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INVESTIGATION OF THE KW REACTOR INCIDENT

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INVESTIGATION OF KW REACTOR INCIDENTINTRODUCTION

The new KW reactor was placed in operation on January 4, 1955, and had been running at relatively low power levels for only 17 hours when it was shut down because of a process tube water leak which appeared to be associated with a slug rupture.

After several days of unrewarding effort to remove the slugs and tube by customary methods, it developed that considerable melting of the tube and slugs had taken place. It was then evident that removal of the stuck mass and repairs to the damaged tube channel would require unusual measures that were certain to extend the reactor outage for several weeks.

On January 11, 1955, David F. Shaw, Manager of the Hanford Operations Office, United States Atomic Energy Commission, wrote to W. E. Johnson, General Manager, Hanford Atomic Products Operation, General Electric Company, stating that Commission regulations recently effected, although not yet published formally, required that a special investigation and report be made of serious unusual operating incidents. Mr. Shaw requested that such an investigation be made of the KW reactor incident, and further requested that D. G. Sturges of the Hanford Operations Office be named as a member of the investigating group to be established for this purpose.

Mr. Johnson acknowledged these requests by letter to Mr. Shaw on January 12, 1955, and on the same date established the following Investigating Committee:

O. H. Greager, Chairman	Manager--Pile Technology, Engineering Department, HAPO, General Electric Company
T. W. Hauff, Secretary	Specialist--Manufacturing Processes, Manufacturing Department, HAPO, General Electric Company
D. G. Sturges	Chief, Operations Division, Hanford Operations Office, USAEC

The Committee was charged with exploring all facets of the KW reactor incident, with determining the causes, with assigning the responsibilities involved, and with making recommendations which would be useful in preventing a recurrence of this or similar incidents in either present or future plants. A date of February 11, 1955, was established for submission of the Committee report.

SUMMARY

The following is a summary of the Committee's work and findings. This summary, the recommendations, and the main body of the report all represent unanimous agreement among the three members of the Committee.

Committee Action

The Investigating Committee began its work on January 13, 1955. The necessary KW reactor personnel contacts were made and a field office was established in the K area administration building (1704-K). As a first step, all of the written records which had been generated during the KW reactor startup period were assembled. These included all of the various log books, data sheets, and instrument-recorder charts. Copies of all pertinent reference documents were also accumulated.

The Committee spent essentially all of the two week period January 14 to 28 in the K area and the KW reactor building getting acquainted with the facilities and supervisory personnel, studying the written records, and interviewing all principal parties to the incident. The ensuing time to the issuance of this report was spent in analyzing the findings, determining advance recommendations for application to the KW reactor re-start (as well as to the KE reactor startup), augmenting the information obtained during the first two weeks, and finally in preparing this report.

Throughout its work, the Committee had the complete cooperation of Reactor Section personnel and their invaluable assistance in developing the facts as to what had taken place.

The Pre-Startup Program

To understand and interpret this incident, it is necessary to consider the comprehensive 100-KW startup program which preceded initial operation. It had been recognized that the K reactors are substantially larger and different in design than any previous Hanford pile. Accordingly, a thorough program (HW-32869, August 26, 1954) had been given careful advance development jointly by the Manufacturing and Engineering Departments. This program had as its primary objective the pre-startup determination of KW pile reactivity changes and behavior under various conditions in order that these characteristics, which are so important from a nuclear safety standpoint, would be understood and subjected to proper control. The program was properly authorized, and had been submitted to and had the concurrence of the USAEC.

The KW reactor was taken over from Construction by the Manufacturing Department on December 6, 1954, and operational work preliminary to the testing program was started immediately. The program itself began with the determination of "dry critical", following which the uranium slug loading was

increased somewhat to give the additional reactivity required for the "dry pile temperature coefficient" test. The reactor was then operated briefly at low power and without cooling to determine the effect of temperature on the reactivity of a dry pile. To assure adequate helium flushing of the loaded process tubes during this dry test, as well as to provide the necessary dry reflector during the "wet critical" determination which followed, about 1500 rear pigtails and 750 front pigtails were blanked at the nozzle end of the pigtail. One-eighth inch thick neoprene disks were used for this purpose.

Following the determination of wet critical loading, a series of tests was run to determine the reactivity effect of a number of materials commonly used for pile flattening and isotope production or of other importance to pile operation. Some of these tests utilized single column charges while others required the loading of a nine-tube test block. Also measured were scram transients and critical sizes to determine the control strength of individual elements of the vertical rod and ball third safety systems. This work completed the partial loading tests, and the next step was to complete the reactor loading.

Deblanking was made a part of the full-pile loading operation, with removal of the neoprene disks from the front and/or rear pigtails being accomplished as each such tube was charged with metal. Additional full-pile rod and Ball 3-X effectiveness tests were then conducted, as was the low-level determination of wet pile temperature coefficient using recirculated hot water heating. Fringe poison shielding tests were run, and the reactivity interaction caused by adjacent columns of enriched "C" material was measured. All of this test work had been essentially completed by December 31, 1954.

The period January 1, 1955, to the time of startup on January 4 was spent in making final preparations for the initial reactor operation. One of the principal jobs remaining was the checkout of the Panellit board with full cold water flow (115,000 gpm and 235 psig front riser pressure) and the full pile loading. These operating conditions had not been possible during the reactor test program, so no complete check had been made previously on the working Panellit pressures which would obtain in the several venturi and orifice zones of the pile when supplied with water at 235 psig pressure. The tube flow distribution system had been designed to yield uniform Panellit pressures of about 140 psig, and all of the Panellit gauges had been calibrated to show a mid-scale dial reading of 50 with a sensing pressure of the anticipated 140 psig. These gauges had been set to trip the safety circuit relays at low and high pressures of 115 psig and 165 psig, respectively.

Water pressure was first brought up to the conditions selected on the 12 to 8 shift January 1, and all but 100 to 105 of the 3,220 gauges responded as expected with dial indications close to 50. Half of these required only minor adjustment. There were 49 gauges listed as showing off-scale readings on visual inspection of the front of the board. The actual pressure on each such gauge was then determined and suitable corrective action planned. Tube 4669 did not appear on this list.

Of the tubes showing abnormal readings, 39 were seen at once to represent poison column control tubes which had been equipped with 3/4" inlet pig-tails and with the Panellit tap connected directly to the inlet nozzle. Arrangements were made to replace these special inlet connections with regular 1" pigtails and venturi assemblies, and this work was accomplished during the next two days. Three of the other abnormal Panellit readings represented mechanical faults in the hydraulic connections, but seven had shown full inlet riser pressure at the venturi throats, and these were specifically checked for the presence of pigtail blanks. Blanks subsequently were found and removed from the front and/or rear of each of these tubes.

By late on January 3 all of the irregularities found on the January 1 Panellit board checkout were presumed to have been corrected, but a final checkout was made during the brief period when the process water flow was again raised to operating level for the conduct of a process pump trip-out test. A number of gauges showed off-scale readings. These were checked with the test gauges and the necessary repairs were made to six sensing lines which showed zero pressure. The Panellits of nine tubes showing high pressure, including tube 4669, simply were re-set to bring the dial reading back to mid-scale.

The 12 to 8 shift on January 4, which immediately preceded the startup, was spent in repairing front and rear face water leaks and in making miscellaneous final preparations. The Panellit board "cleared" satisfactorily when the process water flow was brought up to 120,000 gpm for the actual startup.

The Startup and the Emergency Shutdown

The official startup of the KW reactor was at 8:47 a.m. on January 4, 1955, and the initial rise to low-level operation in the 5 to 10 MW (Megawatts) range proceeded smoothly. This very low level was held for about 10 hours, at which time the unit was shut down briefly for repositioning of neutron monitoring chambers. At 7:35 p.m. the level was raised to about 125* MW and it was necessary to shut down again to reposition other neutron monitoring chambers. This change required about 2-1/2 hours, and at 10:32 p.m. the reactor was again started and the power level was raised to about 220 MW by 10:50 p.m.

All of this operation had been uneventful, as were also the ensuing 2 hours and 45 minutes of seemingly normal performance at the 220 MW level. The plan had been for the power level to be raised 100 MW each operating shift, with a 48-hour run at 1000 MW before going higher. Accordingly at 1:30 a.m. on January 5, the 12 to 8 operating shift made its first power level increase by going quite conservatively to 265 MW.

* NOTE: The power levels shown in this summary were calculated after the incident from bulk water flow and temperature data. Due to malfunctioning of the direct reading power level instrumentation in the Control Room at startup, these calculated levels are about twice as high as were believed to exist by the operating personnel at the time of the incident.

At 1:45 a.m., 15 minutes after the increase in level from 220 to 265 MW, a decrease in reactivity manifested itself and caused the power level to drop rather rapidly to 230 MW. Horizontal control rods were adjusted in an attempt to compensate for the reactivity loss and to re-establish the target power level. These rod adjustments were accompanied by power level cycling, with short-term increases somewhat above the target 265 MW level. } *why*

At 1:57 a.m., when the cycling power level was about 350 MW, an annunciator panel alarm sounded indicating water in the circulating gas duct system at the base of the pile. A quick check on the gas plenum dew cell recorders confirmed the presence of water. The supervisor in charge immediately associated these water indications with the reactivity loss as indicative of a process tube water leak. Similar indications have occurred with tube leaks at other reactors. In accord with established practice, a high speed traverse of process tube outlet water temperatures was initiated using the automatic Flexowriter facility. By this technique it is frequently possible prior to shutdown to locate the leaking tube by interpreting the cool area to be seen in the general pattern of tube outlet temperatures. ✓

At 2:04 a.m., before the tube outlet temperature traverse was complete and when the power level was about 440 MW, the reactor was automatically shut down by the vertical safety rods being tripped by the No. 1 safety circuit. The rod drop was shown by Panellit board signal lights to have been caused by a Panellit trip on reactor tube row #46. Inspection of all 58 gauges on this row within a minute after shutdown showed none with abnormal readings. This indicated that the gauge which caused the trip must have reacted to a transient abnormal condition. Almost simultaneously with the rod drop there were indications of a ruptured slug somewhere in the pile.

