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*South African Uranium
Enrichment Program* [REDACTED]

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August 1977

South African Uranium Enrichment Program



PRÉCIS

South Africa has built its first uranium enrichment plant, a small facility that is thought to have become operational in recent months. This pilot plant, which employs an aerodynamic enrichment process, is expected to produce between 25 and 70 tonnes of reactor-grade uranium per year. The lower end of the range is more likely and corresponds to the annual fuel requirements of one large power reactor. Although the plant may be capable of enriching uranium to moderately high levels, it probably was not designed to produce weapon-grade uranium (90-percent U-235) on a continuous basis. Nevertheless, production of a significant amount of weapon-grade uranium (enough to make at least several nuclear devices per year) could be accomplished in this plant; it would require recycling batches of enriched uranium through the pilot plant—a somewhat difficult operation.

A second enrichment plant, using more sophisticated technology is planned for operation in the mid-1980s. Orders will be placed next year for equipment having long manufacturing times. Although the size of the plant has not yet been decided, it is to be a large plant for commercial production of reactor-grade uranium. If used to supply enriched uranium as feed for the Valindaba pilot plant, it could increase South Africa's capacity to produce weapon-grade uranium. South Africa is seeking both foreign investments and technical assistance for this project and is testing new prototype equipment. If these efforts are successful, South Africa may capture 10 percent of the world-wide enrichment business available in the mid-1980s.



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SOUTH AFRICAN URANIUM ENRICHMENT PROGRAM

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CENTRAL INTELLIGENCE AGENCY
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OFFICE OF SCIENTIFIC INTELLIGENCE

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PREFACE

In 1970 South Africa announced that it had developed a new process for enriching uranium in the fissile isotope U-235 and that it was constructing a pilot plant to demonstrate this process. The announced goal of the program was to convert natural uranium, mined from South Africa's extensive deposits, to a more valuable product for export. Since then there has been much interest in determining South Africa's capability to produce weapon-grade enriched uranium and in predicting the role of this new enrichment process in the international uranium enrichment market.

[REDACTED] Only one scientific report describing the pilot uranium enrichment plant has been released by South Africa. That report was presented to the European Nuclear Conference in Paris in April 1975 by Dr. A. J. A. Roux, head of the South African nuclear program. [REDACTED]

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TECHNICAL FOREWORD

Uranium as found in nature is primarily a mixture of two varieties, or isotopes: uranium-235, the isotope that sustains nuclear reactions, and the fairly inert uranium-238. Nuclear weapons and most nuclear reactors require a greater concentration of U-235 than is found in natural uranium. Consequently, uranium is enriched from the natural state (0.7 percent U-235) to about 3 percent U-235 for power reactor fuel or to about 90 percent U-235 for use in nuclear weapons.

Uranium can be enriched by any of several isotope separation techniques, although only a few methods (e.g., gaseous diffusion, gas centrifuge, and aerodynamic processes such as the Becker nozzle process) are feasible for large-scale application. In each technique uranium is passed through a machine, or *stage*, which separates the feed material into an enriched portion and a depleted portion. The fraction of uranium that is split off to become the enriched portion is called the *cut*.

The degree of enrichment achieved by a stage depends on the *stage separation factor* or *enrichment factor*. In general, decreasing the cut of a stage increases the enrichment factor of the stage, but the flow of enriched material from the stage also decreases. Although a large enrichment factor is desirable, very few isotope separation techniques allow more than a very small degree of enrichment at each stage. To reach a useful U-235 concentration, therefore, uranium must be passed through a succession of stages called a *cascade*. For example, a cascade based on gaseous diffusion, which exhibits an enrichment factor of about 0.004, is made up of more than 1,000 individual stages.

To perform useful enrichment, natural uranium is fed into a stage somewhere in the lower portion of a cascade. The cascade splits that uranium into depleted uranium, which is withdrawn from the low end, or bottom, and enriched uranium, which is withdrawn from the top of the cascade.

The flow of uranium varies from stage to stage in an ideal cascade. The flow is greatest at the stage where natural uranium is fed into the system. On either side of this point the flow gradually decreases and reaches a minimum at the ends of the cascade where product and depleted uranium are withdrawn. In an ideal cascade, each stage would be sized according to its place in the cascade, but the associated cost of building each stage a different size would be unacceptably high. Instead, only a few sizes of equipment are manufactured and installed, with a small resultant loss of efficiency.

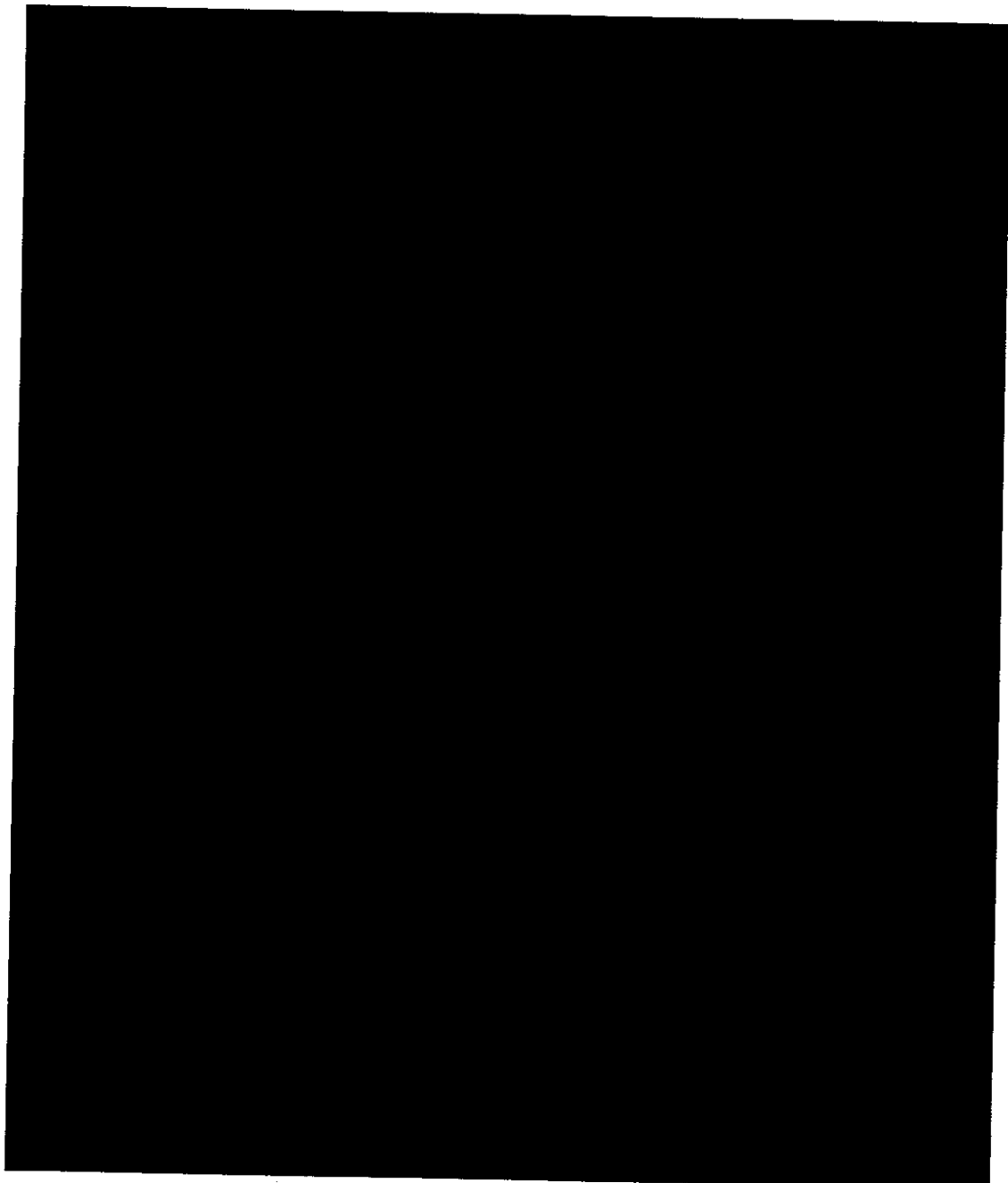
In dividing uranium into enriched and depleted portions, a certain amount of *separative work* is performed. Enrichment tasks are evaluated by the amount of separative work involved; stages and enrichment plants are classified by their capacities to perform separative work.

