Major Technological Risk

An Assessment of Industrial Disasters

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IV. WEDNESDAY, MARCH 28, 1979: THE NUCLEAR ACCIDENT AT THREE MILE ISLAND

On Wednesday, March 28, 1979, thirty-six seconds after 04.00 h, several water supply pumps broke down in unit No. 2 of the nuclear centre at Three Mile Island (TMI) which is ten miles southeast of Harrisburg in Pennsylvania. Thus begins the accident of TMI. During the minutes, the hours, the days that followed a series of events, equipment failure, inappropriate procedures, human error and ignorance were to turn the accident into a major crisis, the worst that the nuclear industry had ever experienced.

The accident focused national and international attention on the nuclear installation of TMI and became the main subject of reflection for hundreds of thousands of people. For people living in the communities of Royalton, Goldsboro, Middletown ... and Harrisburg the rumours, the contradictory official statements, a deficiency of knowledge about the subject of radio- active emissions, the constant possibility of mass evacuation and the fear that a hydrogen bubble in the nuclear reactor might explode were effective and immediate realities.

With these sentences the Commission of Enquiry set up by President Carter two weeks after the accident introduced its detailed report on the event.

1. TMI - A NUCLEAR CENTRE, AN AMERICAN ENVIRONMENT

1st: Technical characteristics

Some simple technical data may be useful for the comprehension of what follows: (according to 1, pp. 81-89 and 2, pp. 76-78). The centre of TMI consists of two units: Reactor No. 1 with a capacity of 800 megawatts (MWe), put into operation in 1974, had supplied, at the time of the accident in reactor No. 2, 20 billion kWh (equivalent to six months electricity consumption of New York) and its rating of reliability had been excellent; the second reactor, the one which was to have the accident, had a capacity of 900 MWe and had only been in commission for three months. These reactors belong in the category called pressurised light water reactors (PWR) , the most frequently used in the world*.

The general functional principle of a nuclear centre is similar to that of all thermal power centres and is concentrated around the following elements: a heat source, in this case a nuclear reactor, permits the evaporation of water; the steam thus generated drives a turbine which is coupled to an alternator that produces electricity. The steam passes its condensation heat on to the water circulating in the piping system which at TMI is cooled by air in cooling towers. The installation comprises mainly**:

- a reactor building consisting of a surrounding concrete wall called a containment wall because of its protective function;
- a building containing the nuclear auxiliaries;
- a building containing the electricity generating installation.

*The French centres in particular are of this PWR category but under Westinghouse, not Babcock and Wilcox, licence like the generators at TMI.

**See Figure 16, page 110.

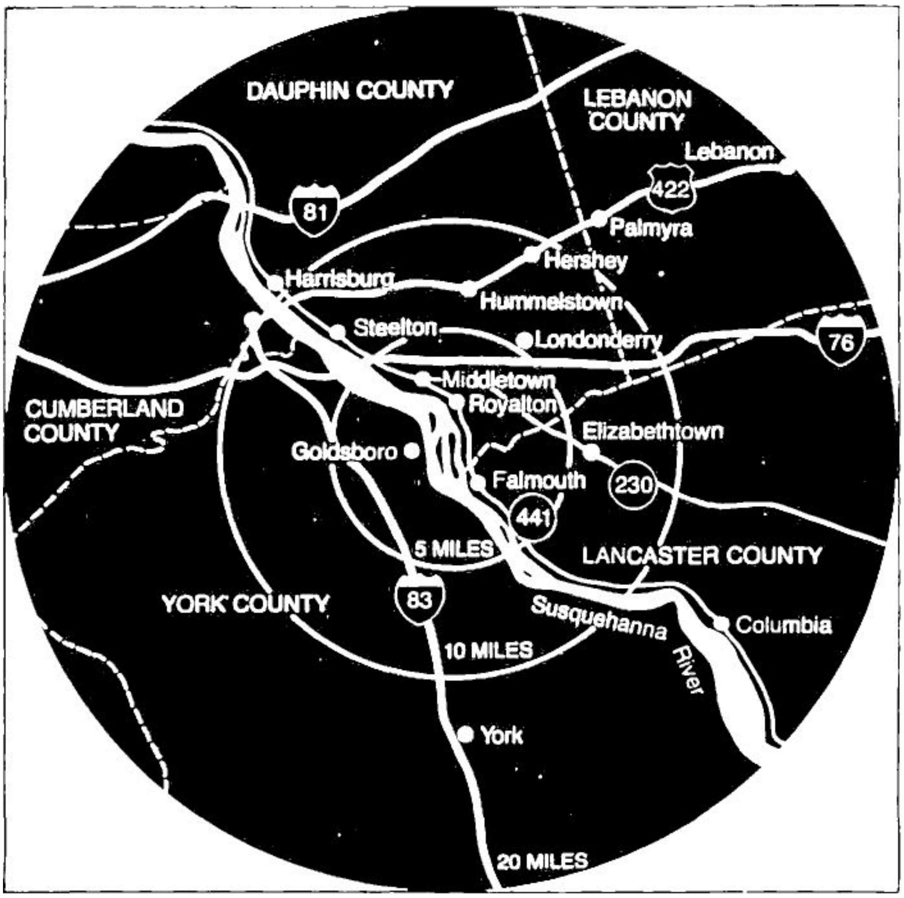

Fig. 15: The centre of TMI is located on land belonging to the community Middletown in the state of Pennsylvania (USA) on the bank of the Susquehanna River, 15 km from the state capital, Harrisburg (90,000 inhabitants). (Source: 1, p. 122)

Three Mile Island

Within the containment wall is the installation for the generation of "nuclear heat". At a centre like the one at TMI one finds within this wall:

- the reactor vessel containing the core where the fission of the atoms of Uranium 235 occurs which releases the heat; the core is cooled with ordinary water which circulates outside the vessel in two 'loops' comprising primary piping and in each of the loops a heat changer, then two primary pumps in parallel. On this circuit is the pressuriser which permits control of the pressure in the circuit; the pressuriser is protected by discharge valves which open when the primary pressure reaches a reading fixed at 156 bar, thus permitting the discharge of excess steam into a so-called discharge tank.

- 'Steam Generators' or GV, where the primary water transmits its heat to the so-called 'secondary circuit' while vaporising the water sent along by supply pumps.

Outside the containment wall is plainly the electricity generating installation. The steam produced by the generators is sent to the turbine by means of a piping system which runs through the containment wall. This steam expands in the turbine where the transformation of thermal energy into mechanical energy, electrical energy, takes place. The steam, when leaving the turbine, condenses in the condensor where it transmits its condensation heat to the water from the cold source. It is subsequently sent back to the supply pumps.

