SOME ASPECTS OF NUCLEAR POWER PLANT SAFETY UNDER WAR CONDITIONS

NUCLEAR REACTOR SAFETY

KEYWORDS: *nuclear safety, war conditions, safety analysis*

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In the summer of 1991, the Krško nuclear power plant in Slovenia found itself in an area of military operations. This was probably the first commercial nuclear power plant to have been threatened by an attack by fighter jets. A number of never-before-asked questions had to be answered by the operating staff and supporting organizations. Some aspects of nuclear power plant safety under war conditions are described, such as the selection of the best plant operating state before the attack and the determination of plant system vulnerability and dose releases from the potentially damaged spent fuel in the spent-fuel pit. The best operating mode to which the plant should be brought before the attack is cold shutdown, and radiological consequences to the environment after the spent fuel is damaged and the water in the pit is lost are not very high. The problem of nuclear power plant safety under war conditions should be addressed in more detail in the future.

INTRODUCTION

Nuclear power plant (NPP) safety under war conditions is an area that is seldom addressed in the literature. Although the physical protection of the plant under such conditions is the task of military, police, and civil defense forces, it is the responsibility of nuclear professionals to investigate possible scenarios and their consequences from the nuclear safety point of view. There are a number of lessons to be learned and implemented into emergency response procedures. One such lesson was learned in the summer of 1991 at the Krško NPP in Slovenia during the military attack by Yugoslav federal forces.

Everybody involved with NPP operation in Slovenia found himself in a situation that had not been encountered before. The Krško NPP was probably the first commercial pressurized water reactor (PWR) in the world to find itself in the middle of a war. The Iraqi research reactors in the 1991 Gulf War were perhaps in a similar situation. Very little guidance on the appropriate preventive measures for such a situation could be found in the literature. A number of preventive steps were taken on the site by the plant personnel. This paper describes the related activities of the Reactor Engineering Division of the "Jožef Stefan" Institute at that time. The division has ~20 people and covers several areas of nuclear safety.

The "Jožef Stefan" Institute supports both the Slovenian Republican Administration for Nuclear Safety (SRANS) and the nuclear power plant with analytical work related to nuclear safety. Immediately after the plant was shut down and it was obvious that a military attack could not be excluded, it was decided, together with the SRANS, that several analyses should be done as quickly as possible to support further decisions regarding operation of the Krško NPP or possible attack mitigation. The work that is described in this paper was performed in the month during and immediately after the war.

BACKGROUND

In the summer of 1991, a small European country, Slovenia, a former republic of Federal Yugoslavia, experienced a short but violent military attack. Among all the military activities, there were also threats of an attack on the Krško NPP [a 1876-MW(thermal), two-loop Westinghouse PWR]. The first anonymous threats of an attack on the plant by military planes were received in May 1991 from unidentified persons from Yugoslavia and also from a leader of a political party in another part of Yugoslavia. The statement received considerable interest in the mass media. The physical security of the plant was tightened.

After the declaration of independence by the parliament of Slovenia on June 27, 1991, the Yugoslav Federal Army staged a military attack on Slovenia. Activities were focused on the national borders, airports, and broadcasting transmitters. Normal life in the country was totally disrupted. During the first 14 days of the attack, there were almost no military activities in the vicinity of the Krško NPP. Nevertheless, the plant power was reduced to 75% of nominal power. The main concern at that time was the possibility of the loss of transmission lines from the plant and thereby a loss-of-off-site-power accident. The Krško NPP was originally designed to be able to sustain a loss of off-site power from a full load, but had never been able to successfully meet appropriate test requirements without a reactor trip. To prevent the reactor from tripping in case of a loss of transmission lines, reactor power was reduced.