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SOUTH AFRICAN URANIUM ENRICHMENT PROGRAM

PROBLEM

To assess the South African enrichment program and to determine the important characteristics of the uranium enrichment plant at Valindaba.

CONCLUSIONS

1. Although technical difficulties delayed startup of the South African plant at Valindaba for more than a year, it is thought to have reached full operation recently.
2. Termed a pilot plant, because of its role in demonstrating South Africa's aerodynamic enrichment process, the plant is expected to produce between 25 and 70 tonnes of reactor-grade uranium annually; an amount near the lower end of this range is considered the most likely.
3. The designed enrichment level for uranium product probably is about 3 percent U-235, which is appropriate for power reactor fuel. The plant may, however, be designed to enrich uranium to a higher level. Highly enriched uranium suitable for nuclear-weapons application probably cannot be produced continuously, but, by recycling uranium through the plant in batches, a significant amount of weapon-grade uranium (enough to make several nuclear devices per year) could be produced.
4. Enrichment technology used in the pilot plant is being modified for use in a commercial enrichment plant, with which South Africa hopes to capture what amounts to about 10 percent of the world-wide reactor-grade uranium enrichment business in the mid-1980s. The technology to be used in the commercial plant has some unique characteristics which require testing in prototype equipment. If this prototype equipment is successful, South Africa should be able to compete well with other enrichment groups.
5. Foreign capital is being sought to assure that the plant can be built to the desired size; the planned plant capacity may have to be reduced if South Africa proceeds alone.

SUMMARY

The aerodynamic uranium enrichment process developed by South Africa is intended to increase the value of exported uranium and to make the domestic nuclear power program independent of foreign fuel suppliers. As with other aerodynamic enrichment processes, such as the Becker nozzle process, the South African process could be used to enrich uranium to 90 percent U-235, suitable for nuclear weapons production.

Details of the specific isotope separation technique used in the South African enrichment process have been tightly held. Other characteristics of the process have been reported, however, such as the working fluid (a mixture of uranium hexafluoride and hydrogen) and a fairly high enrichment factor (0.03).

A small enrichment plant, the Valindaba pilot plant near Pretoria, has been built to demonstrate the South African enrichment process. [REDACTED]

[REDACTED] It probably is not able to produce weapon-grade uranium on a continuous basis. The plant may be operated, however, to produce weapon-grade uranium by recycling material through the plant in batches. The rate at which South Africa could produce weapon-grade uranium in this manner would suffice to make several nuclear devices per year; it might correspond to several dozen devices per year if the highest estimate of plant performance is applicable.

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[REDACTED] The plant is expected to produce annually between 25 and 70 tonnes of reactor-grade uranium. The smaller amount is the most likely and is roughly equivalent to the annual fuel requirements of one large power reactor. Evidence [REDACTED]

[REDACTED] suggests that the plant is operational at nearly full capacity.

A commercial plant that will make use of technology significantly more advanced than that demonstrated at Valindaba is to begin producing reactor-grade uranium by 1984. The plant will use reliable and costly materials, and several components will be altered considerably. Axial compressors will be required, instead of the reciprocating compressors that probably were used throughout the Valindaba plant; South Africa apparently requires technical assistance in this area. Also, South African industry apparently has not developed methods for mass producing high quality separation elements in sufficient quantity; these methods are being developed with foreign assistance. Compact heat exchangers reportedly must

be developed, but this should not be a difficult problem.

To prove the advanced technology needed for commercial application of the South African enrichment process, a small facility is being built to test prototype equipment. The South Africans expect tests on this equipment to lead to commercial equipment orders beginning in 1978. At that time the size and location of the commercial plant probably will be announced.

South Africa hopes to capture 10 percent of the world-wide uranium enrichment business in the mid-1980s with a commercial enrichment capacity of 5,000 tonnes of separative work per year. If attempts to obtain foreign investment are not successful and South Africa has to build the plant alone, however, a smaller capacity is possible. Whatever capacity is chosen, the project should be a success if the efficiency of the commercial plant has been accurately predicted in South African reports, or if South Africa requires that all natural-uranium sales be accompanied by an enrichment contract.

DISCUSSION

THE ENRICHMENT PROCESS

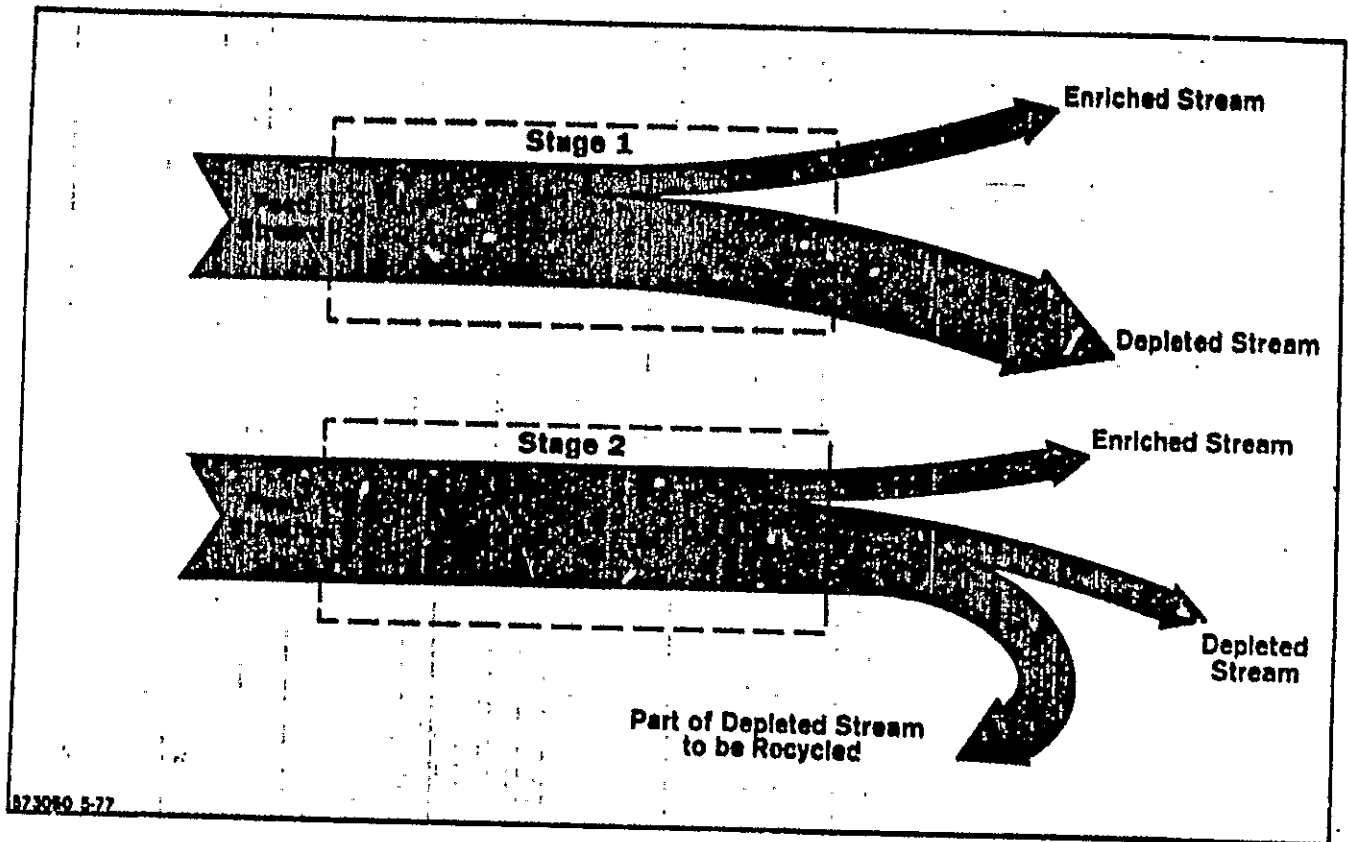
Suspicions that South Africa's enrichment process was a modification of a West German process, the Becker nozzle process, were only partially confirmed in 1973 when Dr. A. J. A. Roux described an aerodynamic process which used a "stationary-walled centrifuge" as the separating element. The operating pressure given for the process gas, a mixture of uranium hexafluoride (UF_6) and hydrogen, was too high to suggest a simple modification of the Becker process. Whereas the Becker process has always operated below atmospheric pressure, Roux stated that all process pressures in the South African plant were above atmospheric and indicated a maximum pressure of up to 6 atmospheres.¹ The two processes, therefore, cannot be equated.

