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Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
Summary of GRS[1] study

Bonn, 27 November 2002

Protection of German nuclear power plants against the background of the terrorist attacks in the USA on 11 September 2001r

Findings of GRS investigations made in the project, "Expert Analyses of Terrorist Scenarios for Aircraft Crashes on German Nuclear Power Plants"

The findings of the GRS investigations, details of which are in appendices

- Load assumptions from mechanical impacts (classified confidential)
- Load assumptions from thermal impacts (classified confidential)
- Sequences of events and vulnerablility of the plants including attachments A to E (classified strictly confidential)

are summarised in the GRS project's working programme under the following headings:

- Mechanical impacts
- Thermal impacts
- Impact on buildings and installations
- Crash scenarios in terms of space, affected plant parts and safety installations
- Sequence of events with regard to system design of plants (vulnerability analysis)
- Precautionary protection measures internal and external to plant facilities.

The **mechanical impacts** which can occur as a result of a passenger aircraft being intentionally crashed were put in concrete terms through accounts made from the engineering standpoint. Here all common passenger aircraft were classified in three weight categories for which reference aircraft were specified. Load-time functions for the main crash onto level and rigid obstacles (perpendicular to the surface affected) were generated for different speeds at impact (100/175 metres per second), taking into account the maximum load including fuel. The load-time functions were determined separately for the aircraft body without engine mass and for reference engines. In this manner, the evolution of the impact process and the classification of the surfaces impacted could be better taken into account. The load-time functions were derived using the approach developed by Riera which was validated using an experimental crash by a Phantom jet into a rigid concrete wall at 215 m/s at Sandia National Laboratories (SNL) at the beginning of the 1990s. The GRS assesses that this approach, when applied to passenger planes, is conservative — given the assumptions then made and the longer period of impact than with a Phantom jet, which is markedly smaller; this question is further examined by an on-going project commissioned by Ministry of Economics.

[1] Gesellschaft für Anlagen- und Reaktorsicherheit mbH, a scientific-technical expert and research company working mainly for nuclear regulators in Germany [translator's note]

In determining the flight parameters, most notably for velocity and angle at impact, target accessibility was also assessed. To this end a professional flight simulator was used. Here flights onto a building with the dimensions of a coal-fired power plant (data for this were available) were carried out several times under diverse conditions for the approaching flight using the Berlin Technical University's simulator and six subjects with specialist flight knowledge. The target accessibility for aircraft in the heaviest weight category was still given for an impact velocity of 175 m/s, although with a reduced likelihood of the target being struck (approximately 50% probability; touching the target was also assessed as a strike). The report is classified as strictly confidential. The data is insufficient for statistically reliable statements to be made on specific questions, e.g. angle distribution. On the question of deviations when a direct strike is assumed, further investigations are to be commissioned by the Ministry of Economics in order to be able to assess the conservativeness of a central impact (a PWR reactor building has a height and diameter of about 60 metres; the span of a big passenger plane is also about 60-62 metres). It is expected that deviations in the simulation tests will be not inconsiderable. Due to the curvature of the cylindrical reactor building deviations of over 20 metres have a considerable effect on the then reduced effective load. The conditions with PWR plants are here much more favourable than those at box-shaped BWR reactor buildings.

For light and medium-weight passenger planes, a velocity at impact of up to 215 m/s for an approach flight at ground level was considered as a result of experience at the World Trade Center. A comparison of these load-time functions shows that the load-time functions for aircraft in the heavy weight category at 175 m/s cover those load-time functions for aircraft in the medium weight category at 215 m/s.

It was further established in general that, irrespective of the type of aircraft and the velocity, an angle to the horizontal of 10° or smaller should be set for the target to be struck in descending flight.

Investigations into the load-bearing capacity of mechanical impacts on buildings require a directly assigned (interaction) area of impact as well as load-time functions. With simplifications made with regard to size and shape, these were determined for each reference aircraft separately for fuselage, wings and turbines. This enabled computations to be made with existing programmes on load-bearing capacity and local perforation.

