FIRE SAFETY IN CIVIL AVIATION

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SUMMARY

A large share of all fatalities in civil aviation are caused by fire. For a passenger who considers traveling by air as just another human activity to spend his lifetime, like walking, sporting or sleeping, the risk of flying is more relevant per time unit than per passenger-kilometer. This approach gives also a partial answer why so much should be done to improve safety in civil aviation and to harden the cabin against fire hazards, although commercial air transportation is already considered to be very safe. It is explained what relations exist between preventive measures and measures that mainly enhance survivability. An overview of types of aircraft accidents is given, which points to what types of measures are applicable and effective. The regulatory authorities should gradually develop the airworthiness requirements along these lines, in concert with technological progress and with an emphasis on quality. This will require much attention for cost-benefit analyses for new as well as old safety measures.

FIRE SAFETY IN CIVIL AVIATION

HOW DANGEROUS IS SAFE?

Safety means "free from danger" or "protected against risk" but this does not give any starting-point for establishing the level of safety. One can say "The aircraft is unsafe because there is a crack in the wing", but it is clearly nonsense to tell someone that an aircraft is safe, because it has no crack in the wing. The reason is that safety is a condition that can be achieved by eliminating an infinite number of possible dangers. Therefore, safety cannot be measured. You can ascertain that something was unsafe, when it is too late, or you can estimate on basis of experience, what the level of unsafety is. To approximate safety you will have to make an addition or an estimation based on theory of chances of all dangers and their possible consequences. What we really do is estimate risk, being proportional to the product of the chance that something dangerous will happen, times the importance of its consequences.

When an aircraft with ten occupants flies from A to B, then the chance that it will encounter an accident is the same as when there are twenty occupants in it, but in the latter case the risk of the journey is twice as high because the consequences of the accident are doubled.

Also when this aircraft not only flies from A to B, but also returns to A, the risk will be doubled because the chance that an accident will happen, is twice as much although the consequences are the same.

The previous remarks all concern safety in an objective sense, but safety does have another, emotional significance: it is a sentiment too. Also this subjective meaning is relevant for the acceptability of a certain risk.

All aircraft manufacturers and airlines proudly advertise that there exists no safer way of public transport than civil aviation. But notwithstanding that, quite a lot is done to enhance safety ever more and also when one reads articles on aviation safety, one often gets the impression that more should be done. Why?

Does it make sense to spend much attention, trouble and money to improve aviation safety, when the level of safety apparently already is so very high?

To save human life is a very worthy goal, but when with the same effort in another area much more lives could be saved, then it is not only reasonable, but also humane, to shift the attention to the latter area.

In transportation, productivity is always measured to standards like passenger kilometers or tonkilometers and therefore one is inclined to use these same standards for indicating the level of safety which has been achieved (as a matter of fact it should be called the level of unsafety instead of the level of safety).

However reasonable and understandable it may be that aviation people use the number of casualties per 1 billion passengermiles as a measure for the level of safety: from the viewpoint of the passenger this measure is not very relevant, when comparing it to the risk of other activities. The présent level in civil aviation, which is about 1.5 casualty per 1 billion passengermiles, would be abominable for an astronaut who paces around the earth with some 20,000 miles per hour and who stays in this satellite for a year.

And also the number of about 90 casualties per 1 billion miles, which is about true for pedestrians in Holland, would lead to the unlikely conclusion that walking is 60 times as dangerous as flying in a transport aircraft.

Both extremes clearly are absurd and the question arises whether there might be another approach, which corresponds better with how a human being experiences safety and unsafety. What a passenger in reality is interested in, is the danger of the activity traveling,

compared to the dangers of all sorts of other human activities like sleeping, walking, shopping, sporting and so on and so forth. Actually he is interested in the danger per unit of time which is connected with those activities.
From data obtained by scanning the Dutch public statistics it was easy to assess that in average 1 in 36 people dies from an accidental cause, irrespective whether this cause is a traffic accident, or a deadly fall from a staircase, or being hit by lightning. At an average lifetime of 650,000 hours, which is about the number of hours in 75 years, this amounts to 4 casualties per 100 million hours of life. Such an average level of (un)safety which at present in the Netherlands applies for all human activities together, is a practical reference for comparison of the danger of several specific human activities.
After some research and calculation, this approach gave birth to the following remarkable list:

THE DANGER OF SEVERAL HUMAN ACTIVITIES

Average:	4	casualties per 100 million hours of life
Walking:	30	------------------,,--------------------
Bicycling:	30	------------------,,--------------------
Driving in a car:	65	------------------,,--------------------
Light motorcycle (moped):	250	------------------,,--------------------
Riding a motorbike:	1400	------------------,,--------------------
Sports flying:	1300	------------------,,--------------------
Gliding:	3000	------------------,,--------------------
Public transport:	10	------------------,,--------------------
Civil aviation:	55	------------------,,--------------------
Playing soccer/football:	?	------------------,,--------------------

