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PILOT PLANT UF₆ TO UF₄ TEST OPERATIONS REPORT

By

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FEBRUARY 1987

FEED MATERIALS PRODUCTION CENTER
Westinghouse Materials Company of Ohio

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CINCINNATI, OHIO 45239

PREPARED FOR THE
U.S. DEPARTMENT OF ENERGY
WEAPONS DIVISION OF OAK RIDGE OPERATIONS
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EXECUTIVE SUMMARY

Westinghouse Materials Company of Ohio (WMC0) operates the Feed Materials Production Center (FMPC) under contract to the Department of Energy (DOE). The FMPC site, located 20 miles northwest of Cincinnati, includes a plant designed for the reduction of uranium hexafluoride (UF_6) to uranium tetrafluoride (UF_4). Limited operation of the upgraded reduction facility began in August 1984 and continued through January 19, 1986. A reaction vessel ruptured on that date causing the plant operation to be shut down. The DOE conducted a Class B investigation with the findings of the investigation board issued in preliminary form in May 1986 and as a final recommendation in July 1986.

A two-phase restart of the plant was planned and implemented. Phase I included implementing safety system modifications, changing reaction vessel temperature control strategy, and operating the reduction plant under an 8-week controlled test. The results of the test period are the subject of this report.

The test operations were successfully conducted between August 22 and October 19, 1986 and were specifically designed to determine the effectiveness of the vessel temperature control strategy and associated safety system devices. A projected production rate was also calculated for the new plant configuration.

The test operations proved that the modified temperature control system can maintain the reaction at temperature setpoints in the 1150 to 1300°F range, providing that a sufficient volumetric flowrate of cooling air is supplied. The automatic temperature shutdown system was proven to effectively prevent the maximum temperature setting from being exceeded.

Additional findings of the test operation include the following:

- New HF/ UF_6 Detectors provided rapid identification of HF leaks.
- The reactor vessel inspection program detected initiation of wall thinning and oxidation spalling between 322 and 456 operating hours.
- A prediction of the vessel life can not be made based on available data and will require continued vessel operation and surveillance. A simultaneous effort to produce an accurate analytical model of the failure is also recommended to maximize vessel life.
- The projected production rate was determined to be between 1400 and 1750 metric tons of uranium per year for one vessel operation, depending on type of feed (enriched or depleted) and setpoint temperature.

INTRODUCTION

The Westinghouse Materials Company of Ohio (WMC0) operates the Feed Materials Production Center (FMPC) as a government owned, contractor operated (GOCO) facility. All FMPC operations are administered through the Department of Energy (DOE) Oak Ridge Operations (OR0) Office. The primary mission of FMPC is to supply uranium metal fuel cores for production reactors at Richland, Washington and Savannah River, South Carolina. A secondary mission is to supply metal for special purposes to DOE facilities at Oak Ridge, Tennessee (Y-12 Plant) and Rocky Flats, Colorado.

The Richland N-Reactor stream is supported by processing enriched uranium scrap residues generated during metal production, plus Purex UO_3 (uranium trioxide) recycle. Enriched UF_6 (uranium hexafluoride) is required to replenish ^{235}U values consumed in the N-Reactor. All three material types are converted to UF_4 (uranium tetrafluoride), known as green salt, which is the starting point for metal production operations.

One method of generating green salt at the FMPC is by direct reaction of hydrogen with enriched uranium hexafluoride (UF_6), according to:

This same basic reaction has also been used at similar reduction facilities including Carolina Metals and the Paducah Gaseous Diffusion Plant (PGDP) in Kentucky.

The UF_6 - UF_4 reduction process ("6/4 process") is shown in Figure 1. The reduction of UF_6 to UF_4 is brought about by mixing uranium hexafluoride,

Figure 1. $UF_6 - UF_4$ Reduction Process

0021-1

vaporized from its storage cylinder in an autoclave, with dissociated ammonia (DA) in the top of a tubular reactor tower. The reaction which occurs is as follows:

This reaction is exothermic to the extent of 71.8 kcal/gmol, and requires an activation energy of approximately 34.6 kcal/gmol to initiate the reaction.⁽¹⁾ This is equivalent to a reaction temperature of approximately 750°F. The reaction mixture must therefore first be heated to initiate the reaction; once ignited, the mixture burns rapidly in a flame-front profile. The solidified green salt, now mixed with the offgases, must be cooled before removal from the reactor.

The reactor itself consists of a twenty-foot long, 16-inch diameter Monel vessel with the top three feet tapering down to a 10-inch inlet diameter. The internal pressure is only a few psig, and the vessel wall thickness is one-half inch nominal. The configuration is illustrated in Figure 2. Vapor phase UF_6 is delivered from the enclosed autoclave via heat traced transfer piping to a heated surge tank. At all times, the UF_6 temperature is kept above 240°F to prevent condensation. From here, it is piped through a flow controller and totalizing flowmeter to the top of the reactor, and mixed in a static mixhead with the dissociated ammonia, using approximately 20% excess hydrogen. The DA is provided by catalytic dissociation of anhydrous ammonia, supplied by the tank farm.

The reactor is divided into four temperature control zones, numbered 1 thru 4 from the top to the bottom. The reactant mixture is preheated as it flows downward through the first zone; heating is supplied by a 45 kW clam-shell heater surrounding the tube. Operating experience has indicated that most stable operation occurs when the heating is such that the mixture reaches

(1) A. L. Myerson and J. J. Chludzinski Jr., Journal of Physical Chemistry, 85 3905 (1981)

Figure 2. Pilot Plant Reaction Vessel Assembly

ignition temperature in Zone 2. Wall temperatures in the burning zone are typically 1150 to 1300°F, with temperatures as high as 1800°F having been recorded.

The green salt is initially formed in the vapor phase, but having a melting point of 1760°F, rapidly condenses to form a finely divided powder, falling through the remaining length of the reactor along with the carrier nitrogen, unreacted hydrogen, and HF vapor. In addition to uranium tetrafluoride, a number of other fluorides may also form, including UF_5 , U_4F_{17} , and U_2F_9 . If significant quantities of these intermediate fluorides are present in the product, the salt will lose its characteristic emerald green color, and become black. In addition, significant quantities of HF may become entrained in the solidified UF_4 .

A vessel support system as shown in Figure 2 is provided to keep the vessel from deforming. Located at the top of the vessel, tension from a yoke and counterweight system provides the mechanical support. Cooling of the vessel wall is also provided, since the attack on the Monel alloy is both by HF on the interior and by air oxidation on the exterior, and both are accelerated by elevated temperatures. Both degradation processes are also aggravated by large thermal gradients in the vessel wall. Temperature control is therefore crucial both to product quality and to the lifetime and safe operation of the vessel.

Cooling air is provided to all four heat zones, with large quantities of cooling air flowing past the lower zones. This controls the vessel wall temperatures to minimize corrosion and oxidation, and cools the downflowing gas-powder mixture. The cooling system consists of a perforated ring header pipe near the bottom of each heat zone. The air flows upward around the vessel and is collected by an exhaust duct near the top of the zone. The four exhaust ducts are then vented to a common stack. Both heat input and cooling air are controlled by thermocouple indications on the wall of the vessel.

At the bottom of the tower the powder falls into a cooling screw equipped with a water-cooled jacket. From here, the offgases are disengaged and the powder is packaged into drums. The offgases are passed through a cyclone separator and sintered metal filters to trap any entrained green salt dust, passed through an activated carbon trap to eliminate any traces of UF_6 , cooled in a heat exchanger, and then passed through a two-stage refrigeration system to condense and collect anhydrous hydrogen fluoride (AHF). The remaining exit gases, primarily nitrogen and unreacted hydrogen with traces of HF, are scrubbed in a water scrubber and vented. The effluent of the scrubber is dilute hydrofluoric acid (DHF), and is collected in polypropylene tanks.

The exiting offgas from the sintered metal filters is analyzed for the presence of UF_6 , which would indicate incomplete reaction and a radiological release into the chemical traps and scrubbing system. This would initiate automatic process shutdown by the Distributed Control System (DCS), the master control system which governs the entire process. In addition to UF_6 release, a number of other checks and process conditions may also initiate automatic shutdown, including HF release and excessive temperatures or pressures.

Because of the high temperatures associated with the burning zone, the initially-molten UF_4 may condense on the surface of the reaction vessel, forming a deposit known as "slag." Buildup of thick layers of this material greatly reduces the overall thermal conductivity of the vessel walls and inhibits the ability of the temperature control system to both heat and cool the reaction mixture. In addition, intimate contact between the Monel vessel and molten green salt leads to accelerated corrosion of the wall, which in turn leads to increased levels of nickel and copper being contained in the product. Periodic deslagging cycles are therefore inserted into the production schedule, during which the reactor is cooled and heated to fracture and loosen the deposit by utilizing the difference in thermal expansion between the green salt and the Monel. Removal of slag during operation is accomplished by periodically activating pneumatic vibrators. These are also shown in Figure 2.

HISTORY/TEST OPERATIONS CRITERIA

On January 19, 1986, during operations of the Pilot Plant Process for converting UF_6 to UF_4 , a reaction vessel cracked allowing reaction gases to escape. An Investigation Board was appointed to determine the cause of the accident and recommend methods to prevent future similar occurrences. A Pilot Plant Restart Plan was issued by Westinghouse on May 3, 1986 which described a two-phase effort designed to bring the Pilot Plant back on-line for production. The first phase consisted of: (1) making modifications to the system and procedures to correct the problems identified by the Investigative Board and (2) Test Operations. These modifications included increased cooling-air capacity, a modified temperature control strategy, improved upper-reactor physical support, and the establishment of a maximum operating temperature of $1400^{\circ}F$ and a maximum setpoint of $1300^{\circ}F$. Test Operations were then carried out to determine if the modifications achieved the desired improvements in safety and allowed the process to achieve acceptable production throughputs at substantially reduced temperatures. The planned second phase will consist of further modifications to the system to allow full two-reactor operation and to correct any deficiencies identified during Test Operations.

The Test Operations Matrix is summarized in Table 1. The tests utilized both depleted and enriched (nominal 1.8 to 2.0% ^{235}U) UF_6 feed to determine the following: (a) production rates achievable at reduced temperatures using two different mixhead designs, (b) the effectiveness of the revised temperature control system, (c) the effects of thermocouple design on temperature indications (to facilitate comparison of FMPC results with results of other 6/4 production sites), (d) the effectiveness of the vessel inspection program, and (e) the effectiveness of the new UF_5 / HF detector system.

An attempt was made to gather and analyze sufficient data to determine which of the modifications made in Phase I would be adequate for full-scale production operation. Data gathered early in the Test Operations indicated a

need for additional modification prior to full production; these modifications were subsequently completed, based upon safety as well as long range production considerations.

Twelve test runs were carried out, the eleven planned plus one additional run using the Paducah mixhead with enriched materials. The temperature, mixhead type, number of cylinders of UF_6 processed, and the enrichment of UF_6 used are shown in Table 1.

Sustainable enriched UF_6 flow rates were investigated for vessel temperatures of 1100, 1150, 1200, and 1300°F. Initial runs were at 1100 and 1150°F, with a vessel inspection being performed prior to proceeding to higher temperatures. There was an alarm at 50°F above the setpoint in each case. The maximum temperature in any zone was limited to 1380°F, at which point the reaction would shut down automatically. Sustainable depleted UF_6 flows were investigated for vessel temperatures corresponding to 1150, 1200, and 1300°F.

The FMPC mixhead was used for both enriched and depleted UF_6 feed. The Paducah mixhead was planned to be utilized only on depleted, because of the greater anticipated difficulty in obtaining design flow rates with depleted UF_6 . However, one Paducah mixhead run was carried out for enriched UF_6 .

Inspections of reaction vessels were carried out before the first run and after every 250 "equivalent operating hours," an equivalent operating hour being defined as one hour with UF_6 flow or two hours at temperatures greater than 1000°F without UF_6 flow.

Successful test operations were defined as tests wherein sufficient data was collected to:

- Calculate the yearly achievable production rate per reactor.
- Establish, after Test Operations, a maximum operating temperature setpoint for production operations.
- Evaluate the effectiveness of the new temperature control system for production operations in the Pilot Plant (Goal: Maximum temperature <50°F over setpoint during the last two runs of the Test Operation).

Table 1
Final Run Matrix Summary

<u>Date</u>	<u>Run</u>	<u>°F</u>	<u>Mixhead</u>	<u>Vessel</u>	<u>Enrichment</u>	<u>Cylinders</u>
-------------	------------	-----------	----------------	---------------	-------------------	------------------

7/14 Inspect Reaction Vessels RV-1 and RV-2

8/22-8/26	1a	1100	FMPC	RV-2	2.0 (E)	1
8/26-8/27	1b	1150	FMPC	RV-2	2.0 (E)	1
8/28-9/1	2	1200	FMPC	RV-2	2.0 (E)	2

9/2 Inspect Reaction Vessel RV-2

9/4-9/6	3	1300	FMPC	RV-2	1.8 (E)	2
9/8-9/9	4a	1150	FMPC	RV-2	1.8 (E)	1
9/10-9/11	4b	1150	FMPC	RV-2	2.0 (E)	1
9/11-9/14	5	1300	FMPC	RV-1	2.0 (E)	2
9/14-9/15	6	1200	FMPC	RV-1	2.0 (E)	1
9/19-9/22	6A	1150	Paducah	RV-2	2.0 (E)	2
9/25-9/26	7	1300	Paducah	RV-2	0.2 (D)	1

9/29 Inspect Reaction Vessels RV-1 and RV-2

10/10-10/11	8	1200	Paducah	RV-2	0.2 (D)	1
10/11-10/13	9	1150	Paducah	RV-2	0.2 (D)	1
10/13-10/15	10	1300	FMPC	RV-2	0.2 (D)	1
10/16-10/17	11	1200	FMPC	RV-2	0.2 (D)	1

10/21 Inspect Reaction Vessel RV-2

- Develop an inspection technique capable of detecting meaningful changes in geometry, metal condition, and support system for the reaction vessels.
- Identify HF/UF₆ detectors that alarm when the HF concentration exceeds 3.0 ppm, while minimizing the level of false alarms for concentrations lower than 3.0 ppm.

1.0 CONCLUSIONS

1.1 Production Rates

- The vessel can be used to produce enriched material at the design UF_6 feed rate of 1100 lb/hr at any temperature from 1150 to 1300°F, as indicated by the FMPC thermocouple and mounting system.
- The sustainable operating rate for depleted UF_6 feed appears to be dependent on vessel temperature where approximately 880 lb/hr can be fed at 1150°F, 950 lb/hr at 1200°F, and 1100 lb/hr at 1300°F. These figures do not include downtime or time required for restarting. Again, temperatures are based on the FMPC thermocouple and mounting system. Capacity appears to be rate limited by the two top zone(s) heating capacity and the two lower zone(s) cooling capacity (See Table 3-2).
- The annual production projections of one-vessel operation for depleted feed material are 1400 MTU/Yr at 1300°F. (Note that these production values would not double in magnitude simply by operation of both vessels simultaneously). These figures are based on temperatures indicated by the FMPC thermocouple and mounting system, and 1985 historical operating information including unplanned shutdowns, deslagging periods, inventory periods, annual preventative maintenance, isotopic changeover, training, non-operating days (holidays, plant shutdowns, etc.), and mandatory inspections (See Table 3-4).
- There appears to be no significant difference between the sustainable operating rates achieved with the Paducah or FMPC-type mixhead, using either enriched or depleted feeds.

1.2 Temperature Control

- The experimental bimodal temperature control strategy, encompassing simultaneous heating and cooling within a zone, appears to be

successful, provided that sufficient cooling air is available. A further temperature-control enhancement made between Runs 7 and 8 to allow for a more linear vessel temperature profile also appears to be successful, again providing sufficient cooling air is available.

- The existing plant air supply is marginally sufficient to supply one vessel near design capacity, and thus it is unlikely that both vessels can be simultaneously operated at design capacity. An estimated cooling air requirement for maintaining temperature control is 1600 SCFM per vessel.
- Using identical thermocouple elements (FMPC-type) on both types of thermocouple stud mounts resulted in the Paducah mounting technique indicating 13% lower during cooling cycles and 13% higher during heating cycles than the FMPC mounting technique. This indicates greater stability and better insulation for the FMPC system. However, the Paducah thermocouple element provides more intimate contact with the vessel wall and results in a 50°F higher indication if mounted with the FMPC thermocouple on the same mount. It must be stressed, the FMPC system may be compared to the Paducah system only if the same local environmental conditions exist.
- Cooling air maldistribution is at least partially responsible for a non-uniformity in the circumferential temperature profile of the reaction vessel. Variations of up to 400°F were noted in the area which had cracked on the previous reaction vessel. The highest circumferential temperature was generally observed at the west side control thermocouple. The air-exit opening is insufficiently sized and is primarily responsible for these circumferential variations, as well as being responsible for forcing cooling air into other zones and causing further temperature control problems.
- For operation with depleted UF₆ at 1300°F, use of the Paducah mixhead substantially reduced the magnitude of the circumferential

temperature gradient. At 1200⁰F, data for the two mixheads indicated no statistical difference.

- The formation of circumferentially asymmetric hot spots may be accounted for by laminar instability of the dissociated ammonia flow, resulting in an off-center burning zone. This is only a theory, however, and additional study is recommended.

1.3 Vessel Inspection

Vessel #2 was inspected on four separate occasions occurring at 0, 139, 322, and 456 equivalent operating hours with the following observations:

- Formation of a tenacious, uniform, surface-oxidation layer became apparent between 322 to 456 hours at elevated temperatures. Some spalling of very thin, small flakes was noted at 456 hours in the hottest areas of Zone 2.
- A circumferentially uniform wall thinning was first detected in the bottom 18 inches of Zone 1 and the top 18 inches of Zone 2 between 322 to 456 hours. This thinning appears to be internal.
- No evidence of bulging was apparent from circumferential wall profile measurements.
- Higher levels of nickel and copper were found in the product during the time period when wall thinning occurred.
- The counterweight system was determined to be stable.
- One-half of the vessel support yoke was found to be gradually bending. However, the bending is very slight and for the anticipated vessel lifetime, it will not interfere with vessel thermal expansion or counterweight clearance.

1.4 Product Quality

- High nickel and copper levels correlate directly with product lots containing material derived from end-of-cylinder deslagging cycles.

1.5 Environmental Performance

- The dust collector losses are within guidelines, with a measured dust collector efficiency of 99.98%.
- HF emissions from the facility were measured during the test period and determined to be 3.80 gm/hr from the dust collector stack and 0.04 gm/hr from the scrubber exhaust (measurements taken during one vessel operation).

1.6 Safety Systems

- The Sensidyne HF/UF₆ detector units proved to be very reliable. Twenty-one confirmed leaks and six unexplained alarms were received in the 129 operating hours following recalibration and stabilization of the unit. Leaks were detectable with an alarm setting of 1.5 ppm, with 78% of the alarms being verified as HF leaks.
- The sensitivity of the Sensidyne detectors appears greater than the previously installed Pyrotronic detectors, although the Sensidyne detectors are more difficult to maintain in higher temperature environments such as in the cooling air exhaust or other areas above the vessels. Only five Pyrotronic detector alarms were received in 129 operating hours with only one being confirmed as a leak. Several of the Pyrotronic alarms were attributed to steam.

2.0 RECOMMENDATIONS

2.1 Reaction Vessel Control and Operation

- Continue use of the modified temperature control strategy including use of all eight thermocouple locations in cooling control logic. Additionally, continued use of the control logic for establishing a linear temperature profile below the burning zone is recommended.
- Investigate the use of UF₆ feed preheating to potentially allow for lower vessel temperature setpoints.
- Increase cooling-air supply to provide 1600 SCFM of clean air for each reaction vessel (3200 SCFM for simultaneous operation of two vessels). Additionally, increase the clam-shell exhaust capacity to 1600 SCFM, providing a more even distribution for exiting air flow.
- Increase the diameter of air supply lines to one inch for Zones 1 and 4.
- Add positioners to cooling-air supply valves, and modify cooling-air control strategy to provide modulated control rather than on/off control.
- Use the FMPC-type thermocouple mount with the threaded stud diameter increased to three-eighths inch, and use a thermocouple element similar to the Paducah (washer-type) design.
- Provide a control room DCS display with the rate of change of the temperature difference between Zones 2 and 3, as a diagnostic tool for identifying the motion of the burning zone.

2.2 Reaction Vessel Equipment and Related Systems

- Continue evaluation (PTA 519) of direct hydrogen analysis without prior scrubbing of HF.
- Expand instrument training to include H₂ and UF₆ analyzers.
- Use the Paducah-design mixhead in preference to the FMPC design. Further design and bench studies should be carried out on the mixhead design, and on the flow patterns of the gas mixture above the burning zone.
- Expand the use of the Hastings conductivity-type flowmeters to include the sample line to the second hydrogen analyzer and lines to both UF₆ analyzers. Provide a read-out of all four DCS flowmeters.
- Reduce the frequency of operating deslagging by, in turn, reducing the current operational frequency of the pneumatic vibrators. Determination of the optimal operational frequency will require additional data concerning the effects of slag buildup on temperature control, vessel pressure, and Ni/Cu levels in the product.

2.3 Reaction Vessel Structural Inspections

- Continue inspections, with modifications to the existing method for measuring the longitudinal profile of the reaction vessel.
- Modify vessel inspections, concentrating on areas changing most rapidly, thus maximizing predictive benefit and reducing schedule impact.
- Increase inspection frequency after initial 500 hours of operation unless predictive efforts (including thermal cycling correlations) provide sufficient quality and safety assurance.

- Establish visual criteria for abbreviated inspections when the heating shells are opened for reasons other than for required inspections.
- Implement on-site replication testing for the outside vessel surface.

2.4 Production Capacity Factors

- Use Zone 2 temperature setpoints ranging from 1150-1200°F for enriched UF₆ and 1250-1300°F for depleted.
- Expand efforts for improving the reliability of all system components to help minimize unplanned shutdowns.
- Implement the following scheduling strategies to further increase on-stream time:
 - Schedule production requirements to reduce isotopic changeover to a minimum.
 - Conduct training during scheduled annual PMP period.
 - Conduct reaction vessel inspections during monthly PMP periods.
 - Ensure that around-the-clock maintenance coverage is available at the Pilot Plant.
 - Improve definition of maintenance requirements for Minor Work Requests.
 - Improve coordination between Plant Operations and Maintenance.
 - Minimize the frequency of deslagging operations.
- Review process constraints involved in operating two reaction vessels simultaneously based on information developed during the test program.
- Provide valve-open-or-closed information to the control room concerning the NH₃ feed-delivery valve at the tank farm.

2.5 Safety Systems

- For Sensidyne units, set alarm level at 2.0 ppm (which is below the American Conference of Governmental Industrial Hygienists (ACGIH) 8-hour exposure level), and the high alarm at 5.0 ppm.
- Continue to gather data on the effects of temperature, maintenance problems, etc., as related to the performance of the Sensidyne units.
- Set HF high alarm level at 5.0 ppm and record each high alarm on the DCS alarm printer.
- Require a supervisor to either shut down the system or prepare a Minor Event Report justifying continuation if the HF high level alarm persists for more than one hour.
- Provide HF detectors for any new systems having the possibilities for HF/UF₆ releases.
- Continue the Requirement for an operating HF detector on the cooling-air exhaust with shut down required within 24 hours in its absence, unless reviewed and authorized continuance by appropriate management.
- Provide an electrolytic HF/UF₆ detector, with no unusual restriction pertaining to maintenance response time, in the following areas:
 - Coldtrap
 - Autoclaves
 - Above Reaction Vessels
 - Above the HF scrubbers
 - HF Recovery Area
- Review specifications and certifications for the anhydrous HF (AHF)

tank/line rupture discs.

- Discontinue the use of pulsating pumping methods for AHF.
- Implement suggestions (from Paducah) for modification of the UF₆ cylinder closing devices.

2.6 Product Quality

- Devise a method to allow for homogeneous sampling of the product.

2.7 Environmental

- Continue daily dust collector stack loss sampling during operating periods until the Auburn Monitor is thoroughly evaluated.

2.8 Future Studies

- Permit the Vessel Inspection Program to continue with development of a quantitative model of expected vessel lifetime, with continued attention to structural modifications of the Monel alloy, its corrosion rate, vessel deformation, and surface appearance.
- Collect additional data on cooling requirements at various flowrates for both depleted and enriched feeds. Accurate and efficient data collection will require installation of both recording rotameters and modulated control valves on the cooling air injection streams. Measurements of the exit exhaust flow rate and temperature should also be made. This will permit a better quantitative evaluation of the cooling air volumetric flow requirements.
- Investigate the feasibility of an additional feed preheating system and implement if feasible to allow evaluation of the effect of feed preheat on cooling air requirements. Since considerably lower cooling air requirements are expected in a preheated system, this

information should be evaluated before major cooling air delivery system modifications are made.

