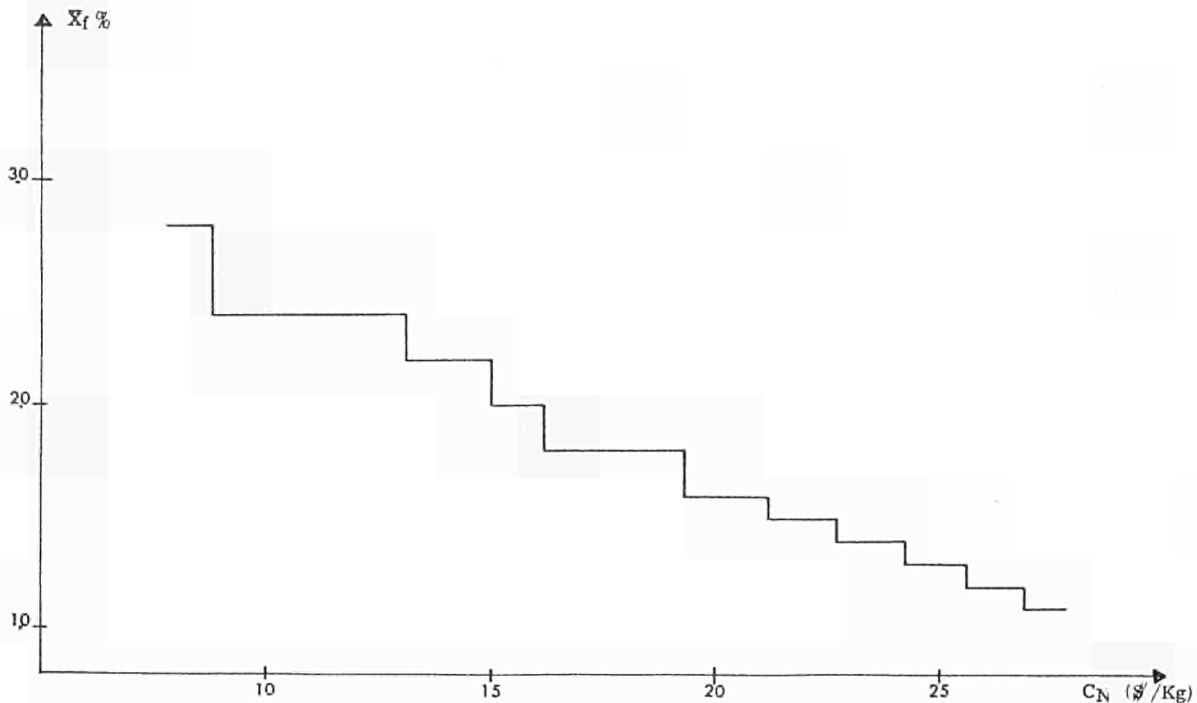

Fig. 2 – Limit enrichments which can be advantageously used as a function of the cost of natural UO$_2$ fabricated from pre-concentrates. Basic cost of natural UF6 : 23.5 $/ kg.

The zigzag nature of the above curve is due to the fact that the hexafluoride costs quoted by the USAEC (on which the curve is based) also follow this pattern.

Fig. 3 gives, for various values of the cost of natural uranium oxide obtained from pre-concentrates (still per kg of contained uranium), the maximum economic unit profit obtainable by the mixing process in relation to the conversion of UF_6 acquired according to the scale given in Table 2. The curve, which is based on a price of 19.5 $ /kg for natural oxide obtained from pre-concentrates, is especially significant since it corresponds to a price of 15.5 $ /kg for pre-concentrates (per kg of contained uranium) and is the exact figure taken as the basis for the above USAEC scale.

