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TECHNICAL REPORT

BROOKHAVEN NATIONAL LABORATORY

Nuclear Engineering Department
Upton, New York

Accident in Continuous-Dissolver Pilot Plant
of Fluoride Volatility Project
on May 15, 1957

by

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SUMMARY AND CONCLUSIONS

A series of explosions, estimated at five, occurred over a period of ten seconds within the continuous dissolver pilot plant of the Fluoride Volatility Project on May 15, 1957, at about 1:50 p.m. in the Hot Laboratory at BNL. A preliminary report⁽¹⁾ on the accident was issued shortly after its occurrence. Separate reports were issued at later dates by AEC⁽²⁾ and BNL⁽³⁾ investigating committees.

Prior to the first explosion, there was no indication whatsoever of any operational abnormalities. The explosions involved 30 gallons of interhalogen mixture and 2 1/2 lbs of unirradiated uranium metal. All the uranium was consumed by the reaction. The interhalogen mixture was approximately 90 mol% BrF₃, 5 mol% BrF₅, and 5 mol% UF₆. A rupture in the equipment and sheet-metal enclosure resulted in one worker being seriously burned by liquid and vapor. He returned to work after three weeks; his recovery is now complete. Three other workers were treated for relatively minor burns and returned to work the next day.

From equipment damage effects, it is estimated that local metal temperatures and pressures reached as high as 2500°F and 6,000 psi, respectively. In addition to the bursting of the rupture disc on the dissolver, the system ruptured at one other point--a canned-rotor pump, having a bursting strength of about 3500 psi, was blown wide open. It is estimated that 470 pounds of interhalogens, and 40 pounds of uranium as UF₆, were vaporized to the atmosphere. Approximately 160 pounds of solution containing 13 pounds of uranium were accounted for in the lines and pressure relief tank. The cost and time required to restore the pilot plant to its original condition are estimated to be \$40,000 and eight months, respectively.

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- (1) "Report on Accident to Fluoride-Volatility-Process Engineering Test Facility in the Semi-Works Area of the Hot Laboratory on May 15, 1957" by O. E. Dwyer, G. Strickland, and F. L. Horn. May 17, 1957.
  - (2) AEC office memorandum on explosion at BNL to K. E. Fields, General Manager, Washington from Merrill Eisenbud, Manager NYOO. June 7, 1957. (Committee Members: W. B. Harris, Charles J. Myerson, and Gordon E. Stubbings)
  - (3) "Report of the Committee of Investigation on the Incident of May 15, 1957" by J. B. H. Kuper, D. D. Jacobus, F. T. Miles, R. L. O'Connor, M. L. Perlman, S. M. Tucker, and C. Raseman. June 14, 1957.

The explosive reactions occurred in the dissolver vessel as a result of violent chemical reactions between uranium and an inter-halogen mixture. Just what the conditions were which "triggered" the explosions, have not been definitely established. Nevertheless, based upon the evidence which has been collected, several possible explanations, listed according to probability, are given in the following report.

In the design of the pilot plant, every precaution was taken to make it as safe as possible. Until the present accident, the possibility of an instantaneous reaction, with its accompanying high-intensity shock wave, was not known.

This report includes a number of recommendations to be followed before operation of the pilot plant should be resumed. These recommendations relate to additional laboratory research, equipment design, facility design, and use of a review committee.

INTRODUCTION

General

The so-called Fluoride Volatility Processes refer to several proposed non-aqueous methods of processing irradiated fuel elements. In each of these methods, the uranium is fluorinated to UF_6 and then decontaminated by distillation. One of these methods, involving the direct fluorination of the uranium by bromine trifluoride (BTF), has been under investigation at BNL since 1950. In 1952, it was demonstrated at BNL that uranium, as UF_6 , could be satisfactorily decontaminated by distillation in small-scale pilot plant equipment; and in 1953, BNL undertook the job of determining the technical feasibility of a continuous dissolver on a pilot-plant scale. The reason for the project was that the economic superiority of the process seemed to depend upon its amenability to continuous operation.

While BNL was concentrating on the engineering phases of the process, ANL* concentrated on its more fundamental aspects, so that the efforts at the two laboratories were complementary.

The BTF process, as presently conceived, is only suitable for handling uranium metal elements.

The construction of the pilot plant was completed early in the fall of 1956; and after some months of testing and revising of equipment, the pilot plant was ready for the running of experiments in January of this year. In addition to the dissolver complex, the plant

*Argonne National Laboratory.

also included the necessary distillation equipment for separation and purification of the constituents in the dissolver effluent.

The chief purpose of the project was to determine the effects of the important operating variables on dissolution rate. These included temperature, fluid velocity, composition of dissolver solution, and uranium history.

Process

The overall dissolution process may be expressed as follows:

All the fission products contained in the irradiated slugs are likewise converted to fluorides having varying degrees of volatility.

In this project, BrF_5 was added to the system to refluorinate the generated bromine to BrF_3 . This reaction may be expressed as follows:

This reaction is endothermic and was carried out in an electrically-heated solvent regenerator maintained at close to 400°F. A portion of the dissolver stream and the requisite BrF_5 were simultaneously fed to the regenerator.

The non-volatile fission-product fluorides, and the plutonium fluoride (PuF_4), were to be concentrated by continuous evaporation of a portion of the regenerator effluent stream. The BrF_3 and UF_6 were separated by distillation, the former for recirculation to the dissolver. The UF_6 , accompanied by certain volatile fission-product fluorides, was to be collected for further purification by distillation.

Equipment

Dejacketed natural uranium slugs were fed into a 6-inch diameter Monel dissolver vessel through a mechanical-interlock system. The slugs were first fluorinated with BrF_5 vapor in the slug lock and then dropped into the dissolver. They rested on a perforated plate. A liquid level of three to four feet of bromine trifluoride (BrF_3) solution was maintained above the slugs. The liquid level was measured by means of a tubular float, located in a side arm of the dissolver, and pneumatically recorded.

A device for measuring the packed height of the slugs was incorporated in the dissolver as shown in Fig. 1. This probe was a hand-operated rack-and-pinion device which was normally kept in the raised position above the slug chute and lowered only when a reading

was taken. The lower end of the probe consisted of six concentric 1/8-inch diameter Monel wire rings. The five inner rings were spaced 7/32-inch apart. The outer ring was 5/8-inch larger in radius than the next inner ring and was also 1/2-inch above the plane of the other rings in order to clear the upper set of lugs which held the support plate. These rings were welded to six triangular vanes attached to the bottom of the rack. When a slug height reading was to be taken, the rack was lowered until the rings rested on the slugs, and a pointer attached to the crank mechanism was read on a scale. Measurements were read to the nearest 0.02 inches. The pinion shaft extended horizontally from the dissolver, and shaft leakage was minimized by pressurizing with helium between two Teflon packing glands on the pinion shaft. This helium pressure was maintained either manually or automatically at about 3 psi above system pressure throughout a run.

