The Technology of Nuclear Reactor Safety

Volume 1

Reactor Physics and Control

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EDITORS
T. J. Thompson
J. G. Beckerley

Prepared under the auspices of the
Division of Technical Information
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The author earnestly believes that such a record will do much to prevent similar accidents from happening again, thus make the safety record of reactors even better than it is. To support this view, one can cite the SL-1 accident which almost certainly occurred because an operator or operators manually withdrew a control rod. It is generally believed that the SL-1 accident was the first case in which manual withdrawal occurred. In reality, it is the third case which has led to a recorded accident. Yet, partly because no one has bothered to set down the lesson, a reactor designed several years after the first such accident carried the same flaw, and a serious accident resulted.

In reviewing the significant accidents (including destructive tests) which have occurred to date, it has appeared logical to divide them into three different categories: those in critical facilities where no fission product burden is likely, those in reactors and involving reactivity changes, and fuel failures in reactors.

The first category, accidents in criticality facilities, is discussed in Sec. 2 and is summarized in Table 2-1. For the most part, there are excellent summaries of these accidents [1, 2, 3, 4] up until about 1960. A few of special interest which have happened since then are described briefly in Sec. 2.

The second category, reactor accidents and destructive tests, is discussed in Sec. 3 and summarized in Table 3-1. Only those incidents involving criticality are included. Three incidents, the BORAX-1 experiment, the EBR-I Meltdown and the SPERT Destructive Test, involved planned transient experiments and, therefore were not really "accidents" in the sense of being totally unexpected. They are included, however, for completeness and for the information they have provided. Another, the Windscale accident, involved reactivity only as one aspect of the initiating cause. Yet, it was a reactor accident from which much can be learned, and it is therefore included.

The third category, fuel element failure, is included to provide information on experience with fuels in operating reactors. The information is summarized in Table 4-1 and brief reviews are presented in Sec. 4 outlining the more serious of these accidents. In general, the more minor fuel element failures and experiences of a generally favorable nature are not reported. Thus, those discussed here may be viewed as typical examples, but by no means do they constitute a complete review of all fuel failures. It will be noted that, as experience is gained, the number of fuel failures generally diminishes with each core loading—except, of course, in the cases where the new core loading represents quite a difference in design or material.

Section 5 outlines briefly important examples of failure experience that have arisen. Section 6 summarizes some of the more general findings.

In addition, a section describing some important examples of failure experience is included as well as a section of general conclusions. The radioactivity evolved in a number of these accidents and the measures taken to carry out appropriate cleanup is discussed in Sec. 7 of the chapter on Radioactive Waste Management.

2 CRITICALITY ACCIDENTS OUTSIDE OF REACTORS

2.1 General

This section summarizes the reported criticality accidents which have occurred outside of nuclear reactors through 1963. In general, the incidents listed are limited to those in which the reactivity exceeded prompt critical. It is also limited to those cases where unforeseen events occurred, cases of a truly accidental nature.

Descriptions (of the pertinent facts) of the accidents which occurred before early 1961 are contained in two excellent summaries by W. R. Stratton [3a, 3b]. In his OECD symposium paper [3b] Stratton analyzed in some detail the characteristics of the bursts where such information exists. Table 2-1 summarizes the principal features of all of these accidents. The table is arbitrarily divided into three parts: metal assemblies in air, heterogeneous assemblies, and hydrogenous solutions. The cause and the quenching or shutdown mechanism are noted in abbreviated form. In criticality accidents, it is usually found that there is one (or at most two) simple cause for the accident, so that a table is sufficient to point out the cause. Critical assemblies are relatively simple devices and the accidents which have occurred to date could not be said to be very complex.

Because the basic causes for the accidents in criticality facilities are closely related to the causes of accidents in reactors, both are summarized together in Sec. 6 of this chapter. Since Stratton's review [3b], there have been five additional accidents to September 1964, three in criticality facilities and two in chemical plants. These are described briefly.