The safety of the installation is ensured by a number of screens called 'barriers' between the fuel and the public and by a certain number of devices which intervene in the case of malfunction. In PWR reactors like the ones at TMI there are three barriers in sequence:

- The first one is made up of the casing which surrounds the fuel tubes. This casing consists of Zircaloy which has a number of advantages from a thermodynamic point of view but has the disadvantage of reacting to water at temperatures above 1.200°c and gives off hydrogen.
- The second one consists of the primary circuit: vessel, loops (rustproof steel of very high quality, a very large number of small diameter) steam generator and primary pump pipes and the pressuriser with its valves and the discharge tank.
- The third one consists of the concrete wall which makes up the reactor building.

In the context of the accident on March 28, 1979 the safety systems involved were :

- The emergency switch off system consisting of an assembly of rods the function of which is to stop the fissioning reaction* and the associated control system.
- The auxiliary supply system of the steam generators employed in case of loss of normal water supply.

* The reactor of TMI-2 had been in service only for a short while : this limited the quantity of residual heat produced and was therefore a minimizing factor in the accident process.

- The safety injection system the function of which is to inject boronated water (neutron poison) into the primary circuit in case of depressurisation of that circuit. This function is generally achieved by three categories of systems: injection at high, medium and low pressure.
- The wall insulation system which permits, upon an indication of high pressure (+ 0.3 bar of relative pressure) to close all auxiliary pipes through which primary water runs and which comes out of the surrounding wall.
- The wall's cooling and ventilation system designed to reduce the temperature and pressure inside the third barrier in order to ensure its intact survival in case of an accident.

2^{nd} : institutional date

The centre at TMI. is operated by Metropolitan Edison, a private company which is a part-owner of the installation ; as is the rule in the United States, TMI belongs to a private group. In order to understand the institutional game that will unfold on the occasion of the accident the responsibilities of the various public authorities must also be spelled out.

The drawing up and the implementation of rescue plans are the responsibility of each state. Accidents to do with radiation are dealt with specifically, as the case may be, by the Health Service or by Civil Defence (Emergency Service) as was the case in Pennsylvania, the agency being called 'Pennsylvania Emergency Management Agency (PEMA)'. In cases of crisis PEMA coordinates action under the responsibility of a council made up of the governor and the lieutenant governor of the state, four members of the state parliament (legislature) and the directors of the various agencies likely to intervene in emergency situations. This council meets in an operation centre (Emergency Operation Centre (EOC)), well equipped and well protected. In the counties there exist local plans which spell out the responsibilities and procedures to be followed in case of an accident, more particularly a nuclear accident; a civil defence director activates an operation centre at state level.

At federal level the pilot organisation is the Nuclear Regulatory Commission (NRC). Other administrations join in for support like EPA (Environmental Protection Agency), DHEW (Department of Health, Education and Welfare), FEMA (Federal Emergency Management Agency). All these agencies have means which they can put at the disposal of the governors in cases of serious accidents while the states remain responsible for the operations.

Before the accident at TMI the NRC recommended the establishment of two zones of emergency intervention around the centres: the first one within a radius of ten miles covering risks of radiation from the cloud of radioactive material; the second comprising between ten and fifty miles deals with risks of contamination by ingestion. The precise limits of these zones must be determined by those responsible in each state. At the time of the accident at TMI the general emergency plan of the state of Pennsylvania existed but its annex, the plan for the protection against radiation for the state and those for the counties, had not yet been approved by the NRC (complements and more details had been requested for the criteria and the conditions for evacuation of people in the neighbourhood of TMI). On the other hand, the Internal emergency plan at the centre had been established and approved. A direct telephone line connected the operator with the civil defence command post (EOC) at the seat of the governor in Harrisburg (2, pp. 10-11).

3rd: The overall situation in March 1979

At the beginning of 1979 there were seventy four nuclear power stations operating in the United States. The American nuclear programme had undergone successive adjustments — downwards. Objections to nuclear power were rather strong in the country and came also from non-marginal scientists; referenda had been organised in various states. Quite recently, on March 15, 1979 the NRC had ordered the closing down of centres which had faulty designs (insufficiency at the level of seismic risks). This decision had been the subject of a number of comments. Important decisions were expected from the White House concerning energy production and more particularly a relaunch of the nuclear programme.

Finally, a fiction film, The Chinese Syndrome_, with Jane Fonda in the leading part, beat the box office records for several weeks in the USA: an incident in a nuclear power station, operators taken, aback in front of control screens that gave false indications, an industry that is faster at hiding facts than at explaining them frankly*: so there was something to stir up the emotions of the inhabitants of Harrisburg in particular where the film had been showing on March 28, 1979 (2, pp. 6-7).

2. FIVE DAYS OF TECHNICAL UNCERTAINTY, POLITICAL CONFUSION AND SOCIAL DISQUIET

1st: Technical uncertainties

The Kemeny report, named after the president of the Commission set up at the request of President Carter, retraces the unfolding of the accident (1, pp. 90-142) and makes clear the succession of technical events which occurred and the parallel development of what the actors in the drama understood and decided to do, that is to say: the operators, then the engineers of the centre and finally those responsible at the NRC. The article written by P. Tanguy (3) spells out the scenario and draws up a balance sheet from it.

We shall still refer back to other reports in order to study the case of TMI (3-13). We shall take up the essential parts even if this entails being incomplete and insufficiently precise.

a) The first moments experienced by the operators in the control room (the first two hours). It all started on Wednesday, March 28, 1979 at 04.00 h 36 seconds while section two at the centre at TMI was running at 97 per cent of its nominal capacity. The initiating incident was the start of two water pumps supplying the steam generator, subsequent to a failure in a common up-stream circuit. This caused, two seconds later, the start of the turbo alternator group, five seconds later the opening of the discharge sluice of the pressure unit** and eight seconds later the emergency stop of the reactor which is effected by the dropping of absorbant rods into the core.

Nothing abnormal up to that moment. It was an incident, serious enough but not of an exceptional nature. However, it resulted in a cascade of alerts, one hundred of them within a few minutes. The operators' reaction as reported by Kemeny is understandable:

* So many intervening factors, in reality, in the event that happened on Wednesday, March 28.

**Since the pressure in the primary circuit rose following the increase in the temperature of the primary water that was caused by the stop of the secondary water supply.