The dissolver solution was recirculated by means of a bank of three Monel canned-rotor pumps. A spare duplicate bank was installed for emergency use. These pumps were developed on the project, in cooperation with Chempump Corporation, and represented an extensive development program. This type of pump is lubricated by passing a portion of the pump discharge stream through a porous sintered-nickel filter, for removal of particles over seven microns in diameter, and then cooling it before introducing it into the pump bearing.

The heat generated in the dissolver was removed by continuous circulation of the dissolver solution through an external water-cooled heat exchanger. The recirculation rate of the solution was such that the temperature of the stream in passing through the dissolver was raised no greater than 1°F. When the heat removal rate was very low, the cooling water for the heat exchanger was recirculated and its inlet temperature was maintained between 160°F and 220°F. The water flow rate was, moreover, controlled automatically and varied between zero and five gpm. For high heat loads and emergency conditions, cold water could be fed directly into the heat exchanger at flow rates up to twenty gpm.

A fifty-gallon dump tank, large enough to hold the entire contents of the dissolver section, was located directly below the dissolver vessel; and a quick-opening 2-inch plug valve connected them.

The design pressure for all process vessels was 300 psi. All equipment and piping were constructed of Monel and were leak checked with a G. E. Halogen Leak Detector* and pressure tested with helium at 200 psi. All welds were radiographed, and any flaws eliminated. Structural testing of all vessels was done hydrostatically in accordance with A.S.M.E. code standards. The heat necessary to maintain the operating temperature was supplied electrically by means of resistance heating. Aluminum foil, in one or more layers, with asbestos-covered wire spacers, was used for insulation.

*Type "H".

A process equipment flowsheet of the dissolver section is shown in Fig. 2. Figs. 3 and 4 are plan and elevation drawings, respectively, of the equipment and piping for this same section. Fig. 5 is a photograph of the lower part of the dissolver, the dump tank, the pumps, and some interconnecting piping, prior to the application of the insulation.

DESCRIPTION OF SAFETY DEVICES AND MEASURES

General

The continuous-dissolver pilot plant was designed, and its operation planned, with the greatest regard for safety. Every known precaution was taken to insure against an accident.

First of all, the material of construction--Monel--was chosen because of its high-temperature strength and good corrosion resistance in both interhalogen and aqueous media. In previous work on the Fluoride Volatility Project, aluminum was the main material of construction, but it was eliminated entirely from the pilot plant on the basis of safety considerations, even at increased costs of time and money. Moreover, every effort was made to obtain high-quality fabrication and construction; e.g., every weld in the equipment complex was radiographed, and those found to have flaws were re-executed until they were shown to be sound.

In designing the equipment and operation of the pilot plant, considerable attention was paid to the danger of vapor-phase reactions; and the ignition studies at ANL, which were in progress at the time, were closely followed⁽⁴⁾. Furthermore, provisions were made for preventing excessive pressures, for containing spills, and for venting leaking vapor to the Hot Laboratory ventilation system.

The pilot plant design and operation were reviewed periodically by Professor B. F. Dodge⁽⁵⁾, Chairman of the Chemical Engineering Department of Yale. Professor Dodge is a consultant to the Nuclear Engineering Department on the Fluoride Volatility Project and reviewed the pilot plant from the standpoint of safety, as well as chemistry and engineering.

(4) ANL-5441 "The Behavior of Uranium, Thorium, and other Selected Materials in BrF_3 , BrF_5 , ClF_3 and F_2 at Elevated Temperatures", by L. Stein and R. Vogel.

(5) BNL CDS No. C-7430 Report by B. F. Dodge - 7/17/53.

The safety measures taken and special equipment employed to take care of the more obvious dangers are described in some detail below.

Safety Rules

A set of safety rules, included in the Appendix, was prepared for Project members in November, 1954. Several meetings were held in which the safety rules and procedures, including the use of safety showers, were explained to the operators. All important operations were carefully reviewed with the men, from the standpoint of safety.

Pressure Relief

Each vessel, including the dissolver, was equipped with a rupture disc. The dissolver rupture disc, rated to burst at about 275 psig, was backed up by a relief valve (3-inch inlet and 4-inch outlet) to prevent complete vaporization of liquid, in case the rupture disc burst. The relief valve was set to open at 150 psig and close at 125 psig. It was connected to the head of the dissolver and exhausted to a 3,000-gallon safety tank which was located outdoors. A relief valve (2-inch inlet and 3-inch outlet) vented this tank to a second 3,000-gallon tank at 40 psig and the latter was, in turn, vented by an identical relief valve to the reactor stack through the Hot Laboratory ventilation system.

The vapor-relieving capacity of the dissolver relief line, with the valve wide open, was calculated to be initially 7400 cfm, corrected to 60°F and 14.7 psig. This corresponds to a mass flow rate of 3400 lbs/min or a time of about 12 seconds to discharge the dissolver contents as vapor.

As an additional precaution, a two-inch by-pass around the disc-valve combination was installed to provide a means of manually controlling the dissolver pressure at pressures below 275 psig. This procedure was to be used in the event of loss of cooling capacity during dissolution, the heat of reaction being removed by vaporizing liquid which would condense in the safety tank. Cold BrF_3 would be added to the dissolver to maintain the liquid level. The UF_6 released during venting would, moreover, lower the reaction rate. Venting by this technique would, of course, be limited to pressures necessary to prevent film boiling at the slug surfaces.

Containment of Leaks

Operators of the pilot plant were protected from liquid and vapor leaks by 1/16-inch steel sheet-metal panels fastened to the steel framework. A floor tray, 6 inches deep, fabricated of 1/8-inch steel sheet served to contain spills. The panels were overlapped with each other and with the tray so that a leak could not result in liquid draining outside. This enclosure was not designed as a blast shield.

The enclosure was kept under a vacuum of about 1-1/2 inches of water to prevent escape of vapors out into the room.

Pilot Plant Ventilation

The dissolver section of the pilot plant was ventilated by two separate blower and filter systems, each rated at 1000 cfm. A fiber-glass roughing filter is followed by a CWS filter capable of removing particles as small as 0.3 micron. Plutonium and most of the fission products form non-volatile fluorides which should remain mostly in the equipment, splash tray, and structure; assuming no rupture of the panelling occurs. The UF_6 would vaporize at operating temperatures, but on cooling below 64°C , (147°F), it would be caught by the filters as a solid. The BrF_3 would pass through the filters, mix with the Hot Laboratory ventilation and Reactor cooling air (dilution factor 255), and then be released up the Reactor stack. The stack is 320 feet high; and the normal on-site dilution factor is 7,000.