The accidents discussed in Secs. 2.2, 2.3 and 2.5 happened in well-designed laboratories for criticality experiments and resulted in no excessive radiation exposures and very little or no damage. The accidents discussed in Secs. 2.2 and 2.3 occurred in general purpose criticality facilities. The accident discussed in Sec. 2.5 occurred in a facility designed to study fast bursts. The public safety was not involved in these accidents, nor is it likely to be in such situations. Much more likely in accidents of this kind is radiation injury to the employees directly involved, particularly in accidents where for some reason personnel are allowed to be present in the area where the nuclear radiation burst takes place.

Of the eight deaths to date from accidents involving the fission chain reaction, three have resulted from exposure to a burst from a critical assembly. In each of these cases there was no compelling reason for personnel to be present in the area at the time of the burst. As shown in Table 2-1 two deaths were at Los Alamos and were due to hand-stacking critical assemblies. These accidents happened near the end of World War II and perhaps can be understood on the basis of military urgency. The third happened in Yugoslavia where six persons were working in a room with a critical assembly in it. The situation was realized after the system had been critical some 3 to 7 minutes and then only when someone smelled ozone. Fortunately, only one of the six persons

					hemisphere - slipped	Q-expansion		
3 April '52	LASL Jemima	92.4 kg U-metal (93% U^{235})	Unreflected, multidisk cylinder	1.5×10^{16}	Computation error made independently by two people, no graph made of reciprocal multiplication	P-none; Q-expansion	Slight warping of pieces	[3,4]
Feb. '54	LASL Godiva	53 kg U-metal (93% U^{235})	Unreflected sphere	5.6×10^{16}	Incorrect operation - reactivity added too fast before chain started	P-none; Q-expansion	Slight warping of pieces	[3,4]
2 Feb. '57 (holiday)	LASL Godiva	54 kg U-metal (93% U^{235})	Sphere, partially unreflected (experiment)	1.2×10^{17}	After reactivity adjusted, graphite-polyethylene mass slipped or slumped closer to sphere	P-none; Q-expansion	Warping, oxidation, near melting at center	[3,4]
6 March '63	UCRL-Livermore Kukla	Over 25 kg U^{235} metal	Nesting cylinders, reflected by Be and polyethylene	$\sim 4 \times 10^{17}$	Shell suddenly slipped down on central cylinder	P-none; Q-expansion, melting	15 kg U burned, 10 kg melted	[12a,12b] Sec. 2.6
				Heterogeneous Critical Assemblies				
June '45	LASL	35.4 kg U-metal ($\sim$83% U^{235}), 0.5 in. cubes	Pseudosphere in polyethylene box, H_2O-reflected	$\sim 3 \times 10^{16}$	H_2O leaked into box - no scram method provided	P-3; R-66, 66, 7.4 rep; Q-boiling of H_2O	None (cubes used in three days)	[3,4]
1 Feb. '51	LASL	2 cyl. U-metal (93.5% U^{235}) 24.4 kg solid 38.5 kg hollow	Adjacent cylinders, Cd surface, paraffin-filled, H_2O-moderated	10^{17}	Solid cylinder lifted on scram signal pneumatically - passed close to second cylinder, adding reactivity as passed by	P-none; Q-scrams of Cd sheet between two cyl; H_2O drop, cyl. lift cont.	Oxide formed-flaking and blistering	[3,4]
2 June '52	ANL ZPR-I	6.8 kg U^{235}-oxide particles in plastic	Inhomogeneous cylinder H_2O-reflected	1.22×10^{17}	Manual withdrawal of central control rod	P-4; R-136, 127, 60, 9 reps; Q-plastic heated, bubbles	Plastic destroyed	[3,4,14]
3 July '56 (day before holiday)	LASL Honeycomb	58 kg U-metal foils (0.002 and 0.005 in.) in slabs of graphite	Split core of 2 flat slabs 1/2 movable on tracks	3.2×10^{16}	Too rapid assembly of unit	P-none; Q-scram ejected Be-rods, reversed carriage on track. No other good Q available	None	[3,4]
15 Oct. '58	Vinca, Yugoslavia	3,996 kg U-metal, D_2O-moderated	Clad rods, lattice, unreflected	2.5×10^{18}	Subcritical multiplication as function of D_2O level, personnel working in room	P-6; R-400, 700, 850, 850, 850, 1,100 rem (fatal), ozone smell gave first warning	None	[1,3]