This curve indicates the possible advantage of the mixing process from the purely technical angle and irrespective of fluctuations in the market prices. In fact, such a curve draws a comparison between the two processes, on the assumption that the economic factors are equal.
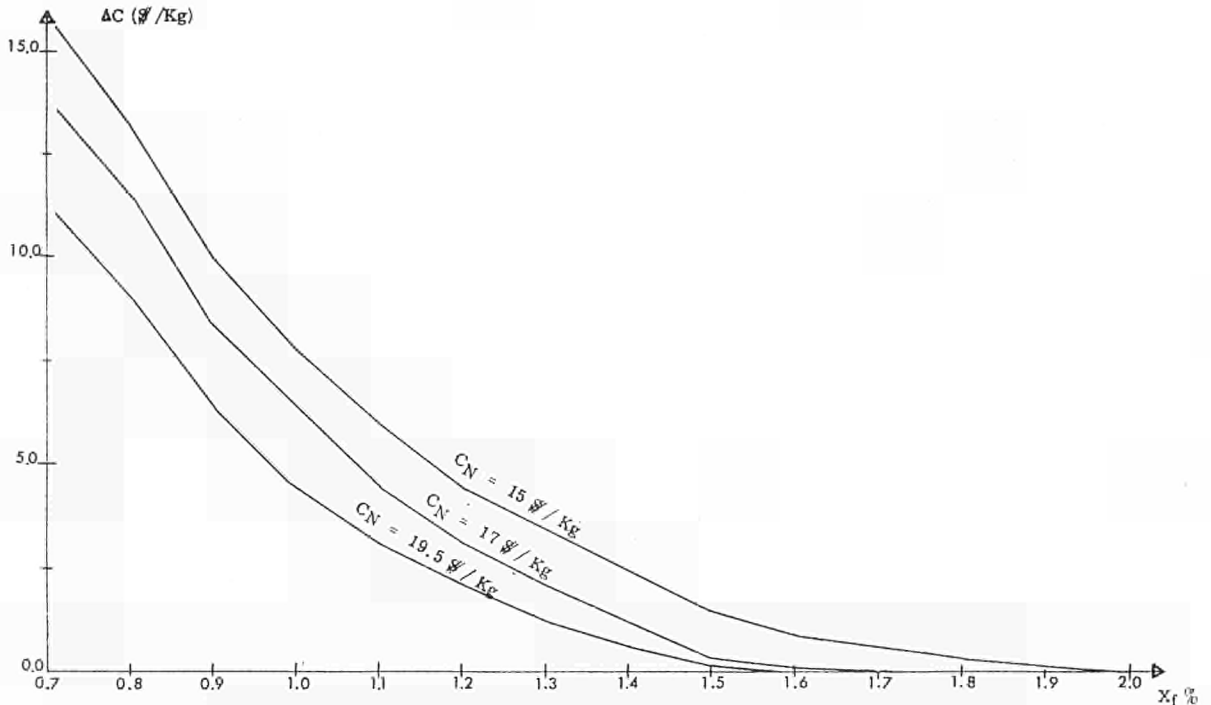
Fig. 3 - Unit gains obtained by mixing as a function of the final enrichment X_f and various prices of natural UO_2 obtained from pre-concentrates. Reference price of natural UF_6 : 23.5 $/kg.

Fig. 4 gives the coefficient alpha (as a percentage of the natural uranium used for mixing) as a function of the various final enrichments and for various $\overline{X}_f$ enrichments of the richer component which is mixed with the natural uranium. On the basis of a price of 17 $ /kg for natural uranium oxide obtained from pre-concentrates and in line with the USAEC scale given in Table 2, Fig. 5 gives the economic advantage of the mixing process in the various cases in which the enrichment of the enriching component is in excess of the optimal figure of $\overline{X}_f$ valid for each individual case. As it moves away from the above-mentioned optimal figure, the profit decreases and may turn into a loss, while the quantity of natural uranium absorbed in the process correspondingly rises.

This is proved by the straight lines, also given in the figure, which represent the alpha factor for the various instances.
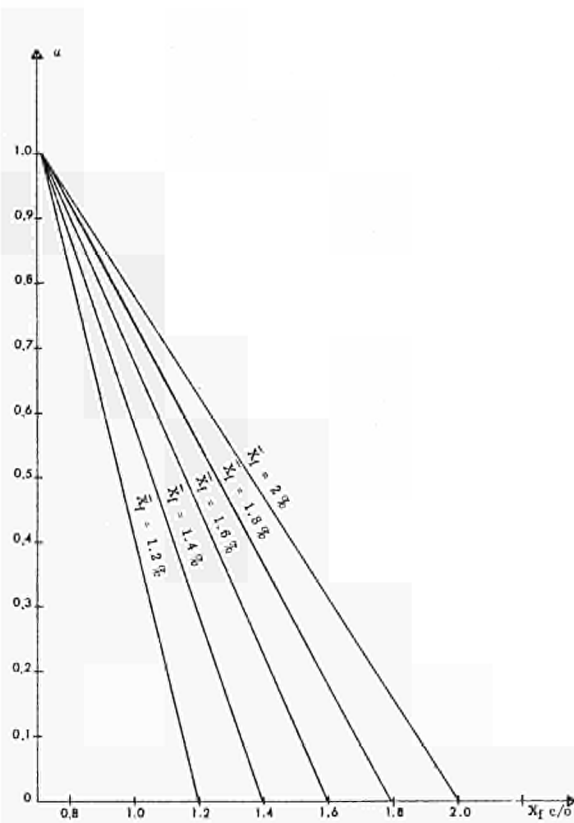
Fig. 4 - $\alpha = \dfrac{\overline{X}_f - X_f}{\overline{X}_f - 0.71}$ as a function of the enrichment for various values of the limit enrichment $\overline{X}_f$.
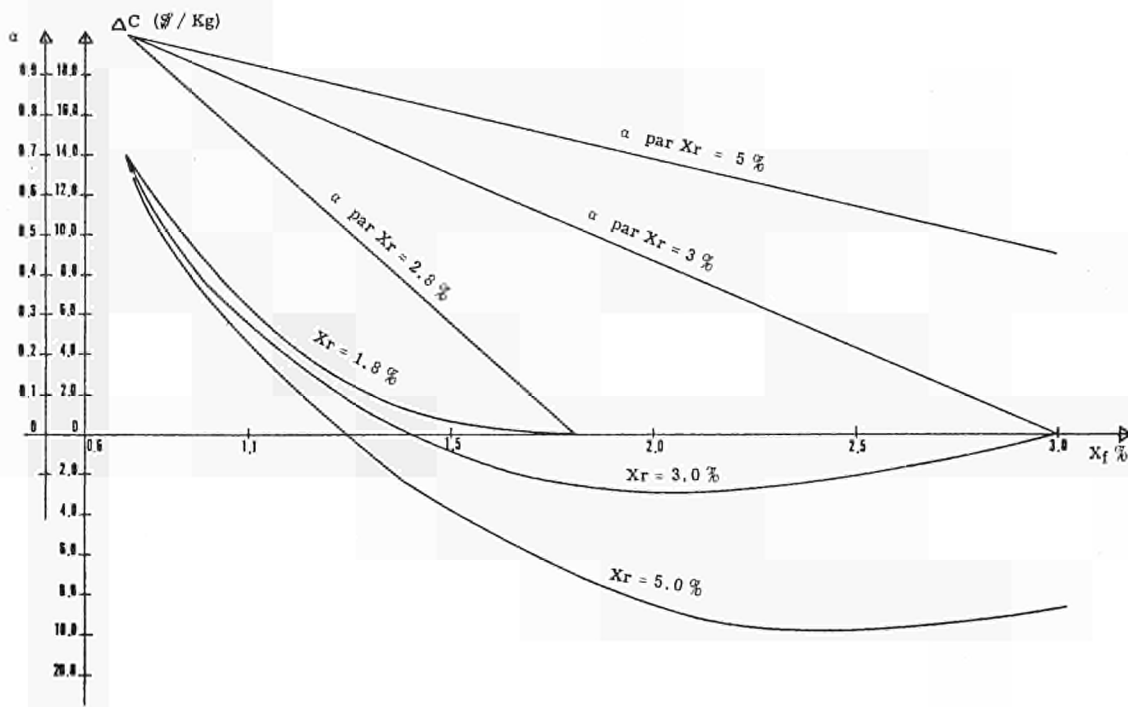
Fig. 5 - α fractions of natural UO_2 to be mixed and ΔC differences between the unit cost of UO_2 obtained from UF_6 and the unit cost of UO_2 mixed as a function of the final enrichment $\overline{X}_f$ and for various values of the enrichment X_f of the richest compound.