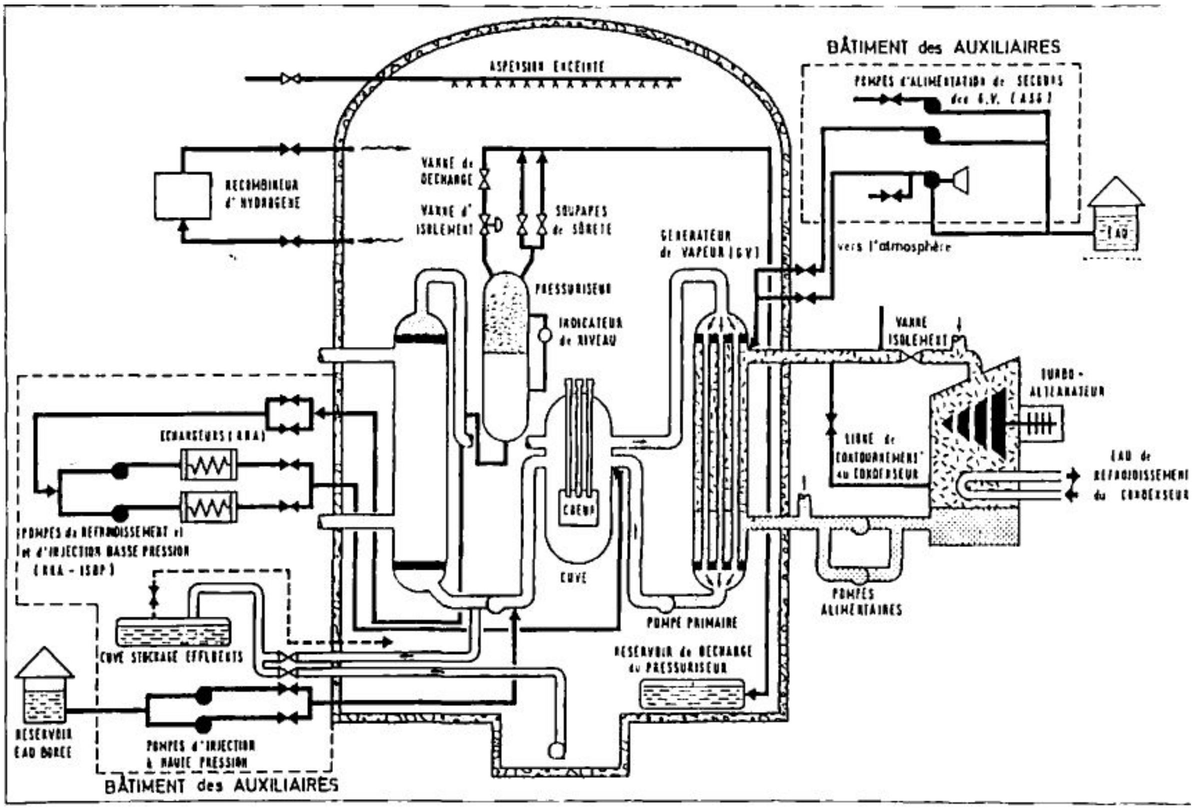

Fig. 16: Diagram of the centre at TMI (Source 2, p. 524)

- I wanted to send the alarm panel to hell; it gave us no usable information.

The problem confronting the operators was to understand what was happening. What information should one get? How to sort out the one hundred odd alerts that rang out in a cacophony of hooters and bells? It was not humanly possible to analyse, to 'digest' this avalanche of data. They were trying to grasp the maximum of information, to identify the situation in which they found themselves and perhaps to relate it to one of the situations which they had studied theoretically during their training.

In this vein, one operator noted that the pumps which supply the steam generators with emergency water did start all right. But nobody realised that this water could not get to the generators because two valves were, mistakenly in the shut position. It took eight minutes until one operator realised this and the valves were opened, permitting this water to cool the primary water. However, according to the experts, this error did not profoundly change the sequence of events. According to P. Tanguy it does not seem, as of today, that this eight minute lapse had a decisive influence on the unfolding of the accident more or less according to the plan of thermohydraulic behavior of the system. On the contrary, it seems probable that the operators' poor comprehension of the course of events had been influenced by the disturbed situation which they had to face. (3, p. 527)

In fact, one can imagine the surprise of the operators who, while expecting that the residual heat {caused essentially by the products of the fission once the rods had been dropped*, since there had been an emergency stop) had been removed by the emergency water, realised that for eight minutes this had not happened.

This situation could only constitute a handicap for the detection of the accident that was unfolding. For, in fact, the operators were faced with a grave situation defined in the safety reports as being "a loss of primary refrigerant on account of an intermediary break in the steam phase at the pressurizer" (4, p. 14). In fact, if the discharge valves of the pressurizer had opened properly (at operating time: five seconds) (permitting the steam of the pressure unit to discharge into the discharge tank** and thus to limit the increase of pressure in the primary circuit following the initiating incident of loss of secondary water) it would have had to shut off again within twelve seconds when the pressure would have dropped sufficiently. The sequence of shutting again was well established but this valve had remained blocked in an open position while the primary circuit emptied (6Ot/h) into the discharge tank. The operators who had the information "pressurizer discharge valve closed" took 2 h.20 minutes to understand what had happened. What actually happened was that the discharge tank, which has a limited capacity, opened its valve very quickly (operating time: three minutes), letting the primary steam overflow into the concrete surrounding wall; then there was a rupture of its explosion disc (operating time fifteen minutes). The water then overflowed into the surrounding wall.

The operators knew that they were in a difficult situation since at operating time: two minutes the safety injection started automatically, indicating chat there was a break somewhere in the primary circuit. Amidst the

* This remaining power is in the order of 7 per cent of the nominal power immediately after the reactor is stopped and then drops rapidly : 4 per cent after 30 seconds, one per cent after two hours.
** See Figure 16, page 110.

multitude of information available the operator picked on the information "level in the pressurizer" and interpreted the rise of that level erroneously:

In fact, the rise of the level was quite normal and foreseeable in the case of a break in the pressure unit; but it seems that the operators at TMI were not trained to deal with this type of situation. (3, p. 526).

This error of interpretation led one operator to reduce the supply of injected water, by stopping one of the pumps:

The rapid rise of the level in the pressurizer made me think that the high pressure injection was excessive and that we would reach 'solid' state (5, p. 2).

One operator later confirmed.

This fear of reaching 'solid' state (this terra means a complete filling of the primary circuit with water) came from what the operators had been taught; that is to say that in a transitory situation it is important "not to lose the steam bubble in the pressurizer" because of the danger of losing control of the pressure in the circuit. The operators entertained this fear for more than four hours, stopping even the second injection pump and only restarted it and reduced the supply level at operating time: ten minutes; and even this despite some doubts:

The pressurizer was almost full; I couldn't believe it at the time. It was too fast ... that was the first damned thing. It had filled up, and we had thought it was already full. It should have been full with water but what afterwards misled us was that the system did not react as if it was 'solid'. We saw no pressure peaks, (5, p. 2) declared one operator two days after the accident.

The operators were therefore not aware that the primary circuit was emptying itself progressively. There had also been the automatic start (at operating time: 7 minutes 30 seconds) of the draining pump that would send the contaminated water to the storage tanks in a building that was not water-tight. The pumping was actually interrupted when an operator realised this transfer : he did not know where this water came from and whether it was radioactive.

The operators were also not aware that the water in the primary circuit was boiling despite the restart of the emergency water supply from the steam generators. However, the readings of neutron flux were abnormally high (that warned the operators that there were bubbles in the core); the primary pumps showed signs of a loss of flow (due to cavitations caused by pumping a mixture of water and steam). The operators first stopped the two pumps of loop B (operating time: 1 h. 14 min.) and twenty five minutes later those of loop A.

b) The next few hours: the hierarchy of the centre is on the spot. Two hours after the start of the accident, the accident situation was still unidentified. The engineer on duty had been on the spot for one hour; other operators, among them three engineers, arrived in the control room. This was when telephone contact was established, the first contact with the outside world, with the engineer who represented the Babcock company, the manufacturer of the boiler, at the centre, and when the question of the position of the discharge valve of the pressure unit was broached.* This led to its closure at operating time 2 h. 22 minutes.

