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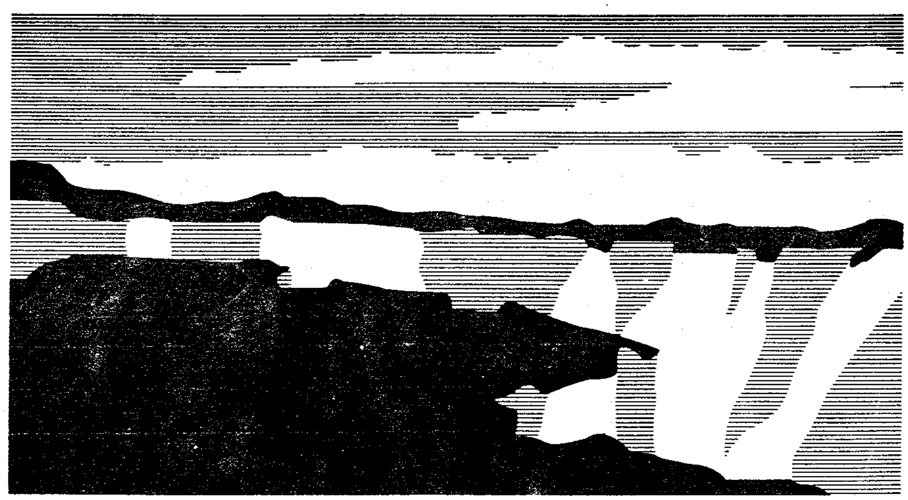

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LESSONS LEARNED
FROM EARLY CRITICALITY ACCIDENTS

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INTRODUCTION

Four accidents involving the approach to criticality occurred during the period July, 1945, through May, 1946. These have been described in the format of the *OPERATING EXPERIENCE WEEKLY SUMMARY* which is distributed by the Office of Nuclear and Facility Safety. Although the lessons learned have been incorporated in standards, codes, and formal procedures during the last fifty years, this is their first presentation in this format. It is particularly appropriate that they be presented in the forum of the Nuclear Criticality Technology SafetyProject Workshop closest to the fiftieth anniversary of the last of the four accidents, and that which was most instrumental in demonstrating the need to incorporate lessons learned.

EXCESSIVE RADIATION EXPOSURE AT PAJARITO LABORATORY

On May 21, 1946, seven scientists and a security guard at the Pajarito Laboratory of Project Y were exposed to excessive levels of radiation resulting from an excursion during an experiment. The accident occurred in Building 1 at Technical Area 18. Two scientists were directly involved in the measurement which was being conducted as a demonstration to illustrate the proper experimental procedure. Five others were involved in the same room with other duties, although they were proximate to the location of the experiment. The security guard was stationed outside of the room and was not a direct observer of the accident. Following the accident the senior researcher present directed the evacuation of the building, notified emergency services for transport to the medical center, recorded the position of those present (although that record has been lost), requested a routine evaluation of induced activity to evaluate dose distribution, and secured the experiment. This event is significant because it may result in a fatality, and it represents the failure to institute appropriate controls which were indicated in three previous accidents. As a result of this exposure, all eight individuals were treated at the medical center. Two are being held for additional observation and treatment, one of whom remains in critical condition with death considered likely.

Following the accident the, Deputy Director of the Laboratory suspended all hand assemblies until a suitable facility to conduct such experiments under remote control had been constructed. In addition, one of the uninvolved observers of the accident was directed to document his observations and recommendations for future actions (copy attached).