The first cease-fire was agreed upon with the help of three ministers from the European Community on June 30, 1991. On the afternoon of July 1, 1991, three Yugoslav Air Force jet fighters flew over the Krško NPP at a very low altitude. This was an obvious threat to the safety of the plant. It became clear that one could not count on the common sense of the attacking force. The SRANS decided to shut down the plant and bring it to a cold shutdown. The power of the plant was slowly reduced, and the plant was finally manually scrammed on July 2, 1991, at 5:10. The cold shutdown condition was reached at 21:30 on the same day.

The military activities escalated over the next few days until the final political agreement was reached with the help of the European Community on July 7, 1991. Fortunately, there was no military attack on the plant during that period. The plant remained in the cold shutdown condition until July 16, 1991, when the SRANS decided that conditions existed for resuming operation and issued a letter withdrawing the request of July 1 for a plant shutdown.

The conflict was later resolved and is still being resolved by political means. A number of diplomatic activities and political pressures prevented a military attack on the facility. Later in the summer, when direct military actions were over, several transmission lines in the region of the plant were damaged by terrorist attacks. Therefore, plant power had to be reduced to 75% again for a longer period. As late as September 1991, it was considered that the situation was stable enough for full-power operation.

BASIC KRŠKO NPP DATA

The Krško NPP has a Westinghouse two-loop PWR with 1882 MW(thermal) and 632 MW(electric) (Ref. 1). It was put in regular operation in 1981. The architect-engineer was Gilbert Associates. Licensing was done on the basis of preliminary and final safety analysis reports, following relevant U.S. Nuclear Regulatory Commission regulations. The plant has a standard Westinghouse engineered safety feature actuation system. The emergency core cooling system has two independent trains of high-pressure pumps, two accumulators, and two low-pressure pumps, which are both also used for the residual heat removal. The high-pressure system injects into the cold legs, while the low-pressure system injects directly into the downcomer. The steel containment is surrounded by an annulus and a concrete shield building. A containment spray system, containment isolation, containment atmosphere cooling, and hydrogen recombiners are installed. Auxiliary feedwater to the steam generators is provided by two electric and one steam-driven pump. Two trains of essential service water are routed from the nearby river by three electric pumps. Emergency on-site power is provided by two diesel generators. There is also an emergency off-site power supply via a separate 110-kV line from the nearby gas power plant.

ANALYSIS OF THE EXPOSURE OF VITAL PLANT SYSTEMS

No NPP anywhere in the world is designed to withstand an air attack by military bombs or missiles! Provisions are taken only against terrorist attacks from the ground by light weapons. Some NPPs are designed to withstand the crash of an aircraft, but without any explosive materials. It was clear at the beginning of the crisis in Slovenia that there was no way to completely prevent damage to the equipment in the case of an attack. All our efforts were therefore directed to the minimization of possible public radiological consequences during such an event.

The critical safety functions under such conditions were checked:

1. subcriticality
2. core cooling
3. heat sink
4. integrity
5. containment
6. inventory.

Subcriticality is not a problem if the plant is shut down and the primary water is properly borated. All the other functions are endangered. The containment is directly exposed to missile attacks and may be considered the most endangered component. Next is the heat sink because the water intake structures and pump stations at the river are also completely exposed. The integrity of the primary system is endangered in the case of heavier bombing. Inventory may be endangered as a consequence of the loss of integrity, while the core cooling is primarily vulnerable through the loss of off-site power. Fortunately, if the plant is shut down, it is much easier to maintain or replace all degraded critical safety functions.

To estimate the vulnerability of different plant systems to the missile attack, the exposure of each system was evaluated and a "rose of vulnerability," similar to the example in Fig. 1, was constructed. The vulnerability of each system after the attack from different sides can be seen. This kind of diagram is helpful in preparing preventive measures and determining the most vulnerable systems.

The rose was constructed with the help of a three-dimensional computer plant layout model. The assumptions were that the system is completely destroyed if it is located on the side from which the attack is coming, that it is damaged if it is in the shade of one building, and that it is not damaged if it is located on the opposite side of the site.

Our main concern was devoted to maintaining the core cooling and the integrity of the spent-fuel pit.

