

PART V: CHAPTER 11

Achievements

1. Part 1: EMIS research and development at Tuwaitha

a-Original know-how target:

The decision was taken in Sept. 1981 to embark upon an EMIS R&D program at Tuwaitha. It was based upon the availability of the necessary programs for the computation of magnetic fields in two dimensions, the experimental work that had been conducted during the period from March 1975 to Dec. 1981 on ion sources for a linear accelerator and upon the available open literature on the subject. The goal was to achieve a theoretical understanding of electromagnetic design adequate to support the design, construction and operation of electromagnetic separators type $J1\sqrt{2}$. This was targeted to continue until Dec. 1991.

b-Original production target:

The original research and development work envisaged in 1982 was to build a double focusing isotope separator magnet of 40 cm central radius (R40) with the objective of constructing electromagnets and their necessary parts so as to ascertain the accuracy of the field computation. It also included the building of two other R40 magnets (Jan. 1985) with one ion source in each to test the performance of such a separator using UCl_4 as feed material.

The R&D work also included the construction of three R100 separators and one R50 separator (of central radius 100cm and 50cm respectively) with the objective of achieving the predicted current at the collector and enrichment, improvement of design of source and collector and establishing procedures of assembly, operation and recovery of feed material, product and waste.

c- Actual theoretical achievements:

The theoretical achievement of this work included:

Verification of the magnetic field design through actual measurements in Sept. 1984.

Establishment of operating conditions including arc characteristics, ion extraction, oven operation and separator process 1) parameters in Jan. 1986.

d-Actual production achievement:

In Jan. 1986 a mass spectrum of the extracted ions from the R40 separator showed clear separation of U-238 and U-235 ions for the first time, but no material was collected. These activities were carried out at Bldg.73. 1.

Several hundred runs were performed on the separator R 100-1 during the period October 1987- Dec. 1990. A maximum uranium enrichment of 13% was achieved in March 1990. By Jan.1991 an average current of U^+ ions of 120 mA was achieved at the collector.

Operation of the R100-2 separator gave a maximum enrichment of 8% with an average current of U^+ ions of 100 mA at the collector.

Operation of the R100-3 separator supplied adequate information about operating the separator with two ion sources, which included a ducting assembly in front of both sources and the use of space charge neutralisation plates above and below the ion source and collectors. This arrangement gave improved results.

Operation of the R-50 separator commenced in March 1987 with Argon ions. In December 1987 a maximum uranium enrichment to 15% was achieved. By Jan. 1991 an average current of U^+ of 40 mA was achieved.

During the period from May 1988 to Jan. 1991, milligram quantities of uranium were obtained in one of the operations having an enrichment of 40-45% using the R50 separator. In total 0.448 kg was produced with enrichment in the

range between (5 - 45)%.

e- Further steps to be implemented to achieve the original target:

The R&D at Tuwaitha was continued to optimize designs and operating conditions for the planned production plants. This included the introduction in April 1985 of open magnet design rather than the closed type. In 1987-1988 a multi-magnet system which was scaled down (1:5) version of the production system was installed. This unit allowed an investigation of magnetic forces and flux density distribution. Furthermore, the design and erection of a multi-source unit similar to those envisaged for the production phase was completed and tested with UCl_4 in Bldg. 80 at Tuwaitha between May 1987 and June 1990.

f- Indigenous production of critical components and equipment:

The indigenous production included the following:

Magnets: Design of the magnets was performed by the physics, mechanical and electrical design groups at Tuwaitha. Three magnets of the R40, one of R50, and three of the R100 types were assembled in Bldg. 80 and 73.1 at Tuwaitha. The iron pieces of the magnets (including poles and return iron) were fabricated at Bader General Establishment (BGE). The magnet coils were fabricated at the General Establishment for Electrical Industries (GEEI) and at Tuwaitha.

The vacuum system for the R40, R 100 and R50 separators: All the required components of the systems including the liners and the conical walls were fabricated at Tuwaitha, BGE and Oqba Bin Nafi General Establishment (OGE). The vacuum pumps and components such as gauges and valves were imported. This was completed in 1987.

Ion source systems: Two ion sources for the R40 separators, four ion source systems for the three R100 separators, and one ion source system for the R50 were

fabricated. Two of the R100 separators had a single source while the third had a double source. The R40 and R50 had a single source. At the early stages a PIG type ion source was chosen. However, by Dec. 1987 a decision was taken to adopt a calutron type (directly heated) ion source. An extraction slit width of 10 mm was the preferred choice. The ion sources were fabricated at Tuwaitha (Bldg. 17). Seven ion sources were produced.

Collector systems: The collector systems for the R100 and R50 separators were fabricated in Iraq using imported materials. They consisted of two 1) pockets and a front plate pocket face of crescent shape. They were electrically isolated from each other. One of the pockets was for the collection of enriched uranium, the second was for the collection of the depleted uranium. Double identical collectors were used in the third R100 separator to accommodate the beams of the two ion sources. Four collector systems were fabricated at Tuwaitha (Bldg. 17).

Power supplies: Power supplies for the operations of R40, R100 and R50 separators were imported. The Faraday cage and the platforms that were insulated from ground and kept at high voltage potential up to +35 kV were designed, fabricated and assembled indigenously at Tuwaitha site (Bldgs. 82, 17). The total quantity produced was 6.

Remote control and data acquisition units: Separator operating parameters were set and controlled through an indigenously built operator console. This allowed assessment of different feedback strategies for power supplies and ovens.

g- Assessed time to achieve target:

The R&D work achieved its major objectives prior to the start of operation of the Tarmiya separators in Feb. 1990. The operation of the separators would have continued until the operation of Tarmiya plant reached its design parameters.

h- Assessed maximum achievable production:

The R&D work was continued to obtain the design parameters of ion current and enrichment. The average ion current continued to increase as the R&D work progressed and eventually exceeded the design value, while the enrichment did not. That required more R&D work.

i- Explanatory notes related to any of the above elements:

The nature of this work was R&D to optimize designs of various system components and to achieve optimal operation parameters to meet design values.

j- FFCD ref.:

Part I section 1 .2.2A, Part IIb Section 4. 1 .3-4. 1 .6.

2. EMIS-Production at Tarmiya and Al-Sharqat

a- Original know-how target

In May 1985 a new approach was proposed with regard to the design of the separator magnets to be of the open type ($\text{JI}\sqrt{2}$ double focusing). Experience gained during the R&D phase at Tuwaitha on the scaled down (1:5) version of the R120 (central radius 120cm) provided the needed know-how. The construction of the Tarmiya buildings started in Dec. 1987 after completion of the design. A decision was taken in Dec. 1987 to build replica of Tarmiya at Al-Sharqat for two purposes: to replace Tarmiya if the latter were rendered completely non-operative, to double the production capacity. The R120 separators initially installed at Tarmiya were to be used to conduct experiments concerning the assembly, operational procedures, electrode configuration, focusing and collection of ions to gain additional known-how.

b- Original production target

The Tarmiya plant was to accommodate seventy identical separators of the

R120 type arranged in two lines. Each line of 35 separators would have 34 double-pole pieces and 2 single pole pieces. Tarmiya would also have twenty R60 (central radius 60cm) separators in two lines, each line was to have 10 separators and to be completed in two steps of 5 units each.

In Sept. 1987 the plan for production, installation, operation and material flow for the Tarmiya was adopted. It was continuously modified to take into account the fabrication capabilities.

The final plan for the installation of the 70 R120 separators at Tarmiya was as follows:

Line	No. of Separator To Be Installed	Start Up on The First Separator	Start Up of The Last Separator
Line 1	7	1/11/1989	15/02/1990
Line2	17	15/03/1990	01/12/1990
Line 1	10	01/01/1991	01/06/1991
Line 2	18	01/07/1991	01/04/1992
Line 1	18	01/05/1992	01/02/1993

Installation of first phase of the R60 separators of 5 units would start on 1/10/1990 and that of the fourth phase of 5 separators on 1 5/3/1992.

The system at the design parameters would produce about 15 Kg U/year of 93% enrichment from natural uranium feed. The design values of the R120 separator were 150 mA collection current of U^+ per source with an enrichment of 18%. The corresponding values for the R60 separator were 50 mA per source and the enrichment of 93 % The R120 and R60 separators would have four and two ion sources respectively.

Construction at the Al-Sharqat site started in Feb.). 1988 and the buildings (main process, substations (132 kV/11 kV and 11 kV/0.4 kV), chemical laboratory, mechanical rooms for air handling, main utility block and restaurant) were not fully completed by Jan. 1991. No processing equipment of any sort was installed at this site. Some equipment for the uranium recovery units were purchased in the quantities required for both Tarmiya and Al-Sharqat.

c- Actual theoretical achievement

Verification of the magnetic field accuracy in open magnets of the series configuration was achieved by designing and installing a special field-measuring instrument to scan the good field region. Field measurement performed in Jan. 1990 showed that the actual magnetic field agreed with the design values to better than 0.1%.

Better understanding of the operation of four arcs sources and the associated problems, such as the effect of electron drain current on the system stability and power requirement, led to the construction of special baffles that improved stability and minimized damage to the liners and insulators.

d-Actual production achievements

In Feb. 1990 the first R120 separator of the first line began operation. It was decided that eight separators rather than seven would be initially installed in line 1. The eighth separator began operation in Sept. 1990. Research work utilizing the installed eight R120 separators focused on 3 objectives: the integration of the various systems of operation increasing the production rate of enriched uranium and improving the availability of the separators.

In July 1990 work started on installing 17 separators of the second R120 line, but only 3 of the 18 double poles had been installed by Jan. 1991. In Nov. 1990 preparation commenced for installing. The R60 separators but none of these

had been installed by Jan. 1991.

Despite the R&D nature of operation, 0.685 kg of uranium of 4% average enrichment was produced by Dec. 1990. The highest enrichment obtained was 9.5%.

The average monthly quantitative performance of the eight separators, achieved over the last three months of operation was 16% of the design separative work. The average availability of the separators was 10%.

e- Further steps to be implemented to achieve the original target:

- First, completing the installation, testing and commissioning as planned.
- Second, to increase the efficiency of the utilization of useful field volume and to make the associated operations easier, modification of the design of the R120 was to include increasing the gap height at the central radius and increasing the distance between the adjacent separators.
- Third, to increase the availability would require improvement of the stability of operation and minimizing the service time.

f- Indigenous production of critical components and equipment

• **The magnets:**

The iron part of the magnets including the double poles, end poles and return iron was designed and fabricated in Iraq to meet the requirements for installing two separators per month. Initially imported soft iron was used. During 1986 the establishment of a foundry at Naser General Establishment (NGE) was initiated and operated in October 1988. Actual production commenced in June 1990. The foundry could produce castings to meet the requirements of the magnet production for both Tarmiya and Sharqat.

Magnet coils were designed and fabricated at Tuwaittha using imported O₂-

free Cu conductor.

- **The vacuum system:**

Vacuum pumps and components, such as valves and gauges were imported.

The vacuum chambers and liners were designed and fabricated in Iraq at Oqba Bin Nafi General Establishment (OGE) and General Establishment for Heavy Engineering Equipment (GEBEE) using imported stainless steel.

- **Ion Sources**

The required ion sources were designed at the Engineering Design Group of PC-3 in Tuwaitha and fabricated at OGE. Materials of construction such as graphite, stainless steel, and insulators were imported.

Eight complete systems (32 ion sources) for R120 were operational during 1990 and one complete system (4 ion sources) were available as spares. Six systems (12 ion sources) for the R60 were fabricated, but were not assembled.

- **Collector systems:**

Each collector system for the R120 separator consisted of four pockets for the enriched ion beam and another four for the depleted ion beam. The face of each pocket was of crescent shape to accommodate the actual beam profile

Each collector system for the R60 separator consisted of two pockets for the enriched and another two for the depleted ion beams.

The collectors were designed and fabricated in Iraq at OGE except for a few mechanical components, such as insulators and flexible hose bellows, that were imported.

Eight collector systems for R120 separators were operational during 1990, and six collector systems for R60 were fabricated but were not commissioned. No additional systems were fabricated.

- **Power Supplies**

The power supplies were to be assembled at Dijjla site according to the planned requirements of the separator operations. The specifications and definition of requirements were based on the know-how acquired at Tuwaitha. All critical components and equipment were imported.

- **Data acquisition and control systems**

The decision to apply large scale computerized acquisition and control system for the Tarmiya projects were started Jan. 1986. The complete specifications and definition of requirements of the system were completed in Dec. 1987 based upon the experience gained from the R&D work at Tuwaitha. Data acquisition and control units were planned to be installed parallel to the installation of the separators, and based on the idea that each separator is controlled modularly by its assigned unit. In July 1989 the design and implementation details of the units were completed.

Eight units were fabricated and assembled. The first unit was completed and installed in Jan 1990 and by Sept. 1990 the eight units were in operation.

The production facility at Dijjla was capable of producing the units according to the planned schedule. All elements and fibre optic components were imported. Printed circuit boards were designed and manufactured at Dijjla. Control software was designed, written and tested by Iraqi personnel at Tuwaitha and Tarmiya sites.

- g- Assessed time to achieve target:**

It was estimated that the Tarmiya plant would achieve its original target about one year from completion of the installation of the plant in Feb. 1993. There was no definite plan for completing the Al-Sharqat site, but work would shift to Al-Sharqat as soon the installation of units at Tarmiya was complete.

h- Assessed maximum achievable production:

It was estimated that LEU feed material of 3% would increase the amount of BEU product by a factor 4. The enrichment of the product would also increase to 98%.

i- Explanatory notes related to any of the above elements:

None.

j- FFCD Ref.:

Part I Section 1.2.2 A, Part IIb Section 4. 1,7-4. 1 .9

3. Production of feed material for EMIS /UCl₄ production at Tuwaitha

a-Original know-how target:

UCl₄ was selected to be the feed material for EMIS and a decision was taken in Jan. 1982 to initiate a program to prepare and purify UCl₄ on a laboratory scale in order to provide design data for a pilot plant. The work included the following:

Laboratory work using glassware with a handling capacity of less than 100 gm per batch. This work continued in parallel with other activities up to Dec. 1987.

Pilot production at a rate of 1 kg/batch using a fluidized bed technique started in March 1986 and terminated in Dec. 1987.

Pilot production at a rate of 25 kg/day started in Jan. 1988 and continued up to Jan. 1991.

Sublimation units of up to 1 kg UCl₄/ batch started June 1987 and continued up to Jan. 1991.

Pilot experiments to produce UCl₄ by a liquid phase reaction were conducted in April 1989 and terminated in Jan. 1991.

b-Original production target:

During the initial stages of EMIS R&D work at Tuwaitha, the production target was set to meet the immediate separator feed requirements. However, as work progressed a target of 25 kg/day was planned which was considered to be sufficient for the R&D work.

c- Actual theoretical achievement:

The laboratory work led to a better understanding of production, handling and purification of UCl_4 .

d-Actual production achievement:

A pilot plant with a maximum operational capacity of 40 kg/day and a nominal capacity of 25 kg/day based upon a rotary kiln technique, was designed and assembled in Bldg. 85. Commissioning of the plant was in Jan. 1988 and it continued production during 1988 - 1990 with a total production of approximately 4.27 tons of UCl_4 .

Six sublimation units were fabricated and installed in Bldg.85 for the production of pure UCl_4 to fill the charge bottles for the EM IS separators. A total quantity of about 1.1 tons of sublimed UCl_4 was produced from the impure UCl_4 prepared.

Three pilot units with design capacities of 1 kg/ batch were designed, fabricated and assembled at Bldg. 85 during the period Nov. 1988 to Dec. 1989 based on liquid phase chlorination. Three similar units based on gas phase chlorination, one of them using a rotary kiln and the other two using a fluidized bed reactor, were also designed, fabricated, and assembled at Bldg. 80 in this period.

The objective was to test other technologies for the preparation of small quantities of UCl_4 . Some of these proved unsatisfactory and were terminated, while

the liquid phase chlorination of UO_3 using CCl_4 proved useful and was to be adopted for the preparation of enriched UCl_4 .

e- Further steps to be implemented to achieve the original target:

The pilot plant (25kg/ day) achieved its original target during July 1988. No further steps were required.

f- Indigenous production of critical components and equipment:

The critical equipment for UCl_4 production (such as the rotary kiln reactor and the vacuum pump that was used for sublimation) were imported. The vacuum chamber for sublimation and its internals and various tanks were fabricated at the Tuwaitha workshops.

g- Assessed time to achieve the original target:

The target was achieved and even exceeded during 1988.

h- Assessed maximum achievable production:

The process operated on a continuous basis for periods extending from few days to few weeks. In some runs its production capacity exceeded the design capacity and reached about 40 kg/day due to variation in the operating conditions such as the residence time. This plant was not designed as a production plant, but it could have reached a production rate of 25 kg/day.

i- Explanatory notes related to any of the above elements:

During the EMIS development program, the feed material quality and quantity satisfied all the program requirements and at no time did it hamper program development.

j- FFCD Ref.

Part ha Section 4.2.2.

4. Yellow - cake production at Al-Qaim

a. Original know-how target:

A chemical complex was established at al-Qaim to produce one million tons of phosphate fertilizer per annum. The design of the unit was based on the Prayon process. Construction of the complex started in 1979 and was commissioned during 1983 - 1984. The uranium content of the phosphoric acid was to be extracted in the form of uranium peroxide UO_4 (yellow cake). The contract for the unit was issued in May 1981 by the Iraqi Ministry of Industry and Minerals to a Belgian company called Mebsbem.

b. Original production target:

The design capacity of the unit was 103 ton U/annum on the assumption of 60 ppm U in the ore and 75 ppm U in the low concentration phosphoric acid yield. It was planned to start production in Dec. 1984.

c. Actual theoretical achievement:

The flow sheet of the unit 340 uranium extraction process was made available by the Mebsbem contracting company. The process consisted of four sections as follows:

- Acid clean up, to make the phosphoric acid feed amenable to solvent extraction.
- Cycle I- Producing U concentrated phosphoric acid solution by solvent extraction.
- Cycle II-producing a partially purified U solution by solvent extraction.
- Refinery - producing a U solid concentrate.

d. Actual production achievement:

The plant (unit 340) was erected and commissioned by the Belgian company in Sept. 1984 and went into production in Jan. 1985. The total quantity produced

was 168 tons of yellow cake extending over the period Jan. 1985 to July 1990.

e. Further steps to be implemented to achieve the original target:

No further steps could be implemented to achieve the design productivity of the unit since the actual content of U in the phosphoric acid, was low, 45-75 ppm and the phosphoric acid produced in the fertilizer complex was often not passed to unit 340 so as to maximize fertilizer production.

f. Indigenous production of critical components and equipment:

None.

g. Assessed time to achieve original target:

Although the design production capacity was not achieved due to the intermittent operation of the unit, it was more than adequate to meet foreseeable needs, and no optimization was planned.

h. Assessed maximum achievable production:

The design basis maximum achievable production was 158 tons/ year of yellow-cake, but due to lower than expected U concentration in the feed material, the maximum achievable production would have been between 95 and 158 tons/ year.

i. Explanatory notes related to any of the above elements:

None.

j. FFCD Ref.:

Addendum II Part 1 C2/7 pp. 24-30, Part IV 8.2.1.

5. Production of Feed Material /Production of Pure UO_2 from UO_4 at A1-Jazira

a- Original know-how target:

The plant was originally designed for the production of nuclear grade UO_2

by Natron Company (Brazil) during the period 1981-1983. An attempt was made during 1983 by Iraqi personnel to design and build a smaller plant of 103 tons/year capacity. However, due to the lack of experience and the process complexity, a decision was made in Nov. 1983 to adopt the Natron design whose construction was completed over the period 1984- 1986. Meanwhile, a site for the plant was selected near Badoosh area north of Mosul, and a new site plan was adopted to meet the requirements of the chosen site that was named Al-Jazira on March 1989.

b-Original production target:

The plant was designed to produce 185 tons/ year of pure UO_2 starting from yellow cake (UO_4) of different physical forms in order to produce feed material (UCl_4) for the EMIS plants, when the R120 separators at Tarmiya are fully operational in Dec. 1993 and those at Al-Sharqat by Dec. 1996. No other requirement for UO_2 was taken into consideration at the time.

c- Actual theoretical achievement:

The design documents received from Natron in 1986 were revised by the Iraqi team to comply with the requirements imposed by the new site and to suit the specifications of the equipment procured from various suppliers. This was completed in July 1987.

d- Actual production achievement:

The plant was erected during the period 1987-1989. It was commissioned during June 1989, started-up and operated during July 1989 to Dec. 1990. During this time 100 tons of pure UO_2 was produced. Many problems were encountered in the course of start-up and commissioning which reduced the production capacity. The mechanical failure of two major vibratory elevators and the high wear rate of stators of monopumps were overcome by introducing modifications.

e- Further steps to be implemented to achieve the original target:

The escape of very fine particles with filtered liquid from the filter cloth of the rotary vacuum filters needed improvement to minimize uranium content in the liquid concrete waste tanks that had already accumulated about 10 tons from previous operation.

f- Indigenous production of critical components and equipment:

Construction of the buildings, installation of the equipment and operation of the plant were performed indigenously by the specialized groups of PC-3. Critical process equipment, such as rotary furnaces were imported.

g- Assessed time to achieve original target:

After start-up and treatment of related problems during the period July 1989 to Dec. 1989, it was estimated that 12 months would be needed to achieve the production target starting from Jan. 1990. However, this was not achieved by Jan. 1991 and a further six months would be required to achieve the original target.

h- Assessed maximum production achievement:

The plant was designed to produce 185 tons/ year of pure UO_2 . This was considered to be the maximum achievable production.

i- Explanatory notes related to any of the above elements:

The plant output exceeded the EM IS program requirements at the time of operation in July 1989. Nevertheless, it was decided to process all the available UO_4 (yellow cake) (Al-Qaim, Niger and Portugal). This would provide enough UO_2 for the production of the required UCl_4 for the R120 separators for several years. The recovered natural uranium from these separators would be reconverted to UO_2 .

j- FFCD Reference:

Part: II, Section: 4.2.1, Page: 129/269

6. Production of feed material for EMIS / UCl_4 production at Al-Jazira

a- Original know-how target:

Based on the experience gathered from the R&D work at Tuwaitha, it was decided in Sept. 1987 to design and construct a UCl_4 production plant at Al-Jazira site (chlorination of pure UO_2 using CCl_4) in a continuous process adopting the rotary kiln technique. March 1989 was the target date to complete the plant design and Jan. 1990 was the target date for commissioning. The UCl_4 produced would be purified by vacuum sublimation using a number of units to be designed in accordance with the experience gained at the Tuwaitha pilot plants.

b- Original production target:

The plant was designed to produce 105 ton/ year of UCl_4 in two production lines starting in Jan. 1990. The product was to be further purified by sublimation in a number of units on a batch basis, in order to feed the EMIS production separators. The uppermost requirement of each R120 separator is 1.7 kg/day of purified UCl_4 (assuming feed rate of 490 gm U/source/day and a design availability of the separator of 55%). Consequently, the uppermost total requirement of the R120 separators planned for Tarmiya and Sharqat plants is about 70 ton/year of purified UCl_4 (assuming a total of 140 separators and about 300 working days/ year) The unpurified UCl_4 required is about 100 ton/ year assuming a sublimation efficiency of 70%.

c- Actual theoretical achievement:

In March 1989 the design took into consideration all problems encountered during the operation of the pilot plant, project 242, at Tuwaitha and introduced improved techniques for handling the feed material and product.

d- Actual production achievement:

The equipment installation was completed in Dec. 1989. After performing all required tests over the period Dec. 1989 to Feb. 1990, one of UCl_4 production lines was put into operation while the other line was still under construction.

Some problems in the flow of the solid material and off gases were experienced. Many trials to optimize operating conditions for high conversion ($> 97\% \text{UO}_2$ to UCl_4) were conducted and continuous operation for more than 72 hours with the required product specifications was achieved in Feb. 1990. During all operations a total of 1200 kg of UCl_4 was produced. However, production was stopped, because the need for UCl_4 could still be met by the Tuwaitha pilot plant.

e- Further steps to be implemented to achieve the original target:

Modification of some equipment that was problematic during the start-up phase of the first production line in addition to other modifications to suit the operation requirements were to be introduced. The second production line and the construction and operation of UCl_4 purification units were still incomplete by Jan. 1991.

f- Indigenous production of critical components and equipment:

The sublimation units were being produced at Tuwaitha. Other critical components such as rotary furnaces were imported. Installation, commissioning and operation were conducted by PC-3 personnel.

g- Assessed time to achieve original target:

It was estimated in Jan. 1991 that 12 months would be needed to achieve the plant design parameters.

h- Assessed maximum achievable production:

The plant was designed to produce 105 tons of pure UCl_4 a year. This was considered to be the maximum achievable production.

i- Explanatory notes related to any of the above elements:

None

j- FFCD Ref.:

Part IIa4.2.1 Page 182/269

7. EMIS - Uranium recovery at Tuwaitha

a- Original know-how target:

An R&D program for the chemical recovery of uranium from various internal parts of separators commenced at Tuwaitha in June 1984 and continued in parallel with the design and construction of the relevant pilot scale plant at Tuwaitha and the production scale recovery at Tarmiya. This work included the following:

Laboratory scale activities started in June 1984 and continued in parallel with other activities up to Jan. 1991.

Pilot plant recovery of natural uranium from various parts of separators operating at Tuwaitha Bldg. 85 started in Sept. 1988 and continued until Jan. 1991.

Pilot plant recovery of enriched uranium from the graphite collectors of separators operating at Tuwaitha Bldg. 85 started in Jan. 1989 and was abandoned in Jan. 1991

b- Original Production targets:

Laboratory and pilot scale recovery of uranium from parts of separators was to meet all the operation requirements of the R100 and R50 separators at Tuwaitha until Jan. 1991.

c- Actual theoretical achievement:

By Dec. 1988 all the theoretical aspects of uranium recovery from various internal separators parts were adequately understood utilizing open literature and the results of laboratory and pilot scale experiments.

d- Actual production achievement:

Throughout the period of work extending from June 1987 to Jan. 1991 about 380kg of natural uranium was recovered from the UCl_4 deposited on the various parts of R100 and R50 separators. This was recovered either manually or by dissolution in laboratory scale equipment or in the pilot scale recovery plant installed at Tuwaitha. During the same period about 0.64 kg of enriched uranium was recovered from the collectors utilizing laboratory methods and equipment. Likewise, about 6.4 kg of depleted uranium was recovered in the same manner.

e- Further steps to be implemented to achieve the original target:

No further steps were found to be necessary.

f- Indigenous production of critical components and equipment:

Most of the components of the pilot plant were fabricated by the mechanical workshop at Tuwaitha.

g- Assessed time to achieve original target:

The original target was met in Jan. 1991.

The recovery facilities met all the requirements of the R&D separators operating at Tuwaitha throughout the period of their operation.

h- Assessed maximum achievable production:

The facilities available were capable of recovering all the uranium feed product or waste to the required efficiency.

i- Explanatory notes related to any of the above elements:

None

j- FFCD Ref.:

Section 4.2.3 and Fig. (8.5-1)

8. EMIS - Uranium Recovery at Tarmiya

a- Original know-how target:

The R&D program for the chemical recovery of uranium from various internal parts of EMIS separators at Tuwaitha started in June 1984 and continued in parallel with the operation of the separators at Tuwaitha provided the know-how for the Tarmiya recovery plant.

b- Original production target:

Recovery of uranium from internal parts of liners and from pockets of the R120 and R60 separators and as follows assuming 100% recovery

- From the R120 separators:
 - 55 kg/ year of enriched U (18%) from product pockets
 - 1400 kg/ year of depleted U from waste pockets
 - 2 1 tons U/year of natural uranium from liners.
- From the R60 separators:
 - 11 kg/year of enriched U (93%) from product pockets
 - 44 kg/year of depleted U from waste pockets
 - 550 kg U/year of 180% enriched from liners.

c- Actual theoretical achievement:

By Dec. 1988 all the theoretical aspects of uranium recovery from EMIS separators were adequately understood from the practical recovery work at Tuwaitha. The information acquired was adequate for the detailed design and construction of the production scale plant at Tarmiya.

d-Actual production achievement:

By Jan. 1991 none of the recovery buildings had all their equipment installed, therefore, no actual recovery of uranium on a production scale at

Tarmiya was achieved before termination of the program. However, a temporary recovery unit was installed in Jan. 1990 at Tarmiya Bldg. 62 to provide washing and cleaning services for the eight R-120 separators that were being commissioned at Tarmiya during 1990. Out of 280 kg natural U as UCl_4 that was handled during operation of R120 separators at Tarmiya in 1990, a total of 267 kg U was recovered as liner wash. The remaining 13-kg of uranium were recovered as enriched U (0.685 kg), depleted U (2.9 kg) and natural U (9.4 kg).

e- Further steps to be implemented to achieve the original target:

To achieve uranium recovery on a production scale it was necessary to complete fabrication of the equipment locally and then to complete their actual on-site installation.

f- Indigenous production of critical components and equipment:

Washing chambers (for liners) and leaching tanks (for collectors) were under fabrication at Al- Rabee factory by Jan, 1991. Other equipment were imported

g- Assessed time to achieve original target:

The installation and commissioning of the recovery plant would have been completed by June 1992.

h- Assessed maximum achievable production:

After commissioning, the capacity of the recovery plant would have been sufficient for the 70 R- 120 and for the 20 R-60 separators that were planned for Tarmiya as described at (b) above.

i- Explanatory notes related to any of the above elements:

None

j- FFCD Ref.:

Section 4.2.3, Table (4.1. 10-6).