The BrF_3 vapor exhausted from the pilot plant at the rate of 2,000 cfm, through the ventilation system, would give an off-site concentration of 0.5 parts per million. On-site concentrations would be about ten times higher, but the length of time that this rate would exist would be relatively short.

Pump Protection and Monitoring

The problem of minimizing the passage of particulate matter through the pumps was important from the standpoint of damage, and considerable effort was expended in prolonging pump life. Small slug fragments, greater than about one millimeter in size, were prevented from entering the pumps by providing for up-flow in the dissolver. In the pump development work, it became evident that very small particles, mostly corrosion products, were causing significant pump wear; they were eliminated by supplying filtered dissolver liquid to the bearing surfaces. The sintered-nickel filter was capable of removing particles down to seven microns in size. For work involving radioactive material, it was planned to use decontaminated BrF_3 as the lubricant to avoid the filter-handling problem. The liquid was cooled to increase its viscosity and to avoid possible boiling in the bearing due to friction.

Since the pump stator can and welds seemed to be a probable source of leakage in the pilot plant, clean compressed air was swept through each pump casing and continuously monitored for small vapor leaks by a nylon-thread leak detector. This type of detector, developed at ANL, is very sensitive to BrF_3 vapor. The thread held a microswitch open and, when broken, actuated a red alarm light at the instrument panel. Laboratory tests showed that the thread would break in about 10 seconds when held over the mouth of a test tube containing BrF_3 at room temperature. It was believed that any vapor leak would be detected before damage occurred to the stator.

Slug Immersion

The importance of maintaining slug immersion at all times was recognized in the early stages of pilot plant design; therefore a device was provided for measuring the packed height of slugs in the dissolver. It was incorporated in the slug interlock system in such a manner that it was impossible to charge slugs into the dissolver unless the probe was completely retracted. The probe (see Fig. 1), although of moderately rugged construction, offered little resistance to flow. The possibility of picking up a slug when a height reading was taken was not visualized; therefore no provision was made for keeping the probe immersed at all times.

ANL made extensive studies on the reactivity of uranium in BrF_3 solutions, since this information was pertinent to the programs of both laboratories. The results reported in ANL-5441 showed that uranium dissolved smoothly in the liquid phase but ignited in the vapor phase under certain conditions. A piece of uranium, wetted with BrF_3 , and then exposed to vapor, ignited in 1 or 2 minutes when the initial temperature was 150°C (302°F) or above; for a 10 mol% UF_6 solution of BrF_3 , 17-18 minutes and a minimum temperature of 170°C (338°F) were required. (The dissolver stream composition at the time of the BNL accident could be considered similar to this solution, since it is believed that BrF_5 acts similarly to UF_6 in raising the ignition temperature.) These lower temperature limits were not sharply defined and probably depended upon uranium surface-to-volume ratio, surface pretreatment, and especially heat transfer conditions. In runs involving wetted uranium exposed to vapor, the pressure increased slightly and some of the uranium remained after ignition. In one of their early runs, the bottom of a nickel test tube melted away and the pressure increased very rapidly to 365 psig. The Monel rupture disc, rated to burst at 400 psi, did not rupture.

When the BNL continuous-dissolver pilot plant was designed, it was believed that the worst that could happen from a "run-away" reaction was possible melting of the dissolver wall and simultaneous build-up of moderate pressures at tolerable rates. As a result, blast-resistant construction was never considered.

Emergency Cooling

The nominal capacity of the dissolver, i.e., two BNL slugs per hour, corresponds to a heat release of about 14,000 Btu/hr. In order to maintain control of a rising temperature condition and/or to operate at higher heat rates, the heat exchanger was designed with a high safety factor. During normal operation, a water flow rate of about 1 to 2 gpm was required, but for emergency use a flow rate of 20 gpm was available. With one bank of pumps circulating the dissolver stream at 44 gpm and at a water rate of 20 gpm, the capacity of the heat exchanger was 150,000 Btu/hr. With all pumps operating,

the heat-removal capacity was 170,000 Btu/hr. These values indicate a safety factor of approximately 10. In a transient test, it was found that the dissolver stream could be cooled from 250° to 200°F in 7 to 8 minutes with dissolver stream and water flow rates of 44 and 20 gpm, respectively.

Reserve Pumps

In view of the importance of maintaining circulation through the dissolver, a second bank of pumps was installed, in case the first bank developed trouble or additional flow was desired for emergency cooling. Operating procedure forbade plant start-up with only one bank of pumps in working order.

Insulation

In 1953, an interhalogen leak at BNL⁽⁶⁾ ignited some glass insulation; for this reason, aluminum foil was used as the insulating material in the pilot plant.

DESCRIPTION OF EVENTS SURROUNDING ACCIDENT

Prior to Accident

On May 15, as dissolver run D-9 was in progress, a series of related explosions occurred in the dissolver section of the pilot plant between 1:45 and 1:50 p.m. This run was being made under temperature, pressure, and flow conditions similar to those of the previous run; the essential difference being that the UF₆ concentration was being increased from approximately 4 to 5 mol% instead of from 3 to 4. The run was started at 10:10 a.m. when five unirradiated BNL slugs* were charged to the dissolver. Operating conditions for the run were:

- a. Temperature of dissolver inlet stream, 250°F.
- b. Temperature differential across dissolver, about 0.5°F.
- c. Dissolver pressure, 175 psig. (pressurized with helium)
- d. Pump suction pressure, 180 psig.
- e. Pump discharge pressure, 195 psig.
- f. Circulation rate through dissolver and heat exchanger, 44 gpm.

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(6) BNL CDS No. C-6976 by G. Strickland, F. L. Horn, L. G. Stang, Jr., C. Scarlett, and E. I. Goodman. January 20, 1953.

*Natural uranium 1.10 inches dia. x 4.0 inches long, 2.56 lbs. each, 12.8 lbs. total.

g. Approximate composition of dissolver stream, 89 $\rightarrow$ 91 mol% BrF_3
 7 $\rightarrow$ 4 mol% BrF_5
 4 $\rightarrow$ 5 mol% UF_6
 < 0.1 mol% Br_2

h. Temperature of lubricant stream to pump shafts, 84 $^{\circ}\text{F}$.

A dissolving time of nine hours, equal to that for run D-8 was expected because the "catalytic effect" of the UF_6 appeared to be leveling off.

Dissolution proceeded normally, and the slug height vs. time plot compared closely with that of run D-8 (see Fig. 6), except that the slugs settled into one plane over a longer period of time and ended up at a height of 0.9 inches instead of 0.8 inches. The shift occurred after three hours--almost 1 hour sooner than in run D-8; this fact was not significant because shifts had occurred in less than three hours in previous runs. The quantity of heat released, based on previous data, should have been 83% of the total; therefore 6,000 Btu remained to be released at the time of the explosion--enough to vaporize 44 lbs of BrF_3 .