Core Cooling

Immediately after the reactor shutdown, it had to be decided to what operational state the plant should be brought. The following proposals were considered:

1. removal of the fuel from the core
2. refueling mode
3. normal cold shutdown.

The analysis had to be performed quickly; therefore, there was no time for any extensive analytical work using sophisticated computer codes. It was mainly based on engineering judgment and expert opinion. The following are the main results of the analysis:

1. Removal of the fuel from the core would certainly ensure that there would be no major danger of the exposure of the population in the case of severe damage of the containment building. But where should

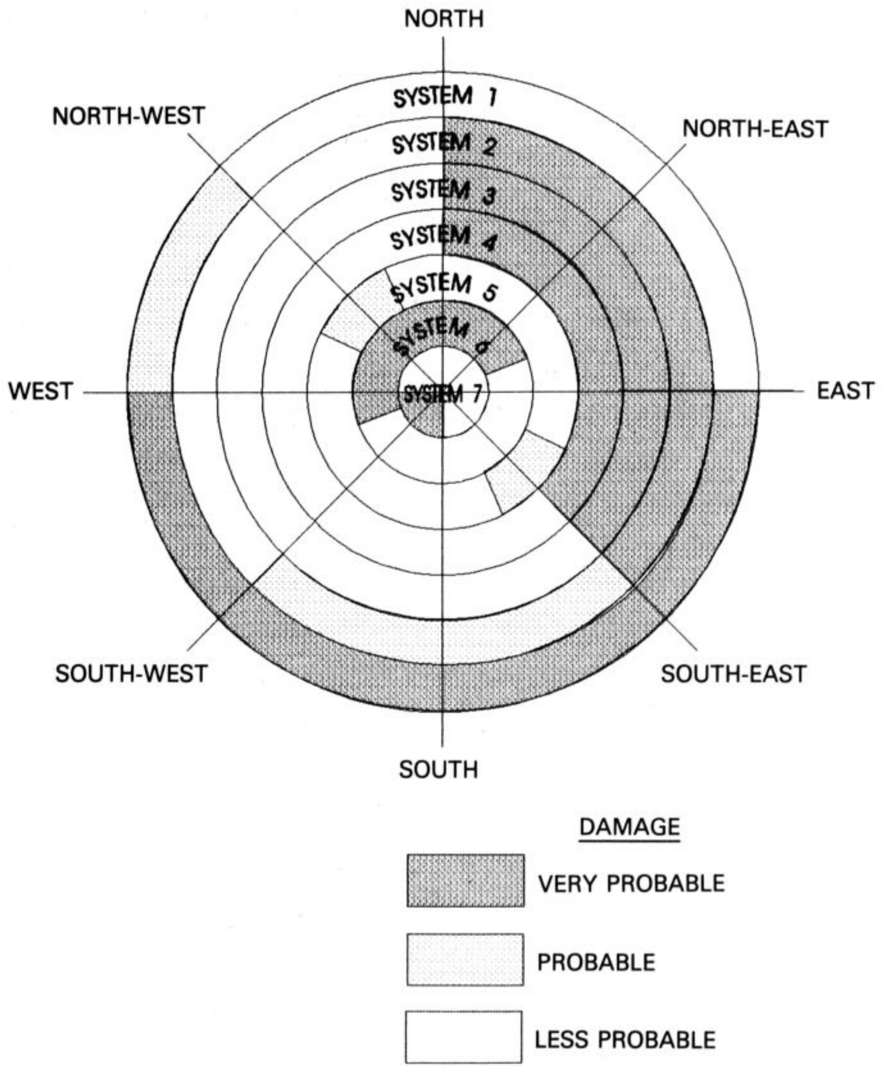

Fig. 1. Vulnerability of NPP systems to air attacks.

the fuel be removed to? The only possibility for immediate removal is into the spent-fuel pit on site. The spent-fuel pit is located outside the containment building, as in most similar NPPs. It is even more exposed than the structures inside the containment. In addition, the process of fuel removal itself increases risk and requires considerable time.