A review of incident reports revealed three similar accidents in the past. Two of these which occurred 10 months earlier were only remotely related. These involved dropping a cylinder of highly enriched uranium (HEU) down a piano wire guide through a cylindrical annulus of uranium hydride. The rapid approach to a super critical configuration resulted in a fission pulse which was terminated when the block dropped out of the annulus under the force of gravity. The experiments were referred to as "tickling the tail of the dragon." Observers located behind a wall of concrete blocks initiated the experiment by actuating the release mechanism with a lanyard. Partial disassembly of the annulus allowed the HEU cylinder to be safely returned to the cocked position by hand. Unfortunately, the act of unstacking and reassembly of the annulus, coupled with the uncertainty of the exact time of initiation with a weak source (relative to the speed of the cylinder through the annulus), resulted in the lack of reproducibility which subsequently resulted in two excessively large bursts (some observers reported that the cylindrical slug expanded sufficiently with fission heating to "stick" in the annulus). Total exposures of the participants were estimated to be less than 25 rep. These accidents are significant because they indicate an appreciation for the potential of excessive exposure and the incorporation of safety devices, albeit of a crude nature. Following the May 21, 1946, accident, it is concluded that management was negligent in failing to recognize the need for effective safety controls, requirements to ensure reproducibility, and the development and implementation of suitable procedures. The documentation of the two accidents was also found deficient.

The other accident reviewed occurred on August 21, 1945, and resulted in a fatality. Although two people were exposed, no independent objective observation was made because the accident was fatal to the researcher and the security guard was not a witness. This accident occurred when the researcher was verifying a critical configuration of a plutonium sphere (two hemispheres) reflected with a stack of tungsten carbide bricks. After the exposure occurred, the researcher carefully unstacked the array and returned the material to storage shelves. The trauma associated with the exposure makes reconstruction of the events leading to the accident impossible to determine with reliability, and the careful and complete dismantlement makes reconstruction impossible. In the aftermath of the May 21, 1946, accident, it was concluded that management was negligent again in failing to recognize the need for effective safety controls, requirements to ensure reproducibility, and the development and implementation of suitable procedures. It is noteworthy that one procedure was implemented which prohibited solo operation of experiments which could be hazardous.

Study of the circumstances leading up to the May 21, 1946, accident results in several observations and recommendations which must be addressed so that hazardous experiments can be conducted without undue risk to facilities and personnel. The chronology of events is presented in detail in the attachment and will only be referenced as required.

A potentially hazardous experiment was conducted on the spur of the moment without adequate planning or preparation.

Although similar experiments had been conducted safely in the past, familiarity apparently led to contempt for the hazards and disregard of all but the most rudimentary safety features.

The area in which the experiment was conducted was cluttered and non essential equipment and personnel hampered the operation (Fig. 1).

Although it is argued (see attachment) that the experiment was not done carelessly, the condition of the experimental area and presence of non participants indicate a cavalier disregard for all but the most rudimentary safety features.

The exact configuration of the experiment at the time of the accident cannot be duplicated with certainty.

Although the components remain essentially intact, the configuration attempted is extremely sensitive to extraneous reflection (e.g., the body and the hands) (Fig. 2) and the exact placement of the shims used to separate the beryllium hemishells (Fig. 3). It is essentially impossible to reconstruct the *exact* configuration of the components or subject them to experimental validation. Although the magnitude of the excursion can be inferred with considerable reliability (the plutonium did not melt and the thin clad remained intact), there are a multitude of configurations which could produce the observed result. The photographs (Figs. 2 and 3) can only provide an approximation of the configuration. The absence of detailed plans of the experiment and record of the results indicates a complete disregard for accepted experimental procedure. The complete lack of a record implies a cavalier attitude and complete disregard for the importance of the experiment and the potential for an accident.

Although there is evidence for increased sophistication in the experiments conducted, there is no evidence to indicate the codification and adoption of procedures.

It is agreed that rules themselves will not prevent accidents, the implementation of formality in the operation, and the recognition of the potential for deviation from expectations and analysis of the consequences, will limit the potential for damage to equipment and significantly reduce the potential for injury to personnel. Indeed, the very act of consideration of accident scenarios may preclude those accidents considered because an accident, by definition, is an event which is not planned.

In conclusion, it is observed that an accident alarm would have neither prevented the consequences of this event nor reduced the probability of occurrence.