The pressure in the primary circuit rose again immediately. The technical experts who analysed the accident in detail confirmed that the operators had information at their disposal which should have led them to the discovery of the failure of that valve:

- The indication of increased temperature downstream from the valve: this indication which is normal at the start of an accident (since the valve is normally open) should have raised the operators' suspicion because it revealed the presence of primary fluid passing through the valve. The operators knew that this valve leaked before the accident (leakage four times higher than normal). This indication was therefore explicable. The idea occurred to them to test this valve** but as they declared a few days after the accident they were reluctant to undertake such a test after the difficulties they had encountered at the reopening of this valve during previous trials (5, p. 2).

- The water level in the discharge tank: this information was not relayed to the control room so that they would have had to check in neighbouring premises.

After the closure of the discharge valve, the operators hoped that natural circulation would establish itself in the primary circuit between the hot point (the core) and the cold points constituted by the steam generators. However, it did not happen; the state of the primary circuit was not conducive (pockets of steam in the high points of the circuit) to natural circulation to be established. The temperatures rose. The operators decided to restart the primary pump.

Until then the different periodical alarms signalled a low level of reactivity. During the third hour of the accident various signals indicated increased levels which led the duty engineer and the watch-keeper of the centre to order a state of emergency on the site a little before 07.00 h.

A few minutes later the chief of the centre arrived in the control room and took over control of the operation by forming a team to deal with the accident and to put the emergency plan into operation. The command post was established in the control room of the other section (TMI 1). General alert was given at 07.24 h by the chief of the centre.

However, the technicians did not succeed in their efforts to get the situation under control. Their problem was the cooling of the core in the knowledge that the primary circuit contained a lot of gas. This was a critical time: at operating time 2h 48 min. ... it was evident that the top part of the core was without cooling fluid, down to two thirds of its height which is 3.66 m (1, p. 100).

*to do this it suffices to shut the isolated valve upstream — see diagram.

** The engineer from Babcok who have known of the incidents which had occurred at the centres of Oconee (June 13, 1975) and David Besse (September 14, 1977) with the discharge valve of the pressurizer should have been forewarned of the problem.

This situation was not foreseen in the original plans and was therefore outside their thinking*. It forced the technicians to improvise and to try and cope as best they could.

At operating time 3 h 13 minutes they had to interrupt the forced circulation in the primary circuit (because of strong vibrations of the pump which had been restarted); they also had to isolate the steam generator of loop B on its secondary site (where minor escapes caused contamination of the secondary water).

The operators decided to release the residual heat into the atmosphere (which constitutes a cold source) and to reduce the pressure in the primary circuit (so as to recreate a liquid condition in the primary circuit). In order to do this they proceeded, height of irony, to reopen the famous discharge valve of the pressurizer and to start the safety injection system, the output of which they were just going to reduce (still in order not to fill up the pressurizer). It seems therefore that in the end the reinstatement of the discharge valve to 'normal' condition after operating time 2 h 22 minutes had done more harm than good.

The radioactivity continued to increase. At operating time 3 h 20 minutes an alarm signal indicated a level of radioactivity in the dome of the enclosing wall of 8 rem/hour which, given the fact that the detector is protected by lead, corresponds to a radioactivity of 800 rem/h. Nearly four hours after the start of the accident the surrounding wall was automatically isolated**. In fact, the surrounding wall was not totally isolated because the pipes continued to transfer the water gathered in the draining trap of the surrounding wall to the storage tanks in the auxiliary building (1, p. 102). The third barrier was therefore by-passed. More than four hours after the start of the accident the operators, after having failed to reduce the pressure in the primary circuit sufficiently (which would have allowed the core to cool through the cooling system normally used when the reactor is not operating) tried to reestablish cooling by means of the steam generators after closing the discharge valves of the pressurizer again and after restoring the safety injection to full out-put. The pressure in the primary circuit was again raised to 140 bar.

c) The course of events: the operators, the responsible technicians of the centre, the experts (NRC) are all in the control room. At 10.05 h a group of five experts from the NRC arrived on the site; two of them went to the control room of TMI 2.

The level of radioactivity increased to the extent that the staff had to put on masks with filters, which did not help communications. The technicians battled on to cool the core ; but the natural convection in the primary circuit was still not established. At 11.38 h the operators returned to their first idea: to force down the primary pressure in order to cool with the cooling system used when the reactor is not operating.

Whence: stoppage of the safety injection (which had worked at full out-put for nearly three hours) and reopening of the discharge valve.

Eight and a half hours after the start of the accident the pressure in the

*We shall see in Chapter 3 what precisely this term means.
**See preceding paragraph on technical characteristics.

primary circuit at last reached 40 bar. The water tanks which belong to the safety injection system emptied their water into the primary circuit and thus stopped depressurisation. It would take another seven hours until a situation was reached which could be called acceptable from the point of view of cooling the core (this cooling being achieved by the generator of loop A and by circulation in the primary circuit ascertained by the pumps).

Meanwhile (at operating time 9 h 50 minutes) a dull noise was heard in the control room. The operators did not realise the significance of this noise and interpreted it as being due to the snapping of a shock absorber in the ventilation when in fact it was a hydrogen explosion inside the surrounding wall (1, p. 107).

During the following night (i.e. from Wednesday to Thursday) the operating staff divulged the presence of an incondensible gas bubble made up essentially of hydrogen in the top of the tank. It was now understood that the hydrogen came from the (exothermic) oxidising reaction of the Zircaloy (of the casings of the fuel which had reached a high temperature) and that the dull noise heard before had been an explosion of the hydrogen which had been set free by the breach of the primary circuit and had combined with the oxygen of the surrounding wall.

From Thursday morning onwards, a new feeling of disquiet settled on the technicians concerning the explosive capacity of the bubble of hydrogen captive in the tank. It proved to be non-existent much later because under the conditions in the upper part of the tank the oxygen required for an explosion could not continue to exist. This fear which was not unanimous among the technicians (the experts from the NRC were convinced of the risk of an explosion, contrary to those from the centre) was sowing an unbearable feeling of fear among the population.

As to the hydrogen in the surrounding wall, it could be eliminated by a system of catalytic recombination, the setting up of which took several days after the difficulties caused by the level of radioactivity.

2nd: Political confusion and social disquiet

Such an accident obviously concerned, in addition to the operators, two categories of participants: the various authorities and the public.

Wednesday, March 28. From 07.00 to 08.00 h: information given to the authorities by the operating company.

At 07.02 h, i.e. three hours after the start of the accident (the command post headed by the chief of the centre had just been set up) the Pennsylvania Emergency Management Agency was put in the picture. PEMA called the rescue centres of the three counties concerned. Those responsible at the NRC receives the information at the start of office hours (07.45 h): they could not be reached earlier.