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15 March '60	Saclay, France Alizé	Partially enriched U H_2O-moderated	Pool reactor, variable fuel normally 4 control rods	3×10^{18}	Mistake in control rod withdrawal. Instrument errors.	P-2; R-slight overdose	None	[6a,6b] Sec. 2.3
10 Nov. '61	ORNL crit. facility	75 kg 93% U^{235} paraffin mod. and reflector	Split core, pseudosphere	$10^{15} - 10^{16}$	Split core assembled at fast speed instead of slow; judgment, procedure errors	P-none; Q-expansion	None	[7,8,9] Sec. 2.4
Before 1955	USSR	Unknown	Unknown	Unknown	Unknown	P-2; R-450, 400 rad	Unknown	[1,3,4]
				Hydrogenous Solutions				
11 Feb. '45	LASL Dragon	$U^{235}H_3$ pressed in Styrex, solid cubes	Subcritical with central cylindrical hole. U-[illegible]	$\sim 6 \times 10^{15}$ (no accident, [illegible]	System overheated during burst as slug dropped through central hole	P-none; Q-thermal expansion	Spoiled cubes by swelling, [illegible]	[3,4]

died. Such accidents should not happen in well organized and controlled criticality laboratories. The usual type of accident that may occasionally happen during the literally thousands of experiments being carried out is exemplified by those described in Secs. 2.3 and 2.5.

In recent years fast burst facilities have been designed, built, and operated which have devices to deliver, in a controlled fashion, fission pulses having an energy release comparable to many of the accidents listed here. The accident discussed in Sec. 2.5 occurred in such a facility. The problems of control of burst reactors are discussed in the Criticality chapter and also in several reviews [4a, 4b].

The accidents described in Secs. 2.4 and 2.6 took place in chemical processing plants. There have now been six such accidents since mid-1958. The systems involved are exceedingly complex and the type of personnel who work with such systems may be accustomed to working in a somewhat imprecise manner. Even if they are aware of the hazard, the idea of criticality in an innocent-looking tank of liquid may still seem unreal, and the likelihood of accident remote.

In general, there are two types of situations existing in such chemical reprocessing plants. In the first, fissile material free of fission products is being processed. There is usually little or no personnel radiation shielding; consequently, in the event of a criticality accident the working operators are very likely to be exposed to hazardous radiation.

Of the six chemical plant accidents to date, four have been with fissile material free of fission products. All four of these accidents resulted in high radiation doses to personnel. One of these at Los Alamos on December 30, 1958, was an accident in which the operator involved received a fatal dose estimated to be 12,000 r. In each of the accidents it was the actions of personnel present that caused the accident and the personnel were trapped in the accident they caused.

In contrast, the handling of fissile materials containing large quantities of fission products must be done behind heavy radiation shielding. If the shielding is sufficient to protect personnel from the normal fission product burden, it is likely to be sufficient to protect them from the radiation accompanying a criticality burst. Twice to date this has proved true. On the other hand, a criticality burst releases energy which could conceivably drive dangerous quantities of radioactive fission products to the area surrounding the plant and thus create a public hazard. In a plant handling fissile material and fission products the safety problem is mainly one of preventing fission product release to the outside. A "clean" (i.e., no fission products) plutonium processing plant may involve both the hazard of radiation from a burst and the hazard of released material since plutonium itself is highly toxic.

2.2 Alizé I Reactor Accident [5,6]

Alizé I is a light-water-moderated and cooled pool type reactor designed for criticality experiments at power levels from 1 to 100 watts. A variety of fuel types and enrichments may be used. Control is accomplished with a number of identical control rods, normally four, located in positions dependent on the experiment in progress. The primary purpose of the reactor includes use in lattice studies, critical mass studies, buckling measurements, and temperature coefficient measurements between 5 and 95°C (41 and 203°F). It is located at Saclay in France.