PART II: Centrifuge Enrichment And Gaseous Diffusion

1. Gaseous Diffusion Barrier Development And Laboratory Scale Production

a. Original know-how target:

In June 1982 it was decided to develop a suitable barrier for the gaseous diffusion (GD) process for the enrichment of uranium with natural UT_6 as feed. The original know-how target was to comprehend the physical processes associated with molecular flow of UF_6 across the diffusion barrier as a function of upstream and downstream pressure including the effect of capillary condensation and its dependence on pore size. It was estimated that the open literature survey and various laboratory experimental set-up could be concluded by Dec. 1984. Based on this know-how, a laboratory-scale production line would be set-up to produce barrier tubes for GD R&D work by Dec. 1985.

b. Original production target:

To achieve an adequate understanding of the method of producing an adequate GD barrier tube and to set-up a laboratory-scale production line for good quality tubes at a rate of 10 m/day by Dec. 1985.

c. Actual theoretical achievement:

An adequate understanding of the flow of UF_6 through porous media was achieved by Dec. 1984. The following studies were completed: -

- Gas flow behavior through and along porous tube wall.
- Characteristic pressure calculations for a porous tube.
- Study of flow through porous barriers.
- Study of the effect of adsorption inside pores.

d. Actual production achievement:

The following was achieved: -

- An R&D laboratory for flow measurements and characterization of GD

barriers was setup in Bldg. 23 in Tuwaitha in Jan. 1984.

- Mechanical and structural characterization of GD barriers were made in Bldgs. 23 and 73 at Tuwaitha in Jan. 1984.
- A suitable anodized aluminum barrier tube for inert gas separation was developed and tested by Dec. 1984.
- A laboratory-scale production line for approximately 10 m/day of inert gas barrier tubes was implemented in Bldg. 23, in Tuwaitha by Dec. 1986. About 600 tubes were produced (60 cm long 10 mm i.d.) for project 301 by April 1987.
- Corrosion rigs for testing GD barriers with corrosive fluids (HF, F₂ and UF₆) were built in Bldg. 15 B in Tuwaitha in period Jan. 1986 - Dec. 1987. In April 1988 a UF₆ corrosion rig was operated in Bldg. 10 (Hall C) in Rashdiya.
- In Sept. 1988 a dynamic corrosion rig for testing four barrier tubes with a single stage diffuser of four tubes of 2.4 m was built in Bldg. 10 (Hall C) in Rashdiya.
- The barrier tube developed for the GD process with UF₆ showed good flow stability for a period of about four months, and a separation factor of 1.002 & 1.003 was achieved in Oct. 1989.

e. Further steps to be implemented to achieve the original target: (see 4.a)

None. In Aug. 1987 the decision to start a centrifuge enrichment program was taken. At the same time it was decided to continue the gaseous diffusion program to the stage of testing the diffusion barrier as a hedge against unforeseen problems with centrifuge enrichment. Therefore, the GD program was stopped in Oct. 1989.

f. Indigenous production of critical components and equipment:

All process specific components, such as barriers, diffusers and cold traps, were fabricated locally at Rashdiya workshop section Bldg. 9 and Bldg. 10 hall C. General engineering materials, such as valves, pipes, pumps, compressor and instruments were imported.

g. Assessed time to achieve original target:

The original target was achieved in Oct. 1989.

h. Assessed maximum achievable production:

This was R&D work no production goal set.

i. Explanatory notes related to any of the above elements:

None

j. FFCD Ref.:

Part IIb, Sec. 4.4 sub sec4.4.4 page 81-91/312

2. Design of a 24-Stage Gaseous Diffusion Cascade for Measurement of The Separation Factor

a. Original know-how target:

In Oct. 1988 a gaseous diffusion cascade was considered. Its aim was to measure the separation factor with UF_6 gas using a single barrier of 3 m long porous tube (5 barriers of 60 cm long) for each stage with 12 metallic diaphragm double bead compressors to be ordered from abroad.

b. Original production target:

The objective was to construct the cascade to measure the barrier separation efficiency with UF_6 gas.

c. Actual theoretical achievement

Since most of the theoretical aspects of gaseous diffusion cascade were

adequately understood by the assigned team, a basic design report for the cascade was issued in Feb. 1989 and the detailed design for the diffuser was completed.

d. Actual production achievement:

None.

e. Further steps to be implemented to achieve the original target:

Since the single diffuser gave a measurable separation factor, the activity of constructing the cascade was cancelled in Oct. 1989. At that time a decision was taken to drop the gaseous diffusion process in order to concentrate efforts on the magnetic centrifuge, as it was certain that magnetic centrifuge technology was more promising.

f. Indigenous production of critical components and equipment:

Engineering materials for construction were procured from abroad and some specific process related components were to be manufactured in Iraq at Rashdiya workshop section Bldg. 9 and Bldg. 10 hall C, such as barrier tubes, diffusers, cold traps, UF_6 handling cylinders, and UF_6 gas.

g. Assessed time to achieve original target:

N/A since the project was cancelled, see (i) below.

h. Assessed maximum achievable production:

None.

i. Explanatory notes related to any the above elements:

When the 24-stage GD cascade was conceived EDC did not believe that it is instrumentation could detect the separation factor of a single GD barrier. EDC found a MS capable of measuring the single barrier separation factor at the 1AEC. This made the cascade concept unnecessary and it was stopped.

j. FPCD Ref.:

PartIb, sec. 4.4, sub. Sec. 4.4.4 page (87/132). (93/132).

3. Production of UF₆

A- Laboratory scale preparation of UF₆ by direct fluorination

a-Original know-how target:

In Jan. 1985 a decision was taken to initiate work on the laboratory-scale UF₆ preparation to familiarize workers with the direct fluorination process. The available know-how in the literature was achieved.

b-Original production target:

None. This was R&D to solve problems associated with the preparation, capture, storage, handling and use of UF₆.

c- Actual theoretical achievement:

By Dec. 1987 enough experience was gained to judge that the original target was considered achieved.

d- Actual production achievement:

In June 1985 few grams of UF₆ were prepared for the first time in Bldg. 15 B at Tuwaitha. The experimentation continued until Dec. 1986. The acquired practical know-how was employed to establish a better laboratory-scale UF₆ preparation unit to produce small quantities of UF₆ (50 g/ batch nominal capacity) beginning Jan. 1986. F₂ gas for the laboratory-scale unit was supplied from imported cylinders, whereas UF₄ was prepared from available UO₂ [see explanatory notes below on sub-activities related to UF₆]. 3.63 kg of UF₆ was prepared using the laboratory-scale unit, in Bldg. 15 B at Tuwaitha, over the period Jan. 1986 to Dec. 1987. This quantity of UF₆ represents the accumulated sum of all the experimental runs output over that period. All items related to the laboratory-scale UF₆ preparation was transferred from Tuwaitha to Rashdiya in Dec. 1987.

After this date, Rashdiya became the only site where UF_6 was prepared until the termination of the program in Jan. 1991. At Rashdiya a second similar UF_6 preparation unit was assembled in Dec. 1988. A total of 6.187 kg UF_6 was prepared at Rashdiya over the period from June 1988 to Jan. 1991 utilizing these two units. Hence the total sum of UF_6 prepared at Tuwaitha Bldg. 15B from Jan. 1986 to Dec. 1987 and at Rashdiya from June 1988 to Jan. 1991 was 9.817 kg UF_6 .

e- Further steps to be implemented to achieve the original target:

No further steps were found to be necessary.

i- Indigenous production of critical components and equipment:

The laboratory-scale UF_6 preparation unit was assembled from available standard imported components and placed in a fume-hood. Standard UF_6 cylinders of the type 1S, 2S and 5A (the 5A cylinder served as a receptacle for UF_6), as well as cold-traps were locally fabricated at Tuwaitha in Bldg.16 and the rest at Rashdiya workshop section Bldg. 9 and utilized with these two units, no other types were indigenously produced [see part II section 4(f) bullet 4 (page 21/62)].

g- Assessed time to achieve target:

The target was achieved and UF_6 was made available for the R&D work on enrichment technologies.

h- Assessed maximum achievable production:

Not applicable due to the experimental nature of the laboratory-scale unit.

B. Pilot and/or production-scale UF_6 by direct fluorination

a- Original know-how target:

The decision to embark upon an indigenous UF_6 production was taken shortly after formation of the Office of Studies and Development (OSD) of the IAEC in Jan. 1982, because gaseous diffusion was one of the enrichment options

considered. By May 1984 there was sufficient know-how to embark upon the design of a 2 kg UF₆/ batch pilot unit employing fluid-bed reactor technique.

b- Original production target:

Originally it was envisaged that UF₆ production capability should match its requirement for the development of the gaseous diffusion program. However, no specific planned production goal or date was fixed at the time, pending the know-how development of both UF₆ production as well as gaseous diffusion. As for the centrifuge program, it was envisaged in June 1989 that by May 1994 a UF₆ production capability of 4 ton UF₆/ year should be available.

c- Actual theoretical achievement:

Studies utilizing the available literature on the production of UF₆ by direct fluorination of UF₄ were carried out during 1982- 1983.

d- Actual production achievement:

A project of 2 kg/batch producing UF₄ from UO₂, and/or UF₆ from UF₄ using fluid-bed reactor technique was designed and executed during May 1984 to May 1985 in Bldg. 15B at Tuwaitha, but was cancelled due to inherent conceptual design faults. Following this cancellation, the basic design of a 2 kg/ batch UF₆ project employing also the fluid-bed reactor technique was completed in Dec. 1986. Detailed engineering design work on the 2 kg/batch UF₆ project was completed by Dec. 1987. The quantities of UF₆ that were required by harrier qualification experiments were very small and could easily be produced by the laboratory-scale unit. Following GI formation, and the re-evaluation of the gaseous diffusion program, even lesser emphasis were put on any UF₆ pilot / production-scale project. Up to program termination in Jan. 1991 this pilot project was not executed.

After the formation of Group I (GI) in May 1987, a number of designs for

UF₆ production employing fluid-bed or flame-type reactor techniques in a continuous process mode were carried out over the period June 1987 to Dec. 1989, but none was executed due to the fact that the gas centrifuge program was still in its very early stages on the one hand and the gaseous diffusion program went through a re-evaluation, which resulted in its cancellation on the other hand.

Finally to cope with the progress of the centrifuge program and to meet possibly larger UF₆ requirements which could not be met with the laboratory-scale units, a pilot and/or production-scale unit was designed with a nominal rate of 1 kg UF₆/hr. This unit was at the beginning of the construction phase at Rashdiya at the time the program was terminated in Jan. 1991.

No UF₆ was ever produced on a pilot/ production-scale.

e- Further steps to be implemented to achieve the original target:

It was envisaged to put the 1 -kg UF₆/hr unit, after completion on a commissioning and/or pilot-mode for a period of less than 6 months intended for familiarization and/or modifications prior to putting the unit on a production-mode. During the commissioning/pilot phase, F₂ gas requirement for the unit would have been supplied from available imported F₂ cylinders, whereas the production phase, F₂ gas requirement would have been supplied from the 0.25 kg F₂ /hr unit which was going to be installed in Bldg.25 at Rashdiya [see explanatory notes below on sub-activities related to UF₆].

f- Indigenous production of critical components and equipment:

No component or equipment belonging to the 1-kg/hr UF₆ unit was produced at the time of the termination of the program in Jan. 1991.

g- Assessed time to achieve target:

It was envisaged that the 1 kg/ hr UF₆ unit would be completed and commissioned by Jan., 1992.

h- Assessed maximum achievable production:

Following mechanical completion of the 1 kg/hr UF₆ unit, assumed in Jan. 1992, it was envisaged to reach the nominal design capacity 1 kg/hr on a continuous basis within 6 months of that date, i.e. by June 1992.

i- Explanatory notes on achievements concerning sub-activities related to UF₆:

(1) UF₄:

(i) Laboratory-scale UF₄ preparation (for UF₆)

- UF₄ preparation know-how had to precede or be concomitant to that of UF₆
 - The wet and dry methods to convert UO₂ to UF₄ were investigated on a laboratory-scale during 1985-1986. The dry method employing refrigerant -12 (R-12) as a fluorinating agent utilizing a Pyrex rotary reactor was highly successful, being relatively trouble-free and producing a satisfactory product for UF₆ preparation.
- About 250 kg of UF₄ was produced from the R- 12 laboratory-scale Pyrex rotary reactor unit from May 1987 to Jan. 1991. Most of this quantity was produced during 1987, 1988 and 1989. Little or no. UF₄ was produced during 1990 and the first 17 days of 1991 when the program stopped. Preparation of this UF₄ was done at Tuwaitha, Bldg. 15 B.

(ii) Pilot/production-scale UF₄

- To cope with progress of the gas centrifuge program, basic designs by EDC department C at Rashdiya were issued in Dec. 1988 for 2 kg UF₄/ hr units employing R-12 or anhydrous HF (AHF). Neither design was executed due to UF₄ availability.
- A rotary kiln reactor was imported from the USA in 1989 to be utilized with the 2 kg UF₄/hr unit utilizing AHF, being the only envisaged critical item.

The present location of the rotary kiln reactor is GEMEJ (see FFCD part IIb table 4.4.9-2 page 233/313).

(2) F₂

(i) Laboratory-scale F₂ generation

- Due to possibility of unavailability of imported F₂ cylinders and/or relatively large amounts being required for UF₆ (production, development of indigenous F₂ generating capability were looked at as early as 1983.
- Theoretical aspects of F₂ generating cell were studied in 1983 and 1986. Experimental aspects were investigated from 1985 through a laboratory-scale unit, commissioned in June 1987, based on a Brazilian design of a laboratory-scale cell. The unit was installed at Tuwaittha, Bldg. 15 B, and generated 6.67 g F₂/hr from Jan. 1988 to Jan. 1991. The generated F₂ was immediately destroyed through scrubbing with KOH solution.

(ii) Pilot/production-scale F₂ generation

- In Jan. 1990, it was decided to implement a 0.25 kg F₂/hr unit design at Rashdiya Bldg. 25 in order to supply the production phase of the 1 kg UF₆/hr unit mentioned above. Implementation was halted in Jan. 1991
- The critical item for the 0.25 kg F₂/hr unit, namely the carbon anodes of the F₂ generating cell had arrived in Feb. 1990.

(3) Production of UF₆ (due to accelerated activities):

From Sept. 1990 technical discussions took place at EDC with the coordinator of PC-3 concerning the request to produce a quantity of UF₆ using enriched UF₄ (56-80%). The discussions resulted in adopting a plan to use both the existing laboratory scale direct fluorination units in Hall C at Rashdiya and to assemble a third unit to reach a production capacity of 0.5 kg of UF₆ per day. This product was to be collected in (2S) cylinders and handed over to the EDC

separation process department for further enrichment. The enriched product was to be handed back to PC-3.

No work was conducted since as no enriched UF_4 ever received. The third laboratory scale UF_6 production unit was never assembled because none of its components were completed.

Ref. for UF_6 parts A and B as well as Explanatory notes (1) and (2) above: FFCD-F Part IIb Section 4.4.6 Ref for Explanatory note (3) above: FFCD-F Part IIIb Section 5.11.3 G

4. Centrifuge enrichment program

a- Original know-how target:

The centrifuge program know-how goals included:

- Understanding the science and the engineering required to design and manufacture subcritical high-speed centrifuges.
- Understanding the science and the engineering required to design and build centrifuge cascade.

The decision to embark on centrifuge enrichment program was taken in Aug. 1987, as the gaseous diffusion proved to be a formidable task and beyond the existing Iraqi capabilities at the time, due to enormous size and numbers of equipment. The decision was also to continue with the gaseous diffusion up to the stage of testing the performance of the anodic barrier.

b- Original production target:

The aim was to design and install a cascade of a 1000 subcritical machine capable of producing 10 kg/year of HEU by Dec. 1994 with natural uranium feed (UF_6).

• HEU Production

The centrifuge program production goal was 10 kg/year of BEU enriched to

93%.

- **Oil bearing centrifuge (see 5 for details)**

The initial goal program was to use oil bearing (Beams) centrifuges rated at about 0.5 kg SWU per machine in a cascade of 4000 machines. The cascade was to be located at Taji. The work on oil-bearing centrifuge began in Sept. 1987 and was expected to have a working prototype in Sept. 1989.

- **Magnetic centrifuge (see 6 for details)**

Since the oil centrifuge program presented numerous technological difficulties, where it was decided to abandon it in favor of the magnetic centrifuge as foreign assistance was available for the latter. The program began in June 1988 and a target was set to arrive at a working prototype in June 1990.

- **Centrifuge manufacturing facilities**

In Oct. 1985 it was decided that the centrifuge parts would be made abroad in sufficient numbers to arrive at a successful prototype.

At the same time EDC began procuring specialized manufacturing equipment for a local production facility at Al-Furat.

Construction of several buildings at Al-Forat started. They were to accommodate the various centrifuge parts production machine, assembly and testing equipment of centrifuges and a piping workshop, in addition to a cascade hall for a (100) centrifuge of the subcritical type. Due to the delays encountered in the execution of Al-Forat project, concentrated efforts were directed toward the conversion of a building sections at Rashdiya to have suitable specification for the required prototype experiments (project 520C). These included rooms for chemical cleaning, quality control balancing, and assembly, in addition to a mechanical test stand and a separation test stand. A suitable clean room condition was provided.

For the Al-Forat project, the intended production capacity of centrifuges was estimated at about 1000 machines per year of the short subcritical type, with maraging steel rotors. However, due to delays in the execution of this project, few machines were installed in a make shift workshop. This workshop was for the production of two centrifuge parts namely the jacket & molecular pump in Nov. 1989, together with the flow forming machine to carry out experiments on maraging cylinder production. The difficulties encountered by the supplier of the flow-forming machine in fixing the technology for producing good maraging cylinders were numerous and more time was needed to overcome these difficulties. Therefore, intentions shifted in April 1989 towards acquiring carbon-fibre cylinders. A number of these cylinders were ordered from outside, and later the acquisition of a carbon fibre winding machine.

- **Cascades (see 7 for details)**

Although no cascade were ever built, several cascade were considered. The following list summarizes the cascade considered:

- Oil bearing centrifuge of 4000 sub-critical machine at Taji.
- Project 521 B, Al-Forat 1 00 sub-critical centrifuge cascade.
- Project 521 B, 100 sub-critical cascade at Rashdiya. The site was changed due to construction delays at Al-Forat. The building was to be constructed, so that it could accommodate a supercritical centrifuge, for which a number of blue prints were acquired in Aug. 1989.

Work actually started in Feb. 1990 to construct the cascade building together with the buildings for UF₆ production (project 236) and Flourine gas production (251). These projects were in their early construction phase in Jan. 1991 when work in the program was halted.

- Project 522, 1000 magnetic subcritical centrifuge cascade at Taji to be

completed in Dec., 1994.

Procurement of cascade requirements were actually started, however, most items did not arrive to Iraq after 2nd Aug. 1990. Circumstances did not allow the start of any investment in the Taji site as the progress of the work did not reach to such a stage. However, work on Taji project continued on basic design works and the project for UF₆ production were transferred to Rashdiya site as an alternative to Taji. The nominal capacity of this project was estimated at about 1 kg/hr. sufficient the the intended 1000 subcritical centrifuge cascade.

- Project 521 C, Additional activities at Sept. 1990.

In Sept. 1990, an additional program was introduced which intended to produce 93% BEU from about 60% BEU. This project was given the number 521 C, intended to employ a cascade of 50 subcritical centrifuges and to be housed in a small building section at Rashdiya, where modification to the building was actually started. It was thought that available centrifuge parts allocated previously for the prototype could be used for that project and to attempt locally the manufacture of the other needed parts. The carbon fibre cylinders were to be provided from the out-of-country training on the carbon fibre winding machine. For the cascade, material available locally was planned to be used instead of the ordered materials intended for project 522.

- **UF₆ production**

The site for project 522 (1000 magnetic centrifuge cascade) was also to be the site for the UF₆ production with a nominal capacity of 1 kg/hr.

- **c-Actual theoretical achievements:**

- Detailed design of centrifuge parts, first issued in Oct. 1988.

- Rotor dynamic analysis, calculation of critical speed stability analysis and unbalance response, stress-strain analysis of the magnetic centrifuge rotor were achieved Dec. 1989/Jan. 1990. The following computer codes were used: CAD20, CAD2I, CAD25, and CAD30 from MTI, USA, in addition to ANSYS which was used for stress-strain calculations and for carbon fiber rotor calculations. All the above mentioned activities were carried out at Rashdiya site (which was belonged to Irrigation Research Centre).
- Magnetic bearing calculation carried out in Oct. 1989 by using software acquired from Buro Magnettechnik-Frankfort-Germany.
- Complete calculation to predict the performance of the hysteresis motor at 400 Hz were carried out Buro Magnettechnik-Frankfort-Germany in Aug. 1989.

d- Actual production achievement:

- Successful separation test with non-reactive gas using oil centrifuge at 350 Hz (114m/s) in June 1989 at Rashdiya Bldg. 22.
- Successful mechanical running of oil centrifuge at 833 Hz (272 m/s) with inherent problems in Nov. 1989 at Rashdiya Bldg. 22.
- Successful achievement of assembled magnetic centrifuge rotor balancing in May 1990 at Rashdiya Bldg. 10 (1000 Hz, 450 m/s).
- Successful development of a working mechanical centrifuge in June 1989 at a 1000Hz and linear speed of 450 in/sec.
- Also the achievement of separation with UF_6 with efficiency of about 1.8 kg SWU reached in July 1990.
- Manufacture of selected centrifuge parts, such as jacket, molecular pump, scoops, and grooving of lower bearings.
- Embark on construction of a centrifuge production facility (Al-Forat project)

in Oct. 1988 which was not completed.

- Gaining experience in production of some precision parts such as molecular pump and jacket at Al-Forat project Bldg. B03, grooving of lower bearing ball in March 1990 at Rashdiya Bldg. 10.

e-Further steps to be implemented to achieve the original target

- Delays in construction of Al-Furat project due to the lack of experience in clean room technology required use of foreign designers and suppliers.
- In Oct. 1989 building 10 at Rashdiya site was modified to permit assembly and testing of centrifuge prototype.
- In Dec. 1989 Building B03 (store of incoming materials) at Al-Forat project was modified into a temporary workshop to produce the jacket, molecular pump and to conduct R&D on maraging steel cylinder manufacture.
- The R&D work to develop the technology for the production of maraging cylinder started in July 1990, and was not completed.
- In Oct. 1990 construction of new buildings for cascade development at Rashdiya site began, but was not completed.

f-Indigenous production of critical components and equipment:

During Nov. 1988 it was decided to acquire facilities for the production of centrifuge parts, and for the assembly and testing of centrifuges at Al-Furat:

The Furat project facilities consisted of:

Building BOO comprising:

- Precision machining workshop.
- Rough machining workshop.
- Hysteresis motors production workshop.

Building BO1 comprising:

- Halls for centrifuge assembly and mechanical testing.

- Hot testing (with UF_6) hall with possible future use has a cascade hall for about 100 centrifuges.

- Piping assembly production workshop.

Building B02 comprising:

- Production of maraging steel cylinders and quality control.
- Lower and upper bearing assembly and packaging.

Other support buildings for quality control of materials, utilities, raw material store, etc.

It was planned to have this project started by Aug. 1990. However, the work was delayed and by Jan. 1991 most buildings were still under construction.

The critical components manufactured locally were as follows:

- Grooving of lower bearing ball at Rashdiya Bldg.10 in March 1990.
- Welding of ball and stem of the lower bearing and scoop assembly at A1-Mutawakil project in March 1990.
- Jacket and molecular pump at Al-Furat Bldg. B03 in March 1990.
- Vessels and some UF_6 cylinders at Rashdiya workshop section Bldg. 9 during 1989 and the rest of UF_6 cylinders were brought from Tuwaitha when G1 moved to Rashdiya in July 1987.
- Scoops
- Hysteresis motor at Rashdiya Bldgs. 1 and 10 in Oct. 1989.
- Construction of mechanical and process (with UF_6 gas) test stands for the prototype development work in March 1990 at Rashdiya Bldg.10.
- Two complete magnetic centrifuges were produced and tested mechanically in June 1990 at Rashdiya Bldg.10, and only one was tested with UF_6 gas in July 1990 at Rashdiya Bldg.10.
- Carbon cylinder rotors were used at Rashdiya Bldg.10.
- Two oil centrifuges were produced and successfully tested, one with non-

reactive gas in June 1989 and the other mechanically in Nov. 1989 at Rashdiya Bldg. 22.

g- Assessed time to achieve original target:

A delay of one year from the original target of 1994 was envisaged due to the delay Al-Furat Project and cascade development work.

h- Assessed maximum achievable production:

Successful prototype development work arriving at a workable magnetic centrifuge, with carbon-fibre cylinder (L=614mm, dia.= 145.5mm).

i- Explanatory notes related to any of the above elements

A decision to use carbon-fibre cylinder instead of maraging cylinders was taken in April 1989 due to numerous difficulties encountered during the trial at the flow forming m/c supplier workshop.

About 50 carbon fiber cylinders were available in April 1990, only about 20 of them were made.

j- FFCD Ref.:

Part IIb sec. 4.4 sub. Sec. 4.4.1 page 1-8/312.

Part IIb set 4.4 sub. Sec. 4.4.1 page 5/312.

Part IIb sec 4.4 sub sec4.4.1 page 1/312 7-8/312).

5. Separation by oil centrifuge (see also 4)

a- Original know-how target:

In Sept. 1987 the use of an oil centrifuge for enrichment was considered. A beams type oil centrifuge was adopted for use in isotope separation of uranium after passing successful mechanical tests. A non-reactive gas mixture was also adopted for preliminary experiments in order to gain experience in separation. The goal was to design and produce a prototype oil centrifuge by Sept.1989.

b- Original production target:

The objective was to build an oil centrifuge for use in uranium isotope separation after having achieved successful separation with the non-reactive gas mixture. The target was to be achieved within 2 years (i.e. by Sept. 1989).

c- Actual theoretical achievement (see 4. c):

Based on available literature an adequate theoretical understanding was achieved for both the centrifuge separation performance and design of process service facilities by April 1988. This led to achieving a successful separation experiment of a non-reactive gas mixture in June 1989.

d- Actual production achievement:

Separation using a non-reactive gas mixture (20% CO₂ + 80%R 114) was achieved in June 1989 with an overall separation factor of 1.04 at rotation speeds of 21000-25000 rpm (350 Hz, 14m/s).

e- Further steps to be implemented to achieve the original target:

When the main effort shifted to developing the magnetic centrifuge, the oil centrifuge was kept running up to Dec. 1989 for training purposes. After this date it was dismantled.

f- Indigenous production of critical components and equipment:

Engineering materials for construction were procured from abroad, such as pipes, valves, instruments, pumps, compressors, frequency converters and motors. Process specific components were manufactured in Iraq, such as the oil centrifuge machine, vessels and cylinders.

g- Assessed time to achieve original target:

The oil centrifuge was kept running up to Dec. 1989 and all facilities were later dismantled.

h- Assessed maximum achievable production:

The total separation factor for a non-reactive gas mixture was 1 .04 compared to the theoretical value of 1 .09.

i- Explanatory notes related to any of the above elements:

No UF_6 was ever introduced into this system because of oil and air leaks into the system.

Throughout all oil centrifuge activities only one successful machine was built and used for separation purposes. Another machine was built and used in the mechanical test stand.

j-FFCF) Ref.:

Part IIb. sec. 4.4 sub Sec. 4.4.5 (127-128)/312. (135-136)/312.

6.Separation by magnetic centrifuge (see also 4)

a- Original know-how target:

In July 1988 the use of the magnetic centrifuge for uranium enrichment was considered. The main target was for isotopic separation of uranium using a successful mechanical running magnetic centrifuge. The aim of the activity was to obtain an optimized magnetic centrifuge that could be used in experimenting centrifuge cascades by Dec. 1990.

b- Original production target:

The objective was to arrive at an optimized magnetic centrifuge having 2 kg U SWU/ year at rotating speeds of 58000 - 60000) rpm (1000 Hz, 450 m/s) by Dec, 1990. The first separation test with UF_6 gas was carried out in June 1990 and by Jan. 1991 full optimization of the separation process parameters were still to be completed.

c- Actual theoretical achievement

Based on available literature an adequate theoretical background was achieved for both the centrifuge flow performances and design of process and services facilities by Nov. 1988. This led to a successful isotope separation of uranium in July 1990.

d- Actual production achievement:

In the period July-Dec. 1990 many separation tests using the same centrifuge were carried out to improve efficiency and to optimize process conditions. Product and waste UF_6 gas collected were remixed and used as feed gas for next runs. The range of process parameters and results obtained from separation tests runs were:

- Maximum speed 58000 - 60000 rpm
 - Frequency 1000 Hz.
 - Tangential speed 450 m/s.
 - Flow rate 5-22 mg/s
 - Overall separation 1.4 - 1.1.
- factor
- SWU 0.27 - 1.89 kg U
 SWU/year

A quantity of about one kg UF_6 existed in the process hall out of about two kg reserved for utilization in the separation experiments.

e- Further steps to be implemented to achieve the original target:

Runs were needed to be carried out to improve separation efficiency to obtain optimized operating conditions (such as operating pressures, upper and lower rotor temperatures, UF_6 product cut). These required repositioning of the scoops inlet.

f- Indigenous production of critical components and equipment:

Engineering materials for construction were procured from abroad and process specific components were manufactured in Iraq (such as vessels, cold traps and some UF₆ cylinders at Rashdiya workshop section Bldg. 9 and the rest of UF (cylinders were brought from Tuwaitha when G1 moved to Rashdiya). Others related to centrifuge were:

- Grooving of lower bearing ball at Rashdiya Bldg. 10)
- Welding of ball and stem of the lower bearing and scoop assembly at Al-Mutawakil project.
- Jacket and molecular pump at Al-Furat Bldg. B03
- Hysteresis motor at Rashdiya Bldgs. 1 and 10.

g- Assessed time to achieve original target:

In Dec. 1990 it was estimated that the optimized centrifuge parameters could be determined by July 1991.

h- Assessed maximum achievable production:

The maximum achievable SWU was estimated to be 2 kg U SWU/year.

i- Explanatory notes related to any of the above elements:

All R&D activities were terminated on Jan. 1991

j-FFCD Ref.:

Part IIb sec. 4.4 sub sec. 4.4.5 page (128-129)/312. (136-137)/312.

7. Design of gas centrifuge cascades (see 4)

a- Original know-how target:

In April 1988 it was decided to develop the understanding of centrifuge

cascade for uranium enrichment. The requirement was to make available a general computation concept and computer code to optimize the cascade design for any number of identical machines (of 2 kg U SWU/year). Also, general design concepts for cascades were considered. The target was to be achieved by Feb.1989.

