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and 11) and this is clearly the leading contender for a cause of the criticality events.

The energy release, measured by the number of fissions, is remarkably near-constant (if the NRX case is eliminated as being a reactor accident and of a different character). Of the remaining ten events, the ratio of largest to smallest is only 156. Apparently, the natural progress of thermal expansion, moderator expansion, and boiling act on time scales fairly independent of the system. Additionally, physical damage is pretty much limited to the reactor experiments and case 3, which had a unique fuel design.

Finally, the risk to operators if an accidental criticality occurs is fairly high. In the 11 events, I can count 13 moderate to serious irradiations and five deaths, most of these having occurred well over two decades ago. It may be the case that designs are better and operator training and discipline are better than in the early years of the atomic energy business, but this has not been demonstrated.

4. A Review of Criticality Accidents Within the European Community, *M. C. Evans (BNFL-UK)*

INTRODUCTION

Three criticality incidents have occurred within the present boundaries of the European Community. They took place in critical facilities, at Saclay, France, and Mol, Belgium, and in a chemical plant at Windscale Works, England.

THE INCIDENCE AT SACLAY, MARCH 15, 1960

The incident[1] occurred in the "Alize" critical assembly and was caused by the withdrawal of a control rod that was not previously fully out. "Alize" was a water-reflected, water-moderated system charged, in this case, with 1.5% enriched UO_2 rods. The rods were 1 m long and 1 cm in diameter; the total UO_2 inventory was 2.2 tonnes.

The experiment being performed required a stable positive period at a very low power level. The critical rod configuration was found experimentally and the rod position required for the necessary period was calculated. After allowing for the decay of delayed neutron precursors, the rods were withdrawn to the calculated position. When the further withdrawal of the control rod that caused the incident occurred, the system was placed on a period of 0.25 s. The subsequent excursion created 3×10^{18} fissions. The core was undamaged and personnel irradiations were trivial.

THE INCIDENT AT MOL, DECEMBER 30, 1965

The incident[2] occurred in the VENUS facility, which is used for the study of water-moderated assemblies. For the experiments in progress, performed in the context of the VULCAIN program, the composition of the moderator and reflector was 70% H_2O and 30% D_2O, the reflecting region extending 30 cm above the top of the core. The cylindrical core region (height and diameter, ~1.0 m) was occupied by an array of 7% enriched UO_2 pelleted rods, the total mass of which was 1.2 tonnes.

Primary reactivity control was provided by eight remotely controlled safety rods and two regulating rods, eight further absorbing rods being available for manual positioning in the core. On the day of the incident, a series of critical experiments had been completed with one safety rod, one manual rod, and one regulating rod withdrawn; the second regulating rod was partially withdrawn. Shutdown was to have been achieved by inserting a safety rod and both regulating rods; however, at the time of the incident the insertion of one of the regulating rods was only partially complete. VENUS was subcritical by one safety rod and, essentially, one regulating rod.

An experiment with a new rod pattern was required. Written instructions describing the shutdown procedure, the insertion of the eighth manual rod, and the removal of another were given to the technician who was to carry out the operation. The written instructions did not require the dumping of the moderator as stipulated in the facility operating rules.

With the second regulating rod partially inserted, the technician removed a manual rod without first having inserted one. During the extraction of the manual rod the reactor became critical. The technician noticed a glow in the bottom of the reactor and immediately dropped the manual rod and left the room.

The incident size was ~4.3×10^{17} fissions. It was stopped by the falling manual rod, the Doppler effect, and finally, the automatic emptying of the moderator in the vessel. No steam was created, there was no damage to the fuel, and no contamination. Later measurements made using a phantom[3] suggested the following approximate doses to the technician: 300 to 480 rem to the head, 500 rem to the chest, 1750 rem to the left ankle, and approaching 4500 rem to the end of his foot. Medical treatment of the technician was successful except that his left foot had to be amputated.

On completion of the VULCAN program in 1966, the reactor internals were modified to allow the study of clean fuel lattices. A fast water dump, whose response is short with respect to filling velocity and associated reactivity addition rate, was installed. The door to the shielded reactor room was interlocked so that opening it initiated the water dump and reactor shutdown. The door remains open during manipulations and an audible signal warns of closure. Two senior staff members are now involved in approving daily reactor operation. These modifications have proved satisfactory during continuing intensive use.[4]

THE INCIDENT AT WINDSCALE WORKS, AUGUST 24, 1970

The plant in which the incident occurred[5,6] was used for the recovery of plutonium from liquid and solid residues. Solutions are transferred from dissolvers and conditioners to constant volume feeders by a vacuum lift system via closed transfer vessels. The incident occurred as a lift of aqueous solution from a conditioner to a vacuum transfer vessel was ending. Subsequent remote investigations showed that the transfer vessel, which should have been empty, still contained an 8.5-in.-thick layer of solvent at a concentration of 55 g Pu/ℓ. The solvent, which might have been entrained in aqueous feed, could have remained trapped above the aqueous layer for some time.

Observations using a replica system showed that as aqueous phase flowed into the transfer vessel, it fell as a streamlined jet into the solvent layer; an emulsion band was created. It is likely that criticality occurred at the cessation of flow and the shutdown mechanism was the collapse of the interface emulsion layer.

Fission product analysis indicated an incident of 10^{15} fissions. A small release (~5 mCi) of fission products occurred via a 400-ft-high stack, but the effects were not detectable at ground level. Whole-body doses received by the two men, who left the building on hearing the criticality alarm, were <1 and 2 rads, respectively.

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1. W. R. STRATTON, "A Review of Criticality Accidents," LA-3611, p. 55, Los Alamos National Lab. (1967).