As is standard practice under such circumstances, the process water flow and pressure were lowered immediately, and entry was made to the rear face. A radiation survey of row 46 revealed an intensity of 1.5 R/hr. at the outlet piping of tube 4669, which was taken to confirm the presence of a rupture in this particular tube. When the rear nozzle cap was removed, intense beta radiation was observed but no water was seen. Normally a low flow of water would emerge from the rear nozzle under such conditions. With all indications confirming the presence of a ruptured slug, and with serious penetration of tube 4669 established by pressure testing, steps were initiated to proceed with ruptured slug removal and tube replacement using conventional methods.

Slug and Tube Removal Efforts

Efforts to remove the slugs and tube from channel 4669 were underway within three hours after the scram on January 5. By January 7, it became apparent that this was not a normal ruptured slug incident since only a few of the uranium pieces could be withdrawn from the tube, and attempts to push the

tube and contents together had failed with pressures up to 19,000 pounds. On that date also the mis-setting of the associated Panellit gauge was discovered, and it was first determined that the tube had probably been operated without cooling water.

From January 7 until January 11 all feasible methods of discharging the stuck tube and charge from the graphite channel were employed without success. Due to lack of structural integrity of the slugs and tube, and adherence of the material to the graphite, it did not prove possible to remove the remaining components even with pushing forces up to 35,000 pounds. In between the repeated pushing and pulling attempts, which proceeded slowly as the required special equipment had not previously been used at the KW reactor, tedious withdrawal methods were used to remove slugs and pieces of tubing from both ends of the channel. Finally, just before abandoning these removal efforts, a core-type cutter was resorted to and three slugs were freed by thus sawing through the adhering process tubing.

On January 11, with about 80" of the initial 340" long tube charge still remaining in the channel, the removal program was reviewed in the light of the graphite damage seen with the borescope, and the extensive slug and tube melting which was evident from Radiometallurgy Laboratory examinations of recovered material. It was concluded that some quite different approach to the removal work would be required, and responsibility for a detailed survey of the channel damage and for the subsequent removal and restoration work was assigned to the Engineering Department.

Channel Removal and Restoration

Additional borescope observations were made in tube channel 4669 and in the adjacent row of vertical safety rod (VER) channels and the four closest process tube channels. Considerable damage to the graphite was found to have occurred in the front section of channel 4669. Several gaps in the block were evident, and these were in accord with other observations which indicated that part of the channel had been broken from its keying to the balance of the stack and displaced about 3" to the rear. Inspection through the adjacent vertical rod slots showed some penetration of melted metal into VER channel #37, as well as a small lateral displacement of the row of graphite blocks adjacent to channel 4669. Some evidence of metallic material at other block junctions of channel 4669 was also seen.

On the basis of these conditions, and evidence that the material remaining in the channel had been so altered as to completely fill the oversize bore of the graphite blocks, it was seen that a choice had to be made between two alternatives: (1) coring out the process channel so as to free the stuck tube and charge, or (2) cutting a sufficiently large hole through the rear shield to allow the entire graphite stringer to be removed and replaced. Design studies with 6" diameter diamond-tipped core drills showed the latter to be a feasible approach, whereas mock-up tests on boring

out the channel indicated that this would be very laborious and time-consuming, as well as presenting a fire hazard when cutting through uranium metal. Accordingly, it was decided on January 14 to proceed with the shield cutting and graphite removal approach. The required special drilling equipment was obtained from off-plant and was placed in operation on January 16 immediately following the necessary preliminary work of clearing away cross-header piping, instrument connections, and other interfering components on the rear face.

This removal and channel restoration work progressed in steady fashion and was completed on February 5, 1955. The approximately 1/2" of lateral graphite movement which had occurred in the vicinity of the VER slot #37 was corrected with appropriate graphite shimming during channel replacement, and the reactor is considered to have been returned to serviceable condition without any impairment of function.

It now appears that the total cost of the entire outage, based upon an indicated return to service on February 15, will approximate \$550,000.

Causes of the Incident

It is the Committee's conclusion, based on the physical evidence and the testimony of individuals primarily involved, that the incident was the result of the reactor having been started and operated without any flow of cooling water to process tube 4669. It is definite also that the Panellit gauge of this tube, which alone could have signalled the lack of water flow, had been set before startup in such a way as to nullify the significance of its reading. In the absence of direct cooling, and with this gauge mis-set, it was inevitable that the heat generation within the uranium slugs as the power level increased would cause melting of the aluminum jackets, the aluminum tube, and finally the uranium itself. The fact that power level instrumentation was malfunctioning, with the result that levels actually were about twice as high as believed at the time, is therefore considered inconsequential to this incident.

The following three closely related causes were established for the reactor thus having been started and operated without cooling to tube 4669:

1. The lack of water flow through the tube was caused by the inadvertent failure to remove from the rear pigtail of this tube the neoprene blank which had been inserted therein during the pre-startup program.
2. The initial Panellit board "clearing" operation conducted on January 1, when the process water flow and pressure were first raised to operating levels, failed to identify this abnormal condition. There is ample evidence that the gauge was reading off-scale at the time of the check.
3. Late on January 3, the eve of the startup, the Panellit gauge of tube 4669 was seen to be reading high, and a Heise gauge check showed its venturi tap to have a pressure of 238 psig. The no-flow significance

of this equality with inlet riser pressure was overlooked, and the gauge dial simply was reset to read the normal "50" (mid-scale).

It is significant to note that the Committee found nothing in connection with this incident to indicate any deliberate or malicious action on the part of individuals or any deficiencies in the basic design, the construction, the fundamental operating concepts, or the process specifications and standards. The safety instrumentation and equipment provided to protect against the potentially disastrous consequences of an incident of this type functioned properly.

Assignment of Responsibility

In view of the three causes described above, and the fact that the incident was due to the sequential effect of all three, the Committee has considered them all in assigning responsibility for the incident.

As regards the failure properly to remove the rear pigtail blank from tube 4669 at the time it was loaded with uranium preparatory to startup, it is the Committee's conclusion that the fault lay in the lack of an adequate debanking control procedure, rather than with any individual directly involved.

In the second instance, the fact that the high Panellit reading of tube 4669 passed unnoticed by responsible personnel when the entire board was first "cleared" under operating flow and pressure conditions on January 1 is ascribed to weaknesses in the board checkout system and cannot be traced to any specific individual.

In the case of the third and last of the three causes cited, the Operations Supervisor I in charge is clearly responsible for having failed to recognize the significance of the high pressure recorded at the time of resetting the Panellit gauge. This failure made it virtually certain that the no-flow condition in tube 4669 would remain undetected until serious damage had resulted.

Factors Contributing to the Incident

As will be apparent from the foregoing statements regarding causes and responsibility assignments, as well as in the recommendations which follow, the Committee found a number of factors which it considers to have contributed significantly to this incident. These may be summarized as follows:

1. Too heavy a burden was carried by the Operations supervisors who were directly in charge of the shifts in the KW reactor building throughout the pre-startup program. Each of these supervisors had only one shift supervisor to assist him with the myriad of details for which he was responsible. This one supervisory assistant had to be assigned rather

exclusively to the front elevator work, which meant that the supervisor in charge was required personally to handle all of the rest of the work being conducted at many locations within the large and complex building. Also contributing to his heavy loading was the fact that considerable numbers of additional nonexempt personnel (both operators and craftsmen) were required on most shifts, and these people had to be drawn from all other reactor areas and assigned on an overtime basis. Being unfamiliar with the 105-KW Building, these people required particularly close surveillance. Another manpower shortage was in the area of supporting specialist personnel, as illustrated by the fact that only one instrument engineer was assigned full time to assist the instrument maintenance people. These supporting specialists are regarded as very important for assistance to the building supervision in evaluating and interpreting equipment performance.

2. There was inadequate written definition of the manipulations to be performed, data records to be taken, and the specific division of functional responsibilities. This inadequacy was very evident in the case of the critical tube deblanking operation, over which control was lost early in the program, and also in the ineffectual Panellit board checkout where functional responsibility was unclear between Operations and Process personnel, and the system employed was clearly too informal.
3. The pre-startup program as originally planned included a carefully allocated 22-day schedule for the work to be done from the time of acceptance of the new facility from Construction to the day of start-up. With take-over on December 6, this schedule would have had the reactor ready to start on December 28. Actually the pre-startup work took 7 days longer than planned, due to a variety of unforeseen delaying factors which occurred during the very complex and elaborate program. It was evident to the Committee that a feeling of urgency, and of need for recovering the lost time, developed in the minds of the building supervision involved. This feeling, coupled with the manpower shortage, very probably was responsible for certain inattention to detail and lack of deliberation as the work was pushed forward.

RECOMMENDATIONS

To prevent a recurrence of this or similar incidents, in either present or future plants, the Committee makes the following recommendations:

1. More effective provision should be made for the manpower requirements of a new reactor startup; specifically: (a) assignment of extra supervisory personnel, particularly to assist the Operations supervisor in charge; (b) direct assignment of a full complement of operators and supporting craftsmen; and (c) assignment of sufficient qualified specialist personnel to provide shift coverage assistance to the re-

responsible Operations supervision in the interpretation and evaluation of equipment and process behavior.