- Continue data collection and interpretation on the effects of the two mixhead designs on the magnitude of the circumferential temperature variations, at various flowrates and temperatures. To improve the quality of this data, installation of a second set of circumferential thermocouples at the top of Zone 2 would be desirable. In both these and the cooling air tests, automatic and reliable electronic archiving of the process data is required.
- Replace the old FMPC-design thermocouple junctions with washer-type junctions similar to the Paducah design. At that time, revised correlations should be developed on the relationship between throughput and temperature, based on the new junction design temperature indication.
- Examine the effect of catalysts on the burning rate of depleted UF_6 feed. It is recommended that tests be run on burning behavior of UF_6 which has been "spiked" with low concentrations of potentially catalytic trace materials at several different concentration levels. This "spiking" would be done by the UF_6 supplier.
- Bench-scale modeling of the flow and mixing patterns within the reactor should be carried out for different mixhead designs. Initial tests would compare the flow regimes of the FMPC and Paducah mixhead designs to attempt to validate the laminar-flow instability theory predicted to cause the observed hot-spots around the reactor circumference. Further tests of improved mixhead configurations could then be performed in the same facility.
- Continue dust collector stack sampling tests to complete evaluation of the Auburn Monitor.
- Perform additional stack sampling of the dust collector and HF scrubber stacks to improve the HF release rate data base.

- Continue gathering data on the relationship between reaction temperature, deslagging frequency, and product impurity level. This should include evaluation of reactor operation with reduced frequency of vibrator operation.

3.0 PRODUCTION RATES

3.1 Introduction and Criteria

One of the principal objectives of the test program was the determination of the functional dependence of production rate on the maximum allowable operating temperature. If it is required to lower the operating temperature in order to increase vessel lifetime and reduce the probability of vessel failure, a reduction in throughput may also be necessary. The specification of operating temperature setpoints then becomes a compromise between production and vessel lifetime.

A total of eighteen cylinders of UF_6 were processed during the program (thirteen cylinders of enriched material and five of depleted) with burning-zone setpoint temperatures ranging between 1100 and 1300°F. A detailed summary matrix for each of the eighteen cylinders is given in Table 3-1, to supplement the summary in Table 1.

The production rate will be the product of the sustainable operating rate multiplied by the on-stream factor. (The on-stream factor is determined by an analysis of the downtime, and is discussed in Section 3.4). Note that the design production capacity of the Pilot Plant is based on 1100 lb/hr UF_6 sustainable production (equivalent to 8.10 metric tons of uranium per day, where 1 lb/hr UF_6 equals 0.00737 MTU/D), with a 75% on-stream factor. This converts to a design daily production capacity of 6.08 MTU. This provides a point of reference for the throughputs observed during the test program. (Note: All rates expressed herein are for one vessel operation).

Figure 3-1 provides a conversion for the tradeoff between sustainable operating throughput and production rate, at various on-stream factors. The figure plots the required sustained flowrate (lb/hr of UF_6) to obtain various net production rates (MTU/D) given on-stream factors between 30 and 100%. As indicated above, an on-stream factor of

Figure 3-1. Sustainable Flow vs "On—Stream Factor"

TABLE 3-1
RUN MATRIX

	<u>Run 1a</u>	<u>Run 1b</u>	<u>Run 2a</u>	<u>Run 2b</u>	<u>Run 3a</u>
Vessel Operated	#2	#2	#2	#2	#2
Mixing Head Type	FMPC	FMPC	FMPC	FMPC	FMPC
Zone 2 Temp. Setpoint (°F)	1100	1150	1200	1200	1300
Zone 1 Avg. Bottom Temp. (°F)	1125	1195	1164	1189	1159
Zone 2 Avg. Top Temp. (°F)	1154	1167	1226	1215	1301
Zone 2 Avg. Bottom Temp. (°F)	1028	1056	1215	1105	1256
UF ₆ Feed From Cylinder (lb)	18215	18215	18175	18170	20785
UF ₆ Through Flowmeter (lb)	15213	15433	15203	15166	17999
UF ₆ Flowmeter Deviation (%)	-16.48	-15.27	-16.35	-16.53	-13.41
UF ₄ Produced, Theoretical (lb)	16248	16248	16212	16208	18540
UF ₄ Produced, Actual (lb)	15448	16128	15458	16804	18214
U Unaccounted (%)	4.92	0.74	4.65	-3.68	1.76
UF ₄ As "Slag" (lb)	768	128	----	744	----
AHF Produced (lb)	----	3060	----	3050	----
HF Recovered as AHF (%)	----	73.7	----	73.6	----
DHF Produced (lb HF)	----	474	----	897	----
HF Unaccounted (lb)	----	606	----	196	----
Isotopic Enrichment	2.0	2.0	2.0	2.0	1.8
Test Time (hrs)	148.9	32.3	18.4	24.1	31.3
Total Downtime (hrs)	125.6	9.6	2.5	4.6	8.8
Process Related (%)	94.0	100.0	100.0	26.4	100.0
Not Process Related (%)	6.0	0.0	0.0	73.6	0.0
Operating Time (hrs)	23.3	22.7	15.9	19.5	22.5
Avg. Operating Flowrate (lb/hr)	781.8	803.1	1146.0	931.8	923.8

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TABLE 3-1
(continued)

	<u>Run 1a</u>	<u>Run 1b</u>	<u>Run 2a</u>	<u>Run 2b</u>	<u>Run 3a</u>
Number Times Plant Started	7	4	3	10	5
Production (MTU/D):					
For The Cylinder	0.90	4.15	7.27	5.55	4.89
For the Time Operated	5.75	5.91	8.44	6.86	6.80
Including Process Related Downtime	0.95	4.15	7.27	6.46	4.89
Including Downtime and Deslag	0.91	3.50	5.48	5.01	4.11
Sustainable Prod. Rate (lb/hr)	972	921	1186	1067	1073
Sustainable Prod. Rate (MTU/D)	7.16	6.79	8.74	7.86	7.91
Sustainable Time / Oper. Time	0.664	0.793	0.974	0.725	0.765

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TABLE 3-1
(continued)

	<u>Run 3b</u>	<u>Run 4a</u>	<u>Run 4b</u>	<u>Run 5a</u>	<u>Run 5b</u>
Vessel Operated	#2	#2	#2	#1	#1
Mixing Head Type	FMPC	FMPC	FMPC	FMPC	FMPC
Zone 2 Temp. Setpoint (°F)	1300	1150	1150	1300	1300
Zone 1 Avg. Bottom Temp. (°F)	1142	1169	1160	1214	1195
Zone 2 Avg. Top Temp. (°F)	1256	1161	1152	1304	1292
Zone 2 Avg. Bottom Temp. (°F)	1231	1156	1161	1201	1212
UF ₆ Feed From Cylinder (lb)	20870	20785	18225	18270	19520
UF ₆ Through Flowmeter (lb)	17493	17495	15207	16189	17133
UF ₆ Flowmeter Deviation (%)	-16.18	-15.83	-16.56	-11.39	-12.23
UF ₄ Produced, Theoretical (lb)	18616	18540	16257	16297	17412
UF ₄ Produced, Actual (lb)	18634	18412	15810	15438	17174
U Unaccounted (%)	-0.10	0.69	2.75	5.27	1.37
UF ₄ As "Slag" (lb)	448	444	492	496	489
AHF Produced (lb)	4500	---	3460	---	4890
HF Recovered as AHF (%)	94.8	---	77.8	---	113.5
DHF Produced (lb HF)	711	---	291	---	655
HF Unaccounted (lb)	-462	---	696	---	-1237
Isotopic Enrichment	1.8	1.8	2.0	2.0	2.0
Test Time (hrs)	24.0	19.0	30.2	29.5	32.0
Total Downtime (hrs)	1.5	0.0	11.2	10.3	11.2
Process Related (%)	75.0	0.0	70.6	77.9	0.0
Not Process Related (%)	25.0	100.0	29.4	22.1	100.0

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TABLE 3-1
(continued)

	<u>Run 3b</u>	<u>Run 4a</u>	<u>Run 4b</u>	<u>Run 5a</u>	<u>Run 5b</u>
Operating Time (hrs)	22.5	19.0	18.9	19.2	20.7
Avg. Operating Flowrate (lb/hr)	928.8	1093.9	962.2	954.0	941.2
Number Times Plant Started	4	1	6	5	4
Production (MTU/D)					
For The Cylinder	6.41	8.05	4.45	4.57	4.49
For the Time Operated	6.84	8.05	7.08	7.02	6.93
Including Process Related Downtime	6.52	8.05	5.00	4.95	6.93
Including Downtime and Deslag	5.19	6.12	4.08	4.05	5.37
Sustainable Production Rate (lb/hr)	988	1111	1090	1039	1060
Sustainable Production Rate (MTU/D)	7.28	8.19	8.03	7.66	7.81
Sustainable Time / Operating Time	0.906	1	0.826	0.84	0.807

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TABLE 3-1
(continued)

	<u>Run 6a</u>	<u>Run 6Aa</u>	<u>Run 6Ab</u>
Vessel Operated	#1	#2	#2
Mixing Head Type	FMPC	Paducah	Paducah
Zone 2 Temp. Setpoint (°F)	1200	1150	1150
Zone 1 Avg. Bottom Temp. (°F)	1189	----	----
Zone 2 Avg. Top Temp. (°F)	1212	----	----
Zone 2 Avg. Bottom Temp. (°F)	980	----	----
UF ₆ Feed From Cylinder (lb)	19470	20885	20055
UF ₆ Through Flowmeter (lb)	18623	16914	14781
UF ₆ Flowmeter Deviation (%)	-4.35	-19.01	-26.30
UF ₄ Produced, Theoretical (lb)	17367	18629	17889
UF ₄ Produced, Actual (lb)	18104	18600	17856
U Unaccounted (%)	-4.24	0.16	0.18
UF ₄ As "Slag" (lb)	434	----	----
AHF Produced (lb)	750	---	4040
HF Recovered as AHF (%)	33.8	---	86.6
DHF Produced (lb HF)	738	---	948
HF Unaccounted (lb)	732	---	-321
Isotopic Enrichment	2.0	2.0	2.0
Test Time (hrs)	20.8	26.6	47.7
Total Downtime (hrs)	1.1	5.4	21.4
Process Related (%)	100.0	45.8	100.0
Not Process Related (%)	0.0	54.2	0.0

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TABLE 3-1
(continued)

	<u>Run 6a</u>	<u>Run 6Aa</u>	<u>Run 6Ab</u>
Operating Time (hrs)	19.7	21.3	26.3
Avg. Operating Flowrate (lb/hr)	988.3	981.9	762.8
Number Times Plant Started	2	4	12
Production (MTU/D):			
For The Cylinder	6.91	5.78	3.09
For the Time Operated	7.28	7.23	5.62
Including Process Related Downtime	6.91	6.48	3.09
Including Downtime and Deslag	5.36	5.17	2.75
Sustainable Production Rate (lb/hr)	960	1051	1087
Sustainable Production Rate (MTU/D)	7.08	7.75	8.01
Sustainable Time / Operating Time	0.971	0.935	0.608

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TABLE 3-1
(continued)

	<u>Run 7</u>	<u>Run 8</u>	<u>Run 9</u>	<u>Run 10</u>	<u>Run 11</u>
Vessel Operated	#2	#2	#2	#2	#2
Mixing Head Type	Paducah	Paducah	Paducah	FMPC	FMPC
Isotopic Enrichment	0.2	0.2	0.2	0.2	0.2
Zone #2 Temp. S.P.	1300	1200	1150	1300	1200
Lb UF ₆ Used From Cylinder	26710	26725	26740	26655	26675
Lb UF ₆ Thru Flowmeter	26468	26288	26489	26445	26348
UF ₆ Flowmeter % Deviation	-0.91	-1.63	-0.94	-0.79	-1.22
Theor. UF ₄ Produced	23825	23839	23852	23776	23794
Actual UF ₄ Produced	24093	24000	23500	23750	23430
% U Unaccounted	-1.12	-0.68	1.48	0.11	1.53
Lb UF ₄ As "Slag"	---	750	750	500	491
Lb AHF Produced	2380	4950	2400	310	2230
% AHF Recovered	78.2	162.5	78.7	10.2	73.3
DHF Produced (lb HF)	694.2	468	236	71.8	385.8
Lb HF Unaccounted	-29.3	-2371.4	412.4	2656.9	425.2
Total Test Time	27.7	27.8	38.0	35.4	27.9
Hrs Total Downtime	2.3	0.2	4.9	7.0	0.9
% Process Related	0.0	0.0	52.0	22.0	0.0
% Other Unrelated	100.0	100.0	48.0	78.0	100.0
Hrs Operating Time	25.4	27.7	33.1	28.4	27.0
Avg Lb/hr While Operating	1051.6	966.5	808.6	939.2	988.3

TABLE 3-1
(continued)

	<u>Run 7</u>	<u>Run 8</u>	<u>Run 9</u>	<u>Run 10</u>	<u>Run 11</u>
Number Of Times Plant Started Production (MTU/D):					
For The Cylinder	7.10	7.08	5.18	5.55	7.05
For The Time Operated	7.74	7.11	5.95	6.91	7.28
Incl. Proc. Rel. Downtime	7.74	7.11	5.52	6.56	7.28
Incl. Downtime and Deslag	6.26	5.85	4.73	5.46	5.95
Sustain. Prod. Rate (lb/hr)	1120	967	854	1038	1012
Sustain. Prod. Rate (MTU/Day)	8.24	7.12	6.29	7.64	7.45
Sustain. Time / Oper. Time	0.881	0.934	0.878	0.899	0.940

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75% and a sustained throughput of 1100 lb/hr intersect on the parametric line representing 6 MTU/D operating production.

Of the eighteen cylinders used during the test program, only one was run completely from start to finish without some sort of shutdown outage. Plots of UF_6 flowrate as a function of time, are presented in Appendix A, along with brief summaries of the related downtime. It is clear from examination of these run histories that careful definition of "sustainable operating rate" is essential in predicting production throughput. A given segment of any run was assumed to contribute to "sustainable operation" only if that segment was at least two hours in duration without shutdown. Total sustainable operation during a run was assumed to include one ramp-up cycle, and one decay at the end of cylinder life; additional ramp-up cycles associated with restarts were not included in sustainable operation. The sustainable operating rate is then obtained by first integrating all qualifying segments of the flowrate versus time curve. This will provide a value for processed UF_6 . This value is then divided by the total time associated with the sustainable operating segments. The resulting rate is intended to be representative of production operation without being penalized by extraneous restarts. The lost throughput due to outages and multiple restarts is accounted for in the on-stream factor, given in Section 3.4. However, no attempt has been made to extrapolate to higher average rates which were achieved, but only for brief operating periods.

3.2 Sustainable Operating Rates For Enriched UF_6

Figure 3-2 illustrates computed values for sustained operating rate for enriched UF_6 feed. A number of comments are appropriate with reference to this figure.

As indicated in Table 3-1, the total integrated UF_6 flowmeter reading for Runs 1 through 6 was always significantly lower (typically about 15%) than the actual UF_6 throughput, measured by weighing the cylinder. This requires that the flowrate history curves for Runs 1 through 6 (Appendix A, Figures A-1 thru A-6A) must be corrected upward

Figure 3-2. Sustainable Operating Rate vs Zone 2 Setpoint
(Vessel #2, Enriched Feed)

by approximately 15%. The sustainable operating rates in Table 3-1 have been corrected for this discrepancy in all cases. The flow indicator was compensated for in the control computer between Runs 6 and 7, to correct this inaccuracy, so that close agreement was observed between indicated and actual flowrates for the remainder of the runs.

Secondly, note that all of the Zone 2 setpoint temperatures are based on the readings of an FMPC lug-type thermocouple. The thermocouple is insulated and shielded in a FMPC-type mounting configuration located in the West azimuthal position at the top of Zone 2. Section 4.4 presents discussion of the accuracy of this configuration, and the extent to which it represents the true surface temperature of the reactor vessel.

Figure 3-2 indicates no clear functional dependence of sustainable flow rate on the burning-zone (Zone 2) setpoint temperature for enriched feed. The data is distributed randomly between approximately 7.0 and 8.50 MTU/D, with an integrated mean sustainable flow for all thirteen cylinders of 1047 lb/hr (7.71 MTU/D).

Based on analysis of the operating logs and run histories, some points are believed to be more representative than others. The values for Runs 1a and 1b are observed to be significantly lower than the bulk of the remaining runs. The test objective required holding a flowrate of 650 lb/hr (indicated) throughout the run (Run 1a) to permit other operational problems to be resolved. This rate was subsequently increased to 850 lb/hr indicated for Run 1b. (1020 actual lb/hr) Since the temperature setpoints and hardware for Runs 1b, 4a, and 4b were identical, and the two latter runs were successfully operated at 1120 actual lb/hr, it is believed that significantly higher flowrates may have been possible for Runs 1a and 1b.

A number of other factors, unrelated to operating temperatures, impacted several of the runs. For example, Run 6a experienced a six-hour period near the end of the run in which the indicated flow was reduced from 1050 to 800 lb/hr, due to plugging of the sintered metal off-gas filters. If operation during this period could have been continued at

the indicated flow of 1050 lb/hr, the computed sustainable operating rate over the entire run would have been increased from 7.08 to 7.57 MTU/D.

Numerous outages are also responsible for the much lower sustainable flow computed for Run 2b as compared to Run 2a (for which the run parameters were identical). A much higher frequency of mechanical shutdowns was experienced during Run 2b, such that most of the run was spent stepping back up to higher flows following outages. The sustainable segments of the run constituted only 73% of the operating time as compared with 95% for Run 2a.

Similar arguments can be made in other cases. The main point is that unrelated or unanticipated hardware difficulties had a significant impact both on the actual flowrates keyed in by the operators, and on the fraction of the run during which the system was stable enough to contribute to sustainable operation. These problems were more frequent during the early part of the test program while using enriched feed material. As such, the sustainable operating rates derived for enriched material have a lower confidence level, as compared to runs with depleted material.

Further evaluation of the observed sustainable rates could lead to their being considered as conservative estimates of what can actually be achieved once the majority of the "bugs" are shaken out of the system. A number of hardware modifications were made to the system between the enriched and depleted runs, most notably, an increase in the cooling-air supply (see Section 4.1). As a result, temperature control became considerably easier during the latter tests. It is believed that with the increased cooling capacity, both higher flowrates and better temperature control could be obtained for enriched material. While this has yet to be substantiated by actual operation, it again suggests that the observed sustainable production figures represent conservative estimates of what the system is capable of delivering.

Neglecting Runs 1a, 1b, and 6a, (due to negative biasing) a mean value

of 7.90 MTU/D was obtained for the sustainable operating rate. This compares to a value of 7.69 MTU/D with the above runs included in the calculation. This latter value still represents a 95% achievement of the originally designed throughput capacity of 8.11 MTU/D (1100 lb/hr). Therefore, it may be concluded that a sustainable rate essentially equal to the design basis rate has been demonstrated for any setpoint temperature between 1150 and 1300°F.

Satisfactory operation at 1100°F has not been demonstrated, despite the computed sustainable rate of 972 lb/hr (7.16 MTU/D). The single run at this temperature (Run 1a) proved very difficult to control, and resulted in a "flame-out" (loss of ignition, allowing unreacted UF₆ into the off-gas handling system). As indicated in the outage summaries in Appendix A, Table A-1, nearly 107 hours of downtime was attributable to this incident, including exposure of personnel to HF while cleaning out the contaminated off-gas system. It was concluded that although an adequate "sustainable" rate was calculated at this temperature (according to the present definition), the overall operation of the reactor was too unstable at this setpoint for it to be considered an acceptable operating temperature.

The test plan also provided for the evaluation of sustainable rate as a function of reaction vessel and vessel mixhead design. Figures 3-3 and 3-4 exhibit the two mixhead designs used interchangeably throughout the test operations. The effect of mixhead design for enriched UF₆ is illustrated in Figure 3-2 by comparing the results of Runs 4a and 4b (1150°F set point, vessel #2, with the FMPC mixhead) with those of Runs 6Aa and 6Ab (same vessel and setpoint, with the Paducah mixhead). The FMPC points average 8.11 MTU/D, while the two Paducah data points average 7.88 MTU/D. Because of the factors influencing the sustainable rates (as discussed previously), it is not possible to conclude that this difference of 3% is statistically significant.

The effect of reaction vessel may be observed by comparing Runs 3a and 3b (vessel #2, 1300°F, FMPC mixhead) and Runs 5a and 5b (same setpoint and mixhead, vessel #1). The vessel #1 data average was 7.20 MTU/D

Figure 3-3. FMPC-Type Mixhead

Figure 3-4. Paducah Mixhead

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while the vessel #2 data average was 7.29 MTU/D. Again, this difference is probably statistically insignificant.

3.3 Sustainable Operating Rates for Depleted UF₆

The results of sustainable operating rate calculations for depleted UF₆ feed are presented in Table 3-1, and plotted in Figure 3-5. Contrary to the case for the enriched material, a definite temperature dependence is observed, with a linear regression fit to the five data points. The equations of the regression fit are as follows:

$$R(\text{MTU/D}) = 0.011 T_{\text{Sp}}(^{\circ}\text{F}) - 6.11 \quad (\text{Eq.3-1})$$

$$R(\text{lbUF}_6/\text{hr}) = 1.486 T_{\text{Sp}}(^{\circ}\text{F}) - 829.0 \quad (\text{Eq.3-2})$$

where:

R = Sustainable Operating Rate, (MTU/D) or (lbUF₆ /hr)

T_{Sp} = Burning-Zone SetPoint Temperature

Table 3-2 presents values of rate versus setpoint, computed using Equations 3-1 and 3-2.

Figure 3-5. Sustainable Rate vs Zone 2 Setpoint
(Vessel #2, Depleted Feed)

TABLE 3-2
SUSTAINABLE FLOWRATE AS A FUNCTION OF BURNING-ZONE SETPOINT
TEMPERATURE FOR DEPLETED UF₆ FEED (RUNS 7 THRU 11)

<u>Setpoint</u> <u>(°F)</u>	<u>Sustainable Flowrate</u>	
	<u>(UF₆, lb/hr)</u>	<u>(UF₆, MTU/D)</u>
1150	880	6.54
1175	917	6.82
1200	954	7.09
1225	991	7.37
1250	1029	7.64
1275	1066	7.92
1300	1103	8.19
1325	1147	8.47
1350	1177	8.74

That the behavior of enriched and depleted material is significantly different is not surprising in light of previous operating experience at EMPC. It has long been observed that enriched UF_6 appears to be more "active," reacting more readily with hydrogen than does depleted material. Because of the higher activity, less preheating is required, such that enriched feed ignites more readily, and also higher in the reactor near the top of Zone 2 or the bottom of Zone 1. Less energy input from the Zone 1 heaters is therefore required, and the setpoint temperature in Zone 2 may be lower while permitting the reaction to ignite and burn stably in that zone. In the case of depleted material, more energy input is typically required, resulting in higher temperatures in the upper two heat zones, and a reaction-zone burning lower in the vessel (typically near the bottom of Zone 2 or the top of Zone 3).

The preceding observations are supported by the results of this test program. The sustainable operating rate for enriched material is not sensitive to temperature (energy input) in the upper zones, as long as the burning-zone temperature setpoint is maintained at a minimum of 1150°F. For the less active depleted material, a well defined temperature dependence is observed, with much greater throughputs possible if higher temperatures in the upper zones are allowed. This requires supplying the increased preheat rate required at high throughputs.

These observations suggest that the factor limiting the throughput of the reactor is qualitatively different based upon the type of feed material (enriched or depleted) being processed. In the case of enriched UF_6 , the flow rate was limited by control problems including ignition too high in the reactor, and the inability to adequately cool the top zones. For depleted UF_6 , the sustainable operating rate may be limited by the capacity to pump sufficient heat into the mixture in the top zone, which forces the mixture to ignite lower in the reactor (due to the mixture descending further before it finally reaches ignition temperature). This, in turn, places a greater load on the cooling system in the lower portion of the reactor to cool the product

adequately, and runs the risk of the burning zone moving out the bottom of the reactor. The impact of this on temperature control strategy is discussed further in Section 4.