The separation factor for the South African separation element was stated to be "1.025 - 1.030 depending on economic considerations." This factor was explained by Roux in 1973 to be the degree of enrichment achieved by a South African separation element.² The fact that Roux described the South African separation factor as depending on economic considerations rather than engineering constraints implies that this separation can be achieved not only in the laboratory but also in an enrichment plant.¹

In the gaseous diffusion process the separation element is a porous membrane; in the Becker process it consists of a curved wall and a knife edge. Except for the vague description given by Dr. Roux, the separation element in the South African process remains unknown.

According to Roux's presentation, the South African process involves a small cut;³ that is, the amount of enriched uranium leaving each stage in an enrichment plant is a small portion of the uranium fed into the stage. Figure 1 shows, for example, flow diagrams of two stages that have a cut of 1/4. The enriched stream of Stage 1 has 1/4 the flow of the feed stream; the depleted stream has the remaining 3/4. This is the usual kind of stage; with a cut of 1/4, the effect of isotope separation is three times greater for the enriched stream than for the depleted stream. The use

¹The value of the cut is discussed in Appendix A.

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Figure 1. Uranium Flow Through Two Types of Stages

of a small cut creates a higher enrichment factor than would be achieved by the same equipment operating with a cut of 1/2, but it complicates the interconnection of stages in a plant. Figure 2 shows how stages like this may be arranged in a cascade to produce useful levels of enrichment (and to deplete the remaining waste to low U-235 concentration). The appropriate arrangement for stages like Stage 1 of figure 1 is seen to be a complicated cascade with three enriched streams. If the cut were smaller there would be an even greater number of enriched streams.

Roux claimed, in his presentation at the European Nuclear Conference, that the small cut associated with the South African process led to the development of a novel cascade arrangement "based on the principle that an axial flow compressor can simultaneously transmit several streams of differing U-235 concentrations without there being significant mixing between them." He called his cascade technique the "helikon technique." It was developed later than the pilot plant technology and hence is not used at Valindaba.

entering each section tends to follow a fairly discrete path along the compressor and reemerges with little mixing, compressed and ready to be fed into the next stage. The actual mixing that will occur in the compressor is not known.

A module consists of "one set of compressors" (interpreted to mean one compressor carrying several

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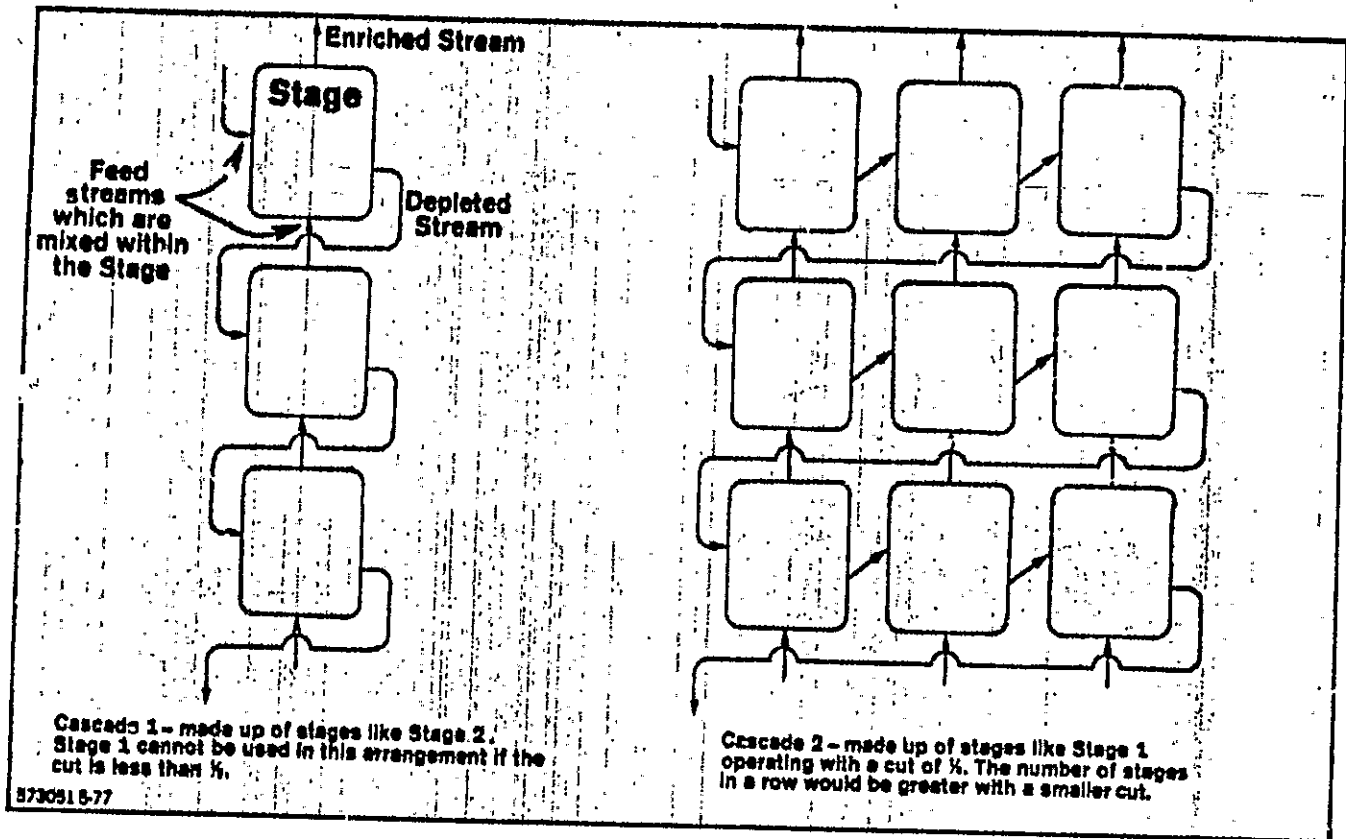
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Figure 2. Two Cascade Techniques

streams)" and one set of separation elements" (which implies that the South African separation unit will also be capable of handling several streams of different U-235 concentration without mixing). Furthermore, according to Roux, a module is not limited to one separation factor of enrichment; a module "can produce various degrees of enrichment up to a maximum of several times the separation factor over the element."¹

Consideration of this information has resulted in a concept of a South African module, shown in figure 4. The axial compressor and separation unit are built into an integrated unit, perhaps including the heat exchanger that is needed to remove the heat generated by compression of the process gas. The entire module is divided into segments, with physical barriers between the segments wherever possible to limit mixing. For the purpose of illustration, six segments are shown.² Each compressor segment has a high-pressure inlet and a low-pressure inlet, because according to Roux,¹ feed streams are separated into enriched streams that are at $\frac{2}{3}$ the original pressure

and depleted streams that are at $\frac{9}{10}$ the original pressure.