Routine dissolver stream samples were taken during the run and later analyzed for uranium content. The results are compared with those of run D-8 in Fig. 7 and are believed to be valid. The leveling off of the UF_6 concentration prior to the accident is anomalous and unrelated to any other observations.

During the course of the run, the instrument readings were observed on separate occasions by engineers Fred L. Horn, Gerald Strickland, and Richard Johnson, the latter being on duty at the time of the accident. No evidence of abnormality was noted at any time by these individuals or by the assisting technicians.

At 1:30 p.m., Horn and Johnson compared the slug height plot with that of run D-8 and, after noting the close similarity in slope, estimated that the total dissolving time would be close to that of run D-8, i.e., about nine hours.

At approximately 1:45 p.m., Robert A. Feindt, a technician, found the slug height to be 0.80 inches. After descending from the platform, he went to get a wrench to tighten the slug feeler crank handle. Operation of the slug feeler was no different than when previously operated.

During and Immediately after the Accident

Within 1-2 minutes after the slug height reading was taken, and without any visual or audible warning of an abnormal process condition, as indicated by the instrumentation, a sequence of about five explosions was heard over a period of several seconds in the region of

the dissolver. At the instant of the first explosion, Johnson and LeRoy Jefferson, a technician, were seated, facing the panel board with their backs to the pilot plant, and Walter Kalinowski, another technician, was facing the pilot plant making an entry into the log book at the operations desk. At the sound of the first explosions, the four individuals in the immediate area rushed to leave the building. All except Feindt were knocked down by the loudest explosion as they ran. Liquid and vapor were suddenly released and caused minor burns on Jefferson, Feindt, and Kalinowski; Johnson received severe burns. All four were also exposed to vapor, Johnson and Jefferson being enveloped in the cloud of vapor which rapidly spread throughout the Hot Area. They evacuated the area within a fraction of a minute, pursuing the paths shown in Fig. 8.

After the first explosion, Feindt turned around briefly and observed a bright glow in the vicinity of the slug lock interlock behind the steel paneling, and saw vapors issuing through seams in the sheet-metal. He started to run as additional explosions occurred. After the loudest explosion, which occurred at or near the end of the series, Johnson glanced back and saw flames in the vicinity of the slug lock interlock; Kalinowski also glanced back then and saw a red glow and vapor in that corner of the building. David Wales, another technician, who was leaving the east end of the Hot Area, first heard a loud noise as though sheet-metal were shaking. He started back, heard a loud explosion, and saw fire and vapor over the top of the steel paneling--the only portion of the equipment in direct view. He then heard another explosion, followed by two more, and finally the loudest explosion. Just before running from the area, he looked back and saw only fumes as Kalinowski and Feindt came running out.

Feindt turned in a fire alarm outside the building and there encountered Johnson. He and two others ripped off Johnson's smoldering shirt and undershirt. At this point, first aid was summoned and when it appeared that Johnson was heading for the shower room, the others left him to be of aid elsewhere. Clemens Auerbach, a member of the Hot Laboratory Analytical Group, saw Johnson outside the building and took him to the Clinic. Horn and Strickland were in their office when the fire alarm rang; they ran upstairs and met Kalinowski running for the men's shower room. He exclaimed that the pilot plant had blown up and proceeded to the shower, where he was later joined by Jefferson. Feindt did not take a shower, owing to the increased concentration of vapor in the shower room by that time. In the meanwhile, Horn and Strickland ran to the Hot Area. Horn arrived first and entered along with Carl Anderson, a technician, since at that time it was not known that all persons had escaped. They entered only a few yards before being driven back by the dense reddish-brown vapor. Strickland ran out of the building to the west exit door to check on other personnel and met Richard H. Boutelle, a member of the Health Physics Group, who happened to be in the nearby Reactor building when he saw the cloud of fumes escaping from the Hot Laboratory. Boutelle was donning a

Chemox mask preparatory to entering the building. Strickland opened the door with his master key, and noticed that the vapor density was so great that visibility was reduced to 2-3 feet. Boutelle penetrated inside the building for a few feet, and with the aid of a portable light saw no one near the exit.

At this time, firemen arrived and began to don Chemox outfits. Meanwhile Horn continued to search for Johnson in the Cold Area not knowing that he had already been taken to the Clinic. Horn met Dr. Robert A. Love, of the Medical Department, and led him upstairs to treat Jefferson, Kalinowski, and Feindt. Dr. Love asked for Johnson, but no one was able to tell him where he was. By that time the fumes had spread to the shower area. Dr. Love then directed the injured to the ambulance. When he left the building, he met Fred H. Williams, Head of Security and Plant Protection Division, who made a radio call and found that Johnson had arrived at the Clinic.

The noise of the explosions and the spreading vapor had caused all personnel to evacuate the building. The firemen entered briefly to open the roll-up door at the west end of the building to improve ventilation. The vapors poured out, and the building gradually cleared, over a period of about half an hour, with the aid of a high wind. In the meanwhile, Boutelle re-entered the Hot Area from its east end and turned on the roof ventilation fans.

The firemen entered to extinguish minor fires in the operating area, due to the burning panel board, log books, and papers. Additional Security and Health Physics personnel had arrived by that time and helped to direct spectators away from the vapors issuing from various parts of the building. The pilot plant enclosure is vented to the Hot Laboratory ventilation system, which in turn feeds to the Reactor stack. Consequently, reddish-brown fluoride vapors could be seen issuing from the stack from a considerable distance.

The course of events was described to Clarke Williams, Chairman, Nuclear Engineering Department; O. E. Dwyer, Head of the Chemistry and Chemical Engineering Division; F. T. Miles, Assistant to the Chairman for LMFR; Powell Richards, Associate Head of the Hot Laboratory Division; and certain others as they arrived. At that time the cause of the accident was not known. As the vapors cleared, it became evident that an explosion had occurred in the vicinity of the circulating pumps, since the three panels in front of the pumps were blown off (see Fig. 9). It was soon noticed that one of the pumps had blown open and was fuming. The distillation section of the pilot plant had been isolated from the dissolver section for this run and was not affected. The firemen were instructed to withdraw from the fuming area because of the danger of skin irritation. They remained in the fumes for several more minutes to extinguish minor recurring fires and then went to the Clinic for treatment.

About an hour after the explosions occurred, Strickland, Horn, Wales, Anderson--and the two remaining members of the Fluoride Volatility Project, George Lekay and J. B. Hughes--went to the Reactor building for showers, were checked by Ray Stong of the Health Physics Division for radioactive contamination, and went to the Clinic for examination by Dr. Love.