Let us now examine the influence of external factors on the sustainable operating rate. The only point which deviates greatly from the regression fit of Figure 3-5 is Run 11, and it is believed that this increased flowrate capability was due to increased cooling air supplied during this run. As previously mentioned in Section 3.2, it was concluded that insufficient cooling air was available to adequately control the reaction; consequently, before any depleted material was used, two portable compressors were installed providing greater delivery capacity than the existing plant cooling air system. Runs 8 through 10 utilized one of the compressors for their cooling-air supply, while for Run 11, both compressor air and plant air were used simultaneously. This additional cooling capacity during Run 11 allowed for higher flowrates while still maintaining temperature control.

Obtaining the design basis flowrate of 1100 lb/hr for depleted material requires, according to Equation 3-1, a setpoint temperature of approximately 1300°F. This is in contrast to the more active enriched material, where 1100 lb/hr appears possible anywhere in the 1150 - 1300°F setpoint range. It is worth noting that for Run 7 (1300°F setpoint), a flowrate in excess of 1200 lb/hr (8.84 MTU/D) was maintained for 14 hours without incurring temperature control problems. In addition, a flowrate of 1315 lb/hr (9.69 MTU/D) was maintained for seven hours without incident. Therefore, as was the case for enriched material runs, it cannot be stated that the observed sustainable flowrates are, in fact, maximum achievable flows.

Finally, we observe the effect of mixhead type on the sustainable operating rate for depleted material. The effects are noted by comparing the two 1200°F tests, Run 8 and Run 11 (Paducah and FMPC mixheads, respectively), and the two 1300°F tests, Runs 7 and 10 (Paducah and FMPC mixheads, respectively). At 1200°F, the sustainable rate for the FMPC mixhead (7.46 MTU/D) exceeds that of the Paducah

mixhead (7.13 MTU/D) by 5%. At the higher 1300^oF setpoint, the trend is reversed, with the Paducah mixhead (8.26 MTU/D) outperforming the FMPC mixhead (7.65 MTU/D) by 8%. As indicated earlier, however, the observed sustainable rate for Run 11 is biased high because of the dual-source augmented air supply. Comparing this to the single air supply of Run 8, it is not clearly evident that the higher flowrate experienced in Run 11 is directly related to the design of the mixhead. The two mixheads have not, therefore, been demonstrated to be statistically different in their throughput capacity.

3.4 Downtime Analysis

An analysis of downtime was performed based on historical data gathered from previous Pilot Plant operations. This analysis was designed to establish a criteria for estimating the "on-stream" factor of the reaction vessels, thereby arriving at a projected estimate of actual on-line production time.

Three specific operational periods were examined to derive estimates of the projected "on-stream" factor.

Period #1 covers the time from April 8, 1985 (when NLO assumed responsibility of the UF₆ to UF₄ conversion process from the engineering firm of Sanders & Thomas, and after final modifications and repairs were made to bring it to an operational state), until July 29, 1985.

Period #2 covers the time from October 1, 1985 until February 10, 1986, during which time the Pilot Plant was shut down due to the vessel failure.

Period #3 covers the time from August 8, 1986 until October 19, 1986. This was the period of current Test Operations, for which this document is being written. Detailed summaries of downtime incurred during these three periods are presented in Tables B-1, B-3, B-5 and B-6 in Appendix B.

A portion of downtime during the periods studied was grouped into the category of "One-Time Outages." The reason for including certain downtime into this category is it is unlikely that these events would recur. Events grouped in the "One-Time Outage" category include:

- Cracking of Reactor Tube -- Implementation of the Reactor Vessel Inspection Program should alleviate this problem. A detailed outline of inspection related downtime is presented in Appendix B.
- Packaging Station Modifications -- Both packaging stations were modified with no additional modifications expected.
- Standby -- This was the result of only being able to operate one reactor at a time. The new refrigeration unit, along with the enhanced ability to purge one reactor while another is on-line, should eliminate this downtime.
- Product Mill -- During the latter part of 1985 and early 1986, the newly designed product mills were installed on both packaging stations. These upgrades reduced associated product mill downtime by 95%.
- Reporting -- During the period from August 8, 1986 thru October 19, 1986, there was planned downtime in the test plan set aside for the test engineers to write reports. This downtime was only related to the test plan and should not recur.
- Control Modifications -- The Distributed Control System (DCS) logic controlling heating and cooling was modified with no future changes expected.
- Temperature Related Problems -- Operations at unstably low temperatures resulted in extensive downtime due to flame-outs and excursions of UF_6 into the off-gas system. Future plans do not include operations at these same low temperatures.

The contributions of One-Time Outages to the total downtime are outlined in Tables B-2, B-4, and B-7 in Appendix B.

The remaining downtime was divided into the two categories. Those downtime events that were expected and not related to mechanical breakdowns were grouped into the "Operating Downtime" category. These include:

- Deslagging -- Periodic deslagging is essential to proper reactor operation, and is an unavoidable delay when operations are underway.
- Isotopic change-overs -- Isotopic change-overs and associated cleanout are required when switching to different enrichment levels.
- Start-ups -- During periods of operation, it is also necessary to restart the reactors. These restarts occur after deslagging, scheduled maintenance, and unscheduled shutdowns.
- Cylinder changes -- With three autoclaves in operation, the reactors need not be shut down to change cylinders unless something happens during the heating of the cylinders. It should be noted, however, that if one autoclave is to be used for the "healing" of cylinders, then the downtime for cylinder changes would increase since the operation would now rely on only two autoclaves.

The second category of expected downtime is the "Scheduled Unavailable Time," which includes five contributions:

- Monthly Preventative Maintenance Periods (PMP) -- Generally, each monthly PM requires approximately 24 hours to complete with 11 separate PMPs occurring each year. Each PMP requires that the system be operational in order to allow for proper examination of the associated safety systems.

- Annual PMP -- Once each year, the plant is shut down to perform PMs on those systems which are scheduled for testing and inspection on an annual basis. This schedule is defined in the Operational Safety Requirements (OSR), with the annual PMP generally requiring five days to complete.
- Holidays -- The only scheduled downtime would occur on the two day Thanksgiving holiday and the two day Christmas holiday. All other days throughout the year the plant will be operational.
- Inventories -- Periods when the plant is required to take inventories may or may not require shutdowns. Work-in-progress inventories do not require shutdowns; however, physical inventories do require shutdowns.
- Training -- Periodic training is required to maintain operator skill on existing equipment, new equipment, and safety systems.

The final category of downtime, "Unscheduled Downtime," includes periods when the reaction vessels were scheduled to operate, but were shut down due to mechanical failures or other unanticipated problems.

The downtime analysis is summarized by the following equations:

$$t_{\text{Total}} = t_{\text{Unavailable}} + t_{\text{Available}}; \quad (\text{Eq. 3-3})$$

$$t_{\text{Unavailable}} = t_{\text{Scheduled Unavailable}} + t_{\text{Vessel Inspection}}; \quad (\text{Eq. 3-4})$$

$$t_{\text{Available}} = t_{\text{Operating}} + t_{\text{Operating Downtime}} + t_{\text{Unscheduled Downtime}}. \quad (\text{Eq. 3-5})$$

Based on the study of historical data during the operating periods that were studied, the total number of hours that were available to operate equaled 6204.4 hours (see Appendix B, Table B-8). During this time, reactor shutdowns not associated with One-Time Outages were grouped into

six categories. The categories, ranked in descending order of magnitude, are shown in Table 3-3.

TABLE 3-3

Unscheduled and Operating Downtime factors

<u>Downtime Event</u>	<u>% of Available (*) Operating Time</u>
Unscheduled outages	17.20%
Deslagging	5.47%
Isotopic change-overs	4.19%
Start-ups	0.61%
Cylinder changes	<u>0.38%</u>
Total Unscheduled and Operating Downtime	27.85%

(*) See Table B-8, Appendix B

The total number of hours in which the 6/4 facility was staffed for operations, minus the number of hours that the reactors were either scheduled to be down, or undergoing inspection was identified as "Available Time," as defined in Eqs. 3-3 and 3-4. The Operating Time (that time during which the reactor is actually producing product) divided by available time, shows that the reactors operated 72.15 percent of time that they were originally scheduled to operate. This should not be confused with the "on-stream" factor, defined as the Operating Time divided by the total elapsed calendar time.

Based on the studies of the three time periods, summarized in Table 3-4, it was computed that the "on-stream" factor for the UF_6 to UF_4 conversion process has historically been 58.9%, neglecting those outages deemed to be one-time-only occurrences. Since it has been concluded that this "on-stream" factor is well below the 75% design basis value,

TABLE 3-4
PROJECTED ANNUAL ON-STREAM FACTOR
(Per Reaction Vessel)

Total Elapsed Time		= 365 days/yr. times 24 hrs./day = 8760 hrs.	
<u>Scheduled Unavailable Time</u>	<u>Days</u>	<u>Hours</u>	<u>% of Total Elapsed Time</u>
Plant shutdown for vacation periods	14	336	3.8
Training	7	168	1.9
Holidays	4	96	1.1
Monthly PMPs	11	264	3.0
Annual PMPs	5	120	1.4
Total Scheduled Downtime	41	984	11.2
<u>Vessel Inspection</u> (see TABLE B-9)		620	7.1
<u>Total Available Time</u>		7156	81.7
<u>Operating Downtime</u> (see TABLE B-8)			
Deslagging (7156 X 0.0547)		391	4.5
Isotopic change-overs (7156 X 0.0419)		300	3.4
Start-ups (7156 X 0.0061)		44	0.5
Cylinder change-overs (7156 X 0.0038)		27	0.3
Total Downtime Due to Operations		762	8.7
<u>Unscheduled Downtime</u> (7156 x 0.1720)		1231	14.1
<u>Estimated "On-Stream" Operating Time</u>		5163	58.9

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anything that can be done to increase this factor should be considered. Proposed recommendations include:

- Minimize deslagging intervals.
- Schedule production requirements to reduce isotopic change-overs to a minimum.
- Conduct training during the scheduled annual PMP.
- Operate during physical inventories.
- Arrange reactor vessel inspections during monthly PM periods.
- Ensure that around-the-clock maintenance coverage is available at the Pilot Plant.
- Operate at temperatures high enough to prevent UF_6 excursions.
- Use three autoclaves to heat and feed UF_6 .
- Improve DA and UF_6 flow control valves and meters.

3.5 Predicted Annual Production Rates

The anticipated annual production rate may now be computed by multiplying the sustainable operating rates calculated in Sections 3.2 and 3.3, by the anticipated on-stream factor of 58.9%, computed in Section 3.4. For enriched material, where no temperature dependence was identified, the mean sustainable rate of 1047 lb/hr UF_6 is used, providing a projected annual production rate of approximately 1650 MTU/Yr.

In the case of depleted material wherein the production rate is dependent on temperature; these results are presented in Table 3-5. Based on the goal of the test plan to identify the best estimate of annual production at the three test temperatures, the production rates for depleted material become 1400 MTU/Yr at 1150⁰F, 1500 MTU/Yr at 1200⁰F, and 1750 MTU/Yr at 1300⁰F.

Note that in using the computed on-stream factor of 58.9%, it is assumed that the downtime experienced during 1985 runs and during the test program due to "one-time outages" will not occur during production. To the best judgment of the authors, all of the items currently included in this category have been dealt with, and will not recur. However, it is certainly possible that other, as yet unidentified, design difficulties will be encountered once production is begun. Consequently, these difficulties may contribute to a lower on-stream time. By the same token, projected design improvements such as improved cooling capacity and geometry, and preheating of feed gases may increase the sustainable operating rates. At present, the above figures are the best estimates that may be drawn from the currently available data.

TABLE 3-5
Functional Dependence of Sustainable Flowrate on Setpoint
Temperature for Depleted UF₆ Feed

Setpoint (°F)	Sustainable Flowrate (Lb/hr UF ₆)	Production Rate (MTU/Yr)
1150	880	1394
1175	917	1453
1200	954	1512
1225	991	1570
1250	1029	1630
1275	1066	1689
1300	1103	1748
1325	1147	1817
1350	1177	1865

4.0 VESSEL TEMPERATURE CONTROL

Two of the five objectives of this test were (1) to determine the effectiveness of the revised temperature control system, and (2) to determine how the thermocouple design affects the temperature readings (to facilitate comparison of FMPC results with results of other 6/4 production sites). The success of meeting these objectives is presented in this section.

Temperature control in the reaction vessel is critical to successful operation. Introduction of sufficient heat into the top of the reactor is necessary for ignition of the UF_6/H_2 mixture, and to prevent unburned UF_6 from exhausting into the off-gas system. The product stream must then be equately cooled before exiting the reactor. An additional constraint arises from structural limitations of the monel reaction vessel. To extend vessel life, the temperature of the vessel walls should be kept as low as is compatible with stable process operation. In addition, temperature gradients should also be minimized, both axially and circumferentially.

4.1 Control Scheme

The reaction vessel temperature is controlled by a combination of electric heaters and cooling air flow, both of which are designed to maintain a preset axial temperature profile. There are four clam-shell heaters surrounding the vessel, encompassing numbered Zones 1 through 4, respectively, from the top of the vessel to the bottom. A cooling-air supply line penetrates the bottom of each heater and feeds a ring to distribute cooling air to the vessel. At the top of each zone a three inch duct extends from each heater to exhaust the heated air to a common stack.

Eight thermocouples, mounted in an axial row on the outside of the vessel, are used in temperature control of the vessel. (There are two thermocouples per zone; one in the top half and one in the bottom half). The thermocouples at the bottom of Zone 1 and at the top of Zones 2, 3 and 4 are used to control the heaters associated with these

zones. In the previous control scheme, these same thermocouples were also the only ones used to control the cooling-air flow to each zone. This might result in excessively high temperatures being recorded at the other four thermocouple locations with cooling air being initiated. For runs involving enriched feed, the control logic was modified so that cooling-air flow in Zones 2 and 3 was controlled by the maximum indication of the two thermocouples contained in each zone. Later, between Runs 7 and 8, this control scheme was extended to Zones 1 and 4. In addition, a maximum temperature limit of 1380°F was incorporated into the DCS, whereupon the reaction would be terminated if any thermocouple temperature indication exceeded this limit.

Controlling the heaters with one thermocouple per zone and the cooling air with both of the zone thermocouples results in a bimodal control situation where both heating and cooling can occur simultaneously. For this control situation to actuate in Zones 2 through 4 with the setpoint control temperatures of both the upper and lower thermocouples at the same setting, the bottom of the zone must be above setpoint and hotter than the top. When the bottom thermocouple reading causes the air to come on, the air which enters at the bottom of the zone cools the bottom more quickly than the top, and the air may cycle off before the top can experience significant cooling effects. With the air off, the zone continues heating up until the top reaches the setpoint temperature and turns the heaters off or cycles the bottom cooling air back on. As compared to past experience with the monomodal control scheme (in which heating or cooling, but not both, was controlled by the indication of a single thermocouple), operation with the bimodal control scheme provides a distinct improvement. It ensures much better protection against a hot-spot developing at the end of the zone opposite from the monomodal controlling thermocouple. It also allows for a fine-tuning of the axial temperature gradient in each zone; consequently, a much more linear temperature profile can be maintained along the entire length of the reaction vessel. This increased profile linearity has been suggested to minimize thermal gradients and hence internal wall stresses.

The case of controlling the axial temperature profile would be further

enhanced if the top and bottom temperature of each zone were separately controlled. This could be done fairly easily considering that the configuration of the heating elements within the clam-shell structure permits independent operation of the upper and lower halves of the heater zones, provided the external wiring is modified. Consideration should therefore be given to increasing the number of heater control zones to eight if it is determined that a linear axial vessel temperature profile is critical to minimizing thermal stresses and extending vessel life.

During the test phase, the temperature profile of the reaction vessel was not always maintained as desired. This is attributed to an insufficient air supply, maldistribution of the air flow and leakage between zones, and is not the fault of the temperature control scheme. These air-related problems will be further addressed in the following sections.

4.2 Cooling Capacity

With adequate air supply to a zone, the air cycles on and off frequently and temperatures in the zone are maintained within the control band. An example of cooling air control during Run 4a is illustrated by the Zone 2 results shown in Figures 4-1 and 4-2. Figure 4-1 shows Zone 2 air cycling on and off frequently with the heat cycling on occasionally. Figure 4-2 shows that the Zone 2 top temperature fluctuated in a band around its setpoint temperature of 1150°F, while the Zone 2 bottom temperature remained approximately 100°F cooler.

If there is an insufficient supply of cooling air to a zone, the cooling air is supplied continuously without the temperature being reduced to the desired level. This is also illustrated in Figures 4-1 and 4-2 for Zone 1. As indicated, between 19:30 and 21:40, the cooling air to Zone 1 was on continuously but the bottom temperature remained above its setpoint temperature of 1050°F. A second illustration of the effects of insufficient cooling air is given in Figure 4-3, a plot of temperature data for Run 7. During this time frame, operation was being maintained

Figure 4-1. Heat and Cooling Air Cycles

Figure 4-2. Zone Temperature Relationships

Figure 4-3. Zones 3 and 4 Temperature vs. Air/Heat

with a UF_6 flow rate ranging between 1300 and 1450 lb/hr (see Appendix A, Figure A-7(c)). Initially, the temperature at the top of Zone 3 was at its setpoint of 1100°F when the Zone 4 cooling air cycled on and remained so for approximately 2 hours. During this time the Zone 3 top temperature increased to about 1300°F , even with the Zone 3 air continuously being cycled. When the Zone 4 air flow ceased, the temperature in Zone 3 returned to 1100°F . Obviously there was insufficient air flow to simultaneously cool Zones 3 and 4, with Zone 4 operation starving the zone above it. Although Zone 2 temperatures were well controlled during this four-hour period, the change in frequency of temperature fluctuations indicates that the Zone 4 air flow reduces the flow rate to Zone 2. Zone 2 air flow is also observed to reduce Zone 3 air flow; this is illustrated by the Zone 2 and Zone 3 temperature fluctuations being out of phase.

It was also difficult to reduce the Zone 4 bottom temperature to a desired level lower than the Zone 4 top temperature. The top of Zone 4 ran cooler than the bottom whenever the Zone 4 air supply was off, apparently due to a large leakage of Zone 3 cooling air into the top of Zone 4. With the Zone 4 top temperature (the control thermocouple) cool, the Zone 4 air remains off and the bottom of the zone heats up. This is clearly illustrated by comparing the temperatures in Figure 4-4 to the Zone 3 and 4 air-supply plots in Figure 4-3. If the zone temperatures are to be controlled independently so as to allow establishment of a linear axial profile, cooling air isolation between zones is required, this being more effective than the current firebrick barriers.

Between Runs 7 and 8, a portable compressor was added to the system to augment the cooling-air supply. The air supply was not increased as much as expected, however, because of overly restrictive feed lines to the four zones. This limitation resulted in only a slight improvement in the overall cooling capacity during Runs 8 through 10. However, during Run 11, a significant increase in cooling capacity was obtained by simultaneously employing both the compressor and the existing plant air supply. This combination provided approximately 1,200 SCFM of

Figure 4-4. Zones 2, 3 and 4 Temperatures vs. Time

cooling air to the reaction vessel. Figures 4-5 through 4-8 contain some of the results of those runs which utilized the increased air flow. As is observed, there was sufficient air to control the temperatures in Zones 1 and 2, but not in Zones 3 and 4. It is estimated that a 25% increase in the total cooling air supply is required to control the temperatures in all four zones. This will support a UF_6 flow rate of 1300 lb/hr. Based on these results, it is recommended that the air supply system be upgraded to deliver at least 1,600 SCFM of cooling air per vessel, and that the restrictive zones' feed lines be replaced.

With the increased air supply, there was sufficient air to cool Zone 2, however, the magnitude of the temperature fluctuations caused by the air cycling on and off increased to 50°F . These temperature fluctuations should be eliminated in that they are not only disruptive to reaction stability, but in theory contribute to accelerated degradation of the reaction vessel. It is further recommended that the existing on/off air control valves be replaced with modulating control valves.

4.3 Circumferential Temperature Variations

In addition to the eight axial thermocouples that are used to control/measure the axial temperature profile of the vessel, there are three additional thermocouples at the Zone 2 bottom elevation that measure the vessel circumferential temperatures. An example of the measured circumferential variation is illustrated in Figure 4-9; measured variations are as large as 400°F . These variations are attributed at least in part to maldistributions in the cooling-air flow caused by the existence of only one small exhaust port and by non-symmetric leakage flow. According to Figure 4-9, at approximately 23:30, the plant shut down (see Figure A-11 (a), Appendix A) and the cooling air was turned off for about two hours. During this time period, the temperatures converged. When the operation was ramped up at 0:05, the air started to cycle on and off again, resulting in the divergence of the temperatures. These large temperature variations are not acceptable structurally, and they could be reduced by increasing the

Figure 4-5. Temperature & Flow vs Time

Figure 4-6. Temperature & Flow vs Time

Figure 4-7. Temperature & Flow vs Time

Figure 4-8. Temperature & Flow vs Time

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Figure 4-9. Vessel Circumferential Temperatures

number of exhaust ports around the top circumference of the heater shell. It is recommended that the heaters be modified to contain, as a minimum, four exhaust ports equally spaced around the heater shell. Additionally, since the existing three-inch exhaust port was sized for only 20 SCFM, the total flow area for the exhaust ports in a single heater zone needs to be increased to at least 50 in². The other openings (in particular, the penetrations for the vibrators) in the shell should be sealed to reduce air leakage.

There is also evidence that the circumferential temperature variation is due to asymmetric burning of the UF₆-H₂ mixture within the vessel. It is known that 6/4 reaction vessels at other facilities have historically exhibited operating hot-spots and preferred failure points whose locations seem stable with time. Carolina Metals periodically rotated and vertically reversed their columns to combat this problem. At the FMPC, both Vessel #1 and Vessel #2 exhibited structural weakness in the same circumferential location at the time of the January, 1986 incident. In addition, the West thermocouple usually indicated the highest temperature among the other circumferential thermocouple locations. This is unexpected since by the geometry of the cooling-air delivery system, the west thermocouple should receive the greatest amount of cooling air when compared to the other three thermocouple locations. All of these factors suggest that the hot-spots may result from asymmetries in the burning process, which may be both exacerbated and incompletely compensated for by non-uniformities in the cooling-air delivery system.

Additional supporting evidence comes from examining the magnitude of the circumferential asymmetry under different operating conditions. There is an indication (although not statistically valid based on the small amount of data presently available) that the magnitude of the wall temperature asymmetry correlates with mixhead type. By defining the magnitude of the asymmetry as the temperature of the hottest thermocouple (usually the West, but sometimes the North thermocouple) minus the temperature of the coolest point (usually the South thermocouple), the curves in Figures 4-10 and 4-11 can be generated.

Figure 4-10. Circumferential Temperature Variation

Figure 4-11. Circumferential Temperature Variation

Figure 4-10 indicates the magnitude of the temperature asymmetry versus UF_6 flowrate at a setpoint of 1200°F , for the FMPC mixhead (Run 10) and Paducah mixhead (Run 7). Figure 4-11 illustrates similar data for a 1300°F setpoint, again for the FMPC and Paducah mixheads, Runs 11 and 8, respectively.

Examination of Figure 4-10 indicates a distinct functional dependence of the temperature asymmetry with flow; however, the significance of this is not presently understood. Figures 4-10 and 4-11 appear to exhibit the same curve shape, but no dependence of temperature variation on mixhead is clearly illustrated. At the higher operating temperature of 1300°F , however, the temperature asymmetry of the FMPC mixhead data greatly exceeds that of the Paducah mixhead data. The potential for a 100°F reduction in hot-spot magnitude provides sufficient grounds to recommend continued use of the Paducah mixhead over the FMPC design.

A possible explanation for this mixhead dependency is provided by considering the nature of the flow patterns set up within the reactor by the two mixhead geometries. Because of the extremely high density ratio of UF_6 compared to H_2 (equal to 175 at 1 atmosphere and 750°F), mixing is likely to be incomplete in either design. In both cases, the UF_6 flow is directed radially outward, likely forming an annular curtain flowing down near the walls of the vessel. Hydrogen and nitrogen will occupy the central volume of the reactor, gradually mixing with UF_6 due to entrainment at the interface. This radial separation of the UF_6 and DA flows is especially probable in the case of the FMPC mixhead, where the DA is actually injected inside the UF_6 curtain.