Conclusions and Recommendations

Study of the events surrounding the May 21, 1946, accident, and the first-person account included as the attachment, leads to the following conclusions and recommendations. Implementation of these recommendations is a necessary but not necessarily sufficient condition for safe operation. Neither procedures, regulations, analyses, nor safety mechanisms can assure safety in experiments. By definition, accidents are events which have not been planned. Although procedures, regulations, analyses, and safety mechanisms can minimize the likelihood of accidents or mitigate the consequences, they cannot provide absolute assurance that they will not occur.

1. The most important components to improve safety are the experience and diligence of the operators.

All experiments shall be subject to an independent, objective, review by a person or persons with laboratory experience in operations similar to those planned. However, the final responsibility for safe operation resides with the operators themselves. Neither oversight organization nor management can be held responsible for safe operation of experiments conducted under their jurisdiction. Oversight organizations and management are responsible to assure that considerations of safety and consequences of accidents are included in the planning and execution of experiments.

2. All experiments shall include at least two independently operating safety mechanisms which render the system safe even if they fail.

This double contingency provides a safing mechanism even in the unlikely event of the failure of one component. These safing mechanisms should be energized in such a way that any failure reduces the system to a safe configuration. Systems which may be used to provide for safe disassembly may be actuated by gravity, pressurized cylinders, cocked springs, or similar energy storage devices.

3. All proposed experiments shall be analyzed for purpose and safety in execution, and the results of that analysis made a part of the plan of the experiment.

These "Experiment Plans" are a necessary, but not necessarily sufficient, requirement for the conduct of an experiment.

4. Reasonable guidelines shall be developed and adopted for operations by hand to effect the construction of experiments which will be conducted under remote control.

It must be recognized that the experiment must be constructed, so some hand assembly is inevitable. It is noted that these are recommended as guidelines rather than rigorous procedures because deviations must be allowed to meet unusual circumstances.

Considerable care must be exercised to avoid replacing good operating practice and common sense with a set of rules that become an end in itself.

5. Experiments shall not be replaced by analysis.

No analysis, however exact it may appear to be, can be of greater accuracy than the assumptions on which it is based. While analysis is an essential part of the planning of any experiment, and analysis of the data provides for interpolation and application of the results, the experiment itself is the Grand Inquisitor, judge, and jury.

6. Interlocks should be installed in experiments (where possible) to assure that a necessary sequence of steps is followed. Where interlocks are not possible, checklists may be employed.

Care must be taken that the interlocks and checklists themselves do not interfere with safe operation, particularly in disassembly. Interlocks and checklists cannot replace experience in safe operation. Physical checklists should not be employed during emergency conditions.

7. All operations must be conducted with the consensus of all defined operators. Where consensus cannot be reached, the operations shall be suspended until an independent review has been performed.

Consensus shall not be required during an emergency when operations shall be conducted under the direction of the senior operator present who shall be identified prior to the start of the operation. It is recommended that oversight organizations be excluded from the room where the operations occur, unless those designated to provide oversight have experience equal to or greater than the operators.

8. Distractions for the crew conducting experiments shall be minimized.

Distractions include, but are not limited to, alarms, non-essential conversations, telephones, and activities not related to the operation.

9. A complete record of the experiment shall be maintained.

This record shall include, but not be limited to, documentation of the purpose, description of the safety features, and the results.

10. All approaches to a potentially critical, or near critical, configuration shall be conducted in a stepwise fashion with the individual steps plotted and independently verified prior to taking the next step, unless the system has been well characterized.

This procedure will assure that the neutron population (multiplication) has come to an equilibrium, and that a single individual has not made an error of interpretation.

The following material was prepared as a first person account of the accident and it is included here as an attachment for the record.

28 May 1946

D. K. Froman

R. E. Schrieber

Report on May 21 Accident at Pajarito Laboratory

The following presents the material you requested last Friday.

Perlman and I had gone to Pajarito Tuesday after lunch to carry out the field checking of the initiators and active material for the Crossroads tests. We carried 5 initiators in the three special shipping cases. Slotin had arranged for the three 49 [2] cores to be brought down that morning.