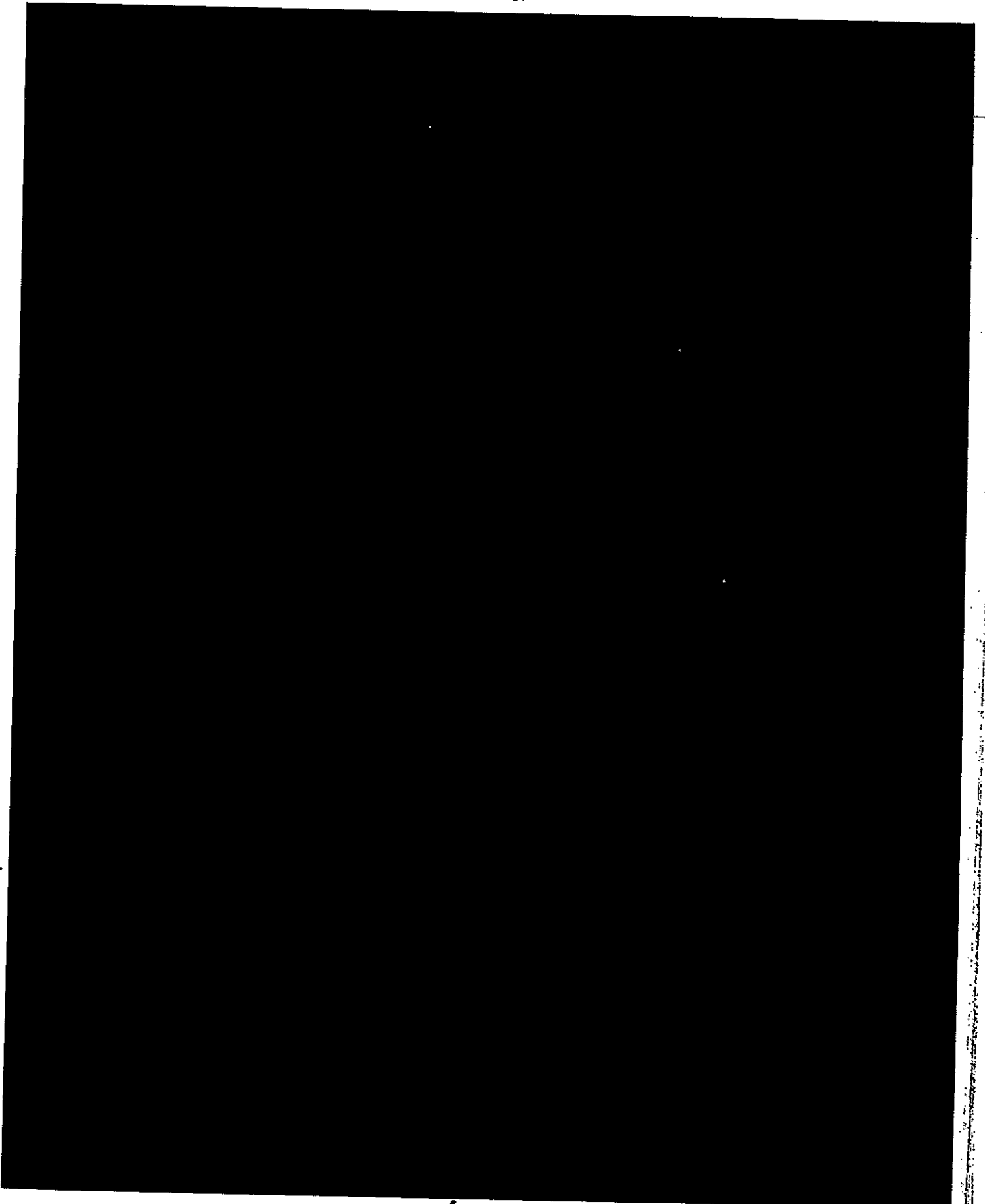
There are certain advantages in such a module. The module could be installed as one group of six stages operating with a cut of $\frac{1}{7}$. This system would ameliorate the complicated cascade arrangement required by individual stages operating with cut of $\frac{1}{7}$, consistent with Roux's remark that the helikon technique was developed because of the small cut associated with the South African process. Also, a module could be further segmented and operated as several smaller groups of six stages. One size of equipment could then be used throughout the cascade, using multiple groups of small segments where the flow requirements are small and using one group of large segments where the flow requirements are greatest. This would reduce the capital costs involved in building a plant.

THE VALINDABA ENRICHMENT PLANT

¹ Reports received while this paper was being processed indicated that the modules consist of 18 segments, or stages, and that each operates with a cut of $\frac{1}{20}$. This does not significantly alter the assessments made in this paper.

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The equation which predicts the maximum enrichment that normally will be achieved by a fixed number of stages arranged in a simple series is the following:

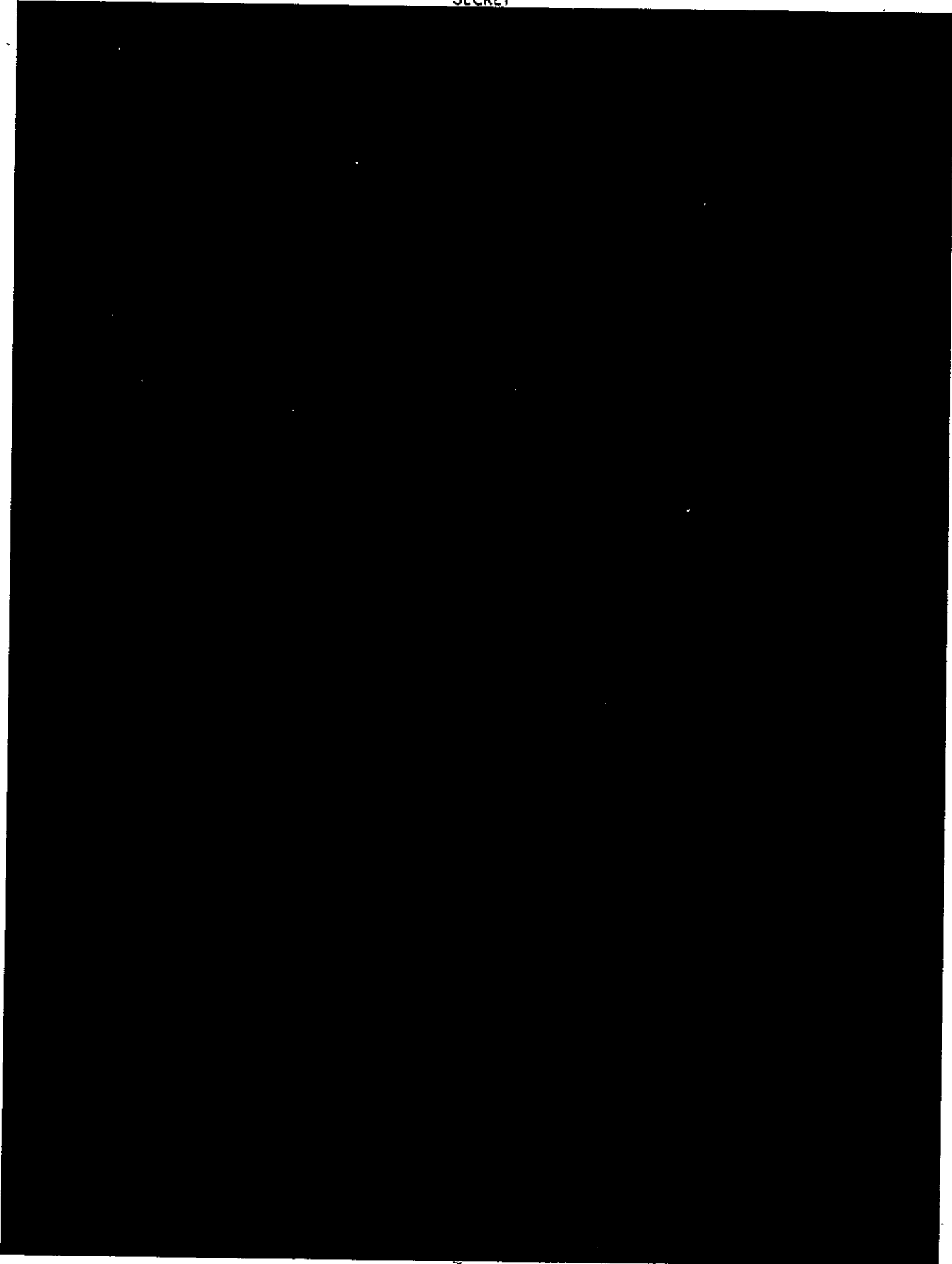
$$y/(1-y) = (x/(1-x)) e^{(\phi N/s)}$$

The variables y and x are the U-235 concentrations of the product and waste material, respectively. The quantities ϕ , and N are the enrichment factor* and number of stages, respectively. The maximum enrichment level, therefore, is related to the U-235 concentration in the waste material and is a function of the enrichment factor and number of stages. Table 1 shows the maximum enrichment levels associated

*The enrichment factor and separation factor differ by 1.