It was also concluded that the reactor vessel and the core are located so deep in the containment and shielded by various structures (containment building, steel containment, concrete structures, steam generators, pressurizer, etc.), so that very strong or concentrated repetitive missile deployment would be needed to destroy it. Fuel removal was therefore rejected.

2. Refueling mode was considered as the only normal operational mode in which the primary system could be opened. The reactor vessel is covered with a few-metres-high layer of water, which would certainly represent some protection against falling structures or missiles. On the other hand, there is a high probability that missile impacts would displace some structures in the containment and deform the seal ring around the reactor vessel. The refueling water would leak into the reactor cavity and be lost as a means of core protection. If the reactor vessel head is removed from the top of the core in such a case, there would be an immediate release of the radioactivity into the containment. This option was also rejected.

3. Cold shutdown mode was found to be the most appropriate option. The primary system is at atmospheric pressure; therefore, there is no problem, even if part of the system gets damaged. Core cooling is provided by the residual heat removal (RHR) system, and the heat is transported via the essential service water system into the river. The core is protected by all the structures above the reactor vessel and by the reactor vessel itself. No complicated maneuvers are necessary to bring the plant into this state.

After selecting the cold shutdown mode as the most suitable operational state of the plant, further vulnerability studies were done. Besides the possibility of direct damage to structures that would cause release of radioactivity, there are two important subjects to be considered:

1. alternating (ac) and direct current (dc) power supply
2. ultimate heat sink.

In the cold shutdown mode, the residual heat from the core is removed by the RHR system via the essential service water system to the river. The RHR pumps are electrically driven. To prevent core heatup, the long-term power supply and ultimate heat sink have to be ensured. But since the residual power of the core is relatively low, it is possible for the plant to withstand a certain period without it. To obtain an estimate of the time during which the plant may lose the power and heat sink without damage, the following scenario was analyzed by a simple hand calculation.

Loss of ac Power and Heat Sink During a Cold Shutdown

It was assumed that prior to the loss of heat removal capabilities (ac power and/or heat sink), the power plant was in cold shutdown for several days, producing ~5 MW of constant heat, which is ~2.6% of full power (in reality, the power level decreases with time). The heat had been removed via the RHR system. There was only ~25% water in the pressurizer; the rest was filled with nitrogen. Both steam generators were filled with water. At the beginning of the transient, heat removal from the primary system via the RHR system is completely lost.

The heat generated in the core would cause the primary system to heat up. Since we have assumed that the power-operated relief valve (PORV) at the top of the pressurizer is closed, the primary pressure would rise. Natural circulation would be established in both primary loops, transferring heat from the core to the secondary side of the steam generators. The secondary side would also heat up, but with some delay. The PORVs at the secondary side were assumed to be opened; therefore, the highest temperature the secondary water could reach is the boiling temperature at atmospheric pressure, i.e., ~373 K. It may be expected that because of the increased pressure, the subcooling in the primary system would not be lost. Therefore, the natural circulation would be sustained, and the heat from the core could be transferred to the secondary side.

The following equation was used to calculate the time needed for both the primary and secondary systems to reach boiling temperature at atmospheric pressure, 373 K (an initial temperature of 323 K was assumed):

$$t_1 = (m_{pr} + m_{SG1} + m_{SG2}) \frac{h_f - h_{pr}}{Q_c} , \qquad (1)$$

where

t_1 = time to heat primary and secondary water to 373 K

m_{pr} = mass of liquid in primary system

m_{SG} = mass of liquid in secondary side of the steam generator

h_f = liquid saturation specific enthalpy at atmospheric pressure

h_{pr} = initial specific enthalpy of primary liquid

Q_c = core power.

Inserting data for the Krško NPP into Eq. (1) gives ~4 h before all the water in the primary and secondary sides reaches boiling temperature.