The experiment being carried out on March 15, 1960 required that a stable reactor period be established at a very low power level. Accordingly, the reactor was made critical and a definite critical rod configuration and position was established. The reactor was then shut down. A calculation was made, based on rod reactivity worths, to establish the rod position configuration necessary for the desired period. After a suitable decay time to reduce the delayed neutron background, the rods were withdrawn to the predetermined position. However, for reasons not completely clear, a rod previously only partially withdrawn was fully withdrawn in the second instance putting the system on a short period. The error could have been due to a miscalculation, a misunderstanding of the first configuration, or to a number of other possible causes. The experimenter was working alone.

It is reported that "the period trip had been switched out of the circuit by mistake and that the power trip levels did not operate, no doubt because their trip level was exceeded too rapidly."[6]* The power proceeded to rise in a period of approximately 1/2 sec to a level of nearly 10 Mw at which time the Doppler effect due to the heating of the partially enriched fuel was sufficient to offset the reactivity added and the power dropped back to just under 1 Mw. Since the instrumentation available on Alizé itself was completely ineffective, the first indication of the problem was given by the instrumentation of an adjacent reactor which alarmed on a short period and showed a rising power trace. Immediate investigation of this odd phenomenon in the adjacent reactor quickly led the operators to Alizé as the cause of the trouble. It was scrammed manually approximately 70 sec after the peak of the power burst.

Comments, Conclusions, Recommendations

(1) The withdrawal of control rods to predetermined positions is often used as a means of setting up a prescribed pattern, but it is normally carried out under the rules and using the instrumentation usual for reactor startup.

(2) Adequate on-scale safety instrumentation information and scram trips are absolutely essential to the safe operation of a reactor.

2.3 ORNL Criticality Excursion [7]

This excursion occurred on November 10, 1961, in the critical experiment laboratories at ORNL

*It may also have been negated by ion chamber saturation or some other reason.