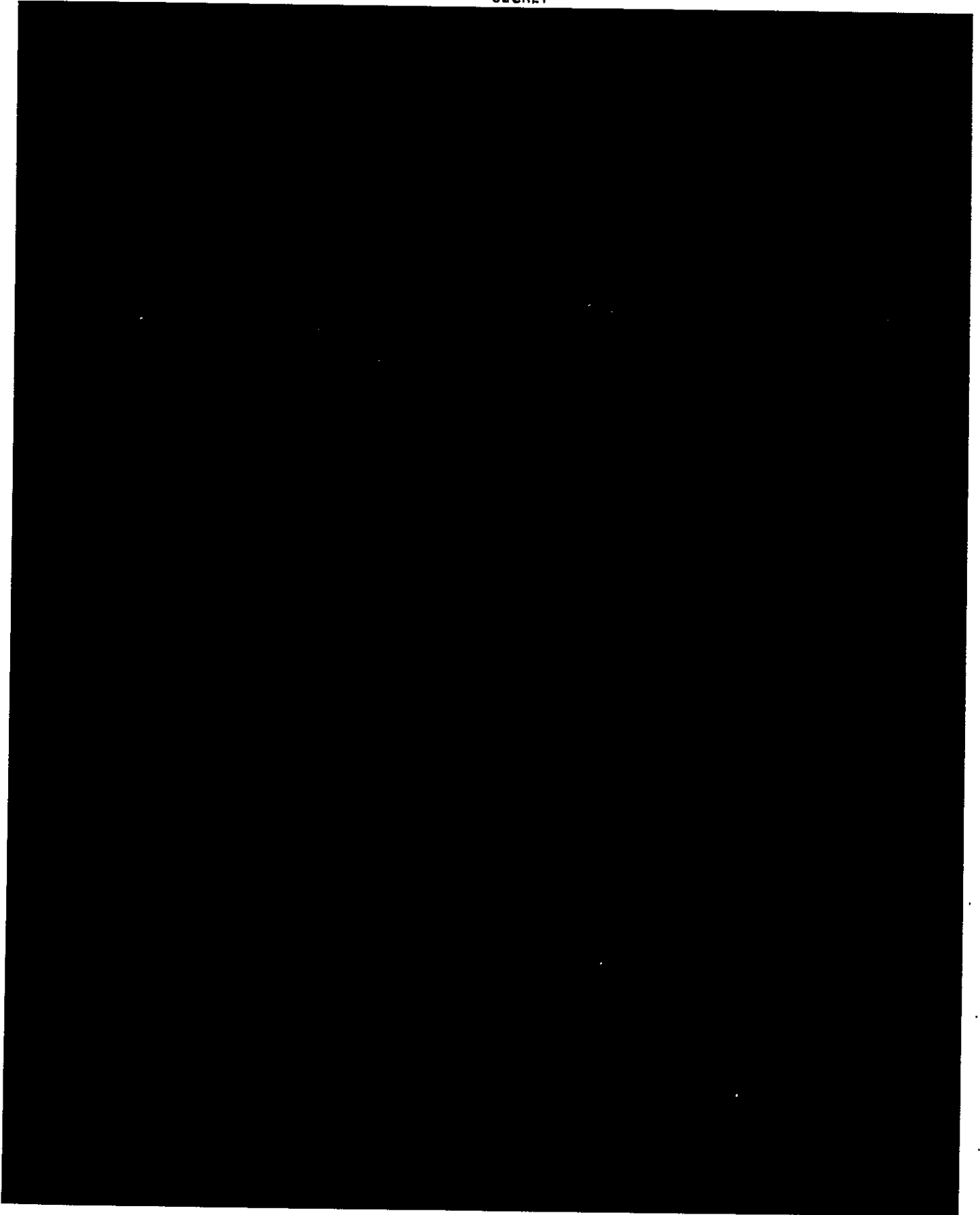
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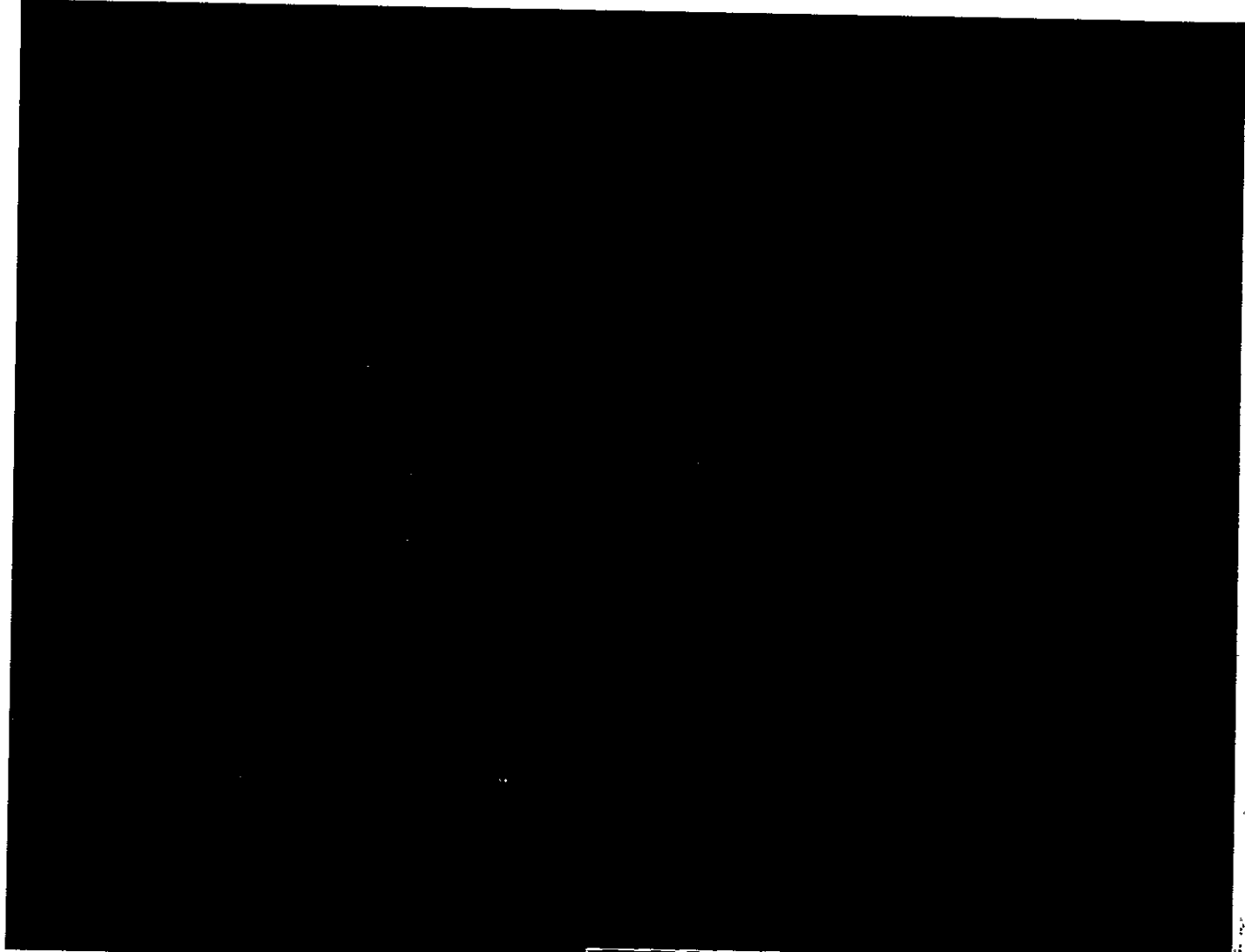
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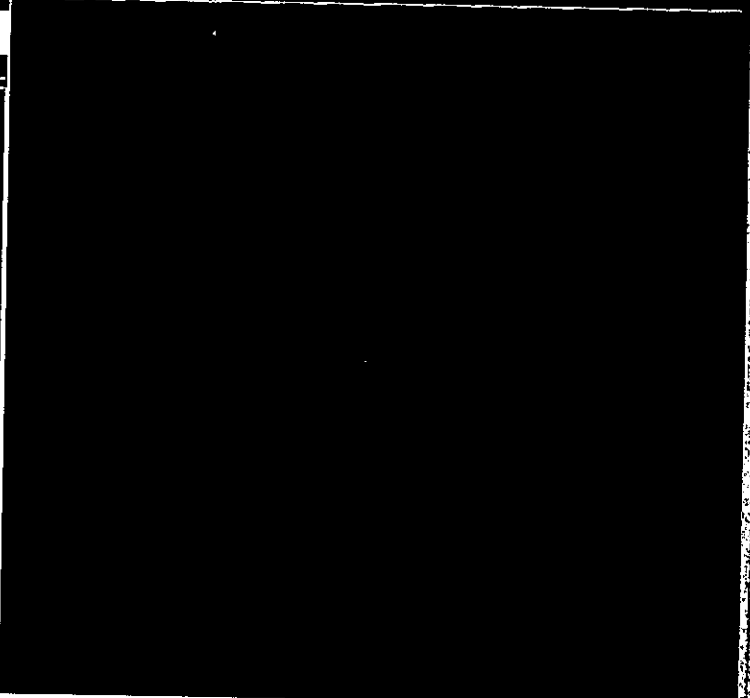
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with a variety of U-235 waste concentrations and enrichment factor values, for normal operations.



there is little use, however, for uranium enriched to levels between 4 and 90 percent U-235.