The output of the cascade design was to include the following:

- Number of stages and number of centrifuges in each stage.
- Feed, product and waste withdrawal rates.
- Basic design document.
- Cascade arrangement.
- Process requirements.
- Vacuum requirements.

b- Original production target:

- 10 kg/year HEU at 93%.
- 4000 oil bearing machine cascade
- 1000 magnetic machine cascade.

c- Actual theoretical achievement

In general computation and optimization of centrifuge cascade were based on adaptation of the background accumulated from previous theoretical studies of gaseous diffusion cascades. Centrifuge arrangements and pipe routing for process lines and vacuum lines and their connections to the centrifuges with the flow inside them were adequately understood by Feb. 1989.

Cascade calculations, optimization and design concepts led to issues of basic and detailed designs for 36 centrifuges cascade in May 1989 and 120 centrifuges cascade in Aug. 1989 (Project 521 and 521A were planned to be installed at Al-Furat and Project 521 B at Rashdiya). A basic report was issued for 1000 centrifuge cascade in July 1989 for planning purposes (Project 522 was planned to be

installed at Al-Taji).

d- Actual production achievement:

None. No cascades were built. No actual cascade installation was ever started. Cascades sites at Al-Furat and Rashdiya were under construction when all activities stopped in Jan. 1991.

e- Further steps to be implemented to achieve the original target:

Experiments to study the behavior of two optimized centrifuges working in parallel or in series were required. These experiments were planned to be carried out after optimizing the prototype which was originally planned to be done by Dec. 1990. The prototype optimization would include obtaining the optimum values for

- Feed flow rate.
- Cut.
- Temperature difference across the cylinder.

These parameters should give the best SWU with minimum mixing losses when centrifuges connected in a cascade.

f- Indigenous production of critical components and equipment:

Software was developed locally for cascade calculations, optimisation and vacuum calculations. These included:

- Single machine separation performance (developed by April 1988 at Rashdiya).
- Single machine flow performance (developed by April 1988 at Rashdiya).
- Cascade calculations and optimization (developed by Feb. 1989 at Rashdiya).
- Vacuum calculations (developed by Feb. 1989 at Rashdiya).

No components and equipment were indigenously produced for cascades activities.

g- Assessed time to achieve original target:

Confirmation of the designs would be achieved after the completion of single centrifuge optimization which was estimated to be done by July 1991. However, the progress achieved by January 1991 does not permit this assessment.

h- Assessed maximum achievable production:

The available software that was developed locally at Rashdiya was adequate for optimising the performance of a cascade of any size.

i- Explanatory notes related to any of the above elements:

The 50 carbon fiber short cylinder centrifuge cascade (the program of additional activity adopted in Sept. 1990) was not part of the original planning and was an insertion into the program for production of 10 kg BEU within 3 months starting from UF_6 feed enrichment of about 60%. However, this cascade and others were not constructed and only some civil works in Rashdiya and Al-Furat sites were carried out. All R&D activities were terminated on Jan. 1991.

j- FFCD Ref.:

Part IIb sec. 4.4 sub.sec. 4.4.5 page (129- 132)/132. (138-140)/312, part IIIb. sub.sec.5.11 sub 5.11.3 page (142-147)/163.

PART III: Nuclear Device Development

1. General Introduction

a- Original know-how target:

In March 1987, IAEC was asked to prepare a report defining the requirements for the development of a nuclear device.

The team which was formed for this task submitted a report in August 1987 defining the requirements, which were thought to be highly exaggerated.

The Nuclear Research Centre at IAEC started in Nov. 1987 to prepare general reports defining the lines of research and development to be adopted to solve scientific and technical issues that were posed. The report was completed in March 1988.

Group 4 was established in April 1988, and assigned the task of device development. G4 was to acquire the required know-how, to carry out all necessary studies, research works, experiments and other associated tasks in order to design and produce a nuclear device by June 1991. However, due to delays in the progress of work the target date was revised to June 1992.

Originally the yield of the nuclear device was not specified. Later 20 k ton was adopted as a yield goal. The device was to be a uranium based, implosion type.

The target date for the completion of the theoretical work and the design of the device was Dec. 1990.

b- Original production target:

• Original

The overall objective was to make a workable design and then produce the device by June 1991.

Dhafir project was responsible for the design and production of the H.E.

lenses and detonators and the actual theoretical achievement regarding this part is given in item 3 below. The responsibility for other parts of the device was given to G-4.

• **Project review**

Progress of the work was reviewed in May 1990. A major delay of at least one-year from initial target was found. Main reasons were:

- Al-Atheer buildings were behind schedule causing serious delays in the installation of equipment.
- Delivery of imported equipment was behind schedule.
- Design and fabrication of equipment such as gas gun system and flash X-ray system were behind schedule.
- Lens development was behind schedule.

Another major review was conducted after Aug. 1990 events. The results of that review are known as additional activities.

• **Additional activities**

Additional activities were carried out after August 1990 events. Projects 601 and 602 for the fuel processing and uranium metal extraction were initiated. Moreover, G4 either initiated or accelerated the following activities:

- A team was formed to work out the detailed design of the device utilizing the fifth version of the basic design report of July 1990 and its accommodation in Al-Hussein missile warhead, which imposed limitations of the size and mass of the device (that is $OD \leq 800$ mm, $mass \leq 700$ kg).
- Dhafir project was to expedite the production of the spherical lenses for a full scale device (r200 mm R400 mm) and these were to be produced by the end of Nov. 1990. PC-3 supported DP in the

production of equipment for vacuum casting of the required lenses. The first vacuum cast lens was produced in mid Jan. 1991.

- The need for G4 to acquire tritium required for the D-T initiator resulted in a special permission to operate the IRT-5000 reactor, which had been shutdown for security reasons following the events of August 1990.
- One full scale experiment using steel instead of uranium should be conducted. After the success of the steel experiment, another experiment should be conducted using natural uranium.
- Since facilities for purification and casting of uranium were not available, a decision was taken to purify uranium to the best possible specification using the existing facilities. Also, the casting and shaping would be made to the best possible tolerances.
- To investigate the utilisation of the vacuum induction furnace type VSG-030B to cast metallic natural uranium for the reflector and tamper. This showed that the furnace chamber needed major modifications and proper moulds needed to be designed. This work continued until Jan. 1991
- Accelerating the manufacturing of bottom pouring induction furnace type 701E. It was partially manufactured but was not operated due to power supply design failure.

Depending of the outcome and success of the additional activities the target date for the device would have been brought back to late 1991 although the order of Aug. 1990 was to complete the device development within six months.

c- Actual theoretical achievement

Theoretical investigations were performed and adequate understanding was

reached in July 1990 in the areas of neutron kinetics, shock wave physics, H.E. experiments, hydrodynamics and electronics to design a workable device. However, in the field of materials behavior under shock loading better understanding was necessary. This lack of understanding continued until Jan. 1991.

Theoretical work utilized available computer codes, and some indigenous computer codes as described in item 2 below.

d- Actual production achievement:

G4 developed a nuclear device design methodology that included a neutronic, hydrodynamic, and coupled calculations.

In July 1988, design criteria were based on basic neutronic calculations. It was assumed that, as a result of shock wave pressure, the uranium density doubles. Critical mass was calculated assuming an infinite reflector. In these calculations, various choices of reflector and tamper were tried (Be, C, U, Fe). Computer codes like ANISN and LOCAL POINT KINETIC modelling were used for these calculations. With the progress of work, 1 -D and 2-D hydrodynamic and coupled neutronic computer codes were used for the optimisation of the design parameters.

Five Basic Design reports were issued. The first was issued in Dec. 1988, the last in July 1990. After Aug. 1990, when G4 was ordered to speed up its activities, several modifications were undertaken. These included a flyer plate for pressure amplification and the addition of D-T initiator. In response to a DP request for definitive mould dimensions, G4 stated that DP should produce moulds for design report revision five "see attached table". The order to G4 implied the accommodation of the device in Al-Hussain missile.

Due to the introduction of the radius (40cm) and weight (700 kg) limitations in late 1990, it was necessary to propose new design for the device. The first step was to divide the available space between G4 and DP groups. It was decided on

Jan. 11, 1991 to use r175 mm R400 mm explosive package. Since the core radius is fixed, changing, the thickness of the tamper - reflector (15 cm) was the only alternative. The first design option proposed by G4 is shown as "1990 request" in the attached table, but this option exceeded the Al-Hussain missile requirements by more than 200 kg. The solution proposed was the adoption of a flyer plate design with D-T initiator. The conceptual design option proceeded through parametric studies using more realistic pressure boundary conditions and a coupled 1 -D neutronic hydrodynamic code. The goal of these conceptual designs was the reduction of the mass to meet the requirement of the Al-Hussain missile.

Owing to additional uncertainties for a confident theoretical calculation, an additional experimental program with a spherical shell was initiated by mid Jan. 1991

This design was not developed further. The attached table gives main parameters of several design options.

e- Further steps to be implemented to achieve the original target:

Theoretical and experimental works were to be further developed (see relevant section in this summary).

f- Indigenous production of critical components and equipment:

All parts of the device were planned to be indigenously produced.

g- Assessed tune to achieve original target:

Probably, by end of 1992, most of design unknowns would have been resolved.

h- Assessed maximum achievable production:

No production goal was ever established.

i. Explanatory notes related to any of the above elements:

- Delivery System

The delivery system was the responsibility of the missile group at MIC (A1-Mustafa project).

1) The first contact between IAEC and MIC took place during the first half of 1988 through a meeting between the leadership and senior staff of both organizations. The main conclusions of that meeting were:

- (1) IAEC should endeavour to decrease the size and weight of the device as far as possible.
- (2) MIC should take the responsibility of developing the carrier rocket that could accommodate the eventual device.
- (3) MIC should organize the design and development of the explosives for trigger system with continuous contacts for co-ordination purposes.

2) During 1989 G4 conducted studies of the requirements for missile delivery.

These requirements included items such as thermal isolation, load distribution for the additional equipment, guidance system, electronic equipment specifications, pressure switches, radio altimeter and partial destruction

3) In August 1990 contact with the missile group was initiated on technical level. These technical contacts continued throughout the period August 1990- Jan. 1991. They included the need to design a warhead for A1-Hussain missile as well as the following limitations:

- (1) The total weight of the device at the time was about 1200 kg and the missile payload was not to exceed 700 kg.
- (2) The outside diameter of the device, at the time, was about 105 cm and the allowable volume in the missile head was a sphere of 80 cm in diameter. (see section 5.6.3 C)

j. FFCD Ref.:

FFCD, Part IIIb, Sec(5.3)

FFCD, Part IIIb, Sec(5. 11 .4A)

2.Design of device: theoretical understanding and calculations

a- Original know-how target:

The decision to achieve a theoretical understanding and to perform calculations for the design parameters of a device was part of the overall decision to work on device development taken in mid. 1987. The original target was to install and develop computer codes and collect data of relevance in order to optimize the parameters of the design options (see item 1 above) through computer calculations by Dec. 1990. During this work at Tuwaitha, the original design was improved by the inclusion of flyer plates, stalling on Jan. 1989, and internal DT-initiators (gaseous and solid compounds), starting on July 1990.

b- Original production target:

Originally the production target was to use the achieved theoretical understanding to prepare indigenous and install ready-made computer codes, and use these codes to produce parameters for an acceptable design option. The original target date was to accomplish this task by Dec. 1990.

c- Actual theoretical achievement

The actual theoretical achievements included, by Jan. 1991, the following:

- Derivation of the relevant theoretical equations of state for the materials.
- The use of the one-dimensional hydrodynamic codes mentioned in (d) below to understand the hydrodynamic behavior of the device.
- The use of the coupled codes mentioned in (d) below to perform a parametric study in which the parameters related to pressure boundary condition, $p = p_0, \mu$, namely; p_0 and μ and the core enrichment were varied and the behavior of the device was calculated in each case with the purpose of understanding how to optimize its performance.
- The modification of the code TOODY so as to handle calculations for a

single lens composed of three parts. However, these calculations met with numerical difficulties.

- Calculations for flyer plates using the one-dimensional code WONDY III a (see item 4 below for details).
- Estimation of the neutron yield from an internal Po-Be initiator.
- Calculations for the neutron yield from an internal DT-initiator using the one-dimensional hydrodynamic codes.
- Rough estimate for the amount of explosives needed in the device on the basis of thermodynamic and adiabatic compression of metallic uranium. The result was that approximately 100-250 kg of high explosives would be needed to achieve the super critical condition for metallic uranium.

d- Actual production achievement:

The actual production achieved included, by Jan. 1991, the following:

- Preparation of indigenous and installation of ready-made computer codes covering the equations of state, hydrodynamic, neutronic and coupled areas as shown in table below:

Computer Code Name	Area of Application (Source)
WONDY III a	1 -D Lagrangian hydrodynamics (SANDIA/ USA)
ONED	1 -D Lagrangian hydrodynamics (indigenous)
ISHTAR	1 -D Lagrangian hydrodynamics (indigenous)
SUMER	1 -D Eulerian hydrodynamics (indigenous)
TOODY	2 -D Lagrangian hydrodynamics (SANDIA/ USA)
AKAD	2 -D Eulerian -Lagrangian hydrodynamics

	(indigenous)
ANISN	neutronics using the S_N method (USAEC)
LOCAL POINT KINETIC	point kinetics (indigenous)
CODE	
AX-1	coupled Lagrangian hydrodynamics -neutronic (S_4) (ANL/USA)
TDA 1	coupled Lagrangian hydrodynamics -neutronic (S_4) (indigenous)
DTF-IV	neutronic (S_N) (IAEA)
TDM	coupled Lagrangian hydrodynamics -neutronic (S_N) (indigenous)
LINEARIZED	linearized 3 -D Lagrangian hydrodynamics
PERTURBATION CODE	(indigenous)
DAIXY	neutronic solving the diffusion equation (CEA/France)
MEDUSA	for calculation of neutron yield from DT reactions, Lagrangian hydrodynamics plus averaged reaction rates (Belfast Library)
GGTC	neutronics for macroscopic cross-section preparation (ISPRA/ Italy)
EOS CODES	For calculation of equations of state (indigenous)

- The use of some of the codes mentioned above to produce results relating to the design options as follows:
 - The use of the codes ANISN and LOCAL POINT KINETIC for the purpose of estimating design parameters (radii of core, reflector and tamper, core enrichment and yield) (July 1987 - Dec. 1990).

- The use of one-dimensional hydrodynamic codes mentioned in table above for the purpose of calculating the compression of the core as a result of applying different boundary pressures and, hence, estimating the required boundary pressure to achieve the super critical condition (June 1988 - Jan. 1991).
- The use of the coupled computer codes mentioned in table above for the purpose of optimizing the some design parameters calculated in the preceding steps (Jan. 1989-Jan. 1991)
- The use of the indigenous two-dimensional hydrodynamic code mentioned in table above to perform calculations for the two-dimensional behavior of the device with the purpose of estimating asymmetry effects. However, these calculations met with numerical difficulties and problems of computer time (June 1990 - Jan.1991).

As a result of these calculations design parameters were obtained, but no final design was selected.

All this work was performed on the NEC/750 computer. Some work related to the development of the equation of state calculations was performed on a personal computer.

e- Further steps to be implemented to achieve the original target:

To achieve a better theoretical understanding, more reliable calculations for the device design parameters, and a better definition of the design, the following were needed:

- More detailed equations of state and constitutive models (responsibility of the theoretical and experimental groups).

- More realistic pressure boundary condition from incorporation of explosive lenses behavior in the calculations (assigned to the theoretical and experimental groups),
- Adequate benchmark and experimental data (assigned to the theoretical and experimental groups),
- Better understanding of the expansion phase (responsibility of the theoretical group),
- More detailed understanding of DT-initiator and flyer plate behavior (responsibility of the theoretical group),
- More coupled calculations to optimize the design parameters (assigned to the theoretical group).

f- Indigenous production of critical components and equipment:

In this theoretical work the critical elements were the theoretical equations of state, computer codes, experimental results and design parameters calculations. Indigenous production in these areas was as follows:

- Derivation of adequate theoretical equations of state for the relevant materials.
- Preparation of indigenous equations of state, hydrodynamics, neutronic and coupled codes (see table in (d) above).
- Installation of ready-made hydrodynamic, neutronic, and coupled codes (see table in (d) above).
- Calculation of design parameters based on neutronic, hydrodynamic, and coupled codes.

g-Assessed time to achieve original target:

G4 would have achieved a proper theoretical understanding of a working device based on the available computer codes around Dec. 1991. This would have

allowed the performance of more reliable calculations for optimizing the design parameters by June 1992. Additionally experimental verification of these calculations would have been necessary. As far as the accelerated activities are concerned, see item 1 above.

h- Assessed maximum achievable production:

Not applicable since work is theoretical.

i. Explanatory notes related to any of the above elements:

- Other aspects related to the calculation of explosive lenses and the theoretical understanding of flyer plates are dealt with in items 3 and 4 below respectively.
- All this theoretical work and calculations were, performed at Tuwaitha, Bldg. 3.

j. FFCD Ref.:

FFCD, Part IIIa, Sec. (5.3), PP. 26-69/309

FFCD, Part IIIb, Sec. (5.11.4 A), pp. 157-158/163

3. High explosives, theoretical understanding and practical implementation

a- Original know-how target:

In Oct. 1987, Al-Qa Qaa (Dhafir Project) was assigned responsibility for the study, design and manufacture of explosive lenses and exploding bridge wire (EBW) detonators. G4 planned to use the experience and capabilities of QGE to accelerate this work. Also, G4 planned to verify its theoretical studies and designs with experiments. The target was to finish all theoretical studies Dec. 1990 except for the work on P.B.X, which was planned to continue till June 1991.

b- Original production target:

Production of proper EBW detonators and pressed lenses was planned to start in Jan. 1990, while cast lenses were planned to be produced in beginning Nov. 1990.

c- Actual theoretical achievement

In the period Jan. 1988 - Dec. 1990 studies and reports on classical (conventional) explosives, composite explosives, and plastic bonded explosives (P.B.X.) were prepared. Technical reports on firing systems and detonation velocity measurement were prepared by the electrical subgroup. An indigenous 2-D LENS DESIGN CODE was prepared in April-May 1990. A report on the design of (EBW) detonators was written in July 1990. Calculations for flyer plates were added to the same computer code mention above in May-July 1990. Also, studies and experiments in all the above-mentioned fields were still going when the war started. Test results were used to refine designs for EBW detonators, flyer plates, ... etc.

d- Actual production achievement:

In the period from Oct. 1987 to Dec. 1988, many preliminary experiments were done using one or more explosive charges hitting targets (steel plates or small

spheres) followed by inspection of the deformation on those targets, and some preliminary measurements were made. The main purpose of those experiments was to determine the requirements for a theoretical design program, studies of explosives, production equipment and measuring instruments.

The achievements were as follows:

- About 200 EBW detonators were produced at project site (Al-Qaqaa), most of them were sent to Al-Atheer for testing. Best results showed less than 100 ns jitter time when testing the simultaneity of 32 detonators fired at the same time in June 1990.
- Tens of pressed plane and spherical wave lenses were produced and tested at QGE, later they were sent to Al-Atheer for testing. Tests ran from Jan. 1990 onwards. One of those tests, that was done Jan. 1991 on a r30 R180 mm spherical lens showed formation of a spherical implosion shock wave.
- In Dec. 1990 and Jan. 1991, parts of lenses of r75 R300 mm radii were cast. They were intended for R&D work of DP. Attempts were started to machine those parts to the required dimensions, but no complete lens was assembled. For the r200 R500 mm lenses, only two attempts for casting were carried out in Jan. 1991, but those parts were not tested or machined due to the events of Jan. 1991
- The electrical subgroup built and developed firing systems for EBW detonators in the period June. 1989 - Sept. 1990. Also, this group conducted many tests concerning detonation velocity measurements for different explosives, measurement of detonation time of detonators and detection of the detonation wave front of explosive charges.
- Starting in Jan. 1990, tens of kilograms of classical explosive mixtures were prepared for production of lenses. In June 1990 a few kilograms of composite explosives were prepared. Small cylindrical bars of those

explosives were sent to the electrical subgroup for testing. Also, small quantity of PBX was produced in the laboratory in Sept. 1990. Tests of these samples clarified the need for an isostatic press, which was out of Iraq capabilities.

- Equipment was erected at project site in Aug. 1990 for machining of cast parts of HE lenses. Attempts were made to machine the first and the third layers of r75 R300 mm cast lenses, and the results were encouraging, but the work stopped due to the events of Jan. 1991.

e- Further steps to be implemented to achieve the original target:

Due to the non-delivery of equipment for vacuum casting of explosives, design of such equipment was done by Dhafir project personnel in Oct. 1990, and then sent for manufacturing. However, most of them were not completed due to the events of Jan. 1991.

f- Indigenous production of critical components and equipment:

Equipment for vacuum casting of HE such as two cooling chambers, two casting chambers and mixer-melter were designed and manufactured. The capacity of each chamber was about 1m^3 while the capacity of the melter was about 0.4m^3 .

Hexagonal and pentagonal molds for r200 R500 and r75 R300 lenses were also fabricated.

g- Assessed time to achieve original target:

About six months were needed to achieve the original target and the delay was due to the non-arrival of the equipment from abroad.

h- Assessed maximum achievable production:

It was planned to produce two complete cast lenses (with r75 R300 mm) daily starting from Jan. 19, 1991. This number was to increase to four cast lenses from Feb. 1, 1991 onward (assuming that some additional parts of vacuum casting

equipment were received). The production of one r200 R500 mm cast lens daily was planned to start on Feb. 1, 1991 (after receiving the fabricated molds in Jan. 26, 1991). In Jan. 12, 1991, G4 requested the production of r 1 75 R400 mm lenses, however no work was carried out on this request by DP group.

i. Explanatory notes related to any of the above elements:

There was a set of H.E. experiments performed PC-3/G4 explained in item 5 below.

j-FFCD Ref.:

Part IIIa sec. 5.8

4. Flyer Plates

a- Original know-how target:

G4 decided to perform flyer plate calculations at Tuwaitha in Jan. 1989. The original know how target was to gain a comprehensive understanding of the behavior of flyer plate and then to use this knowledge to calculate the design parameters for more refined design options in which the overall size would be reduced and the requirements on the explosive lenses would be easier to achieve. The original target date to complete this task was Dec. 1990.

b- Original production target:

The original production target was to calculate parameters for a design option of a device employing flyer plates by Dec. 1990.

c- Actual theoretical achievement

The theoretical achievements are:

- The calculation of pressure amplification and shock wave propagation for aluminum flyer plates in contact with an explosive layer using the one-dimensional hydrodynamic code WONDY IIIa and the benchmarking of

these calculations against standard results from similar calculations available in the literature in June-August 1990.

- The calculation of flying shells hitting a sphere using the code WONDY IIIa and the observation of fracture in these calculations. Attempts to treat this fracture were made but were not wholly successful. This was performed by Nov. 1990.

d- Actual production achievement:

Actual production achievements are as follows:

- The hydrodynamic calculation, using the code WONDY IIIa, of an initial design option incorporating a flying shell. It was noticed that flyer plate fracture was a problem in these calculations, fracture had to be treated through more realistic constitutive models. This work was performed between June 1990 and Jan. 1991.
- The conduct of experiments by Dhafir Project (DP) beginning Nov. 1987 using high explosives (BE), seismic detonators and various targets (such as steel plates and small spheres). The object of these experiments was to gain experience in this type of work so that later experimental requirements could be defined more precisely. In some of these experiments an aluminum flyer plate was used.
- The conduct of HE experiments in the period Jan. 1990- July 1990 in bunker 100 at Al - Atheer to study the effect of shock waves on the assembly of a dummy (cold) Po-Be cylindrical initiator.

e- Further steps to be implemented to achieve the original target:

- More complete understanding of the behavior of flying shells was needed through additional calculations and experiments.
- Treatment of the observed fracture in the theoretical calculations was a

problem to be solved through more accurate constitutive models.

- Incorporation of flyer shells in the coupled calculations and performing such calculations for a design option with flying shells to get more reliable design parameters.
- Conduct of further experiments to provide information about the behavior of flyers to supplement and confirm the theoretical understanding.

f- Indigenous production of critical components and equipment:

- One-dimensional hydrodynamic codes were essential for flyer plate design calculations. The code WONDY IIIa was used throughout the calculations for flyers, and no indigenous production of other codes was attempted for this purpose.
- As far as Dhafir Project's work is concerned, see item 3 above.
- As far as the experimental work of G4 is concerned, see item 5 below.

g- Assessed tune to achieve original target

About Dec. 1991, it would have been possible to achieve an adequate theoretical understanding of the principles of flyers based on computer codes. This would have allowed more reliable calculation of parameters for the initial flyer plate design option by June 1992. As far as accelerated activities are concerned, see item 1 above.

h- Assessed maximum achievable production:

A possible future extension of this work involved the use of more than one concentric flying shell for the purpose of more pressure amplification.

i. Explanatory notes related to any of the above elements:

- The design option mentioned in (d) above was not one of the original design options given in item 1 above. The need to consider a flyer plate design arose from the requirement to reach 3 Mbar pressure and to reduce

the overall weight and dimensions of the device.

- Item 3 (High explosives: theoretical understanding and practical implementation) and item 5 (Experimentation: High explosive (BE.) experiments) include some experiments related to this work.
- All theoretical work was performed at Tuwaitlia, Bldg. 3.

j- FFCD Ref.:

FFCD, Part IIIa, Sec. (5.3.6 A), pp. 64-65/309

FFCD, Part IIIb, Sec. (5.11.4 A), pp. 157/163

FFCD, Part IIIa, Sec. (5.4), pp. 92/309.

FFCD, Part IIIa, Sec. (5.8), pp. 277/309

5. High explosive (H.E.) Experiments

a- Original know-how target:

Develop understanding of H.E. shock wave physics to design the H.E. lens system for the nuclear device.

The design development and production of the necessary HE package to produce the required 3 Mhar pressure at the tamper outer boundary was the responsibility of QGE (Dhafir Project). A range of H.E. experiments was needed for the qualification and verification of QGE's (DP) explosive package both as individual items and the complete system including full mock-up tests. Tools and equipment like high-pressure instrumentation, fast time electronics and high speed cameras were needed for the experiments. Therefore, in May 1988 IAEC/PC-3 had to develop the necessary know-how to achieve the target by May 1991.

b- Original production target:

To develop the know-how required for verification of the performance of the explosive package, it was necessary to achieve the following:

- To design and construct a facility suitable for BE. experiments by April 1989.
- To develop or acquire suitable probes and sensors for measurement of high pressure, shock wave velocity, shock wave front and temporal behavior by Jan. 1990. However, the inability of QGE (DP) to supply the lenses when required caused a one year delay in the May 1991.
- To develop or acquire suitable instruments for fast recording and general on-line data acquisition including high speed cameras, Computer Automated Measurement And Control (CAMAC) system and logic analyzers by Jan. 1990.
- To conduct experiments to verify the performance of H.E. lens systems.
- To analyze the experimental results and to suggest improvements in the H.E. package is considered adequate. The original production target (May 1991) was extended in June 1990 to May 1992 to achieve a suitably qualified H.E. package at Al-Atheer site bunker 100.

c- Actual theoretical achievement

- A comprehensive literature survey provided a suitable theoretical background to the technical personnel involved and this was accomplished by Dec. 1989.
- Documents for the safe handling, storage and use of H.E. were prepared and adopted by Dec. 1989,
- Experiments were designed and conducted in the period Jan. 1990 - Jan. 1991 at Al- Atheer site bunker 100.

About forty experiments were performed to investigate and verify:

- Plane wave generator performance.
- Cylindrical internal neutron initiator performance.
- Qualification of the spherical wave lenses.

- Detonation speeds of cylindrical charges.

d- Actual production achievement:

The following activities were conducted -

- Design, construction and testing of bunker 100 at Al-Atheer. This was a facility for testing H.E. up to 200 kg TNT. This facility was commissioned in July 1989.
- The experimental results of the plane wave generator showed the production of a plane wave front.
- Plane wave generator tests for the cylindrical initiator were made during the period Jan. 1990 - Jan. 1991. The results of these tests were not reproducible, which resulted in the use of the gas gun (RPK rifle) to test the initiator (see item 7).
- Spherical wave tests with two types of small pressed single lenses. A convergent shock wave was being produced. The highest pressure recorded was 317.8 kbar at the interface between the spherical lens and a steel shell in direct contact with the lens. These experiments were conducted in Dec. 1990.
- Experiments on cylindrical charges were made at the request of QGE and Bilal Al-Shuhada' during the period from July 1990 - Jan. 1991 to supply the BE. manufacturers with the detonation speeds of these charges. These data were useful for the optimization of their products.

e- Further steps to be implemented to achieve the original target:

- Single and multiple spherical lens experiments had to be done to qualify the lens system.
- Tests were required to qualify the initiator.
- Flash X-ray systems were required for dynamic imaging of implosions.
- Full mock-up tests of the device were required to verify lens design,

synchronicity and pressure conditions.