The authorities learned at 07.35 h that general alert had been raised on site by the chief of the centre at 07.24 h. The state governor of Pennsylvania was informed about the situation. Teams were sent out in the vicinity to measure radioactivity.

b) 08,25 h: Control of the information slips out of the hands of the authorities and the operating company. After a journalist from the local radio station had alerted his station having noticed police and fire police in Middletown, the station's director of information telephoned the centre to talk to their public Relations service. By mistake he was put through to the control room.

"I cannot discuss (it) just now, we have a problem" (1, p. 103)

was the answer combined with the advice to call the company's headquarters, which gave some details but insisted that there was no danger. Radio Harrisburg announced the accident in its news bulletin on this basis.

At 09.15 h the White House was informed by the NRC.

At 09.26 h Associated Press broadcast the information. This promptness which was partly due to accident gave the officials short notice: a good many among then were put in the picture by the media, the mayor of Harrisburg first learned about the accident from a phone call by a radio station in Boston (!).

c) End of the morning: the first contradictory information. The operating company loses credibility. At the end of the morning the Lieutenant Governor, Mr Scranton, called a press conference and made a brief statement:

The Metropolitan Edison Company has informed us that there has been an accident at TMI 2. Everything is under control. There is no danger to the public ... There has been a small release of radioactivity into the atmosphere. All safety equipment has functioned correctly. The company keeps constant control of the-radioactivity around the site since the start of the accident. No increase in the level of radioactivity has been discovered; the level has remained normal (1, p. 106).

Until midday the Public Relations service of the company continued to deny the existence of radioactive escapes. However, at 11.00 h all non-essential staff left the island.

The Mayor of Middletown, the town where the centre is located, was assured by telephone by the board of Metropolitan Edison that no radioactive leak had occurred. Twenty seconds later he learned from the radio that there had been radioactive escapes. The operating company told him only five hours later.

This confusion in the information given on escape or non-escape of radio- activity originated mainly from a lack of coordination within the operating company. Metropolitan Edison. This caused it to lose its credibility in the eyes of the public and the authorities.

d) Afternoon: The media are on the spot. Information swamps the United States. The information media began to swarm out: numbers of radio and news-paper reporters, photographers, cameramen. Lieutenant Governor Scranton held a second press conference. The style was quite different from the one in the morning:

The situation is more complex than the operating company had us believe earlier on. We have taken measures. For the time being we think there is still no danger to the public. Metropolitan Edison has given you and has given us contradictory information. We are about to have a meeting with the people in charge of the company and hope to be able to answer most of your questions. There has been an escape of radioactivity outside the centre ... The company has informed us that the steam which contained a measurable quantity of radioactivity escaped between 11.00 and 13.30 h (1, p. 109).

Millions of Americans learned about the accident from the TV news at 19.00 h. The mayor and the municipal council at Goldsboro, 2.5 km from the centre, started talking to the inhabitants of the small community from door to door. They told them what they had learned through the media and through official channels. They brought up the case that the governor might order general evacuation and advised the inhabitants to judge for themselves the opportunity to evacuate without waiting any further while themselves considering this not to be worthwhile.

e) Thursday, March 29: relative calm. The morning papers, regional and national, reported the accident on their front pages on the basis of partial and often contradictory information.

On the spot the level of radioactivity remained high in several parts of the centre. Outside there did not seem to be a serious problem. However, at 14.10 h a helicopter registered a short emission of radiation: 3,000 millirem per hour above the centre. During the afternoon the NRÇ also became worried about the release of mildly radioactive water from the centre. This was discharge water: the tanks were now full up. This was-done without informing the communities or the press, and it did not augur -well for public relations. When the information about these, releases reached him, the president of NRC insisted that they be stopped immediately. This was at. 18.00 h; 180,000 litres had been shed. A solution had to be found for this discharge water of which 1,800,000 litres were already in storage. After hours, of discussions the Department of Environmental Resources of the state, issued a press communique in which it acknowledged the, very reluctant, acceptance of the need to release this water. The water releases were stopped shortly after midnight.

At the end of the afternoon the governor held a press conference. A member of the NRC announced to the journalists that there was no longer any danger for people from the island. The Governor did not agree with him; the events were soon to confirm his doubts. At 18.30 h the NRC received an analysis of the cooling water from the reactor; it appeared that the core had been much more seriously damaged than had been thought until then. At 22.00 h this news was telephoned to the Governor's office: There is now a greater possibility of radioactive leakage. Nothing had changed at the centre except this new knowledge which the NRC now had of the situation.

f) Friday. March 30: confusion — 200,000 people leave the area spontaneously. A 'horrible coincidence', to use a phrase by the commission's president, Kemeny, weighed heavily on this confusion. At 07.10 h, without warning the authorities, the operations supervisor at TMI 2 decided to transfer radioactive gas from a tank (located in an auxiliary building and destined for supply to the primary circuit) to a discharge tank, as the pressure in the former inhibited the circulation of the cooling fluid. The supervisor knew that that this would have damaging consequences on the level of radioactive emission as the whole system involved was not water-tight. In fact, when measures had to be taken, 1,000 millirem/hour were registered at 07.56 h, 1,200 millirem/hour at 08.01 h at 40 metres above the centre. It appeared that there was disquiet at the NRC about the discharge tank* if it did fill up completely there was a risk of rupture of the safety disc and of a prolonged and substantial escape of radioactivity. Just so: at 09.00 h came a warning that the tank was full. One of the experts made a rapid calculation: the rupture of the disc would cause an emission of 1,200 millirem/hour. Some ten or fifteen seconds later someone announced that 1,200 millirem/hour had been measured at TMI ... This caused consternation. In order to understand the situation, the Kemeny report stresses, it must be pointed out that the communications between the NRC officials and the operating company had never been good. Later on the NRC found out that the radioactive emission did not come from the discharge tank, that ic had not been full. However at the time, under the shock and without querying the figure of 1,200 millirem/ hour, action was taken.

The NRC let PEMA know that people high up in the organisation had recommended that the Governor order evacuation. A radius of ten miles was suggested. However, the director of the Bureau of Radiation Protection thought that evacuation was not necessary. The director of the emergency service of Dauphin county had been warned by Metropolitan Edison of the existence of radioactive emission (08.34 h). Twenty minutes later PEMA confirmed this but stressed that no evacuation was necessary. At 09.25 h the director of PEMA informed him that an official evacuation order was expected within the next five minutes; those responsible at the service in the other two counties of the region received the same message. The fire police stations within a radius of ten miles were alerted and an appeal broadcast: an evacuation order might be given.

Shortly after 10.00 h the Governor talked on the telephone to the president of the NRC: no evacuation was necessary; nevertheless, a suggestion was made to the Governor: to request everybody living within a radius of five miles to stay at- home for the next half hour. The Governor agreed and later in the morning advised everybody living within a radius of ten miles to stay at home. The Governor also demanded from the president of the NRC that an expert be sent to him. An hour later the president phoned the Governor and told him that an expert was being put at his disposal and that special communication links between TMI, the Governor's office, the White House and the NRC were being set up.