Just before 5:00 p.m., Dwyer, Horn, Strickland, and L. G. Stang, Jr., Head of the Hot Laboratory Division, conferred at the Hot Laboratory regarding the condition of the pilot plant, and concluded that since there was no water leak in the vicinity of the pilot plant, and since the rest of the pilot plant was isolated from the damaged section by valves, there was no continuing hazard. At 5:30 p.m., Dwyer and Strickland talked briefly with Johnson at the hospital, and he volunteered the information that conditions were perfectly normal prior to the accident. Later, Strickland entered the pilot plant area wearing a Chemox outfit and saw no external damage to the process equipment other than the exploded pump. The dissolver instrument panel was severely damaged, as shown in Fig. 10, and all pertinent recorder charts were destroyed.

EXTENT OF DAMAGE TO PILOT PLANT EQUIPMENT

Pumps

The two banks of pumps described earlier are referred to as "East" and "West", the latter being in service at the time of the accident. The west bank contained pumps 4, 5, and 6, listed in the order of their proximity to the dissolver. Pump No. 4 was the one which ruptured. The inner and outer walls of the stator housing were both blown open, and a portion of the steel-laminated stator was burned away, as shown in Figs. 11 and 12, presumably by the escaping fluid. Both walls were ruptured at the same spatial position, and there is good evidence to indicate they ruptured simultaneously.

On the basis of a destructive pressure test on a duplicate pump, which burst at 3400 psi, it is estimated that the pressure at this point in the system was probably in the neighborhood of 5000 psi. Careful examination of the components of the pump revealed that it had been in excellent operating condition.

Pump No. 5 had, apparently, almost reached the bursting point; its stator wall was greatly expanded, and its rotor wall was depressed. Pump No. 6 showed similar effects but to a lesser degree.

Dissolver

Measurements were made of the dissolver after the explosion. The 6-inch schedule-40 Monel pipe, of which the dissolver was constructed, was found to have a maximum outside diameter of 6.701 inches at a point 2 inches above the slug plate. New pipe was measured and found to have a maximum diameter of 6.629 inches.

Circumferential measurements were made in the vicinity of the support plate. Just at the plate, the external circumference was found to be 0.23 inch larger than the upper section of the dissolver; and at about 3/4-inch below the plate the circumference of the bottom pipe cap was found to be about 0.60 inch larger than a normal cap. These measurements indicate that the most violent explosion occurred just below the support plate. Calculations, based on the physical properties of the metal and the expansion of the dissolver, indicate that a pressure in the neighborhood of 6000 psi was probably attained.

Examination of the dissolver interior (see Figs. 13 and 14) showed pyrochemical effects along most of its length. The most intense heat existed at the bottom of the vessel judging by the extent of the fused surface. Of the original 6 upper and 8 lower lugs, which were welded to the dissolver wall for the purpose of holding the support plate, only 2 adjacent upper lugs remained and were in partially melted condition. Intense heat also existed in the vicinity of the retracted slug height probe, where burned areas up to approximately 0.04 inch in depth were made in the dissolver wall.

Slug Plate

The 1/2-inch perforated slug plate (see Fig. 15) was found blown up against the bottom of the slug height probe, almost 4 ft from its original position. A radiograph (see Fig. 16) taken prior to disassembly of the dissolver illustrates this. Approximately 2 sq. inches of the edge of the plate was melted away. It was warped and showed signs of having been exposed to intense heat, more on its downward than on its upward side.

Slug Height Probe

The slug height rack was found blown up against the pipe cap forming the top of the dissolver. Inspection of indentations in this cap showed that the rack was blown up against the cap 4 or 5 times, the last impact being the most severe. This was evident on the outside of the cap, where the protrusion was about 3/16-inch high. All the rings and most of the vanes of the probe (see Figs. 17 and 18) were melted away. A section of one of the vanes had been bent upward 180° by the slug plate. Metallurgical examination indicated that it was probably bent after being heated. The rack was bent in several places, the lower end of which was found approximately 2 inches off center.

Relief Valve

The rupture disc on the dissolver burst, and approximately 100 lbs of dissolver contents passed to the outdoor safety tank through the relief valve. The effective portion of the rupture disc was completely demolished and the inner edge extensively fused, as shown in Fig. 19.

The valve seat showed evidence of having been exposed to high temperature and was partially melted away. Particles of fused metal and one of the dissolver lugs were found in the valve. The aluminum paint on the valve body was charred and blistered.

Dissolver Dump Valve

The 2" dump valve connected to the bottom of the dissolver was found to contain fused metal on the upper surface of the plug. The upper surface of the plug also was slightly damaged by pyrochemical action. Moreover, four of the dissolver lugs were identified in the mass of fused material on the plug.

Piping

A bulge was detected in a straight section of the 2-inch Monel pipe connecting the dissolver to the pump-suction manifold. Micro-meter measurements showed the normal diameter (2.376"-2.378") from the dissolver up to the bulge where it suddenly increased to 2.424". Measurements beyond this point showed a gradual taper, over a distance of four feet, to the normal diameter. Examination of the bulged area revealed no sign of damage to the inside surface. Near the point where the pump discharge pipe joined the dissolver, there were several other expanded sections in the 2-inch pipe, the largest resulting in a diameter increase of 0.020 inch.

SUMMARY OF DAMAGE TO HOT LABORATORY

The physical damage to the building and facilities was caused by the fluoride fumes which filled the Hot Area and to a lesser extent the Cold Area. The damage was limited to the etching of glass and the corrosion of metal surfaces mainly on instrumentation, periscopes, and manipulators in the Hot Area. A detailed report of the damage is included in a memorandum dated May 28, 1957 to Clarke Williams from L. G. Stang, Jr.

The machine shop equipment was corroded by the fumes; however, the machinery and tools were cleaned and polished and back in operation in three days' time.

The rest of the Cold Area required thorough cleaning to remove traces of uranium which could interfere with analysis, counting, and tracer work. The Hot Area required extensive cleaning to remove the uranium dust on all surfaces.

The total loss in general damage to the building, and equipment, and working time, exclusive of the Volatility Project, is between 4000 and 4500 man-hours of time, and about \$8,000 in equipment and supplies.

WHAT CAUSED THE ACCIDENT?

It is clear that the explosions which occurred were the result of violent chemical reactions between the uranium slugs in the dissolver and the chemicals which were present. There were, apparently, three separate points in the dissolver vessel where violent reactions occurred. The most violent reaction was located immediately below the normal position of the slug support plate; another reaction evidently occurred on the support plate while in or near its normal position; and the third occurred at the dissolver wall 44 inches above the support plate, near the estimated liquid-level height in the dissolver. From the available evidence, it is not possible to explain the cause of the accident, i.e., how the series of explosions was initiated. Two different mechanisms have been considered, but neither is entirely consistent with, nor wholly supported by, the available facts. These are presented below, the first being probably the more credible.