2. Detailed written instructions and procedures, including specific definition of functional responsibilities, should be prepared and used in the performance of critical checkout operations on vital reactor components and control facilities. It is recommended specifically that these instructions and procedures incorporate a requirement for duplicate checking and appropriate review by qualified personnel.
3. Complete data records should be kept for all calibrations and adjustments of instruments which are critical to reactor operational safety. In the case of such key instruments as the Panellit gauges, where a multiplicity of similar signals is involved, each individual instrument observation should be recorded. This total recording of normal as well as abnormal readings is intended to assure completeness of both observation and interpretation of significant data.
4. Positive control measures should be employed to insure the recovery of all materials which are introduced temporarily into process tubes (or associated water piping) and which are intended to--or conceivably might--significantly obstruct process tube water flow. A piece-count type of accountability is recommended for this purpose.
5. The initial startup of a new facility such as this must be conducted in a very deliberate manner, with ample time allowed during startup for a thorough checkout of all equipment under conditions typical of those to be encountered in actual operations.

DISCUSSION

As noted in the Summary, this report documents the work and findings of the Committee which investigated the KW reactor incident. Its content represents unanimous agreement among the three Committee members.

Insofar as possible, and in most cases, the information presented is based upon and supported by the factual records and the testimony of the individuals who were most directly involved with the incident. However, in view of the large bulk volume of the testimony transcripts and the single-copy nature of the original records obtained (e.g., instrument recorder charts and operating data sheets), it has been impractical to include all of this information in this report. This material therefore has been assembled and made to comprise a separate file record document entitled "KW Reactor Incident--Investigation Record", HW-34847.

Except for the inclusion of a brief description of the KW reactor, the outline followed in this detailed portion of the report follows closely that of the Summary. Selected photographs, sketches, and other illustrative material all are appended to the report.

Brief Description of KW Reactor

The KW reactor and associated water plant, together with the essentially identical KE area facilities, were constructed under Project CA-512. The over-all management of this project was handled by the Hanford Operations Office, USAEC, and the prime contractor for construction was the Kaiser Engineers Division of the Henry J. Kaiser Company. The Engineering Department, Hanford Atomic Products Operation, General Electric Company, performed the reactor design work. Design of the associated water plants was done by Chas. T. Main, Inc.

Project CA-512 received formal authorization on August 19, 1952, and construction started on September 10, 1952. The KW reactor facility was declared "ready for use" on December 6, 1954, and was taken over by Manufacturing from Construction on that date. Of the total indicated CA-512 project cost of \$162,000,000, about \$47,000,000 is estimated to represent the investment in the KW reactor.

Like the older reactors, the K piles are graphite-moderated and single-pass water cooled. They differ principally in point of size, having 3,220 tubes as against 2,004 in the others. Moreover, the K reactor tubes are longer by about 6 feet, and this enables them to accommodate 38 standard 8" long uranium slugs versus 32 in the older reactors. Also, the K tubes were made slightly larger in diameter so as approximately to double the water annulus area. The 3,220 tubes are arranged in a 7-1/2" square lattice (versus 8-3/8" in the older reactors), and the total array comprises 58 horizontal rows of 58 tubes each, except for a triangle of 36 tubes omitted from each corner (See Fig. 1).

The 3,220 tubes with the enlarged annulus enabled the design flow of a K reactor to be 140,000 gpm with an inlet riser pressure of 280 psig under equilibrium full-power operating conditions. These figures compare with about 40,000 to 50,000 gpm at 370-400 psig at all of the older reactors, except C pile, where the equilibrium flow is about 82,000 gpm at 420 psig supply pressure.

As in the case of the older reactors, reactivity control in the K piles is obtained with the required number of horizontal control rods and vertical safety rods, the latter being backed-up with hoppers of 3/8" iron balls. All of this control and safety equipment is interlocked with a number of instrumental trip circuits so as to be actuated automatically in the event of emergency need. These safety circuits are essentially the same as in the older reactors, although certain design differences are noteworthy.

The pressure monitor system of each K reactor for the first time includes trip-actuated signal lights on all of the vertical rows of gauges on the Panellit board in the Control Room (See Fig. 2). Heretofore only the horizontal rows of gauges have been equipped with such lights. This new coordinate light system is intended to identify the individual gauge that initiates a scram, and thus facilitate determination of the tube flow abnormality responsible for the Panellit trip. It should be noted that it had not been possible to place the vertical row lights in service at the KW reactor prior to startup, because of synchronization difficulties with the horizontal row light system.

The tube outlet temperature instrumentation provided at the K reactors is unique in that all 3,220 of the individual tube resistance thermometers can be connected into the No. 1 safety circuit so as to shut down the reactor automatically whenever a pre-set maximum temperature limit is exceeded in any one of the 3,220 tubes (See Fig. 3). At the older reactors, thermocouples are provided at the outlet of each tube with indicating and recording means in the Control Room, but there is no connection into the safety circuit. However, considerable difficulty was experienced with the tube outlet thermometers of the KW temperature monitor system prior to startup, and the safety circuit feature of the system necessarily had been bypassed.

The only other instrumentation difference which appears noteworthy in connection with the incident investigated relates to the means provided for process tube water leak detection. The K reactors (for the first time at Hanford) are equipped with conductivity cells located in small collection sumps at the bottom of each vertical front and rear gas plenum. These cells are arranged to afford the earliest possible detection of liquid water drainage within the reactor, and they are wired to transmit this indication to the annunciator panel in the Control Room. Water drainage in the older reactors is indicated and alarmed only by water level contacts which are installed in large drip legs on the main inlet and outlet gas

lines. (Note: It was the conductivity cells at KW reactor which gave the Control Room alarm confirming the presence of a water leak.)

Description of the Incident

A full description of the incident requires a discussion of several aspects of the comprehensive startup program which preceded initial operation of the reactor since it is apparent that the incident occurred as a result of actions which took place during that startup period.

Pre-Startup Program--Pigtail Blanking

A thorough pre-startup program, which is described in detail in document HW-32869, dated August 26, 1954, was adopted after a period of several months' detailed discussion and careful planning by the Manufacturing and Engineering Departments. This program had as its primary objective the determination of KW reactivity changes and behavior under various conditions, in order that these characteristics would be thoroughly understood and subjected to proper control. The understanding of these reactivity changes has long been stipulated by the Advisory Committee on Reactor Safeguards as an essential requirement for advances in reactor safety. The pre-startup program gave special emphasis to those technical investigations which the General Electric Company, the Atomic Energy Commission, and the Safeguards Committee had jointly agreed were of prime interest in this connection. As a consequence, the technical testing portion of the KW startup program was much more elaborate and more time-consuming than that of any previous startup program.

The KW reactor was taken over by the Manufacturing Department on December 6, 1954. Technical data collecting by the Engineering Department began on December 10, 1954. The period between December 6 and December 10 was utilized by the Manufacturing Department in familiarizing operating personnel with the general characteristics of the reactor facilities and with preparation for the technical testing program.

The initial step of the testing program was the determination of the critical size of the dry pile, following which the uranium slug loading was increased to provide the additional reactivity necessary to determine the dry pile temperature coefficient. In the latter step the reactor was operated briefly at low power and without cooling to determine the effect of temperature on the reactivity of a dry pile.

The accurate determination of the dry pile temperature coefficient and a thorough understanding of the reactivity characteristics which it reflects are of utmost importance to an understanding of the probable behavior of the reactor should it lose its cooling water during operation. To insure a high degree of accuracy in these measurements it was desirable to flush the loaded process tubes with helium in order to

eliminate the air which is, of course, a strong neutron absorber. To minimize the use of helium, all of the empty process tubes which were connected to the same cross headers as those tubes which were loaded for the dry pile temperature coefficient test were blanked at the nozzle end of the pigtail. One-eighth inch thick neoprene disks which slipped into the connector nut on the pigtail were used for this purpose. (See Fig. 4)

The blanking operation served another useful purpose in that it prevented water flow in the blanked tubes and, therefore, provided the dry reflector necessary for the accurate determination of the wet critical size of the reactor.

The use of pigtail blanks during technical testing prior to startup is not new at Hanford. A similar blanking procedure was performed during the pre-startup testing of the C pile. At that time, lead disks were used. These lead disks proved unsatisfactory in that, in a number of instances, the central portion was punched out when tightening up the pigtail nut and partially blocked the cone screens ahead of the orifices. A thorough study was made to determine the proper characteristics of the pigtail blanks to be used for the KW startup and the blanks finally chosen were carefully tested to make certain that they would not collapse under test conditions and lodge in the pigtail or nozzle.

A pre-startup estimate had been made of the size of the dry critical pile as well as the size of the loading required for the dry pile temperature coefficient test. A further estimate had been made of the size of the wet critical loading. Based on these estimates, a pattern had been established for those tubes to be fitted with pigtail blanks. (See Fig. 21) Approximately 1,400 rear pigtails and 700 front pigtails were scheduled to be blanked. Some 1,400 tubes were involved. Tube 4669 was not in the original blanking pattern.