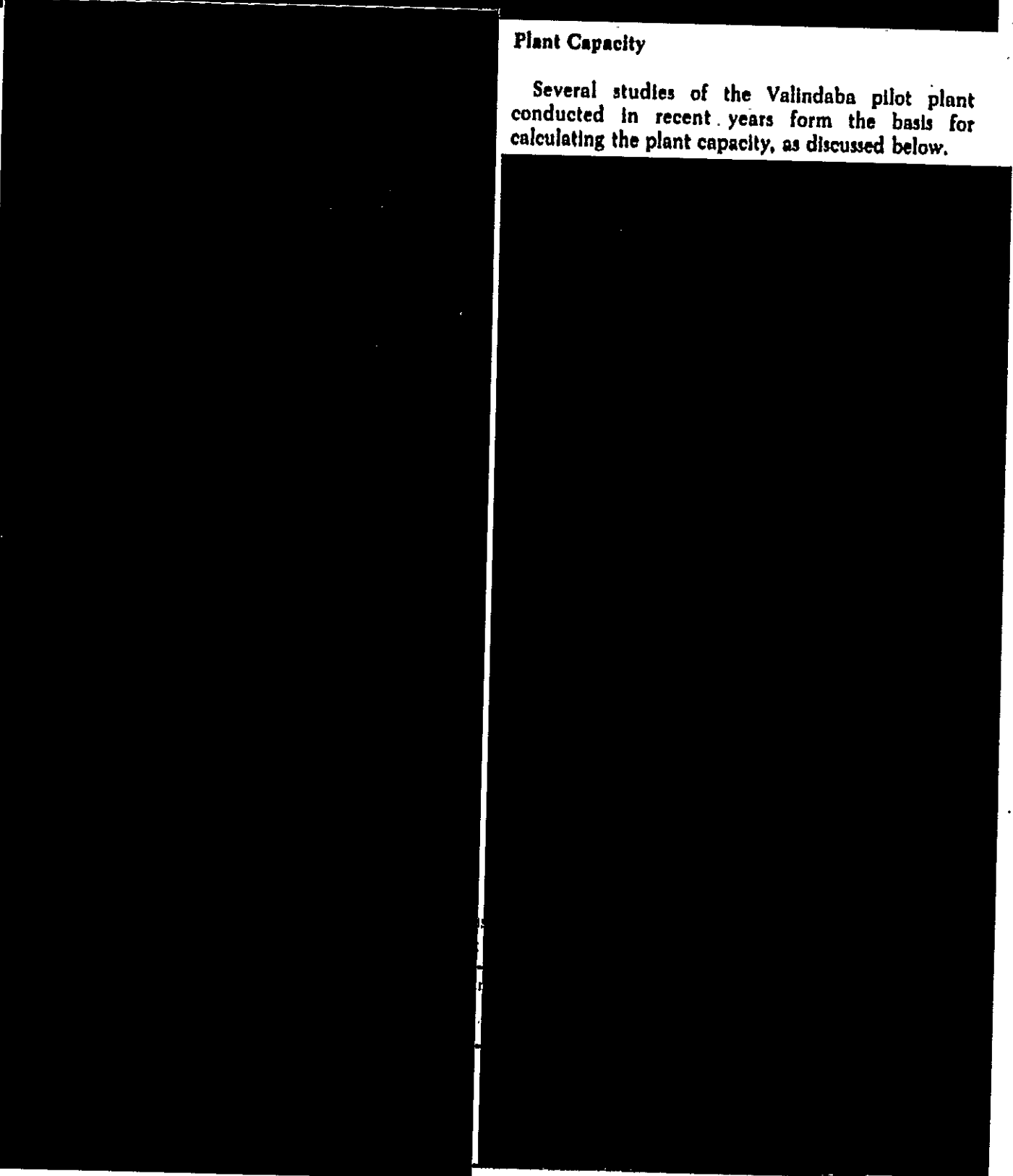
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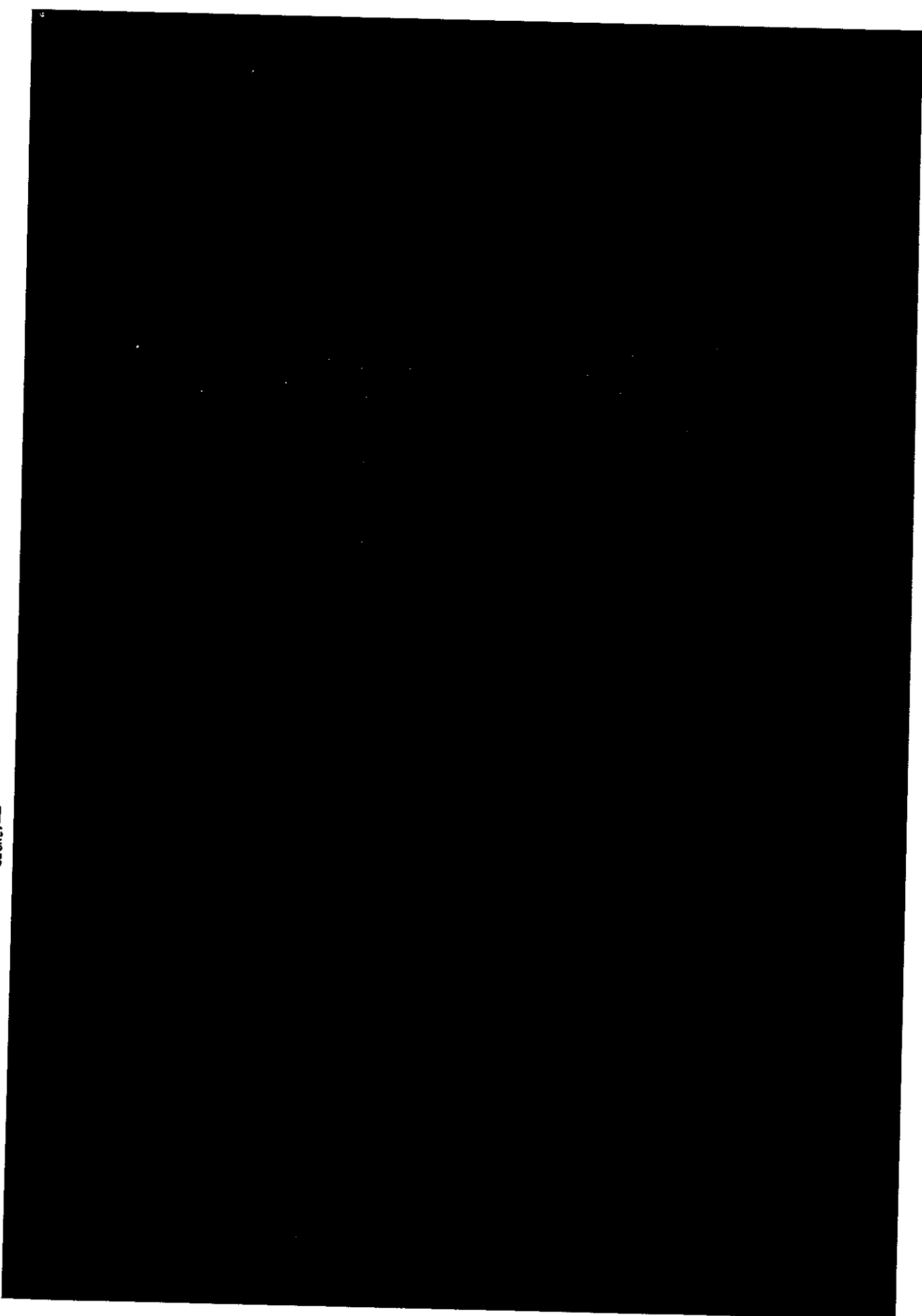


Plant Capacity

Several studies of the Valindaba pilot plant conducted in recent years form the basis for calculating the plant capacity, as discussed below.



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each requiring 24 tonnes of 3.25-percent-enriched uranium annually.

Operational Status

There is little evidence and much debate concerning the operational status of the Valindaba enrichment plant. In the absence of physical evidence, one must choose among conflicting reports to assess plant operations.