One particularly critical point in discussions in the project was whether the top speed of 175 m/s used to derive the mechanical load-time functions was the maximum velocity that could be assumed. The GRS pointed out in its report that even if, in a particular case, a greater velocity cannot be ruled out for the heavy aircraft, the load-time functions in the Riera model had been derived so conservatively [central strike (angle of inclination of aircraft on approach flight not taken into account, direct hit without deviations on curved surfaces); fuel containers not bursting before they impact, i.e. with full amount of fuel within the geometric impact area] that higher speeds can also be tolerated. It cannot at present be said what reserves are available here, but this is being investigated (Ministry of Economics project). No objection against this upper velocity being used as a basis has been raised, either, by the RSK[2].

To determine the **thermal impacts**, existing knowledge of the behaviour of various combustible materials was evaluated and an examination made of the extent to which this could be transferred to the scenarios relevant here, partly with the aid of fire tests carried out by the Environment Ministry on aircraft fuel used in passenger air traffic. The major fire loads

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[2] Reaktorsicherheitskommission, German Reactor Safety Commission [translator‘s note]

which are to be found in the aircraft and which can be introduced by an aircraft crashing onto the plant site, and might possibly then enter its buildings, were also determined for the each of the reference aircraft. Unlike with the mechanical impacts, generally valid assumptions on loads cannot be made for thermal impacts since plant-specific conditions which affect the behaviour of a fire can have a decisive influence. To proceed with methodical consistency, four groups of sequences of events in which there is damage to buildings of differing extents were defined (**4 categories of damage** from no entry of kerosene to maximum entry), as were the sizes of openings in buildings of relevance to the entry of fire loads and ventilation conditions which can result from a deliberate plane crash given differing building designs (especially the thickness of the walls). The results of the loads on buildings specific to a plant could then be allocated to these categories of damage for the three reference aircraft. **Aircraft fuel** was determined divided into **three parts** for these cases. One part of the fuel sprays outside the building and partly burns, another (possibly including solid fire loads) is introduced into the building, and the third forms a pool of fuel on the plant premises. These results were compiled in a table by the GRS. The investigations showed that ventilation conditions had a considerable effect on the course of the fire inside a building. Three **representative fire scenarios** were worked out such that the different possibilities for fires induced by aircraft crashing into a nuclear power plant could be circumscribed or attributed to one of these scenarios. For this, the methodology by which the effects of fires can be determined was developed further. This methodology was then tested on examples of real plant conditions. Its basic applicability in plant-specific studies was confirmed. The data on fires required for plant-specific analyses with recognized fire simulation models was compiled. The investigations showed that, when a reactor building was perforated and fire loads entered, the effects of the fire induced can be controlled if the aircraft fuel entering is only able to spread in the immediate area, for example because of the spatial conditions involved. In the event that other buildings, such as the switchgear building, should be partially destroyed the usual period for which the constructional separations between the intact and the destroyed parts of the buildings resist fire is not sufficient to prevent a fire from spreading without additional fire-fighting measures being taken. When performing the analyses of the sequences of events, the fire simulation computations carried out using this methodology provide information on what redundancies and safety features can be regarded as still operative and which must be regarded as inoperative.

The approach used in investigating the **load-bearing capacity** (effect on buildings and installations) of the buildings in need of protection was based on the assumptions of loads determined for the reference aircraft and concentrated on analysing the load-bearing characteristics of a reactor building of the last generation. The results of these analyses were used to make estimates for other buildings. As to the question of damage from the impact of rigid parts it was possible by using penetration formulae to deduce that the potential for damage was low where the thickness of the walls was greater than one meter. Possible local damage to safety-relevant installations caused by back wall spalling[3] remains confined to the locally affected redundancy. As regards perforation of the structure of the buildings hit by the plane's fuselage, the computations showed that with last generation reactors there is a considerable potential for the walls involved to resist local perforation and that perforation is not to be expected. However, detailed plant-specific computed proofs still need to be made. Results of the investigations into the stability of the reactor building and possible bending failure showed that nuclear power plants of the last generation were stable and that bending failure was equally not to be expected, so that no significant amounts of kerosene would be able to enter.

