Numerical Simulation of Fuel Spillage Following an Aircraft Impact onto a Nuclear Power Plant

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1. Summary

The possible consequences of fuel discharging from the tanks of an impacting aircraft is of interest in security analysis concerning nuclear power plant buildings. In the problem presented here the propagation of approximately 4.4 m^3 of fuel from the fuselage tank of a Phantom F4 through the pre-damaged roof structure of a sensitive building is simulated by means of the fluid-dynamics code DYSMAS/E. The results of this investigation show that under worst-case conditions about 17 % of the total mass of fuel may flow through the cracked structure, whereas in most cases the actual inflow will be much less.

2. The Fluid-Dynamics-Code DYSMAS/E

The valuation of hydrodynamic and structural dynamic phenomena in the extreme short-time range is normally outside the scope of analytical investigations. For the evaluation of the strongly non-linear state changes occuring, IABG has developed a computer program family with the intention to simulate the real-world physical processes and phenomena numerically.

The program system DYSMAS/E (**DY**namic **S**ystem **M**echanics - **A**dvanced **S**imulation / Euler) is used for the description of hydrodynamic processes. Its scope of application covers the analysis of complex transient flow fields, the propagation of shock waves in fluid media considering their interaction with rigid and free boundaries, as well as the simulation of explosive burn processes.

Based on state-of-the-art simulation algorithms the development of the fluid-dynamics processor DYSMAS/E was advanced since 1979. Today the total size of the software amounts to about 15000 statements in 120 subroutines.

This fluid-dynamics processor is completed with a series of dedicated pre- and postprocessors to interface the DYSMAS/E input and output data with the peripheral hardware. Especially the family of graphical post-processors have proved invaluable for the analysis of highly transient flow fields.

3. Problem Description

For the assessment of possible dangers from fuel spilling following the crash of an aircraft the fluid-impact processes are simulated numerically. Some simplifying but nevertheless realistic assumptions are made:

These include the hypothetical situation of the crash of a fully loaded Phantom F4 aircraft on to the roof structure of an auxiliary building in a nuclear power plant. For normal impact onto the flat roof of the building a crash velocity of 215 m/s is assumed. The mass of the fuselage tank fuel of 4.4 m^3 is 3340 kg. The concrete roof has a thickness of 1.4 m. Considering these data and the strength of the roof structure reinforcement an estimation of the amount of local damage show that the structure is cracked but not perforated.

Additionally the following assumptions are made:

- The fluid crashes vertically downwards on to the center of the concrete slab;
- The geometrical shape of the fuselage tank is assumed to be cylindrical with a length of 7.33 m and a diameter of 0.875 m;
- The total fuel mass maintains its cylindrical form and the crash velocity of 215 m/s up to the moment of the impact, i.e. due to the inertia of the fluid a rupture of the tank hull does not occur prior to the cracking of the structure;
- The discharge flow of the fuel is not influenced by the ruptured tank hull and aircraft cockpit structure;
- The damage of the concrete roof structure due to the aircraft impact is terminated, a propagation of this damage during the discharge of the fluid is not considered;
- The type of roof damage considered interferes with the horizontal flow of the fuel in the crack region (fig.1).

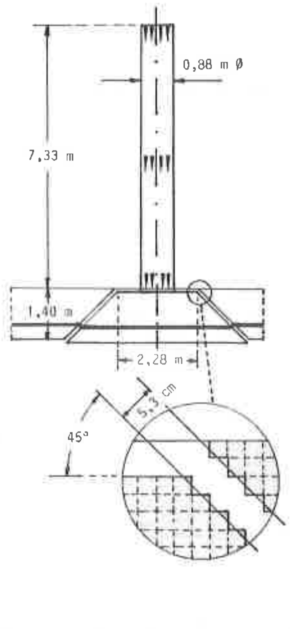


Fig. 1: Problem Geometry

The shape and distribution of the cracks resulting under real-world 3-D conditions lead to a discretization of the grid with unrealistically small cell sizes. As this would sum up to a very large number of cells, economy required the idealized concentration of the total distribution of small cracks to only one typical specimen of circular toroidal shape and an average width of 5.3 cm. Additionally this idealization now opened the possibility of using a 2-D rotational symmetry for the computer analysis.