- The dynamic calibration of the PVDF pressure sensors was required.

f- Indigenous production of critical components and equipment:

- Apart from the streak camera, and the logic analyzer, which were imported, all other experimental devices and equipment were prepared and integrated locally at Al-Atheer site bunker 100 from general engineering materials and components that were imported.
- Bunker 100 was designed and constructed locally.
- Flash X-ray systems were designed and fabricated locally (see item no. 6).

g. Assessed time to achieve original target:

It was estimated that the original target would be achieved by May 1992, As far as the accelerated activities are concerned, see item 1 above.

h- Assessed maximum achievable production:

Development work and experiments needed to be continued to incorporate flyer plates and shells to achieve optimization of the design of the H.E. package and the overall device concept.

i. Explanatory notes related to any of the above elements:

The work was carried out in co-ordination with QGE, and from Jan. 1990 frequent meetings were held between PC-3 and QGE/DP. The results of experiments were shared and discussed during these meetings. There was also a set of H.E. experiments done by QGE/DP explained in item 3 above.

j. FFCD Ref.:

Part IIIa, Sec. 5.4 page 94/3 09

6. Flash X-ray Systems

a- Original know-how target:

In May 1989 the flash X-ray systems, were considered necessary to record the transient phenomenon of implosion mock-up tests. It was therefore necessary to develop the capability and know-how to design, fabricate and test these systems. G4 decided to aim at the highest possible photon energy to achieve the maximum penetration depth. The target date to develop this know-how was July 1990.

b- Original production target:

A decision was made in 1989 to construct flash X-ray system indigenously. May 1991 was the planned target to utilize the flash X-ray systems in the implosion mock-up experiments.

c- Actual theoretical achievement

The knowledge required to design flash X-ray systems was attained by the end of 1989, although not all engineering issues had been overcome.

d- Actual production achievement:

Three types of flash X-ray systems were designed

- The 180 kV system.
- The 600 kV system.
- The 1200 kV system.
- The 180kV system was completed and tested at Tuwaitha by October 1989. It was moved to Al-Atheer in May 1990.
- The 600kV system was assembled and tested with the production of static images at Al - Atheer in Oct. 1990. It was to be assembled in a special metallic container. The assembly was not completed due to high voltage capacitor break down because of gas insulation failure. This problem was under study when the work was terminated in January 1991.

- Components of the 1200kV system were fabricated at Al-Rabee factory.

The epoxy resin insulator was completed as well as the X-ray tube itself.

The assembly of the 1200 kV system had not commenced by January 1991

The following experimental tests were conducted on the 180 kV flash systems at Al-Atheer site Bldg. 6200:

- Determination of the focus spot of the X-ray using a pin hole camera and an X-ray film.

- Determination of the angular distribution of X-ray dose rates using 36 personal-pocket type dosimeters.

- Determination of the highest possible X-ray dose rate by changing the position of the anode with respect to the cathode, also using pocket dosimeters.

- Testing the system with static and dynamic imaging.

e- Further steps to be implemented to achieve the original target:

To complete fabrication, assembly and testing of the 1200 kV system and to build three duplicate 1200 kV systems of the 1200 kV.

f- Indigenous production of critical components and equipment:

All critical system components were designed and fabricated locally at Tuwaitha Bldg. 66 and Al-Atheer Bldg. 6200. General engineering materials were imported.

g- Assessed time to achieve original target:

It was estimated that the 600 kV system would be assembled and tested by March 1991. The 1200 kV system was planned to be completed by July 1991.

h- Assessed maximum achievable production:

Four systems would be needed for the device mock-up test. These four systems could have been fabricated and tested by Dec. 1991.

i- Explanatory notes related to any of the above elements:

None.

j- FFCD Ref.:

Part IIIa, sec. 5.4

7. Gas Gun System

a- Original know-how target:

In Oct. 1989 two main targets were laid down:

- Understanding the behavior of metals under impact and shock wave loading.
- Testing the performance of the cylindrical initiator.

The target date for the completion of the whole project was Feb. 1991.

b- Original production target:

By May 1991, it was anticipated starting experiments on the gas gun systems.

By January 1991, it was anticipated that construction of mechanical components and systems would be complete.

c- Actual theoretical achievement

Design studies were performed for two systems. The first one was the single stage system where the projectile speed 2000 m/s. The second was a double stage system with the speed of projectile of 8000 m/s. The work was conducted at Tuwaitha site Bldg.3.

d- Actual production achievements:

A special building (Laboratory 6610) for housing the two gas gun systems was under construction in Al-Atheer site in 1990 but was not completed by January 1991. This building was situated south-east of Bunker-100.

e- Further steps to be implemented to achieve the original target:

None.

f- Indigenous production of critical components and equipment:

For "hot" cylindrical initiator test, which was planned to be carried out using the double stage gas gun system (projectile speed of 8000 m/s), a shielded test chamber was designed and manufactured (completed in Oct. 1990) at Al-Rabee.

Some mechanical parts of the gas gun systems such as fixtures and support structure, were manufactured and installed in the Bldg. 66 10, The manufacturing was done in Al-Rabee.

g- Assessed time to achieve target:

Delays were anticipated due to manufacturing difficulties with tubes. These delays would have shifted the experimental testing by about 6 months. Therefore, August 1992 would be the anticipated date to start experiments on the gas gun systems.

h- Assessed maximum achievable production:

Experiments were to be carried out as required.

i- Explanatory notes related to any of the above elements:

An RPK ritle to be used to simulate the gas-gun set-up was installed in building 6660 at Al - Atheer in August 1990. It was intended to acquire know-how on the measurement of the assembling time of the initiator at a speed of (600-1000) m/s. The assembly time was found to be 12-18 μ s.

j- FFCD Ref.:

Part IIIa sec. 5.4-page 73/309.

8. Firing system, synchronicity

a- Original know-how target:

In May 1987 a decision was made to form an electronic team whose main task was to design and build a firing system for the device to synchronously detonate multiple exploding bridge wires (EBWs). In May 1988 a know-how target date of three years (May 1991) was adopted.

b- Original production target:

The objective was to design and build a firing system to detonate 32 exploding bridge wires (EBWs) simultaneously with a jitter time less than 100 ns (a time short compared to the shock wave propagation time within the device). The target date for this task was Dec. 1991.

c- Actual theoretical achievement

In April 1988 two mathematical model options were proposed to simulate the circuit of the exploding bridge wire. In June 1988 a computer program for each option was written to investigate the effect of the circuit elements on the behavior of the current and voltage during the detonation of the EBW. In Jan. 1989 computed results were compared with published report data (*SAND-75-0041*, 1975) and showed agreement with both mathematical models.

In Dec. 1988 the theoretical aspects and the mathematical model to simulate the behavior of the firing circuit were adequately understood.

d- Actual production achievement:

Starting Jan. 1989, experiments were conducted at Tuwaitha Bldg. 82 on the firing system with different numbers of EBWs ranging from 2 up to 32 using ignitrons, thyratrons and spark gaps as conducting switches. Efforts were concentrated on designing a firing system having the smallest jitter time and the highest burst current.

Jitter time in the range 5 to 10 nanoseconds (for simultaneous detonation of 32 EBWs) was obtained with laboratory models of EBWs and 50 to 70 nanoseconds for actual detonators manufactured at Dhafir project (QGE).

A number of measuring instruments were designed and built during the period 1989-1990 which were required in experiments of department 40F and the other activities with Group 4 of PC3. This equipment was used to measure time interval and jitter time for different sets of EBWs, detonators and lenses. Between Jan. - June 1990 G4 built a 5 kg experimental firing system for the 32 EBW fire set.

e- Further steps to be implemented to achieve the original target:

Satisfactory experimental results were obtained in verifying the design options of the firing system. In Dec. 1990 efforts were concentrated on the following objectives:

- Further miniaturisation of the firing system
- Environmental testing of the components, parts of the system and a completely assembled system.
- Design review of the firing system to operate with the required reliability.
- Obtaining of suitable electronic components of a military standard.

f- Indigenous production of critical components and equipment:

The firing system and most of the time measuring equipment were indigenously produced such as:

- sets of laboratory firing systems to detonate multiple EBWs (ranging from 2 up to 32 EBWs).
- Measuring equipment for short time intervals in the order of 10 μ s with an accuracy of 0.5 ns and long time intervals in the range of 250 μ s with an accuracy of 10 ns.

- Multichannel measuring systems (up to 64 channels).
- Measuring set for maximum time difference to measure jitter time.
- Three electrodes spark gaps.
- Modification of imported high inductance capacitors
- Triggering circuit to activate the spark gap.
- Pulse current sensing elements (integrating Rogowski coils), voltage sensing elements and ionization probes.
- Laboratory model of EBWs
- Miniaturised mechanical structure of the system which provides the low inductance path in the firing circuit.

Some imported components of dual use were used in parallel with indigenous production of similar items such as the capacitors and the spark gaps.

g. Assessed time to achieve original target:

It was estimated that the original know-how target could be achieved by Dec. 1991.

h. Assessed maximum achievable production:

To achieve the original target stated in section b above laboratory firing sets were designed, built and tested with multiple laboratory models of EBWs and real detonators during the period Dec. 1988 - June 1990 as follows:

- 1 set to detonate 2 EBWs in Dec. 1988.
- 1 set to detonate 4 EBWs in April 1989(see section i below).
- 1 set to detonate 8 EBWs in June 1989.
- 1 set to detonate 16 EBWs in Aug. 1989.
- 1 set to detonate 32 EBWs in Dec. 1989(see section i below).
- 1 set (miniaturized system) to detonate 32 EBWs in June 1990 (see section i below). The last firing system was tested with laboratory EBWs and

real detonators. The achieved jitter time with real detonators of 50-70 nanosecond was considered to be adequate for the foreseen device and also for purpose of experiments with real lenses.

i. Explanatory notes related to any of the above elements:

Two options could be used to improve the reliability of the firing system. This could be achieved by either increasing the reliability of individual components or by adding redundant elements for the critical parts.

To achieve a reliability figure in excess of 0.999 for the firing system it could be worthwhile to duplicate the critical parts in the system (such as detonators).

- In Jan. 1990 preliminary experiments with real detonators provided by Dhafir project (DP) showed large discrepancies in jitter time. In Feb. 1990 a decision in PC-3 project was taken to design and build a firing system (to detonate four EBWs) to be used by DP to improve their detonators production.
- Remains of 32 EBWs firing sets were handed over to the IAEA action team during the meeting held in Baghdad in July 19-30, 1997.

j. FPCD Ref.:

Part IIIa Sec. 5.6

9. Neutron Initiators

A- Internal (Po-Be) initiator

a- Original know-how target:

This was the first initiator to be adopted for the device. In May 1988 it was decided that Group 4 should develop this option and accumulate the necessary know-how to allow a working prototype to be fully tested before May 1991.

The neutron intensity was required to be $> 10^7$ n/s.

b- Original production target:

The following activities were planned -

- To develop a few detailed design options (cylindrical and spherical). These designs were finished by May 1988.
- To fabricate the components locally. The fabrication process continued from May 1988 to Jan. 1991.
- To test the cylindrical cold initiator assembly with the RBK rifle and later with the gas gun. The RPK rifle tests were started from Oct. 1989 and continued up to Jan. 1991, while the gas gun tests were anticipated to be done by Feb. 1992.
- To test the cylindrical hot source design with the gas gun.
- To test the spherical initiator in a hot mock-up experiment by Dec. 1991.

c- Actual theoretical achievement

The following activities were completed -

- A comprehensive literature survey was completed by July 1988.
- A number of possible α -emitter options (such as ^{228}Th , ^{227}Ac , ^{226}Ra , ^{239}Pu , ^{238}Pu and ^{210}Po) were considered and ^{210}Po was the selected option due to its high specific activity.
- Calculation of the effect of impurities in the Po sample was made.
- The neutron yield was calculated (neutrons/ 10^6 α -particles) for all possible options. Approximately 10 mg of ^{210}Po was considered to be adequate for the device initiator. This amount is necessary to account for the radioactive decay considering storage of at least six months.

d- Actual production achievement:

The following was achieved -

- A test laboratory for the initiator was set-up in Tuwaitha site Bldg. No.66

by Dec. 1988. This laboratory was moved to Al-Atheer (Bldg. 6660) in July 1989.

- A measurement of the cold initiator assembly time that was made with the RPK rifle at speeds ranging from (600- 1000) m/s was in the range 12-18 μ s.
- The neutron yield was measured for 3 samples of sandwich type ^{210}Po -Be sources, and found to be 10^4 , 6.2×10^5 , 2×10^6 n/s. These measurements agreed well with the calculated neutron yield based on the amount of ^{210}Po electroplated.
- The integrity of the gold separating foil was tested and proved to be adequate.
- A total of 20 cylindrical cold initiator samples were produced from Jan. 1989 - Dec. 1990.
- Only one cold spherical initiator sample was produced in Dec. 1990.
- In July 1990 a glove-box was designed and fabricated locally at Al-Rabee site for use in the hot test with the gas-gun.

e- Further steps to be implemented to achieve the original target:

- A hot test of the initiator had to be carried out successfully with the two-stage gas-gun.
- It was intended to simulate the initiator assembly with a hydrodynamic code that simulates the implosion process in order to test the integrity of the initiator assembly. Up to Jan. 1991 the hydrodynamic codes could not accommodate this particular problem.
- An overall mock-up test with high explosives had to be carried out to qualify the overall design and assembly of the initiator.

f- Indigenous production of critical components and equipment:

All the critical components were designed and fabricated locally. The ^{210}Po samples were received from the radiochemistry department at Tuwaitha. Be sheet was imported as well as liquid and plastic scintillator materials. Instruments and general engineering materials were imported.

g- Assessed time to achieve original target:

It was estimated that the original target could be attained by Dec. 1991.

h- Assessed maximum achievable production:

It is estimated that 4 initiators of the cylindrical and spherical type could be produced annually with the available know-how and the available reactor.

i- Explanatory notes related to any of the above elements:

In order to investigate the option of the $\text{T(d,n)} \alpha$ as an internal neutron initiator, it was decided to calculate the interaction rates of T-D, D-D and T-T. These calculations were performed at the end of Sept. 1990 at Al-Atheer site.

Work was also conducted to detect tritium with an EMI 4530B photo multiplier tube by using scintillations in argon gas. This work was done in Al-Atheer in Oct. 1990. It was planned to recover tritium from β light device balls available at Saddam GE and fill a borosilicate glass ball of 2 cm diameter with a mixture of Ar, N, T and D gases with a ratio of $M_{\text{Ar}} 10 M_{\text{T}}, M_{\text{T}}=M_{\text{D}}$ and $M_{\text{N}}=0.01 M_{\text{Ar}}$

j- FFCD Ref.:

Part IIIa, sec., 5.4

B- External initiator

a- Original know-how target:

In Nov. 1988 it was decided to study the feasibility of neutron production

using a dense plasma focus (DPF) device which could be triggered to produce around 10^6 neutrons within few microseconds. It was planned to build a working prototype by Nov. 1990.

b- Original production target:

In Nov. 1988 it was decided to adopt a device similar to Sandia's (USA) Mather type DPF device with a nominal energy of 1 kJ. It was to be designed and fabricated locally so that it can be tested as an external initiator by May 1991

c- Actual theoretical achievement

A literature survey was conducted that provided a reasonable understanding of the principles and techniques involved by March 1989.

d- Actual production achievement:

A Mather type DPF was designed, constructed and installed in Tuwaitha in Dec. 1989. When the system was tested, no neutrons were detected and the work was stopped. G4 tried to revive the DPF activities by seeking help from Kalisky Institute for Plasma and Fusion Research in Warsaw (Poland). An initial contract was signed in July 1990 but was not implemented due to the August 1990 events.

e- Further steps to be implemented to achieve the original target:

More work was needed to be done to diagnose the problems that impeded neutron production.

f- Indigenous production of critical components and equipment:

All components (such as spark gap, electrodes and vacuum chamber) were fabricated and assembled locally.

g- Assessed time to achieve target:

Could not be estimated.

h- Assessed maximum achievable production:

Not applicable.

i- Explanatory notes related to any of the above elements:

A small sealed tube neutron generator to be used as an external initiator was considered. The $T(d,n) \alpha$ nuclear reaction was to be used for neutron production. Deuterons had to be accelerated to several tens of kilovolts to hit a tritium target. Only a literature survey on the $T(d,n) \alpha$ reaction was carried out and no practical work was done.

j- FFCD Ref.:

Part IIIa Sec. 5.4 page 77/309.

10. Radiochemical separation of polonium

a- Original know-how target:

The first theoretical study concerning the separation of polonium from irradiated bismuth was performed in early 1989. The target date for accumulating all the theoretical aspects and the practical experience needed for Po-210 separation was Dec. 1989.

b- Original production target:

The aim of the polonium separation was to separate by the end of 1990 the maximum amount of polonium on the milligram level from irradiated bismuth to be used for experimental investigations and for the electrodeposition purposes. This is to be used as an initiator in the device development program utilizing the ${}^9\text{Be}(\alpha, n){}^{12}\text{C}$ nuclear reaction.

c- Actual theoretical achievement

By the end of 1989, the theoretical aspects of the Po-210 separation from irradiated bismuth were understood from the available literature.

d- Actual production achievement:

During 1989 and 1990 four campaigns were performed in Bldg. 9 at Tuwaitha in which bismuth metal and its oxide were irradiated in IRT-5000 reactor. The irradiated quantities were 7 kg oxide, 5 kg oxide and 5 kg metal, 14.7 kg metal and 15 kg metal. Polonium was extracted from the irradiated material and the maximum amount extracted in one of the campaigns was about 6 mg polonium-210. While the amount of polonium-210 extracted in two campaigns were 3 mg per each and about 2 mg in the remaining campaign. Hence, the total amount of Po-210 extracted was about 14 mg.

e- Further steps to be implemented to achieve the original target:

To complete the process facilities in building 65 (Polonium Production Building) at Tuwaitha which was originally planned to be completed by the end of 1990. It was incomplete by Jan. 1991 and would have required considerable effort to complete it.

f- Indigenous production of critical components and equipment:

Most components and equipment were imported except some simple items such as PVC dissolver tank, aluminum containers for bismuth irradiation and extraction and stripping batteries made of perspex that were indigenously manufactured at Tuwaitha Bldg.16.

g- Assessed time to achieve target:

After the completion of building 65 expected during 1991 and following the installation of all the utilities and equipment, about six months were needed to achieve the production target.

h- Assessed maximum achievable production:

Processing of one irradiated cassette of 25 kg bismuth metal per month after optimum irradiation and cooling periods of approximately two months which

yielded about 10mg polonium 210. Hence, under optimum operation conditions and normal operation mode of the reactor it could be expected to produce about 60 mg Po-210 in the solution per year. The number of sources produced per year would depend on the development of the electrodeposition of polonium on the required sources.

i- Explanatory notes related to any of the above elements:

The polonium separation work was considered to be prerequisite part for polonium electroplating.

j- FPCD Ref.:

Part IIIb sec. 5.10.3 pages 34-48/154,

11. Electroplating of polonium in

a- Original know-how target:

The first theoretical study concerning the possibility of polonium electroplating was performed in early 1989. The target date of accumulating all the theoretical aspects and the practical experience needed for Po-210 metal eletctroposition was the end of 1989.

b- Original production target:

The main task of the polonium electroplating was to prepare bullet shape pieces made of gold firmly coated with at least 2mg of polonium metal, evenly distributed over bullet surface. This was planned to be completed by the end of 1990.

c- Actual theoretical achievement

By the end of 1989, the theoretical aspects of the Po-210 metal electrodeposition were adequately understood from the available literature.

d- Actual production achievement:

The governing parameters of polonium metal electrodeposition were well studied and understood in Bldg. 9 at Tuwaitha. During 1989 and 1990 about 10 sources of polonium-210 metal were prepared by electrodeposition on gold discs. The sources contained 0.065-1.33 mg polonium-210. In order to study the parameters associated with neutron production via Po-Be reaction, activity 40B prepared three neutron sources of sandwich type. During the first half of Jan. 1991 a source of 0.1 mg polonium metal was electrodeposited on a stainless steel base bullet. This was an experiment to optimize the procedure to electrodeposit polonium on the gold bullet that would be used in the cylindrical initiator.

e- Further steps to be implemented to achieve the original target:

The facilities in Bldg. 65 (polonium production building) at Tuwaitha would have to be completed and few experiments regarding the distribution and adherence of Po-210 over the gold base bullet shape were required.

f- Indigenous production of critical components and equipment:

Most of the components and equipment were imported except few items such as electrodeposition cells made of perspex that were indigenously made at Tuwaitha Bldg. 16.

g-Assessed time to achieve original target:

After the completion of Bldg. 65 at Tuwaitha expected during 1991 and implementation of few additional experiments on electroplated polonium distribution and adherence over the gold base bullet shape, about six months were assessed to be needed to achieve the production target.

h-Assessed maximum achievable production:

The maximum target was to produce at least 2mg/batch electroplated polonium metal distributed over a gold base bullet shape on demand.

i- Explanatory notes related to any of the above elements:

The polonium electroplating work is considered as a complementary part of the polonium separation.

j- FFCD Ref.:

Part IIIb sec. 5.10.3 page 34-48/154.

12. Fusing system

a- Original know-how target:

Consideration of a fusing system suitable for missile delivery of the device commenced in Sept. 1988. A know-how target date of one year later was adopted.

b- Original production target:

To achieve a workable fusing system by Dec. 1991.

c- Actual theoretical achievement

A literature survey of the subject was conducted in 1989 and documented in a report that covered the following basic ideas and suggestions in connection with fusing system: -

The military specification for airborne electronic equipment were to be adopted.

Additional aneroids (pressure switches) and a radio altimeter were required to measure altitude and time in the last 10 km of the mission. A scenario for the last 10 km of the mission was developed.

A mechanism for preventing device trigger must be adopted in case the mission went out of control and had to be linked to mission abort signal.

After conducting a literature survey of the subject and understanding the issues involved, it was estimated that 18 months would be needed to complete the work (i.e. June 1991).

d- Actual production achievement:

In Sept. 1990 discussions were conducted with the missile group (Al-Mustafa project) in order to accommodate the device in an Al-Hussein missile and the following limitations were discussed.

The device was considered to be too heavy to be delivered by the available Al-Hussein missiles. The total design weight of the device at the time was about 1000- 1300 kg and the missile warhead allowed a device weight not to exceed 700 kg.

The outside diameter of the device at the time was about 90- 105 cm and the missile warhead could accommodate a sphere of 80 cm in diameter.

A mock-up test was suggested and discussed with the telemetry group (special projects/MIC) to study the behavior of the arming and detonation system during the last 10 km of mission. The test included the projection from an aircraft of a missile bead equipped with a simulated device together with telemetry equipment

A laboratory set up for the mock-up test was prepared including the design of special circuits to adapt the signals of the firing system to the encoder of the telemetry equipment.

An experimental set up was prepared and used at Al-Atheer site to study the behavior of aneroids obtained from the missile group

The test was successful and revealed the following:

- It was possible to adjust the aneroids to operate at altitudes in the range 5 and 10 km.
- It was found from the repeatability test that the error in the pressure that activated the aneroids was within (5-10) mbar which was equivalent to (80-170) m at altitudes between (5-10) km.
- The aneroids under test were suitable for sensing altitudes between 5 to

10 km and the radio altimeter was required for altitudes below 5 km.

- A survey of the available altimeters utilized by the Iraqi Air Force was conducted and a list of requirements was prepared as a guide for the selection of a suitable altimeter for the fusing system

e- Further steps to be implemented to achieve the original target:

Apart from the difficulties encountered in accommodating the device in the missile a preliminary design of the mounting structure was carried out to fix a hypothetical device (weight 700kg and diameter 80 cm) in the warhead of Al-Hussein missile.

An actual dummy warhead was delivered to Al-Atheer site in Sept. 1990 to facilitate the design work related to the mounting structure of the device.

Three design options were proposed, the first option that was adopted required connecting upper and lower flanges of the device to two flanges welded to the wall of the warhead.

Preliminary calculations of stresses were carried out in Oct. 1990 at Al-Atheer, which showed that some of the structure parts needed modification to withstand the induced combined stresses

f- Indigenous production of critical components and equipment:

Apart from required critical components and equipment (such as the inertial guidance system, radio altimeter, airborne electronic components and Pressure switches) significant efforts were required to solve the problem of accommodating the device in the missile and the detailed design of the mounting structure to fix the device in the missile warhead.

g- Assessed time to achieve original target:

It was estimated that the original target could be achieved by Dec. 1991.

h- Assessed maximum achievable production:

This task started after August 1 990 and the preliminary design works and experiments mentioned above were considered part of the achievement of the original target.

i- Explanatory notes related to any of the above elements:

- The details of the delivery system was the responsibility of the missile group at MW (AlMustafa project) and is considered within the missile FFCD. It is, therefore, not discussed in detail here. More details are contained in Part III, item 1.
- Apart from the literature survey of the subject, which was conducted in 1989, no further work or interaction took place with the missile group until August 1990.
- The design of the device was not frozen at the time and the question of accommodating the device in an Al-Hussein missile was under constant review.
- Priority was given to the main tasks of Dept. 40F, which were required to be completed before the design could be frozen.
- A decision was taken not to disclose this activity to the missile organisation as a security measure until the design is frozen.
- The work resumed in Sept. 1990 when the task was considered to be part of the device development program within the program of additional activities.

j- FFCD Ref.:

part IIIa, sec. 5.6.3 C , sec. 5.9.

13. Preparation of metallic natural uranium

a- Original know-how target:

In Jan. 1988 it was decided to develop the know-how for the preparation of natural metallic uranium on the laboratory scale to be used for G4 activities and to gain experience. The work, to be performed in Bldg. 73 at Tuwaitha, was envisaged to start with experiments on the conversion of pure UO_2 to the intermediate UF_4 powder by the wet method which were planned to be completed by April 1988. The experiments would proceed to the reduction of UF_4 to metallic uranium which was envisaged to be completed by Dec. 1988.

b- Original production target:

To assemble the laboratory scale units for the preparation of both UF_4 and metallic uranium with the aim of achieving an adequate understanding of the parameters required for the uranium metal production on a pilot scale. This target was planned to be completed in Dec. 1988.

c- Actual theoretical achievement

The know-how was fully achieved by Feb. 1989.

d- Actual production achievement:

The laboratory units were utilized until Jan. 1991. By then, a total quantity of 1110 kg of natural uranium metal was produced by these laboratory units in Bldg. 73 from pure UO_2 powder.

e- Further steps to be implemented to achieve the original target:

No further steps were necessary since the laboratory units were to be abandoned as soon as the pilot plant in Bldg. 64 began operation in Jan. 1991.

f- Indigenous production of critical components and equipment:

Special glove boxes, waste vessels, bombshell were produced indigenously at Tuwaitha, Bldg. 16.

g- Assessed time to achieve original target:

By Jan. 1991 the original target was fully achieved.

h- Assessed maximum achievable production:

1110 kg of metallic uranium was produced in batches at the rate of 20 kg/day by this method. A pilot scale production was later implemented and this laboratory scale work was no longer needed.

i- Explanatory notes related to above elements:

None.

j- FFCD Ref.:

Part IIIb Sec. 5.10.1

14. Production of metallic natural uranium

a- Original know-how target:

Experience was gained during 1988 from the laboratory-scale experiments carried out in Bldg.73 at Tuwaitha. A total quantity of 1110 kg of natural uranium metal was produced from pure UO_2 using wet conversion to UF_4 followed by reduction to metal with magnesium. A pilot scale production of natural uranium metal was planned to be completed in Dec. 1990 and installed in Bldg.64 at Tuwaitha.

b- Original production target:

A daily batch production level of 20 kg metallic uranium was to be achieved in Dec. 1990 and used in the device development program.

c- Actual theoretical achievement

Production procedure and flow sheet were fully developed.

d- Actual production achievement:

- The unit for the production of UF_4 in Bldg. 64 was assembled and tested at Bldg. 64 at Tuwaitha by producing UF_4 from 10kg natural UO_2 in Jan. 1991.
- The equipment and facilities for the conversion of UF_4 to uranium metal were assembled and the start up test conducted in Dec. 1990 at Bldg. 64 at Tuwaitha,
- The waste treatment unit was assembled and tested in Dec. 1990.

e- Further steps to be implemented to achieve the original target:

Completion of all assemblies and conduct of the test and commissioning. It was estimated in Dec. 1990 that 2 months would be needed to achieve that (i.e. Feb. 1991)

f- Indigenous production of critical components and equipment:

Reactors for UF_4 , vessels, tanks, filtration unit, reduction bombshell and control panels were produced indigenously at Bldg. 16 at Tuwaitha.

g- Assessed time to achieve original target:

It was estimated in Dec. 1990 that 3 months would be needed to achieve the original production target (i.e. March 1991)

h- Assessed maximum achievable production:

20 kg uranium metal/day.

i- Explanatory notes related to any of the above elements:

No metallic uranium was produced by this pilot plant.

j- FPCD Ref.:

Part IIIb 5.11.2.

15. Uranium metal casting

a- Original know-how target:

The know-how target was to cast and machine main weapon parts (core, reflector and tamper). The work started by April 1988 and it was planned to be completed by the end of 1991.

b- Original production target:

To manufacture required uranium parts on demand.

c- Actual theoretical achievement

- Attempts were made to use theoretical calculation to define the thermal distribution required to cast directionally solidified uranium hemispheres.
- Using the purchased computer aided casting program [CAD-CAST (Institute of metals.). USA] to achieve the required parameters necessary to have equiaxed solid cast.

d- Actual production achievement:

Total uranium mass which was casted around 90-100 kg to produce the following:

- Uranium rods (1.2 and 3 cm dia. and 15 cm long).
- Hemispheres (5 cm dia.).
- Spheres (2 and 5 cm dia.).
- Pellets (1 cm dia. and 1 cm long).

e- Further steps to be implemented to achieve the original target:

- Modification of vacuum copper melting and casting furnace type VSG 30 B to be capable of melting and casting the core, reflector and tamper in

hemispherical shapes.

- Design of proper molds to cast the above three parts.
- Coating the VSG 30 B crucible with Y_2O_3 and $MgZrO_3$ using plasma spraying.
- Complete existing machining facilities to be suitable to machine uranium parts.
- Design and manufacture glove boxes to handle uranium for both casting and machining process.

f- Indigenous production of critical components and equipment:

- Manufacturing of graphite and ceramic crucibles at G3 workshop at Tuwaitha Bldg.9.
- Partial manufacturing of vacuum melting and casting furnace type 701E at G3 workshop at Tuwaitha Bldg. 16. The 701 E was to be capable of 25 kg casts (1 .5 l crucible).

The following achievements were reached:

- Modification of lab-scale induction furnace type Radyne to be capable of melting about 3 kg uranium at G3 workshop at Tuwaitha Bldg. 16 (June 1988).
- Manufacturing of graphite crucibles coated with proper protective refractories such as Y_2O_3 and $MgZrO_3$ (6 cm dia. & 10 cm length) at G3 workshop at Tuwaitha Bldg.16 and using plasma spraying system at Al-Rabee and Al-Atheer (Nov. - Dec 1989).
- Design and manufacturing molds for casting natural uranium rods, hemispheres, and spheres at G3 workshop at Tuwaitha Bldg.16 (throughout 1988- 1989).
- Casting uranium rods (1-3 cm dia.) hemisphere and spheres (2-5 cm dia.) at

G3 workshop at Tuwaitha Bldg, 16 and A1-Atheer (throughout 1988-1989).