5 - RECOVERY OF URANIUM SLIGHTLY DEPLETED IN RELATION TO NATURAL URANIUM SUPPLIED BY PROCESSING PLANTS

This material is supplied by processing plants, after the extraction of fission products and plutonium, in the form of purified uranyl nitrate, i.e., the form most suitable for mixing with similar uranyl nitrates of a higher degree of enrichment.

The case which may be of value is that of materials which were originally used in natural uranium reactors and which have undergone a fairly low degree of irradiation (after large irradiation doses the material is so depleted as to be useless). This is the case with plutonium-breeding reactors or material extracted from natural uranium reactors during the initial stage of operation for reaching steady state in the fuel cycle.

In order to recover the above-mentioned material, it must be converted to UF_6 by subjecting the compound to an isotopic separation enrichment process.

It is not clear, however, what the attitude of the USAEC would be in such an instance and at all events it would be impossible to take its scale in Table 1 as a guide, since as a general rule it applies to material originally supplied by the USAEC.

On the other hand, the uranyl nitrate can be given a value as a function of its enrichment, if this material is used in the mixing process. In this case, it is possible to calculate, as a function of the cost of natural uranium oxide, which is taken as a basis, the limit values which can be ascribed to the depleted nitrate for use in a mixing process with richer materials in order to provide finally a compound of natural or higher enrichment.

Referring back to the graph in Fig. 1, in which the curve of the cost of UO_2 (deduced from UF_6 obtained at USAEC prices) is plotted, and the straight line tangent to this curve which passes through the point representing the cost of the natural uranium oxide obtained from pre-concentrates, the points appearing on the extension of this straight line in the zone of degrees of enrichment below the natural level, represent the limit values for the various enrichments which can be justifiably ascribed to depleted UO_2, so that for the purposes of the mixing process natural uranium or the depleted uranium in question are equally suitable for use as the poor component.

If instead we want to obtain a value for the uranyl nitrate and not the uranium oxide, the cost of converting nitrate into oxide, estimated at 1.2 $ /kg, is subtracted from the figures quoted above.

Table 4

Limit values for depleted uranium oxide and the corresponding nitrate

X%	C_N = 15 $/kg		C_N = 17 $/kg		C_N = 19.50 $/kg	
	UO_2 $/kg	nitrate $/kg	$UO2$ $/kg	nitrate $/kg	$UO2$ $/kg	nitrate $/kg
0.56	–	–	–	–	2.19	0.98
0.58	–	–	1.65	0.44	4.49	3.25
0.60	1.88	0.67	4.00	2.77	6.80	4.55
0.65	6.85	5.60	9.93	8.65	12.56	11.32
0.70	13.81	12.55	15.81	14.49	18.35	16.98

According to these criteria, we then obtain Table 4, which gives the limit values attributable, per kg of contained uranium as a function of the enrichment, to uranyl nitrate and to the corresponding uranium oxide.