Blanking was begun shortly after the Manufacturing Department took over the reactor on December 6 and the initial blanking pattern was completed on December 10. A piece of striped Scotch tape was wrapped around each of the pigtails in which a blank was inserted (See Fig. 5). The dry critical loading, and as a consequence the loading required for subsequent tests, turned out to be somewhat larger than estimated. It was necessary to expand the blanking pattern by about 115 tubes. Tube 4669 was one of those added when the pattern was increased in size. (See Fig. 21)

Following the determination of the dry pile temperature coefficient, the uranium loading was increased to determine the size of the wet critical pile. During this operation many tubes having pigtail blanks were charged with uranium slugs. The procedure in effect called for removal of the pigtail blanks as the tubes were charged. At the same time the striped tape was removed. Subsequent to the determination of

the wet critical loading, an extended series of tests on other reactivity effects was run. In addition, the control strength of the rod and ball third safety system was measured, after which the loading of the reactor was completed. The loading sequence sheets and charge cards indicate that tube 4669 was first loaded with uranium metal on December 19. The loading sequence sheet also indicates that front and rear pigtail blanks supposedly had been removed from this tube assembly at that time.

Subsequent to completion of the full pile loading on December 29, tests on the effectiveness of the rod and ball 3X systems were conducted as well as a low level determination of the wet pile temperature coefficient and a number of other measurements of specific pile characteristics. The technical test program was completed on December 31, 1954. During the testing program subsequent to loading tube 4669, the power of the pile had never been allowed to exceed 50 KW.

Pre-Startup Program--Panellit System Calibration and Checkout

The period from January 1, 1955 to the time of startup on January 4 was spent in making final preparations for initial reactor operation. One of the principal jobs remaining was the checkout of the Panellit pressure monitoring system under full cold water flow (115,000 gpm for 235 psig front riser pressure) and the full pile loading. These operating conditions, of course, had not been possible during the reactor test program so no complete check had been made up to this time of the Panellit system under actual working pressures and full loading conditions.

A full understanding of the checkout of the Panellit system requires some discussion of the work performed on the system prior to its initial checkout under full scale operating conditions on January 1. The Panellit system provided for the K reactors contains a new feature intended to specifically pinpoint any Panellit gauge which trips as a result of either too high or too low pressure reading. In the old piles, the Panellit board is equipped with row lights, the proper one of which will light up if a gauge on that particular cross header row trips. The K pile Panellit boards (See Fig. 2) have in addition to the row light system, a system which is supposed to flash a light indicating the vertical column in which the tripped gauge will be found. At the time KW pile was turned over to the Manufacturing Department, the row light system was in good operating condition but the coordinate system was not working, due to certain inherent deficiencies.

In order to determine the scope of the effort which would be necessary to correct the basic deficiencies observed in the coordinate system, the KW Instrument group made a complete measurement of the high and low trip points for every one of the 3,220 gauges. Four measurements were made on each gauge as follows: (1) the high pressure at which the Panellit gauge would light the horizontal row light, (2) the low pressure at which

the Panellit gauge would light the horizontal row light, (3) the high pressure at which the Panellit gauge would light the vertical column light, and (4) the low pressure at which the gauge would light the vertical column light. Each one of these trip pressures was actually measured on a Heise gauge (See Fig. 6). The source of the pressure was an accumulator system in the 105-KW Building which provides a precisely controlled hydrostatic pressure at the Panellit board.

A review of the measurements made during this period on Panellit gauge 4669 indicates that this gauge was in proper working condition.

This detailed check of the trip points on the Panellit board was completed on December 27. From then through December 31, work on the board consisted of the replacement of faulty jumpers, the elimination of shorts in the electric circuitry, and numerous minor corrections.

On the 12 to 8 shift on January 1, 1955, water pressure was brought up and the pile was put under full operating water flow for the first time. It had been planned well in advance of this date, that this full flow test would be utilized to effect the initial clearing of the Panellit board.

The Panellit gauges at the K piles read from 0 to 100 (See Fig. 7), this representing a range of 100 psi. During the construction program, each of the gauges was set at a mid-point reading of approximately 50 for an actual pressure on the gauge of 140 psig. The zero of the gauge, therefore, represented a base of 90 psig. The low trips on the gauges were set at a nominal reading of "25", equivalent to 115 psig, and the high trips were set at a nominal reading of "75", equivalent to 165 psig.

It had been estimated, based upon the pre-established pile flow conditions, that a flow of approximately 117,000 gallons per minute should clear the Panellit board, or in other words, would bring the pressure on each of the gauges to a point where the gauge would be within standard operating limits. The 117,000 gallons per minute was the cold flow necessary to obtain the same Panellit pressures as would be obtained under the full hot flow conditions which would be realized during full-scale operation of the pile.

It had been estimated that perhaps as many as 800 gauges would be outside standard operating limits when the initial board clearing test was conducted. This would have required an extensive amount of gauge calibration and resetting. Consequently, a substantial crew of instrument personnel not regularly assigned to the K reactor was called out to perform the anticipated work in conjunction with the flow test on January 1.

Full flow to the pile was started on the 12 to 8 shift on January 1 at a rate of approximately 120,000 gallons per minute. This proved to be

somewhat high to provide the required front riser pressure of 235 psig and the flow was gradually cut back to 115,000 gallons per minute. At this flow the front riser pressure was correct and a scanning of the Panellit board was begun. There were a surprisingly small number (between 100 and 105) of gauges which gave readings outside standard operating limits.

The exact procedure which took place in checking the Panellit board to clear it at this time is somewhat obscure in certain details. It has been stated that Instrument personnel assisted by Operations personnel checked the board and recorded the numbers of all of those gauges which were off-scale on either the high or low pressure side. We have been unable to find any original records listing the data so recorded. K. W. Hess, the process engineer who had made the calculations which were the basis for the pre-test gauge settings and the bulk water flow conditions for the test, analyzed and evaluated data from whatever records were kept. He prepared from these records a list of 49 tubes which were reading off-scale on either the high or the low pressure side of the gauge. Tube 4669 does not appear on the list which Hess made.

At the same time Manufacturing Department personnel were running the Panellit board clearing test, C. L. Miller and A. W. Thiele of the Pile Technology Section made a quick scan of the Panellit board in an effort to determine approximately how many tubes within the critical loading patterns might not have had pigtail blanks removed as required. The presence of pigtail blanks would have been signalled by off-scale readings on the high pressure side of the Panellit gauges. The Pile Technology group was primarily interested in determining whether there was a large number of such failures to deblank, and was not particularly concerned with whether blanks had been left in specific tubes. The number of tubes which they observed might still be blanked was sufficiently small to have been negligible in its effect on any of the technical data which had been taken and as a consequence, the Pile Technology group did not pursue this matter. However, Miller and Thiele did record informally the numbers of the tubes which they had observed were reading off-scale or outside of standard operating limits. This list, which appears as page 271 of the Technical Log for the KW startup tests (HW-34459-RD), contains tube 4669.

The list prepared by K. W. Hess contains the numbers of 39 tubes (reading high trip) which were equipped with front and rear face ball valves. These ball valves were installed to enable the use of poison column charge-discharge during pile operation. The tubes were not equipped with venturis and the Panellit line was connected to a tap on the nozzle. Furthermore, the nozzles were equipped with undersize pigtails. Since these tubes were to be used during initial operations as regular process tubes and were loaded with uranium slugs, the high Panellit pressures obtained with the front face ball valve assembly could not be tolerated.

These tubes were flagged immediately for correction which was to consist of the replacement of the front face ball valve with a standard nozzle and venturi assembly.

Three of the abnormal Panellit readings which Hess listed were analyzed as mechanical faults in the hydraulic connections. Seven of the gauges listed read full inlet pressure at the venturi throats and at the suggestion of Hess they were specifically checked for the presence of pigtail blanks. Blanks were subsequently found and removed from the front and/or rear of each of these tubes. Two of the tubes, 3754 and 3851, were checked on the 12 to 8 shift on January 1, and pigtail blanks were found in the front pigtails. On the 4 to 12 shift the same day, blanks were removed from the rear pigtails of tubes 2381, 2357, and 2753, and from the front pigtails on tubes 2580 and 2381.

In addition to those gauges which were reading off-scale, there were 52 gauges which were in the warning zones which are 0 to 10 pounds above the low pressure trip and 0 to 10 pounds below the high pressure trip (See Fig. 7). These 52 gauges were checked by Operations and Instrument personnel and were reset so that their mid-point readings were at approximately 140 psig. The calibration of all of these gauges were recorded on standard IBM data sheets provided for this purpose.

It must be noted that the Panellit board was not cleared at the time of this test. At the end of the checkout, there were still in excess of 40 gauges which were reading off-scale.

During the next two days, the ball valve assemblies were replaced with regular front face nozzles, and as was indicated previously, the seven tubes so designated on the list prepared by K. W. Hess were checked and pigtail blanks removed.

For a number of reasons the process pump trip-out tests, which were a part of the construction acceptance test procedures (ATP), had been delayed so that they could be run with an actual charge of slugs in the pile. This trip-out test, which would permit determination of the performance of the process water pumps under conditions simulating loss of outside electric power, were scheduled to be run early on the 4 to 12 shift on January 3. The test was postponed until late in the shift because of a delay in completing the replacement of the front face ball valve assemblies. Sufficient front face nozzle assemblies were finally obtained from the KE warehouse to permit completion of this replacement shortly before 10:30 p.m.

The water pressure was brought up at 10:30 p.m. to permit checking of the tubes on which the ball valve assemblies had been changed. Shortly thereafter the simulated power failure test was run.

When the water pressure was brought up, Operations and Instrument personnel checked out the Panellit board. This checkout was performed

before the trip-out test. A number of gauges showed off-scale readings during this check of the Panellit board. These were checked against the test gauges and instructions were issued to repair six sensing lines which showed zero pressure. The Panellit gauges of nine tubes showing high pressures ranging from 185 pounds as checked by the Heise gauge up to 238 pounds, simply were reset to bring the dial reading back to mid-scale.