Evidence supports the contention that the flow of H_2 may not be axisymmetric; that is, it may tend to attach itself to one wall of the vessel, such that the flame front burns significantly off-center, resulting in a circumferential hot-spot. This is illustrated by examining the Reynolds numbers (Re) of the UF_6 and H_2 flows. The Reynolds number is a dimensionless number characterizing the nature and

degree of turbulence inherent in a flowing fluid. The superficial Reynolds number Re_S for gas flowing in a circular pipe may be expressed as:

$$Re_S = 4 \dot{m} / \pi D \mu , \quad (\text{Eq. 4-1})$$

where:

$\dot{m}$ - fluid mass flowrate

D - inner diameter of flow channel

μ - fluid viscosity

At the approximate ignition temperature of 750°F, with 1100 lb/hr of UF_6 flow and 20 mole percent excess hydrogen, the superficial Reynolds number for the UF_6 flow is 14000. The Re_S for the associated hydrogen flow is equal to 225. While the UF_6 flow is well within the turbulent flow regime ($Re > 2100$), the hydrogen flow is deep within the laminar regime, and will be strongly affected by recirculation eddies and other flow instabilities introduced by the mixing geometry.

Unpublished studies carried out at the Westinghouse Research and Development Center by one of the authors, D. F. McLaughlin, have shown that at very low Reynolds number, uniformly-distributed downward flow in a vertical circular pipe may, within a distance of a few pipe diameters from the point of injection, become highly asymmetric and concentrate in a small fraction of the available flow cross-section, close to one wall. The point of attachment is also typically the coolest circumferential location. The flow patterns are complex, and may change abruptly with small changes in superficial Reynolds number and flow injection geometry. Similar phenomena have been reported in the literature.^(2,3) If such phenomena were occurring with the DA flow in

(2) W. Cherndon et al., Journal of Fluid Mechanics, 84, Part 1, 13, 1978.

(3) A. Iribarne et al., AIChE Journal, 18, 689, 1972.

the 6/4 reactor tower, one would expect the formation of a hot-spot, occurring at the coolest location nearest the point of introduction of the gases. This is exactly what was observed during the Test Operation, with the hot-spot consistently at or very close to the West circumferential position.

Although evidence for this scenario is circumstantial, the existing evidence is consistent. Since none of the variables in Equation 4-1 may be readily adjusted, the only means for increasing the overall superficial Reynolds number and reducing the potential for asymmetric DA flow is to introduce more complete mixing. The very low Reynolds numbers responsible for this sort of laminar instability will only persist if the hydrogen flow is highly separated from the turbulent UF_6 stream. The FMPC mixhead, which should result in greater separation of the UF_6 and DA flows (and therefore amplify any instability), exhibited a considerably greater hot-spot intensity with a 1300°F operating temperature. At the lower temperature of 1200°F, hot-spot intensity was found to be dependent on flowrate; this is also consistent with the model.

It is therefore recommended that flow modeling studies be carried out on the 6/4 reactor mixing system, using dynamically-similar bench models. This will allow the proposed theory to be experimentally tested outside of a production environment, as well as providing a facility where the impact of such things as mixhead design modifications and gas premixing might be examined.

4.4 Thermocouple Comparisons

One of the goals of the test plan was to develop a database comparing the FMPC thermocouple indication to that of other element and mounting configurations used in the Paducah and Carolina Metals 6/4 facilities. Thermocouple indication and its proximity to the actual vessel wall temperature are affected by mounting configuration, element design and environmental influences (radiative heating, convective cooling, etc.), all of which differ among the three plants. Tests were designed to evaluate the first two variables, and provide recommendations as to the most reliable hardware design. The uncertainties inherent in a direct plant-to-plant comparison due to different thermal environments are discussed near the end of this section.

As indicated, an objective of the test plan was to evaluate the relative performance of three alternative thermocouple mounting configurations. The first mounting technique, the previously preferred "FMPC-system," is used for all of the zone control thermocouples and is illustrated in Figure 4-12. These thermocouple elements are type-K thermocouple elements and are mounted on a lug which is in turn fixed to a threaded stud, welded onto the vessel wall. This is surrounded by a 2" length of three-inch diameter monel pipe, also welded to the wall, designed to deflect cooling air and minimize convective cooling losses to the thermocouple. The entire assembly is packed with loose Fiberfrax insulation to shield the thermocouple from the thermal radiation of the shell and adjacent heaters.

Two other thermocouple mounting configurations were compared with the FMPC method. The first of these, referred to in this report as the "Paducah-mount," is similar to that used in the 6/4 facility which operated at the PGDP and is shown in Figure 4-13. It is similar to the FMPC mount in that an identical type-K "lug-type" thermocouple element is used, shielded below by a monel air deflector, but differs in that

* As received Thermocouple is modified as follows: Drill the 5/32" hole to 1/4" and make 1/4" flat bend of about 60-80° at 1/4"-1/2" from hole and then check calibration.

Figure 4-12. "FMPC-Type" Thermocouple and Mounting

the shield is semicircular, and no Fiberfrax packing is used. The second comparison thermocouple, referred to as a "rod-type" thermocouple, is also a type-K, mounted in a one-quarter inch diameter thermocouple well, and is spring loaded to butt against the vessel. (This is shown in Figure 4-14, "Design 1"). This thermocouple is not shielded nor insulated and is intended to be in intimate contact with the vessel shell. Initially, this type of thermocouple was used at the FMPC and is reportedly still in use at Carolina Metals in a similar operation. All three thermocouples were mounted on the outer wall of the vessel in Zone 2 (at the same elevation) for comparison with the existing lower control thermocouple. This location generally contains the "burning zone" in the reactor and consequently, undergoes a substantial amount of cooling. Also, this is the zone where the previous vessel developed a crack.

Two data sets were examined to determine the difference in system response between the three mounting techniques. Comparison data was selected from a "deslagging cycle" since it contains both cooling and heating periods and also a wide range of temperatures, not found in ordinary operation. The thermal environment varies slowly, and is either pure heating or pure cooling. Results for the deslagging cycle following Run 3b are shown in Figures 4-15 and 4-16.

The Paducah-mounted lug-type thermocouple averaged $13.1 \pm 1.0\%$ below the control during cooling, and $14.0 \pm 4.4\%$ above the control during heating, indicating that this mounting configuration is biased both by convective losses to cooling air and radiative heating from the heaters. The temperature trace is also much more irregular than any of the other curves, suggesting less stability.

The rod-type Carolina Metals thermocouple exhibited a $19.5 \pm 1.9\%$ negative deviation during cooling and $4.4 \pm 4.7\%$ positive deviation during heating. This large negative sensitivity to convective cooling is to be expected from the unshielded mounting geometry. The results of both of these lower-shielding configurations indicates that the FMPC mounting scheme is much less sensitive to changes in the environment,

Figure 4-14. "Rod-Type" Thermocouple

Figure 4-15. Zone 2 Thermocouple Response
During Deslagging Cycle Cool-Down

Figure 4-16. Zone 2 Thermocouple Response
During Deslagging Cycle Heat-Up

making this technique more suitable for controlling the zone temperatures (especially if simultaneous heating and cooling are involved).

Following Run 7, a side-by-side comparison of the FMPC and Paducah thermocouple elements was performed. The Paducah thermocouple element resembles a washer which can be attached to the mounting stud using a nut, with the couple junction on the "washer" inside diameter. The comparison was done by mounting the two thermocouple elements together on the same mounting stud of the FMPC mount, with the Paducah unit outside of the FMPC lug. A typical temperature trace is shown in Figure 4-17. The fluctuation in all three temperature indications correlates directly with the cycling of the cooling-air flow. The rod-type thermocouple is again found to be far more sensitive to convective cooling effects, and to be much less suitable for control purposes. In the same shielded mounting configuration, the magnitude of the fluctuation exhibited by the FMPC lug-type thermocouple element exceeds that of the washer-type Paducah element. This suggests that the FMPC element was subjected to greater exposure and response lag time due to the distance between the tube wall and the element (refer to Figure 4-12). The results demonstrate that the Paducah thermocouple element provides more intimate contact of the thermocouple junction with the vessel, resulting in a temperature indication 50⁰F higher than during typical operations with the FMPC thermocouple element in the same mount.

The circumferential temperature variation between the two thermocouple systems is of even greater magnitude than the temperature differences described above. As mentioned earlier, temperature variations as large as 400⁰F may exist during normal operation at one axial location as is shown in Figure 4-18. This is attributed to variations in the cooling-air flow distribution over the surface of the reaction vessel, due to the existence of only one small exhaust port. The Paducah air inlet is simply a one-half inch pipe directed at the vessel, as opposed to a sparger-ring around the vessel as is used at the FMPC. As a result, the circumferential variations at PGDP are likely to be quite different than those at the FMPC. For these and other reasons, temperature data from

Figure 4-17. Thermocouple Element Response Comparison

Figure 4-18. Vessel Circumferential Temperature Variations

the Paducah Plant can not be reliably compared to the FMPC operation.

4.5 Control of the Reaction Zone Location

Mandatory for safe and stable operation of this process is the ability to control the position of the reaction-zone inside the vessel. The preferred location is Zone 2. If the reaction zone migrates downward into Zone 3, insufficient heat-transfer area is available to adequately cool the exit stream, and the cooling capacity of the delivery screw may be exceeded. A portion of the buffer zone is also sacrificed which then would tend to make the process more susceptible to "flameouts." Further migration into Zone 4 ultimately results in UF_6 gas exiting the vessel before reaction is complete. This, in turn, results in UF_6 being present in the off-gas system, causing immediate shutdown of plant operations. During the test period through Run 7 there were approximately a dozen instances of UF_6 detected in the off-gas system, followed by an automatic plant shutdown.

The causes can be classified into two groups: those due to insufficient heat supply to allow the reaction to initiate, and those due to insufficient hydrogen to allow complete reduction of the UF_6 . UF_6 and/or dissociated ammonia flow indication problems account for the non-temperature related problems. The remainder are attributable either to the vessel being too cool at startup to initiate a reaction, or to a gradual downward migration of the reaction zone. Downward migration of the reaction zone occurs if excessive cooling or insufficient heat is supplied at the top of the reaction vessel, since the reactants will have to travel further down the reaction vessel before reaching ignition temperature. Additionally, buildup of slag inhibits inward heat transfer such that some downward migration of the reaction may be unavoidable during latter periods of a given run. Figure 4-19 illustrates several oscillating cycles, during the startup of Run 7, of the reaction-zone front between Zones 2 and 3. Just before 09:00, the Zone 2 bottom temperature drops while the Zone 3 top temperature simultaneously rises. The pattern reverses after about 10 minutes as the flame retreats back into Zone 2. A similar excursion is observed at

Figure 4-19. Motion of Burning Zone During Startup

approximately 10:45.

An excellent example of an uncontrolled reaction-zone migration is demonstrated by data plotted from Run 4b, shown in Figure 4-20. From 04:30 to 05:15, the Zone 2 bottom temperature gradually drops while the Zone 3 top temperature rises rapidly, indicating that the reaction zone had migrated from Zone 2 to Zone 3. Although the Zone 2 bottom temperature is initially 125°F over the setpoint, the top of the zone (containing the control thermocouple) is at a lower temperature than the setpoint temperature. The control system is therefore calling for the heaters to operate, which is essential in driving the reaction upward. This action fails, however, to move the reaction upward; consequently, the reaction moves downward from the top of Zone 3, with increasing temperature, into Zone 4 at approximately 05:15. At 05:34 the reaction exited the vessel and the process shut down automatically due to UF₆ being detected in the off-gas system.

Figure 4-21 indicates the rate of temperature change for the top of Zone 3 during the same time period. Note that if a rate of temperature change indication was made available to an operator, he would have had a one-half hour notice of the approaching problem. However, since the existing control room display has only a 0 to 1800°F temperature scale, it does not possess the resolution that is necessary for an operator to reliably interpret the developing situation.

The Zone 3 rate of temperature change function was generated digitally via the DCS and a display made available to the operator during Runs 8 thru 11. This was done in hopes that it could provide a simple and potentially valuable alarm signal to prevent flameout or shutdown due to UF₆ emissions. However, no situations arose to allow for actual testing of this function. An alternative control function would be $d/dt (T_{2b} - T_{3t})$, where T_{2b} is the temperature indicated by the Zone 2 bottom thermocouple, and T_{3t} is the temperature indicated by the Zone 3 top thermocouple. This function would provide maximum sensitivity to motion of the flame past the Zone 2/Zone 3 interface, and is recommended for future operations.

Figure 4-20. Example of Flame Migration To Zone 3

Figure 4-21. Rate of Temperature Change for Zone 3

If the temperature in Zone 1 at the point of reactant introduction is too great, ignition may occur at an unreasonably high level in Zone 1 (especially with enriched UF_6 feed). According to the present configuration, cooling air may only be injected at the bottom of this zone, providing no means to effectively cool the upper region of Zone 1. Experience has indicated that once burning begins in this region, it is nearly impossible to force the flame downward without process shutdown. In addition, the lack of cooling may cause local vessel overheating and accelerated slagging of the reaction vessel walls and the mixing head. The control scheme must therefore prevent early ignition in the uppermost zone, as well as being capable of correcting for the tendency of the flame to migrate downward into Zones 3 and 4. The approximate, generalized vessel temperature profiles, as indicated in the previous Standard Operating Procedure (SOP), are as follows:

Zone	Temp - for Enriched Feed	Temp - for Normal Feed
	($^{\circ}\text{F}$)	($^{\circ}\text{F}$)
1	1150	1350
2	1050	1200
3	900	900
4	800	800

Past operating experience has demonstrated the importance of minimizing operating temperatures at both the top and bottom of the reaction vessel, although a somewhat arbitrary temperature profile was used along the length of the vessel. From the problems encountered with initial vessel overheating, it is clear that the maximum temperature is desired in Zone 2 with a somewhat lower temperature in Zone 1. Previous operating experience has also indicated that 700-900 $^{\circ}\text{F}$ is an optimum temperature range for Zone 4 in order to minimize HF entrainment in the product. The Zone 3 setpoint, according to the SOP, is arbitrary. It is recommended that this last value be increased to linearize the vessel profile; it is likely that this would help extend vessel life, as well as allow the heat of reaction to be dissipated over a larger area.

To test the feasibility of this strategy, between Runs 7 and 8, the temperature setpoints and control strategy were modified to allow for a more linear temperature distribution over the bottom five thermocouples (from the typical location of the burning zone downward). This amounted to the DCS using two different setpoints per zone with the second setpoint being calculated by extrapolation. The control strategy functioned quite well within the physical limits of the cooling air capacity and its continued future use is highly recommended.

If a fully linear temperature profile is desired to minimize thermal stress and lengthen vessel life, the Zone 1 top temperature needs to be increased. At high UF_6 flow rates, insufficient heater power is currently available to maintain the extrapolated linear setpoint.

4.6 Energy Balances

An attempt was made during the test operations period to collect data necessary for performing a heat balance around the 6/4 process in order to quantify the actual required amount of vessel cooling. This requires operating at various UF_6 flowrates and quantifying the amount of heat gain experienced by the cooling air.

Because the flow of entering cooling air and its zone exit temperatures were unknown prior to Run 8, early estimates on the cooling requirements were calculated using an overall vessel energy balance with an assumed vessel exit temperature. The results have indicated that 403,900 to 517,200 BTU/hr of cooling should be required overall. There are several problems with this approach, however. The first is that the results cannot provide information as to how the cooling is to be distributed. The second, and perhaps the most significant problem, is that it is difficult to calculate the volume of cooling air necessary to provide the required amount of heat removal.

The mode of heat transfer from the vessel would be expected to be by radiation to the heater refractory, and by convection to the air from

the vessel wall and the heater refractory. To compute the actual coolant requirement by heat balance over the reactor, the vessel product exit temperature, cooling air inlet and exit temperatures, heater input power, and cooling screw heat removal rate all must be known.

The vessel exit temperature has been the subject of some controversy since the initial process conceptual design. The conceptual design listed 900⁰F as the exit temperature and this was carried through the actual design and sizing of the cooling screw, vessel cooling system, and associated utilities. If the actual vessel exit temperature were much hotter, less vessel cooling would be required than has been calculated.

Because of the difficulty in measuring the actual temperature of the reaction products as they exit the vessel, data was collected to construct an energy balance around the cooling screw. This allows indirect calculation of the vessel exit temperature since the temperature rise of the screw cooling water comes from the heat in the material which exits the vessel. The results of 18 heat balances at various periods of operation are given in Appendix E, Table E-1 and show the calculated vessel exit temperatures to range from 679 to 1232⁰F with the average being 1000⁰F.

During Runs 8 thru 11, a Monel thermocouple well was mounted in the transition-piece between the vessel and the cooling screw inlet. The results indicate that the average temperature is approximately 750⁰F. A comparison of calculated vessel exit temperatures versus measured temperatures is provided in Figure 4-22. There is a good correlation of one temperature relative to another but the results do not agree in absolute magnitude with the measured absolute temperatures. The measured values consistently fall 150 to 250⁰F below those computed from the cooling screw heat balances. It is difficult to know which of the results are the more correct, since several factors are likely to have biased the measurement below the actual gas temperature. The thermocouple well was not allowed to extend into the vessel flow stream due to concerns that a large piece of slag could fall, shearing off the

Figure 4-22. Vessel Gas Exit Temperature Measurements vs. Calculations

thermocouple well, and causing a HF, UF₆, or H₂ leak. For this reason, unfortunately, the thermocouple well would more likely be surrounded by a region of cooler stagnant gas than the higher velocity offgas stream. Also, it is likely that the thermocouple did not make good contact with the wall of the thermowells since no "heat transfer media" such as silicone oil was used; it was felt that these media would not hold up at the high operating temperatures.

Rotameters were installed in the cooling air supply and thermocouples installed in each zone's hot air exit between Runs 7 and 8. The data collected provided a more detailed determination of the amount of cooling required on a zone by zone basis. The results of 14 energy balances are summarized in Figure 4-23 and indicate that approximately 750,000 BTU/hr of cooling would be desirable to permit flowrates of up to 1400 lb/hr. The results, although a bit scattered, closed to within an average of 9%, which is acceptable for this type of calculation.

The slopes of the three curves in Figure 4-23 are equivalent to the specific energies (Btu/lb) for the cooling air, cooling screw, and heater, so that the difference between the slope of the heat removal curve (530 BTU/lb) and the heater input curve (167 BTU/lb) must be the heat input due to chemical reaction. This value equals 363 BTU/lb, equivalent to 71 kcal/gmol UF₆, in excellent agreement with the heat of reaction of 71.8 kcal/gmol given by Myerson and Chludzinski ⁽⁴⁾ (see Introduction). The required heater input of 167 BTU/lb also corresponds to 33 kcal/gmol, very close to the reported energy of activation of 37.6 kcal/gmol from the same reference.

Although the energy balances "close" within acceptable limits, there are two serious problems. First, the measured amount of air supply that was supplied to the zones, when heated, should not be removable through the

(4) A. L. Myerson and J. J. Chludzinski, Journal of Physical Chemistry 85, 3705, 1981.

Figure 4-23. Vessel Heating and Cooling Requirements for Depleted Feed

three-inch exhaust outlets. Secondly, using standard heat transfer models, convective heat transfer from a surface to a low velocity air stream should take place at only a fraction of this rate, and thus this cooling rate should be physically impossible. Rough calculations, assuming a heat transfer coefficient derived from basic engineering models, indicate that 90-95% of the cooling air would have to prematurely escape the heater annulus and not exit through the exhaust outlet to satisfy these two physical criteria. The combination of this and the vessel exit temperatures arrived at by the two independent methods would suggest to one that if the published value for the heat of reaction used in the overall vessel energy balance is correct, then the mode of heat removal from the vessel is poorly understood.

The apparent effect of throughput on cooling screw overall heat transfer coefficient, U , is shown in Figure 4-24 and defined as:

$$U = \frac{Q}{A\Delta T_{LM}} \quad (\text{Eq. 4-2})$$

where

Q = heat removal rate

A = total surface area available for heat transfer

ΔT_{LM} = log mean temperature difference between product and cooling screw wall surface

The strong correlation with product flow is likely due to the definition of heat transfer surface area used. The total available jacketed area was used in the calculation of the heat transfer coefficients, since the actual area covered by the product is not precisely known. Obviously the screw is not 100% full; the greater the flow, the greater will be the filling of the screw, with increased surface area available for heat transfer. This leads to a higher value for the apparent heat transfer coefficient. The "true" value for U would then be calculated only for the highest flowrates when the screw was nearly 100% filled.

Because the delivered product temperature has never been previously documented for baseline data, it is now included as a function of

Figure 4-24. Overall Heat Transfer Coefficient for the Cooling Screw
(Based on Total Available Surface Area)

throughput in Figure 4-25. This is important since the original conceptual design for the plant lists 250°F as opposed to the average of 445°F measured during the test period.

Figure 4-25. Product Exit Temperature vs. UF_6 Flowrate for Depleted Feed

5.0 VESSEL INSPECTION RESULTS

An inspection plan for the reaction vessels was developed and executed during the Test Operations to monitor the behavior and gradual deterioration of the vessels. The plan was prepared for the purpose of ultimately defining a routine inspection sequence and frequency for the reaction vessels in the Pilot Plant. The intent of the inspection plan is to provide an early warning of impending failure, which could preclude recurrence of a sudden breach of the vessel and reduce the risk of a UF₆ or HF leak from the 6/4 conversion process. The plan is intended to apply to the Pilot Plant vessels which have operated at temperatures in excess of 1000°F for any portion of time with or without the flow of UF₆ or dissociated ammonia (DA).

5.1 Inspections Performed During Test Operations

The inspection plan outlines specific attributes of the vessels and accompanying support system to be measured and the locations, techniques, frequency and conditions of measurement. For the Test Operations period, the inspections were conducted in accordance with a schedule of test runs performed for the Test Operations. Baseline measurements were performed on the vessels prior to the start of any operations and at the operating increments listed in Table 5-1.

The attributes measured or examined during each of the inspection periods included:

- Surface condition of the vessel (recorded with color photographs)
- Effective outside diameter and circumference of the vessel at several axial positions
- Longitudinal surface profile and alignment of the vessel at several orientations

TABLE 5-1
FREQUENCY OF VESSEL INSPECTIONS
DURING TEST OPERATIONS

<u>Vessel</u>	<u>Date of Inspection</u>	<u>Following Completion of Run Nos.</u>	<u>Incremental Hours of Operation over 1000°F</u>		<u>Combined Equivalent</u>	<u>Relative Proportion of Time at Temperature</u>
			<u>With UF₆</u>	<u>Without UF₆</u>		
#1	7/14/86	Baseline	---	---	---	---
	9/29/86	5-6	60.1	33.2	76.7	25% at 1200°F 75% at 1300°F
#2	7/14/86	Baseline	---	---	---	---
	*9/02/86	1-2	84	110	139	57% at 1150°F 43% at 1200°F
	9/29/86	3-7	156.9	51.4	182.6	25% at 1150°F 75% at 1300°F
	10/21/86	8-11	116.2	35.5	133.9	28% at 1150°F 45% at 1200°F 27% at 1300°F
	Totals		357.1	196.9	455.5	
* Inspection witnessed in part by a representative from the FMPC DOE Site Office, the DOE Oak Ridge Operations office, the Paducah Site of MMES, and the Westinghouse AESD, which satisfied a DOE condition for Restart						

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- Wall thickness of the vessel at several orientations and elevations
- Flatness of the vessel support yoke
- Clearance distance between the ends of the vessel support yoke and the top horizontal beam support
- Clearance distance between the counterweights and the step ledges below the weights, or the exposed axial dimension of the counterweights above the guide sleeve

Recorded values for the above measurements are contained in the inspection record files. Graphical representations of the data for vessel #2 are contained in Appendix C, Figures C-1 thru C-25.

In addition to the measurements specified in the inspection plan, the movement (if any) of the top of the reaction vessels was monitored by measuring the variation in the distance between fixed markers on the UF₆ and DA feed lines above the mixheads. Since the principal vessel support is at the bottom, the potential for a tilting change in the vertical orientation of the reaction vessel could be detected by a movement of the top relative to the bottom of the vessel. This movement would result in changes in the flexible joints of the gaseous feed lines located at the top of the vessel, providing an early warning signal for changes that might result in feed-line ruptures. Results of these measurements for vessel #2 are illustrated in Figure C-25, Appendix C.

5.2 Results of the Vessel Inspections

The periodic inspections of the vessels are primarily intended to focus on changes in characteristics that signal reaction vessel deterioration. Because of the relatively short period of operation experienced by vessel #1, the first and only interim results for this vessel did not reveal any significant structural or positional changes. The relative changes noted between baseline values and first interim results for vessel #2 in Figures C-1 thru C-25 are also

representative of the measurements recorded for vessel #1 following Runs 5 and 6.