6 - RECOVERY OF ENRICHED URANIUM SUPPLIED BY PROCESSING PLANTS

This uranium is produced in irradiated fuel processing plants, after the extraction of pluto-
nium and fission products, in the form of purified uranyl nitrate.

Originally, the above-mentioned fuel was irradiated in enriched-uranium power reactors,
and in the present instance it is assumed that after irradiation the uranium has a degree of enrichment
considerably in excess of the natural level.

This case is particularly valuable for the purposes of the mixing process in that the above-
mentioned material (in view of the enrichment of the contained uranium) is especially useful in that
the material is found both in a form already suited to mixing and at a stage in the various manufac-
turing processes sufficiently close to uranium oxide.

The possibilities for recovering and utilizing the material are as follows :

(a) Conversion to hexafluoride, dispatch to an isotopic separation plant to undergo a process
of enrichment up to the desired level, followed by fabrication of uranium oxide from the
hexafluoride.

(b) Mixing with uranyl nitrate of various enrichments, also supplied by processing plants,
in order to obtain nitrates of intermediate enrichment, and the subsequent production of
oxide.

(c) Mixing with more highly enriched uranyl nitrate (obtained from enriched hexafluoride) in
proportions enabling a nitrate of a desired enrichment to be obtained, and the subsequent
conversion of this compound into oxide.

(d) Mixing with natural uranyl nitrate (obtained from natural uranium pre-concentrates) in
order to obtain a nitrate of an enrichment half-way between the two (if such an enrichment
is desired), and the subsequent production of oxygen as in case (c).

In order to illustrate graphically the respective practical applications and limitations for the
various cases considered, Fig. 6 contains the same graph as Fig. 1, having the unit costs, always
expressed per kg of contained uranium, of the uranium oxides obtained from various sources as the
ordinates and the corresponding degrees of enrichment as the abscissae. The known curves of the
cost C_1 relating to the UO_2 (obtained from enriched UF_6) and the known straight line R_1 of the cost
of UO_2 obtained by mixing enriched materials obtained from UF_6 and natural materials obtained from
pre-concentrates (first passing through the point representing natural UO_2 obtained from pre-concen-
trates and tangent to the curve of UO_2 obtained from UF_6).are then plotted on the graph.

If used as in case (a), the value of this uranyl nitrate will for all enrichments be identical
with the corresponding value of the UF_6 minus :

(a) The cost of conversion to UF_6 (estimated at 5.6 \$ /kg);

(b) Transportation costs (estimated at 5 \$ /kg);

(c) Wastage during conversion and interest payable during the above-mentioned operations
(estimated to amount to a total of 1 %).

The value of such a nitrate will therefore be :

$$C_{nit} = (C_{UF_6} - 10.6) \times 0.99 \ \$ \ /kg.$$

Since (assuming that the enriched initial fuel is supplied by the USAEC) UF_6 can, in   n
fact, be sold as if produced under official conditions, it is therefore reasonable to ascribe the above
values to the nitrate in question, which is the normal pratice. Furthermore, since all the comparisons
are made here at the uranium oxide stage, we shall add to the above-mentioned values the cost of
converting nitrate into UO_2 (estimated at 1.2 \$ /kg) and the figures for wastage and interest payable
(estimated at 1.2 %). The cost of UO_2 thus obtained is therefore :

$$C_{UO_2} = C_{nit} \times 1.012 + 1.2 \ \$ \ /kg$$

giving the curve C_2 shown in the graph. This curve gives the cost of the UO_2 as a function of the enrichment, if it is produced from nitrate obtained by processing and bought on the terms offered by the USAEC. This curve is lower than the preceding C_1, which fact is of only minor importance inasmuch as the nitrates obtained by processing have enrichments which on the whole are not the same as those required for new applications.
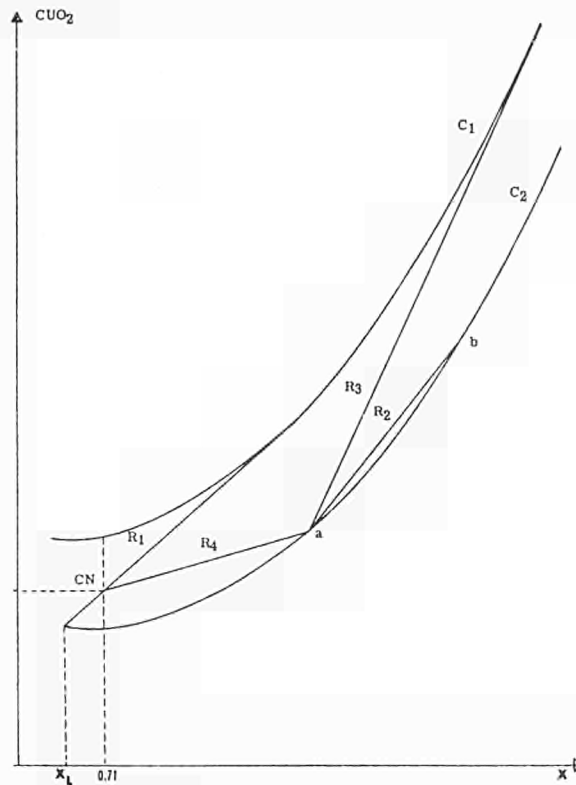

Fig. 6 - Qualitative diagram for the study of the recovery of enriched uranium originating from processing plants.