- Machining uranium rods to produce pellets at G3 workshop at Tuwaitha Bldg. 16 and A1-Atheer (April - June 1 989).
- Al-Li block was implemented at Li enrichment project (Aug. 1989).

g- Assessed time to achieve original target:

End 1991- June 1992.

h- Assessed maximum achievable production:

To produce required uranium parts on demand

i- Explanatory notes related to any of the above elements:

None.

j- FFCD Ref.:

Part IIIa Section 5.5.7 page 127~129/252

16. R eprocessing of nuclear irradiated fuel (project 22)

a- Original know-how target:

The reprocessing laboratories (Bldg.9) were designed and equipped by the Italian Company SNIA TECHINT in 1978. They were designed to carry out R and D work in the field of reprocessing of spent nuclear fuel type EK-10 utilizing the PUREX process. Research activities during the period up to 1988 accumulated the know-how and experience.

b- Original production target:

To demonstrate Pu production through the reprocessing of one irradiated fuel cassette type EK-10 and three indigenously produced EK-07's. The second objective was to make a comparison between the amount calculated using the radiochemical computer code and the amount recorded experimentally. No production target date was set because the work was concentrated on gaining the.

Knowledge and experience.

c- Actual theoretical achievement

The ORIGEN computer code was run to assay the burn up of uranium fuel (EK-10) and the mock-up fuel (EK-07).

SEPHIS computer code was run to optimize the flow-sheet parameters of the Purex process.

The amounts of plutonium extracted compared well with the content of plutonium in the irradiated pins as calculated by ORIGEN

d- Actual production achievement:

In April 1988 an irradiated fuel cassette No.3045 of type EK-10, that was exempted from the safeguard regulations of the IAEA, was reprocessed and 2.26 gm of plutonium was obtained. In August 1988 four pins of irradiated EK- 10 were reprocessed and 0.078gm of plutonium was obtained. In Feb. 1990 three home-made cassettes of type EK-07 were irradiated and reprocessed and approximately 3gm of plutonium was obtained.

e- Further steps to be implemented to achieve the original target:

No further steps were implemented to achieve higher than gram scale separation of plutonium

f- Indigenous production of critical components and equipment:

The cassettes of EK-07 type were fabricated in the workshops of activity 3E at Tuwaitha Bldg.16. The fuel pins of the cassettes were fabricated in activity 40G at Tuwaitha Bldg 73.

g- Assessed time to achieve original target:

Capabilities to reprocess the home-made irradiated EK-07 fuel existed and there was no assessed time for an assigned separation of plutonium.

h- Assessed maximum achievable production:

The maximum achievable production of plutonium from reprocessing of EK-07 cassettes was estimated to be approximately 10g Pu/year limited by the laboratory capacity. There was no specific use made of this material other than the preparation of an α source by electrodeposition.

i- Explanatory notes related to above elements:

None

j- FFCD Ref.:

Part III b Sec 5.10.5

17~ Recovery of uranium from HEU fuel elements

a- Original know-how target:

The extraction of HEU from fresh and burnt fuel (project 601). It was to be converted to the metallic form (project 602) to be used as part of the additional activities adopted in Aug., 1990. The experience gained from research work in the radiochemical laboratories (Bldg.9) and the technological hall (Bldg 73B) at Tuwaitha was adequate for the program.

b- Original production target:

Reprocessing of fresh and burnt fuel (39 cells of 93% enrichment producing about 12kg of U of 93% enrichment, 68 cells of fresh 80% enrichment producing about 13.5 kg U of 80% enrichment and 68 cells of burnt 80% enrichment producing about 11 kg U of 60% enrichment. All of these cells were expected to be processed in the above sequence by Jan. 1992.

c- Actual theoretical achievement

The purex flow-sheet has been well tested and experience was gained through research work in radiochemistry.

d- Actual production achievement:

The hot cells and utilities in Bldg. 22 at Tuwaitha were modified to meet the requirement of such reprocessing. A dummy cassette made of an aluminum alloy (AG3) similar in material and dimensions to cassette of the real fuel of 93% enrichment was fabricated at Tuwaitha. This was dissolved in Jan. 1991 according to the flow sheet and natural uranyl nitrate solution containing a quantity of uranium equivalent to that in the real cell was added to the solution. The complete flow- sheet was preformed on this cold run giving satisfactory results.

None of the real fuel cells was processed.

e- Further steps to be implemented to achieve the original target:

The execution of the work.

f- Indigenous production of critical components and equipment:

Dissolver, scrubbing column, tanks, cylindrical vessels, control board and piping were indigenously fabricated to equip the hot cells of Bldg.22 (LAMA Bldg.) at Tuwaitha.

g- Assessed time to achieve target:

It was estimated that approximately 12 months from Jan. 1991 would be needed to achieve the original target.

h- Assessed maximum achievable production:

One fuel cell per batch daily starting end of Jan. 1991

i- Explanatory notes related to any of the above elements:

Projects 601 and 602 were parts of the additional activities formulated on Aug. 18, 1990. The uranium of 93% enrichment that would be extracted would be directly used by group four (G4) for the device development, while the extracted uranium of 80% and 60% enrichment would be enriched further to 93% o by a

short cascade using the centrifuge technology at EDC.

The requirements of the additional program included also,

- Purification of metallic uranium would be conducted to specification using the existing facilities.
- Work would continue to concentrate on using tritium and its production utilizing the IRT-5000 reactor.
- Steps were taken to provide support to G4 to enhance its capabilities to meet the demands of the plan and also to expedite the construction of the remaining facilities at the Al-Atheer site.

j-FFCD Ref.:

Part I sec. 1.2.4 and Part IIIb sec. 5.11.1

18. Production of metallic uranium from HEU fuel elements

a- Original know-how target:

The solution containing enriched uranium that is obtained from the reprocessing of fresh and burnt HEU fuel element was to be converted to uranium metal which would be used in the device development program as part of the additional activities adopted in Aug. 1990.

Experience was gained during 1988 from the preparation of natural uranium metal starting from UO_2 and its conversion by the wet method to UF_4 followed by reduction of the latter to the metal.

b- Original production target:

Conversion of the recovered uranium from the solutions resulting from reprocessing of 13.5 kg Li of 80% enrichment of fresh fuel and slightly burnt fuel containing 12 kg U of 93% enrichment would be converted to the metallic form in Bldg. 64 at Tuwaitha. Moreover, 11 kg U of about 60% enrichment that was burnt in the IRT reactor would be converted to UF_4 and UF_6 so as to be further enriched

by the short cascade to 93%. Conversion would be conducted in unison with the output of project 601.

c- Actual theoretical achievement

Production and know-how for the conversion of uranium solution to UF_4 powder by the wet method and its reduction to the metal using magnesium was fully developed and tested for natural uranium.

d- Actual production achievement:

The complete set of equipment and utilities to be used was nearly ready for operation in Bldg. 64. This included precipitation unit to UO_4 , calcination reduction facilities to UO_2 powder, conversion equipment to UF_4 powder and reduction facilities to metallic uranium using magnesium or calcium metal. Other equipment and facilities were under completion. The flow sheet was tested in Feb. 1989 on natural uranium on laboratory scale in Bldg. 73 at Tuwaitha, No actual HEU solution was handled before Jan. 1991.

e- Further steps to be implemented to achieve the original target:

Complete the units and the assembling of equipment and to conduct tests using natural uranium in Bldg. 64. This was planned to be completed in Feb. 1991.

f- Indigenous production of critical components and equipment:

Vessels, tanks, metallic filtration unit, calcination and reduction and control panel were produced at Tuwaitha Bldg. 16.

g- Assessed time to achieve original target:

It was estimated that approximately 12 months from Jan. 1991 would be needed to achieve the original target.

h- Assessed maximum achievable production:

Conversion of the solution resulting from the reprocessing of one fuel cell

per batch daily starting at the end of Jan. 1991

i- Explanatory notes related to above elements:

As given earlier under item 17.i.

j- FFCD Ref.:

Part I Sec 1.2.4 and part III b 5.11.2

PART IV: Miscellaneous

1. Chemical Enrichment I Ion Exchange:

a- Original know-how target:

As a result of a general review of uranium enrichment methods that was conducted in May 1988, it was decided to adopt the isotopic chemical exchange system for R&D. Research work was conducted with the purpose of establishing the technical requirements for a process similar to the Japanese REDOX chromatographic method for the chemical exchange system U (IV) - U (VI) on macroreticular anion or cation exchangers. The know-how was to be realized by Oct. 1990.

b- Original production target:

Feed materials were UCl_4 - UO_2Cl_2 - HCl

The main tasks, which were to be realized by Oct. 1990, were as follows:

- Preparation of a suitable macroreticular ion exchange resin.
- Selection of a suitable catalyst to accelerate the isotopic exchange system.
- To perform experiments on a single or groups of 2 cm diameter x 200 cm high glass columns with the aim of determining the enrichment factor, height equivalent to theoretical plate in order to assess band stability and related Operating conditions.
- Regeneration of the oxidant and reductant.

- Calculation of the basic chromatographic and isotopic parameters.

The production objective was to produce 4 tons/year of 3% enriched uranium by Dec. 1992, in order to provide LEU to feed the EMIS plants at Tarmiya and Al-Sharqat.

c-Actual theoretical achievement

Most of the theoretical aspects of the basic chromatographic and isotopic parameters were adequately understood by the research team through exploitation of open literature by the end of 1989.

d- Actual production achievement:

- Laboratory experiments started at Tuwaitha (Bldgs. 85 and 90) in June 1988 and continued until Jan. 1991. An enrichment factor around 1 .0007 was obtained experimentally. Most of the know-how tasks were realized by Dec. 1990.
- Basic design reports were issued on assumed parameters for the following:
 - Production of the ion exchange resin for pilot experiments.
 - Isotopic studies.
- Basic design reports were issued on assumed parameters for the production plant for both the resin and enrichment of uranium.

e- Further steps to be implemented to achieve the original target:

- Complete the R&D work at Tuwaitha.
- Complete the basic and detailed designs for the production plants for the resin and production of 4 tons/year of 3% enriched uranium.
- Import equipment for the production plants.
- Install, test and commission the plants.

f- Indigenous production of critical components and equipment:

All chemicals and several parts of the laboratory systems and pilot plant

were not within Iraq's industrial manufacturing capabilities. Jacketed glass columns (of 2.5, 5, 10, 15 and 30 cm diameter) were purchased to be utilized for R&D experimentation. Other equipment (vessels, pumps, thermostatic circulators, temperature and pressure controllers) was also imported for the R&D work. No equipment for the pilot or production plants was imported. Some of the equipment in Bldg. 90 was destroyed during the events of Jan. 1991 and some later. The rest is available under monitoring.

g-Assessed time to achieve original target:

It was estimated that 12 months were required to construct the plant after the equipment is received. Estimated completion date was around Dec. 1992.

h- Assessed maximum achievable production:

The production plant was designed to produce 4 tons/year of 3%-enriched uranium by ion exchange chromatography.

i- Explanatory notes related to any of the above elements:

The LEU that would be produced from the production plant would be useful as feed to the stage-1 EMIS separators in order to increase the overall EMIS plant output by a factor of 4. During the R&D experiments conducted no significant product material was produced. This work was terminated in Jan. 1991 and work on pilot plant construction never started.

j-FFCD Ref.:

Part II b sec. 4.5.1 page 198/252 sec. 4.5.2 page 201/252, sec. 4.5.2 A page 201/252, sec. 4.5.2 B page 203/252.

2. Chemical Enrichment / Solvent Extraction

a- Original know-how target:

As a result of a general review of uranium enrichment methods that was

conducted in May 1988, it was decided to adopt the isotopic chemical exchange system for R&D. Research work was conducted with the purpose of establishing the technical requirements for a process similar to the French CHEMEX process which depended on the U (III) - U (IV) (feed $\text{UCl}_4\text{-HCl}$) two phase liquid-liquid chemical exchange system. The know-how was to be realized by Oct. 1990.

b- Original production target:

The main tasks, which would be realized by Oct. 1990, were as follows:

- Optimum extraction and stripping parameters for the head end and tail end processes.
- Determination of the rate constants for the isotopic and extraction processes.
- Determination of the isotope separation factor.
- Development of on-line analytical method for uranium species
- Reduction of U (IV) to U (III) by an electrochemical cell.

The production objective was to produce 4 tons/year of 3% enriched uranium by Dec. 1992 in order to provide LEU feed to the EMIS plants at Tarmiva and Al -Sharqat.

c-Actual theoretical achievement:

Most of the theoretical aspects of the solvent extraction process were adequately understood by the team through exploitation of open literature by the Oct. 1989. Cascade calculations were made using a locally developed computer code.

d- Actual production achievement:

Optimization of pulsed column parameters using 2m high and 8 cm diameter pulse column was conducted at Tuwaitha (Bldg. 90). An enrichment factor of 1.0025 was measured using test tube experiments. Trials were also performed to

select a chemical exchange system based on crown ethers. Laboratory experiments continued until Jan. 1991. Most of the know-how tasks were realized by Dec. 1990.

- Basic design reports was issued on assumed parameters for a pilot plant, which was to be. used for the verification of the isotopic and hydrodynamics of the system.
- Basic design report was issued on assumed parameters for the production plant for the enrichment of uranium.
- Equipment for the pilot plant including pulsed columns, electrochemical cell and pumps were ordered from France. None were delivered.

e- Further steps to be implemented to achieve the original target:

- Complete the R&D work at Tuwaitha.
- Complete the basic and detailed design of the pilot plant and import equipment to install it at Tuwaitha (Bldg.90).
- Complete the basic and detailed design of a production plant with a capacity of 4 tons/year of 3% enriched uranium.
- Import equipment for the production plant.
- Install, test and commission the plant.

f- Indigenous production of critical components and equipment:

It was not possible to produce critical components indigenously. However, a number of vessels were fabricated at the Tuwaitha workshops for R&D work, but proved unsatisfactory.

g- Assessed time to achieve original target:

It was estimated that 12 months were required to construct the pilot plant after the equipment was received. Estimated completion date was Dec. 1992.

h- Assessed maximum achievable production:

The production plant was designed for the production of 4 tons/year of 3% enriched uranium.

i- Explanatory notes related to any of the above elements:

The LEU that would be produced from the production stage would be useful as feed to the stage- 1 EMIS separators in order to increase the overall EMIS plant output by a factor of 4. During the R& D experiments conducted no significant product material was produced. This work was terminated in Jan. 1991 and work on pilot plant construction never started.

j-FFCD Ref.:

Part II b sec. 4.5 page 198/252 sec. 4.5.3 page 209/252 sec 4.5.4 page 222/252, sec. 4.5.5) page 227/252, sec. 4.5.6 page 229/252.

3. Laser isotope separation

a- Original know-how target:

In Sept. 1981, the IAEC directed the physics department of NRC to conduct a research program on laser isotope separation (LIS) of uranium, and to develop the necessary experience needed to achieve the separation on laboratory scale. No specific date was set due to the lack of experience in this technology.

b- Original production target:

This was an R&D program which had no production goal.

c-Actual theoretical achievement

The relevant publications in the open literature were used to guide the work since there was no theoretical group to support the laser activity

d- Actual production achievement:

- In the atomic vapor laser isotope separation (AVLIS) approach, only two

experiments were carried out at Tuwaitha Bldg. 10, in July 1986 and in June 1989 using uranium metal but no conclusive results were achieved.

- In molecular laser isotope separation (MOLIS) approach:

In June 1985 five grams of UF_6 was prepared at Tuwaitha Bldg. 10 and a set of experiments on IR dissociation of UF_6 were carried out at Tuwaitha Bldg. 23 using Ammonia laser in one set in Dec. 1986 and CF_4 lasers in the other set in Dec. 1989. This caused a multiphoton dissociation with no isotopic selectivity.

e- Further steps to be implemented to achieve the original target:

As a consequence of the negative experimental results the LIS was not selected for development to a pilot scale for uranium enrichment, but work continued on a research scale. In Feb. 1990, an order was placed for a Cu-Vapor laser from Vast Technology (Australia), and the order was partially delivered before the events of August 1990.

Four hyeartons (CX-1735A) and part of the power supply were received before August 1990. This part of the power supply was destroyed during the war. (see FFCD Part IIb page 291/313). The hyeartons are located at the Laser Research Center/MIC and inspected by the IAEA action team.

f- Indigenous production of critical components and equipment:

The process-specific components cannot be obtained by direct procurement since their supply was governed by export licenses from the supplier countries. It was therefore necessary to attempt fabricating the critical components locally. The level of fabricating capabilities available could not deliver the required specifications or quality.

- In Oct. 1990, a home-made (at Tuwaitha Bldg. 23) Cu-Vapor laser system operated with an average estimated power of 1-3 W, but the system had several mechanical and electrical problems with poor reliability.

- TEA-CO₂ laser was operated, in June 1989; a maximum energy of 10 J 100 ns obtained using three pairs of electrodes.
- A 12 μm NH₃ laser optically pumped by a TEA-CO₂ laser was constructed in Sept. 1984.
- A 16 μm CF₄ laser was constructed ill Nov. 1988.
- Molecular beam was constructed in July 1990.

g- Assessed time to achieve target:

The R&D program made insufficient progress to permit an assessment of the time needed to reach tile goal.

h-Assessed maximum achievable production:

The LIS program was an R&D program. No production target was ever established.

i- Explanatory notes related to any of the above elements:

In May 1988, a general review of uranium enrichment methods was conducted. As far as LIS program is concerned it was noted that:

- LI S method may be tile most difficult method among others for uranium separation.
- The enormous size of research programs of the international laboratories suggest that ²³⁵U production by laser will demand very large investment of time and money as well as a very high level of technological sophistication. The scientific and technological infrastructure of Iraq are not up to sucil challenge.
- The LIS was suspended as an option for pilot plant for production of enriched uranium.

j- FFCD Ref.:

Part IIb Sec.4.6

4. Tritium production and handling

a- Original know-how target:

The decision to embark upon R&D on tritium production and handling was taken in July 1990 as tritium was the basic component needed for D-T based initiators that were considered to be a possible alternative option. Accordingly, a number of samples of Li-compounds (less than 100 mg)

and Li-Al alloy strips (4x2x0.1 cm) were prepared, irradiated in the IRT-5000 reactor and then processed to produce tritium.

It was planned that by Dec. 1990, the process for irradiation and recovery of tritium from irradiated Li-compounds and Li-Al alloy could be adequately understood. Also practical experience was gained for the preparation of Li and U hydrides and deuterides needed for D-T initiator studies.

b- Original production target:

The objective was to prepare about 100mg of tritium as a basic component for D-T initiator through irradiation of Li-Al alloy and then store it on uranium as UT_3 .

In Oct. 1990 work was started to issue a conceptual design for irradiation of Li-Al alloy and to issue a basic design for laboratory units to extract and recover about 100 mg of tritium from irradiated Li-Al alloy. The completion of the design was targeted for Jan. 1991.

c-Actual theoretical achievement

By Dec. 1990, irradiation calculations for LiO_2 and Li-Al alloy as well as design studies to construct the irradiation device were prepared. The expected amount of the generated tritium was calculated.

d- Actual production achievement:

The following activities were carried out at Tuwaitha Bldg. 22.

Early work was carried out for the purpose of eventual preparation of neutron generator targets (see explanatory note) as follows: During 1987-1990, (10-100 mg) of different Li- compounds (oxide, carbonate, hydroxide) were irradiated and processed in a laboratory unit. A mixture of trace tritium species obtained were analyzed and found to be mainly T_2O , HTO and T_2 species. Also five small strips of Li-Al alloy (4x2x0.1 cm) containing 1-3% of natural Li were prepared and irradiated and then processed to give a mixture of HT and T_2 species. In addition, about 5 g of each of LiH and LiD was prepared. The total amount of the tritium produced during 1987 -- 1990() was in the order of 0.2 mg through irradiation of Li-compounds.

In Sept. 1990, about 100 g of each of uranium hydride (UH_3) and uranium deuteride (UD_3) were prepared for the purpose of testing internal neutron initiator. These compounds did not contain tritium.

e- Further steps to be implemented to achieve the original target:

The β -light tritium balls available at Saddam GE were intended to be used as a tritium source to perform the experiments planned for filling the glass balls (1 cm radius) with D_2/T_2 mixture needed for experimental initiator studies.

f- Indigenous production of critical components and equipment:

The following small laboratory units were manufactured at Tuwaitha and used in Bldg. 22:

- Unit for the processing, recovery and storage of tritium species from irradiated samples of Li-compounds.
- Device for preparation of Li-Al alloy (4x2x0.1 cm).
- Unit for preparation of LiH, LiD, UH and UD (5-100 g) as to get experience and know-how for the preparation of UT_3 as a basic component needed for D-T initiator as a possible alternative option.

- Unit for production of glass balls (1 cm radius).
- System for the diffusion of gases (H_2 , D_2 , He) in glass balls (1 cm radius).

These units were manufactured during July-Oct. 1990.

g- Assessed time to achieve target:

After execution of the planned detailed design and manufacturing of the irradiation, and storage devices for tritium, six months starting from Jan. 1991 were assessed to be needed to achieve the production target.

h- Assessed maximum achievable production:

If the planned units mentioned above were executed, about 100 mg of tritium would have been collected per year.

i- Explanatory notes related to any of the above elements:

Early work that began in 1987 was carried out the purpose of eventual preparation of neutron generator (NG) targets.

j- FFCD Ref.:

Part IIIb sec. 5. 10.4.

5. Lithium isotopic enrichment / Solvent extraction

a- Original know-how target:

6Li is a good example of a light isotope that could be adopted to demonstrate the method of chemical enrichment, thereby justifying the general method used and paving the way for a demonstration of uranium enrichment via chemical exchange techniques. It is also an important ingredient of fusion based devices. Both techniques of solvent extraction and ion exchange chromatography were considered for realising lithium isotopic enrichment. However, results in July 1989 favored the system crown ether-solvent extraction chemical exchange system. Parameters required for the pilot plant design were planned to be realised by Oct. 1990 through the following tasks

- Determination of the isotope separation factor.
- Determinations of the rate of mass and isotopic exchange reactions.
- Determination of extraction and stripping isotherms.
- Spectroscopic and thermodynamic studies on the nature and structure of the extracted species.
- Selection of a suitable crown ether and various extraction parameters.

b- Original production target:

Based on a squared off cascade, calculations were made for 10 kg/year and 100 kg/year prototype plants of 99% ^6Li to be constructed at Tuwaitha. The objective was to reach the target by June 1992.

c- Actual theoretical achievement

A better understanding of the isotopic effect using the solvent extraction technique Cascade calculations were made using a locally developed computer code.

d- Actual production achievement:

A rotary annular contactor (RAC) was chosen, a laboratory scale column of dimensions 50 cm long 5 cm inner diameter and 1 cm annular width was designed and fabricated at Tuwaitha (Bldg. 16. Experiments were conducted at site Tuwaitha (Bldg. 90), on an RAC column, and on three laboratory mixer settler batteries (23 ml per stage) to study the hydrodynamics and stability of the chemical exchange system. An enrichment factor around 1.03 was obtained experimentally. Main know-how tasks were realized by Dec. 1990. During the experiments conducted no significant product material was produced.

e- Further steps to be implemented to achieve the original target:

Based on squared off cascade, calculations were made the two plants produce 99% ^6Li of 10 kg/year and 100 kg/year. Calculations were made for bigger

RAC pilot plant contactor with 8-15 cm diameter and 140- 150 cm length. The steps to complete this task were:

- Complete and issue basic detailed design report.
- Purchase equipment that Iraq could not produce.
- Construct the facilities. Install the equipment.
- Test and commission the facilities.

f- Indigenous production of critical components and equipment:

The RAC was manufactured at Tuwaitha (Bldg. 16), electronic speed controllers were built at Tuwaitha (Bldg. 61) as well. Other critical parts were to be ordered from abroad.

g-Assessed time to achieve original target:

It was estimated that 12 months were needed to construct the plant after the equipment is fabricated or received from abroad. Estimated completion date was around June 1992.

h-Assessed maximum achievable production:

The pilot plant was designed to produce 10 kg/year and 100 kg/year of 99% ⁶Li. This work did not proceed far enough to permit a meaningful estimate of maximum production.

i- Explanatory notes related to any of the above elements:

During the experiments conducted no significant product material was produced. This work was terminated in Jan. 1991 and work on pilot plant erection never commenced.

j- FFCD Ref.:

Part IIb sec. 4.7 page 244/252, sec. 4.7.2 page 245/252, sec. 4.7.3 page 249/252.

6. Basic design of an indigenous reactor

a- Original know-how target:

Project 182 was adopted by IAEC in Nov. 1984. The Nuclear Research Centre (NRC) at Tuwaitha was assigned with the task of preparing the basic design document for an indigenous plutonium production reactor based on heavy water as moderator and reflector and metallic natural uranium fuel elements. The reactor was a material testing type with a thermal power of 40 MW_{th} so that maximum use could be made of what remained from the equipment of the 7th July reactor (OSRIS) that was destroyed by Israeli aggression on June 7, 1981. The required know-how for the basic design was already available at NRC in the reactor physics department and other supporting departments. Various standard reactor codes (such as ANISN, ORIGEN, WIMSD4, IREM0D) were available in the computer library and were in constant use. It was expected that the basic design phase of the project would be completed by Dec. 1985.

b- Original production target:

The basic design document was to include steady state and kinetic neutron physics calculations, fuel burn-up and plutonium production rate, thermo hydraulic calculations, reactor shielding design, safety report, fuel element design and selection of reactor internal materials as well as in-core instrumentation. A survey of heavy water production techniques was also required. The basic design was to be issued in Dec. 1986.

c-Actual theoretical achievement

The planned reactor was for material testing and plutonium production. However, the facilities of fuel reprocessing available were totally inadequate to utilize the reactor for plutonium production even if the project was implemented.

Standard nuclear reactor codes that were available in the program library at

the NRC computer (NEC 750) were used. The reactor design was generally based on the Canadian NRX reactor at Chalk River. The main difference was that around June 1986, the fuel fabrication department requested changing the reactor fuel from metallic natural uranium to ceramic (UO_2). This request was approved and caused a delay of a few months in order to recalculate the relevant reactor parameters. A number of studies and reports related to the design of project 182 were completed in Dec. 1987 but a formal basic design report was not issued. It was estimated from the burn-up calculations that this reactor could produce approximately 10 kg Pu/year.

d- Actual production achievement:

In May 1988 the IAEC reviewed enrichment technologies and also project 182 in order to decide on optimum methods the future production of HEU and/or plutonium. It was decided to abandon project 182 in favour of the chemical enrichment process for uranium. Most of the personnel of NRC that were engaged on this project were transferred to establish Group 4 in department 3000 at Tuwaitha.

e- Further steps to be implemented to achieve the original target:

None.

1- Indigenous production of critical components and equipment:

Not applicable.

g- Assessed time to achieve original target:

Not applicable.

h- Assessed maximum achievable production:

Not applicable.

i- Explanatory note related to any of the above elements:

None

j-FFCD Ref.:

Part IV chapter 6 section 6.11.

PART V: CHAPTER 11

Achievements

1. Part 1: EMIS research and development at Tuwaitha

a-Original know-how target:

The decision was taken in Sept. 1981 to embark upon an EMIS R&D program at Tuwaitha. It was based upon the availability of the necessary programs for the computation of magnetic fields in two dimensions, the experimental work that had been conducted during the period from March 1975 to Dec. 1981 on ion sources for a linear accelerator and upon the available open literature on the subject. The goal was to achieve a theoretical understanding of electromagnetic design adequate to support the design, construction and operation of electromagnetic separators type $\Pi\sqrt{2}$. This was targeted to continue until Dec. 1991.

b-Original production target:

The original research and development work envisaged in 1982 was to build a double focusing isotope separator magnet of 40 cm central radius (R40) with the objective of constructing electromagnets and their necessary parts so as to ascertain the accuracy of the field computation. It also included the building of two other R40 magnets (Jan. 1985) with one ion source in each to test the performance of such a separator using UCl_4 as feed material.

The R&D work also included the construction of three RI00 separators and one R50 separator (of central radius 100cm and 50cm respectively) with the objective of achieving the predicted current at the collector and enrichment, improvement of design of source and collector and establishing procedures of assembly, operation and recovery of feed material, product and waste.

c- Actual theoretical achievements:

The theoretical achievement of this work included:

Verification of the magnetic field design through actual measurements in Sept. 1984.

Establishment of operating conditions including arc characteristics, ion extraction, oven operation and separator process l) parameters in Jan. 1986.

d-Actual production achievement:

In Jan. 1986 a mass spectrum of the extracted ions from the R40 separator showed clear separation of U-238 and U-235 ions for the first time, but no material was collected. These activities were carried out at Bldg.73. 1.

Several hundred runs were performed on the separator R 100-1 during the period October 1987- Dec. 1990. A maximum uranium enrichment of 13% was achieved in March 1990. By Jan.1991 an average current of U^+ ions of 120 mA was achieved at the collector.

Operation of the R100-2 separator gave a maximum enrichment of 8% with an average current of U^+ ions of 100 mA at the collector.

Operation of the R100-3 separator supplied adequate information about operating the separator with two ion sources, which included a ducting assembly in front of both sources and the use of space charge neutralisation plates above and below the ion source and collectors. This arrangement gave improved results.

Operation of the R-50 separator commenced in March 1987 with Argon ions. In December 1987 a maximum uranium enrichment to 15% was achieved. By Jan. 1991 an average current of U^+ of 40 mA was achieved.