At 11.40 h the president of the NRC telephoned the Governor and offered the apologies of his organisation: the NRC had been mistaken and evacuation was not necessary. Nonetheless, after various discussions, the Governor decided to recommend evacuation of pregnant women and children of pre-school age within a radius of five miles; all schools in that area were closed. This «as announced shortly after 12.30 h.

On the part of the operating company, the situation looked hardly brighter as regards public relations. During a press conference the vice president of Metropolitan Edison lost credibility again: he knew nothing of the problem of that 1,200 millirem/hour and acknowledged his refusal to give all available information. The following day the White House complained to the industrial group about the large number of contradictory statements which had been issued by them.

All these things caused a large number of residents to leave. Evacuation plans were being prepared. A radius of five miles affected 25,000 people. Within a perimeter of ten miles there were 130,000 people, three hospitals and old people's homes. 650,000 people, thirteen hospitals and a prison were within twenty miles.

At 14.00 h Denton* arrived on the spot accompanied by a dozen people from the NRC. The prime preoccupation was the elimination of the hydrogen bubble that had developed in the reactor. Of course, it was not expected to explode immediately but one had to get rid of it. Towards 20.30 h Denton put the

*The expert delegated to the Governor as promised by President Carter.

Governor in the picture: the core was severely damaged; the bubble caused a problem for the cooling of the core; no immediate evacuation was necessary. At 22.00 h the two men called a press conference in the course of which the Governor said again that there was no need for evacuation, retired the council asking them to stay at home but upheld his recommendation that pregnant women and pre-school age children should leave. The Health Department (DHEW) was worried about the possible fall-out of radioactive iodine and undertook the collection of iodide of potassium. An exceptional mobilisation of the industries involved was needed to meet this request; remedy began to arrive the following day. Finally, one controversy remained: Had the White House dissuaded the Governor from requesting the declaration of a state of emergency by President Carter?

During the day 50 per cent of the residents of the area within a five mile radius had spontaneously left as well as a third of the population within the ten mile zone. Altogether about 200,000 people left the area. The event obviously received wide media coverage.

g) Saturday, March 3I: the worry about an explosion of the hydrogen bubble. The big worry about a possible hydrogen explosion came during the weekend. That this had been an unfounded fear, an unfortunate error, the Kemeny report stresses, was never subsequently understood by the public, partly because the NRC never made any effort to admit that it had been mistaken (1, p. 126).

The risk of a hydrogen explosion and possible evacuation of a million people made the front pages of the morning papers. At 09.00 h those respon~-sible at Metropolitan Edison indicated at a press conference that the gas bubble had diminished in size by about two thirds since the night before,- at the same time H. Denton estimated a reduction of only 10 to 15 per cent. Those responsible at the operating company announced that they would not hold any more press conferences. During the morning a NRC press centre with seven communications people was installed in Middletown; H. Denton was confirmed as official spokesman. At that time 300 journalists were on the spot.

It was known that the danger of an explosion of the bubble would become serious if there was a significant presence of oxygen. Towards midday, after analysis, it appeared that there was indeed a formation of oxygen. The president of the NRC advised E. Denton to warn the Governor of the potential danger. Towards 13.00 h, however, the analyses showed that the oxygen would not cause a dangerous situation for another two or three days. During the night on Saturday other calculations indicated that the percentage of oxygen in the bubble was at the threshold of inflammability. Towards 18.45 h the question of the effect of an explosion had already been studied: the tank would stand up to it.

At 14.45 h the president of the NRC let it be known that a precautionary evacuation of a ten to twenty mile zone might be necessary if the engineers considered it necessary to let the bubble out of the reactor. This could damage the core and also make the bubble explode. In the evening at 20.30 h Associated Press stated the worries of certain NRC experts concerning the Possibly imminent explosion of that bubble. During a press conference H. Denton and the Governor confirmed that there was no imminent danger and that there was no difference of opinion among the NRC experts. However there was contradiction, the Kemeny report stresses (1, p. 130), and H. Denton had analyses made ... all the more so as President Carter had announced his arrival for the next day. The Health Department continued to work on a Possible evacuation and was determined to proceed with it immediately should the nrc not give assurances about the cooling of the reactor.

h) Sunday, April 1: more confusion. Throughout the night from Saturday to Sunday the offices in charge of preparing plans for evacuation were inundated with telephone calls : the citizens worried about the contradictory information about the hydrogen bubble. The fact that the federal administration had taken charge of the situation deprived the local authorities rather largely of access to the information and of their initiative in the action (1, p. 131). A local member of the House of Representatives who could reach neither the Governor nor the Lieutenant Governor on the telephone let it be known shortly before midnight on Saturday that failing information Dauphin county would issue an evacuation order for the following morning 09.00 h. At 02.00 h a meeting was suggested; it was to take place at 09.00 h. On this occasion the director of PEMA too complained about the difficulty he had encountered in trying to get information. That morning too the Catholic bishop of Harrisburg authorised the curates of the parishes in the region to give general absolution to the faithful during Sunday mass (this canonical dispensation is authorised only in case of war or serious crisis).

At 14.00 h President Carter arrived and visited the centre before holding a press conference. In mid-afternoon new readings showed that the bubble in the reactor was diminishing. For the rest of the afternoon the NRC knew that there was no longer any danger of an explosion. Partly because this was not yet certain, the news was not released.

i) Monday, April 2: caution at the NRC. At 11.00 h at a press conference H. Denton announced a very substantial diminution of the size of the bubble; but calculations would still be necessary (the operating company had already let it be known that the bubble had disappeared). H. Denton acknowledged that there could have been error or exaggeration on the part of the NRC; he displayed very cautious optimism so as not to lose credibility. During the afternoon in a public statement the mayor of Middletown disclosed that he had given orders to the municipal police to shoot all possible pilferers.

.j) Epilogue: end of Act One — Start of Act Two — also set in uncertainty. The accident at TMI did not end with the disappearance of the bubble; a small bubble remained, there was still gas in the cooling water and the reactor itself had been seriously damaged. There were still periodical but small escapes of radiation and some feared a major escape of radioactive iodine 131. The schools remained closed. The Governor's recommendation for the evacuation of pregnant women and pre-school age children remained in force. There was discussion among those responsible as to whether iodide of potassium should be distributed; in the end and in view of the small doses of dispersed radioactivity as well as on account of the risk of reviving fear among the population unnecessarily it was decided not to go ahead with this distribution.

On April 4, the schools were reopened except within a radius of five miles; the evacuation recommendation remained in force. The NRC wanted a marked event before lifting this recommendation : a significant reduction of the temperature of the core for instance.