In checking the Panellit system, an instrument mechanic is at the back of the board (See Fig. 8). Another instrument mechanic and a pile operator check the front of the board. Any gauges which read out of standard are checked on the Heise gauge by the instrument mechanic at the rear of the panel. He calls out the pressure read from the Heise gauge which is recorded by the pile operator on a standard form provided for that purpose. The pile operator then instructs the instrument mechanic on the back of the board to adjust the gauge to mid-point if such adjustment appears appropriate. The instrument mechanic on the front of the board reads the adjusted reading, which is recorded by the pile operator.

The Operations Supervisor I or the Chief Operator ordinarily supervises the checking of the Panellit board. At the time of the January 3 check-out of the board, the Operations Supervisor I was present during the time when eleven of the fifteen gauges reading off-scale were checked and actually issued the instructions to have them adjusted to mid-scale. The Operations Supervisor was called away, before the check of the board had been completed, to conduct the trip-out test. The Chief Operator was engaged in other duties, so the check of the board was completed by the pile operator. Tube 4669 was checked during this time and was found to read 238 psig, the same as the cross-header pressure, all of which indicated no flow in the tube.

The pressures read on the Heise gauges for all of the fifteen tubes observed to be off-scale were recorded on standard IBM data sheets, as was the mid-point setting to which the nine tubes showing abnormally high pressures were adjusted. The data sheet was turned in to the Operations Supervisor.

The 12 to 8 shift on January 4 was spent in repairing front and rear face water leaks and in making miscellaneous final preparations for the startup of the reactor. It was during this shift that several of the sensing lines, which had showed zero pressure during the Panellit board checkout on the previous shift, were corrected. A final check was made of the Panellit board when the process water flow was brought up to 120,000 gallons per minute about two hours prior to the actual startup. A number of gauges which were in the warning ranges were readjusted to mid-point at this time, but the board cleared otherwise with all gauges operating within standard limits.

The Startup

At 8:47 a.m. on January 4, 1955, the reactor was started and was taken to an initial power level of between five and ten megawatts (MW). The

pile operated in this power level range until 3:25 p.m. on January 4, 1955. At that time the pile was shut down to install shielding which had been left out of the No. RT3A test hole facility on the X-1 level.

At some point during the 8 to 4 shift on January 4, it was observed that the power level recorder was giving false readings. No explanation was found at the time for the readings. (It was found subsequently that a loose thermocouple connection was responsible, in part at least, for the erroneous readings. This was not determined until several days after the incident.)

At about 7:00 p.m. on January 4, the pile was shut down and several of the neutron monitoring chambers were repositioned. At 7:35 p.m. the power level was raised to about 125 MW.*

At 8:03 p.m. the pile was again shut down to reposition the No. 3 Beckman chamber and the octant monitoring chambers. At 10:32 p.m. the reactor was again returned to power and the power level was raised to about 220 MW, this increase being achieved by 10:50 p.m. For about the next three hours, the operation was uneventful and apparently normal.

Pre-startup plans called for the power level to be raised 100 MW each operating shift, with a 48 hour run at 1000 MW before going higher than this level. At the start of the 12 to 8 shift on January 5, preparations were made to increase power level by another 100 MW. Since this was the first time that this shift had handled the pile at any appreciable power level, the operating supervisor in charge decided to take the 100 MW increase in steps of about 20 MW so that the chief operator and the pile operators could get a feel for the characteristics of the control facilities and the instrumentation. Accordingly at 1:30 a.m. on January 5 the power was increased to a level which in retrospect turned out to be 260 MW.

At 1:45 a.m., 15 minutes after this increase in level, there was a sudden loss of reactivity in the pile and the power level dropped sharply to approximately the level at which it had been prior to the increase. The horizontal control rods were adjusted in an effort to compensate for the reactivity loss and to re-establish the target power level. These rod adjustments were accompanied by power level cycling with short term increases substantially above the target power level.

* The power levels quoted are those which it has been determined subsequent to the incident were the actual levels at which the pile was operating at the times indicated. Due to the malfunctioning of the power recorder, the actual power levels recorded on the power recorder chart and in operating supervisor's log and the console log were about one-half the correct values. The true power level values were calculated after a detailed analysis of the available bulk water flow and temperature data.

At 1:57 a.m., with the power level at about 350 MW, the annunciator panel alarm signalled the presence of liquid water in the circulating gas duct system (See Fig. 9). The annunciator panel at KW pile gives both a visual and an auditory signal as a result of an abnormal condition in any of the circuits connected to the panel. A light flashes on for that circuit which is showing the abnormality, and at the same time a loud horn sounds. The circuit in question is connected to conductivity cells in small collection sumps in the circulating gas duct system at the base of the pile.

The supervisor in charge immediately checked the dew cell recorders which indicate the presence or absence of water vapor in the gas plenum chambers. The dew cell recorders confirmed the presence of water in the circulating gas system. These water indications, along with the reactivity loss, were immediately interpreted by the supervisor as indicative of a process tube water leak. He ordered that a high speed traverse of the process tube water temperatures be initiated using the automatic Flexowriter facility. This is established practice and frequently makes it possible to locate a leaking tube prior to shut down. In the event of a leaking process tube, there is usually a cool area to be seen in the general pattern of tube outlet temperatures which makes it possible to isolate the area in which search for a leaking tube need be made.*

At 2:04 a.m., before the temperature traverse could be completed, the reactor was scrammed as a result of the vertical safety rods being tripped by the No. 1 safety circuit. The scram was shown by the Panel-lit board signal lights to have been caused by a Panellit trip on reactor tube row 46. Inspection of all 58 gauges on this row within a minute after shut down showed none with abnormal readings. Almost simultaneously with the rod drop, there were several apparent indications of a ruptured slug somewhere in the pile. In retrospect, there is some question as to whether the apparent slug rupture indications were actually due to fission product activity or to power level fluctuation as a result of the power level cycling which was going on at the time. All of the instruments concerned are quite sensitive in their response to power level changes, as well as to fission product activity.

In view of the indications of a process tube leak, the process water flow and pressure were lowered immediately. Entry was made to the rear face, and a radiation survey was made of row 46. The survey revealed an intensity of 1.5 R per hour in the outlet piping of tube 4669. This was taken to confirm the presence of a ruptured slug in this particular tube. Tube 4669 was immediately isolated from the water flow. Hydrostatic pressure testing of the tube revealed that it had failed.

* The thermohm of tube 4669 did not and could not read any higher than the ambient temperature of the number 46 rear cross-header, as the pigtail blank completely isolated it from the overheated tube.

Initial Removal Efforts

In view of the unusual conditions surrounding the apparent rupture--the low specific power, the extremely low exposure of the metal, and the unusually rapid rate of water in-flow to the pile--the operating supervisor carefully checked all process standards relative to ruptured slugs, and then called the KW Operations Superintendent for advice before proceeding with removal operations.

At 2:45 a.m. on January 5 steps were initiated for removal of the rupture. When the rear nozzle cap was removed from tube 4669, there was no flow of water from the tube. A beta reading of about 17 R per hour was obtained.

Initial efforts to push the charge were made with the charging machine at pressures of 1200 pounds. The column would not move. Since the possibility of a rupture during this early stage of operations was completely unforeseen, no particular effort had been made to have complete removal equipment available in the area prior to startup. As a consequence, initial efforts to remove the charge were hampered somewhat by a shortage of equipment. Removal equipment was finally obtained and installed on the front elevator.

On the 8 to 4 shift on January 5, an effort was made to push the charge at forces up to 9,000 pounds. The charge would not move. The front and rear nozzles were then removed and the front Van Stone flange was cut. After these steps, the tube was subjected to pushing forces of 6,000 pounds. At these forces, the tube moved 1-1/2 inches.

During the next two days all conventional slug removal techniques were applied in an effort to remove the tube and metal column from the pile. Pushing forces up to 19,000 pounds were used with limited results, as were substantial pulling forces. During these efforts, the tube broke. Several short sections of tube were removed, both from the front face and the rear face. Pulling devices were used to effect this removal. A number of slugs were removed by splining them from the tube.

On the 12 to 8 shift on January 7, a borescope was used in the front portion of channel 4669, and it was observed that the aluminum jacket on the front slug remaining in the column had melted. This was the first observed indication of the severity of the damage which had occurred in the channel.

On January 7 a check of the Panellit gauge for tube 4669 revealed that it was set for a very high pressure. The gauge was removed from the panel, checked on the test stand. While found to be mechanically and electrically in order, it developed that the gauge was actually set to read mid-point on the dial at a pressure of 238 psig, and that the low trip was set for 216 psig and the high trip for 266 psig. A check of

available data turned up the IBM data sheet prepared on the 4 to 12 shift on January 3, which confirmed that gauge 4669 had been set at that time to read mid-point at a pressure of 238 psig, and that seven other gauges had been set to read mid-point at pressures of approximately 200 psig.

During the period from January 7 until the 8 to 4 shift on January 10, efforts to remove the metal column and the tube by conventional pushing and pulling methods were continued. Forces up to 35,000 pounds were applied. On the 8 to 4 shift on January 10, use of a peripheral cutter was started. This cutter, known as the "cookie cutter" was a peripheral saw which cut away the tube surrounding the slugs. The cutter was used for two days and enabled removal of three slugs.

Although precautions had been taken to minimize the possibility of a fire due to ignition of any uranium chips which might result from the "cookie cutting" operation, concern over this finally resulted in discontinuance of the cutting operation on January 11. Up to this time 28 slugs and 40 feet of the tube had been removed.