During the period from May 1988 to Jan. 1991, milligram quantities of uranium were obtained in one of the operations having an enrichment of 40-45% using the R50 separator. In total 0.448 kg was produced with enrichment in the

range between (5 - 45)%.

e- Further steps to be implemented to achieve the original target:

The R&D at Tuwaitha was continued to optimize designs and operating conditions for the planned production plants. This included the introduction in April 1985 of open magnet design rather than the closed type. In 1987-1988 a multi-magnet system which was scaled down (1:5) version of the production system was installed. This unit allowed an investigation of magnetic forces and flux density distribution, Furthermore, the design and erection of a multi-source unit similar to those envisaged for the production phase was completed and tested with UCL₄ in Bldg. 80 at Tuwaitha between May 1987 and June 1990.

f- Indigenous production of critical components and equipment:

The indigenous production included the following:

Magnets: Design of the magnets was performed by the physics, mechanical and electrical design groups at Tuwaitha. Three magnets of the R40, one of R50, and three of the R100 types were assembled in Bldg. 80 and 73.1 at Tuwaitha. The iron pieces of the magnets (including poles and return iron) were fabricated at Bader General Establishment (BGE). The magnet coils were fabricated at the General Establishment for Electrical Industries (GEEI) and at Tuwaitha.

The vacuum system for the R40, R 100 and R50 separators: All the required components of the systems including the liners and the conical walls were fabricated at Tuwaitha, BGE and Oqba Bin Nafi General Establishment (OGE). The vacuum pumps and components such as gauges and valves were imported. This was completed in 1987.

Ion source systems: Two ion sources for the R40 separators, four ion source systems for the three R100 separators, and one ion source system for the R50 were fabricated. Two of the R100 separators had a single source while the third had a

double source. The R40 and R50 had a single source. At the early stages a PIG type ion source was chosen. However, by Dec. 1987 a decision was taken to adopt a calutron type (directly beated) ion source. An extraction slit width of 10 mm was the preferred choice. The ion sources were fabricated at Tuwaitha (Bldg. 17). Seven ion sources were produced.

Collector systems: The collector systems for the R100 and R50 separators were fabricated in Iraq using imported materials. They consisted of two l) pockets and a front plate pocket face of crescent shape. They were electrically isolated from each other. One of the pockets was for the collection of enriched uranium, the second was for the collection of the depleted uranium. Double identical collectors were used in the third R100 separator to accommodate the beams of the two ion sources. Four collector systems were fabricated at Tuwaitha (Bldg. 17).

Power supplies: Power supplies for the operations of R40, R100 and R50 separators were imported. The Faraday cage and the platforms that were insulated from ground and kept at high voltage potential up to +35 kV were designed, fabricated and assembled indigenously at Tuwaitha site (Bldgs. 82, 17). The total quantity produced was 6.

Remote control and data acquisition units: Separator operating parameters were set and controlled through an indigenously built operator console. This allowed assessment of different feedback strategies for power supplies and ovens.

g- Assessed time to achieve target:

The R&D work achieved its major objectives prior to the start of operation of the Tarmiya separators in Feb. 1990. The operation of the separators would have continued until the operation of Tarmiya plant reached its design parameters.

h- Assessed maximum achievable production:

The R&D work was continued to obtain the design parameters of ion current

and enrichment. The average ion current continued to increase as the R&D work progressed and eventually exceeded the design value, while the enrichment did not. That required more R&D work.

i- Explanatory notes related to any of the above elements:

The nature of this work was R&D to optimize designs of various system components and to achieve optimal operation parameters to meet design values.

j- FFCD ref.:

Part I section 1 .2.2A, Part IIb Section 4. 1 .3-4. 1 .6.

2. EMIS-Production at Tarmiya and Al-Sharqat

a- Original know-how target

In May 1985 a new approach was proposed with regard to the design of the separator magnets to be of the open type ($\Pi\sqrt{2}$ double focusing). Experience gained during the R&D phase at Tuwaitha on the scaled down (1:5) version of the R120 (central radius 120cm) provided the needed know-how. The construction of the Tarmiya buildings started in Dec. 1987 after completion of the design. A decision was taken in Dec. 1987 to build replica of Tarmiya at Al-Sharqat for two purposes: to replace Tarmiya if the latter were rendered completely non-operative, to double the production capacity. The R120 separators initially installed at Tarmiya were to be used to conduct experiments concerning the assembly, operational procedures, electrode configuration, focusing and collection of ions to gain additional known-how.

b- Original production target

The Tarmiya plant was to accommodate seventy identical separators of the R120 type arranged in two lines. Each line of 35 separators would have 34 double-pole pieces and 2 single pole pieces. Tarmiya would also have twenty R60 (central

radius 60cm) separators in two lines, each line was to have 10 separators and to be completed in two steps of 5 units each.

In Sept. 1987 the plan for production, installation, operation and material flow for the Tarmiya was adopted. It was continuously modified to take into account the fabrication capabilities.

The final plan for the installation of the 70 R120 separators at Tarmiya was as follows:

Line	No. of Separator To Be Installed	Start Up on The First Separator	Start Up of The Last Separator
Line 1	7	1/11/1989	15/02/1990
Line2	17	15/03/1990	01/12/1990
Line 1	10	01/01/1991	01/06/1991
Line 2	18	01/07/1991	01/04/1992
Line 1	18	01/05/1992	01/02/1993

Installation of first phase of the R60 separators of 5 units would start on 1/10/1990 and that of the fourth phase of 5 separators on 1 5/3/1992.

The system at the design parameters would produce about 15 Kg U/year of 93% enrichment from natural uranium feed. The design values of the R120 separator were 150 mA collection current of U^+ per source with an enrichment of 18%. The corresponding values for the R60 separator were 50 mA per source and the enrichment of 93 % The R120 and R60 separators would have four and two ion sources respectively.

Construction at the Al-Sharqat site started in Feb.). 1988 and the buildings (main process, substations (132 kV/11 kV and 11 kV/0.4 kV), chemical laboratory, mechanical rooms for air handling, main utility block and restaurant) were not

fully completed by Jan. 1991 . No processing equipment of any sort was installed at this site. Some equipment for the uranium recovery units were purchased in the quantities required for both Tarmiya and Al-Sharqat.

c- Actual theoretical achievement

Verification of the magnetic field accuracy in open magnets of the series configuration was achieved by designing and installing a special field-measuring instrument to scan the good field region. Field measurement performed in Jan. 1990 showed that the actual magnetic field agreed with the design values to better than 0.1%.

Better understanding of the operation of four arcs sources and the associated problems, such as the effect of electron drain current on the system stability and power requirement, led to the construction of special baffles that improved stability and minimized damage to the liners and insulators.

d-Actual production achievements

In Feb. 1990 the first R120 separator of the first line began operation. It was decided that eight separators rather than seven would be initially installed in line 1. The eighth separator began operation in Sept. 1990. Research work utilizing the installed eight R120 separators focused on 3 objectives: the integration of the various systems of operation increasing the production rate of enriched uranium and improving the availability of the separators.

In July 1990 work started on installing 17 separators of the second R120 line, but only 3 of the 18 double poles had been installed by Jan. 1991. In Nov. 1990 preparation commenced for installing. The R60 separators but none of these had been installed by Jan. 1991.

Despite the R&D nature of operation, 0.685 kg of uranium of 4% average enrichment was produced by Dec. 1990. The highest enrichment obtained was

9.5%.

The average monthly quantitative performance of the eight separators, achieved over the last three months of operation was 16% of the design separative work. The average availability of the separators was 10%.

e- Further steps to be implemented to achieve the original target:

- First, completing the installation, testing and commissioning as planned.
- Second, to increase the efficiency of the utilization of useful field volume and to make the associated operations easier, modification of the design of the R120 was to include increasing the gap height at the central radius and increasing the distance between the adjacent separators.
- Third, to increase the availability would require improvement of the stability of operation and minimizing the service time.

f- Indigenous production of critical components and equipment

- **The magnets:**

The iron part of the magnets including the double poles, end poles and return iron was designed and fabricated in Iraq to meet the requirements for installing two separators per month. Initially imported soft iron was used. During 1986 the establishment of a foundry at Naser General Establishment (NGE) was initiated and operated in October 1988. Actual production commenced in June 1990. The foundry could produce castings to meet the requirements of the magnet production for both Tarmiya and Sharqat.

Magnet coils were designed and fabricated at Tuwaitha using imported O₂-free Cu conductor.

- **The vacuum system:**

Vacuum pumps and components, such as valves and gauges were imported.

The vacuum chambers and liners were designed and fabricated in Iraq at Oqba Bin Nafi General Establishment (OGE) and General Establishment for Heavy Engineering Equipment (GEBEE) using imported stainless steel.

- **Ion Sources**

The required ion sources were designed at the Engineering Design Group of PC-3 in Tuwaitha and fabricated at OGE. Materials of construction such as graphite, stainless steel, and insulators were imported.

Eight complete systems (32 ion sources) for R120 were operational during 1990 and one complete system (4 ion sources) were available as spares. Six systems (12 ion sources) for the R60 were fabricated, but were not assembled.

- **Collector systems:**

Each collector system for the R120 separator consisted of four pockets for the enriched ion beam and another four for the depleted ion beam. The face of each pocket was of crescent shape to accommodate the actual beam profile

Each collector system for the R60 separator consisted of two pockets for the enriched and another two for the depleted ion beams.

The collectors were designed and fabricated in Iraq at OGE except for a few mechanical components, such as insulators and flexible hose bellows, that were imported.

Eight collector systems for R120 separators were operational during 1990, and six collector systems for R60 were fabricated but were not commissioned. No additional systems were fabricated.

- **Power Supplies**

The power supplies were to be assembled at Dijjla site according to the planned requirements of the separator operations. The specifications and definition

of requirements were based on the know-how acquired at Tuwaitha. All critical components and equipment were imported.

- **Data acquisition and control systems**

The decision to apply large scale computerized acquisition and control system for the Tarmiya projects were started Jan. 1986. The complete specifications and definition of requirements of the system were completed in Dec. 1987 based upon the experience gained from the R&D work at Tuwaitha. Data acquisition and control units were planned to be installed parallel to the installation of the separators, and based on the idea that each separator is controlled modularly by its assigned unit. In July 1989 the design and implementation details of the units were completed.

Eight units were fabricated and assembled. The first unit was completed and installed in Jan 1990 and by Sept. 1990 the eight units were in operation.

The production facility at Dijjla was capable of producing the units according to the planned schedule. All elements and fibre optic components were imported. Printed circuit boards were designed and manufactured at Dijjla. Control software was designed, written and tested by Iraqi personnel at Tuwaitha and Tarmiya sites.

- g- Assessed time to achieve target:**

It was estimated that the Tarmiya plant would achieve its original target about one year from completion of the installation of the plant in Feb. 1993. There was no definite plan for completing the Al-Sharqat site, but work would shift to Al-Sharqat as soon the installation of units at Tarmiya was complete.

- h- Assessed maximum achievable production:**

It was estimated that LEU feed material of 3% would increase the amount of BEU product by a factor 4. The enrichment of the product would also increase to

98%.

i- Explanatory notes related to any of the above elements:

None.

j- FFCD Ref.:

Part I Section 1.2.2 A, Part IIb Section 4. 1,7-4. 1 .9

3. Production of feed material for EMIS /UCL₄ production at Tuwaitha

a-Original know-how target:

UCL₄ was selected to be the feed material for EMIS and a decision was taken in Jan. 1982 to initiate a program to prepare and purify UCL₄ on a laboratory scale in order to provide design data for a pilot plant. The work included the following:

Laboratory work using glassware with a handling capacity of less than 100 gm per batch. This work continued in parallel with other activities up to Dec. 1987.

Pilot production at a rate of 1 kg/batch using a fluidized bed technique started in March 1986 and terminated in Dec. 1987.

Pilot production at a rate of 25 kg/day started in Jan. 1988 and continued up to Jan. 1991.

Sublimation units of up to 1 kg UCL₄/ batch started June 1987 and continued up to Jan. 1991.

Pilot experiments to produce UCL₄ by a liquid phase reaction were conducted in April 1989 and terminated in Jan. 1991.

b-Original production target:

During the initial stages of EMIS R&D work at Tuwaitha, the production

target was set to meet the immediate separator feed requirements. However, as work progressed a target of 25 kg/day was planned which was considered to be sufficient for the R&D work.

c- Actual theoretical achievement:

The laboratory work led to a better understanding of production, handling and purification of UCl_4 .

d-Actual production achievement:

A pilot plant with a maximum operational capacity of 40 kg/day and a nominal capacity of 25 kg/day based upon a rotary kiln technique, was designed and assembled in Bldg. 85. Commissioning of the plant was in Jan. 1988 and it continued production during 1988 - 1990 with a total production of approximately 4.27 tons of UCl_4 .

Six sublimation units were fabricated and installed in Bldg.85 for the production of pure UCl_4 to fill the charge bottles for the EM IS separators. A total quantity of about 1.1 tons of sublimed UCl_4 was produced from the impure UCl_4 prepared.

Three pilot units with design capacities of 1 kg/ batch were designed, fabricated and assembled at Bldg. 85 during the period Nov. 1988 to Dec. 1989 based on liquid phase chlorination. Three similar units based on gas phase chlorination, one of them using a rotary kiln and the other two using a fluidized bed reactor, were also designed, fabricated, and assembled at Bldg. 80 in this period.

The objective was to test other technologies for the preparation of small quantities of UCl_4 . Some of these proved unsatisfactory and were terminated, while the liquid phase chlorination of UO_3 using CCl_4 proved useful and was to be adopted for the preparation of enriched UCl_4 .

e- Further steps to be implemented to achieve the original target:

The pilot plant (25kg/ day) achieved its original target during July 1988. No further steps were required.

f- Indigenous production of critical components and equipment:

The critical equipment for UCl_4 production (such as the rotary kiln reactor and the vacuum pump that was used for sublimation) were imported. The vacuum chamber for sublimation and its internals and various tanks were fabricated at the Tuwaitha workshops.

g- Assessed time to achieve the original target:

The target was achieved and even exceeded during 1988.

h- Assessed maximum achievable production:

The process operated on a continuous basis for periods extending from few days to few weeks. In some runs its production capacity exceeded the design capacity and reached about 40 kg/day due to variation in the operating conditions such as the residence time. This plant was not designed as a production plant, but it could have reached a production rate of 25 kg/day.

i- Explanatory notes related to any of the above elements:

During the EMIS development program, the feed material quality and quantity satisfied all the program requirements and at no time did it hamper program development.

j- FFCD Ref.

Part ha Section 4.2.2.

4. Yellow - cake production at Al-Qaim

a. Original know-how target:

A chemical complex was established at al-Qaim to produce one million tons of phosphate fertilizer per annum. The design of the unit was based on the Prayon process. Construction of the complex started in 1979 and was commissioned during 1983 - 1984. The uranium content of the phosphoric acid was to be extracted in the form of uranium peroxide UO_4 (yellow cake). The contract for the unit was issued in May 1981 by the Iraqi Ministry of Industry and Minerals to a Belgian company called Mebsbem.

b. Original production target:

The design capacity of the unit was 103 ton U/annum on the assumption of 60 ppm U in the ore and 75 ppm U in the low concentration phosphoric acid yield. It was planned to start production in Dec. 1984.

c. Actual theoretical achievement:

The flow sheet of the unit 340 uranium extraction process was made available by the Mebsbem contracting company. The process consisted of four sections as follows:

- Acid clean up, to make the phosphoric acid feed amenable to solvent extraction.
- Cycle I- Producing U concentrated phosphoric acid solution by solvent extraction.
- Cycle II-producing a partially purified U solution by solvent extraction.
- Refinery - producing a U solid concentrate.

d. Actual production achievement:

The plant (unit 340) was erected and commissioned by the Belgian company in Sept. 1984 and went into production in Jan. 1985. The total quantity produced was 168 tons of yellow cake extending over the period Jan. 1985 to July 1990.

e. Further steps to be implemented to achieve the original target:

No further steps could be implemented to achieve the design productivity of the unit since the actual content of U in the phosphoric acid, was low, 45-75 ppm and the phosphoric acid produced in the fertilizer complex was often not passed to unit 340 so as to maximize fertilizer production.

f. Indigenous production of critical components and equipment:

None.

g. Assessed time to achieve original target:

Although the design production capacity was not achieved due to the intermittent operation of the unit, it was more than adequate to meet foreseeable needs, and no optimization was planned.

h. Assessed maximum achievable production:

The design basis maximum achievable production was 158 tons/ year of yellow-cake, but due to lower than expected U concentration in the feed material, the maximum achievable production would have been between 95 and 158 tons/ year.

i. Explanatory notes related to any of the above elements:

None.

j. FFCD Ref.:

Addendum II Part 1 C2/7 pp. 24-30, Part IV 8.2.1.

5. Production of Feed Material /Production of Pure UO_2 from UO_4 at A1-Jazira

a- Original know-how target:

The plant was originally designed for the production of nuclear grade UO_2 by Natron Company (Brazil) during the period 1981-1983. An attempt was made during 1983 by Iraqi personnel to design and build a smaller plant of 103 tons/year

capacity. However, due to the lack of experience and the process complexity, a decision was made in Nov. 1983 to adopt the Natron design whose construction was completed over the period 1984- 1986. Meanwhile, a site for the plant was selected near Badoosh area north of Mosul, and a new site plan was adopted to meet the requirements of the chosen site that was named Al-Jazira on March 1989.

b-Original production target:

The plant was designed to produce 185 tons/ year of pure UO_2 starting from yellow cake (UO_4) of different physical forms in order to produce feed material (UCl_4) for the EMIS plants, when the R120 separators at Tarmiya are fully operational in Dec. 1993 and those at Al-Sharqat by Dec. 1996. No other requirement for UO_2 was taken into consideration at the time.

c- Actual theoretical achievement:

The design documents received from Natron in 1986 were revised by the Iraqi team to comply with the requirements imposed by the new site and to suit the specifications of the equipment procured from various suppliers. This was completed in July 1987.

d-Actual production achievement:

The plant was erected during the period 1987-1989. It was commissioned during June 1989, started-up and operated during July 1989 to Dec. 1990. During this time 100 tons of pure UO_2 was produced. Many problems were encountered in the course of start-up and commissioning which reduced the production capacity. The mechanical failure of two major vibratory elevators and the high wear rate of stators of monopumps were overcome by introducing modifications.

e- Further steps to be implemented to achieve the original target:

The escape of very fine particles with filtered liquid from the filter cloth of the rotary vacuum filters needed improvement to minimize uranium content in the liquid concrete waste tanks that had already accumulated about 10 tons from previous operation.

f- Indigenous production of critical components and equipment:

Construction of the buildings, installation of the equipment and operation of the plant were performed indigenously by the specialized groups of PC-3. Critical process equipment, such as rotary furnaces were imported.

g- Assessed time to achieve original target:

After start-up and treatment of related problems during the period July 1989 to Dec. 1989, it was estimated that 12 months would be needed to achieve the production target starting from Jan. 1990. However, this was not achieved by Jan. 1991 and a further six months would be required to achieve the original target.

h- Assessed maximum production achievement:

The plant was designed to produce 185 tons/ year of pure UO_2 . This was considered to be the maximum achievable production.

i- Explanatory notes related to any of the above elements:

The plant output exceeded the EM IS program requirements at the time of operation in July 1989. Nevertheless, it was decided to process all the available UO_4 (yellow cake) (A1-Qaim, Niger and Portugal). This would provide enough UO_2 for the production of the required UCl_4 for the R120 separators for several years. The recovered natural uranium from these separators would be reconverted to UO_2 .

j- FFCD Reference:

6. Production of feed material for EMIS / UCl_4 production at Al-Jazira

a- Original know-how target:

Based on the experience gathered from the R&D work at Tuwaitha, it was decided in Sept. 1987 to design and construct a UCl_4 production plant at Al-Jazira site (chlorination of pure UO_2 using CCl_4) in a continuous process adopting the rotary kiln technique. March 1989 was the target date to complete the plant design and Jan. 1990 was the target date for commissioning. The UCl_4 produced would be purified by vacuum sublimation using a number of units to be designed in accordance with the experience gained at the Tuwaitha pilot plants.

b- Original production target:

The plant was designed to produce 105 ton/ year of UCl_4 in two production lines starting in Jan. 1990. The product was to be further purified by sublimation in a number of units on a batch basis, in order to feed the EMIS production separators. The uppermost requirement of each R120 separator is 1.7 kg/day of purified UCl_4 (assuming feed rate of 490 gm U/source/day and a design availability of the separator of 55%). Consequently, the uppermost total requirement of the R120 separators planned for Tarmiya and Sharqat plants is about 70 ton/year of purified UCl_4 (assuming a total of 140 separators and about 300 working days/year) The unpurified UCl_4 required is about 100 ton/ year assuming a sublimation efficiency of 70%.

c- Actual theoretical achievement:

In March 1989 the design took into consideration all problems encountered during the operation of the pilot plant, project 242, at Tuwaitha and introduced improved techniques for handling the feed material and product.

d- Actual production achievement:

The equipment installation was completed in Dec. 1989. After performing all required tests over the period Dec. 1989 to Feb. 1990, one of UCl_4 production lines was put into operation while the other line was still under construction.

Some problems in the flow of the solid material and off gases were experienced. Many trials to optimize operating conditions for high conversion ($> 97\% \text{UO}_2$ to UCl_4) were conducted and continuous operation for more than 72 hours with the required product specifications was achieved in Feb. 1990. During all operations a total of 1200 kg of UCl_4 was produced. However, production was stopped, because the need for UCl_4 could still be met by the Tuwaitha pilot plant.

e- Further steps to be implemented to achieve the original target:

Modification of some equipment that was problematic during the start-up phase of the first production line in addition to other modifications to suit the operation requirements were to be introduced. The second production line and the construction and operation of UCl_4 purification units were still incomplete by Jan. 1991.

f- Indigenous production of critical components and equipment:

The sublimation units were being produced at Tuwaitha. Other critical components such as rotary furnaces were imported. Installation, commissioning and operation were conducted by PC-3 personnel.

g- Assessed time to achieve original target:

It was estimated in Jan. 1991 that 12 months would be needed to achieve the plant design parameters.

h- Assessed maximum achievable production:

The plant was designed to produce 105 tons of pure UCl_4 a year. This was considered to be the maximum achievable production.

i- Explanatory notes related to any of the above elements:

None

j- FFCD Ref.:

Part IIa4.2.1 Page 182/269

7. EMIS - Uranium recovery at Tuwaitha

a- Original know-how target:

An R&D program for the chemical recovery of uranium from various internal parts of separators commenced at Tuwaitha in June 1984 and continued in parallel with the design and construction of the relevant pilot scale plant at Tuwaitha and the production scale recovery at Tarmiya. This work included the following:

Laboratory scale activities started in June 1984 and continued in parallel with other activities up to Jan. 1991.

Pilot plant recovery of natural uranium from various parts of separators operating at Tuwaitha Bldg. 85 started in Sept. 1988 and continued until Jan. 1991.

Pilot plant recovery of enriched uranium from the graphite collectors of separators operating at Tuwaitha Bldg. 85 started in Jan. 1989 and was abandoned in Jan. 1991

b- Original Production targets:

Laboratory and pilot scale recovery of uranium from parts of separators was to meet all the operation requirements of the R100 and R50 separators at Tuwaitha until Jan. 1991.

c- Actual theoretical achievement:

By Dec. 1988 all the theoretical aspects of uranium recovery from various internal separators parts were adequately understood utilizing open literature and the results of laboratory and pilot scale experiments.

d- Actual production achievement:

Throughout the period of work extending from June 1987 to Jan. 1991 about 380kg of natural uranium was recovered from the UCl_4 deposited on the various parts of R100 and R50 separators. This was recovered either manually or by dissolution in laboratory scale equipment or in the pilot scale recovery plant installed at Tuwaitha. During the same period about 0.64 kg of enriched uranium was recovered from the collectors utilizing laboratory methods and equipment. Likewise, about 6.4 kg of depleted uranium was recovered in the same manner.

e- Further steps to be implemented to achieve the original target:

No further steps were found to be necessary.

f- Indigenous production of critical components and equipment:

Most of the components of the pilot plant were fabricated by the mechanical workshop at Tuwaitha.

g- Assessed time to achieve original target:

The original target was met in Jan. 1991.

The recovery facilities met all the requirements of the R&D separators operating at Tuwaitha throughout the period of their operation.

h- Assessed maximum achievable production:

The facilities available were capable of recovering all the uranium feed product or waste to the required efficiency.

i- Explanatory notes related to any of the above elements:

None

j- FFCD Ref.:

Section 4.2.3 and Fig. (8.5-1)

8. EMIS - Uranium Recovery at Tarmiya

a- Original know-how target:

The R&D program for the chemical recovery of uranium from various internal parts of EMIS separators at Tuwaitha started in June 1984 and continued in parallel with the operation of the separators at Tuwaitha provided the know-how for the Tarmiya recovery plant.

b- Original production target:

Recovery of uranium from internal parts of liners and from pockets of the R120 and R60 separators and as follows assuming 100% recovery

- From the R120 separators:
 - 55 kg/ year of enriched U (18%) from product pockets
 - 1400 kg/ year of depleted U from waste pockets
 - 2.1 tons U/year of natural uranium from liners.
- From the R60 separators:
 - 11 kg/year of enriched U (93%) from product pockets
 - 44 kg/year of depleted U from waste pockets
 - 550 kg U/year of 180% enriched from liners.

c- Actual theoretical achievement:

By Dec. 1988 all the theoretical aspects of uranium recovery from EMIS separators were adequately understood from the practical recovery work at Tuwaitha. The information acquired was adequate for the detailed design and construction of the production scale plant at Tarmiya.

d-Actual production achievement:

By Jan. 1991 none of the recovery buildings had all their equipment installed, therefore, no actual recovery of uranium on a production scale at Tarmiya was achieved before termination of the program. However, a temporary

recovery unit was installed in Jan. 1990 at Tarmiya Bldg. 62 to provide washing and cleaning services for the eight R-120 separators that were being commissioned at Tarmiya during 1990. Out of 280 kg natural U as UCl_4 that was handled during operation of R120 separators at Tarmiya in 1990, a total of 267 kg U was recovered as liner wash. The remaining 13-kg of uranium were recovered as enriched U (0.685 kg), depleted U (2.9 kg) and natural U (9.4 kg).

e- Further steps to be implemented to achieve the original target:

To achieve uranium recovery on a production scale it was necessary to complete fabrication of the equipment locally and then to complete their actual on-site installation.

f- Indigenous production of critical components and equipment:

Washing chambers (for liners) and leaching tanks (for collectors) were under fabrication at Al- Rabee factory by Jan, 1991. Other equipment were imported

g- Assessed time to achieve original target:

The installation and commissioning of the recovery plant would have been completed by June 1992.

h- Assessed maximum achievable production:

After commissioning, the capacity of the recovery plant would have been sufficient for the 70 R- 120 and for the 20 R-60 separators that were planned for Tarmiya as described at (b) above.

i- Explanatory notes related to any of the above elements:

None

j- FFCD Ref.:

Section 4.2.3, Table (4.1. 10-6).

PART II: Centrifuge Enrichment And Gaseous Diffusion

1. Gaseous Diffusion Barrier Development And Laboratory Scale Production

a. Original know-how target:

In June 1982 it was decided to develop a suitable barrier for the gaseous diffusion (GD) process for the enrichment of uranium with natural UT_6 as feed. The original know-how target was to comprehend the physical processes associated with molecular flow of UF_6 across the diffusion barrier as a function of upstream and downstream pressure including the effect of capillary condensation and its dependence on pore size. It was estimated that the open literature survey and various laboratory experimental set-up could be concluded by Dec. 1984. Based on this know-how, a laboratory-scale production line would be set-up to produce barrier tubes for GD R&D work by Dec. 1985.

b. Original production target:

To achieve an adequate understanding of the method of producing an adequate GD barrier tube and to set-up a laboratory-scale production line for good quality tubes at a rate of 10 m/day by Dec. 1985.

c. Actual theoretical achievement:

An adequate understanding of the flow of UF_6 through porous media was achieved by Dec. 1 984. The following studies were completed: -

- Gas flow behavior through and along porous tube wall.
- Characteristic pressure calculations for a porous tube.
- Study of flow through porous barriers.
- Study of the effect of adsorption inside pores.

d. Actual production achievement:

The following was achieved: -

- An R&D laboratory for flow measurements and characterization of GD

barriers was setup in Bldg. 23 in Tuwaitha in Jan. 1984.

- Mechanical and structural characterization of GD barriers were made in Bldgs. 23 and 73 at Tuwaitha in Jan. 1984.
- A suitable anodized aluminum barrier tube for inert gas separation was developed and tested by Dec. 1984.
- A laboratory-scale production line for approximately 10 m/day of inert gas barrier tubes was implemented in Bldg. 23, in Tuwaitha by Dec. 1986. About 600 tubes were produced (60 cm long 10 mm i.d.) for project 301 by April 1987.
- Corrosion rigs for testing GD barriers with corrosive fluids (HF, F₂ and UF₆) were built in Bldg. 15 B in Tuwaitha in period Jan. 1986 - Dec. 1987. In April 1988 a UF₆ corrosion rig was operated in Bldg. 10 (Hall C) in Rashdiya.
- In Sept. 1988 a dynamic corrosion rig for testing four barrier tubes with a single stage diffuser of four tubes of 2.4 m was built in Bldg. 10 (Hall C) in Rashdiya.
- The barrier tube developed for the GD process with UF₆ showed good flow stability for a period of about four months, and a separation factor of 1.002 & 1.003 was achieved in Oct. 1989.

e. Further steps to be implemented to achieve the original target: (see 4.a)

None. In Aug. 1987 the decision to start a centrifuge enrichment program was taken. At the same time it was decided to continue the gaseous diffusion program to the stage of testing the diffusion barrier as a hedge against unforeseen problems with centrifuge enrichment. Therefore, the GD program was stopped in Oct. 1989.

f. Indigenous production of critical components and equipment:

All process specific components, such as barriers, diffusers and cold traps, were fabricated locally at Rashdiya workshop section Bldg. 9 and Bldg. 10 hall C. General engineering materials, such as valves, pipes, pumps, compressor and instruments were imported.

g. Assessed time to achieve original target:

The original target was achieved in Oct. 1989.

h. Assessed maximum achievable production:

This was R&D work no production goal set.

i. Explanatory notes related to any of the above elements:

None

j. FFCD Ref.:

Part IIb, Sec. 4.4 sub sec4.4.4 page 81-91/312

2. Design of a 24-Stage Gaseous Diffusion Cascade for Measurement of The Separation Factor

a. Original know-how target:

In Oct. 1988 a gaseous diffusion cascade was considered. Its aim was to measure the separation factor with UF_6 gas using a single barrier of 3 m long porous tube (5 barriers of 60 cm long) for each stage with 12 metallic diaphragm double bead compressors to be ordered from abroad.

b. Original production target:

The objective was to construct the cascade to measure the barrier separation efficiency with UF_6 gas.

c. Actual theoretical achievement

Since most of the theoretical aspects of gaseous diffusion cascade were

adequately understood by the assigned team, a basic design report for the cascade was issued in Feb. 1989 and the detailed design for the diffuser was completed.

d. Actual production achievement:

None.

e. Further steps to be implemented to achieve the original target:

Since the single diffuser gave a measurable separation factor, the activity of constructing the cascade was cancelled in Oct. 1989. At that time a decision was taken to drop the gaseous diffusion process in order to concentrate efforts on the magnetic centrifuge, as it was certain that magnetic centrifuge technology was more promising.

f. Indigenous production of critical components and equipment:

Engineering materials for construction were procured from abroad and some specific process related components were to be manufactured in Iraq at Rashdiya workshop section Bldg. 9 and Bldg. 10 hall C, such as barrier tubes, diffusers, cold traps, UF_6 handling cylinders, and UF_6 gas.

g. Assessed time to achieve original target:

N/A since the project was cancelled, see (i) below.

h. Assessed maximum achievable production:

None.

i. Explanatory notes related to any the above elements:

When the 24-stage GD cascade was conceived EDC did not believe that it is instrumentation could detect the separation factor of a single GD barrier. EDC found a MS capable of measuring the single barrier separation factor at the 1AEC. This made the cascade concept unnecessary and it was stopped.

j. FFCD Ref.:

PartIIb, sec. 4.4, sub. Sec. 4.4.4 page (87/132). (93/132).