Ignition of Uranium in Vapor Phase

The following sequence of events is suggested:

1. When the slug height probe assembly was retracted after the 1:45 reading, a piece of uranium was caught between the wire rings of the probe and lifted partially or completely into the vapor space. A slug 93% dissolved is shown in Fig. 20 illustrating ragged ends that conceivably could have been caught in the probe.
2. Due to inadequate heat removal, owing to the presence of the vapor, the temperature of the uranium rose rapidly (in 1 to 2 minutes) to the ignition point. A portion of the probe was melted away, allowing the burning uranium mass to drop into the liquid and onto the support plate.
3. The fallen slug remnant first heated a second slug remnant on the plate and then, on reaching a certain threshold

temperature, exploded. This resulted in (a) driving down the support plate by shearing the bottom set of holding lugs, (b) driving up dissolver liquid and probe with sufficient force to disengage the rack and pinion, (c) driving the rack up against the top dissolver cap, (d) bursting of the rupture disc and opening of the pressure relief valve.

4. The probe fell onto the hot slugs resting on the support plate, further melting the probe.
5. The second slug, enveloped in vapor but still immersed in liquid, increased in temperature to the point where it melted a hole at the lower end of the inclined plate, allowing all the slugs on the plate to fall through.
6. The second slug now exploded, driving the support plate, probe, and remaining liquid upward. The rack was driven against the dissolver cap for the second time.
7. The rack and plate then fell toward the bottom of the dissolver.
8. The three remaining slugs at the bottom of the dissolver then exploded in rapid succession, driving the plate and slug-height rack upward. The last explosion was the most violent and bent the rack and jammed both the rack and the support plate in the positions shown in Fig. 16. The pump presumably ruptured during the last, or next to the last, explosion. It was estimated that the series of explosions extended over a 5 to 10 second period.

The relief valve presumably opened with each explosion; and ignited uranium and Monel metal was blown up into it. The close proximity of the probe to the ignited and exploding slugs resulted in its virtual destruction.

The suggestion that the explosions were "triggered" by a slug of uranium being lifted into the vapor phase or to the liquid-vapor interface is, indeed, questionable. It is difficult to imagine how a slug could get caught between the grid wires of the probe. The diameter of the slugs was 0.80 inch (83% dissolved); they were approximately 3 inches long; they weighed about 1/2 lb each; and they were lying flat on the plate. The annular spacing between the wires on the probe was far less than the diameter of the slugs. Moreover, the condition in the vapor space, based on ANL ignition studies, should not have been conducive to spontaneous ignition. For example, the temperatures of uranium and vapor were approximately 145 and 120°C, respectively, and the composition of the vapor was roughly 75% helium, 9% UF_6 , 10% BrF_5 and 6% BrF_3 . By comparison with the conditions of the ANL ignition studies described earlier, it is apparent that both the

temperature and BrF_3 concentration would have been too low to induce ignition.

If it is assumed that a slug was lifted by the probe, it is more likely that it was lifted just to the interface, where it was partly in the vapor phase and partly in the liquid. This could have been possible, since the liquid level was estimated to be about an inch below the retracted probe. It may be that a partially immersed slug will "take off" more quickly than one located in the vapor phase.

Ignition of Uranium in Liquid Phase

The following sequence of events is suggested:

1. As a result of the formation of some relatively volatile compound, whose identity is not known, film-boiling occurred on the surface of one or more slugs. This led to a rapid rise in temperature and, concomitantly, reaction rate; and an explosion ensued. This explosion would produce the same effects as the first explosion in step 3 of the previous section.
2. The succeeding events would be the same as those described under steps 4 through 8 above.

There have been indications⁽⁷⁾ that volatile compounds are produced in interhalogen mixtures under certain conditions. However, arguments may be advanced in contradiction to the "film-boiling" hypothesis. For example, all previous experience with the dissolution of uranium immersed in liquid interhalogens has shown smooth easily-controlled reactions. Moreover, in pilot plant run no. D-4 at ANL, smooth dissolution was obtained under nucleate boiling conditions but otherwise similar to those existing in the BNL dissolver at the time of the accident. Their conditions were 120°C ., 3.7 to 5.1 mol% UF_6 , a total pressure of 25 psig, no circulation, and no BrF_5 . In the BNL case, the pressure was seven times greater, which would have suppressed boiling considerably, but the BrF_5 content was about 5%. There is some evidence that the presence of BrF_5 in interhalogen mixtures is a necessary condition for the formation of certain volatile compounds, which have not as yet been identified.

The authors will be frank to admit that the above explanations are somewhat imaginative, but they are the best they can offer to explain the available evidence.

Two other possible causes of the accident were suggested by personnel of ANL* in a meeting on the Fluoride Volatility Process at Brookhaven July 30, 1957.

In the first, a small leak in the rupture disc could have, in turn, leaked through the seat of the safety valve causing a drop in

(7) Zeitschrift für anorganische und allgemeine chemie, v. 202, p. 49-61 1931.

*W. J. Mechem and W. A. Rodger, respectively.

dissolver pressure. The drop in pressure may have caused film boiling and slug ignition. This explanation is not too likely because a drop in pressure was not noticed prior to the accident. Moreover, the sequence of events from the leak to the initial explosion would probably last several minutes; in addition similar boiling conditions at ANL have not caused ignition.

In the second, the fifth slug on charging the slugs from the lock was slowed sufficiently by the preceding slugs to become lodged on the weld bead at the entrance to the dissolver. The slug remained submerged in the liquid at this point until the final slug height reading was taken, whereupon it dislodged onto the upper side of the probe. Subsequently the probe was raised into the vapor space, where the uranium ignited. Since the burned spot on the dissolver wall was centered slightly below the probe's raised position, and since tests have shown an extremely small probability of a slug lodging at this point, this possible cause seems remote.

Two additional possible explanations for the accident are (1) a uranium fragment was carried to the liquid surface by the rising dissolver solution and there ignited, and (2) the formation of some explosive compound may have "triggered" the series of explosions. However, both of these explanations, after some study, appear to be somewhat remote.

Some credence was given to the last explanation when the filter vessels were removed for inspection. A black residual liquid, found in the vessels, when drained onto clean aluminum foil, partially evaporated, and then ignited spontaneously, issuing a shower of sparks for a few seconds. When the vessels were shaken, several flareups occurred from the liquid dropping onto the aluminum. The residue after ignition was a white powder.