The vertical-alignment measurement of vessel #1 was determined during the interim inspection, to be five-sixteenths of an inch from true vertical over a 4-foot length. Since no baseline measurement of this attribute was available for vessel #1, one cannot ascertain whether this slight out-of-alignment condition is a change from baseline or represents the actual baseline configuration. The lack of any discernable change in dimension between markers on the UF₆ and DA feed lines would support the latter condition. However, since the alignment of the vessel will be disturbed and will have to be re-established after installation of a new cooling screw at the lower end, a new baseline value will be measured for subsequent monitoring.

Since the majority of the Test Operations involved reaction vessel #2, the inspections during this phase of Pilot Plant operations focused on this reaction vessel. In addition to the baseline measurements, three separate interim inspections were performed on vessel #2 at the times and conditions listed in Table 5-1. During the first of these inspections, the measurement techniques were witnessed in part by representatives from the FMPC DOE Site Office, the DOE Oak Ridge Operations Office, the Paducah Site of Martin Marietta Energy Systems, and the Westinghouse Advanced Energy Systems Division. Observation and participation by personnel from these organizations satisfied a condition for Restart as specified by the DOE approval letter for commencement of the Test Operations.

Figures 5-1 and 5-2 illustrate the orientation of wall-thickness inspection points (measured ultrasonically) on the outside vessel surface at several elevations between the vibrator mount rings in Zones 1 and 3. Figure 5-3 illustrates typical results obtained from these measurements, being a plot of wall thickness versus axial position 1 thru 16, all at circumferential position "C" near the longitudinal weld. The four different curves represent the four separate inspections on vessel #2 outlined in Table 5-1. Beginning-of-life thicknesses were

Figure 5-2. Circumferential Location of Vessel Inspection Measurements

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Figure 5-3. Ultrasonic Thickness (UT) Measurements, Vessel #2, Axis C

generally measured and found to be 0.520 to 0.535 inch except near the weld, where values tended to be near 0.505 inch due to the welds being ground flush in fabrication. The fourth (last) set of measurements clearly show the start of a thinning process in the upper third of the measured vessel length; this is the hottest region of the reaction vessel. The thinning appears to be circumferentially uniform as plotted in Figure C-12. A complete set of plots for all circumferential locations, A thru K, is included in Appendix C. Note that orientations A and K are adjacent to the longitudinal weld in the vessel, which accounts for the axial variations in wall thickness at these positions.

The thinning of the vessel wall appears to be totally related to corrosion and erosion of the inside vessel surface, rather than by oxidation and scaling of the outside surface. The evidence supporting this contention includes the vessel girth measurements and the visual inspection results of the outside surface. The circumferential and diametral measurements, (see Appendix C, Figures C-13 and C-14) indicated no change in the outside configuration of the vessel. The visual observations revealed the formation of a tenacious, dark grey, uniform oxide layer throughout the heated regions; Figure 5-4 indicates this for a typical section. The surface appears to be free of any cracks and other imperfections found on previous vessels operated at the Pilot Plant. However, some very thin oxide scale has flaked off in two local locations around the vibrator mount ring in Zone 2 (Figure 5-5). The scale, which came off in fine (small surface area) pieces, is less than two or three-thousandths of an inch in thickness. The vessel surface is visibly rust-colored in the local spots where the oxide scale is missing.

Longitudinal profile measurements for orientation "C" are shown in Figure 5-6 with Figures C-15 thru C-20 illustrating profiles for all those orientations that were accessible with the device used to measure surface profile. (The discontinuity in the plots represents the location of the vibrator mount ring in the center of Zone 2). The absolute values of the sloped curves are not significant; however, the

Figure 5-4. Formation of Uniform Oxide Layer

Figure 5-5. Local Oxide Layer Scaling

Figure 5-6. Longitudinal Profiles at Circumferential Location C, Vessel #2

relative change in the slope of the successive lines and the local deviations from parallel require evaluation to assess the presence of local deformations in the vessel. cursory examination of these data suggest the possibility of an incipient bulge at elevation "3C". However, further field investigation revealed no indications of bulging.

Monitoring of the vessel support system has not revealed any substantial movement except for an apparent upward deformation of the east half of the yoke; the west half appears unchanged. The total measured change is approximately 50 to 60 mils. Yoke flatness as a function of time is illustrated in Figures C-21 and C-22. No apparent changes in top-support clearance or counterweight clearance occurred during Test Operations (see Figures C-23 and C-24).

The measurement distances between markers on the UF₆ and DA feed lines did not change with time as shown by Figure C-25. Since no baseline data was recorded for the UF₆ feed-line markers, these results indicate vessel #2 did not shift in position during this period.

Two key experiences during these initial measurements instigated follow-up action prior to the first interim inspection. The first action necessitated the development of a template for more accurately marking the matrix for vessel wall thickness and profile measurements. The second action resulted from the profile measurements, which indicated the levels used for vertically aligning the device on the vessel surface were not perpendicular to the plane of the device. Since time did not permit corrections to the device, careful characterization of the reference condition was made to provide data for correcting the measured vessel profile data. (The referenced conditions were determined prior to the first interim inspections). In addition, a suggestion has been proposed for a device to enhance the method of taking profile measurements.

5.3 Corrosion Rates

The vessel which failed on January 19 was metallurgically examined and reported on by Blue⁽⁵⁾. In this report, an Arrhenius-type correlation was proposed for the prediction of vessel thinning as a function of temperature and exposure time:

$$\text{Corrosion (Mil/Month)} = 1.46 \times 10^8 \times e^{-15566/T \text{ (K)}} \quad (\text{Eq. 5-1})$$

Actual vessel exposure conditions as summarized in Section 5.1 were used with this correlation to calculate the amount of thinning that would be predicted. The results are listed below:

VESSEL #1

<u>Date of Inspection</u>	<u>Equivalent hours of Operation</u>	<u>%Time at</u>	<u>Temp (°F)</u>	<u>Predicted Corrosion For Period (mil)</u>	<u>Predicted Cumulative Corrosion (mil)</u>
9/29/86	76.7	25	1200	0.182	0.182
		75	1300	0.422	0.604

VESSEL #2

<u>Date of Inspection</u>	<u>Equivalent hours of Operation</u>	<u>%Time at</u>	<u>Temp (°F)</u>	<u>Predicted Corrosion For Period (mil)</u>	<u>Predicted Cumulative Corrosion (mil)</u>
9/02/86	139.0	57	1150	0.445	0.445
		43	1300	0.566	1.011
9/29/86	182.6	25	1150	0.256	1.267
		75	1300	3.386	4.653
10/21/86	133.9	28	1150	0.210	4.863
		45	1200	0.571	5.434
		27	1300	0.894	6.328

(5) Blue, S.C., "Investigation of a Failed UF₆ Reduction Tower," MMES Document #KY/L-1406, 8, 1986.

Vessel thinning was first detected for vessel #2 at the 10/21/86 inspection. The measured thinning was 10 mils. This is in excellent agreement with the predicted value of 6.3 mils from Blue's correlation considering the difference within the measuring instrument's resolution. If actual corrosion rates are slightly greater than predicted, it may be that the actual vessel temperature is slightly warmer than indicated by the thermocouple by 50 to 100°F.

6.0 PRODUCT QUALITY

6.1 Results of Product Quality Testing

Table 6-1 indicates Pilot Plant specifications for final product (UF_4) composition including metals contamination, isotope purity, and volatiles content, for enriched and depleted material. Results of the product testing of 111 "lots" of UF_4 (97 enriched and 14 depleted) produced during the Test Operations are presented in Table 6-2. A lot consists of 36 cans of product, varying in weight dependent upon enrichment level, packaging requirement, or special process use. Because lots do not readily correspond to specific periods of operation at given temperature setpoints, it is difficult to draw any conclusions about the effect of actual operating temperature on product quality.

Figures 6-1 and 6-2 present the contaminant levels of nickel and copper contained in the product. These two metals are the principal components comprising the reaction vessel's structural material, Monel 400. (The composition of Monel 400, by weight percentage, is 63% Ni, 28-34% Cu, 2.5% Fe, and 2.0% Mn). Seven of the 97 enriched lots were out-of-specification (OOS) in nickel and copper content, while four of the 14 depleted lots were reported as being OOS.

TABLE 6-1
PILOT PLANT UF₄ SPECIFICATIONS

<u>MATERIAL</u>	<u>DEPLETED</u>	<u>ENRICHED</u>
Total U	75.75% minimum (min)	75.75% min.
UF ₄	99.0% min.	99.0% min.
Ammonium Oxalate		
Insoluble (AOI)	0.5% maximum (max)	0.5% max.
UO ₂ F ₂	0.5% max.	0.5% max.
U ⁺⁶	0.40% max.	0.40% max.
Volatiles	0.05% max.	0.05% max.
Fe (Iron)	20 ppm max.	50 ppm max.
Cr (Chromium)	25 ppm max.	15 ppm max.
Cu (Copper)	25 ppm max.	20 ppm max.
Ni (Nickel)	40 ppm max.	40 ppm max.
Al (Aluminum)	15 ppm max.	40 ppm max.
C (Carbon)	13 ppm max.	
²³⁵ U	0.1935% min.	± 0.003% max.(sweetener)
	0.2065% max.	± 0.006% max.(non-sweetener)

TABLE 6-2
PRODUCT QUALITY RESULTS

LOT #	UO ₂ F ₂ (% by wt.)	HF (% by wt.)	UF ₄ (% by wt.)	U (% by wt.)	Ni (PPM)	Cu (PPM)	Fe (PPM)	²³⁵ U (% Enriched)
3177	0.30	0.15	99.55	75.68	32	12	14	1.947
3178	0.18	0.03	99.79	75.77	5	5	7	1.982
3179	0.50	0.04	99.46	75.75	5	5	6	1.982
3180	0.01	0.04	99.95	75.76	5	5	8	1.985
3181	0.44	0.02	99.54	75.78	5	5	5	1.984
3182	0.62	0.15	99.23	75.69	5	5	9	1.984
3183	0.56	0.74	99.70	75.21	94	5	19	1.981
3184	2.33	0.04	99.63	75.78	5	34	19	1.998
3185	0.23	0.03	99.74	75.75	5	5	14	2.000
3186	0.01	0.02	99.97	75.80	5	5	32	2.000
3187	0.01	0.03	99.96	75.79	5	5	30	2.000
3188	0.01	0.01	99.98	75.80	5	5	16	2.000
3189	0.19	0.04	99.77	75.76	12	7	25	1.999
3190	0.75	0.08	99.17	75.71	154	76	36	1.998
3191	0.01	0.02	99.97	75.80	12	5	14	1.994
3192	0.01	0.01	99.98	75.80	5	5	26	1.997
3193	0.01	0.02	99.97	75.79	5	5	65	1.997
3194	0.01	0.01	99.98	75.80	5	5	51	1.997
3195	0.01	0.01	99.98	75.81	5	5	13	1.997
3196	0.01	0.01	99.98	75.81	7	5	12	1.997
3197	0.01	0.02	99.97	75.80	5	5	17	1.997
3198	0.80	0.13	99.07	75.70	5	5	19	1.992

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TABLE 6-2
(continued)

LOT #	UO ₂ F ₂ (% by wt.)	HF (% by wt.)	UF ₄ (% by wt.)	U (% by wt.)	Ni (PPM)	Cu (PPM)	Fe (PPM)	²³⁵ U (% Enriched)
3199	0.52	0.11	99.37	75.72	7	5	9	1.994
3200	0.01	0.04	99.95	75.79	75	32	14	1.991
3201	0.01	0.01	99.98	75.80	5	5	12	1.991
3202	0.01	0.01	99.98	75.82	5	5	10	1.992
3203	1.07	0.19	99.74	75.68	5	5	12	1.993
3204	0.01	0.02	99.97	75.80	5	5	10	1.991
3205	NOT REPORTED TO DATE							
3206								
3207	0.01	0.03	99.96	75.80	24	11	25	1.799
3208	0.01	0.01	99.98	75.80	5	5	15	1.796
3209	0.01	0.01	99.98	75.80	5	5	12	1.796
3210	0.01	0.01	99.98	75.80	5	5	13	1.794
3211	0.01	0.01	99.98	75.79	35	16	17	1.797
3212	0.01	0.04	99.95	75.79	54	30	22	1.795
3213	0.01	0.01	99.98	75.80	9	7	23	1.798
3214	0.01	0.06	99.93	75.81	5	5	11	1.798
3215	0.01	0.04	99.95	75.80	8	5	12	1.799
3216	0.01	0.02	99.97	75.80	7	5	14	1.810
3217	0.01	0.01	99.98	75.79	5	5	22	1.800
3218	0.01	0.01	99.98	75.79	5	5	19	1.800
3219	0.01	0.01	99.98	75.78	16	14	24	1.799
3220	0.01	0.01	99.98	75.80	10	14	20	1.798
3221	0.01	0.03	99.96	75.77	28	14	15	1.806
3222	0.06	0.03	99.91	75.80	5	5	17	1.804
3223	0.01	0.01	99.98	75.79	5	5	14	1.806
3224	0.01	0.03	99.96	75.79	5	5	20	1.806
3225	0.01	0.01	99.98	75.78	21	11	26	1.807
3226	0.16	0.02	99.82	75.79	5	5	16	1.805
3227	0.01	0.02	99.97	75.79	5	5	9	1.809
3228	0.01	0.04	99.95	75.78	5	5	14	
3229	0.01	0.05	99.94	75.77	34	5	16	1.989

TABLE 6-2
(continued)

LOT #	UO ₂ F ₂ (% by wt.)	HF (% by wt.)	UF ₄ (% by wt.)	U (% by wt.)	Ni (PPM)	Cu (PPM)	Fe (PPM)	²³⁵ U (% Enriched)
3230	0.01	0.02	99.97	75.81	5	5	10	1.993
3231	0.01	0.02	99.97	75.80	5	5	8	1.993
3232	0.01	0.01	99.98	75.82	5	5	8	1.995
3233	0.39	0.08	99.53	75.78	18	13	37	1.994
3234	0.22	0.10	99.68	75.77	5	15	13	1.996
3235	0.01	0.05	99.68	75.68	104	50	17	1.970
3236	0.01	0.03	99.96	75.80	9	5	13	1.993
3237	0.01	0.02	99.97	75.80	10	5	10	2.002
3238	0.01	0.02	99.97	75.79	5	5	10	2.005
3239	0.01	0.01	99.98	75.80	5	5	10	2.001
3240	0.01	0.01	99.98	75.79	5	5	11	2.010
3241	0.01	0.01	99.98	75.79	5	5	13	2.011
3242	0.01	0.06	99.93	75.75	5	5	12	2.010
3243	0.01	0.01	99.98	75.78	42	18	14	1.977
3244	0.01	0.01	99.98	75.75	5	5	11	2.001
3245	0.01	0.01	99.98	75.76	5	5	10	2.001
3246	0.01	0.01	99.98	75.71	5	5	11	2.002
3247	0.01	0.01	99.98	75.72	5	5	13	2.004
3248	0.01	0.02	99.97	75.78	5	5	8	2.003
3249	0.01	0.05	99.94	75.74	8	5	10	2.002
3250	0.01	0.01	99.98	75.77	5	5	10	2.002
3251	0.01	0.01	99.98	75.76	5	5	9	1.962
3252	0.01	0.02	99.97	75.77	5	5	11	1.996
3253	0.01	0.01	99.98	75.78	5	5	9	1.962
3254	0.62	0.02	99.36	75.79	5	5	8	1.962
3255	0.01	0.01	99.98	75.79	5	5	10	1.964
3256	0.01	0.05	99.94	75.79	5	5	9	1.962
3257	0.01	0.02	99.97	75.77	5	5	9	1.963
3258	-----No Lot By This Numerical Indication-----							
3259	0.22	0.10	99.68	75.68	5	5	43	1.963

TABLE 6-2
(continued)

LOT #	UO ₂ F ₂ (% by wt.)	HF (% by wt.)	UF ₄ (% by wt.)	U (% by wt.)	Ni (PPM)	Cu (PPM)	Fe (PPM)	²³⁵ U (% Enriched)
3260	0.39	0.16	99.45	75.70	5	6	54	1.962
3261	0.74	0.04	99.22	75.76	16	11	18	1.960
3262	0.01	0.01	99.98	75.78	5	5	15	1.961
3263	0.01	0.01	99.98	75.68	5	5	12	1.960
3264	0.01	0.01	99.98	75.70	5	5	13	1.960
3265	0.01	0.01	99.98	75.76	5	5	17	1.961
3266	0.01	0.01	99.98	75.78	5	5	14	1.984
3267	0.62	0.66	98.72	75.78	170	76	24	2.003
3268	0.18	0.05	99.77	75.78	18	14	20	2.010
3269	0.58	0.05	99.37	75.81	14	11	27	2.012
3270	0.01	0.03	99.97	75.80	11	11	16	2.010
3271	0.01	0.02	99.97	75.36	5	11	16	2.012
3272	0.01	0.02	99.97	75.77	5	8	22	2.011
3273	0.01	0.02	99.97	75.78	5	8	17	2.011
3274				75.80				
0078	0.01	0.06	99.93	75.74	5	6	8	0.3170
0079	0.01	0.02	99.97	75.80	8	11	9	0.2053
0080	0.01	0.01	99.98	75.77	7	10	8	0.2060
0081	0.01	0.01	99.98	75.76	31	15	7	0.2040
0082	0.01	0.01	99.98	75.76	16	15	9	0.2042
0083	0.40	0.09	99.51	75.71	70	26	8	0.2025
0084	0.01	0.02	99.97	75.76	18	12	55	0.2008
0085	0.01	0.01	99.98	75.78	8	10	11	0.2000
0086	0.01	0.02	99.97	75.77	80	36	17	0.2023
0087	0.01	0.02	99.97	75.78	10	15	10	0.2024
0088	0.01	0.07	99.92	75.76	88	24	12	0.2024
0089	0.01	0.01	99.98	75.79	7	9	12	0.2017
0090	0.01	0.02	99.97	75.79	8	10	10	0.2018
0091	0.01	0.02	99.97	75.78	114	53	12	0.3810

* lot # 3177-3274: Enriched
lot # 78-91: Depleted

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Figure 6-1. Product Quality (Enriched UF_6 Feed, Runs 1 through 6a)

Figure 6-2. Product Quality (Depleted UF_6 Feed, Runs 7 through 11)

6.2 Impact of Slag Buildup on Product Quality

The contamination values are noteworthy in that the out-of-specification (OOS) lots greatly exceed both the specification and the contaminant content of the remainder of the sample population. Those high-Ni/Cu samples correlate directly with lots packaged during deslagging cycles with no UF_6 flow. The vessel was subjected to a deslagging cycle at the end of nearly every cylinder's operational life, and with only four exceptions, every lot taken from the "end-of-run" material exhibits out-of-specification nickel and copper levels. That the slag removed under these circumstances is high in Ni and Cu is understandable, since this material is in intimate contact with the vessel wall during a large percentage of the total run, consequently causing corrosion and subsequent erosion of the Monel.

Due to inherent problems in the sampling technique (dip-sampling powder from the top of the drum), the levels reported here cannot be taken as representative of the entire lot. Deslagging naturally occurs continuously during operation, attributable to the action of the vibrators, but the larger and denser slag particles tend to settle in the drum and may not be accounted for by the current sampling technique. To obtain more statistically valid information, a more reliable sampling procedure involving screening and blending must be established.

Clearly, if the slag layer corrodes the vessel surface, then minimizing the frequency and duration of deslagging should improve product quality. This will be accomplished by initiating the deslagging process only as often as necessary to maintain temperature control of the reactor. Additionally, the continuous deslagging due to the pneumatic vibrators will be addressed by reducing the frequency of vibrations per minute. Consideration should also be given to basing operating deslagging periods on process variables rather than on a predetermined frequency. The effect of vibrator-operation frequency on metals levels should also be examined, once a statistically-valid sampling procedure is in place.

It is worth noting that deslagging was accomplished relatively easily during the Test Operations, both for operating deslagging, and deslagging cycles performed at the end of each cylinder's operational life. The slag was either thinner, softer, more brittle, or sloughed off in smaller pieces than had been experienced in the past. Thus, throughout the entire Test Operation, the cooling screw only jammed once or twice, but it was never necessary to open the inspection port. This is probably explained by the fact that deslagging was carried out essentially after every cylinder during the Test Operation, while two to three cylinders of UF_6 were typically processed between deslagging operations previously.

There may also exist a correlation between the degree of slag buildup and the mixhead design. In Figure 6-2, for depleted UF_6 , the nickel levels in the deslagging-cycle lots for the FMPC mixhead were 114 and 88 ppm at 1200 and 1300°F, respectively (see Table 3-1). For the Paducah mixhead, 70 and 31 ppm were reported for the same temperature. The design of the Paducah mixhead (see Figure 3-4) should produce a flow pattern in which DA flows down the vessel inner wall, mixing with a core flow of UF_6 ; essentially the reverse is true for the FMPC design, with the UF_6 flowing down the inner wall. The protective effect of the nitrogen (from the DA) at the wall, as well as the hypothesis that the flame front proceeds into the UF_6 layer because of the greater mobility of H_2 , suggest that the reaction may occur further from the wall for the Paducah design, resulting in reduced slag deposits. However, insufficient data exists to quantitatively support this position.

6.3 Bulk Density and Particle Size

Several lots of depleted material were sampled for bulk density and particle size distribution, with the results presented in Table 6-3.

TABLE 6-3
BULK DENSITY AND PARTICLE SIZE DISTRIBUTION FOR DEPLETED UF₄

		PARTICLE DISTRIBUTION					
		(% by weight, based on a 50 g sample)**					
<u>Lot #</u>	<u>Bulk Density g/cm³</u>	<u>+10</u>	<u>+20</u>	<u>+30</u>	<u>+40</u>	<u>-80*</u>	<u>-325*</u>
0086	3.15	8.8	4.0	1.0	0.9	87	73.8
0087	3.33	1.4	1.6	0.5	0.6	5.9	92.7
0088	2.96	3.1	2.5	0.8	0.7	6.8	91.9
0089	3.37	1.5	1.1	0.5	0.6	6.0	92.8
0090	3.30	5.8	2.4	0.8	0.7	6.0	92.8
0091	- -	9.7	2.6	1.1	1.1	9.9	89.0

*(Taken from different sample.)

**Legend:

- +10 Percent weight retained on #10 seive (>2mm)
- +20 Percent weight retained on #20 seive (>841um)
- +30 Percent weight retained on #30 seive (>595um)
- +40 Percent weight retained on #40 seive (>420um)
- 80 Percent weight passing #80 seive (<177um)
- 325 Percent weight passing #325 seive (<44um)

7.0 ENVIRONMENTAL

7.1 Dust Collector Losses

A Single-point Stack Sampler was used to determine the dust collector losses. The stack sampler unit operates by drawing an air sample via a one-quarter inch sampling-tube from the exhaust line, and passing it through the stack filter. The filter, when changed, is submitted for analysis of total uranium content. The amount reported is used to determine the computed total loss through the exit exhaust during the time period.

To compute the losses in the G-1 and G-2 dust collectors, the stack factor must first be determined. The stack factor is the ratio of the volumetric gas flow intercepted by the sample port to the total volumetric flow in the stack. For G-1 and G-2 collectors, the stack factor (SF) is calculated as follows:

$$SF = \frac{D_{stack}^2 U_{stack}}{D_{sample}^2 U_{sample}} \times .001 \quad (\text{Eq. 7-1})$$

where:

SF = stack factor

D_i = diameter

U_i = gas velocity

The stack velocity is measured with a pitot tube, while the sample nozzle velocity is taken directly from the flowmeter reading. The factor of .001 converts from milligrams to grams of material. For the Pilot Plant system, the SF was equal to 2.2 grams emitted from the stack per milligram of sample collected. A collected filter sample of 0.1 mg therefore correlates to $(0.1) \times (2.2)$ or 0.22 gm lost to the stack.

The results for the G-1 and G-2 dust collectors are shown in Table 7-1. The total loss over the entire Test Operations period, from August

1. The total loss over the entire Test Operations period, from August 22 to October 18, was 75.70 gm (0.167 lbs) of uranium.

The dust collector's efficiency, E, is determined from the ratio of the total computed stack losses to the total material recovered in the dust collector system:

$$E = \frac{\text{lb recovered}}{\text{lb recovered} + \text{lb lost}} \times 100\% \quad (\text{Eq. 7-2})$$

The result from the test run indicate a 99.98% dust collector efficiency in removing dust. This value compares to the manufacturer's efficiency rating of 99.99%.