The consistent discretization of the crack and the flow geometry demanded fluid cells with a size of only 2.5 cm in the critical region. In horizontal direction the expanse of 50 square meters of concrete structure necessitated 120 cells, additionally a vertical height of 10 m was discretized using 178 cells, so the total grid was comprised of 21360 cells.

4. Results of the Simulation

The evaluation of the results of the simulation was done with specific interest in the transient flow field developing near the collapsing fluid column and the phenomena in the crack region. The presentation of the fluid material distribution shows the behaviour in the vicinity of the impact area and the crack inlet in a qualitative way (fig.2). The initial state of the simulation is included at the time of 0.0 sec, giving the global geometrical configuration. The consecutive figures depict the propagation of the fuel material in the vicinity and into the toroidal crack.

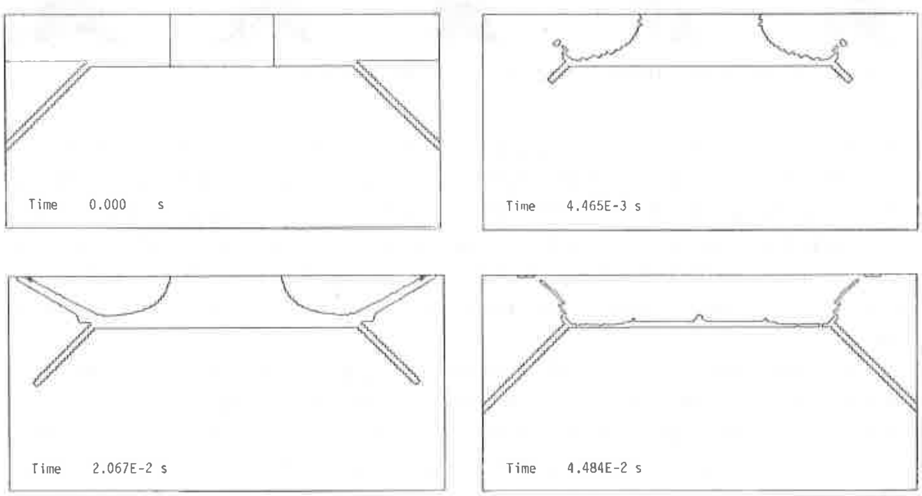


Fig. 2: Fuel Material Distribution in the Vicinity of the Impact Region and Inside the Crack

The following series of pictures describe 10 discrete time-points within the initial phase of the simulation by means of velocity vector plots of the flow field in the lower part of the fuel column near the impact region (fig. 3). The propagating shock wave in the fuel and the deflection of the fuel at the concrete surface are clearly visible. Initially, just before the fuel impact, all velocity vectors are parallel and directed vertically downward. Several microseconds later the fluid in the impact area is suddenly stopped, resulting in a pressure wave propagating upward against the direction of the flow. In the wake of this shock wave an underpressure area develops.