The following equation can be used to estimate the time t_{1b} before all the water on the secondary sides of both steam generators is boiled dry:

$$t_{1b} = (m_{SG1} + m_{SG2}) \frac{h_s - h_{pr}}{Q_c} \quad , \tag{2}$$

where h_s is the saturated steam specific enthalpy. Specific plant data gave ~27 h.

If we also consider boiling water in the primary system (in which case the PORV on the pressurizer should be opened), we have some 47 h available before the entire primary system completely dries out.

To remove the residual heat by steaming secondary water while maintaining the water level in the steam generators, the following amount of water has to be added from the river:

$$q_b = \frac{Q_c}{h_s - h_r} \quad , \tag{3}$$

where h_r is the river water specific enthalpy. For the conservatively assumed core residual power of 5 MW, the water flow rate q amounts to <2 kg/s.

There is one further concern connected with heat removal by natural circulation from the core to the secondary side of the steam generator. If the primary water starts to boil, the natural-circulation flow in the primary loops may be interrupted because of the formation of steam in the upper parts of the steam generator U-tubes. If the PORV on the pressurizer is left closed, pressurization of the primary system can be expected. That would prevent the primary coolant from boiling. The following calculation checks the amount of the primary pressure increase.

The following equation is used to calculate the level change in the pressurizer after heatup of the entire primary system from 323 to 373 K:

$$\Delta l = \frac{m_{pr}}{A_{pr}} \left(\frac{1}{\rho_{100}} - \frac{1}{\rho_{50}} \right) \quad , \tag{4}$$

where

A_{pr} = pressurizer cross section

ρ_{50} = primary coolant specific density at 323 K

ρ_{100} = primary coolant specific density at 373 K.

For the amount of primary coolant in our NPP and the cross section of its pressurizer, we estimated the level increase to be 1.3 m.

In a cold shutdown, there is nitrogen in the upper part of the pressurizer. If we assume it to be an ideal gas, we can estimate the pressure increase after the calculated level change in the pressurizer (the compressibility of the primary coolant is, of course, neglected):

$$\rho_{100} = \rho_{50} \frac{T_{100} V_{50}}{T_{50} V_{100}} \quad , \tag{5}$$

where

$\rho_{50}, T_{50}, V_{50}$ = pressure, temperature, and nitrogen volume at 323 K, respectively

$\rho_{100}, T_{100}, V_{100}$ = pressure, temperature, and nitrogen volume at 373 K, respectively.

The pressure in the plant would rise from atmospheric to 1.57 bar. That would prevent the primary coolant from boiling, provided the heat is transferred to the secondary water at 373 K.

Results are summarized in Table I. These results give the operator ample time for mitigating actions. More than a whole day is available to provide the required amount of water for heat removal. This amount is rather small (<2 kg/s) and could easily be supplied by a mobile pump, i.e., a fire engine. This water supply does not even have to be constant and continuous. The level in the secondary sides of the steam generators may be recovered in batches every few hours if necessary.

This scenario has assumed a closed primary system. But even if the primary system is open or damaged, one can expect that reflux boiling in the steam generator U-tubes would provide enough heat transfer for successful core cooling. This phenomenon, however, could not easily be calculated by hand. More thorough system analysis code calculations are needed.

All the calculations in Eqs. (1) through (4) were done under the assumption that there is no heat loss from the primary and secondary systems into the containment and environment. But since this is not true and heat losses at that power level are expected to be relatively high, an even longer time before complete dryout and even less water for the successful heat removal would be needed. In that respect, our assumption is conservative.