The accident did not end with the cooling of the core either. There had been more than 3.5 million litres of contaminated water inside the confinement wall or in the tanks of the auxiliary building in April; radioactive gases remained in the surrounding wall; the core was severely damaged; radioactive elements contaminated the walls, the soil and the machines in several buildings. There was an unprecedented amount of decontamination work to be done, estimated at a cost of between 80 and 200 million dollars; it would need several years. In addition the operating company requested permission from the NRC to release Krypton 85 into the atmosphere in small quantities (in order to regain within the limits).

Entry inside the surrounding wall will not be possible until the radioactive gases have been extracted. Nobody knows exactly what state the core of the reactor is in. The accident will therefore continue to cause anxiety,- workers will continue to be affected by further quantities of radioactivity. Five of them had doses above the norm in August 1979. For the public there remain strong reasons for concern.

3. SOME LESSONS TO BE LEARNED FROM TMI

Without attempting an exhaustive analysis and without substituting for the technicians in their detailed analysis of what happened, in order to draw all possible conclusions a certain number of lessons impose themselves immediately on the neophytes who try to understand as best they can what happened and why it happened in the way it did. The lessons are of two orders: of the technical order i.e. relating to the installation as such and to its way of working; then of the social and political order i.e. relating to the problems of information and relations between the various parties: the operating company, the safety authority and the public.

1st: Technical lessons*

For the layman, the accident at TMI has revealed certain difficulties or insufficiencies likely to exist in the workings of a nuclear centre.

a) The difficulties encountered by the operators in controlling the state of their installation in an accident situation. This accident has shown clearly the profusion of information which the operators found themselves confronted with from the time of the initiating incident: the complexity of the surveillance of the large number of the centre's components. It will be necessary for the technicians to visualise in advance the interfacing of the operators and the total of information in order to draw from them the essential data which are, at the time, 'digestible' by man.

b) The difficulty of conceiving systems of surveillance or information which are simple to interpret and unambiguous. The example of the information 'discharge valve of pressure unit shut1 is very revealing since in the event it was not the valve that was shut (it had remained wedged open) but the order to shut which had been given (the information "cut off power supply to the control motor" is read as "valve shut").

c) The difficulty of protecting oneself against failures of a common order. These failures which are difficult to foresee often reveal themselves a posteriori as being evident i.e. once the incident has occurred. They require detailed analysis of every system, keeping in mind surrounding systems (geographical proximity can favour such an eventuality) and the functionally linked systems.

In this way the common mode failure of the water supply pumps could have been identified (they had a common auxiliary circuit) or the common mode failure of the closure of the two valves in the emergency water circuit (the valves had probably been closed in order to test the emergency water pumps and it had been forgotten to reopen them) .

This research into potential common mode failures is really indispensable

* These questions will be taken up again and developed later on (in Chapter 4).

since such failures render all the efforts made by the designers of the system useless (even attempts to improve reliability by duplication of components are made useless).

d) *The lack of knowledge of the operators and perhaps also of the designers in the knowledge of the post-accidental situations*. The hesitation of the operators in achieving an acceptable situation from the point of view of the cooling of the core, show at which point the systematic study of the cooling of a core by a mixture of water and steam had failed. The operators had to proceed by trial and error skillfully, by the way, to get on top of the situation; starting the safety injection system and then stopping it, closing the discharge sluice of the pressure unit and then opening it. A better knowledge based on reliability analysis would no doubt have permitted faster control and less damage to the core.

The hydrogen explosion in the surrounding wall, wrongly interpreted, was another demonstration of this lack of knowledge.

e) *The sloppiness of the operating company in its instructions*. It seems that a conscientious attitude on the part of the operating company would have had to lead it to a stoppage of its installation, knowing the existing difficulties with the discharge valve of the pressure unit which in the end turned out to be the source of the accident.

The operators stated to the Commission of Enquiry that they knew that this valve leaked abnormally and that it had some weaknesses (failure to close during previous tests). Keeping in mind the knowledge of this state of dilapidation, the operators were led to gross errors of interpretation and judgement. One can doubtless confirm that if the valve had been in proper order before the accident, the operators would not have needed 2 h 20 minutes, with the same information available, to discover its failure.

This is, incidentally one of the conclusions drawn by P. Tanguy (3, p. 531).

f) *Lack of conscientiousness in the design*. The designers put three barriers in sequence between the fuel and the public in such a way that in case of failure of the first (casing) and the second (primary circuit) the dangerous products could be confined in the surrounding wall (the third barrier).

The accident at TMI has shown clearly that in fact this third barrier could be by-passed (via the ducts). True, it played a fundamental part since it fulfilled its function well in confining the gaseous products; but a more conscientious design would not have permitted that the water from the primary circuit that had leaked into the draining trap of the surrounding wall, could also be transferred to the exterior of that wall.

The knowledge of the failures which had occurred on the same type of discharge valve of the pressure unit in the centres at Oconee and at David Besse should have led the designers, in this case the Babcock and Wilcox company, to review the design of this valve on its installation.

To conclude our comments on the difficulties and insufficiencies we take up once more the statements made by the Kemeny commission:

A number of factors have contributed to the inappropriate action of the operators such as the insufficiencies in their training, the lack of clarity in their conduct procedures, the failure of organisations to draw the right lessons from previous incidents and the deficiencies in the design of the control room. These insufficiencies are the work of the operating company, of the builders and of the Federal Commission which regulates nuclear energy. This is why the operator error does or does not 'explain' this particular case: these insufficiencies in the end brought about an accident like the one at TMI, of this we are convinced.

2nd: Lesson on the capacity for social control of the event

The climate of uncertainty, even fear, which reigned during those few days is due on the one hand, to a number of difficulties in communications between the various parties, difficulties leading to erroneous or contradictory information; on the other hand, to the inefficiency in the preparation of plans by the various authorities which were to be enacted in case of serious accident.

More precisely and without wanting to generalise abusively a certain number of points have to be revealed from the experience gained in Pennsylvania at the end of March 1979.

a) The difficulty of 'controlling' information. One might think, in such circumstances, that a good filtering of information would permit a better management of collective agitation, better anticipation of psychic stress and also better safeguarding of the chances of the adopted development programme.

The experience at TMI shows how fragile this construction is. One error at a telephone switchboard, and the Director of a Press Service is connected to the control room: the information goes on the air. Local and national personalities are alerted by the radio, at the steering wheel of their cars while they go to their jobs, or by a phone call from a journalist who works several hundred kilometres away (Boston). A press conference is organised but the authorities do not have the information, as we have seen, because of the reticence of the operating company. A press conference is organised by the operating company but it does not know that what it wants to silence is already too well known; it loses its temper: "Nothing obliges me to tell you what I know". Thus credibility goes out of the window.

Certainly, H. Denton (NRC) appears much better qualified but there is a great difficulty : How does one 'control' information when it is by its nature, we are in a disaster situation, incomplete, uncertain, explosive, sometimes aberrent, including phenomena which threaten to amplify the problem?

b) The difficulty of managing the uncertainty. TMI has confronted people in responsibility with an accident of a new type. The number of unknowns in the equation to be solved ruled out assured reasoning. Faced with an explosion, a fire, an avalanche one 'sees', one 'clears the ground', one narrows down the unknowns.