Channel Removal and Restoration

When the first phase of the slug and tube removal program was discontinued on January 11, some 80 inches of the original 340-inch tube charge still remained in the central portion of channel 4669. The exact condition of this section could only be guessed at. The progressive nature of slug melting and alteration from the fringe region toward the center, as observed in "hot cell" examination of removed slugs and tube sections, suggested a badly swollen, conglomerate mass that could be freed from its surrounding graphite stringer only by a cutting or circumferential sawing operation.

Figures 10, 11, 12, and 13 illustrate this progressive damage. Figure 10 is a photograph of the ninth slug from the front and shows the early stages of the damage. The enlargement at the ends is the result of "upsetting" the aluminum end-caps through the pushing forces applied during the first phase removal efforts. Figure 11 illustrates an advanced stage of swelling and general damage in the eleventh slug from the front. The rib impressions are clearly visible in the outer surface. The piece is actually hollow, as shown in Figure 12 which is an end view of a section taken from the piece. The exit point for molten metal which escaped from the piece and tube (also pierced at this point) is clearly visible between the rib impressions; this exit point also corresponds to a weep hole, provided in each graphite block to permit water drainage in the event of a process tube leak. Figure 13 illustrates the general damage at the surface and changed character of the twelfth slug from the front. Small chips and loose material fell off during handling.

In addition to the possibility of a core-cutting operation along the bore of the graphite stringer, there was the alternative approach of

cutting through the rear face and shield of the pile and withdrawing the entire graphite stringer and its remaining contents. Mock-up tests and feasibility studies on these two possible methods were initiated as a first step in the Engineering Department program of removal and restoration, together with an extensive program of further borescopic examination to permit more complete characterization of the situation which existed in and around channel 4669.

The borescopic examination program included detailed study of channel 4669 itself, of the seven vertical safety rod (VSR) slots adjacent to this channel, and of the four adjacent process tube channels. These inspections showed that the graphite of channel 4669 had suffered considerable damage, including openings broken through into two of the VSR slots; gaps, cracks, and chips were visible throughout much of the front section. The channel had been displaced about 3 inches to the rear and there was evidence of slight lateral displacement of the adjacent filler block rows. However, gross damage and shifting were localized to stringer 4669, indicating that removal and replacement of this channel would restore the pile to good condition.*

The mock-up tests and studies carried out January 12 and 13 likewise favored the approach of removing and replacing channel 4669. Diamond drilling tests on samples of the heavy aggregate concrete used in the shield showed that this could be drilled at a reasonable rate. The core-cutting operation, on the other hand, proved to be quite difficult and time-consuming and presented an element of fire hazard within the reactor during any cutting of the pyrophoric uranium metal. These considerations, together with the advantage to be gained by restoring the VSR slots to good condition **, led to the decision on January 14 to proceed with cutting a hole in the rear shield and removal of the entire graphite stringer.

* The graphite in the tube channels consists of trunnion blocks on four foot centers, with tube blocks about 46 inches long between the trunnions. There are eight such tube blocks; the blocks on the extreme front and rear are keyed to the adjacent graphite. The bore of the tube blocks is somewhat greater than the outside diameter of the process tube, while the trunnion block bore is only slightly greater. The general arrangement is shown in Figures 22 and 23, which present an artist's conception of the condition of channel 4669 graphite, as established by borescopic examination. This sketch was used in planning and executing the subsequent removal operations. The original graphite stacking details for the region of channel 4669 are shown in an isometric drawing, Figure 24.

** See Figure 25 for an artist's visualization of the opening into VSR #37 slot from the tube block, and the metal intrusion into this vertical channel. The front end of the unremoved charge corresponded approximately to this opening.

Work preparatory to drilling started at once. It was necessary to disconnect a number of temperature sensing element leads from the rear of the tubes around the channel. The two cross headers above and below 4669 were cut, and after removing the valves at either end of these headers and the pigtail connections from them to the process tubes, the halves of these headers were spread apart. Nozzles were removed from some adjacent tubes. These steps provided access to the face of the rear shield, and when completed on January 16, a core-drilling machine was set up with a 6-inch diamond-tipped drill. The drilling operation required is well illustrated in Figures 14, 4, and 15, which show in some detail a typical tube assembly from the rear face nozzle to the die block which is located inside and flush with the graphite stack. As shown, the drill bit encountered successively a 1-inch skin plate, 43 inches of heavy aggregate concrete, a second 1-inch skin plate, a nominal 6-inch gas plenum chamber, and finally two 5-inch cast iron, thermal shield sections.

The first drilling machine, obtained from the Bureau of Reclamation at Grand Coulee, proved inadequate and a second, more powerful machine was purchased in Spokane and set up on January 18. Drilling progressed steadily with this rig and the hole through the remaining 34 inches of biological shield and the 10-inch cast iron thermal shield was completed on January 20. The drilling operation is pictured in Figure 16, which also shows the working area which was available on the rear face of the reactor near channel 4669.

Removal of the graphite stringer and remaining metal began on January 21. By the next morning all graphite had been removed downstream of the section containing the metal. All components withdrawn were identified as to orientation and order of removal, in order to facilitate later examination and study. Figure 17 shows a graphite block coming out of the pile; this block is typical of the downstream blocks which were in generally good condition, except where small pieces had been chipped out. Figure 18 gives a view looking directly into the channel, and in addition to showing the end of a graphite block (undersized with respect to the space between filler rows), gives an idea of the degree of access provided and the problems associated with manipulation of tools at distances of up to 20-30 feet.

The tube blocks containing the remaining charge were withdrawn in one section without unusual incident on January 22. As will be seen in Figure 19, the two graphite tube blocks and connecting trunnion block were intact except for the upstream end, which was broken. A piece of metal, corresponding to the sixteenth slug from the front of the original charge, protruded from this end. It is interesting to note the small globules of silvery metal deposited on the top surface of this section; these appear to be aluminum droplets which condensed from the vapor state.

Removal of the remaining graphite, which consisted generally of short, broken pieces, was completed January 25, and the final cleanup and inspection work done by January 28. The tube entry block (first upstream block) was left in place, even though cracked, to preserve the front face keying which it affords. Removal operations during this final 5-day period were complicated by the fragmented nature of much of the graphite channel upstream of the metal-containing section; and by the presence of extremely radioactive metallic material outside the tube block pieces themselves. In addition to many smaller pieces, there were two slabs of such material (one of them pictured in Figure 20) recovered from the region where the 80-inch section of unremoved charge had been located. These were each about 12 inches long and of such width and thickness as to suggest that they had been cast between the tube blocks in 4669 and the adjacent filler blocks.* The metal has been found to consist in part of uranium-aluminum alloys, and is very highly pyrophoric. One of the large pieces caught fire and was entirely consumed as a result of sparking which occurred when it was transferred to a Radiometallurgy Building "hot cell" and allowed to touch down on a metal pan. The other piece also sparked rather heavily during removal manipulations at the rear face of the pile.

The presence of melted metal outside the process tube channel raised a serious question as to the amount of metal which might have become distributed through adjoining sections of the pile. Radiation monitoring instruments therefore were used in traverses of the four adjacent process channels and the seven associated VBR channels. These traverses, as well as the final checkout on 4669 itself, showed no detectable amounts of uranium present. An approximate material balance on all slug material removed from 4669 was similarly reassuring, indicating that no more than 12 pounds, and perhaps no more than 6 pounds, of uranium were unaccounted for. This amount of uranium has found its way into the older piles, through slug and tube ruptures, without unduly complicating their operation. The cleanout of channel 4669 accordingly was regarded as complete at this point, with restoration the next step to be accomplished.

A thorough examination of the reactor was made during the final cleanout and monitoring operations above. This verified the earlier conclusion that movement of graphite stringers adjacent to channel 4669 had been quite minor. A rearward movement of 1/2 inch at most was found, while the filler blocks next to the upstream end of the 80-inch section had

* The tube blocks are 3.63 inches square. The square hole in which they fit is 3.75 inches square. Thus, side gaps of 1/16-inch and a top gap of 1/8-inch exist between the tube blocks and filler blocks. It is likely that this uranium-bearing material was forced out through tube block weep-holes in molten form and chill-cast against the graphite. Each tube block contains one weep-hole, as mentioned earlier.

been pushed about 1/4 inch to either side of the channel. No vertical displacement was found, and no other damage of consequence was detected. The restoration work within the graphite stack thus required only the installation of a replacement process tube stringer, with graphite shims placed in the approximately two foot long section where the channel had been widened. This stringer had been designed and fabricated while removal operations were in progress, and shims were made up as soon as the channel widening was noted. Installation was accomplished without great difficulty; the shims were effective in holding the stringer against the vertical channel for VSR #37, which was located within the span of the widened section.

Following installation of the replacement stringer (done with the new process tube in place), the rear thermal shield was pushed back against the graphite in the region of 4669, was then plugged with a mild steel assembly, and a slightly modified rear sleeve installed in the biological shield. Heavy aggregate mortar was tamped into place in the annulus around this sleeve, and special end plates on the sleeve were then welded to the outer skin of the rear face. This repair of the rear shield was followed by the repair or repositioning of piping components which had been cut into or moved to make space for the drilling, and by the reassembly of vertical safety rod equipment for the seven channels which had been cleared for inspection and monitoring use. With the reconnection of instrument leads in the affected area, restoration of the pile was complete on January 31. A program of component checking and testing was carried out by the Engineering Department, and the pile was turned over to the Manufacturing Department on February 5 for further functional and operational tests prior to being placed in production service once more.