It therefore follows that in order to take advantage of the favourable market conditions indicated by curve C_2 an enrichment adjustment process is required which can precisely consist in mixing nitrates of various degrees of enrichment.

Points a, b, etc., of curve C_2 represent, for example, the characteristics of given quantities of the materials obtained by processing and therefore available. Attention is drawn to the point at which curve C_2 intersects R_1. This point determines the lower enrichment limit (X_1) for which it is practical to use these nitrates, i.e., for enrichments below this limit it is expedient to sell such material to the USAEC as provided for in case (a).

In fact, the USAEC would in this instance give this nitrate a value higher than that which it would have as a result of mixing with enriched nitrate produced from hexafluoride, in order to obtain a product of the required enrichment.

The above limit naturally depends on the cost of UO_2 made from pre-concentrates and thus on the market price of these commodities.

Naturally, the lower this price is, the higher the above-mentioned limit will be. It should be noted that while the market price of pre-concentrates, in relation to the USAEC costing policy, v, has a substantial effect on all the practical considerations discussed in the previous chapters, the above price does not greatly influence our judgment of the overall advantages offered by the mixing process, as far as utilization of uranium enriched by processing (beyond the above limit) and all the following considerations are concerned. The considerations which follow are, therefore, not contingent on incidental market and policy fluctuations, but depend. to a large extent solely on objective technical factors.

Returning to Fig. 6, if the uranyl nitrate relating to point (a) on curve C_2 is mixed with that corresponding to point (b) and if an oxide is then fabricated, we obtain compounds (according to their various enrichments, obtained in turn in line with the proportions in which the two components are mixed), the prices of which are represented by points (a) and (b) where the straight line R_2 intersects C_2. If, at the same time as particular quantities of material at enrichments as indicated by the abscissae of points a, b, are made available by the processing plant, a material with an enrichment between

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the two were required, the mixing of the two nitrates (case b) would be practicable and afford an appreciable advantage both in relation to USAEC supplies (curve C_1) and to the mixture (straight line R_1) of material obtained from pre-concentrates and USAEC materials.

Obviously, if this should come about, the situation is most unlikely to be such that the assumed demand would exhaust the quantities a, b; it would probably deplete them or at the most exhaust one of them.

In other words, once all the possible mixtures of the nitrates of varying enrichments have been carried out (since such operations are naturally among the most advantageous), in order to satisfy all the demands which it is arithmetically possible to satisfy with such mixtures, two remnants will inevitably be left over which as such cannot possibly meet the customers' requirements the remnant which is the richest from the isotopic standpoint is poorer than the poorest of all the materials required.

For the sake of simplicity, let us assume that there is only one remnant and that its characteristics are described by point (a) in Fig. 6.

In this case, the material can be mixed with more highly enriched nitrate (case C) obtained from fresh UF_6. The considerations discussed in chapter 3 can be repeated here. In fact, the only purely quantitative difference, as compared with the cases discussed in that chapter, is that here the poorer component of the mixture does not possess a natural enrichment but has an enrichment and cost defined by point (a).

In this case, too, there will be a straight line, R_3, passing through (a) and tangent to curve C_1, the points of which have as their coordinates the enrichments of the various possible final products of the mixture and their corresponding costs.

The tangent point of this straight line R_3 to curve C_1 establishes the most suitable enrichment for the richer component for use in the mixture and the enrichment limit of the final product which can be profitably obtained.

The ordinates of the straight line R_3 at equal enrichment, are below those of curve C_1 and straight line R_1, which means that it is advantageous to use the nitrate obtained by processing both in relation to UO_2 obtained from enriched UF_6 and with regard to UO_2 obtained by mixing nitrates obtained from pre-concentrates with nitrates derived from UF_6. The above ordinates of R_3 are, however, above the corresponding ordinates of R_2, which confirms as far as it is possible the advantage of the alternative described by case (b), as was in fact to be expected.

It should be noted, furthermore, that the tangent point of R_3 and C_1 corresponds to an enrichment greater than the corresponding tangent point of R_1 and C_1, as a result of which the field of application of the above nitrates enriched by mixing with nitrates derived from UF_6 is more extensive, from the standpoint of the suitable final enrichments, than that considered in chapters 3 and 4. Finally, (case d), the remnant possessing the same characteristics as those of point (a) in Fig. 6 could be mixed with uranyl nitrate of natural enrichment obtained from pre-concentrates. The cost of the oxide then fabricated from the mixed product as a function of the enrichment is given by the points on the straight line R_4 joining point C_N with point (a), C_N representing the cost of natural UO_2 obtained from pre-concentrates.

When the enrichment is the same, the ordinates of this straight line R_4 are above the corresponding ones of curve C_2 but below those of the straight line R_1, thus indicating the advantage of equal enrichment with regard to the mixing of UO_2 obtained from UF_6 with UO_2 obtained from pre-concentrates.