Here, the person responsible has to rely on experts who find it difficult to explain theoretically and empirically what is happening, as H. Lewis notes:

The later development of the accident and in particular the formation of a hydrogen bubble had not been foreseen by any of the prior analyses partly because these analyses never went beyond the first phases of the accidental sequence. The operators therefore soon found themselves faced with a situation which had not been foreseen and for which they had not been trained (7, p. 85). Here, the experts had measuring devices which did not give them reliable readings (apparatus blocked to the maximum, apparatus broken down, disturbing background noises etc.). The models for comprehension of what was happening failed: one did not know how to construct new models in real time (this was the difficulty in understanding the phenomenon of the massive production or hydrogen for instance).

To this background uncertainty must be added that which attached to messages that originated from extremely varied interests. The builders, the operating company, the federal safety agency all had their own objectives; this cannot be without influence on the information given to the decision maker. This is immediately true concerning some of the most competent experts. H. Denton (NRC) did say for instance that he had put the brakes on the production of optimistic messages in the last phases of the critical period in order not to harm the image of the NRC, which doubtless resulted in a blackening of the picture presented; what is true in one sense is true in the other when one considers the behaviour of the operating company. This absence of clarity became still more massive as the number of experts grew. D. Nelkin in particular writes:

Hundreds of specialists from the NRC and other federal and national agencies came to THI. Other experts came from companies, the nuclear industry, anti-nuclear groups. Their evaluations of the problem, of its dimensions and its causes were just as varied as their interests, their pre-occupation with the future of nuclear policy and the image they wanted to create (6, p. 3).

c) The difficulty of dealing with an unprecedented situation. In the case of TMI the evacuation plans were not ready. The telephone links between the various responsible authorities had not been set up. The crisis headquarters had not been constituted. The authorities (NRC) could not be reached before the opening of offices etc. The confusion could only be massive.

What one had to know how to do was not operational. It was a matter of going beyond the normal limits: dealing with the unprecedented, possible evacuation of a million people based on uncertain information, the uncertainty being impossible to remove until after the critical period.

One ended up by resorting to methods which are incongruous to our age of high technological sophistication: the mayor of Goldsboro ran around the streets with his municipal council and went from door to door with nothing better to offer than: use your own judgement. We dare not tell you to leave your houses (1, p. 111).

4. BALANCE SHEET

The Kemeny report estimated that despite serious damage to the centre the largest part of the radioactivity was contained within the surrounding wall and that the leaks which occurred will have only a negligible effect on the physical health of individuals. The major effect of the accident occurred on the level of psychic stress.

The report acknowledges that even small doses of radiation can have genetic effects. However in the case of TMI they have been really minimal. If there are effects they will be so small in number that they cannot be statistically established.

The financial cost to the operating company is estimated at one or two billion dollars. This cost would become much higher if it were proved to be impossible to put the centre back into operation (1, p. 13).

Finally, the accident has diminished the public's confidence in the nuclear industry. The Commission of Enquiry did not stop at this point. It asked the question: What if .. ? What would have happened if things had not gone the way they did? We shall come back later to this rather uncommon approach. There could have been fusion of the core :

The NRC estimates that if the drying up of the core had occurred earlier in in the course of events fusion would have been quasi certain (10, p. 13).
One may ask oneself: if it had happened, would there have been time to protect the public ?

Nevertheless, this particular centre, on account of its exceptional location, the greater than usual thickness of the concrete surrounding wall, would have been able to contain the radioactivity which would have resulted from that fusion, as the Kemeny report stresses before pointing out that one cannot be absolutely certain of the result, that there might also have been faulty handling in the fusion situation ...

In any case, the Kemeny commission concludes, accidents as serious as the one at TMI cannot be permitted to happen in the future (1, p. 15).

Nevertheless, let us dwell on the possible effects of the incident on health. There is no unanimity concerning the amount of radioactivity released: the estimates have varied widely. An independent enquiry carried out by an anti-nuclear engineer gives the following information : on April 11 the level of radioactivity twenty miles from the centre was five times the normal; on April 16 the level of radioactivity thirty miles from the centre was fifty times the normal. The figures are obviously very different from those given by the NRC which estimated that at the end of April the radioactivity five miles from the centre had reverted to an almost normal level.

Let us also remember here the problem of uncertainty. This is an essential dimension of risks and disasters in our time. Various technical reports were able to give evidence of the fact that:

Three hours after the accidental process a large number of indicators of the level of radioactivity went beyond the limit of their scale (8).

The greater part of the detectors was unusable at that time (9, p. 12). This was because the environment contained rare radioactive gases : Xenon and Krypton; the level of background noise was therefore artificially raised. Do we therefore not really know what escaped there*?, asked G. Gibson, one of those responsible at the NRC, in the course of the enquiry. "Exactly", was the answer.

As a French technical report remarks this uncertainty may be prolonged: In the course of a conversation Commissioner Bradford (from the NRC) dwelt on the legal difficulties which may have to be dealt with as a result of the absence of safe data concerning the radioactive leaks during the first days. (10, p. 15).

There will still be the difficulty of being sure about the future. The

*This was the chimney of the auxiliary building; the needle of the indicators which were installed there was positioned at the maximum of their scale.

removal of the water in the surrounding wall had not yet been started at the end of summer in 1980. One could read these lines in a specialised document:

The officer responsible for the protection against radiation in Pennsylvania (Th. Geruski, Director of the State Bureau for Radiation Protection) estimates that the evacuation of the population living around the accident reactor at TMI "is an imminent eventuality" and will remain so at least during the four years needed for cleaning up and repair (11, p. 2).

5. CONCLUSION

Whatever else might be said about it, the accident at TMI did come as a surprise. The operators were put out of action by phenomena which they did not know. Before control over the situation could be reestablished, scenarios of disaster could have developed. The technical uncertainty was strongly felt for a long time. Effects on health will probably be minimal but assurances in this respect must doubtless remain cautious. The potential danger is actually far from negligible. The economic cost of such an incident is enormous. Finally, as we shall see later on, this event forces a review, to say the least, of certain safety principles.

To conclude this chapter, which we are convinced, requires complementing, spelling out and corrections, we shall quote these essential observations from the report by President Carter:

We are convinced that if the operating companies and the safety authorities do not make changes they will end up by destroying public confidence completely, and they shall be responsible for the elimination of nuclear energy as a viable source of energy (1, p. 25).

One ultimate remark, nevertheless. This judgement by the commission set up by President Carter is especially valid for countries which treat alternative sources of energy lightly or have set things up in such a way as to treat them lightly. In other countries which could not or did not want to equip themselves with sufficient strategic flexibility a different scenario would be more probable in case of a nuclear disaster: recourse to force, the pursuit of nuclear development policy by other means. One must, nonetheless, remain cautious. A large-scale nuclear disaster could also result in, for instance, considerable breakdown at the level of the responsible organisations.

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