We arrived about 1:30 P.M. and found the multiplication measurements on the composite core, started that morning, still in progress. Since the source being used in this test interfered with our field-checking measurements we waited for about one hour to start our work. (It turned out that one of the 25 [2] shells had been left out by accident during the morning measurements so part of the multiplication measurement had to be repeated.)

At about 2:30 PM, Perlman and I started the counts on initiator Au-18. Meanwhile, Graves came in. A half-scale shot was being fired by M-4 at the lower Pajarito Site. We suspended operations during the shot but finished our neutron and gamma counts about 3:15 PM. Meanwhile Graves and Slotin discussed the critical assembly work. In the course of the conversation, Graves asked Slotin to demonstrate a critical assembly since he (Graves) was planning to do some experiments during Slotin's absence and wanted some indoctrination. At first Slotin said that he didn't have the proper materials for one. Then he remembered that we had the 49 cores there so he said he would do one "in about two minutes" in a beryllium tamper after we (Schrieber and

Perlman) had finished our counts. I remarked that if he were going to do it in two minutes I was going to leave but would stick around if he took a half-hour for it. This was not intended seriously since we all had confidence in Slotin's ability and judgment.

We finished our counting at about 3:15 PM and I put on rubber gloves and started to take the initiator from its case to check the counting. The neutrons from the driving source to be used by Slotin during the assembly would not affect this check so Slotin started his experiment. I was working on the initiator so did not pay close attention to Slotin's operations since I assumed he had done this before and knew how far he could go safely. I did, however, glance around at intervals so the following is my observation and is not based on subsequent conversation. I cannot swear to all the details but state what I believe to be true.

The beryllium tamper was set up on a low steel table near the north end of the room. Slotin stood before the table facing south and Graves stood behind him to his right. Perlman was working with me at a bench along the east side of the room about 15 ft. away. Kline, Young, Cieslicki and Cleary (SPO Security Guard) were around the assembly table at various distances but I do not know their precise positions.

The table on which Slotin was working was fitted with various detectors, some operating counters and others driving Esterline-Angus recorders. I believe that these were tested before the assembly was started. Kline and Cieslicki were running these so could give definite information. A strong Pu-Be source was used as a driving source. I do not know where it was put during the assembly.

I had assumed that the approach to critical would be rather slow so continued to work on the initiator, thinking that when the multiplication got to an interesting point I would turn and watch. It could not have been more than two or three minutes after the start that I turned because of some noise or sudden movement. I saw a blue flash around the Be tamper and felt a heat wave simultaneously. At the same instant, Slotin flipped the outer top tamper shell off (The tamper was made of two concentric shells, 9" and 13" O.D., I believe). This stopped the reaction.

The blue flash was clearly visible in the room although it (the room) was well illuminated from he windows and possibly from the overhead lights. I believe that the flash appeared only around the hole in the upper tamper hemisphere and around the equatorial gap. Slotin's left hand, which was holding the top hemisphere, was definitely in the glowing region. The total duration of the flash could not have been more than a few tenths of a second. Slotin reacted very quickly in flipping the tamper piece off. The time was about 3:00 PM.

A few seconds after the accident, only Slotin, Graves, and myself were left in the room. Perlman had run up the corridor a few steps and was waiting, the other four had gone out the east door or up the corridor. The rest of us left immediately, going up the corridor.

Slotin called for an ambulance and then prepared a sketch showing our positions art the time of the accident.

Slotin had picked up a Watts ionization chamber meter which must have been near the assembly. We attempted to measure the radiation from the various articles with this but it was so active itself (about 15 div. on the 10^{10} scale) that nothing conclusive could be found out.

After about 5 minutes, at Slotin's suggestion, I took a handful of film badges and put them on the tamper. I carried the Watts meter. The room was quite hot, the meter going over full-scale near the assembly, so I did not linger.