Spent-Fuel Pit

Thermal and Stress Analysis of the Spent Fuel in the Spent-Fuel Pit

It has already been mentioned that the spent-fuel pit was of concern. It is not protected by the containment and is therefore more susceptible to damage. To obtain the necessary data for a further analysis of possible dose releases to the environment, a thermal and stress analysis of the fuel in the pit was performed with the FRAPCON2-V1M5B computer code.[2,3] Spent-fuel elements from all 10 yr of operation of the Krško NPP are stored in the pit. At the time of the military crisis, the most recent fuel in the pit was from the last refueling, which was performed ~6 months previously. The following were our initial assumptions before the calculation:

TABLE I

Important Times and Parameters After a Loss of All Off-Site Power in a Cold Shutdown

Time to heat up primary and secondary systems to boiling temperature (h)	4
Time to boil both steam generators dry (h)	27
Time to boil both steam generators and primary system dry (h)	48
Amount of feedwater needed to remove heat by boiling (kg/s)	1.9
Primary pressure during heat removal by boiling secondary water (bar)	1.57

TABLE II

Results of the Thermal and Stress Analysis

	Fuel Irradiation (days)		
	500	1000	1500
Gap pressure at the end of burnup (MPa)	11.3	12.2	13.5
Gap pressure in the pit (MPa)	4.55	5.01	5.55
Fraction of decay gases in the gap (%)	1.88	3.16	5.43

1. The assumed standard fuel element used in the calculation was initially filled with helium with a conservatively high internal pressurization.

2. The inlet coolant temperature for burnup calculations was assumed to be 561.75 K.

3. The operating pressure during operation was assumed to be 15.5 MPa.

4. The assumed primary mass flow rate during operation was 3486 kg/s.

5. The temperature of the water in the pit was 357 K.

6. The pressure in the spent-fuel pit was atmospheric.

7. There was no flow in the pit.

8. The axial power distribution in the fuel was a chopped cosine.

9. The average fuel rod linear power was 18.0378 kW/m.

The burnup history was divided in steps of 50 days. It was assumed that after the fuel element was reloaded from the core into the spent-fuel pit, it was at 1% nominal power for another 50 days. After that, the power dropped to 0.1% and remained at that level.

Cases where the fuel has been in the core for 500, 1000, and 1500 days were analyzed to conservatively cover all burnups. The most important results are summarized in Table II. These could be used in further radiological consequence analysis code calculations.

Analysis of Potential Radiological Consequences After the Loss of Cooling Water in the Spent-Fuel Pit

Under normal conditions, the risk contribution of the spent-fuel pit is small. It was addressed in Ref. 4, where it was concluded that for the typical U.S. PWR, ~4 weeks are available before all the water is evaporated and the fuel starts to heat up. The probability of a loss of water for a longer period is very low. Under war conditions, the probability of the loss of water in the spent-fuel pit is not negligible. The potential dose to the population around the plant has to be evaluated to prepare the necessary emergency preventive measures.

A scenario where all water is immediately lost was the basis for our analysis. Further, we assumed that immediately after the loss of water, all the fuel elements in the pit are damaged and all the noble gases from the fuel and the fuel gap are released into the environment. Potential doses originating from direct gamma irradiation in the vicinity of the pit were neglected.

At the time of the crisis, the most recent fuel in the spent-fuel pit had been out of the core for >6 months. Therefore, its decay power was rather small. We assumed two different release scenarios in our dose calculations:

1. release from one-third of the core, delayed for 6 months:
    a. full release of noble gases
    b. otherwise as in the WASH-1400 PWR-1A scenario[4]: 0.4 for the Cs-Rb, Te-Sb, and ruthenium groups; 0.05 for the Ba-Sr group; and 0.003 for lanthanides.
2. release of all decay gases as in case 1 but with only 1% of the particulates.

Case 2 is more realistic because the probability of particulate release from the relatively cold fuel is very low. An accident in which the spent fuel would be explosively brought out of the building was not considered possible and thus not evaluated.

Ground release was assumed, and the influence of atmosphere mixing around buildings was neglected. All radioactive material was assumed to escape into the atmosphere within 2 h, and for 24 h after the accident, there was no evacuation of the population. It was assumed that there was no precipitation during and after the accident. To determine the effect of meteorological conditions, four different weather conditions were analyzed (the atmosphere stability increases in Pasquill categories A through F):

1. Pasquill category A: wind 1 m/s (extremely unstable weather conditions)
2. Pasquill category C: wind 2 m/s
3. Pasquill category D: wind 6 m/s
4. Pasquill category F: wind 2 m/s (stable atmosphere).