7.2 Auburn Monitor - Stack Sampler Comparison

The Auburn Monitor particulate detection system was evaluated during the Test Operations as an on-line instrument to report the degree of dust collector loss in the stack. The results of the Auburn unit were compared with those from the particulate stack sampler.

During Runs 1 thru 6A, the stack sampler filter element was removed and analyzed daily, while the Auburn Monitor reading was recorded hourly. Extreme scatter was observed in the Auburn data, thus making any correlation impossible. The sensitivity setting of the instrument was reduced as a result of this experience, having concluded that the instrument was responding spuriously to external noise and vibration. (Note that similar problems have been encountered with the UF_6 vortex-shedding flowmeter responding to noise from the pneumatic vibrators, giving false readings large enough to cause automatic shutdown).

Once the sensitivity was reduced, the performance of the Auburn Monitor improved considerably. In addition, the sampling frequency of the stack sample filter was reduced from daily to once in every three days. Because of the short duration of the remaining Runs 7 through 11 (seven days), only two stack samples were available for comparison to the Auburn; consequently, no correlation could be made. It is recommended

TABLE 7 - 1
DUST COLLECTOR RESULTS

Date Filter Placed In Sampler	<u>DUST COLLECTOR G-1</u>		<u>DUST COLLECTOR G-2</u>		Run-End Indication
	Reported Loss On Filter (mg)	Total U Loss Per Day (g)	Reported Loss On Filter (mg)	Total U Loss Per Day (g)	
22-Aug-86	0.08	0.176	0.05	0.11	Run 1
23-Aug-86	0.06	0.132	0.11	0.242	
24-Aug-86	0.07	0.154	0.06	0.132	
25-Aug-86	0.04	0.088	0.04	0.088	
26-Aug-86	0.09	0.198	0.05	0.11	
27-Aug-86	0.07	0.154	0.12	0.264	
28-Aug-86	0.7	1.54	0.40	0.88	
29-Aug-86	0.16	0.352	0.04	0.088	
30-Aug-86	0.07	0.154	16.6	36.52	
31-Aug-86	2.76	6.072	0.92	2.024	Run 2
01-Sep-86	0.02	0.044	0.04	0.088	
02-Sep-86	0.0	0.0	0.15	0.33	
03-Sep-86	0.05	0.11	0.0	0.0	
04-Sep-86	0.04	0.088	0.13	0.286	Run 3
05-Sep-86	0.0	0.0	0.08	0.176	
06-Sep-86	0.05	0.11	0.0	0.0	
07-Sep-86	0.23	0.506	0.07	0.154	
08-Sep-86	0.0	0.0	0.0	0.0	
09-Sep-86	0.06	0.132	0.03	0.866	
10-Sep-86	0.05	0.11	0.06	0.132	

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TABLE 7 - 1
(continued)

<u>DUST COLLECTOR G-1</u>			<u>DUST COLLECTOR G-2</u>		Run-End Indication
Date Filter Placed In Sampler	Reported Loss On Filter (mg)	Total U Loss Per Day (g)	Reported Loss On Filter (mg)	Total U Loss Per Day (g)	
11-Sep-86	0.07	0.154	0.09	0.198	Run 4
12-Sep-86	0.14	0.308	0.12	0.264	
13-Sep-86	2.20	4.84	1.15	2.53	
14-Sep-86	1.0	2.20	2.93	6.446	Run 5
15-Sep-86	0.0	0.0	0.0	0.0	
16-Sep-86	0.14	0.308	0.07	0.154	Run 6
17-Sep-86	0.14	0.308	0.07	0.154	
20-Sep-86	0.06	0.132	0.33	0.726	Run 6A
27-Sep-86	0.05	0.11	0.12	0.264	
01-Oct-86	0.03	0.066	0.04	0.088	Run 7
08-Oct-86	0.06	0.132	0.04	0.088	
15-Oct-86	0.29	0.638	0.04	0.088	Runs 8, 9, 10
18-Oct-86	1.61	3.542	0.07	0.154	Run 11
TOTAL	<u>10.39</u>	<u>22.858</u>	<u>24.02</u>	<u>52.844</u>	

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that further evaluation be conducted once the plant is again operational, and that both the Auburn and the stack sampler be retained as detection devices.

7.3 Independent Emissions Study Results

The dust collector and HF scrubber emissions studies conducted by Northern Kentucky Environmental Services (NKES) have been concluded. The resulting summary reports emission rates of both HF and particulates through the dust collector and scrubber vent stacks. The results of this study are summarized in Table 7-2.

The bag-house dust collector in the Pilot Plant and the scrubber vent on the HF scrubber were evaluated for emissions. The various stack parameters were also determined for each system. The dust collector was sampled using USEPA methods 1-5 with single point automatic isokinetic sampling. The scrubber impingers were filled with 0.1N NaOH, HF was then trapped in the impingers and analyzed according to standard SIE techniques. The scrubber vent was sampled and the HF scrubbed with NaOH and analyzed as above.

TABLE 7-2
Emissions Results Summary

<u>Dust Collector</u>		
Run	Emissions	Quantity (lb/hr)
1	HF	0.032×10^{-3}
2	HF	2.16×10^{-3}
3	HF	22.6×10^{-3}
Avg	HF	8.26×10^{-3}
1	Particulate	4.79×10^{-4}
2	Particulate	5.49×10^{-4}
3	Particulate	12.2×10^{-4}

<u>Scrubber Vent</u>		
2" vent	HF	9.53×10^{-5}

Dust Collector Stack Conditions

Velocity	50.5 ft/sec
Volume	126,000 scfh
Temperature	546 ⁰ R
Area	0.721 ft ²

8.0 SAFETY SYSTEMS

8.1 HF Detectors

Sensidyne and Pyrotronic units are installed throughout the pilot plant for the detection of HF and UF₆ vapors. Two units are installed in each of the cooling air exhausts for early detection of HF/UF₆ in the event of a vessel crack. Additional units were installed throughout the production area for early detection of HF/UF₆ leaks from the vessel.

The criteria of the test plan provides for a HF/UF₆ detection system capable of detection and subsequent alarm indication at HF concentrations as low as 3.0 ppm. This allows for maintaining the employee exposure below the eight-hour 3.0 ppm exposure limit set by the American Conference of Governmental Industrial Hygienists (ACGIH). The Sensidyne units are capable of detecting HF before it can be visually or olfactorily detected, at concentrations as low as 0.1 ppm within an accuracy of ± 0.2 ppm. The level of sensitivity of the Pyrotronic units is not currently known.

Operating experience during the Test Operations indicated that during a 129 hour operating period, 5 Pyrotronic alarms occurred versus 29 Sensidyne alarms, at a 1.5 ppm alarm-level setting. Of the Pyrotronic alarms, 1 was verified as a leak, and 4 were unconfirmable. Of the Sensidyne alarms, 21 were verified as leaks, 2 were verified as false, and 6 were unconfirmable. This amounts to a 20% confirmation level with the Pyrotronics versus 78% with the Sensidynes at a 1.5 ppm alarm level. Due to the greater detection capability of the Sensidyne units, it is recommended that electrolytic detectors be used for HF/UF₆ detection instead of the ionization detectors. A detection unit is recommended in the following areas:

- Cooling Air Exhaust
- Coldtrap
- Autoclaves
- Above Reaction Vessels
- Above the HF Scrubber
- HF Recovery Area

Presently, in the cooling air exhaust, at least one unit must be operational with a 24-hour period allotted for repair or replacement. The performance during this test period was satisfactory and this practice is recommended to be continued.

The increased number of detection units combined with the increased sensitivity has greatly improved the 6/4 working environment. During the Test Operations, Health and Safety monitored the production area for HF. The highest concentration detected was 0.16 ppm, which is only 5% of the allowable ACGIH exposure limit. Although quantitative data on past HF ambient levels is not available, operators who have worked in this area have stated that the current HF level is considerably improved.

It is recommended that the low-level alarm on the Sensidynes (or comparable electrolytic detector) be set at 2.0 ppm. This provides a higher confidence of true indication than that achieved at the 1.5 ppm alarm setting, and maintains an environment well within the ACGIH guidelines for HF environmental limits. A high alarm level of 5.0 ppm is recommended. The response required by the low level alarm is detailed in the SOP for the 6/4 operations, while the high-level alarm is to be automatically documented by the DCS. If the HF source cannot be found and the alarm persists for one hour, then the supervisor must shut down or prepare a Minor Event Report to justify his decision to continue operations. A portable HF detection unit is recommended to provide temporary monitoring of a suspected area.

The drawback with the Sensidyne unit lies in the high level of maintenance which they require; these units are inspected and calibrated monthly. The four units located in the cooling-air stacks and the two middle ceiling units (Vessel #1, west and Vessel #2, east) require the most maintenance. These units are exposed to a large flow of air at temperatures in excess of 100°F. This large flux of high temperature air results in membrane-cap failure and a premature loss of the electrolyte. The membrane is an important contributor in maintaining an adequate level of electrolyte and consequently warranted further

investigation. Additional bench tests were conducted by personnel in the FMPC instrument shop. Twenty-nine detector electrodes were tested and found to be in accord with manufacturing specifications. The average 50% response time was measured to be approximately 45 seconds and the average peak response time was found to be approximately 245 seconds. With the present installation of detector assemblies in the Pilot Plant, detector electrode reliability is significantly reduced due to a high rate of membrane-cap failures. The membrane-caps of the cooling-air exhaust detectors were observed to fail within hours whereas the other detectors were capable of a week or more of operation before failure. The sampling system on the cooling-air exhaust detectors currently is being modified so as to extend the detector life.

8.2 Hydrogen Safety System

A number of modifications were made to the Hydrogen Safety System circuitry to improve reliability, and to the exhaust fan to minimize the potential for accumulation of explosive mixtures. A manual actuation system was also added. Since the system was never activated automatically or manually during Test Operations, no conclusions can be made about its performance. However, test results were deemed acceptable at each Preventative Maintenance Review.

8.3 Rupture Discs

The AHF rupture discs in service were replaced with reverse-buckling type rupture discs for evaluation. The AHF transfer line rupture disc burst once during operation, while the AHF storage tank rupture disc appeared to have failed once, prematurely, due to a "pin-hole" perforation. The exact sequence of events leading up to the rupture of these units has not been satisfactorily reconstructed, although it is highly possible that the pipeline rupture disc failed prematurely due to the pulsing action of the transfer pump. For this reason replacement of the pulsating pumping system will be implemented with the installation of the HF recovery system.

recommended to continue to transfer the AHF by means of the pulsating pumping system.

8.4 Containment/Confinement System

One of the original goals of the Test Operations was to evaluate the necessity and potential design of a containment or confinement system to surround the entire 6/4 reaction tower, and prevent release of UF_6 and HF into the environment in case of another vessel crack. The cost and complexity of such a system is obviously high, and would not be warranted if other process modifications reduced the possibility of future vessel failures to an acceptably low level. In particular, the Vessel Inspection Program is aimed at and designed to prevent exactly that event.

Based on the Test Operations to date, data on vessel lifetime is incomplete. While considerable information has been obtained on the rate of corrosion of the vessel walls and structural changes in the Monel, it is not yet possible to quantify the expected vessel lifetime. The Vessel Inspection Program will continue as a part of routine production operation, and as more information becomes available, it should become possible to quantify the risk of vessel failure as a function of time. If at that time it is determined that the risk of vessel failure and environmental release remains too high even under the modified operating conditions and inspection program, then it would be recommended that a committee be established to design an appropriate vessel containment or confinement system.

9.0 ADDITIONAL EVALUATIONS

9.1 Hydrogen Analysis of HF-laden Offgas

A direct reading system for H_2 in the 6/4 reactor offgas, without prior scrubbing of HF, was proposed as an alternative to the present system. The existing system passes a sample of the offgas first through an HF scrubber, and then a desiccant bottle to remove moisture before reaching the analyzer for an H_2 reading. A safety complaint concerning this set-up inspired an investigation to eliminate both units, and begin monitoring the content of the HF-laden offgas directly. After consultation with the Horiba representative, this test procedure appeared feasible.

The results from the first set of trial runs were negative, however. The unit did not indicate the correct H_2 percentage readings to the DCS. In addition, some parts inside the Horiba Analyzer were apparently susceptible to thermal and chemical attack, resulting in a system malfunction. The analyzer was inspected and repaired by the Instrument Shop; the flame resistors, filters, and sample cell contacts were all damaged due to this harsh environment.

9.2 Evaluation of Replacement Activated Carbon Pellets

The past supplier (WITCO) discontinued the manufacture of petroleum grade activated carbon; WITCO was the only manufacturer of this material. A replacement activated carbon source was needed with specifications being the same as the WITCO-type carbon, especially in the areas of density, ash content and hardness. Several suppliers were contacted who met the specifications.

The replacement pellet samples were obtained and used during part of the test runs. There was no deviation from the standard procedure, nor did the operating conditions change due to the replacement carbon. The density of the replacement carbon (pellets) is identical to that of the original carbon pellets. Results revealed no abnormal effects in the

off-gas system and the continued use of these replacement pellets is therefore recommended.

9.3 Determination of HF(gas) Entrained in Product

This test was performed at the end of Run 11 to determine if a high HF-level detection system is required due to the HF release during green salt blending. The amount of HF absorbed in a sample green salt (UF_4) drum was tested in the unused packaging station area. The drum gases were passed through a scrubber by using a nitrogen purge supply. The pH of the scrubber liquor was measured at time intervals with the HF concentration calculated from the following:

$$\text{pH} = -\log [\text{H}^+] = -\log [\text{HF}] \quad (\text{Eq. 9-1})$$

The total HF released from the drum may then be determined by multiplying the HF molarity by the known volume of scrubber liquor. A total of eight drums were tested to calculate an average HF content. The average amount of HF entrained in a sample UF_4 product drum was determined to be 0.173 lb HF/can, which may be used for design purposes.

9.4 Coldtrap Sizing Requirements

The sizing of the existing coldtrap was examined to verify whether it has sufficient capacity to evacuate the UF_6 feed lines in the worst possible situation without requiring a second standby operable reactor.

Field dimensions of each of the feed lines to the reactors, the surge tank, and each of the three lines from the autoclaves were taken to determine the volume of UF_6 to be evacuated. A total of 43 lbs of UF_6 was found to be the worst case amount that would ever need to be evacuated out of feed lines. This would consist of 21 lbs from the surge tank, 9 lbs from the reactor lines, and 13 lbs from the autoclave lines. To complete this evacuation, the entire system's pressure would have to equalize with the 80 psia pressure of a cylinder, and then all the lines would need to be cleaned. This is the worst possible case,

more typically the system pressure will be close to atmospheric pressure in which case a total of about 8 lbs of UF_6 will need to be evacuated. An energy balance was used to determine the total amount of cooling required to freeze out the UF_6 . The coldtrap has a refrigeration capacity of 1500 BTU/hr which should be able to freeze out the 43 lbs of UF_6 in approximately 2 hours, assuming it can be transferred into a cylinder without sealing over its opening. Eight pounds of UF_6 , the amount to be expected if the system were originally bled down to atmospheric pressure, is estimated to require 20 minutes to transfer out of the system.

The time estimated to transfer UF_6 out of the piping, should the vessel be abruptly shut down, is 2 hours maximum. Since starting a second vessel with proper approvals may exceed 2 hours, it is pointless to continue to maintain a standby vessel. It is advocated that the coldtrap alone is sufficient for emergency evacuations of piping to the vessel, and that the policy of maintaining a standby vessel be discontinued as a requirement for operation.

APPENDIX A

UF₆ FLOW HISTORIES

This Appendix presents UF_6 flow versus time plots for the eleven runs (Figures A-1 through A-11) as well as indication of the causes of each outage. Zone 2 temperatures are included for Run 6a and subsequent to Run 7 when these data became available electronically.

Table A-1 presents brief downtime descriptions of the eleven tests.

Figure A-1(a). UF₆ Flowrate History (Run 1, Cylinder a, Part 1)

Figure A-1(b). UF₆ Flowrate History (Run 1, Cylinder a, Part 2)

Figure A-1(c). UF₆ Flowrate History (Run 1, Cylinder a, Part 3)

Figure A-1(d). UF₆ Flowrate History (Run 1, Cylinder b, Part 1)

Figure A-1(e). UF₆ Flowrate History (Run 1, Cylinder b, Part 2)

Figure A-2(b). UF₆ Flowrate History (Run 2, Cylinder a, Part 2 and Cylinder b, Part 1)

Figure A-2(c). UF₆ Flowrate History (Run 2, Cylinder b, Part 2)

Figure A-3(a). UF₆ Flowrate History (Run 3, Cylinder a, Part 1)

Figure A-3(b). UF₆ Flowrate History (Run 3, Cylinder a, Part 2 and Cylinder b, Part 1)

Figure A-3(c). UF₆ Flowrate History (Run 3, Cylinder b, Part 2)

Figure A-3(d). UF₆ Flowrate History (Run 3, Cylinder b, Part 3)

Figure A-4(a). UF₆ Flowrate History (Run 4, Cylinder a, Part 1)

Figure A-4(b). UF₆ Flowrate History (Run 4, Cylinder a, Part 2)

Figure A-4(c). UF₆ Flowrate History (Run 4, Cylinder b, Part 1)

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Figure A-4(d). UF₆ Flowrate History (Run 4, Cylinder b, Part 2)

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Figure A-5(a). UF₆ Flowrate History (Run 5, Cylinder a, Part 1)

Figure A-5(b). UF₆ Flowrate History (Run 5, Cylinder a, Part 2 and Cylinder b, Part 1)

Figure A-5(c). UF₆ Flowrate History (Run 5, Cylinder b, Part 2)

Figure A-5(d). UF₆ Flowrate History (Run 5, Cylinder b, Part 3)

Figure A-6(a). UF₆ Flowrate and Zone 2 Temperature History
(Run 6, Cylinder a, Part 1)

Figure A-6(b). UF₆ Flowrate and Zone 2 Temperature History
(Run 6, Cylinder a, Part 2)

Figure A-6(c). UF₆ Flowrate and Zone 2 Temperature History
(Run 6, Cylinder a, Part 3)

Figure A-6A(a). UF₆ Flowrate and Zone 2 Temperature History
(Run 6A, Cylinder a, Part 1)

Figure A-6A(b). UF₆ Flowrate History (Run 6A, Cylinder a, Part 2 and Cylinder b, Part 1)

Figure A-6A(c). UF₆ Flowrate History (Run 6A, Cylinder b, Part 2)

Figure A-6A(d). UF₆ Flowrate History (Run 6A, Cylinder b, Part 3)

Figure A-6A(e). UF₆ Flowrate History (Run 6A, Cylinder b, Part 4)

Figure A-7(a). UF₆ Flowrate and Zone 2 Temperature History (Run 7, Part 1)

Figure A-7(b). UF₆ Flowrate and Zone 2 Temperature History (Run 7, Part 2)

Figure A-7(c). UF₆ Flowrate and Zone 2 Temperature History (Run 7, Part 3)

Figure A-7(d). UF₆ Flowrate and Zone 2 Temperature History (Run 7, Part 4)

Figure A-8(a). UF₆ Flowrate and Zone 2 Temperature History (Run 8, Part 1)

Figure A-8(b). UF₆ Flowrate and Zone 2 Temperature History (Run 8, Part 2)

Figure A-8(c). UF₆ Flowrate and Zone 2 Temperature History (Run 8, Part 3)

Time of Day (hrs) (Data Taken 10/10-11/86)
Figure A-8(d). UF₆ Flowrate and Zone 2 Temperature History (Run 8, Part 4)

Figure A-9(a). UF₆ Flowrate and Zone 2 Temperature History (Run 9, Part 1)

Figure A-9(b). UF₆ Flowrate and Zone 2 Temperature History (Run 9, Part 2)

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Figure A-9(c). UF₆ Flowrate and Zone 2 Temperature History (Run 9, Part 3)

Figure A-9(d). UF₆ Flowrate and Zone 2 Temperature History (Run 9, Part 4)

Figure A-9(e). UF₆ Flowrate and Zone 2 Temperature History (Run 9, Part 5)

Figure A-10(a). UF₆ Flowrate and Zone 2 Temperature History (Run 10, Part 1)

Figure A-10(b). UF₆ Flowrate and Zone 2 Temperature History (Run 10, Part 2)

Figure A-10(c). UF₆ Flowrate and Zone 2 Temperature History (Run 10, Part 3)

Figure A-10(d). UF₆ Flowrate and Zone 2 Temperature History (Run 10, Part 4)

Figure A-10(e). UF₆ Flowrate and Zone 2 Temperature History (Run 10, Part 5)

Figure A-11(a). UF₆ Flowrate and Zone 2 Temperature History (Run 11, Part 1)

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Figure A-11(b). UF₆ Flowrate and Zone 2 Temperature History (Run 11, Part 2)

Figure A-11(c). UF₆ Flowrate and Zone 2 Temperature History (Run 11, Part 3)

Figure A-11(d). UF₆ Flowrate and Zone 2 Temperature History (Run 11, Part 4)

TABLE A-1
RUN DOWNTIME HISTORIES

RUN 1 Start 8/22 2:40

<u>Date</u>	<u>Hours Downtime</u>	<u>Reason For Downtime</u>
8/22	0.88	Dissociator problems
8/22	6.0	Tighten reactor flange
8/22	0.73	Dissociator problems
8/22	1.98	"Flameout" due to running too cool
8/23	45.95	Cleaning offgas system due to "flameout"
8/25	18.3	Incomplete conversion
8/26	15.93	Deslagging vessel; switching to new cylinder
8/26	0.63	Overtemperature in top of reaction vessel
8/26	6.97	Overtemperature in top of reaction vessel
8/27	2.02	Incomplete conversion; burning zone dropped
8/28	End 3:09	

Summary of Downtime Causes

(99.39 hrs.)

48.22%	Running reaction vessel too cool
16.03%	Deslagging and switching cylinders
20.04%	Incomplete conversion (too cool or DA problem)
7.65%	Temperature control problems
6.04%	Mechanical problems
1.62%	Dissociator and DA flow control problems

RUN 2 Start 8/28 12:35

<u>Date</u>	<u>Hours Downtime</u>	<u>Reason for Downtime</u>
8/28	1.47	Overtemperature in top of reaction vessel
8/28	1.07	Overtemperature in top of reaction vessel
8/28	2.2	Deslag and switch to Cylinder 2
8/29	4.37	Cleaning out offgas system due to 8/22 problem

TABLE A-1
(continued)

8/29	0.75	DA Rotameter bouncing
8/29	47.67	Cleaning out condensers due to 8/22 problem
8/31	0.18	High reactor pressure, filter blowback was on
8/31	0.45	UF ₆ surge tank pressure problems
9/1	0.15	UF ₆ in offgas analyzer reading 65 ppm
9/1	0.12	DA flow valve positioner problems
9/1	1.7	DA flow valve positioner problems
9/1	1.23	DA flow valve positioner problems
9/1	End 13:30	

Summary of Downtime Causes

(61.36 hrs.)

88.23%	Running reaction vessel too cool
1.06%	Mechanical problems
6.42%	Dissociator and DA flow control problems
4.29%	Temperature control problem

RUN 3 Start 9/4, 14:49

<u>Date</u>	<u>Hours Downtime</u>	<u>Reason for Downtime</u>
9/4	0.47	Overtemp in top of reaction vessel
9/5	0.35	Overtemp in Zone 2 of reaction vessel
9/5	0.18	Overtemp in Zone 2 of reaction vessel
9/5	7.77	Overtemp in Zone 2 of reaction vessel and subsequent deslag
9/5	0.82	Empty cylinder
9/5	0.78	Overtemp in Zone 1
9/6	0.37	Lost differential pressure during dust collector switch over
9/6	0.33	Overtemp bottom Zone 2
9/6	End 22:12	Empty cylinder/deslagging

TABLE A-1
(continued)

Summary of Downtime Causes

(11.07 hrs.)

19.1% Reaction Temperature Control
 77.6% Deslag and/or cylinder change
 3.3% Maintenance

RUN 4 Start 9/8, 14:49

<u>Date</u>	<u>Hours Downtime</u>	<u>Reason for Downtime</u>
9/9	25.6	Empty cylinder/isotopic changeover
9/10	0.67	Instrument mechanic error
9/10	1.45	Instrument mechanic error
9/10	1.18	High level in AHF tank
9/11	0.65	Reaction fell out bottom
9/11	7.26	Reaction fell out bottom, and subsequent deslag
9/11	End 18:34	

Summary of Downtime Causes

(36.81 hrs.)