The afore-mentioned general treatment of the problem can be applied to all cases arising in practice; in order to determine the advantages to be derived from a given process, it is sufficient to know the following: a curve of the C_1 type (and thus the corresponding rates for UF_6 on the basis of which the curve is plotted), point C_N (i.e., the cost of the available pre-concentrates) and the enrichment of the final products required.

The various possibilities are too numerous to enable all the alternatives to be tabulated in full here.

By way of a guide, we are considering here the possibility of re-enriching UO_2 obtained by re-processing, having enrichments X_p of 1.2 %, 1.6 % and 1.8 % respectively, by mixing it with pure UO_2 obtained by re-processing but with greater X_r enrichments.

As a function of the final enrichments X_f, the costs of the UO_2 thus obtained are then calculated and the unit gains ΔC in relation to the cost of UO_2 obtained from UF_6, which are given in Table 5, from which we can also see the fraction α of the poorest component which must be added to the mixture in order to obtain the desired enrichment.

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Table 5

X_f %	$X_r = 1,4\%$			$X_r = 1,6\%$			$X_r = 1,8\%$		
	α	C $/kg	Δ C $/kg	α	C $/kg	Δ C $/kg	α	C $/kg	Δ C $/kg
				$X_p = 1,2\%$					
1,25	0,750	66,35	17,08	0,875	66,45	16,98	0,917	66,70	16,83
1,30	0,500	71,75	17,06	0,750	71,95	16,86	0,833	72,05	16,76
1,40	0,000	82,50	17,27	0,500	82,95	16,82	0,667	83,25	16,52
1,50	-	-	-	0,250	93,85	17,09	0,500	94,30	16,64
1,60	-	-	-	0,000	104,90	17,41	0,333	105,30	17,01
1,70	-	-	-	-	-	-	0,167	116,30	17,68
1,80	-	-	-	-	-	-	0,000	127,60	17,85

X_f %	$X_r = 1,8\%$			$X_r = 2,0\%$			$X_r = 2,5\%$		
	α	C $/kg	Δ C $/kg	α	C $/kg	Δ C $/kg	α	C $/kg	Δ C $/kg
				$X_p = 1,6\%$					
1,70	0,500	116,25	17,63	0,750	116,40	17,48	0,889	116,70	17,18
1,80	0,000	127,60	17,85	0,500	128,05	17,39	0,779	128,30	17,14
1,90	-	-	-	0,250	139,60	17,62	0,667	140,00	17,22
2,00	-	-	-	0,000	151,20	18,00	0,555	151,75	17,15
2,20	-	-	-	-	-	-	0,333	175,45	17,70
2,50	-	-	-	-	-	-	0,000	210,80	19,10

X_f %	$X_r = 2,0\%$			$X_r = 2,5\%$					
	α	C $/kg	Δ C $/kg	α	C $/kg	Δ C $/kg	α	C $/kg	Δ C $/kg
				$X_p = 1,8\%$					
1,90	0,500	139,40	17,82	0,857	139,48	17,74	-	-	-
2,00	0,000	15,20	18,00	0,714	151,36	17,84	-	-	-
2,20	-	-	-	0,428	175,12	18,03	-	-	-
2,50	-	-	-	0,000	210,80	19,10	-	-	-

The possibility is then considered of re-enriching UO_2 obtained from re-processing plants with fresh UO_2 of a higher enrichment.

The tangents to the curve C_1 were drawn from the points on curve C_2 corresponding to the enrichments X_p = 1.2 %, 1.6 %, 1.8 %, thus singling out the straight lines relating to the minimum cost and the ultimate practical limits of enrichment.

Table 6 below gives such enrichment limits for the three initial enrichments considered together with the equations of the three tangents, thus giving us the cost of the mixture as a function of the final enrichment required X_f.

Table 6

X_p	Favourable enrichment limits %	Mixture cost $/kg
1.2	2.8	$61.00 + 128.77 (X_f - 1.2)$
1.6	4.5	$104.90 + 131.02 (X_f - 1.6)$
1.8	5.0	$127.60 + 132.10 (X_f - 1.8)$