The analysis was performed with the CRAC2 computer code.[5,6] The 80-km area around the plant was divided in 12 regions of different widths. It was assumed that there is no population in the inner region (within 563 m around the plant). The dose was calculated for an individual at the center of each region. The CRAC2 code calculates the total dose and contribution to this dose from the cloud, contaminated air, and particles deposited on the ground. The whole-body dose was calculated, as well as the dose to individual organs (thyroid, lungs, etc.).

Results obtained for both cases are compared in Table III (taken from Ref. 7). It can be concluded that the main contribution to the whole-body dose comes from particulates on the ground since the dose for case 2, where the source term contains 100 times fewer particulates, is ~100 times smaller.

This can also be observed in Fig. 2 (Ref. 7), where results for case 2 are summarized. Fortunately, a very small release of particulates can be expected since the fuel is at a low temperature. The lowest contribution comes from the passing cloud. The next smallest contribution, from inhalation, can successfully be reduced further by simple preventive measures.

The effects of the weather are shown in Fig. 3 (Ref. 7). It can be seen that the prevailing weather conditions have a considerable influence. Even higher doses can be expected if precipitation is included in the initial assumptions.

All these results would be much less favorable if some of the fuel in the spent-fuel pit were out of the core for a shorter period. All our results were obtained under the assumption that the most recent fuel, one-third of the core, has been in the spent-fuel pit for 6 months.

TABLE III

Doses After the Loss of Spent-Fuel Pit Water: Pasquill Category C

Distance (m)	Organ	Dose (Sv)	
		Case 1	Case 2
282	Whole body	1.98	0.02
	Thyroid	1.65	0.017
845	Whole body	0.45	0.005
	Thyroid	0.37	0.004
68 400	Whole body	3.6×10^{-4}	4.0×10^{-6}
	Thyroid	3.0×10^{-4}	3.0×10^{-6}