There is every indication that KW reactor is being returned to service with no impairment of function. It should be noted in passing, however, that the necessity for complete removal and replacement of graphite stringer 4669 made relatively unimportant a situation which might have become, under other circumstances, a relatively serious matter. This statement refers to the extensive damage done to channel 4669 by the pushing forces applied in the early unsuccessful attempts to dislodge the stuck tube and slug charge by conventional means. Forces as high as those employed at KW (up to 35,000 pounds) have been used without apparent damage at the older piles. The K piles differ from the older ones in graphite stack design, however, and the experience gained in this first encounter with a stuck charge at K indicates that the matter of permissible pushing forces in these new units should be made the subject of both design study and experimental investigation.

Causes of the Incident

Based on the physical evidence and the testimony of the individuals primarily involved, it can be concluded unequivocally that the incident was the result of the reactor having been started and operated without

flow of cooling water in process tube 4669. It is definite, also, that the Panellit gauge of this tube, which alone could have signalled the lack of water flow, had been set before startup in such a way as to nullify the significance of its reading. Three closely related causes have been established.

1. Failure to Remove Rear Pigtail Blank from Tube 4669.

While there is no positive proof of the fact, it seems almost certain that the lack of water flow through the tube was caused by the inadvertent failure to remove from the rear pigtail of this tube the neoprene blank which had been inserted therein during the pre-startup program. Several of the individuals concerned with the pre-startup program indicated that absolute control over the pigtail blanks was not thought to be required inasmuch as the Panellit board would pick up any blanks which were inadvertently left in pigtails. As was pointed out in the chronology of the pre-startup program, seven blanks were discovered through the medium of high pressure readings on the Panellit board, on January 1. Control over the blanking program for all practical purposes ceased to exist early in the pre-startup operations.

2. Failure to Identify Abnormal Condition of 4669 on January 1 Panellit Check.

An opportunity to locate and remove the blank in the pigtail of tube 4669 was presented on January 1 when the initial clearing operation on the Panellit board was conducted. As previously noted, seven blanked tubes were found during this clearing operation and the blanks were removed. There is ample evidence to indicate that the Panellit gauge of tube 4669 was reading off-scale at the time of this clearing operation, indicating that the tube flow was obstructed. This statement is based upon observations of the Panellit board by Pile Technology personnel at the time. For some reason, which it has not been possible to ascertain, Manufacturing Department personnel conducting the clearing operation failed to identify the abnormal condition in tube 4669.

3. Improper Setting of Panellit Gauge 4669 on January 3.

A final opportunity to locate the blank in the pigtail of tube 4669 was presented on January 3, just prior to startup of the pile. At that time a check of the Panellit board showed that the gauge of tube 4669 was reading off-scale. A Heise gauge check showed the pressure on this tube to be 238 psig (the same as the inlet riser pressure) and thus indicating conclusively that there was no flow in the tube. Despite this indication, the gauge dial was reset to read mid-scale at the abnormal pressure. This mis-setting of the gauge made it possible to clear the Panellit board. The final check

of the Panellit board on the succeeding shift, immediately prior to startup on January 4, indicated a normal operating condition for tube 4669.

The mis-setting of the Panellit gauge for tube 4669 was the only deviation from process standards and specifications which had any bearing on the KW incident. A review of the pertinent process standards and specifications has revealed compliance in all except the following three instances:

1. The low-pressure cross-tie system between KW and KE water plants was by-passed during the operation of the KW reactor at low power level (5-10 MW). This was authorized by the Manager, Manufacturing Department, who restricted the power level to 10 MW under this condition. The KE water plant was turned over to General Electric operating forces at 5:22 p.m. January 4, 1955. The proper valving of the cross-tie to KW was made before the power level of the latter was raised above 10 MW.
2. The sensitivity of the No. 1 galvanometer was outside of standards. Functional checks of the galvanometer later revealed a metal filing lodged between the moving coil and the magnet. The sensitivity calibration of this galvanometer cannot be made unless the reactor is in operation, and some degree of deviation from standards is unavoidable until optimum chamber location is determined.
3. The process tube temperature monitoring trip had been by-passed by authorization of the Engineering Department until the integrity of this system, being used for the first time on the K reactors, could be established.

Assignment of Responsibility

The Committee considered carefully each of the three causes described above in its efforts to establish responsibility for the incident. Much of the interrogation of the people directly involved was aimed at uncovering the exact nature of each man's assigned responsibility and the extent to which any of his acts of omission or commission may have contributed to any one of these sequential events which led to the incident. The findings and conclusions of the Committee are presented below for each of the causes involved:

1. Failure to Remove Rear Pigtail Blank from Tube 4669

A thorough inquiry into the circumstances surrounding the blanking and blank removal operations at KW has established the normal working relationships that were involved in these operations, and the methods that were considered sufficient at the time to guard against oversight in removing rear face blanks before the start of normal operations. The work records are not adequate to identify the

individual or individuals who worked on 4669, and it is not possible to establish with any certainty an individual responsibility for this oversight.

Any work on the front or rear face pigtails of the piles is classed as maintenance work, and is performed by nonexempt Maintenance craftsmen assigned to work under the general direction of Operations personnel. There is little question then but that one or more Maintenance workers failed to carry out the scheduled operation of uncoupling the rear pigtail on tube 4669, and of removing the neoprene disk, at the time this tube was charged with metal. In some unexplained manner an identifying strip of tape, which had been placed on all such pigtails to signify the presence of a pigtail blank, also was removed without the corresponding deblanking operation which its removal was intended to signify. Records maintained at the front face elevator and the Control Room console, and posted on the basis of inter-com messages received from the rear face, also showed the erroneous entry that the rear pigtail blank of tube 4669 had been removed.

The inability to identify the actual workmen involved seems relatively inconsequential, since it is the Committee's conclusion that, in any case, the primary fault lay in the lack of an adequate deblanking control procedure rather than with the individual operator or craftsman directly involved. While arrangements had been made for the identification of each pigtail containing a neoprene disk (striped tape attached), and while entries were made on the front face charging sheet to signify removal of both front and rear face pigtail blanks, it is obvious that neither of these provided positive control for the deblanking operation, as evidenced by the fact that at least nine blanks were located by other means subsequent to the completion of the deblanking operations. It is this fact, together with an apparent acceptance of three errors per thousand operations as not unusual under the circumstances, that has led the Committee to recommend a piece-count type of accountability for all materials which are introduced temporarily into process tubes and which are intended to--or conceivably might--significantly obstruct process tube water flow.

2. Failure to Identify Abnormal Condition of 4669 on January 1 Panel-lit Check.

As in the case above, the Committee has been unable to identify the specific individuals who failed to note the high reading of Panellit gauge 4669 at the time the board was being checked out initially under conditions of full water flow. Testimony was obtained from several individuals to the effect that all gauges which read off-scale at this time were listed on work sheets, and that these work sheets were used in turn to compile tabulations

of those gauges which were out of standard in any respect. The Committee was never able to locate the work sheet which should have shown 4669 as reading "high trip", and since the retabulation of off-standard gauges does not contain any entry regarding 4669, there is no way of establishing whether the error occurred in failing to note the condition of the gauge itself or in transcribing data from the work sheet to the final data sheets.

Evidence was found that the high reading of 4669 had been observed, among others, by a member of the Pile Technology Section who was present in the Control Room and interested in locating blanked tubes which might have had an influence on the pile reactivity traverses in which he had been engaged. In questioning this man, it developed that no effort had been made to communicate his observation to the operating crew, on the basis that he felt that he was merely making certain observations that already were receiving the full attention of the operating personnel.

The Committee also questioned a number of the people concerned with the Panellit board "clearing" operation on the night of January 1 in an effort to establish clearly the responsibility for conducting this critical operation. There seems to be little question but that the KW Operations Superintendent expected this "clearing" to provide the final check against any overlooked pigtail blanks remaining in the reactor cooling system. It developed from these questions that the allocation of responsibility between Operations and Process Sub-Section personnel involved in the work had not been established unequivocally. This situation, together with what it considered to be inadequacies in both written procedures for such an important operation and in the recording of associated data, led the Committee to make its recommendations with respect to these points.

3. Improper Setting of Panellit Gauge 4669 on January 3.

The Committee has questioned at length those persons who occupied positions of responsibility in connection with the all-important Panellit gauge episode the night of January 3, when 4669 was readjusted to give a completely erroneous dial setting some ten hours before official startup of the pile. Further questioning might well have made it possible to identify the instrument technicians and pile operator(s) who were directly involved in resetting the gauge, but it has not been considered that these men shared in this error to any significant degree and no effort was made to identify them specifically. In this case the responsibility for mis-setting the gauge must be placed clearly on the Operations Supervisor I in charge, R. W. Hooper, who received for review and approval the data sheet which showed the high pressure reading to which the Panellit gauge had been adjusted, and which established beyond question the fact that this tube had no flow of process water. Mr. Hooper has accepted this responsibility without question. It is significant

to note that this supervisor also approved the improper setting of several other Panellit gauges during the final hour of this shift. These settings were definitely outside the limit imposed by process standards, although no serious consequences resulted from this error during the brief period that the pile was in operation.

The very great significance of the error on Panellit gauge 4669 follows, of course, from the fact that once the gauge was set to read mid-scale at full cross-header pressure there was no warning to subsequent shifts of the abnormal situation, and such a setting made it virtually certain that the no-flow condition in 4669 would remain undetected until serious damage had resulted.

Factors Contributing to the Incident

As is reflected in the foregoing discussion of causes and of responsibilities, the Committee found a number of factors which it considers to have contributed significantly to this incident.