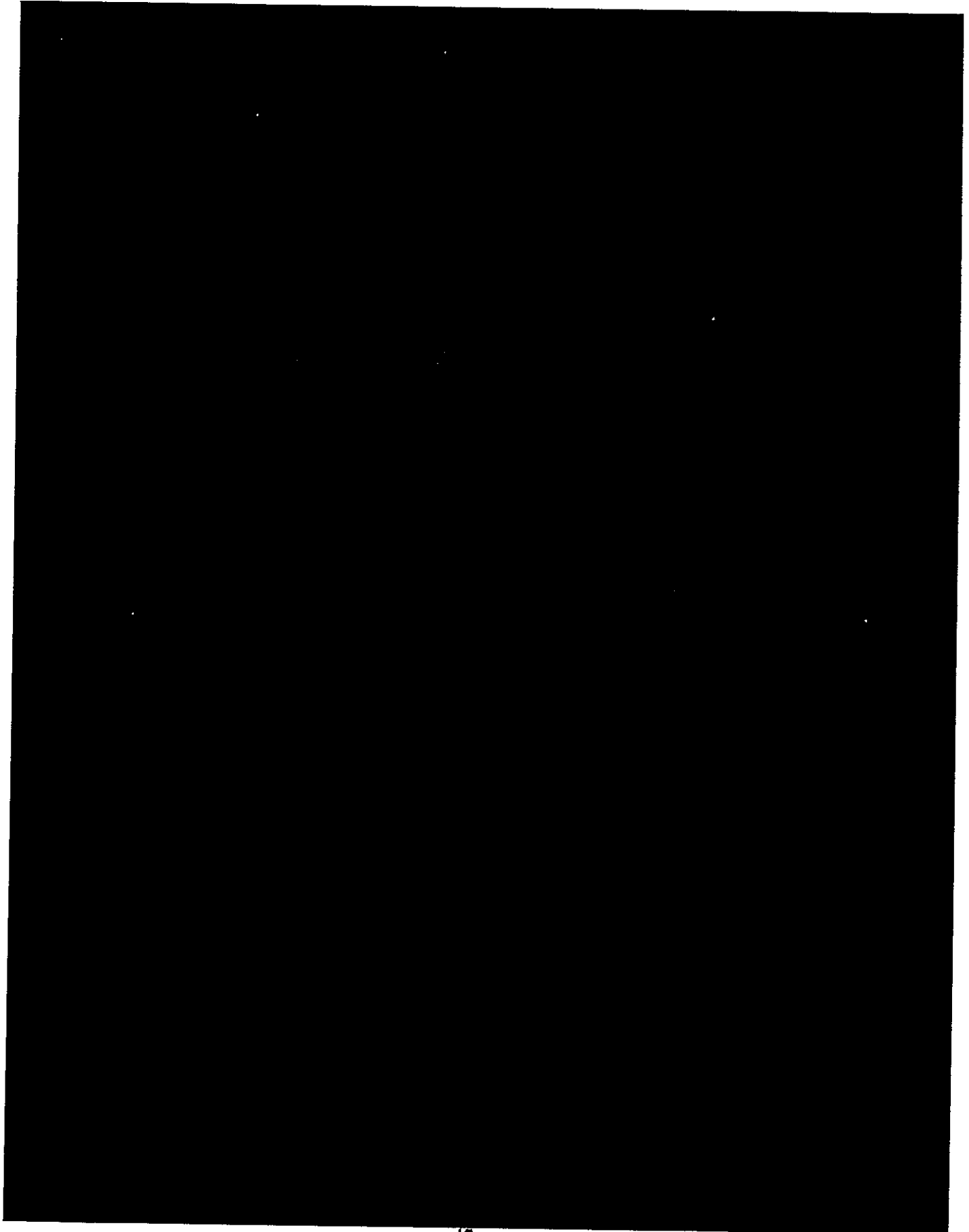
In his April 1975 presentation, Dr. Roux confirmed that "part of the pilot plant together with its associated hydrogen separators and all other ancillary equipment has been successfully brought into operation."¹

The
Koeberg nuclear power station near Cape Town will consist of two 925-MWe pressurized-water reactors,

¹Based on West German experience with the Becker aerodynamic isotope separation process.

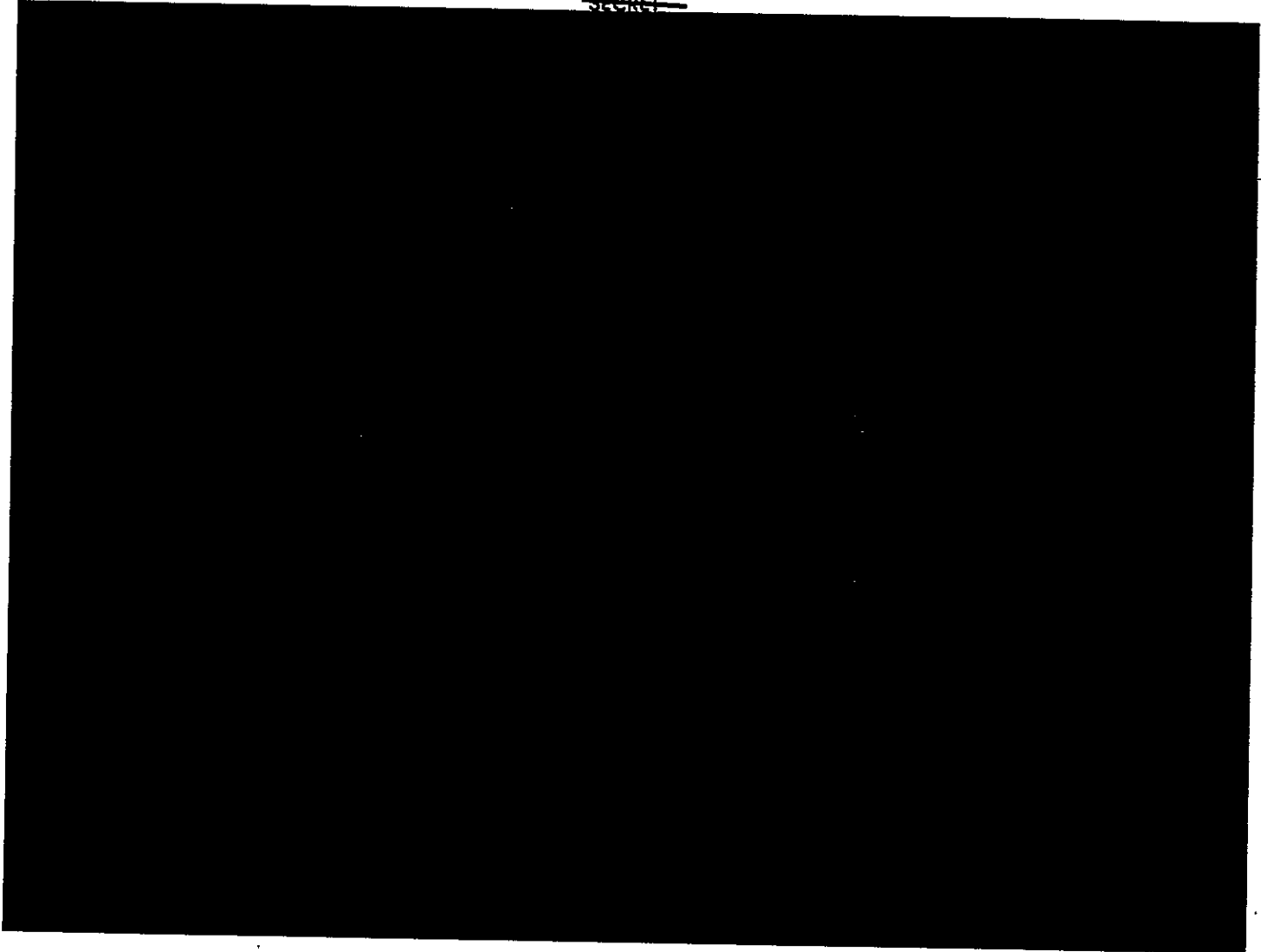
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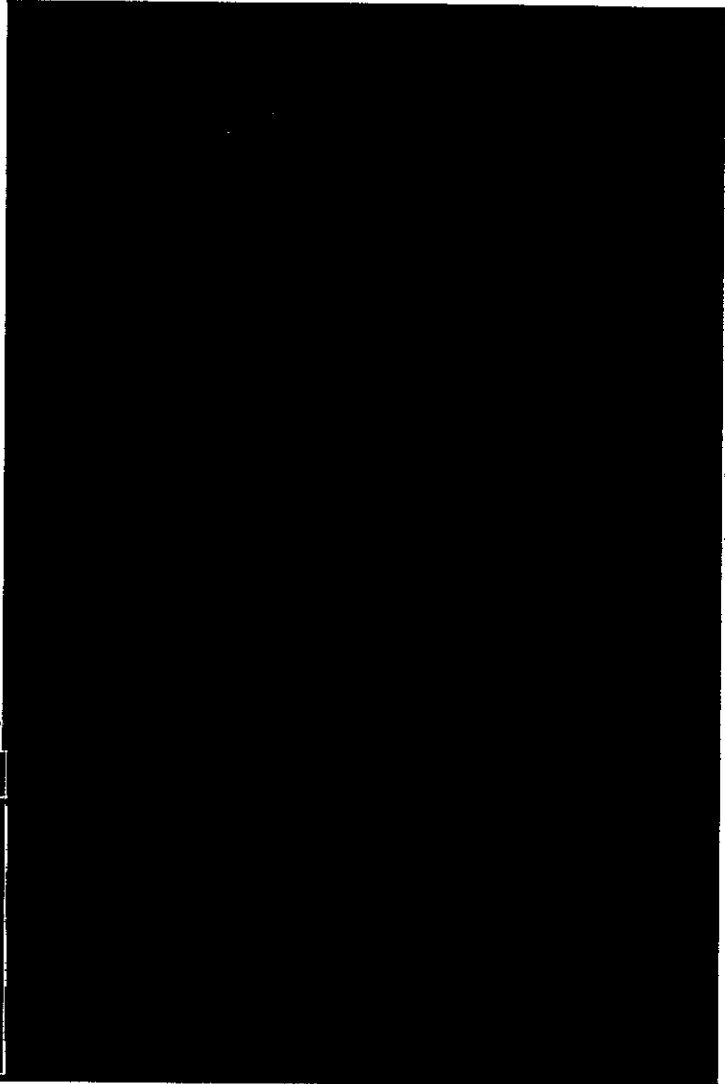
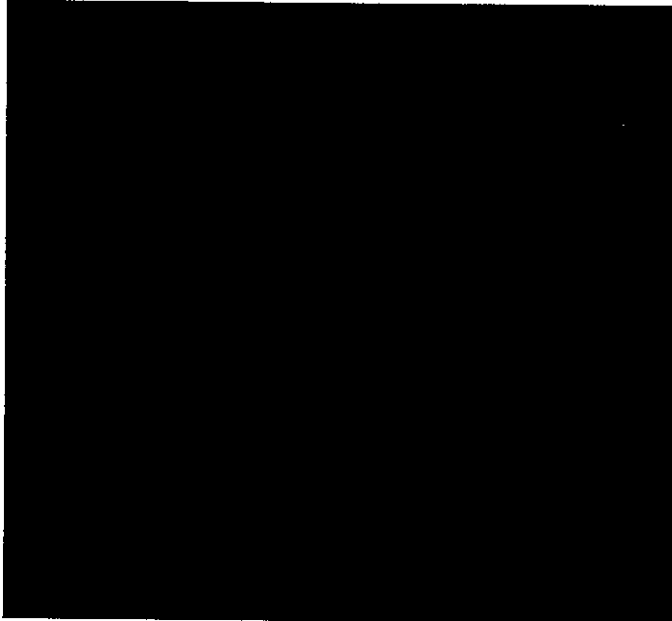