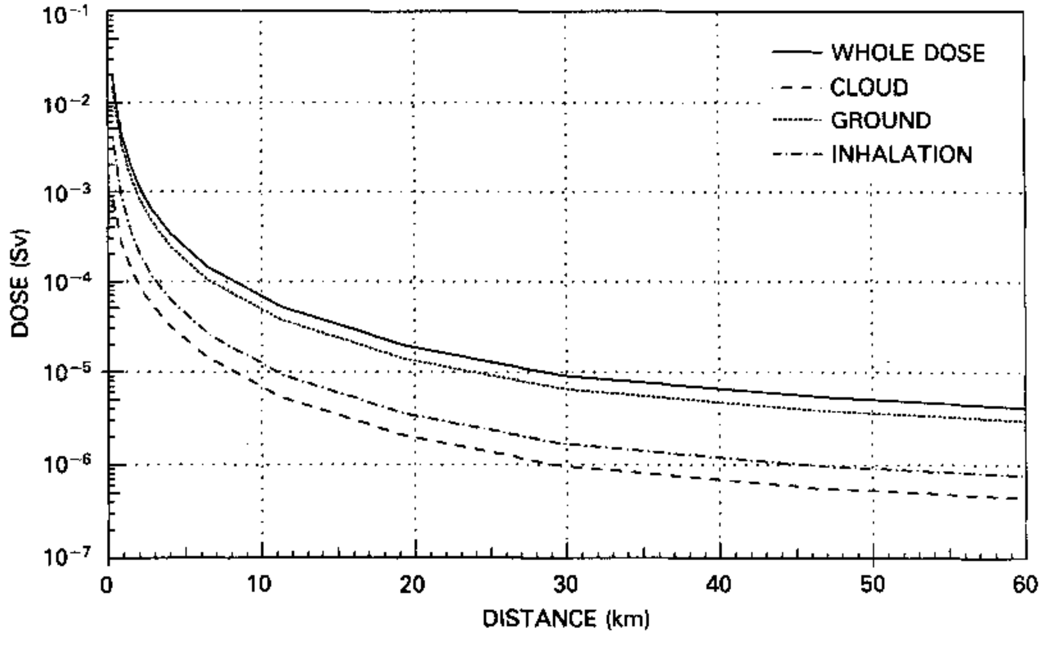

Fig. 2. Whole-body dose after a release from the spent-fuel pit: case 2.

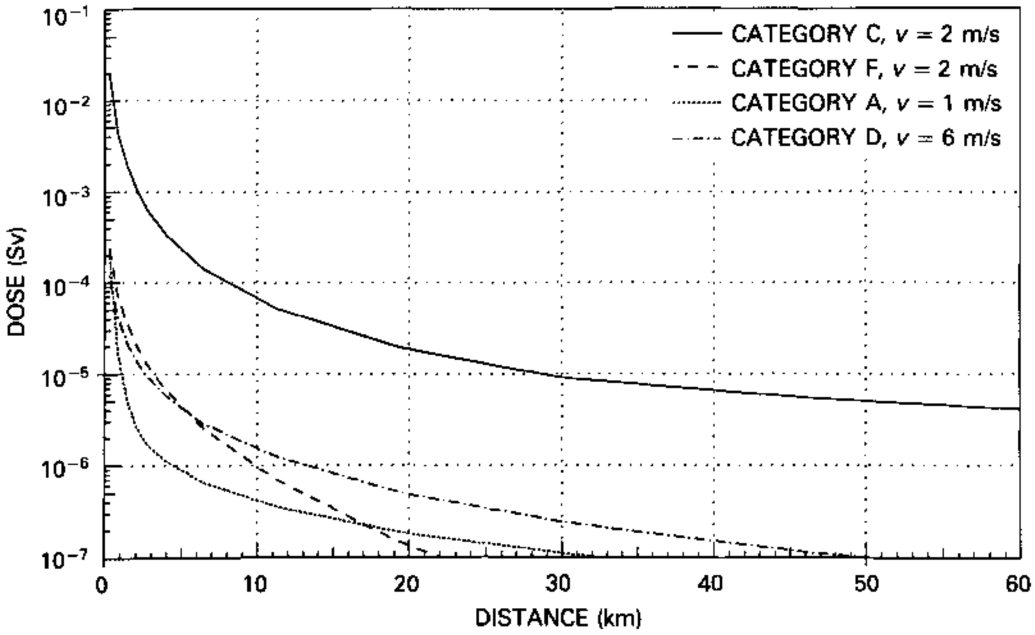

Fig. 3. Whole-body dose under different weather conditions.

CONCLUSIONS

Three aspects of NPP operation under war conditions were presented. A quick analysis during the crisis showed that the consequences of a military attack on the plant by jet fighters could be serious, but with the proper preventive measures and preparations, the environmental consequences could be minimized. A plant in the cold shutdown condition can endure a loss of off-site power and cooling long enough to establish a variety of possible emergency solutions. Dose releases from the destroyed spent-fuel pit are relatively small unless the damaged fuel is released into the environment in the form of dust. The analyses presented here have initiated further detailed studies of the vulnerability of NPPs in a war.

More attention should be given to this subject by the national and international bodies responsible for nuclear safety all over the world. In addition to purely political measures by the international community that would minimize the probability of a military attack on NPPs, detailed studies covering all different aspects of nuclear safety under war conditions should be initiated and included in emergency plans for each NPP. Help in a form of expert advice should be available and provided to any reactor operator whose power plant would be in an area of military activity. The efforts of the international research community should be devoted to gaining a better understanding of the true vulnerabilities and to enhancing measures for the protection of NPPs in the event of military attack.

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