3. Production of UF₆

A- Laboratory scale preparation of UF₆ by direct fluorination

a-Original know-how target:

In Jan. 1985 a decision was taken to initiate work on the laboratory-scale UF₆ preparation to familiarize workers with the direct fluorination process. The available know-how in the literature was achieved.

b-Original production target:

None. This was R&D to solve problems associated with the preparation, capture, storage, handling and use of UF₆.

c- Actual theoretical achievement:

By Dec. 1987 enough experience was gained to judge that the original target was considered achieved.

d- Actual production achievement:

In June 1985 few grams of UF₆ were prepared for the first time in Bldg. 15 B at Tuwaitha. The experimentation continued until Dec. 1986. The acquired practical know-how was employed to establish a better laboratory-scale UF₆ preparation unit to produce small quantities of UF₆ (50 g/ batch nominal capacity) beginning Jan. 1986. F₂ gas for the laboratory-scale unit was supplied from imported cylinders, whereas UF₄ was prepared from available UO₂ [see explanatory notes below on sub-activities related to UF₆]. 3.63 kg of UF₆ was prepared using the laboratory-scale unit, in Bldg. 15 B at Tuwaitha, over the period Jan. 1986 to Dec. 1987. This quantity of UF₆ represents the accumulated sum of all the experimental runs output over that period. All items related to the laboratory-scale UF₆ preparation was transferred from Tuwaitha to Rashdiya in Dec. 1987.

After this date, Rashdiya became the only site where UF_6 was prepared until the termination of the program in Jan. 1991. At Rashdiya a second similar UF_6 preparation unit was assembled in Dec. 1988. A total of 6.187 kg UF_6 was prepared at Rashdiya over the period from June 1988 to Jan. 1991 utilizing these two units. Hence the total sum of UF_6 prepared at Tuwaitha Bldg. 15B from Jan. 1986 to Dec. 1987 and at Rashdiya from June 1988 to Jan. 1991 was 9.817 kg UF_6 .

e- Further steps to be implemented to achieve the original target:

No further steps were found to be necessary.

i- Indigenous production of critical components and equipment:

The laboratory-scale UF_6 preparation unit was assembled from available standard imported components and placed in a fume-hood. Standard UF_6 cylinders of the type 1S, 2S and 5A (the 5A cylinder served as a receptacle for UF_6), as well as cold-traps were locally fabricated at Tuwaitha in Bldg.16 and the rest at Rashdiya workshop section Bldg. 9 and utilized with these two units, no other types were indigenously produced [see part II section 4(f) bullet 4 (page 21/62)].

g- Assessed time to achieve target:

The target was achieved and UF_6 was made available for the R&D work on enrichment technologies.

h- Assessed maximum achievable production:

Not applicable due to the experimental nature of the laboratory-scale unit.

B. Pilot and/or production-scale UF_6 by direct fluorination

a- Original know-how target:

The decision to embark upon an indigenous UF_6 production was taken shortly after formation of the Office of Studies and Development (OSD) of the IAEC in Jan. 1982, because gaseous diffusion was one of the enrichment options

considered. By May 1984 there was sufficient know-how to embark upon the design of a 2 kg UF₆/ batch pilot unit employing fluid-bed reactor technique.

b- Original production target:

Originally it was envisaged that UF₆ production capability should match its requirement for the development of the gaseous diffusion program. However, no specific planned production goal or date was fixed at the time, pending the know-how development of both UF₆ production as well as gaseous diffusion. As for the centrifuge program, it was envisaged in June 1989 that by May 1994 a UF₆ production capability of 4 ton UF₆/ year should be available.

c- Actual theoretical achievement:

Studies utilizing the available literature on the production of UF₆ by direct fluorination of UF₄ were carried out during 1982- 1983.

d- Actual production achievement:

A project of 2 kg/batch producing UF₄ from UO₂, and/or UF₆ from UF₄ using fluid-bed reactor technique was designed and executed during May 1984 to May 1985 in Bldg. 15B at Tuwaitha, but was cancelled due to inherent conceptual design faults. Following this cancellation, the basic design of a 2 kg/ batch UF₆ project employing also the fluid-bed reactor technique was completed in Dec. 1986. Detailed engineering design work on the 2 kg/batch UF₆ project was completed by Dec. 1987. The quantities of UF₆ that were required by harrier qualification experiments were very small and could easily be produced by the laboratory-scale unit. Following GI formation, and the re-evaluation of the gaseous diffusion program, even lesser emphasis were put on any UF₆ pilot / production-scale project. Up to program termination in Jan. 1991 this pilot project was not executed.

After the formation of Group I (GI) in May 1987, a number of designs for

UF₆ production employing fluid-bed or flame-type reactor techniques in a continuous process mode were carried out over the period June 1987 to Dec. 1989, but none was executed due to the fact that the gas centrifuge program was still in its very early stages on the one hand and the gaseous diffusion program went through a re-evaluation, which resulted in its cancellation on the other hand.

Finally to cope with the progress of the centrifuge program and to meet possibly larger UF₆ requirements which could not be met with the laboratory-scale units, a pilot and/or production-scale unit was designed with a nominal rate of 1 kg UF₆/hr. This unit was at the beginning of the construction phase at Rashdiya at the time the program was terminated in Jan. 1991.

No UF₆ was ever produced on a pilot/ production-scale.

e- Further steps to be implemented to achieve the original target:

It was envisaged to put the 1 -kg UF₆/hr unit, after completion on a commissioning and/or pilot-mode for a period of less than 6 months intended for familiarization and/or modifications prior to putting the unit on a production-mode. During the commissioning/pilot phase, F₂ gas requirement for the unit would have been supplied from available imported F₂ cylinders, whereas the production phase, F₂ gas requirement would have been supplied from the 0.25 kg F₂ /hr unit which was going to be installed in Bldg.25 at Rashdiya [see explanatory notes below on sub-activities related to UF₆].

f-Indigenous production of critical components and equipment:

No component or equipment belonging to the 1-kg/hr UF₆ unit was produced at the time of the termination of the program in Jan. 1991.

g- Assessed time to achieve target:

It was envisaged that the 1 kg/ hr UF₆ unit would be completed and commissioned by Jan., 1992.

h- Assessed maximum achievable production:

Following mechanical completion of the 1 kg/hr UF₆ unit, assumed in Jan. 1992, it was envisaged to reach the nominal design capacity 1 kg/hr on a continuous basis within 6 months of that date, i.e. by June 1992.

i- Explanatory notes on achievements concerning sub-activities related to UF₆:

(1) UF₄:

(i) Laboratory-scale UF₄ preparation (for UF₆)

- UF₄ preparation know-how had to precede or be concomitant to that of UF₆
 - The wet and dry methods to convert UO₂ to UF₄ were investigated on a laboratory-scale during 1985-1986. The dry method employing refrigerant -12 (R-12) as a fluorinating agent utilizing a Pyrex rotary reactor was highly successful, being relatively trouble-free and producing a satisfactory product for UF₆ preparation.
- About 250 kg of UF₄ was produced from the R- 12 laboratory-scale Pyrex rotary reactor unit from May 1987 to Jan. 1991. Most of this quantity was produced during 1987, 1988 and 1989. Little or no. UF₄ was produced during 1990 and the first 17 days of 1991 when the program stopped. Preparation of this UF₄ was done at Tuwaitha, Bldg. 15 B.

(ii) Pilot/production-scale UF₄

- To cope with progress of the gas centrifuge program, basic designs by EDC department C at Rashdiya were issued in Dec. 1988 for 2 kg UF₄/ hr units employing R-12 or anhydrous HF (AHF). Neither design was executed due to UF₄ availability.
- A rotary kiln reactor was imported from the USA in 1989 to be utilized with the 2 kg UF₄/hr unit utilizing AHF, being the only envisaged critical item.

The present location of the rotary kiln reactor is GEMEJ (see FFCD part IIb table 4.4.9-2 page 233/313).

(2) F₂

(i) Laboratory-scale F₂ generation

- Due to possibility of unavailability of imported F₂ cylinders and/or relatively large amounts being required for UF₆ (production, development of indigenous F₂ generating capability were looked at as early as 1983.
- Theoretical aspects of F₂ generating cell were studied in 1983 and 1986. Experimental aspects were investigated from 1985 through a laboratory-scale unit, commissioned in June 1987, based on a Brazilian design of a laboratory-scale cell. The unit was installed at Tuwaita, Bldg. 15 B, and generated 6.67 g F₂/hr from Jan. 1988 to Jan. 1991. The generated F₂ was immediately destroyed through scrubbing with KOH solution.

(ii) Pilot/production-scale F₂ generation

- In Jan. 1990, it was decided to implement a 0.25 kg F₂/hr unit design at Rashdiya Bldg. 25 in order to supply the production phase of the 1 kg UF₆/hr unit mentioned above. Implementation was halted in Jan. 1991
- The critical item for the 0.25 kg F₂/hr unit, namely the carbon anodes of the F₂ generating cell had arrived in Feb. 1990.

(3) Production of UF (due to accelerated activities):

From Sept. 1990 technical discussions took place at EDC with the coordinator of PC-3 concerning the request to produce a quantity of UF₆ using enriched UF₄ (56-80%). The discussions resulted in adopting a plan to use both the existing laboratory scale direct fluorination units in Hall C at Rashdiya and to assemble a third unit to reach a production capacity of 0.5 kg of UF₆ per day. This product was to be collected in (2S) cylinders and handed over to the EDC

separation process department for further enrichment. The enriched product was to be handed back to PC-3.

No work was conducted since as no enriched UF_4 ever received. The third laboratory scale UF_6 production unit was never assembled because none of its components were completed.

Ref. for UF_6 parts A and B as well as Explanatory notes (1) and (2) above: FFCD-F Part IIb Section 4.4.6 Ref for Explanatory note (3) above: FFCD-F Part IIIb Section 5.11.3 G

4. Centrifuge enrichment program

a- Original know-how target:

The centrifuge program know-how goals included:

- Understanding the science and the engineering required to design and manufacture subcritical high-speed centrifuges.
- Understanding the science and the engineering required to design and build centrifuge cascade.

The decision to embark on centrifuge enrichment program was taken in Aug. 1987, as the gaseous diffusion proved to be a formidable task and beyond the existing Iraqi capabilities at the time, due to enormous size and numbers of equipment. The decision was also to continue with the gaseous diffusion up to the stage of testing the performance of the anodic barrier.

b- Original production target:

The aim was to design and install a cascade of a 1000 subcritical machine capable of producing 10 kg/year of HEU by Dec. 1994 with natural uranium feed (UF_6).

• HEU Production

The centrifuge program production goal was 10 kg/year of BEU enriched to

93%.

- **Oil bearing centrifuge (see 5 for details)**

The initial goal program was to use oil bearing (Beams) centrifuges rated at about 0.5 kg SWU per machine in a cascade of 4000 machines. The cascade was to be located at Taji. The work on oil-bearing centrifuge began in Sept. 1987 and was expected to have a working prototype in Sept. 1989.

- **Magnetic centrifuge (see 6 for details)**

Since the oil centrifuge program presented numerous technological difficulties, where it was decided to abandon it in favor of the magnetic centrifuge as foreign assistance was available for the latter. The program began in June 1988 and a target was set to arrive at a working prototype in June 1990.

- **Centrifuge manufacturing facilities**

In Oct. 1985 it was decided that the centrifuge parts would be made abroad in sufficient numbers to arrive at a successful prototype.

At the same time EDC began procuring specialized manufacturing equipment for a local production facility at Al-Furat.

Construction of several buildings at Al-Forat started. They were to accommodate the various centrifuge parts production machine, assembly and testing equipment of centrifuges and a piping workshop, in addition to a cascade hall for a (100) centrifuge of the subcritical type. Due to the delays encountered in the execution of Al-Forat project, concentrated efforts were directed toward the conversion of a building sections at Rashdiya to have suitable specification for the required prototype experiments (project 520C). These included rooms for chemical cleaning, quality control balancing, and assembly, in addition to a mechanical test stand and a separation test stand, A suitable clean room condition was provided.

For the Al-Forat project, the intended production capacity of centrifuges was estimated at about 1000 machines per year of the short subcritical type, with maraging steel rotors. However, due to delays in the execution of this project, few machines were installed in a make shift workshop. This workshop was for the production of two centrifuge parts namely the jacket & molecular pump in Nov. 1989, together with the flow forming machine to carry out experiments on maraging cylinder production. The difficulties encountered by the supplier of the flow-forming machine in fixing the technology for producing good maraging cylinders were numerous and more time was needed to overcome these difficulties. Therefore, intentions shifted in April 1989 towards acquiring carbon-fibre cylinders. A number of these cylinders were ordered from outside, and later the acquisition of a carbon fibre winding machine.

- **Cascades (see 7 for details)**

Although no cascade were ever built, several cascade were considered. The following list summarizes the cascade considered:

- Oil bearing centrifuge of 4000 sub-critical machine at Taji.
- Project 521 B, Al-Forat 1 00 sub-critical centrifuge cascade.
- Project 521 B, 100 sub-critical cascade at Rashdiya. The site was changed due to construction delays at Al-Forat. The building was to be constructed, so that it could accommodate a supercritical centrifuge, for which a number of blue prints were acquired in Aug. 1989.

Work actually started in Feb. 1990 to construct the cascade building together with the buildings for UF_6 production (project 236) and Flourine gas production (251). These projects were in their early construction phase in Jan. 1991 when work in the program was halted.

- Project 522, 1000 magnetic subcritical centrifuge cascade at Taji to be

completed in Dec., 1994.

Procurement of cascade requirements were actually started, however, most items did not arrive to Iraq after 2nd Aug. 1990. Circumstances did not allow the start of any investment in the Taji site as the progress of the work did not reach to such a stage. However, work on Taji project continued on basic design works and the project for UF₆ production were transferred to Rashdiya site as an alternative to Taji. The nominal capacity of this project was estimated at about 1 kg/hr. sufficient the the intended 1000 subcritical centrifuge cascade.

- Project 521 C, Additional activities at Sept. 1990.

In Sept. 1990, an additional program was introduced which intended to produce 93% BEU from about 60% BEU. This project was given the number 521 C, intended to employ a cascade of 50 subcritical centrifuges and to be housed in a small building section at Rashdiya, where modification to the building was actually started. It was thought that available centrifuge parts allocated previously for the prototype could be used for that project and to attempt locally the manufacture of the other needed parts. The carbon fibre cylinders were to be provided from the out-of-country training on the carbon fibre winding machine. For the cascade, material available locally was planned to be used instead of the ordered materials intended for project 522.

- **UF₆ production**

The site for project 522 (1000 magnetic centrifuge cascade) was also to be the site for the UF₆ production with a nominal capacity of 1 kg/hr.

c-Actual theoretical achievements:

- Detailed design of centrifuge parts, first issued in Oct. 1988.

- Rotor dynamic analysis, calculation of critical speed stability analysis and unbalance response, stress-strain analysis of the magnetic centrifuge rotor were achieved Dec. 1989/Jan. 1990. The following computer codes were used: CAD20, CAD2I, CAD25, and CAD30 from MTI, USA, in addition to ANSYS which was used for stress-strain calculations and for carbon fiber rotor calculations. All the above mentioned activities were carried out at Rashdiya site (which was belonged to Irrigation Research Centre).
- Magnetic bearing calculation carried out in Oct. 1989 by using software acquired from Buro Magnettechnik-Frankfort-Germany.
- Complete calculation to predict the performance of the hysteresis motor at 400 Hz were carried out Buro Magnettechnik-Frankfort-Germany in Aug. 1989.

d- Actual production achievement:

- Successful separation test with non-reactive gas using oil centrifuge at 350 Hz (114m/s) in June 1989 at Rashdiya Bldg. 22.
- Successful mechanical running of oil centrifuge at 833 Hz (272 m/s) with inherent problems in Nov. 1989 at Rashdiya Bldg. 22.
- Successful achievement of assembled magnetic centrifuge rotor balancing in May 1990 at Rashdiya Bldg. 10 (1000 Hz, 450 m/s).
- Successful development of a working mechanical centrifuge in June 1989 at a 1000Hz and linear speed of 450 in/sec.
- Also the achievement of separation with UF_6 with efficiency of about 1.8 kg SWU reached in July 1990.
- Manufacture of selected centrifuge parts, such as jacket, molecular pump, scoops, and grooving of lower bearings.
- Embark on construction of a centrifuge production facility (AI-Forat project)

in Oct. 1988 which was not completed.

- Gaining experience in production of some precision parts such as molecular pump and jacket at Al-Furat project Bldg. B03, grooving of lower bearing ball in March 1990 at Rashdiya Bldg. 10.

e- Further steps to be implemented to achieve the original target

- Delays in construction of Al-Furat project due to the lack of experience in clean room technology required use of foreign designers and suppliers.
- In Oct. 1989 building 10 at Rashdiya site was modified to permit assembly and testing of centrifuge prototype.
- In Dec. 1989 Building B03 (store of incoming materials) at Al-Furat project was modified into a temporary workshop to produce the jacket, molecular pump and to conduct R&D on maraging steel cylinder manufacture.
- The R&D work to develop the technology for the production of maraging cylinder started in July 1990, and was not completed.
- In Oct. 1990 construction of new buildings for cascade development at Rashdiya site began, but was not completed.

f- Indigenous production of critical components and equipment:

During Nov. 1988 it was decided to acquire facilities for the production of centrifuge parts, and for the assembly and testing of centrifuges at Al-Furat:

The Furat project facilities consisted of:

Building BOO comprising:

- Precision machining workshop.
- Rough machining workshop.
- Hysteresis motors production workshop.

Building BO1 comprising:

- Halls for centrifuge assembly and mechanical testing.

– Hot testing (with UF_6) hall with possible future use has a cascade hall for about 100 centrifuges.

– Piping assembly production workshop.

Building B02 comprising:

– Production of maraging steel cylinders and quality control.

– Lower and upper bearing assembly and packaging.

Other support buildings for quality control of materials, utilities, raw material store, etc.

It was planned to have this project started by Aug. 1990. However, the work was delayed and by Jan. 1991 most buildings were still under construction.

The critical components manufactured locally were as follows:

- Grooving of lower bearing ball at Rashdiya Bldg.10 in March 1990.
- Welding of ball and stem of the lower bearing and scoop assembly at Al-Mutawakil project in March 1990.
- Jacket and molecular pump at Al-Furat Bldg. B03 in March 1990.
- Vessels and some UF_6 cylinders at Rashdiya workshop section Bldg. 9 during 1989 and the rest of UF_6 cylinders were brought from Tuwaitha when G1 moved to Rashdiya in July 1987.
- Scoops
- Hysteresis motor at Rashdiya Bldgs. 1 and 10 in Oct. 1989.
- Construction of mechanical and process (with UF_6 gas) test stands for the prototype development work in March 1990 at Rashdiya Bldg.10.
- Two complete magnetic centrifuges were produced and tested mechanically in June 1990 at Rashdiya Bldg.10, and only one was tested with UF_6 gas in July 1990 at Rashdiya Bldg.10.
- Carbon cylinder rotors were used at Rashdiya Bldg.10.
- Two oil centrifuges were produced and successfully tested, one with non-

reactive gas in June 1989 and the other mechanically in Nov. 1989 at Rashdiya Bldg. 22.

g- Assessed time to achieve original target:

A delay of one year from the original target of 1994 was envisaged due to the delay Al-Furat Project and cascade development work.

h- Assessed maximum achievable production:

Successful prototype development work arriving at a workable magnetic centrifuge, with carbon-fibre cylinder (L=6 14mm, dia.= 145.5mm).

i- Explanatory notes related to any of the above elements

A decision to use carbon-fibre cylinder instead of maraging cylinders was taken in April 1989 due to numerous difficulties encountered during the trial at the flow forming m/c supplier workshop.

About 50 carbon fiber cylinders were available in April 1990, only about 20 of them were made.

j- FFCD Ref.:

Part IIb sec. 4.4 sub. Sec. 4.4.1 page 1-8/312.

Part IIb set 4.4 sub. Sec. 4.4.1 page 5/312.

Part IIb sec 4.4 sub sec4.4.1 page 1/312 7-8/312).

5. Separation by oil centrifuge (see also 4)

a- Original know-how target:

In Sept. 1987 the use of an oil centrifuge for enrichment was considered. A beams type oil centrifuge was adopted for use in isotope separation of uranium after passing successful mechanical tests. A non-reactive gas mixture was also adopted for preliminary experiments in order to gain experience in separation. The goal was to design and produce a prototype oil centrifuge by Sept.1989.

b- Original production target:

The objective was to build an oil centrifuge for use in uranium isotope separation after having achieved successful separation with the non-reactive gas mixture. The target was to be achieved within 2 years (i.e. by Sept. 1989).

c- Actual theoretical achievement (see 4. c):

Based on available literature an adequate theoretical understanding was achieved for both the centrifuge separation performance and design of process service facilities by April 1988. This led to achieving a successful separation experiment of a non-reactive gas mixture in June 1989.

d- Actual production achievement:

Separation using a non-reactive gas mixture (20% CO₂ + 80%R 114) was achieved in June 1989 with an overall separation factor of 1.04 at rotation speeds of 21000-25000 rpm (350 Hz, 14m/s).

e- Further steps to be implemented to achieve the original target:

When the main effort shifted to developing the magnetic centrifuge, the oil centrifuge was kept running up to Dec. 1989 for training purposes. After this date it was dismantled.

f- Indigenous production of critical components and equipment:

Engineering materials for construction were procured from abroad, such as pipes, valves, instruments, pumps, compressors, frequency converters and motors. Process specific components were manufactured in Iraq, such as the oil centrifuge machine, vessels and cylinders.

g- Assessed time to achieve original target:

The oil centrifuge was kept running up to Dec. 1989 and all facilities were later dismantled.

h- Assessed maximum achievable production:

The total separation factor for a non-reactive gas mixture was 1 .04 compared to the theoretical value of 1 .09.

i- Explanatory notes related to any of the above elements:

No UF_6 was ever introduced into this system because of oil and air leaks into the system.

Throughout all oil centrifuge activities only one successful machine was built and used for separation purposes. Another machine was built and used in the mechanical test stand.

j- FFCE) Ref.:

Part IIb. sec. 4.4 sub Sec. 4.4.5 (127-128)/312. (135-136)/312.

6.Separation by magnetic centrifuge (see also 4)

a- Original know-how target:

In July 1988 the use of the magnetic centrifuge for uranium enrichment was considered. The main target was for isotopic separation of uranium using a successful mechanical running magnetic centrifuge. The aim of the activity was to obtain an optimized magnetic centrifuge that could be used in experimenting centrifuge cascades by Dec. 1990.

b- Original production target:

The objective was to arrive at an optimized magnetic centrifuge having 2 kg U SWU/ year at rotating speeds of 58000 - 60000) rpm (1000 Hz, 450 m/s) by Dec, 1990. The first separation test with UF_6 gas was carried out in June 1990 and by Jan. 1991 full optimization of the separation process parameters were still to be completed.

c- Actual theoretical achievement

Based on available literature an adequate theoretical background was achieved for both the centrifuge flow performances and design of process and services facilities by Nov. 1988. This led to a successful isotope separation of uranium in July 1990.

d- Actual production achievement:

In the period July-Dec. 1990 many separation tests using the same centrifuge were carried out to improve efficiency and to optimize process conditions. Product and waste UF_6 gas collected were remixed and used as feed gas for next runs. The range of process parameters and results obtained from separation tests runs were:

- Maximum speed 58000 - 60000 rpm
- Frequency 1000 Hz.
- Tangential speed 450 m/s.
- Flow rate 5-22 mg/s
- Overall separation 1.4 - 1.1.

factor

- SWU 0.27 - 1.89 kg U
SWU/year

A quantity of about one kg UF_6 existed in the process hall out of about two kg reserved for utilization in the separation experiments.

e- Further steps to be implemented to achieve the original target:

Runs were needed to be carried out to improve separation efficiency to obtain optimized operating conditions (such as operating pressures, upper and lower rotor temperatures, UF_6 product cut). These required repositioning of the scoops inlet.

f- Indigenous production of critical components and equipment:

Engineering materials for construction were procured from abroad and process specific components were manufactured in Iraq (such as vessels, cold traps and some UF₆ cylinders at Rashdiya workshop section Bldg. 9 and the rest of UF (cylinders were brought from Tuwaitha when GI moved to Rashdiya). Others related to centrifuge were:

- Grooving of lower bearing ball at Rashdiya Bldg. 10)
- Welding of ball and stem of the lower bearing and scoop assembly at Al-Mutawakil project.
- Jacket and molecular pump at Al-Furat Bldg. B03
- Hysteresis motor at Rashdiya Bldgs. 1 and 10.

g- Assessed time to achieve original target:

In Dec. 1990 it was estimated that the optimized centrifuge parameters could be determined by July 1991.

h- Assessed maximum achievable production:

The maximum achievable SWU was estimated to be 2 kg U SWU/year.

i- Explanatory notes related to any of the above elements:

All R&D activities were terminated on Jan. 1991

j- FFCD Ref.:

Part IIb sec. 4.4 sub sec. 4.4.5 page (128-129)/312. (136-137)/312.

7. Design of gas centrifuge cascades (see 4)

a- Original know-how target:

In April 1988 it was decided to develop the understanding of centrifuge

cascade for uranium enrichment. The requirement was to make available a general computation concept and computer code to optimize the cascade design for any number of identical machines (of 2 kg U SWU/year). Also, general design concepts for cascades were considered. The target was to be achieved by Feb.1989.

The output of the cascade design was to include the following:

- Number of stages and number of centrifuges in each stage.
- Feed, product and waste withdrawal rates.
- Basic design document.
- Cascade arrangement.
- Process requirements.
- Vacuum requirements.

b- Original production target:

- 10 kg/year HEU at 93%.
- 4000 oil bearing machine cascade
- 1000 magnetic machine cascade.

c- Actual theoretical achievement

In general computation and optimization of centrifuge cascade were based on adaptation of the background accumulated from previous theoretical studies of gaseous diffusion cascades. Centrifuge arrangements and pipe routing for process lines and vacuum lines and their connections to the centrifuges with the flow inside them were adequately understood by Feb. 1989.

Cascade calculations, optimization and design concepts led to issues of basic and detailed designs for 36 centrifuges cascade in May 1989 and 120 centrifuges cascade in Aug. 1989 (Project 521 and 521A were planned to be installed at Al-Furat and Project 521 B at Rashdiya). A basic report was issued for 1000 centrifuge cascade in July 1989 for planning purposes (Project 522 was planned to be

installed at Al-Taji).

d- Actual production achievement:

None. No cascades were built. No actual cascade installation was ever started. Cascades sites at Al-Furat and Rashdiya were under construction when all activities stopped in Jan. 1991.

e- Further steps to be implemented to achieve the original target:

Experiments to study the behavior of two optimized centrifuges working in parallel or in series were required. These experiments were planned to be carried out after optimizing the prototype which was originally planned to be done by Dec. 1990. The prototype optimization would include obtaining the optimum values for

- Feed flow rate.
- Cut.
- Temperature difference across the cylinder.

These parameters should give the best SWU with minimum mixing losses when centrifuges connected in a cascade.

f- Indigenous production of critical components and equipment:

Software was developed locally for cascade calculations, optimisation and vacuum calculations. These included:

- Single machine separation performance (developed by April 1988 at Rashdiya).
- Single machine flow performance (developed by April 1988 at Rashdiya).
- Cascade calculations and optimization (developed by Feb. 1989 at Rashdiya).
- Vacuum calculations (developed by Feb. 1989 at Rashdiya).

No components and equipment were indigenously produced for cascades activities.

g- Assessed time to achieve original target:

Confirmation of the designs would be achieved after the completion of single centrifuge optimization which was estimated to be done by July 1991. However, the progress achieved by January 1991 does not permit this assessment.

h- Assessed maximum achievable production:

The available software that was developed locally at Rashdiya was adequate for optimising the performance of a cascade of any size.

i- Explanatory notes related to any of the above elements:

The 50 carbon fiber short cylinder centrifuge cascade (the program of additional activity adopted in Sept. 1990) was not part of the original planning and was an insertion into the program for production of 10 kg BEU within 3 months starting from UF_6 feed enrichment of about 60%. However, this cascade and others were not constructed and only some civil works in Rashdiya and Al-Furat sites were carried out. All R&D activities were terminated on Jan. 1991.

j-FFCD Ref.:

Part IIb sec. 4.4 sub.sec. 4.4.5 page (129- 132)/132. (138-140)/312, part IIIb. sub.sec.5.11 sub 5.11.3 page (142-147)/163.