The differences between the cost of fresh UO_2 and the costs given by the above-mentioned tangents represent the financial advantage of the mixing process under consideration. These gains are shown in the graph in Fig. 7 as a function of the final enrichment required and for the three enrichment values of the material obtained by processing which were examined.
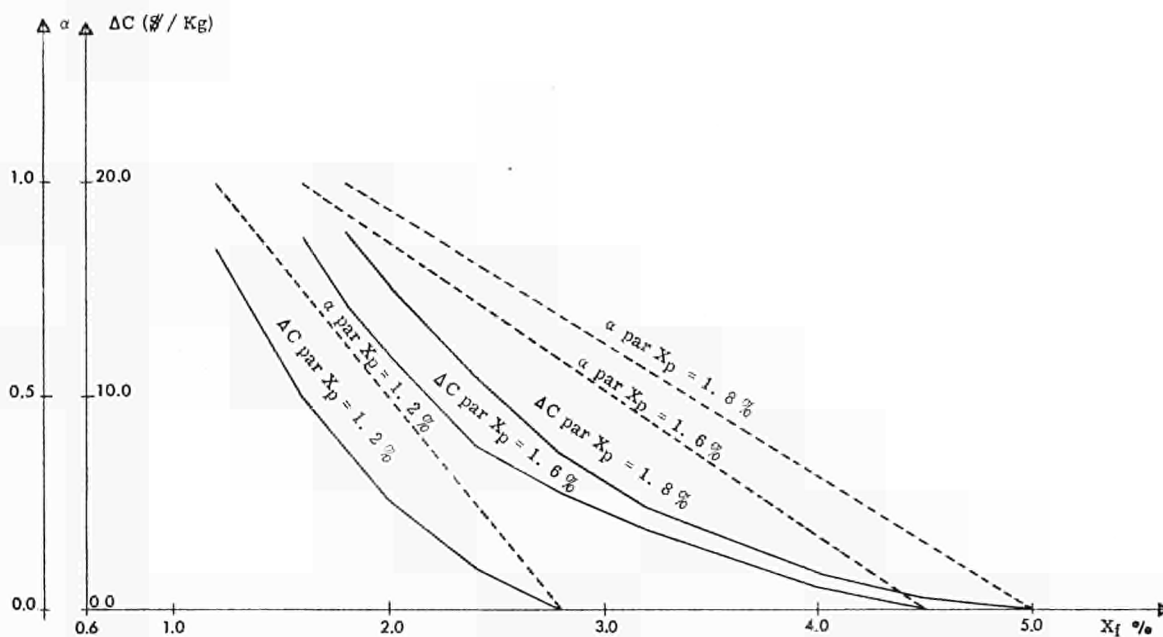

Fig. 7 - $\alpha = \dfrac{X_r - X_f}{X_r - X_p}$ and Δ C gains representing the difference between the cost of UO_2 obtained by mixing UO_2 fabricated from UF_6 with reprocessed UO_2 and the cost of UO_2 obtained from UF_6.

This graph also contains the straight lines giving the coefficient α. Finally, consideration was given to the case in which enriched UO_2 obtained from re-processing plants is mixed with natural UO_2 obtained from pre-concentrates.

Assuming that the cost of such natural UO_2 is $C_N = 17$ \$ /kg, the first thing to be established is the enrichment X_1 beyond which the above-mentioned mixing process is advantageous in relation to the enrichment of natural UO_2 by mixing with enriched UO_2 obtained from UF_6 according to the minimum cost line. This enrichment X_1, derived from the point corresponding to a cost of natural uranium of 17 \$ /kg, gives $X_1 = 0.64$ %.

The three points on C_2 corresponding to enrichment values of 1.2 %, 1.6 % and 1.8 % (all of them to the right of the X_1 determined above) are then joined up with the point fixing the cost of natural UO_2 obtained from pre-concentrates and the three straight lines are obtained which give the cost of UO_2 enriched by mixing natural UO_2 obtained from pre-concentrates with re-processing UO_2

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having the above enrichments. These straight lines have the following equations :

$$C = 17 + 89.79 (X_f - 0.71) \text{ \$/kg for } X_r = 1.2 \%$$
$$C = 17 + 98.76 (X_f - 0.71) \text{ \$/kg for } X_r = 1.6 \%$$
$$C = 17 + 101.46 (X_f - 0.71) \text{ \$/kg for } X_r = 1.8 \%$$

The differences between the cost of UO_2 enriched by mixing with UO_2 obtained from UF_6, according to the straight line representing the maximum economic advantage and the costs given by the preceding expressions, show, at the enrichment spacing under consideration, the financial advantage to be derived from mixing natural UO_2 obtained from pre-concentrates with UO_2 obtained by re-processing rather than with UO_2 obtained from UF_6.

This advantage, together with the straight lines giving the coefficient α, are given in Fig. 8.
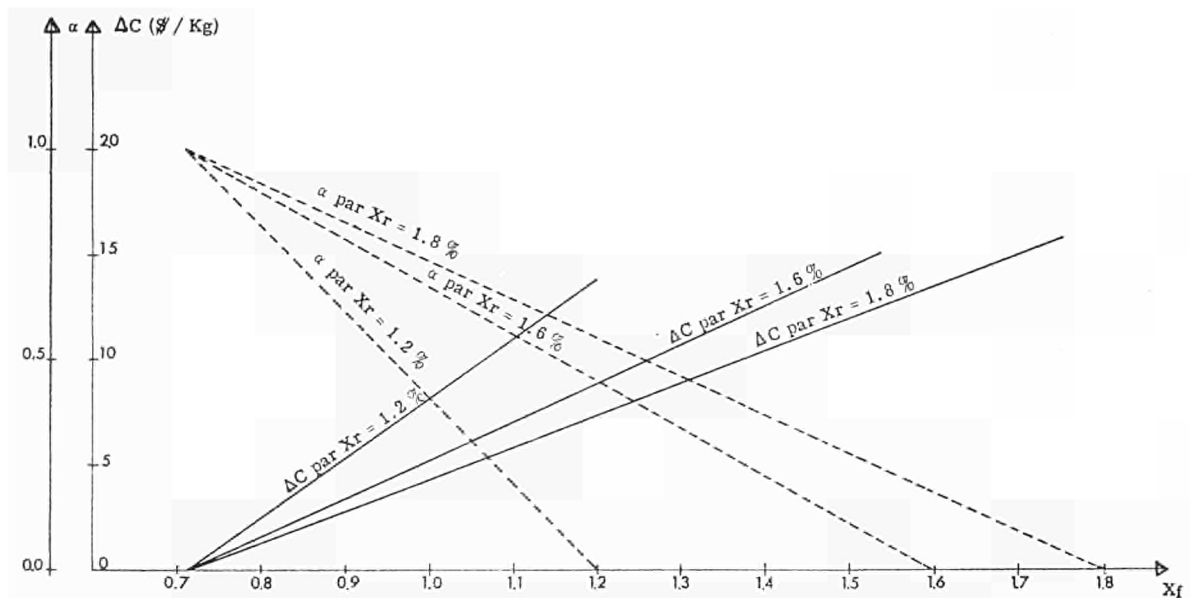