[3] spalling is the flaking of or deterioration of the surface (of concrete) [translator's note]

With regard to the load bearing capacity of the different reactor buildings of older nuclear power plants it can be assumed that, in the individual case, limited design reserve margins may be available. This is testified to by investigations made in the past into the absorbable impact load from RSK load functions (Phantom jets). But it is not possible to make any general statements here. The margins are not however sufficient to bear the maximum loads (impact by heaviest plane at the top speed).

With regard to the effects of induced vibrations on systems and components, the investigations with computations, using established dynamic computational models, showed that for short excitation times the resulting acceleration values were much higher than those on which the design of the last generation plants were based. According to the participating experts, more extensive analyses are needed in order to obtain realistic results for the consequent damage. Such investigations with improvements to the model used are being undertaken in the current Ministry of Economics project. Initial analyses by the GRS indicate that the effects of vibrations are likely to remain within acceptable limits on account of the very short excitation times involved.

To establish **spatial crash scenarios** for the reactor sites, a system of three categories of approach flight was developed (approach from this direction is more likely, less likely and impossible). In order to find out whether it is possible to hit the reactor building or other safety-relevant buildings an analysis of topographical features and surrounding buildings was carried out by considering simplified geometrical features. The plant parts and safety functions affected were determined for the five representative nuclear power plants (three pressurised water reactors and two boiling water reactors, as detailed below) differently designed with regard to withstanding plane crashes. Those selected were Obrigheim and Brunsbuettel (not designed to withstand crashes), Biblis B (designed to withstand impact of Starfighter jet), and Emsland and Kruemmel (designed to withstand impact of Phantom jet).

To estimate the **vulnerability** of the plants **five groups of plant configurations**, referred to above (different design to withstand crashes and different plant type), were formed. For each category, the possible spatial crash scenarios were individually evaluated by using the representative plants. To carry out analyses of sequences of events a list of **nine damage scenarios** covering the spectrum of possible damage was drawn up (reactor building hit: and stays intact; there is no loss of coolant accident; there is a loss of coolant accident; reactor building is hit and aircraft debris strikes other buildings; and so forth). Engineering judgements were made to assess if the sequence of events resulting from a damage scenario could be controlled by the non-affected safety installations to avoid damage to the reactor core or loss of integrity of fuel elements, resulting in major radioactive releases. For each damage scenario and reference plant it was then demonstrated methodically which scenarios can be controlled and which cannot. However, hard statements on this can only be made on the basis of plant-specific analyses. The investigations indicate that the assumptions made on failures of systems and components caused by induced vibrations have considerable influence on the results.

Initial conclusions on the vulnerability of all German nuclear power plants could be drawn from the results for the five groups of plants. As expected the reactors can be ranked according to their ability to control different damage scenarios. On the basis of the simplified analyses into the sequences of events the following order of controllability is expected: Emsland (convoy plant), Kruemmel (boiling water reactor), Biblis B, Obrigheim, Brunsbuettel (boiling water reactor).

An initial appraisal was made of **precautionary internal and external protective measures** and reserve margins of engineered safety features. The level of protection can be raised by making alterations to plant and installations and taking additional protective measures including improvements in organisation. The measures involved here are to reduce the accessibility of the target or improve the controllability of sequences of events in a plant. The question of whether the vulnerability of a plant under real threat of attack could be reduced by shutting the reactor down for a limited time was also examined. The GRS assessed that, in the case of a plant under a definite threat, the effects examined above would be under greater control when the reactor is in a depressurised operational state. This was less important with highly-protected plants (regarding the construction of the reactor building and the emergency systems, and the latter's system design) than with plants which were less comprehensively protected. The organisations which participated in the investigations agree that the use of additional construction measures to improve the load bearing capacity of mechanical loads was, considering the problems connected with this, at the moment impossible to appraise.