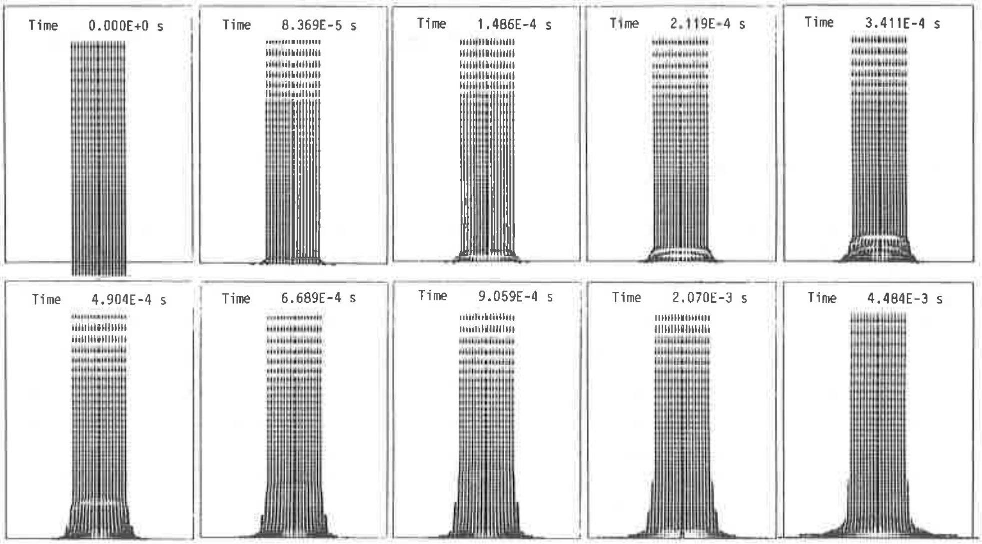


Fig. 3: Fuel Velocity Distribution (Initial Phase)

Fig.4 gives the transient pressure at the crack inlet. The advent of the fluid front in this area after about 3 ms is characterized by a very short shock pressure peak of 270 MPa. Afterwards the pressure stabilizes at a dynamic pressure value of 18 MPa, disclosing a typical quasi steady-state horizontal flow velocity of about 200 m/s up to a time of approximately 35 ms after the impact. After that time the pressure is gradually reduced to the ambient.

The right-hand picture gives the transient height of the fuel column (fig.5), illuminating the background of this final pressure decay: The height of the fluid column is decrementing linearly up to a time of 30 ms due to a constant velocity of the fuel afterflow into the impact area. After that time the fuel supply is exhausted and the vertical velocity gradually reduces to zero. The deflection of the flow maintains steady-state conditions for the discharge flow until no more fluid flows into the impact region. Then with the ebbing of this flow the dynamic pressure collapses.

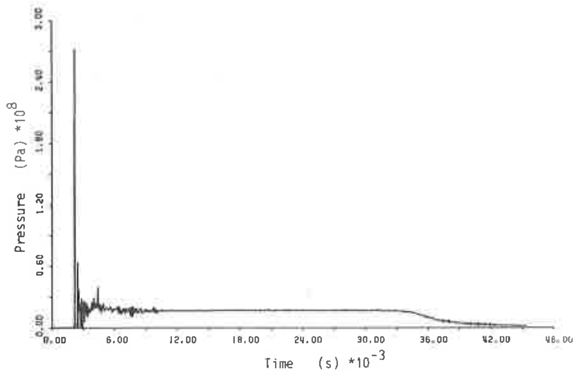


Fig. 4: Pressure Transient at Crack Inlet

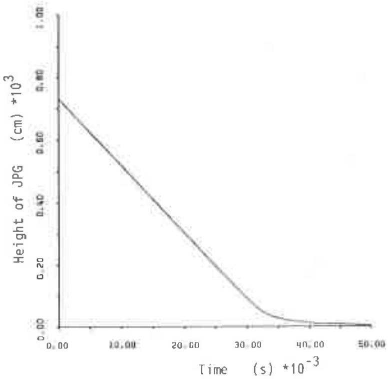
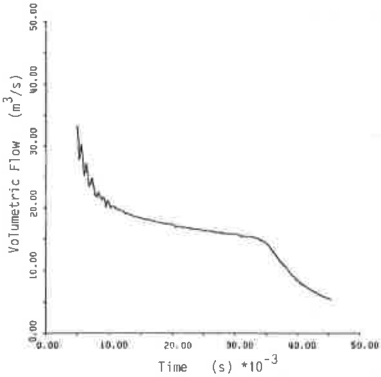