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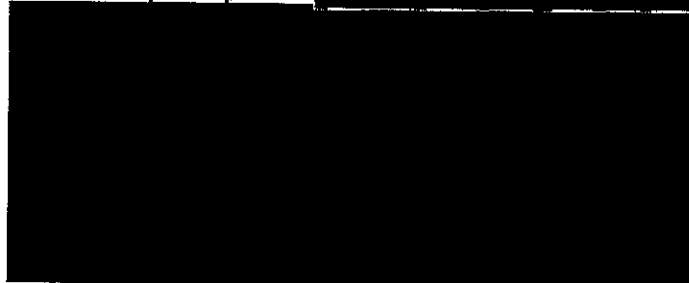
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APPENDIX A

Estimate of Cut and UF_6 Concentration at Valindaba



The cut is defined as the ratio of the enriched flow to the feed flow or, in this estimate, (1 percent of the enriched stream flow rate) / (sum of the enriched and depleted stream flow rates multiplied by the feed concentration of UF_6).



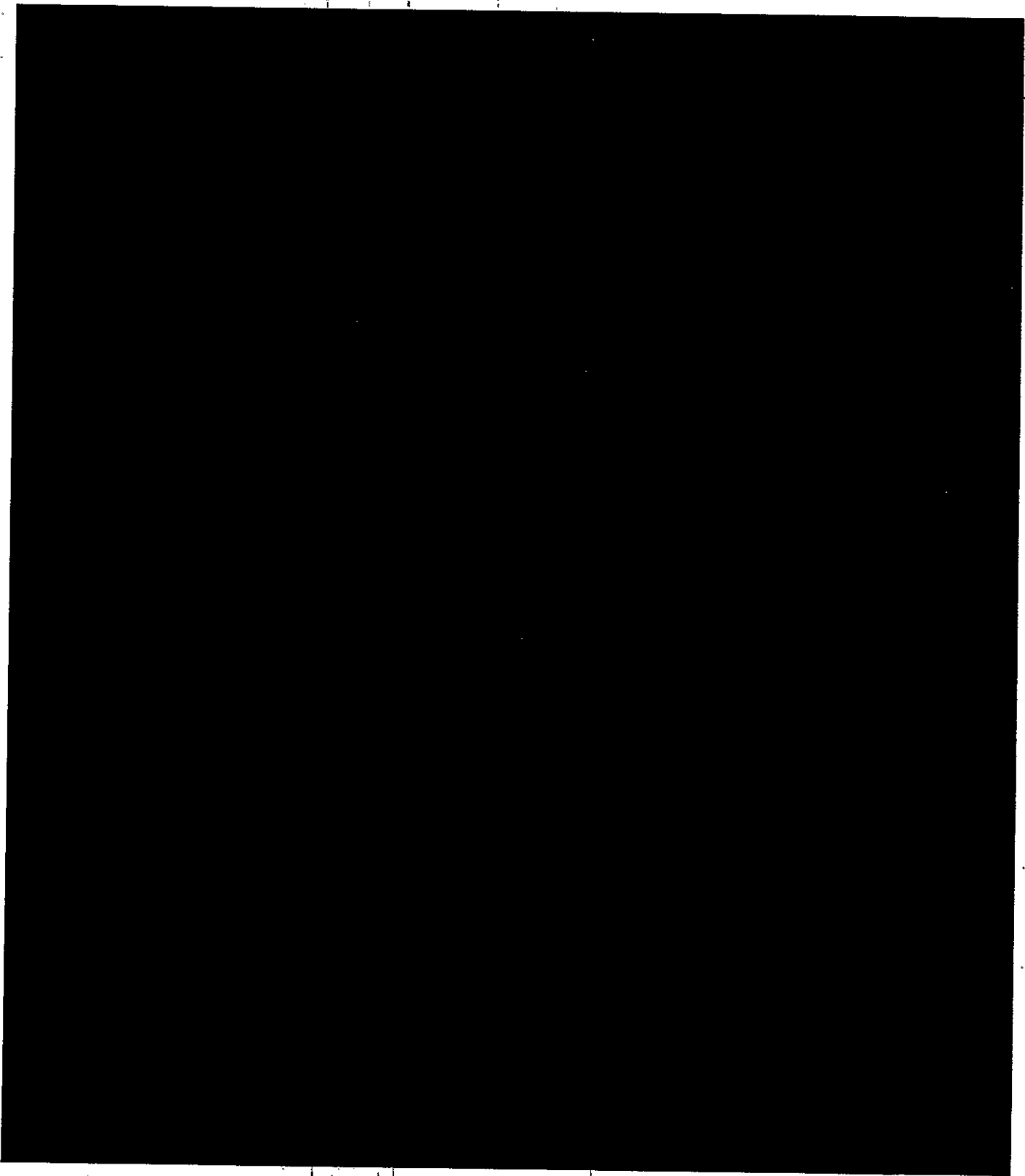
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~~SECRET~~**APPENDIX B****Discussion of Process Equipment at Valindaba**

Consideration of figures 6, 7, and 8 and other photographs published by South Africa led to the diagram shown in figure 11. Geometric relationships were altered to simplify the diagram. Small diameter piping, and vessels associated with only small diameter piping, have been ignored in the diagram. The components associated with small diameter

of the compressor probably refer to A. H. Pillman and Sons, a firm that apparently has provided parts for at least two sizes of reciprocating compressors.²⁰ A turnbuckle connecting the top of the compressor to the adjacent unit indicates the high-pressure side of the compressor, and hence the direction of gas flow through the compressor.

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