Discussion on measures to reduce target accessibility (impeding sight, changing the plane's parameters before a crash) concluded that more detailed examinations needed to made here. Erecting objects outside a plant could be an effective measure to reduce the accessibility of the target or the forces acting on it. A more extensive assessment, however, required that in-depth investigations be made by experts into pilot behaviour, incorporating cost-benefit analyses. With regard to possible technical improvements to plants, examinations into sequences of events indicate that overall conditions for being able to control sequences of events can be significantly improved. These could be described in greater detail by conducting in-depth, plant-specific examinations.

In the view of the GRS the methods and procedures used in the project are overall in keeping with the state of knowledge today. But they are often approximations with borderline considerations. Therefore, the phenomena and effects being considered (e.g. fireballs, fire scenarios, the Riera model in deriving load-time functions) cannot be corroborated in the scientific sense. The methods and procedures are nevertheless a suitable basis on which to conduct plant-specific analyses. This emerged from the discussions among all those participating in the project. Limitations were particularly evident in the investigations into induced vibrations. However, before this question is further examined by costly plant-specific analyses, the influence of the short duration of excitation and the non-linear effects ought first to be analysed generically to provide a basis for improved approaches with which to carry out plant-specific investigations.

The findings also recommend that more extensive studies should be carried out to validate the assumptions made and their results, and to meet the necessity to determine more realistic results. The latter applies particularly to determining load-time functions derived from mechanical impacts, and to determining excitations of systems and components resulting from induced vibrations. Investigations into these are already being carried out in a project supported by the Ministry of Economics.

Damage Scenarios and Expected Consequences for Individual Plants in Germany

Note:

Within the scope of the expert investigations of GRS, only five reference plants (Emsland, Krümmel, Biblis B, Obrigheim and Brunsbüttel) have been examined more closely (however not by plant-specific analyses). Taking this into account, the validity of the details presented here is, for the other plants, limited. The other plants have been assigned to the five reference plants according to a rough scheme (criterion of assignment: design against accidental airplane crash); the topography of the individual plants has been left out of consideration for the other, assigned plants.

In addition, the investigations can be beset with considerable uncertainties in individual cases – for example, regarding the extent to which induced vibrations of individual components or systems will lead to failure, and regarding the thermo-hydraulic behaviour of individual plants for the different load cases.

These uncertainties can only be cleared up by plant-specific analyses.

Specific conditions for the load cases:

v1 = 175 m/s; v2 = 100 m/s

A = large airplane (e.g. A[4]340, Boeing 747)

B = intermediate-size airplane (e.g. A300)

C = small airplane (e.g. A320)

I. <u>Pressurized Water Reactors:</u>

Reference plant Emsland (design against Phantom jet)
also Neckarwestheim 2, Isar 2, Brokdorf, Philippsburg 2, Grohnde and Grafenrheinfeld

Load Cases	Damage Scenarios	Expected Consequences
All types, all velocities	No penetration of reactor building, no primary leakages	Sequence of events is controllable
A v1	No penetration, primary leakages induced by vibrations	Sequence of events is controllable
A v1	No penetration, primary leakages, destruction of control room[5] by debris, fire	Control of events is uncertain, releases occur if containment is damaged, is controllable if plant personnel intervenes early
A v1	Destruction of valve compartment[6], non-isolatable main steam leakage	Sequence of events is controllable
All types, all velocities	Destruction of other safety-relevant buildings	Sequence of events is controllable

[4] translator's note: in this context, A stands for Airbus.
[5] translator's note: the control room of German NPPs is located in a separate building (switchgear building), not in the reactor building.
[6] translator's note: the main steam valve and feedwater valve compartment.