Fig. 8 - $\alpha = \dfrac{X_r - X_f}{X_r - 0,71}$ et gains ΔC représentant la différence entre le coût de l'UO_2 enrichi que l'on obtient en mélangeant de l'UO_2 naturel préparé à partir de préconcentrés avec de l'UO_2 retraité et le coût de l'UO_2 enrichi que l'on obtient en mélangeant de l'UO_2 naturel préparé à partir de préconcentrés avec de l'UO_2 préparé à partir d'UF_6 suivant la droite des coûts minima. Coût de l'UO_2 naturel préparé à partir de préconcentrés C_N = 17 \$/kg.

7 - OTHER POSSIBILITIES AND ADVANTAGES IN THE MIXING PROCESS

In addition to the advantages, which can be expressed in more or less precise economic terms, which have been outlined in the previous chapters, the mixing process also presents interesting possibilities from other viewpoints.

(a) The possibility of standardizing the base materials produced by a firm manufacturing nuclear fuel. In fact, such a firm, which has at its disposal two or three quantities of uranium with various and suitable enrichments, could, for example, and within certain limits obtain fuels of any required enrichment within a certain space of time by mixing these materials in the appropriate proportions.

(b) The possibility of making economic use (while dispensing with the need for complicated operations of a technical-commercial nature) of the processing wastes and left-overs.

(c) The possibility of obtaining, rapidly and easily, small quantities of uranium of any par-
ticular enrichment which are required, e.g., by research projects. In view of the small
quantities involved, the saving effected as described in the previous chapters is of no
great importance, and the various enrichments desired could also be obtained by mixing,
e.g., natural uranium with highly-enriched uranium.

(d) The possibility of obtaining, at a considerable saving, fuels having a very extensive range
of enrichments. This might be of use in reactors for improving the flux distribution and
the relative disadvantage factors. It would, in point of fact, be possible to vary the en-
richment in one single fuel continuously along the axis, for example, by inserting uranium
oxide pellets of different levels of enrichment. For technical reasons this would be im-
possible using the conventional method.

8 - CONCLUSIONS

(a) The mixing of natural uranium obtained from pre-concentrates with enriched uranium
obtained from UF_6 in order to obtain a uranium having an intermediate enrichment offers
a field of application (Fig. 2) which depends on the cost of UF_6 and of the pre-concentrates.

Under present conditions, the final enrichment limit for which the above process is suited
lies between 1.2 and 2.0 %.

(b) The advantages of the mixing process decrease when the above-mentioned limit is ap-
proached. Under present conditions (Fig. 3) major advantages are to be gained up to
final enrichments of 1.2 %.

(c) This process makes it possible to produce very economically slightly enriched (0.8 % +
1.0 %) fuels, which could be used to advantage in reactors designed to operate on natural
uranium. The mixing process therefore eliminates (or at least minimizes) the cost dis-
parity between natural and enriched fuels.

(d) There is in every case a special optimum enrichment of the richest component for use in
the mixture (Fig. 2). Assuming that this appropriate maximum enrichment is used in
every case and that the final enrichment required is, for example, 1.2 %, the amount of
natural uranium absorbed during this process is of the order of 50 to 60 % of the weight
of the final product under present market conditions (Fig. 4).

If the enrichment of the rich component is stepped up in relation to the final value, the ad-
vantage of the process decreases but the percentage of natural uranium absorbed increases
(Fig. 5).

(e) The mixing process makes it possible to use uranium which is slightly depleted in relation
to natural uranium by providing each material having a given isotopic enrichment with a
limit value of practicality (Table 4).

(f) The mixing process offers substantial advantages in the use of material obtained by pro-
cessing.

There are various alternatives in this instance : inter-mixing among themselves (Table 5),
mixing with enriched uranium obtained from UF_6 (Fig. 7) and mixing with natural uranium
(Fig. 8).

(g) The mixing process lends a certain flexibility to the fabrication of enriched fuel (chapter
7).