After about 12 or 15 minutes, I went down again. The meter had meanwhile cooled down to about 5 divisions on the 10^{10} scale so was fairly usable. The reading about 10 ft. from the assembly was about 20 divisions on the 10^{10} scale but again off-scale nearer. I tried the G-M counter in its Columbia shield which was under the bench near the east door. It had been left turned on but with the "Counts" off during the accident. It was working and clicked at about 4 or 5 scales per second. The Super-Zoute on this same bench had been left on and was jammed at full-scale. I did not explore further because the room was too "warm" to stay long safely. I took Slotin's and my jackets back up the corridor as I left. I do not believe that I was in the room more than a minute.

No one else entered the room after the accident before we left. Werner (machinist at Pajarito) was going to close the outside doors after we left. He was warned not to go inside nor to stay in the vicinity long.

P.F.C. Cleary (Security Guard) phoned for an emergency relief after the ambulance had arrived (about 15 minutes). We suggested that he ask for two men to come and he relayed by telephone our instructions that one should stay outside the building where he could watch the laboratory outside door and the other stay at the end of the corridor furthest from the hot lab. They were told to stay out of the room under all circumstances.

Incidentally, the boys leaving via the east door had warned the MP's so the gates were opened and all personnel had gone perhaps 50 yds. up the exit road. They remained there until we called them back about 15 minutes after the accident.

The foregoing is my recollection of what happened. I repeat that my observations may not have been correct as to what happened during the few seconds following the accident.

The following section is an attempt to give an impersonal analysis of the accident with the sole purpose of trying to analyze the causes and so help prevent its re-occurrence.

1. Slotin was <u>not</u>, by any possible interpretation, guilty of what legal minds like to call "criminal negligence". The monitors were set up and running, an adequate number of observers were present who, by their silence, agreed to the procedure, and he had provided a safety device in the form of wedges to keep the tamper from dropping if it slipped. The fact that this safety device failed does not alter the situation as far as this point is concerned.

I feel emphatically that there should never be an attempt to establish legal responsibility for the accident. If this should be attempted, it is my opinion that, excepting Perlman and Cleary, all should be held equally responsible since the rest of us knew enough about critical assemblies to voice a protest if we objected to the procedure. No such protest was made.

2. The assembly was made too rapidly and without adequate consideration of the details of the method. A "dry run" without the active material to check the details of the mechanical operations should have been

made.

3. Only those persons actually concerned with the assembly should have remained in the room.

4. No conventional safety devices operating from a neutron monitor could have prevented the accident. The neutron rise was too rapid to have the reaction stopped by any of the devices I have seen used at Los Alamos.

5. While operation of such an assembly by remote control would have eliminated the hazard from this particular "burst", it might well have become a real explosion with equal or greater damage to personnel in spite of shielding walls unless a positive and fast-acting safety device were a part of the assembly. In this case, Slotin was that safety device.

I do not know what safety recommendations for future assemblies will evolve as a result of this accident. There are several points I should like to make.

1. The formulation, approval and publishing of a new set of rules will not prevent more accidents. As stated in item (1) of the preceding section, the existing rules were nominally complied with. In addition to the restatement of rules, there must be a continuous and vigorous campaign to keep the people participating in this work aware of the potential danger in every assembly. Perhaps the work should be rotated among a number of people. As soon as a person ceases to be nervous about the work he should be transferred to another job.

2. Any new assembly should be planned in detail a considerable time in advance. The plan should be sent to several responsible people, any one of which could veto the plan or ask for a clarification.

3. Every new assembly should be attended by one or more observers whose job would be to stop any procedure which they consider hazardous.

4. Wherever feasible, an assembly should be done by remote control provided that this control incorporates safety devices guaranteed to stop the reaction in the shortest possible time.

5. A complete account of each assembly should be kept, possibly with a running commentary fed into a wire recorder and either a movie camera or an automatic still camera.

6. New critical assemblies should never be reduced to a routine matter to be "run through before lunch".

7. A detailed file of all critical assemblies should be kept up do date. This file would be valuable as a guide in making future assemblies and could also be evidence for removing assemblies known to be safe from the rather severe restrictions which will undoubtedly be imposed on all untried assemblies.

Cc: Froman
File