Manpower Shortage

It is believed that too heavy a workload was carried by the Operations Supervisors who were directly in charge of the shifts in the KW reactor building throughout the pre-startup program. Each of these supervisors had only one shift supervisor to assist him with the myriad of details for which he was responsible. This one supervisory assistant had to be assigned rather exclusively to the front elevator work, which meant that the supervisor in charge was required personally to handle all of the rest of the work being conducted at many locations within the large and complex building. Also contributing to his heavy loading was the fact that considerable numbers of additional nonexempt personnel (both operators and craftsmen) were required on most shifts, and these people had to be drawn from all other reactor areas and assigned on an over-time basis. Being unfamiliar with the 105-KW Building, these people required particularly close surveillance.

Another manpower shortage was in the area of supporting specialist personnel, as illustrated by the fact that only one instrument engineer was assigned full time to assist the instrument maintenance people, during the critical pre-startup checkout of control instrumentation. The Committee was told that as many as five such assigned instrument engineers were employed to advantage in this work during the C reactor startup. Such supporting specialists are regarded as very important for assistance both to Operations and Maintenance supervision in evaluating and interpreting equipment performance.

The foregoing manpower situation, particularly as it pertained to the load carried by the Operations Supervisors in charge of shifts, was very evident in the testimony taken from R. W. Hooper, the Operations Supervisor I on the 4 to 12 shift, January 3, when the Panellit gauge

of tube 4669 was mis-set. With his single shift supervisor fully engaged with work in progress on the front face elevator of the pile, Hooper personally had to direct all of the rest of the work, including the following:

1. Preparation for, and liaison with the Power Sub-section relative to the simulated power failure and emergency trip-out of the process water pumps in Building 190. This work was being performed as an uncompleted phase of Acceptance Test Procedure #1451.
2. In connection with 1, the conduct of a time check on the three process water trip relays which intertie with the ball 3-X system; contrary to expectation, these relays were not centralized in a single electrical equipment room, and it was necessary for Hooper to help the electricians check the circuit drawings and discover that these relays were instead installed at three widely separated locations.
3. Completion of the replacement of ball valve assemblies on the front of poison column control tubes. This work had been left for his shift, due partly to the unavailability of replacement parts, and it fell to him to obtain the remaining parts by working through the Engineering Department and Kaiser Engineers.
4. Adjustment of the pile gas system oil seals to standard. The required settings were not readily available, and it was necessary for him to refer to the appropriate Acceptance Test Procedure. This information had to be located and then studied.

Hooper himself summed up all this varied activity by saying that it was "one mad whirl, especially the last part of the shift", which was when the process pump trip tests and the Panellit board checking were conducted (10:30 to 11:30 p.m.).

Inadequate Procedure Definition and Data Recordings.

It became apparent early in the investigation that there had been inadequate written definition of the several critical manipulations to be performed, and that the recording of vital data had in many cases been incomplete or handled in too informal a fashion. For example, a very general procedure for deblanking the pigtailed had been set forth in the Operations Startup Guide, but this had not been made to include specific instructions with regard to just who was to perform which step in the operation, nor had any really effective system for assuring complete deblanking been established. These deficiencies in system are considered to underlie the loss of control over blank removal which was suffered rather early in the pre-startup program.

Similarly, there were no specific written procedures which required complete data recording or multiple checking for the critical Panellit

board checkout. The readings of all 3,220 gauges were not required to be recorded and this seems clearly to have been an important factor in overlooking the high-trip condition of Panellit 4669 on the occasion of the January 1 Panellit board checkout. The informality with which Panellit data records were handled may be illustrated by two examples: (1) The original data sheets of January 1, on which were said to have been listed the tube numbers and Heise gauge readings for each of the 49 Panellits which were showing high or low trip when the reactor water pressure was first raised, have never been located, despite the thorough search which was made at the request of the Committee; and (2) The Panellit data sheet of January 3, on which operators had tabulated the gauges which had been reset (including 4669), was found on a clip-board in the Control Room office on January 7, without benefit of review in the interim.

There was evidence also of a lack of definition in the area of functional responsibility between Operations and Process personnel in connection with the Panellit system. This situation was also a factor during the Panellit board checkout on January 1, at which time the Operations Supervisor I in charge of the building (M. E. Jackson) considered the Panellit work to be under the rather independent supervision of the Process Engineer (K. W. Hess). The latter, on the other hand, considered that he had only a trouble-shooting function in support of the Operations supervisor. It is noteworthy also that this engineer was the man who had determined that a 140 psig Panellit gauge pressure was to be expected with the full operating cold flow of 120,000 gpm. He therefore was naturally interested primarily in this aspect of the Panellit board clearing operation. In any case, it seems clear that no one responsible for the conduct of this clearing operation was looking primarily for the presence of pigtail blanks, even though supervision generally had recognized that some blanks were virtually certain to have been left in, and that the Panellit system afforded the only means for their detection.

Tensions in Adherence to Startup Schedule

The pre-startup program as originally planned included a carefully allocated 22-day schedule for the work to be done from the time of acceptance of the new facility from Construction to the day of startup. With take-over on December 6, this schedule would have had the reactor ready to start on December 28. Actually the pre-startup work took 7 days longer than planned, due to a variety of unforeseen delaying factors which occurred during the very complex and elaborate program. It was evident to the Committee that a feeling of urgency, and of need for recovering the lost time, developed in the minds of the building supervision involved. This feeling, coupled with the manpower shortage, very probably resulted in certain inattention to detail and lack of deliberation as the work was pushed forward.

Miscellaneous Other Factors

In addition to the principal contributing factors already described, the investigation brought out a number of other smaller but possibly significant points. Examples of these are:

1. The intercom system between the front and rear elevators was not affording really clear communication. This may have led to confusion of tube numbers in the course of the pile loading and de-blanking operations.
2. There were indications that the operating personnel had not become as familiar with the unusual features of the new KW facility as might have been desirable. One reason for this appeared to be the fact that, for the first time at Hanford, the initial facility testing operations (conducted under ATP's, "Acceptance Test Procedures") had not included participation by the Manufacturing Department.
3. As has been noted, the K reactors are unique in that they have an inlet riser pressure at full cold flow of only 240 psig with a venturi pressure of only 140 psig, whereas the older reactors operate with riser pressures of 365 to 420 psig and Panellit pressures in the range of 210 to 270 psig. The 238 psig reading on tube 4669, which was disregarded during the Panellit board checkout on January 3, would have been within the range of normal expectancy at the other reactors.

Factors like the foregoing are rather intangible. However, they make even more necessary the use of carefully planned specific procedures and multiple checking for every critical operation.

ACKNOWLEDGEMENTS

The Committee enjoyed the complete cooperation of Reactor Section personnel throughout the investigation, and their assistance was invaluable in getting familiar with the KW reactor facilities and in developing the facts as to what had taken place. In this category, special thanks are due Preston P. Eddy (Operations Analyst, KW Operations Unit, Reactor Section, Manufacturing Department) who was specifically assigned to help the Committee in these ways.

Special acknowledgement is due also to Richard L. Plum (Operations Division, Hanford Operations Office, UHABC) for his excellent work in recording and transcribing the testimony which was taken.

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APPENDIX

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FIGURE 1
KW REACTOR - VIEW OF FRONT FACE

~~SECRET~~

FIGURE 2
PANELLIT BOARD (FRONT VIEW)

FIGURE 3
TEMPERATURE MONITOR EQUIPMENT
ROOM

FIGURE 4
DETAIL OF REAR FACE PIPING

FIGURE 5

**KW REAR PIGTAIL, SHOWING BLANK
AND STRIPING**

FIGURE 6
HEISE GAUGE

FIGURE 7
PANELLIT GAUGE

FIGURE 8
PANELLIT BOARD (REAR VIEW)

FIGURE 9
ANNUNCIATOR PANEL

HW-34834

FIGURE 10
9TH SLUG FROM FRONT

FIGURE 11
11TH SLUG FROM FRONT

FIGURE 12
CROSS SECTION OF 11TH SLUG FROM FRONT

FIGURE 13
12TH SLUG FROM FRONT

FIGURE 14
GENERAL LAY OUT OF REAR SHIELDING AND PIPING

HW-34834

FIGURE 15
DETAIL OF REAR THERMAL SHIELDING

FIGURE 48
CORE DRILLING THROUGH REAR SHIELD

H W 34834

FIGURE 17
REMOVING GRAPHITE - CHANNEL 4" (9)

FIGURE 18
REMOVAL OPERATIONS - CHANNEL 4669

H W 34834

FIG. TR#19 • M

80" CHANNEL AND CHARGE SECTION

H W 34834

FIGURE 20

SLAB OF URANIUM ALLOY - CHANNEL 4669

H W 34834

UNCLASSIFIED

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HW-34834

FIGURE 21
DIAGRAM of KW REACTOR FACE SHOWING PIGTAIL BLANKING ZONES

UNCLASSIFIED

FIGURE NO. 22
DAMAGED GRAPHITE UPSTREAM
OF REMAINING CHARGE
(SKETCHED FROM VISUAL INSPECTION
OF INTERIOR OF CHANNEL)

UNCLASSIFIED

UNCLASSIFIED

HW-34334

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FIGURE NO. 23
DAMAGED GRAPHITE DOWNSTREAM
OF REMAINING CHARGE
(SKETCHED FROM VISUAL INSPECTION
OF INTERIOR OF CHANNEL)

UNCLASSIFIED

SKETCHED BY GRAPHICS UNIT
RGT 116-55
REVISED 2-8-65

UNCLASSIFIED

REPRODUCED IN
PART ONLY

[illegible]

UNCLASSIFIED

UNCLASSIFIED

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FRONT FACE

UNCLASSIFIED

FIGURE 25
UPSTREAM END OF REMAINING CHARGE AS VIEWED
FROM VERTICAL SAFETY ROD SLOT NO. 37