Reference plant Biblis B (design against Starfighter jet)
also Unterweser and Neckarwestheim 1

Load Cases	Damage Scenarios	Expected Consequences
A v1,2	Extensive destruction of reactor building, early release of activity	Control of events is uncertain
B v1,2, C v1,2	No penetration, or locally restricted penetration, no primary leakage	Sequence of events is controllable
B v1,2, C v1,2	No penetration, primary leakage by induced vibrations	Sequence of events is controllable, release of primary coolant if containment is damaged
B v1,2, C v1,2	No penetration, or locally restricted penetration, primary leakage induced by vibrations, destruction of control room by debris and fire	Control of events is uncertain, release of primary coolant if containment is damaged
B v1,2, C v1,2	Crash onto the valve compartment with failure of isolation of secondary circuit	Sequence of events is controllable
All types, all velocities	Destruction of other buildings relevant for safety	Sequence of events is controllable if personnel takes measures in time (emergency residual heat removal chain)
A v1,2	Aircraft engine penetrates wall of reactor building, local fire in annulus[7]	Sequence of events is controllable

Reference plant Obrigheim (no explicit design against accidental airplane crash)
also Biblis A and Stade[8]

Load Cases	Damage Scenarios	Expected Consequences
A v1,2, B v1,2, C v1	Extensive destruction of reactor building, early release of activity	Control of events is uncertain
C v2	No penetration of reactor building, no primary leakages	Sequence of events is controllable
C v2	No penetration of reactor building, primary leakages induced by vibrations	Sequence of events is controllable, release of primary coolant if containment is damaged
C v2	No penetration, primary leakage induced by vibrations, destruction of control room by debris and fire	Sequence of events is controllable if remote shutdown station is activated in time, release of primary coolant if containment is damaged

[7] translator's note: annulus is the space between reactor building wall and containment.
[8] translator's note: Stade NPP was meanwhile permanently shut in November 2003.

All types, all velocities	Destruction of other buildings relevant for safety	Sequence of events is controllable, possibility of releases from external spent fuel pool[9] needs to be investigated
A v1,2, B v1,2	Aircraft engine penetrates wall of reactor building, local fire in annulus	Sequence of events is controllable

II. Boiling Water Reactors:

Reference plant Krümmel (design against Phantom jet)
also Gundremmingen B and C

Load Cases	Damage Scenarios	Expected Consequences
A v1	Penetration of outer wall and extensive damage inside reactor building, large primary leakage	Control of events is uncertain, release of primary coolant if containment is damaged
A v1	No penetration of reactor building, primary leakage induced by debris or vibrations	Sequence of events is controllable
A v1	Locally restricted penetration of reactor building, primary leakage	Sequence of events is controllable, release of primary coolant if containment is damaged
A v1	No penetration, or locally restricted penetration of reactor building, primary leakage, destruction of control room by debris and fire	Control of events is uncertain, release of primary coolant if containment is damaged
A v2, B v1,2, C v1,2	No penetration, or locally restricted penetration of reactor building, no primary leakage	Sequence of events is controllable
All types, all velocities	Destruction of other buildings relevant for safety	Sequence of events is controllable

[9] translator's note: this applies only to Obrigheim; Obrigheim NPP is the only German NPP with an external spent fuel pool.

Reference plant Brunsbüttel (no explicit design against accidental airplane crash)
also Isar 1[10] and Philippsburg 1

Load Cases	Damage Scenarios	Expected Consequences
All types, all velocities	Extensive destruction of reactor building, early release of activity	Control of events is uncertain
All types, all velocities	Destruction of other buildings relevant for safety	Sequence of events is controllable
All types, all velocities	Aircraft engine penetrates wall of reactor building, fire spreads inside building	Control of events is uncertain
All types, all velocities	Wreckage hits roof of reactor building, roof girder falls into the spent fuel element pool[11], fuel elements remain covered by water	Limited release from the fuel element storage pool
All types, all velocities	Wreckage hits roof of reactor building, roof girder falls into the spent fuel element pool, fuel elements are no longer covered by water, plus jet fuel fire	Considerable release from the fuel element storage pool

[10] translator's note: BMU acknowledged an error in the summary – the heading for the most vulnerable category of reactors was worded unprecisely. Isar 1 has, in fact, some protection against airplane crash. It is designed to withstand a Starfighter crash. The wrong wording of the heading does, however, not change the fact that Isar 1 belongs into the category of most vulnerable reactors, says BMU.

[11] translator's note: In German boiling water reactors, the spent fuel storage pool is located in a particularly vulnerable position – high up in the reactor building. It is located somewhat lower in pressurized water reactors.