The filter discs--about a dozen in all--in the vessels were clean except for a slight black residue on the upper one. Chemical analysis of the white powder showed one per cent uranium, twelve per cent nickel, five per cent copper, eight per cent bromine (as bromides) and fifteen per cent fluorine (as fluorides). Analysis of the black solid residue on the filters showed roughly half of these values.

The black and white residues were heated to 350°C in a crucible. They lost 85 and 58% by weight, respectively. The residues were mainly nickel and copper. Heavy brown fumes were evolved and burned readily. A spectrographic analysis of both the black and white solids also showed the presence of nickel, copper, uranium, and iron, indicating the balance to be organic material. There is the possibility that the fluorothene oil used in assembling the pumps may be involved. The amount of oil used was at most 250 grams and had been in the system for several months.

RECOMMENDATIONS

With respect to the design and operation of pilot plant facilities for dissolving irradiated uranium in interhalogen mixtures, recommendations are given below to minimize the risk of explosive reactions. These recommendations fall into three categories: (a) Suggested research to learn more about the chemical kinetics of uranium-interhalogen reactions; (b) suggested equipment design characteristics and operating procedures to eliminate foreseeable causes of violent chemical reactions; and (c) suggested features for such facilities for the protection of personnel in the event of an explosion.

Recommended Research

Laboratory studies should be conducted for the purpose of determining the threshold conditions under which "runaway" reactions can occur. Parameters to be studied include: (a) history and composition of slug material, (b) composition of interhalogen mixtures, (c) vapor phase versus liquid phase kinetics, (d) partial immersion kinetics, (e) temperature, and (f) pressure.

Recommended Equipment Features

1. All vessels should have rupture discs (BNL pilot plant has them).
2. The dissolver should possibly have two rupture discs--one in the vapor space and the other in the liquid space. The one in the liquid space would be for the purpose of separating reactants and, therefore, reducing the magnitude of a "runaway" event.
3. Rupture discs should be distributed among pipe lines, as well as on vessels.
4. It should be impossible to bring a piece of uranium either into a vapor phase or to a liquid-vapor interface. The vapor phase and the liquid-vapor interface should be minimized.
5. There should be no structural weak spots in the pilot plant system, i.e. all major components should be designed to withstand about the same pressure.

Recommended Features for Facility

1. The pilot plant should be housed in a special building of inexpensive construction.
2. There should be a blast shield encasing the pilot plant. This shield should have an inner steel membrane which is leak tight against pressures up to 5 psig. This is a practical design pressure for containment, in a reasonable volume, of the vapors generated from all the liquid.

3. A scrubbing and filtration system should be provided to remove vapors and particulate matter from the pilot plant enclosure in case of a "blow".
4. There should be a safety shower outside the building.

A final recommendation, which does not really belong in any of the above three categories, is that an ad hoc committee should be appointed to review critically the design of the pilot plant before it is built and the equipment and experimental procedures before it is operated. This committee should include engineers from other laboratories who are familiar with the hazards of the Fluoride Volatility process.

LIST OF FIGURES

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APPENDIX

BROOKHAVEN NATIONAL LABORATORY

M E M O R A N D U M

Date: November 1, 1954

To: Volatility Studies Group Members

From: G. Strickland

Subject: Safety Rules

The attached safety rules for handling the special materials we are concerned with have been developed for your protection as well as for that of others working in the vicinity; consequently, they should be recognized and complied with.

Those of you with considerable experience are already familiar with most of the rules presented; the rules new to you are equally important as the others. Occasionally, it may be necessary to deviate from the rules; in such an instance the action taken should be based on safety considerations rather than on convenience. If time permits, another experienced member of the group should be consulted before the action is taken.

These rules are intended to guide our planning so that safe operation will result; in order to achieve this condition, you are urged to suggest ways in which the manner of handling these materials can be improved so that we may all benefit from your experience and ideas.

SAFETY RULES

For Handling: BrF_3 - Bromine Trifluoride

BrF_5 - Bromine Pentafluoride

ClF_3 - Chlorine Trifluoride

Br_2 - Bromine

* * * * *

I. Precautionary Measures

A. Personal

These materials, in both liquid and vapor form, are extremely irritating to mucous membranes, skin and eyes, and they can cause serious burns. Inhalation of the vapors is hazardous because injury to the respiratory tract can occur. Fortunately, these materials possess good warning properties because of the sharp, penetrating odor. They are toxic in air concentrations as low as several parts per million; however, their odor is detectable in lower concentrations. A self-contained oxygen breathing apparatus (Chemox) provides the best respiratory protection currently known.

1. Avoid contact with the skin and eyes; wear leather gloves and face shields. Safety glasses should be worn at all times in the local operating area.
2. Avoid inhaling vapors; provide sufficient ventilation.
3. A Chemox breathing apparatus should be relied upon only in areas of low concentration unless an emergency of extreme importance, such as rescue, arises. An apparatus suitable for sustained work in areas of high concentration is not yet available.

B. Chemical

These materials are also extremely reactive; contact with non-fluorinated organic and inorganic substances, or with metals which do not form a protective fluoride film, can result in explosive reactions. Contact with water, oil, grease or organic solvents can result in violent reactions under uncontrolled conditions. Personnel working with these materials should be thoroughly familiar with the chemical reactions which can occur upon contact with the materials of equipment or adjacent to it (in the event of a leak).

1. Avoid contact with any material which is not known to be resistant to the chemical involved under your particular operating conditions.
2. Give consideration to the effect that a leak or spill will have on materials adjacent to the equipment and take necessary precautions to insure that all contingencies are provided for.
3. Chemical reactions of significant rate must be carried out under controlled conditions which provide for adequate heat removal and pressure relief.

C. Mechanical

1. The temperature and pressure limitations of containers for these materials should be recognized at all times.
2. Barriers for personnel protection against direct release of the material should be provided.
3. The equipment arrangement should be devised so that no one can be trapped amidst or behind the equipment.
4. Heated equipment should be provided with suitable temperature controls and pressure relief devices.
5. Cooling media which will react with these materials should be separated from them by double wall construction.

II. Countermeasures

A. First Aid

Immediate action is necessary in order to combat injuries caused by these materials. All injuries should be immediately reported to the Medical Department since more extended treatment than that outlined below may be required.

1. In case of liquid contact with skin and mucous membranes, flush immediately with large quantities of water; use the emergency shower if necessary and remove all affected clothing. Apply the solution labeled "For Bromine or Fluoride Burns" (saturated magnesium sulfate).
2. In case of liquid or vapor contact with the eyes, flush immediately with large quantities of running water for 15-30 minutes. Use the eye fountain when it is convenient.
3. In case vapors are inhaled, the patient should be immediately removed from the contaminated atmosphere and kept warm and quiet until a physician arrives.