2. G. PENNELLE, "Description et Analyse de l'Accident de Criticité survenu au Reacteur VENUS à Mol en däte du 30 Décembre 1965," *Proc. First Int. Congress Radiation Protection*, Rome, Italy, 1966. p. 1223.

3. N. C. PARMENTIER et al., "Problèmes de Dosimétrie lors de l'accident." *Proc. First Int. Congress Radiation Protection*, Rome, Italy, 1966.

4. J. DEBRUE, CEN/SCK, Mol, Belgium, Private Communication.

5. J. T. DANIELS, H. HOWELLS, and T. G. HUGHES, "Criticality Incident—August 24, 1970, Windscale Works," *Trans. Am. Nucl. Soc.*, **14**, 35 (1971).

6. T. G. HUGHES, "Criticality Incident at Windscale," *Nucl. Eng. Int.*, p. 95 (Feb. 1972).

5. The Hanford Pulser Accident, *E. D. Clayton (PNL)*

Eight criticality accidents are known to have occurred within the United States in operations external to reactors, excluding experimental systems where the intent was the study or measurement of criticality itself.[1]

In the realm of criticality accident experience, the Hanford accident of April 7, 1962, remains one of the more interesting and complex of any to date. Since details have never been broadly circulated, the accident will be reviewed for the lessons gained. This accident, and subsequent recovery operations, were unusual for the following reasons:

1. The reaction continued for ~37 h before termination, whereas criticality accidents normally terminate within periods ranging from seconds to minutes. No super critical chain reaction had remained uncontrolled for this long before. (Excluding criticality that occurred in the earth in the Republic of Gabonaise in primeval time).[2]

2. There was no spread of contamination.

3. There was no physical damage.

4. There was no serious radiation dosage to any staff member.

5. A remotely controlled mechanical robot was used for the first time in the aftermath of such an accident to perform various operations, position detectors, conduct surveys, turn valves, etc. (see Fig. 1).

6. *In situ* multiplication data were obtained on the solution in the vessel in a reverse approach-to-criticality during the recovery operations, which led to interesting conclusions regarding the shutdown mechanism.

7. The method of shutdown was not the result of simple evaporation or boiling off of solution by itself from fission heating, nor of expulsion of solution from the vessel.

8. Both administrative errors and mechanical failures combined in a sequence of events leading to criticality.

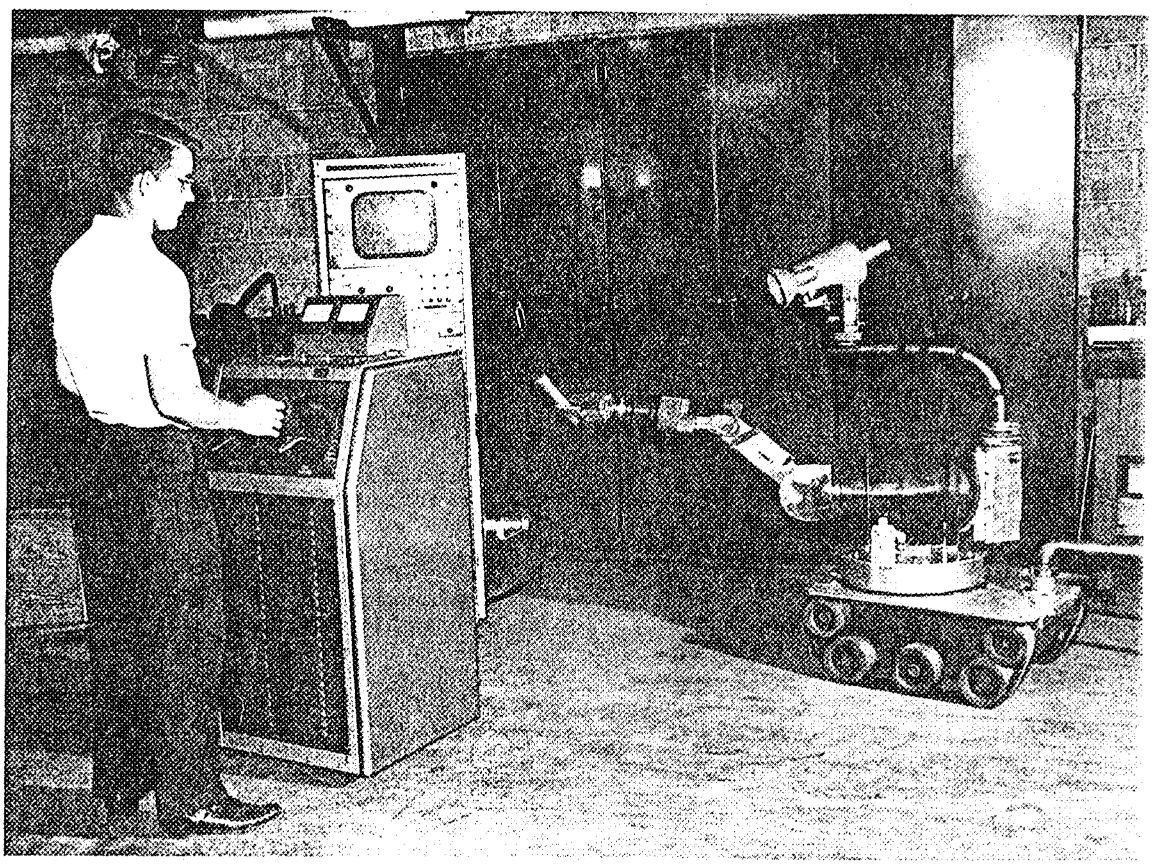

Fig. 1 Remotely controlled mechanical robot used in plant recovery operation.