PART III: Nuclear Device Development

1. General Introduction

a- Original know-how target:

In March 1987, IAEC was asked to prepare a report defining the requirements for the development of a nuclear device.

The team which was formed for this task submitted a report in August 1987 defining the requirements, which were thought to be highly exaggerated.

The Nuclear Research Centre at IAEC started in Nov. 1987 to prepare general reports defining the lines of research and development to be adopted to solve scientific and technical issues that were posed. The report was completed in March 1988.

Group 4 was established in April 1988, and assigned the task of device development. G4 was to acquire the required know-how, to carry out all necessary studies, research works, experiments and other associated tasks in order to design and produce a nuclear device by June 1991. However, due to delays in the progress of work the target date was revised to June 1992.

Originally the yield of the nuclear device was not specified. Later 20 k ton was adopted as a yield goal. The device was to be a uranium based, implosion type.

The target date for the completion of the theoretical work and the design of the device was Dec. 1990.

b- Original production target:

• Original

The overall objective was to make a workable design and then produce the device by June 1991.

Dhafir project was responsible for the design and production of the H.E.

lenses and detonators and the actual theoretical achievement regarding this part is given in item 3 below. The responsibility for other parts of the device was given to G-4.

- **Project review**

Progress of the work was reviewed in May 1990. A major delay of at least one-year from initial target was found. Main reasons were:

- Al-Atheer buildings were behind schedule causing serious delays in the installation of equipment.
- Delivery of imported equipment was behind schedule.
- Design and fabrication of equipment such as gas gun system and flash X-ray system were behind schedule.
- Lens development was behind schedule.

Another major review was conducted after Aug. 1990 events. The results of that review are known as additional activities.

- **Additional activities**

Additional activities were carried out after August 1990 events. Projects 601 and 602 for the fuel processing and uranium metal extraction were initiated. Moreover, G4 either initiated or accelerated the following activities:

- A team was formed to work out the detailed design of the device utilizing the fifth version of the basic design report of July 1990 and its accommodation in Al-Hussein missile warhead, which imposed limitations of the size and mass of the device (that is $OD \leq 800$ mm, $mass \leq 700$ kg).
- Dhafir project was to expedite the production of the spherical lenses for a full scale device ($r200$ mm $R400$ mm) and these were to be produced by the end of Nov. 1990. PC-3 supported DP in the

production of equipment for vacuum casting of the required lenses.

The first vacuum cast lens was produced in mid Jan. 1991.

- The need for G4 to acquire tritium required for the D-T initiator resulted in a special permission to operate the IRT-5000 reactor, which had been shutdown for security reasons following the events of August 1990.
- One full scale experiment using steel instead of uranium should be conducted. After the success of the steel experiment, another experiment should be conducted using natural uranium.
- Since facilities for purification and casting of uranium were not available, a decision was taken to purify uranium to the best possible specification using the existing facilities. Also, the casting and shaping would be made to the best possible tolerances.
- To investigate the utilisation of the vacuum induction furnace type VSG-030B to cast metallic natural uranium for the reflector and tamper. This showed that the furnace chamber needed major modifications and proper moulds needed to be designed. This work continued until Jan. 1991
- Accelerating the manufacturing of bottom pouring induction furnace type 701E. It was partially manufactured but was not operated due to power supply design failure.

Depending of the outcome and success of the additional activities the target date for the device would have been brought back to late 1991 although the order of Aug. 1990 was to complete the device development within six months.

c- Actual theoretical achievement

Theoretical investigations were performed and adequate understanding was

reached in July 1990 in the areas of neutron kinetics, shock wave physics, H.E. experiments, hydrodynamics and electronics to design a workable device. However, in the field of materials behavior under shock loading better understanding was necessary. This lack of understanding continued until Jan. 1991.

Theoretical work utilized available computer codes, and some indigenous computer codes as described in item 2 below.

d- Actual production achievement:

G4 developed a nuclear device design methodology that included a neutronic, hydrodynamic, and coupled calculations.

In July 1988, design criteria were based on basic neutronic calculations. It was assumed that, as a result of shock wave pressure, the uranium density doubles. Critical mass was calculated assuming an infinite reflector. In these calculations, various choices of reflector and tamper were tried (Be, C, U, Fe). Computer codes like ANISN and LOCAL POINT KINETIC modelling were used for these calculations. With the progress of work, 1-D and 2-D hydrodynamic and coupled neutronic computer codes were used for the optimisation of the design parameters.

Five Basic Design reports were issued. The first was issued in Dec. 1988, the last in July 1990. After Aug. 1990, when G4 was ordered to speed up its activities, several modifications were undertaken. These included a flyer plate for pressure amplification and the addition of D-T initiator. In response to a DP request for definitive mould dimensions, G4 stated that DP should produce moulds for design report revision five "see attached table". The order to G4 implied the accommodation of the device in Al-Hussain missile.

Due to the introduction of the radius (40cm) and weight (700 kg) limitations in late 1990, it was necessary to propose new design for the device. The first step was to divide the available space between G4 and DP groups. It was decided on

Jan. 11, 1991 to use r175 mm R400 mm explosive package. Since the core radius is fixed, changing, the thickness of the tamper - reflector (15 cm) was the only alternative. The first design option proposed by G4 is shown as "1990 request" in the attached table, but this option exceeded the Al-Hussain missile requirements by more than 200 kg. The solution proposed was the adoption of a flyer plate design with D-T initiator. The conceptual design option proceeded through parametric studies using more realistic pressure boundary conditions and a coupled 1 -D neutronic hydrodynamic code. The goal of these conceptual designs was the reduction of the mass to meet the requirement of the Al-Hussain missile.

Owing to additional uncertainties for a confident theoretical calculation, an additional experimental program with a spherical shell was initiated by mid Jan. 1991

This design was not developed further. The attached table gives main parameters of several design options.

e- Further steps to be implemented to achieve the original target:

Theoretical and experimental works were to be further developed (see relevant section in this summary).

f- Indigenous production of critical components and equipment:

All parts of the device were planned to be indigenously produced.

g- Assessed tune to achieve original target:

Probably, by end of 1992, most of design unknowns would have been resolved.

h- Assessed maximum achievable production:

No production goal was ever established.

i. Explanatory notes related to any of the above elements:

- Delivery System

The delivery system was the responsibility of the missile group at MIC (A1-Mustafa project).

1) The first contact between IAEC and MIC took place during the first half of 1988 through a meeting between the leadership and senior staff of both organizations. The main conclusions of that meeting were:

- (1) IAEC should endeavour to decrease the size and weight of the device as far as possible.
- (2) MIC should take the responsibility of developing the carrier rocket that could accommodate the eventual device.
- (3) MIC should organize the design and development of the explosives for trigger system with continuous contacts for co-ordination purposes.

2) During 1989 G4 conducted studies of the requirements for missile delivery. These requirements included items such as thermal isolation, load distribution for the additional equipment, guidance system, electronic equipment specifications, pressure switches, radio altimeter and partial destruction

3) In August 1990 contact with the missile group was initiated on technical level. These technical contacts continued throughout the period August 1990- Jan. 1991. They included the need to design a warhead for A1-Hussain missile as well as the following limitations:

- (1) The total weight of the device at the time was about 1200 kg and the missile payload was not to exceed 700 kg.
- (2) The outside diameter of the device, at the time, was about 105 cm and the allowable volume in the missile head was a sphere of 80 cm in diameter. (see section 5.6.3 C)

j. FFCD Ref.:

FFCD, Part IIIb, Sec(5.3)

FFCD, Part IIIb, Sec(5. 11 .4A)

Content (kg)	15.4	18.9	1.4	11.6	4.0	14.9	1.9	1.9
Dimensions (cm)	15.4	18.9	1.4	11.6	4.0	14.9	1.9	1.9
Content (kg)	15.4	18.9	1.4	11.6	4.0	14.9	1.9	1.9
Dimensions (cm)	15.4	18.9	1.4	11.6	4.0	14.9	1.9	1.9
Content (kg)	15.4	18.9	1.4	11.6	4.0	14.9	1.9	1.9
Dimensions (cm)	15.4	18.9	1.4	11.6	4.0	14.9	1.9	1.9
Content (kg)	15.4	18.9	1.4	11.6	4.0	14.9	1.9	1.9
Dimensions (cm)	15.4	18.9	1.4	11.6	4.0	14.9	1.9	1.9

PC3 821 released (Nov 1989)	Thickness(cm)	6	9	6	30	0.5	21.0	51.5	1513	20
	Mass(kg)	17.01	248.8	194.8	827.0	125	461	1413	417	20
	Thickness(cm)	6	9	6	20	0.75	21.0	41.7	985	20
	Mass(kg)	17.01	248.8	194.8	399.9	125	461	985	41.5	20
PC3 821 released (Jul 1990)	Thickness(cm)	5.76	238.2	189.7	20	0.75	20.8	443	962	1062
	Mass(kg)	15.05	238.2	189.7	393.9	125	443	962	1062	20
	Thickness(cm)	5.76	238.2	189.7	20	0.6	20.8	46.4	1150	1250
	Mass(kg)	15.05	238.2	189.7	582.2	125	443	1150	41.5	20
Big Qa Qua Models (Oct. 1990)	Thickness(cm)	5.76	238.2	189.7	20	0.75	20.8	46.4	1150	1250
	Mass(kg)	15.05	238.2	189.7	582.2	125	443	1150	41.5	20
	Thickness(cm)	5.76	238.2	189.7	20	0.75	20.8	46.4	1150	1250
	Mass(kg)	15.05	238.2	189.7	582.2	125	443	1150	41.5	20
Late 90 request	Thickness(cm)	5.76	238.2	189.7	20	0.75	20.8	46.4	1150	1250
	Mass(kg)	15.05	238.2	189.7	582.2	125	443	1150	41.5	20
	Thickness(cm)	5.76	238.2	189.7	20	0.75	20.8	46.4	1150	1250
	Mass(kg)	15.05	238.2	189.7	582.2	125	443	1150	41.5	20

G-4 : Group 4 - PC-3 project
 DP: Dhafr Project - QGE
 r: Internal lens radius
 R: External lens radius

* Weight of the steel casing was assumed to be (100-150 kg) (0.5 - 1 cm thick). An average value is given in the table. It was considered that casing thickness had consequently mass/cm² will be looked into seriously with the object of optimising the final design parameters, since it was considered at that time that the casing was not on the critical path of activities.

** Weight of the supports was estimated to be around 100kg.

⊙ G4 had the capability to estimate the yield, however these figures reflect an arbitrary yield goal.

2.Design of device: theoretical understanding and calculations

a- Original know-how target:

The decision to achieve a theoretical understanding and to perform calculations for the design parameters of a device was part of the overall decision to work on device development taken in mid. 1987. The original target was to install and develop computer codes and collect data of relevance in order to optimize the parameters of the design options (see item 1 above) through computer calculations by Dec. 1990. During this work at Tuwaitha, the original design was improved by the inclusion of flyer plates, stalling on Jan. 1989, and internal DT-initiators (gaseous and solid compounds), starting on July 1990.

b- Original production target:

Originally the production target was to use the achieved theoretical understanding to prepare indigenous and install ready-made computer codes, and use these codes to produce parameters for an acceptable design option. The original target date was to accomplish this task by Dec. 1990.

c- Actual theoretical achievement

The actual theoretical achievements included, by Jan. 1991, the following:

- Derivation of the relevant theoretical equations of state for the materials.
- The use of the one-dimensional hydrodynamic codes mentioned in (d) below to understand the hydrodynamic behavior of the device.
- The use of the coupled codes mentioned in (d) below to perform a parametric study in which the parameters related to pressure boundary condition, $p = p_0, \mu$, namely; p_0 and μ and the core enrichment were varied and the behavior of the device was calculated in each case with the purpose of understanding how to optimize its performance.
- The modification of the code TOODY so as to handle calculations for a

single lens composed of three parts. However, these calculations met with numerical difficulties.

- Calculations for flyer plates using the one-dimensional code WONDY III a (see item 4 below for details).
- Estimation of the neutron yield from an internal Po-Be initiator.
- Calculations for the neutron yield from an internal DT-initiator using the one-dimensional hydrodynamic codes.
- Rough estimate for the amount of explosives needed in the device on the basis of thermodynamic and adiabatic compression of metallic uranium. The result was that approximately 100-250 kg of high explosives would be needed to achieve the super critical condition for metallic uranium.

d- Actual production achievement:

The actual production achieved included, by Jan. 1991, the following:

- Preparation of indigenous and installation of ready-made computer codes covering the equations of state, hydrodynamic, neutronic and coupled areas as shown in table below:

Computer Code Name	Area of Application (Source)
WONDY III a	1 -D Lagrangian hydrodynamics (SANDIA/USA)
ONED	1 -D Lagrangian hydrodynamics (indigenous)
ISHTAR	1 -D Lagrangian hydrodynamics (indigenous)
SUMER	1 -D Eulerian hydrodynamics (indigenous)
TOODY	2 -D Lagrangian hydrodynamics (SANDIA/USA)
AKAD	2 -D Eulerian -Lagrangian hydrodynamics

	(indigenous)
ANISN	neutronics using the S_N method (USAEC)
LOCAL POINT KINETIC	point kinetics (indigenous)
CODE	
AX-1	coupled Lagrangian hydrodynamics -neutronic (S_4) (ANL/USA)
TDA 1	coupled Lagrangian hydrodynamics –neutronic (S_4) (indigenous)
DTF-IV	neutronic (S_N) (IAEA)
TDM	coupled Lagrangian hydrodynamics –neutronic (S_N) (indigenous)
LINEARIZED	linearized 3 -D Lagrangian hydrodynamics
PERTURBATION CODE	(indigenous)
DAIXY	neutronic solving the diffusion equation (CEA/France)
MEDUSA	for calculation of neutron yield from DT reactions, Lagrangian hydrodynamics plus averaged reaction rates (Belfast Library)
GGTC	neutronics for macroscopic cross-section preparation (ISPRA/ Italy)
EOS CODES	For calculation of equations of state (indigenous)

- The use of some of the codes mentioned above to produce results relating to the design options as follows:
 - The use of the codes ANISN and LOCAL POINT KINETIC for the purpose of estimating design parameters (radii of core, reflector and tamper, core enrichment and yield) (July 1987 - Dec. 1990).

- The use of one-dimensional hydrodynamic codes mentioned in table above for the purpose of calculating the compression of the core as a result of applying different boundary pressures and, hence, estimating the required boundary pressure to achieve the super critical condition (June 1988 - Jan. 1991).
- The use of the coupled computer codes mentioned in table above for the purpose of optimizing the some design parameters calculated in the preceding steps (Jan. 1989-Jan. 1991)
- The use of the indigenous two-dimensional hydrodynamic code mentioned in table above to perform calculations for the two-dimensional behavior of the device with the purpose of estimating asymmetry effects. However, these calculations met with numerical difficulties and problems of computer time (June 1990 - Jan.1991).

As a result of these calculations design parameters were obtained, but no final design was selected.

All this work was performed on the NEC/750 computer. Some work related to the development of the equation of state calculations was performed on a personal computer.

e- Further steps to be implemented to achieve the original target:

To achieve a better theoretical understanding, more reliable calculations for the device design parameters, and a better definition of the design, the following were needed:

- More detailed equations of state and constitutive models (responsibility of the theoretical and experimental groups).

- More realistic pressure boundary condition from incorporation of explosive lenses behavior in the calculations (assigned to the theoretical and experimental groups),
- Adequate benchmark and experimental data (assigned to the theoretical and experimental groups),
- Better understanding of the expansion phase (responsibility of the theoretical group),
- More detailed understanding of DT-initiator and flyer plate behavior (responsibility of the theoretical group),
- More coupled calculations to optimize the design parameters (assigned to the theoretical group).

f- Indigenous production of critical components and equipment:

In this theoretical work the critical elements were the theoretical equations of state, computer codes, experimental results and design parameters calculations. Indigenous production in these areas was as follows:

- Derivation of adequate theoretical equations of state for the relevant materials.
- Preparation of indigenous equations of state, hydrodynamics, neutronic and coupled codes (see table in (d) above).
- Installation of ready-made hydrodynamic, neutronic, and coupled codes (see table in (d) above).
- Calculation of design parameters based on neutronic, hydrodynamic, and coupled codes.

g-Assessed time to achieve original target:

G4 would have achieved a proper theoretical understanding of a working device based on the available computer codes around Dec. 1991. This would have

allowed the performance of more reliable calculations for optimizing the design parameters by June 1992. Additionally experimental verification of these calculations would have been necessary. As far as the accelerated activities are concerned, see item 1 above.

h- Assessed maximum achievable production:

Not applicable since work is theoretical.

i. Explanatory notes related to any of the above elements:

- Other aspects related to the calculation of explosive lenses and the theoretical understanding of flyer plates are dealt with in items 3 and 4 below respectively.
- All this theoretical work and calculations were, performed at Tuwaitha, Bldg. 3.

j. FFCD Ref.:

FFCD, Part IIIa, Sec. (5.3), PP. 26-69/309

FFCD, Part IIIb, Sec. (5.11.4 A), pp. 157-158/163

3. High explosives, theoretical understanding and practical implementation

a- Original know-how target:

In Oct. 1987, Al-Qa Qaa (Dhafir Project) was assigned responsibility for the study, design and manufacture of explosive lenses and exploding bridge wire (EBW) detonators. G4 planned to use the experience and capabilities of QGE to accelerate this work. Also, G4 planned to verify its theoretical studies and designs with experiments. The target was to finish all theoretical studies Dec. 1990 except for the work on P.B.X, which was planned to continue till June 1991.

b- Original production target:

Production of proper EBW detonators and pressed lenses was planned to start in Jan. 1990, while cast lenses were planned to be produced in beginning Nov. 1990.

c- Actual theoretical achievement

In the period Jan. 1988 - Dec. 1990 studies and reports on classical (conventional) explosives, composite explosives, and plastic bonded explosives (P.B.X.) were prepared. Technical reports on firing systems and detonation velocity measurement were prepared by the electrical subgroup. An indigenous 2-D LENS DESIGN CODE was prepared in April-May 1990. A report on the design of (EBW) detonators was written in July 1990. Calculations for flyer plates were added to the same computer code mention above in May-July 1990. Also, studies and experiments in all the above-mentioned fields were still going when the war started. Test results were used to refine designs for EBW detonators, flyer plates, ... etc.

d- Actual production achievement:

In the period from Oct. 1987 to Dec. 1988, many preliminary experiments were done using one or more explosive charges hitting targets (steel plates or small

spheres) followed by inspection of the deformation on those targets, and some preliminary measurements were made. The main purpose of those experiments was to determine the requirements for a theoretical design program, studies of explosives, production equipment and measuring instruments.

The achievements were as follows:

- About 200 EBW detonators were produced at project site (Al-Qaqaa), most of them were sent to Al-Atheer for testing. Best results showed less than 100 ns jitter time when testing the simultaneity of 32 detonators fired at the same time in June 1990.
- Tens of pressed plane and spherical wave lenses were produced and tested at QGE, later they were sent to Al-Atheer for testing. Tests ran from Jan. 1990 onwards. One of those tests, that was done Jan. 1991 on a r30 R180 mm spherical lens showed formation of a spherical implosion shock wave.
- In Dec. 1990 and Jan. 1991, parts of lenses of r75 R300 mm radii were cast. They were intended for R&D work of DP. Attempts were started to machine those parts to the required dimensions, but no complete lens was assembled. For the r200 R500 mm lenses, only two attempts for casting were carried out in Jan. 1991, but those parts were not tested or machined due to the events of Jan. 1991
- The electrical subgroup built and developed firing systems for EBW detonators in the period June. 1989 - Sept. 1990. Also, this group conducted many tests concerning detonation velocity measurements for different explosives, measurement of detonation time of detonators and detection of the detonation wave front of explosive charges.
- Starting in Jan. 1990, tens of kilograms of classical explosive mixtures were prepared for production of lenses. In June 1990 a few kilograms of composite explosives were prepared. Small cylindrical bars of those

explosives were sent to the electrical subgroup for testing. Also, small quantity of PBX was produced in the laboratory in Sept. 1990. Tests of these samples clarified the need for an isostatic press, which was out of Iraq capabilities.

- Equipment was erected at project site in Aug. 1990 for machining of cast parts of HE lenses. Attempts were made to machine the first and the third layers of r75 R300 mm cast lenses, and the results were encouraging, but the work stopped due to the events of Jan. 1991.

e- Further steps to be implemented to achieve the original target:

Due to the non-delivery of equipment for vacuum casting of explosives, design of such equipment was done by Dhafir project personnel in Oct. 1990, and then sent for manufacturing. However, most of them were not completed due to the events of Jan. 1991.

f- Indigenous production of critical components and equipment:

Equipment for vacuum casting of HE such as two cooling chambers, two casting chambers and mixer-melter were designed and manufactured. The capacity of each chamber was about 1 m^3 while the capacity of the melter was about 0.4 m^3 .

Hexagonal and pentagonal molds for r200 R500 and r75 R300 lenses were also fabricated.

g- Assessed time to achieve original target:

About six months were needed to achieve the original target and the delay was due to the non-arrival of the equipment from abroad.

h- Assessed maximum achievable production:

It was planned to produce two complete cast lenses (with r75 R300 mm) daily starting from Jan. 19, 1991. This number was to increase to four cast lenses from Feb. 1, 1991 onward (assuming that some additional parts of vacuum casting

equipment were received). The production of one r200 R500 mm cast lens daily was planned to start on Feb. 1, 1991 (after receiving the fabricated molds in Jan. 26, 1991). In Jan. 12, 1991, G4 requested the production of r 1 75 R400 mm lenses, however no work was carried out on this request by DP group.

i. Explanatory notes related to any of the above elements:

There was a set of H.E. experiments performed PC-3/G4 explained in item 5 below.

j-FFCD Ref.:

Part IIIa sec. 5.8

4. Flyer Plates

a- Original know-how target:

G4 decided to perform flyer plate calculations at Tuwaittha in Jan. 1989. The original know how target was to gain a comprehensive understanding of the behavior of flyer plate and then to use this knowledge to calculate the design parameters for more refined design options in which the overall size would be reduced and the requirements on the explosive lenses would be easier to achieve. The original target date to complete this task was Dec. 1990.

b- Original production target:

The original production target was to calculate parameters for a design option of a device employing flyer plates by Dec. 1990.

c- Actual theoretical achievement

The theoretical achievements are:

- The calculation of pressure amplification and shock wave propagation for aluminum flyer plates in contact with an explosive layer using the one-dimensional hydrodynamic code WONDY IIIa and the benchmarking of

these calculations against standard results from similar calculations available in the literature in June-August 1990.

- The calculation of flying shells hitting a sphere using the code WONDY IIIa and the observation of fracture in these calculations. Attempts to treat this fracture were made but were not wholly successful. This was performed by Nov. 1990.

d- Actual production achievement:

Actual production achievements are as follows:

- The hydrodynamic calculation, using the code WONDY IIIa, of an initial design option incorporating a flying shell. It was noticed that flyer plate fracture was a problem in these calculations, fracture had to be treated through more realistic constitutive models. This work was performed between June 1990 and Jan. 1991.
- The conduct of experiments by Dhafir Project (DP) beginning Nov. 1987 using high explosives (BE), seismic detonators and various targets (such as steel plates and small spheres). The object of these experiments was to gain experience in this type of work so that later experimental requirements could be defined more precisely. In some of these experiments an aluminum flyer plate was used.
- The conduct of HE experiments in the period Jan. 1990- July 1990 in bunker 100 at Al - Atheer to study the effect of shock waves on the assembly of a dummy (cold) Po-Be cylindrical initiator.

e- Further steps to be implemented to achieve the original target:

- More complete understanding of the behavior of flying shells was needed through additional calculations and experiments.
- Treatment of the observed fracture in the theoretical calculations was a

problem to be solved through more accurate constitutive models.

- Incorporation of flyer shells in the coupled calculations and performing such calculations for a design option with flying shells to get more reliable design parameters.
- Conduct of further experiments to provide information about the behavior of flyers to supplement and confirm the theoretical understanding.

f- Indigenous production of critical components and equipment:

- One-dimensional hydrodynamic codes were essential for flyer plate design calculations. The code WONDY IIIa was used throughout the calculations for flyers, and no indigenous production of other codes was attempted for this purpose.
- As far as Dhafir Project's work is concerned, see item 3 above.
- As far as the experimental work of G4 is concerned, see item 5 below.

g- Assessed tune to achieve original target

About Dec. 1991, it would have been possible to achieve an adequate theoretical understanding of the principles of flyers based on computer codes. This would have allowed more reliable calculation of parameters for the initial flyer plate design option by June 1992. As far as accelerated activities are concerned, see item 1 above.

h- Assessed maximum achievable production:

A possible future extension of this work involved the use of more than one concentric flying shell for the purpose of more pressure amplification.

i. Explanatory notes related to any of the above elements:

- The design option mentioned in (d) above was not one of the original design options given in item 1 above. The need to consider a flyer plate design arose from the requirement to reach 3 Mbar pressure and to reduce

the overall weight and dimensions of the device.

- Item 3 (High explosives: theoretical understanding and practical implementation) and item 5 (Experimentation: High explosive (BE.) experiments) include some experiments related to this work.
- All theoretical work was performed at Tuwaitlia, Bldg. 3.

j- FFCD Ref.:

FFCD, Part IIIa, Sec. (5.3.6 A), pp. 64-65/309

FFCD, Part IIIb, Sec. (5.11.4 A), pp. 157/163

FFCD, Part IIIa, Sec. (5.4), pp. 92/309.

FFCD, Part IIIa, Sec. (5.8), pp. 277/309

5. High explosive (H.E.) Experiments

a- Original know-how target:

Develop understanding of H.E. shock wave physics to design the H.E. lens system for the nuclear device.

The design development and production of the necessary HE package to produce the required 3 Mhar pressure at the tamper outer boundary was the responsibility of QGE (Dhafir Project). A range of H.E. experiments was needed for the qualification and verification of QGE's (DP) explosive package both as individual items and the complete system including full mock-up tests. Tools and equipment like high-pressure instrumentation, fast time electronics and high speed cameras were needed for the experiments. Therefore, in May 1988 IAEC/PC-3 had to develop the necessary know-how to achieve the target by May 1991.

b- Original production target:

To develop the know-how required for verification of the performance of the explosive package, it was necessary to achieve the following:

- To design and construct a facility suitable for BE. experiments by April 1989.
- To develop or acquire suitable probes and sensors for measurement of high pressure, shock wave velocity, shock wave front and temporal behavior by Jan. 1990. However, the inability of QGE (DP) to supply the lenses when required caused a one year delay in the May 1991.
- To develop or acquire suitable instruments for fast recording and general on-line data acquisition including high speed cameras, Computer Automated Measurement And Control (CAMAC) system and logic analyzers by Jan. 1990.
- To conduct experiments to verify the performance of H.E. lens systems.
- To analyze the experimental results and to suggest improvements in the H.E. package is considered adequate. The original production target (May 1991) was extended in June 1990 to May 1992 to achieve a suitably qualified H.E. package at Al-Atheer site bunker 100.

c- Actual theoretical achievement

- A comprehensive literature survey provided a suitable theoretical background to the technical personnel involved and this was accomplished by Dec. 1989.
- Documents for the safe handling, storage and use of H.E. were prepared and adopted by Dec. 1989,
- Experiments were designed and conducted in the period Jan. 1990 - Jan. 1991 at Al- Atheer site bunker 100.

About forty experiments were performed to investigate and verify:

- Plane wave generator performance.
- Cylindrical internal neutron initiator performance.
- Qualification of the spherical wave lenses.

- Detonation speeds of cylindrical charges.

d- Actual production achievement:

The following activities were conducted -

- Design, construction and testing of bunker 100 at Al-Atheer. This was a facility for testing H.E. up to 200 kg TNT. This facility was commissioned in July 1989.
- The experimental results of the plane wave generator showed the production of a plane wave front.
- Plane wave generator tests for the cylindrical initiator were made during the period Jan. 1990 - Jan. 1991. The results of these tests were not reproducible, which resulted in the use of the gas gun (RPK rifle) to test the initiator (see item 7).
- Spherical wave tests with two types of small pressed single lenses. A convergent shock wave was being produced. The highest pressure recorded was 317.8 kbar at the interface between the spherical lens and a steel shell in direct contact with the lens. These experiments were conducted in Dec. 1990.
- Experiments on cylindrical charges were made at the request of QGE and Bilat Al-Shuhada' during the period from July 1990 - Jan. 1991 to supply the BE. manufacturers with the detonation speeds of these charges. These data were useful for the optimization of their products.

e- Further steps to be implemented to achieve the original target:

- Single and multiple spherical lens experiments had to be done to qualify the lens system.
- Tests were required to qualify the initiator.
- Flash X-ray systems were required for dynamic imaging of implosions.
- Full mock-up tests of the device were required to verify lens design,

synchronicity and pressure conditions.

- The dynamic calibration of the PVDF pressure sensors was required.

f- Indigenous production of critical components and equipment:

- Apart from the streak camera, and the logic analyzer, which were imported, all other experimental devices and equipment were prepared and integrated locally at Al-Atheer site bunker 100 from general engineering materials and components that were imported.
- Bunker 100 was designed and constructed locally.
- Flash X-ray systems were designed and fabricated locally (see item no. 6).

g. Assessed time to achieve original target:

It was estimated that the original target would be achieved by May 1992, As far as the accelerated activities are concerned, see item 1 above.

h- Assessed maximum achievable production:

Development work and experiments needed to be continued to incorporate flyer plates and shells to achieve optimization of the design of the H.E. package and the overall device concept.

i. Explanatory notes related to any of the above elements:

The work was carried out in co-ordination with QGE, and from Jan. 1990 frequent meetings were held between PC-3 and QGE/DP. The results of experiments were shared and discussed during these meetings. There was also a set of H.E. experiments done by QGE/DP explained in item 3 above.

j. FFCD Ref.:

Part IIIa, Sec. 5.4 page 94/3 09