B. Leaks and Spills

Non-contained leaks and spills present both personal and fire hazards. The type of action necessary to cope with the situation will largely depend upon the magnitude of the hazard and the vapor pressure of the materials involved, since contact with these materials must be minimized.

1. In the event of a non-contained leak or spill, the area should be evacuated as soon as it is feasible to do so. Large leaks of materials having even low vapor pressures and small leaks of materials having high vapor pressures will make it mandatory to immediately evacuate the area. In other situations, if it is judged possible to safely isolate, minimize or vent the hazard before leaving the area, the attempt should be made. If the situation is doubtful, evacuate the area immediately.
2. Non-contained leaks and spills should be approached only by personnel wearing the Chemox breathing apparatus and protective clothing.
3. Non-contained spills should be absorbed in calcium fluoride powder (Fluorite) and transferred to permit vaporization in a hood.
4. Large contained spills should be reduced in volume first by transferring the material into an evacuated vessel. The remainder of the material may then be permitted to vaporize or may be handled as above.
5. All personnel handling these materials should be familiar with the use of the Chemox breathing apparatus.
6. Small leaks may be temporarily stopped by freezing the zone with CO₂ discharged from a fire extinguisher. Steps should then be taken to minimize the release of material.

C. Fires

Fires involving these materials are particularly dangerous because accelerated reactions as well as other leaks and spills may develop. The type of action required will depend upon the magnitude of the existing hazard and the potential for the initiation of other hazards. Call the Fire Department immediately.

1. In the event of a fire, it is important that immediate steps be taken to eliminate or reduce the flow of material which has initiated the fire - if it is judged possible to perform these operations safely. If conditions are considered unsafe, the area should be immediately evacuated.

2. The area should be approached only if the probability that an accelerated reaction or an explosion will occur is low. Personnel should wear the Chemox breathing apparatus and protective clothing.
3. The only material to be used in fighting fires involving these materials is CO_2 . Extinguishers should be located so that they are readily accessible. The action of CO_2 is limited to that of cooling the reactants and thereby lowering the reaction rate. The exclusion of oxygen is not required since it is not consumed in the primary reactions involving these materials. The secondary reactions will consume oxygen; hence blanketing the area with CO_2 will extinguish fires of this type. Water should never be used on fires involving these materials.

III. Operations

A. Operating Procedures

1. At least two persons should always be present when any operations are performed on a system. They should not necessarily remain adjacent to each other, but the assistant(s) should be in the vicinity of the operation to be of aid in an emergency.
2. All personnel directly concerned with the equipment should be thoroughly familiar with all standard and emergency operating procedures.
3. Should any abnormal event occur, immediate steps should be taken to determine its cause even though shutdown is required. The condition should be corrected and approved by the person directly responsible before operation is resumed. All such events should be noted in the log book.

B. Equipment Preparation

1. Any agent (solid, liquid or gas) which can react undesirably with these materials should not come in contact with the equipment interior unless provision is made for removal of the trapped, absorbed and adsorbed agent.
2. Equipment which does not have a residual fluoride film should be properly degreased with unused Freon 113, and cleaned and flushed with helium* in preparation for prefluorinating (conditioning) the system with a gaseous mixture of helium and ClF_3 . The rate of ClF_3 addition should be controlled so that its partial pressure builds up slowly. After this step the system should be vented and flushed with helium to remove the ClF_3 . The system will then be prepared to contain the interhalogens; if the system is not to be used immediately, it should be kept under a slight positive helium pressure.

*Purified nitrogen may be substituted for helium.

3. The entrance of atmospheric moisture to a system containing liquid or gaseous interhalogens should be prevented because the hydrolysis products formed present undesirable contamination and corrosion products. In the case of ClF_3 , extreme care should be taken because the chlorine oxides formed can decompose with explosive force under conditions not yet well defined.

C. Heating Equipment

1. Electrical heating devices should be controlled to apply heat slowly to equipment containing these materials in order to prevent a reaction with the container wall at local hot spots.
2. Concentrated heat sources, such as welding torches, should not be applied to equipment until it is properly drained, flushed with helium, and the residual fluoride film is removed sufficiently far from the heat-affected zone.

D. Miscellaneous

1. Commercial shipment of these materials is permitted only in the proper Interstate Commerce Commission cylinders.
2. Cylinders or equipment containing these materials should be securely chained or supported.
3. Equipment containing these materials should be appropriately labelled or tagged.

/ed

FIG. 2

NOTES:
 1. SLUG LOCK ASSEMBLY OMITTED FROM THIS WEN.
 2. SAFETY LINE FROM DT OMITTED.
 3. REFER TO SK-29-53-9 FOR H.C. COOLING WATER PIPING.

REVISION		DATE	BY	CHK
1	REVISED	4-15-53	WJ	WJ

BROOKHAVEN NATIONAL LABORATORY	
UPTON, N. Y.	
PLANT	
PILOT PLANT - FIRST SEC.	
NIGHTLIT STUDIES GROUP	
SK-29-53-31C	

DATE	4-25-53	BY	WJ	CHK	WJ
REVISION	1	DATE	4-25-53	BY	WJ

Fig. 5 General View of Dissolver Section Before Operation

PLEASE REFER TO NEG # 8-454-57

Fig. 9 View of Blown-Off Sheet Metal Panels

Fig. 10 Dissolver Section Instrument Panel After Explosion

PLEASE REFER TO NEG[#] 8-508-57

Fig. 11 Pump No. 4 After Explosion Before Removal from System

PLEASE REFER TO NEG# 8-506-57

Fig. 12 Pump No. 4 After Explosion After Removal from System

BURNED OUT
AREA
ADJACENT
TO SLUG
HEIGHT PROBE

Fig. 13 Composite View of Sectioned Dissolver Interior After Explosion - Top

PLEASE REFER TO NEG # 8-503-57

Fig. 14 Composite View of Sectioned Dissolver Interior After Explosion - Bottom

PLEASE REFER TO NEG[#] 8-802-57

Fig. 15 Slug Support Plate After Explosions

Fig. 16 Radiographs of Slug Support Plate Blown Up Against Slug Height Probe

PLEASE REFER TO NEG # 8-510-57

Fig. 17 Slug Feeler, Overall View, After Explosion

PLEASE REFER TO NEG # 8-505-57

Fig. 18 Slug Feeler Probe End After Explosion

PLEASE REFER TO NEG[#] 8-511-57

Fig. 19 Blown-Out Dissolver Rupture Disc

PIECE OF DISC - # Q-509-57

Fig. 20 Partially Dissolved Uranium Slug; 93% Dissolved, 0.50" dia. x 3"
Overall Length

PLEASE REFER TO NEG # 8-507-57