69.6% Isotopic changeover
 9.0% Maintenance
 1.8% Reaction Temperature Control
 19.7% Deslag

RUN 5 Start 9/11 21:25

<u>Date</u>	<u>Hours Downtime</u>	<u>Reason for Downtime</u>
9/12	2.28	Bolts on bottom RV-1 flange falling out
9/12	0.42	UF ₆ in offgas
9/12	0.73	UF ₆ in offgas

TABLE A-1
(continued)

9/12-9/13	6.87	UF ₆ in offgas
9/13	4.1	Empty cylinder and deslag
9/13	7.72	Autoclave went into containment, problem with conductivity meter
9/13	1.18	Rotary valve on packout plugged
9/14	2.33	Autoclave went into containment, breaker inadvertently triggered off
9/14 End 14:56		

Summary of Downtime Causes

(25.63 hrs.)

13.5%	Maintenance
31.3%	Reaction Temperature Control
16.0%	Deslag
39.21%	Autoclaves

RUN 6 Start 9/14 23:35

<u>Date</u>	<u>Hours Downtime</u>	<u>Reason for Downtime</u>
9/15	1.05	Differential pressure over reaction vessel too high

9/15 End 20:20

Summary of Downtime Causes

(1.05 hrs.)

100%	Maintenance
------	-------------

TABLE A-1
(continued)

RUN 6a Start 9/19 03:59

<u>Date</u>	<u>Hours Downtime</u>	<u>Reason for Downtime</u>
9/19	0.67	Zone 1 top temperature
9/19	2.9	H ₂ analyzer problem
9/19	1.78	Zone 2 temperature
9/20	0.18	Empty cylinder and subsequent deslag
9/20	2.05	UF ₆ in offgas
9/20	4.62	UF ₆ in offgas
9/20	4.05	UF ₆ in offgas and subsequent deslag
9/20	2.77	UF ₆ in offgas
9/21	2.08	UF ₆ in offgas
9/21	1.58	Maintenance work on UF ₆ meter
9/21	0.01	Maintenance work on UF ₆ meter
9/21	0.65	Maintenance work on UF ₆ meter
9/21	0.63	UF ₆ in offgas
9/21	0.57	UF ₆ in offgas
9/21	2.43	UF ₆ in offgas
9/22	End 6:20	

Summary of Downtime Causes

(26.97 hrs.)

65.26%	Temperature Control Problem
19.06%	Maintenance
15.68%	Deslagging and Switching Cylinders

TABLE A-1
(continued)

RUN 7 Start 9/25 8:02

<u>Date</u>	<u>Hours Downtime</u>	<u>Reason for Downtime</u>
9/25	1.43	Maintenance work on cyclones
9/25	0.62	Lost differential pressure while switching dust collectors
9/26	0.23	Lost seal leg
9/26	End 11:45	.

Summary of Downtime Causes

(2.28 hrs.)

100% Maintenance

RUN 8 Start 10/10 1:34

(0.15 hrs. out of 27.80 = 1%)

100% Mechanical

End 10/11 5:22

RUN 9 Start 10/11 12:52

(4.93 hrs out of 38.0 = 13%)

48% Mechanical

52% Reaction Temperature control (flameout)

End 10/13 3:38

TABLE A-1
(continued)

RUN 10 Start 10/13 23:47

(6.97 Out of 35.35 = 20%)

78% Mechanical

22% Reaction Temperature Control

End 10/15 10:28

RUN 11 Start 10/26 17:32

(0.87 out of 27.86) = 3.1 %)

100% Mechanical

End 10/17 21:35

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APPENDIX B

Production Operation

Downtime Data

This Appendix contains detailed reports of downtime, derived from actual Pilot Plant operations during three periods. The first period (Period #1) covers the time from April 8, 1985 (when NLO assumed responsibility of the UF_6 to UF_4 conversion plant from Sanders and Thomas, and after final modifications and repairs were made to bring the plant to operational readiness) until July 29, 1985. The second period (Period #2) covers the time from October 1, 1985, through February 10, 1986. During this period (on January 19), vessel #2 developed a leak, resulting in complete plant shutdown until the Test Operations began on August 8, 1986. The third period (Period #3) covers the time of the Test Operations, from August 8, 1986, until October 19, 1986.

Table B-1 presents detailed information on the principal downtime incidents which occurred during Period #1, and which occurred more than once. Table B-2 presents an overview of the downtime, classifying the information from Table B-1 into categories of Operating Downtime (deslagging, cylinder changeover, start-up, and isotopic changeover) and One-Time Outages (having to do with reactor gasket leaks, seal leg level probes, and the product mill, all of which have been repaired and are not expected to recur). The three One-Time Outage problems are considered to be related to design problems persisting from the initial startup of the plant, which once corrected, will not occur again. Table B-2 also presents the scheduled downtime for holidays and Preventative Maintenance Procedures (PMPs) which occurred during Period #1. The total Available Time is computed as the difference of the total elapsed calendar time, minus the Scheduled Unavailable Time and the time associated with the One-Time Outages. The total time due to mechanical difficulties not associated with the One-Time Outages is also presented as the Unscheduled Downtime.

Table B-3 presents similar detailed historical downtime descriptions for Period #2, which in this case includes all downtime (as opposed to Table B-1, where Scheduled Downtime was not reported). Table B-4 presents a summary of the Period #2 downtime. Three principal problem areas are identified as One-Time Outages. These include the reactor tube crack investigation (which resulted in the entire plant being shut down from January 19 until February 10 in Period #2), modifications to the green salt packing station, and difficulties with the product mill (which was finally repaired during the

interval between Periods #2 and #3). The fourth One-Time Outage contribution ("standby") derives from the fact that the downtime reported in Table B-3 was computed on the basis of two operating 6/4 towers. During much of this period, only one tower was operative, so that the idle period of the second tower is reported as standby downtime. Again, the Available Time and the Unscheduled Downtime not associated with the three One-Time Outages are reported.

Tables B-5 and B-6 present detailed, week-by-week, downtime descriptions for Period #3, that covering the current Test Operations. Table B-5 provides information for vessel #1, while Table B-6 describes the downtime incidents for vessel #2. Table B-7 summarizes the downtime scenario for both vessels. Four general areas contribute to One-Time Outages during this period. As before, standby of one vessel was included in Tables B-5 and B-6, and is factored out at this point. Modifications to the control system and DCS were done during this time. Vessel inspections were begun during the test operations, and are included as One-Time Outages for the purposes of the present calculation; predictions of vessel inspection downtime is treated independently in the downtime analysis in Section 3.4. Finally, a fourth category of One-Time Outage is defined which includes "temperature-related" shutdowns. These include outages due to over-temperature and UF_6 excursion shutdowns that resulted from experimental operation at flowrates or temperatures exceeding the range of normal expected operation.

Table B-8 presents a tabular summary of the Operating Downtime, Available Time, and Unscheduled Downtime for the three operating periods. The various categories are summed, and a calculated mean ratio of operating time to available time equivalent to 0.7215 was determined. Therefore, of the total Available Time that the facility was staffed and scheduled to be operational (and not idled by vessel inspection), the plant was producing product 72.15% of the time, as averaged over the total of 6204 available hours.

This figure is used in Table B-9 to compute the anticipated number of operating hours per year for a single reactor UF_6 to UF_4 conversion facility. From Table 3-3 in Section 3.4, the total number of anticipated hours of scheduled unavailability (due to holidays, inventories, etc.) is

interval between Periods #2 and #3). The fourth One-Time Outage contribution ("standby") derives from the fact that the downtime reported in Table B-3 was computed on the basis of two operating 6/4 towers. During much of this period, only one tower was operative, so that the idle period of the second tower is reported as standby downtime. Again, the Available Time and the Unscheduled Downtime not associated with the three One-Time Outages are reported.

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This figure is used in Table B-9 to compute the anticipated number of operating hours per year for a single reactor UF_6 to UF_4 conversion facility. From Table 3-3 in Section 3.4, the total number of anticipated hours of scheduled unavailability (due to holidays, inventories, etc.) is

given as 984 hours per year. The contribution to downtime due to vessel inspection is more difficult to calculate, since inspection is to be carried out every 250 "equivalent operating hours" (defined in the History/Test Operations Criteria section as one hour with UF_6 flow). For the purposes of this analysis, it is assumed that for every operating hour producing product, the vessel will be at temperature with no flow for 15 minutes. Therefore, 200 operating hours is assumed to be equivalent to 250 "equivalent operating hours." Since a vessel inspection requires approximately 24 hours to complete, the downtime associated with vessel inspection may be computed by multiplication of the operating time by 24/200.

The calculation in Table B-9 then solves for the operating time, using the above value of 984 hours per year of Scheduled Downtime, the above expression for vessel inspection downtime, and the ratio of Operating Time to Available Time derived in Table B-8. The predicted annual on-stream factor may then be computed as 58.93%; a total of 7156 hours of Available Time is predicted per year, representing 81.69% of the elapsed calendar time. These numbers are summarized in Table 3-4, and discussed in Section 3.4.

Table B-10 presents actual production data for the year 1985, in order that the predicted production rates from Section 3.5 may be compared to previous actual data. Table B-10 indicates that during the 245 days between the April 8, 1985, start up and the end of 1985, the plant exhibited 210 days of Available Time (as defined above), or 85.7% of the total elapsed time. This compares to 81.69% predicted in Table B-9. Note that the increased future downtime associated with vessel inspection is offset by two weeks outage due to a plant strike in this comparison. Comparing production rates, it is seen that the production rate for the 1985 operations was 726.26 metric tons of uranium in 245 elapsed calendar days, or 2.96 MTU/D. This may be compared to the design basis of 6.08 MTU/D presented in Section 3.1, representing 48.7% of the design capacity.

An on-stream factor may also be computed for this time period. To provide a consistent basis for comparison, the on-stream factor will be calculated ignoring the time associated with the One-Time Outages. From Tables B-2 and B-4, Periods #1 and #2 exhibited a total of $(1029.8 + 4027.7) = 5057.5$ hours of downtime; neglecting the $(389.8 + 2668.6) = 3058.4$ hours associated with

One-Time Outages, the downtime becomes $(5057.5 - 3058.4) = 1999.1$ hours. The elapsed total time is $(2712.0 + 6384.0) = 9096.0$ hours; again subtracting the One-Time Outage downtime gives an effective elapsed time of $(9096 - 3058.4) = 6037.6$ hours. The actual operating time is the difference between the total time and the downtime, or $(6037.6 - 1999.1) = 4038.5$ hours. The on-stream factor therefore becomes $(4038.5 / 6037.6) = 66.89\%$.

TABLE B-1
PERIOD #1 FACILITY PERFORMANCE
(April 8, 1985 to July 29, 1985)

The following is text from documentation concerning process problems resulting in multiple shutdowns, and the number of hours of downtime resulting from those causes. The period of time that is covered in this document is from April 8th, 1985 until July 29th, 1985.

"Since starting the current campaign on April 8th, 1985, the reactors have been shut down (other than scheduled shutdowns) 222 times for a total of 1029.8 hours. 157 of these 222 shutdowns have been caused by reasons that have occurred more than one time.

Following is a summary of what shut the reactors down.

<u>Number of Shutdowns</u>	<u>Hours Down</u>	<u>Reason</u>
23	98.5	Deslagging Reactors
21	97.3	Repacking Product Mill
19	59.8	Waiting On Maintenance
13	46.6	Hydrogen Analyzer
20	162.5	Level Probes For Seal Legs
6	3.2	Blowing Down Filters
5	48.5	Plugged Filters
5	70.2	Bottom Reactor Gasket Leak
5	2.4	Low DA Flow
4	16.5	Packaging Station Solenoids
4	18.5	Nitrogen Purge Rotameters
3	51.5	Plugged Carbon Traps
3	1.1	Seal Leg Ran Out
2	34.0	Vortex Shedding Meter
2	6.5	Scrubber Pumps
2	6.6	High Pressure In Reactors
2	9.6	Refrigeration Unit
2	1.5	Nitrogen Supply
2	7.0	Packaging Station Screw
2	5.0	Packaging Station Port Leak
2	11.0	DA Flowmeter
2	2.0	Broken Studs For Packing Glands
2	7.0	HF Leaks At Cooling Screw
2	1.7	Steam Shut Off Autoclaves"

TABLE B-2
PERIOD #1 DOWNTIME SUMMARY
(April 8, 1985 to July 29, 1985)

Total elapsed time (113 days x 1 reactor) = 2712.0 hours.

<u>Reason</u>	<u>Hours</u>	<u>Percent of</u> <u>Total Elapsed Time</u>
Holidays	48.0	1.77
PMPs	96.0	3.54
Totals	144.0	5.31

<u>One Time Outages</u>	<u>Hours</u>	<u>Percent</u>
Product Mill Problems	157.1	5.79
Seal Leg Level Probes	162.5	5.99
Reactor Gasket Leaks	70.2	2.59
Totals	389.8	14.37

<u>Unavailable Time Due to Operations</u>	<u>Hours</u>	<u>Percent</u>
Deslagging	98.5	4.52
Isotopic Changes	53.2	1.96 (1 occurrence)
Start-ups	11.3	0.52
Cylinder Changes	9.4	0.35
Totals	172.4	7.35

Available Time = 2712.0 - 144.0 - 389.8 = 2178.2 hrs

TABLE B-2
(continued)

Total Elapsed Time (113 days x 1 reactor) = 2712.0 Hours.

Unscheduled Downtime Or Outages

	<u>Hours</u>
(A) Total Downtime For All Reasons	= 1029.8
(B) Scheduled Unavailable Time	= 144.0
(C) One Time Outages	= 389.8
(D) Operating Downtime	= 172.3

Unscheduled Downtime A = B - C - D = 323.7 hrs

Operating Time = 2712 - 1029.8 = 1682.2 hrs

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TABLE B-3
 PERIOD #2 FACILITY PERFORMANCE
 (October 1, 1985 thru February 10, 1986)

<u>% Of Downtime</u>	<u>Hours Down</u>	<u>Reason</u>
26.2	1056.0	Reactor Tube Leak Investigation
14.7	592.0	New Pack Out Station
13.8	554.9	Standby
4.6	184.3	Deslagging
4.5	183.0	HF Leak at Product Mill
4.0	159.3	Isotopic Changeover
3.6	144.0	Holiday
2.8	112.0	Broken Shaft in Product Mill
2.7	110.0	Product Mill
2.4	96.0	Not Scheduled-Holiday
1.9	77.0	Off-gas System Blockage
1.8	72.0	Repairing Rotary Valve
1.7	70.0	PMP
1.6	65.3	HF Leak at Weigh Tank
1.2	48.0	Inventory
1.2	48.0	Install New Rollers in Mill
1.2	48.0	Repacking Product Mill
1.0	39.6	Mill
0.9	38.0	Packaging Station Screw
0.6	24.0	Installing Rotary Valve
0.5	18.8	Off-gas Blockage
0.4	17.4	Slag/High Differential Pressure
0.4	16.0	Cooling Water Broken Main
0.4	16.0	Safety System PMP
0.4	16.0	DA Flowmeter Calibration
0.4	14.1	Start Up
0.3	13.8	Cylinder Change
0.3	12.0	S-07 Valve
0.2	10.0	Product Mill Jammed
0.2	10.0	N-01 Valve
0.2	9.0	Plugged Pressure Tap
0.2	8.4	Seal Leg Level Probes
0.2	8.0	Repairing Pinholes in Off-gas Line
0.2	8.0	Hydrogen Analyzer
0.2	6.5	Slag

TABLE B-3
(continued)

0.1	6.0	Replace Chain Valve on AHF Weigh Tank
0.1	5.5	Solenoid Valve Primary Filter
0.1	5.4	Rotary Valve
0.1	5.0	Preheater Frozen
0.1	5.0	Plugged Mix Head
0.1	5.0	Holiday Shut Down
0.1	4.2	DA Valve
0.1	4.1	Partial Refrigeration Unit
0.1	4.0	DA Flowmeter
0.1	4.0	Shutdown for Strike
0.1	3.8	Replace Pump for Hydrogen Analyzer
0.1	3.5	Adjust Conveyor Rollers
0.1	3.5	Seal Leg Boot
0.1	3.2	Low DA Flow
0.1	3.2	Start Up/Purging
0.1	3.0	3" Screw Stopped
0.1	3.0	High Temperature in Scrubbers
0.1	3.0	Reactor Tube Cracked
0.1	3.0	Weld Bolt on 3" Screw
0.1	3.0	Repack South End of 9" Inch Screw
0.1	3.0	Change Cyclone Flapper Valve
0.1	2.7	High Reactor Pressure
0.1	2.7	Mill-Added Packing
0.1	2.5	High Differential Pressure Slag
0.1	2.4	Hydrogen Analyzer Scrubber Drain
0.1	2.2	Leak at Seal Leg Fill Port
0.1	2.2	Low Seal Leg
0.0	2.0	Dust Collector Inspection
0.0	1.9	Repair No.1 & No.6 Valves
0.0	1.8	Ran Seal Leg Out
0.0	1.2	High Reactor Differential Pressure
0.0	1.2	9" Screw Jammed/Slag
0.0	1.1	Ammonia Supply
0.0	1.0	Sheared Key on Rotary Valve
0.0	1.0	Low Differential Pressure G-2 Dust Collector
0.0	1.0	Thermocouple Number Three Heating Zone

TABLE B-3
(continued)

0.0	1.0	Zone 3 Temp Probe
0.0	1.0	Triac Third Heater Zone
0.0	1.0	Plugged Downcomer
0.0	1.0	Chemical Trap Thermocouple
0.0	1.0	Loose Chain on Rotary Valve
0.0	0.9	Dissociator #1 Kicked Out
0.0	0.9	HF Leak at 9" Inch Screw
0.0	0.8	Power Failure
0.0	0.8	Dust Collector, Low Differential Pressure
0.0	0.7	High Differential Pressure
0.0	0.6	G-1 Dust Collector
0.0	0.6	DA Control Valve
0.0	0.6	Dissociator Kicked Out
0.0	0.5	High Pressure From Filters
0.0	0.5	Heating Cylinder
0.0	0.2	Tighten Base on Rotary Valve

4027.7

HOURS AVAILABLE = 6384.0
 HOURS DOWN = 4027.7
 UF₄ PRODUCED (1b) = 1086175.0
 % DESIGN CAPACITY = 17.3

TABLE B-4
PERIOD #2 DOWNTIME SUMMARY
(Oct. 1, 1985 to Feb. 10, 1986)

Total elapsed time (133 days x 2 reactors) = 6384.0 hours.

Scheduled Unavailable Time

<u>Reason</u>	<u>Hours</u>	<u>Percent</u>
Holidays	245.0	3.84
Strike	4.0	0.06
PMPs	86.0	1.35
Inventories	48.0	0.75
Totals.....	383.0	6.00

One Time Outages

Reactor Tube Crack	1056.0	16.54
Packing Station Mod.	592.0	9.27
Standby	554.9	8.69
Product Mill Problems	465.7	7.20
Totals.....	2668.6	41.80

Unavailable Time Due to Operations

Deslagging	192.0	5.76	
Isotopic Changes	159.3	4.78	(3 occurrences)
Start-ups	17.3	0.52	
Cylinder Changes	14.3	0.43	
Totals.....	382.9	11.49	

Available Time = 6384.0 - 383.0 - 2668.6 = 3332.4 hrs

TABLE B-4
(continued)

Unscheduled Downtime or Outages

	<u>Hours</u>
(A) Total downtime for all reasons	=4027.7
(B) Scheduled unavailable time	= 383.0
(C) One time Outages	=2668.6
(D) Unavailable time due to operations	= 382.9

Unscheduled Downtime = A - B - C - D = 593.2 hrs

Operating Time = 6384 - 4027.7 = 2356.3 hrs

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TABLE B-5
VESSEL #1 DOWNTIME SUMMARY

<u>Date</u>	<u>Hours Down</u>	<u>Reason</u>
09/08/86	24.0	Standby
09/09/86	24.0	Standby
09/10/86	24.0	Standby
09/11/86	20.0	Standby
09/11/86	1.0	RDA Alarm
09/12/86	2.3	Replace Loose Bolts Bottom Flange
09/12/86	7.5	UF ₆ Analyzer
09/13/86	6.0	A/C # 3 In Containment
09/13/86	0.5	Repair Rotary Valve
09/13/86	0.5	Heating Cylinder
09/14/86	3.0	Deslagging
09/14/86	3.0	Autoclave In Containment
09/14/86	3.0	Heating Reactor
09/14/86	2.0	Replace Thermocouple
09/14/86	1.5	Repair Rotary Valve
<u>% Of Downtime</u>	<u>Hours Down</u>	<u>Reason</u> 09/08/86 thru 09/15/86
75.3	92.0	Standby
6.1	7.5	UF ₆ Analyzer
4.9	6.0	A/C # 3 In Containment
2.5	3.0	Heating Reactor
2.5	3.0	Deslagging
2.5	3.0	Autoclave In Containment
1.8	2.3	Replace Loose Bolts Bottom Flange
1.6	2.0	Repair Rotary Valve
1.6	2.0	Replace Thermocouple
0.8	1.0	RDA Alarm
0.4	0.5	Heating Cylinder
	<u>122.3</u>	
HOURS AVAILABLE	=	192.0
HOURS DOWN	=	122.3
UF ₆ PRODUCED (1b)	=	32674.0
% DESIGN CAPACITY	=	17.3

TABLE B-5
(continued)

<u>Date</u>	<u>Hours Down</u>	<u>Reason</u>
09/15/86	3.5	Deslagging
09/15/86	1.0	High Differential Pressure
09/16/86	24.0	PMP
09/17/86	24.0	Standby
09/18/86	24.0	Standby
09/19/86	24.0	Standby
09/20/86	8.0	Standby
09/20/86	16.0	Standby
09/21/86	24.0	Standby
<u>% Of Downtime</u>	<u>Hours Down</u>	<u>Reason</u> 09/15/86 thru 09/21/86
75.4	112.0	Standby
16.2	24.0	PMP
5.4	8.0	Standby
2.4	3.5	Deslagging
0.7	1.0	High Differential Pressure
	<u>148.5</u>	
HOURS AVAILABLE	=	168.0
HOURS DOWN	=	148.5
UF ₄ PRODUCED (1b)	=	16988.0
% DESIGN CAPACITY	=	10.3

TABLE B-6
VESSEL # 2 DOWNTIME SUMMARY

<u>Date</u>	<u>Hours Down</u>	<u>Reason</u>
08/18/86	24.0	Reactor Tube Leak Investigation
08/19/86	24.0	Reactor Tube Leak Investigation
08/20/86	24.0	Reactor Tube Leak Investigation
08/21/86	24.0	Reactor Tube Leak Investigation
08/22/86	1.0	Loose Bolts on Bottom Flange
08/22/86	2.5	Start Up Heating Up
08/23/86	8.0	Off-Gas Lines Plugged
08/23/86	8.0	Off-Gas Lines Plugged
08/23/86	2.0	High Temperature in Lower Zones
08/24/86	16.0	Off-Gas Lines Plugged
<u>% Of Downtime</u>	<u>Hours Down</u>	<u>Reason</u> 08/18/86 THRU 08/24/86
71.9	96.0	Reactor Tube Leak Investigation
18.0	24.0	Off-Gas Lines Plugged
6.0	8.0	Off-Gas Lines Plugged
1.9	2.5	Start Up
1.5	2.0	High Temperature In Lower Zones
0.7	1.0	Loose Bolts On Bottom Flange
	<u>133.5</u>	
HOURS AVAILABLE	=	168.0
HOURS DOWN	=	133.5
UF ₄ PRODUCED (1b)	=	13120.0
% DESIGN CAPACITY	=	8.0

TABLE B-6
(continued)