Fig. 5: Height of Fuel Column

After the transient behaviour of the pressure and velocity at the inlet is known, the investigation of the flow into the crack can be considered. Fig.2, giving the transient fuel material distribution shows that, initially, the material of the fuel front is pressed into the crack. The inflow behaviour is determined by the local pressure distribution, i.e. as soon as the fuel mass flow exceeds the choking condition at the crack inlet, the exceeding fluid will discharge along the concrete surface. As the modelling of the crack included a step at the downstream side of the crack inlet (fig. 1), a stagnation point develops with a zone of elevated pressures. This pressure continues to press the fuel into the crack but, additionally, the stagnation energy can be seen to deflect the superfluous fuel upwards, overflowing the step.

An estimation of the amount of fuel which can be expected to flow through the crack under worst-case conditions was done in two different ways: At the end of the simulation when the height of the fuel column has been reduced to a few centimeters, the amount of fuel inside the crack and the cratered surface is totalled. This will give an upper bound of the volume as it can be assumed that a part of the surface fluid will continue to discharge across the step.
This value can be checked using a second method. Averaging the fuel velocity in a cross section of the toroidal crack the volumetric flow rate can be deduced. The transient behaviour of this variable is given in fig.6, starting at a time of about 5 ms, as soon as the fuel front reaches the control section. This diagram shows that, initially, a rather high volumetric flow will occur, stabilizing at an almost steady-state level of about 15 m^3/s. After the exhaustion of the fuel supply and the collapse of the stagnation pressure at the crack inlet after 35 ms the volumetric flow will asymptotically reduce to zero. The integration of this volumetric flow accounts for the amount of fuel flown through the control section considered.

Fig.7 shows the transient behaviour of this integrated volume as well as the limiting value of the estimation described above. It can be seen that both methods are in very good agreement with a maximal value of about 0.75 m^3.



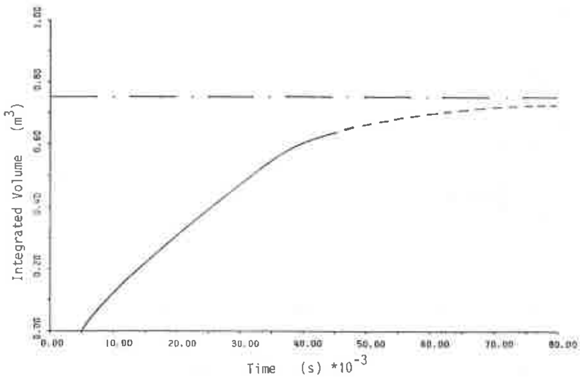


Fig. 6: Fuel Volumetric Flow Rate Inside the Crack

Fig. 7: Total Fuel Volume Inside the Crack

5. Concluding Remarks

The geometrical simplifications used for this discretization can be assumed to present a 'worst-case' configuration, as it is evident that the totalling of the crack distribution will over-estimate the resulting average flow velocity. Even if the total crack flow cross section is identical the friction forces acting at the internal crack surfaces are highly non-linear dependent upon the bulk flow diameter. Additionally a certain blocking of at least part of the cracks by the demolished aircraft structure can be expected, along with a definite disturbance of the quasi steady-state flow conditions. If, finally, a minimal inclination of the roof surface is taken into account - which can be anticipated under real-world conditions - long-time damages of the plant due to seepage of the residual fuel can be expected to be non-existent as the residual fuel volume, with only about 0.3 % of the original supply remaining in the critical region, is assumed to be able to escape freely.

Though this investigation has shown that under worst-case conditions about 0.75 m^3 (i.e. 17 %) of the aircraft fuel may flow through the cracked roof structure into the upper storage of the auxiliary building, this estimation can be expected to be too pessimistic. Considering the various structural barriers inside the building an endangering of the security of critical parts of the plant can be excluded.