Table 6–1

Causes of Accidents

Cause	Location (Date) Facility or Experiment
1. Personnel working in critical area (all fatalities)	LASL (21 Aug. '45, 21 May '46) Pu sphere; Vinca, Yugoslavia (15 Oct. '58) D_2O critical; LASL (30 Dec. '58) Pu soln.; NRTS (3 Jan. '61) SL-1; UNC (24 July '64) U soln.
2. Personnel working with non-safe fluid geometry	ORNL (16 Nov. '58) 55-gal. drum; LASL (30 Dec. '58) Pu soln.; NRTS (16 Oct. '59, 25 Jan. '61) fuel reprocess; Hanford (7 April '62) Pu soln; UNC (24 July '64) U soln.
3. Loss of coolant*	Canada (12 Dec. '52) NRX; Hanford (4 Jan. '55) KW Reactor; Canada (July–Aug. '55) NRX; Canada (23 May '58) NRU; Santa Susana, California (13 July '59) SRE; Waltz Mill, Pa. (3 April '60) WTR
4. Loss of flow	ORNL (1948) X-10; NRTS (June '54) MTR; Hanford (4 Jan. '55) KW Reactor; Saclay, France (26 Nov. '57) EL-2; Saclay, France (13 April '58) EL-3; Saclay, France (12 Feb. '59) EL-2; NRTS (12 Dec. '61) ETR; NRTS (13 Nov. '62) MTR
5. Scram of control rods or control method causes accident	LASL (1 Feb. '51) critical; ORNL (1 Feb. '56) critical; LASL (3 July '56) Honeycomb; Vinca, Yugoslavia (15 Oct. '58) D_2O critical
6. Reactivity inserted too fast – source and startup	Hanford (16 Nov. '51) critical Pu soln.; LASL (3 Feb. '54) Godiva; Hanford (3 Oct. '54) production; Hanford (6 Jan. '55) production; LASL (3 July '56) Honeycomb
7. Positive feedback effects, an important factor	Canada (12 Dec. '52) NRX; Hanford (4 Oct. '54, 4 Jan. '55) production; Canada (July, Aug. '55) NRX; NRTS (29 Nov. '55) EBR-1; United Kingdom (9 Oct. '57) Windscale No. 1; Santa Susana, Calif. (13 July '59) SRE
8. Instruments caused accident	NRTS (18 Nov. '58) HTRE-3
9. Instruments off	LASL (Dec. '49) Water Boiler; Vinca, Yugoslavia (15 Oct. '58) D_2O critical; Saclay, France (15 March '60) Alizé; NRTS (3 Jan. '61) SL-1
10. Power decrease indicated, control rods withdrawn	Hanford (3 Oct. '54) production; NRTS (18 Nov. '58) HTRE-3; Waltz Mill, Pa. (3 April '60) WTR
11. Flat slab geometries or two units approaching	LASL (21 May '46) Pu hemispheres; LASL (1 Feb. '51) crit. cylinders; LASL (3 Feb. '54) Godiva; ORNL (1 Feb. '56) $U^{235}O_2F_2$ soln.; LASL (3 July '56) Honeycomb; LASL (30 Dec. '58) Pu soln.; ORNL (10 Nov. '61) critical
12. Experiment not well planned, parts performed unexpectedly	LASL (4 June '45) hand-stacked crit.; LASL (18 April '52) Jemima; ORNL (26 May '54) homog. crit.; NRTS (29 Nov. 55) EBR-1; LASL (12 Feb. '57) Godiva; UCRL (26 March '63) Kukla
13. Mis-estimates of effects of reactivity	LASL (11 Feb. '45) Dragon; LASL (18 April '52) Jemima; NRTS (22 July '54) BORAX-1; NRTS (29 Nov. '55) EBR-1; NRTS (5 Nov. '62) SPERT-1
14. Control rods withdrawn manually or by abnormal means	LASL (Dec. '49) Water Boiler; ANL (2 June '52) ZPR-1; Canada (12 Dec. '52) NRX; NRTS (3 Jan '61) SL-1

*In NRX and WTR incidents, boiling caused loss of coolant and fuel melting. The SRE incident could also be categorized as a loss of flow accident.

primary cooling system unless subsequent overpressure ruptures it.

In most reactors the accidents with the greatest potential for serious effects are those involving reactivity changes. This type of accident can occur while fission heat is already being generated in the fuel, or such heat may be generated because of the reactivity accident. This type of accident has the potential of utilizing all the forms of available energy to assist in dispersing the fission product burden of the core through the various containment barriers. Accidents involving reactivity changes do not have the advantage of being "sequential" in character.

To date nine cores have been destroyed or seriously damaged. Of these only two (BORAX-I and SPERT-I Destructive Test) can be said to have been destroyed on purpose as a part of a test. Three reactors have been put out of action by accidents and [illegible] Windscale No. 1 and

of its useful life and was no longer believed to be a competitive research tool. It was dismantled and replaced by another higher flux research reactor—the OWR. These nine cases of core destruction all represent economic accidents of a serious nature involving radioactivity cleanup, down time, and rebuilding.

To date no accident has seriously involved the health and safety of the general public. The accident which came closest to doing this was the Windscale accident, which contaminated an area of about 200 square miles (52,000 hectares) around the reactor with a temporary low concentration of radioactive fall-out affecting the local milk supply. It cannot be said to have affected seriously the health and safety of the general public.

From the nuclear viewpoint and from the control viewpoint critical assembly and power reactor accidents have many similarities. Therefore, while recognizing that there are important differences, void effect gives a positive reactivity change, the violent reaction described could for an instant during the interaction be made even worse by it. (These considerations are discussed in the chapter on Fast Reactor Kinetics.) These effects should be investigated in such reactors as well as in water-cooled reactors.

Even if the energy limit considered in this section should be proved not to exist, it is necessary to continue to search for such limiting processes or ways of putting limits on conceivable reactor transients. The present discussion illustrates the type of limit that is sought and the methods by which such limits could be either proved or disproved.

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