<u>Date</u>	<u>Hours Down</u>	<u>Reason</u>
08/25/86	12.0	Inspection Of Mix Head
08/25/86	4.0	Checking Plant Air
08/25/86	6.5	Clean UF ₆ Analyzer
08/26/86	15.0	Autoclave Containment
08/26/86	3.0	Heating UF ₆ Cylinder
08/27/86	3.0	Total Refrigeration Repair
08/27/86	6.0	Deslagging
08/28/86	5.8	DA Flow
08/28/86	2.3	High Temperature Zone 1
08/28/86	4.5	Deslagging
08/29/86	3.5	DA Flow
08/29/86	4.5	Scrubbers
08/30/86	16.0	Plugged Off-Gas Lines
08/31/86	20.0	Plugged Off-Gas Lines
<u>% Of Downtime</u>	<u>Hours Down</u>	<u>Reason</u> 08/25/86 thru 08/31/86
34.0	36.0	Plugged Off-Gas Lines
14.2	15.0	Autoclave Containment
11.3	12.0	Inspection Of Mix Head
9.9	10.5	Deslagging
6.1	6.5	Clean UF ₆ Analyzer
5.4	5.8	DA Flow
4.2	4.5	Scrubbers
3.8	4.0	Checking Plant Air
3.3	3.5	DA Flow
2.8	3.0	Heating UF ₆ Cylinder
2.8	3.0	Total Refrigeration Repair
2.1	2.3	High Temperature Zone 1
	<u>106.0</u>	
HOURS AVAILABLE	=	168.0
HOURS DOWN	=	106.0
UF ₄ PRODUCED (1b)	=	39794.0
% DESIGN CAPACITY	=	24.1

TABLE B-6
(continued)

<u>Date</u>	<u>Hours Down</u>	<u>Reason</u>
09/01/86	7.3	DA Flow
09/01/86	8.0	Tube Inspection
09/02/86	24.0	Tube Inspection
09/03/86	24.0	Tube Inspection
09/04/86	1.5	High Temperature Zone 1
09/04/86	5.5	Logic Changes To DCS
09/04/86	8.0	Tube Inspection
09/05/86	5.5	Deslagging
09/05/86	5.5	Logic Testing
09/05/86	2.5	Cylinder Heating
09/05/86	1.0	High Temperature Zone 1
09/06/86	0.5	Low Differential Pressure Dust Collector
09/07/86	16.0	Cylinder Valve Closer
09/07/86	8.0	Autoclave Leaking

<u>% Of Downtime</u>	<u>Hours Down</u>	<u>Reason</u>	09/01/86 thru 09/07/86
54.6	64.0	Tube Inspection	
13.6	16.0	Cylinder Valve Closer	
6.8	8.0	Autoclave Leaking	
6.2	7.3	DA Flow	
4.7	5.5	Logic Testing	
4.7	5.5	Deslagging	
4.7	5.5	Logic Changes to DCS	
2.1	2.5	Cylinder Heating	
2.1	2.5	High Temperature Zone 1	
0.4	0.5	Low Differential Pressure Dust Collector	

117.3

HOURS AVAILABLE	=	168.0
HOURS DOWN	=	117.3
UF ₄ PRODUCED (1b)	=	36722.0
% DESIGN CAPACITY	=	22.3

TABLE B-6
(continued)

<u>Date</u>	<u>Hours Down</u>	<u>Reason</u>
09/08/86	5.0	Automatic Cylinder Valve Closers
09/08/86	2.0	A/C #3 O-Ring
09/08/86	8.0	A/C O-Ring
09/09/86	14.0	Isotopic Changeover
09/10/86	11.5	No Shift Engineer Available
09/11/86	5.8	Deslagging
09/11/86	5.5	Standby
09/11/86	3.5	Lost Reaction At Bottom Of Reactor
09/12/86	24.0	Standby
09/13/86	24.0	Standby
09/14/86	16.0	Standby

<u>% Of Downtime</u>	<u>Hours Down</u>	<u>Reason</u>	09/08/86 thru 09/15/86
58.3	69.5	Standby	
11.7	14.0	Isotopic Changeover	
9.6	11.5	No Shift Engineer Available	
6.7	8.0	A/C O-Ring	
4.9	5.8	Deslagging	
4.2	5.0	Automatic Cylinder Valve Closers	
2.9	3.5	Lost Reaction At Bottom Of Reactor	
1.7	2.0	A/C #3 O-Ring	

119.3

HOURS AVAILABLE	=	192.0
HOURS DOWN	=	119.3
UF ₄ PRODUCED (1b)	=	33824.0
% OF DESIGN CAPACITY	=	18.0

TABLE B-6
(continued)

<u>Date</u>	<u>Hours Down</u>	<u>Reason</u>
09/15/86	24.0	Standby
09/16/86	24.0	Change Mixhead
09/17/86	16.0	PMP
09/17/86	8.0	Change Mixhead
09/18/86	16.0	Plugged Off-Gas Lines
09/18/86	8.0	PMP
09/19/86	3.5	Hydrogen Analyzer
09/19/86	1.0	RDA Test
09/20/86	6.0	Lost Reaction
09/20/86	4.0	Deslagging
09/20/86	3.0	UF ₆ Flow Control Valve
09/20/86	0.5	Cylinder Change
09/21/86	8.5	UF ₆ Flow Control Valve

<u>% Of Downtime</u>	<u>Hours Down</u>	<u>Reason</u> 09/15/86 thru 09/21/86
26.1	32.0	Change Mixhead
19.6	24.0	PMP
19.6	24.0	Standby
13.1	16.0	Plugged Off-Gas Lines
9.4	11.5	UF ₆ Flow Control Valve
4.9	6.0	Lost Reaction
3.3	4.0	Deslagging
2.9	3.5	Hydrogen Analyzer
0.8	1.0	RDA Test
0.4	0.5	Cylinder Change

 122.5

HOURS AVAILABLE	=	168.0
HOURS DOWN	=	122.5
UF ₄ PRODUCED (1b)	=	28344.0
% DESIGN CAPACITY	=	17.2

TABLE B-6
(continued)

<u>Date</u>	<u>Hours Down</u>	<u>Reason</u>
09/22/86	17.5	Isotopic Change Over
09/23/86	16.0	Isotopic Change Over
09/23/86	1.5	Thermocouple
09/24/86	24.0	Thermocouple
09/25/86	3.0	Leak At Cyclone Flange
09/25/86	8.0	Thermocouple
09/26/86	4.0	Deslagging
09/26/86	8.0	Measure Reactors
09/27/86	24.0	Measure Reactors
09/28/86	24.0	Measure Reactors
<u>% Of Downtime</u>	<u>Hours Down</u>	<u>Reason</u> 09/22/86 thru 09/28/86
43.1	56.0	Measure Reactors
25.8	33.5	Isotopic Change Over
25.8	33.5	Thermocouple
3.1	4.0	Deslagging
2.3	3.0	Leak At Cyclone Flange
<hr/> 130.0		
HOURS AVAILABLE	=	168.0
HOURS DOWN	=	130.0
UF ₄ PRODUCED (1b)	=	29796.6
% DESIGN CAPACITY	=	18.1

TABLE B-6
(continued)

<u>Date</u>	<u>Hours Down</u>	<u>Reason</u>
09/29/86	24.0	Tube Inspection
09/30/86	24.0	Tube Inspection
10/01/86	24.0	Engineers Working On Report
10/02/86	24.0	Engineers Working On Report
10/03/86	24.0	Engineers Working On Report
10/04/86	24.0	Engineers Working On Report
10/05/86	24.0	Engineers Working On Report
<u>% Of Downtime</u>	<u>Hours Down</u>	<u>Reason</u> 09/29/86 thru 10/05/86
71.4	120.0	Engineers Working On Report
28.6	48.0	Tube Inspection
	<u>168.0</u>	
HOURS AVAILABLE	=	168.0
HOURS DOWN	=	168.0
UF ₄ PRODUCED (1b)	=	0.0
% DESIGN CAPACITY	=	0.0

TABLE B-6
(continued)

<u>Date</u>	<u>Hours down</u>	<u>Reason</u>
10/06/86	24.0	Engineers Working On Report
10/07/86	24.0	Engineers Working On Report
10/08/86	24.0	Engineers Working On Report
10/09/86	24.0	Engineers Working On Report
10/10/86	2.0	Ratio
10/11/86	6.5	Deslagging
10/11/86	1.0	Ratio
10/11/86	2.0	UF ₆ Analyzer
10/12/86	2.0	Lost Reaction
10/12/86	1.3	Low Seal Leg
<u>% Of Downtime Hours Down</u>		<u>Reason 10/06/86 thru 10/12/86</u>
86.6	96.0	Engineers Working On Report
5.9	6.5	Deslagging
2.7	3.0	Ratio
1.8	2.0	UF ₆ Analyzer
1.8	2.0	Lost Reaction
1.2	1.3	Low Seal Leg
	<u>110.8</u>	
HOURS AVAILABLE	=	168.0
HOURS DOWN	=	110.0
UF ₄ PRODUCED (1b)	=	45000.0
% DESIGN CAPACITY	=	27.3

TABLE B-6
(continued)

<u>Date</u>	<u>Hours Down</u>	<u>Reason</u>
10/13/86	16.0	Mix Head Change
10/13/86	0.8	Thermocouple
10/13/86	4.0	Deslagging
10/14/86	1.0	UF ₆ Analyzer
10/14/86	2.0	A Scrubber Level Probes
10/14/86	0.5	Dust Collector Differential Pressure
10/15/86	3.0	Deslagging
10/15/86	3.0	Waiting On J.O.R. To Be Approved
10/15/86	8.0	H ₂ Analyzer
10/15/86	1.0	Lost Reaction
10/16/86	18.0	H ₂ Analyzer
10/17/86	3.0	Deslagging
10/18/86	24.0	Phase 2
10/19/86	24.0	Phase 2

<u>% Of Downtime</u>	<u>Hours Down</u>	<u>Reason</u>	10/13/86 thru 10/19/86
44.3	48.0	Phase 2	
24.0	26.0	H ₂ Analyzer	
14.8	16.0	Mix Head Change	
9.2	10.0	Deslagging	
2.8	3.0	Waiting On J.O.R. To Be Approved	
1.8	2.0	A Scrubber Level Probes	
0.9	1.0	Lost Reaction	
0.9	1.0	UF ₆ Analyzer	
0.7	0.8	Thermocouple	
0.5	0.5	Dust Collector Differential Pressure	

 108.3

HOURS AVAILABLE	=	168.0
HOURS DOWN	=	108.3
UF ₄ PRODUCED (1b)	=	47179.0
% DESIGN CAPACITY	=	28.6

TABLE B-7
PERIOD #3 DOWNTIME SUMMARY
(Aug 8, 1986 to Oct. 19, 1986)

Total Elapsed Time (63 days x 2 reactors) = 3024.0 Hours.

Scheduled Unavailable Time

<u>Reason</u>	<u>Hours</u>	<u>Percent</u>
PMPs	48.0	1.59
Totals.....	48.0	1.59

One Time Outages

Standby & Reporting	1877.0	62.07	
Inspection	233.0	7.71	
Control Modifications	12.0	0.40	
Temp. Related	160.2	5.30	Specifically Related To Test
Totals.....	2282.2	75.47	

TABLE B-7
(continued)

Unavailable Time Due To Operations

Deslagging	48.8	7.03
Isotopic Change-over	47.5	6.85 (1 occurrence)
Start-Ups	9.0	1.30
Totals.....	105.3	15.28

Unscheduled Downtime Or Outages

Available Time = 3024.0 - 48.0 - 2282.2 = 693.8 hrs

(A) Total Downtime For All Reasons	=	2586.6 hrs.
(B) Scheduled Unavailable Time	=	48.0
(C) One Time Outages	=	2282.2
(D) Unavailable Time Due To Operations	=	105.3

Unscheduled Downtime = A - B - C - D = 151.1 hrs.

Operating Time = 3024 - 2586.6 = 437.4 hrs.

TABLE B-8
UNAVAILABILITY SUMMARY

<u>Item</u>	(1) <u>PERIOD #1</u> 4/85-7/85	(2) <u>PERIOD #2</u> 10/85-2/86	(3) <u>PERIOD #3</u> 8/86-10/86	<u>Total</u>
Available Hours	2178.2	3332.4	693.8	6204.4
Deslagging Time	98.5	192.0	48.8	339.3 (5.47%)
Isotopic Change-overs	53.2	159.3	47.5	259.9 (4.19%)
Startups	11.3	17.3	9.0	37.6 (0.61%)
Cylinder Changes	9.4	14.3	0.0	23.7 (0.38%)
Unscheduled Outages	323.7	593.2	151.1	1067.3 (17.20%)
Unscheduled Down-time	496.0	976.1	256.4	1727.8 (27.85%)

$$\frac{\text{Operating Time}}{\text{Available Time}} = 1 - \frac{[1727.8]}{[6204.4]} = 0.7215$$

(1) See TABLE B-2

(2) See TABLE B-4

(3) See TABLE B-7

TABLE B-9
DETERMINATION OF PROJECTED ON-STREAM FACTOR

$$\text{total} = \boxed{\begin{array}{c} \text{scheduled + inspection} \\ \text{unavailable} \end{array}} + \boxed{\begin{array}{c} \text{regular operating + unscheduled + operating} \\ \text{downtime} \qquad \qquad \qquad \text{downtime} \end{array}}$$

time unavailable

time available

$$t_{\text{inspection}} = \left[t_{\text{operating}} \right] \left[\frac{24}{200} \right]$$

$$t_{\text{total}} = 8760 \text{ hours (Basis 1 year)}$$

$$t_{\text{scheduled unavailable}} = 984 \text{ hours (See TABLE 3-4)}$$

$$t_{\text{available}} = \left[\frac{1}{0.7215} \right] \left[t_{\text{operating}} \right] \quad (\text{See TABLE B-8})$$

$$\text{Therefore: } 8760 \text{ hrs.} = 984 + \left[\frac{24}{200} \right] \left[t_{\text{operating}} \right] + \left[\frac{1}{0.7215} \right] \left[t_{\text{operating}} \right]$$

$$t_{\text{operating}} = 5163 \text{ hours}$$

$$t_{\text{operating}} / t_{\text{total}} = 0.5893$$

$$t_{\text{available}} = \frac{t_{\text{operating}}}{0.7215} = \frac{5163}{0.7215} = 7156 \text{ hours}$$

TABLE B-10
PILOT PLANT PRODUCTION HISTORY FOR 1985

<u>Week Of:</u>	<u>MTU/week</u>	<u>Comments</u>
04/08/85	14.36	
04/15/85	14.38	
04/22/85	0.00	Plugged Line to AHF Surge Tank
04/29/85	10.61	3 Days Running Time
05/06/85	18.56	
05/13/85	13.88	Isotopic Change Over To Normal
05/20/85	3.16	Plugged Sintered Filters
05/27/85	12.89	HF Leaks, 1 Day PMP, and 1 Day Holiday
06/03/85	20.19	Feed Rate Increased From 900 to 1050 lb./hr
06/10/85	28.79	Both Reactors Available, No Simultaneous Runs
06/17/85	19.19	
06/24/85	18.65	5 hrs Simultaneous Run, 1 Day PMP
07/01/85	24.67	1 Day Holiday
07/08/85	19.08	
07/15/85	0.00	Planned Vacation Shutdown
07/22/85	25.70	1 Day PMP
08/05/85	30.30	
08/12/85	25.95	Isotopic Change Over To Enriched
08/19/85	42.12	Isotopic Change Over To Normal
08/26/85	28.80	1 Day PMP
09/02/85	33.95	
09/09/85	35.67	Feed Reduced To 800 lb/hr. DHF Storage Prob
09/16/85	0.00	Training
09/23/85	0.00	Training
09/30/85	14.21	1 Day PMP, 1 Day Down Preparing For Strike
10/07/85	0.00	Strike
10/14/85	0.00	Strike

TABLE B-10
(continued)

10/21/85	0.00	Maintenance/PMP
10/28/85	28.59	Vessel #1 & Vessel #2 Alternating
11/04/85	27.29	Isotopic Change Over Enriched To Normal
11/11/85	40.80	Feed Rate Increase From 800 To 1300 lb/hr.
11/18/85	33.70	Only One Reaction Vessel Available, Broken Mill Shaft
11/25/85	0.10	Planned Shut Down, Holiday & Isotopic Change
12/02/85	32.40	Initial Production of Depleted
12/09/85	46.70	Running Vessel #2 Only
12/16/85	47.90	Running Vessel #2 Only
12/23/85	13.49	Only Ran 2 Days Due To Holidays

210 days 726.26 MTU (Average 3.46 MTU/day)

Given a design basis of 6.08 MTU/day/reactor, this equates to a 56.9% design capacity for one reactor. During the period of 11/11/85 to 12/16/85 the plant averaged 4.8 MTU/day or 78.9% designed capacity for one reactor. The plant did operate 210 days of 245 days available to operate, which equates to an 85.7% operational ratio.

APPENDIX C

Experimental Results of

Vessel Inspections

This Appendix presents experimental results obtained during the vessel inspection program on Vessel #2. Figures C-1 thru C-11 illustrate changes in vessel-wall thickness taken from ultrasonic measurements for eleven circumferential locations (A through K) as functions of axial position 1 through 16 (see Figures 5-1 and 5-2 for diagram). Figure C-12 illustrates the circumferential uniformity of the thinning process. Figures C-13 and C-14 present the time dependence of vessel circumference and diameter variations (respectively) at four axial positions. Figures C-15 thru C-20 indicate longitudinal profiles at six circumferential coordinates ("B", "C", and "G" thru "J") in an effort to identify any indications of bulge development.

Figures C-21 and C-22 presents support-yoke flatness data, while yoke and counterweight clearances are indicated on Figures C-23 and C-24. The final figure (Figure C-25) presents alignment data for markers placed on the DA and UF₆ feed lines.

Figure C-1. Ultrasonic Thickness Measurements, Vessel #2

Figure C-2. Ultrasonic Thickness Measurements, Vessel #2

Figure C-3. Ultrasonic Thickness (UT) Measurements, Vessel #2

Figure C-4. Ultrasonic Thickness Measurements, Vessel #2

Figure C-5. Ultrasonic Thickness Measurements, Vessel #2

Figure C-6. Ultrasonic Thickness Measurements, Vessel #2

Figure C-7. Ultrasonic Thickness Measurements, Vessel #2

Figure C-8. Ultrasonic Thickness Measurements, Vessel #2

Figure C-9. Ultrasonic Thickness Measurements, Vessel #2

Figure C-10. Ultrasonic Thickness Measurements, Vessel #2

Figure C-11. Ultrasonic Thickness Measurements, Vessel #2

Figure C-12. Thickness Measurements Around Reactor Circumference at Axial Location 2, Vessel #2

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Figure C-13. Circumference Measurements, Vessel #2

Figure C-14. Diametral Measurements, Vessel #2

Figure C-15. Longitudinal Profiles at Circumferential Location B, Vessel #2

Figure C-16. Longitudinal Profiles at Circumferential Location C, Vessel #2

Figure C-17. Longitudinal Profiles at Circumferential Location G, Vessel #2

Figure C-18. Longitudinal Profiles at Circumferential Location H, Vessel #2

Figure C-19. Longitudinal Profiles at Circumferential Location 1, Vessel #2

Figure C-20. Longitudinal Profiles at Circumferential Location J, Vessel #2

Figure C-21. Yoke Flatness Measurements, East Side of Vessel #2

Figure C-22. Yoke Flatness Measurements, West Side of Vessel #2

Figure C-23. Yoke Top-Support Clearance, Vessel #2

Figure C-24. Yoke Counter--Weight Clearance, Vessel #2

Figure C-25. Feed-Line Motion Measurements, Vessel #2

APPENDIX D

Uranium Material Balance

TABLE D-1
URANIUM MATERIAL BALANCE

The following summarizes the Uranium accountability mass balance.

1b UF_4 = 1b UF_6 (1 lb-mole UF_6 / 352 lb UF_6) (1 lb-mole UF_4 / 1 lb-mole UF_6)
(314 lbs UF_4 / 1b-mole UF_4)

$$\text{lbs } \text{UF}_4 = \text{lbs } \text{UF}_6 (0.892)$$

	<u>ENRICHED</u>	<u>DEPLETED</u>
UF_6 Consumed (lbs)	251,640	133,505
UF_6 in Cold Trap and Alumina (lbs)	208	0
UF_6 fed to RV system (lbs)	251,432	133,505
Theoretical lbs UF_4 (lbs)	224,277	119,086
Actual Product UF_4 (lbs)	222,080	118,773
UF_4 from Dust Collectors (lbs)	596	543
Carbon Traps (lbs UF_4)	773	0
Scraps (lbs UF_4)	349	0
Contaminated burnables (lbs UF_4)	0	28
Samples (lbs UF_4)	350	30
Unaccounted UF_4 (lbs)	-129	+288
% Accounted	99.94	100.24

TOTAL % ACCOUNTED: 99.95 0021-130

APPENDIX E

Vessel Engergy Balance Results

Table E-1 presents results from heat balance calculations performed around the cooling screw. Table E-2 contains results of similar calculations performed around the entire vessel. Results from both appear in Figures 4-22 through 4-24, and are discussed in Section 4.6.

TABLE E-1
COOLING SCREW ENERGY BALANCE RESULTS

Date	Time	UF ₆ Flow (lb/hr)	Product Temperature (°F)	Calculated Temperature (°F)	Heat Removal (Btu/hr)	Overall Heat Transfer (Btu/hr/ft ² /°F)	Measured Temperature (°F)
9/25/86	19:40	1000	414	1022	58500	3.95	
9/25/86	21:50	1200	456	1126		4.70	
9/26/86	00:00	1400	542	1221		6.26	
10/10/86	08:41	1100	441	1038	74250	4.66	
10/10/86	14:25	1200	565	1232	94875	5.23	924
10/11/86	15:28	850	275	766	44000	3.40	577
10/11/86	18:10	850	334	824	48000	3.51	654
10/11/86	19:10	850	383	1035	56000	3.73	639
10/14/86	03:10	1150	434	979	70550	4.52	777
10/14/86	03:45	1200	430	1050	84000	5.26	825
10/14/86	04:50	1250	437	1061	88000	5.47	853
10/14/86	06:15	1300	525	1149	96400	5.55	909
10/14/86	02:15	1100	450	1027	73800	4.65	818
10/15/86	07:55	1050	434	951	60750	3.97	706
10/16/86	20:10	800	238	679	38750	3.26	558
10/16/86	21:49	900	380	830	46500	3.32	709
10/16/86	23:20	1000	420	931	58125	3.89	737
10/17/86	15:52	900	465	1111	65875	4.00	826
Avg		1061	424	1002	66148	4	751

TABLE E-2
VESSEL ENERGY BALANCE RESULTS

	Date Time	10/10/88 05:15	10/10/86 14:25	10/11/86 05:07	10/11/86 15:28	10/11/86 18:00
UF ₆ Flow (lb/hr)		900	1200	850	850	850
Zone #2 Set Point (°F)		1200	1200	1150	1150	1150
Total Cooling Air Used (SCFM)		960	775	601	----	776
Heater Input (BTU/hr)		94913	242680	----	160597	166685
Activation Energy (BTU/lbMole)		37122	71186	----	66506	69027
Heat Removed via Air (BTU/hr)		400465	652471	606425	557045	639035
Heat Flux (BTU/hr/ft ²)		19421	31643	29410	27015	30991
Heat Flux (BTU/lbUF ₆ /ft ²)		22	26	35	32	36
% Heat Found In Excess of Req'd		+3.6%	+8.7%	----	+25%	+43%

	Date Time	10/14/86 03:10	10/14/86 04:50	10/14/86 06:15	10/14/86 17:50	10/14/86 02:15
UF ₆ Flow (lb/hr)		1150	1250	1300	1050	1100
Zone #2 Set Point (°F)		1300	1300	1300	1300	1300
Total Cooling Air Used (SCFM)		1054	948	----	897	1137
Heater Input (BTU/hr)		174894	190119	219908	176549	139544
Activation Energy (BTU/lbMole)		53533	53538	59544	59186	44654
Heat Removed via Air (BTU/hr)		729565	735174	646906	549886	328250
Heat Flux (BTU/hr/ft ²)		35381	35653	31373	26668	15919
Heat Flux (BTU/lbUF ₆ /ft ²)		31	29	24	25	14
% Heat Found In Excess Of Req'd		+36%	+28%	+5.7%	+8.5%	-32%

	Date Time	10/16/86 21:49	10/16/86 23:20	10/17/86 15:52	10/17/86 17:06
UF ₆ Flow (lb/hr)		900	1000	900	1000
Zone #2 Set Point (°F)		1200	1200	1200	1200
Total Cooling Air Used (SCFM)		781	----	806	1211
Heater Input (BTU/hr)		129747	115184	152254	205558
Activation Energy (BTU/lbMole)		50745	40545	59548	72358
Heat Removed Via Air (BTU/hr)		436343	427997	378430	505836
Heat Flux (BTU/hr/ft ²)		21161	20756	18353	24531
Heat Flux (BTU/lbUF ₆ /ft ²)		24	21	20	25
% Heat Found In Excess Of Req'd		-5%	+1%	-11%	+1%