Because the available data were not adapted for this particular purpose some reservation is required with respect to the exactitude of these numbers, but probably they will not deviate very much from the real actual values. And as a matter of course, care is needed with the interpretation of the numbers, because this method, like any other approach, has several restrictions.
For instance, only the number of lethal casualties is considered and the number of non-lethal wounded persons is omitted. But there is quite a difference in the "lethality" of the various types of accidents. For several of the activities from the list, the lethality is about 10%, which means that there are about 9 times as many seriously wounded persons as lethal casualties. This applies for walking, bicycling, driving a car or a motorbike. Remarkable is the low lethality of moped-accidents, namely 4% which means that apart from those 250 casualties per 100 millions of hours of moped-driving, there are also 6000 seriously wounded persons. Therefore an activity at which accidents have a low lethality appears in the list relatively safer (less unsafe) than it is in reality. Lethality of flying accidents (both sports-flying and civil aviation) is in the order of 50%, which is relatively high. To illustrate this restriction I added playing soccer or football, of which I did not have any data. But anyone can understand that for instance soccer-accidents, which happen relatively often, are hardly ever lethal. Therefore adding the real number of lethal accidents per 100 million hours of playing such a game, whatever this number would be, would certainly give an optimistic view which is not justified because these games certainly are not without danger of serious injuries.
Gliding is added to the list not only because I am a glider pilot myself, but to reveal another restriction of the method. It is true that the number of casualties per 100 million glider flying hours is relatively high, but one should not only look at the flying hours, but take into account that the glider pilot in average spends 20 times more time on his hobby than the time he actually flies. Therefore: the hobby gliding is not by any means as dangerous as you should think when you only look in the list. (By the way: the high number in the list is yet again a very strong motive for trying to improve safety in gliding).
It is remarkable that the level of safety in public transport by bus and by train (which I unfortunately could not split up) according to this approach, is apparently much better than the level of safety in civil aviation. I repeat that this applies only for transportation considered as a human activity on time-basis, and of course this approach is not suitable to indicate the safest choice when you have to choose whether to take a bus, a train or an aircraft for a certain journey. In that case you will have to return to a level of (un)safety measured per passengermile.
Very interesting is the development of safety over the years. In a period of 20 years, safety of road traffic was ameliorated by a factor 4, which means that in about 1965 the number of casualties per 100 million car driving hours which is now about 65, used to be about 260. During that same period the amelioration of the safety in civil aviation was by a factor 3. You may say that in road traffic more has been achieved with safety measures than during the same period in civil aviation, but another factor is that in the same period the speed of traveling in aviation was increased much more than the average speed of road traffic.

And yet, also this approach still does not yield a fully satisfactory answer to the question why so much attention should be paid to enhance safety in civil aviation. But that may become clearer when one takes a closer look at the nature of the various reasons that exist for trying to promote safety.

DIFFERENCE BETWEEN DANGER AND RISK

Risk and danger are more or less synonymous, but there certainly is a difference. Risk has a more quantitative notion, while danger has a more qualitative significance. In my opinion the best way to describe their mutual relationship is to state that risk is the integral of danger over a specific time period. In contrary, danger can be considered to be the risk per time-unit.
Since human activities always comprise a lot of sub-activities with varying dangers, I prefer in the following the notion risk, because of its more tangible and quantitative character.

REASONS FOR TAKING SAFETY MEASURES IN ORDER TO DIMINISH THE RISK OF ANY HUMAN ACTIVITY

These reasons are determined by the answers to the following questions:

1) How unsafe is the activity?

2) How unacceptable is its risk because of:
   - the importance of the consequences
   - whether or not this risk is accepted voluntarily and wittingly
   - emotional factors
   - irrational factors
   - political factors

3) Can the risk be influenced successfully with respect to:
   - the chances that an accident will happen during the activity
   - the importance of the consequences of an accident

4) How important are the economic factors like:
   - the interest of the activity for all concerned
   - the cost of applicable safety measures
   - the social cost of an accident.

I want to elaborate a little on some of these questions.

ad 1: The first one was tackled already in the previous. It is self-evident that there is more reason to take safety measures, when the number of lethal (and nonlethal) casualties per 100 million hours spent on that activity is large than when it is only a small number.

ad 2: As for the unacceptability of a certain risk there exists a disproportionate relation between the magnitude of the consequences of an accident and the unacceptability of its risk. It is clearly proven by research that according to whether the consequences are more serious, the unacceptability is very much greater. A lethal accident is considered to be vastly more serious than an accident which is not. A single accident causing the death of 300 people is experienced as much more serious - and much less acceptable - than three hundreds of accidents each causing one lethal casualty.
Especially important to the acceptability of a risk is whether this risk is accepted voluntarily and wittingly or whether the risk is forced upon someone without his knowing or without his consent. The stuntman in a motion-picture gets paid to take over very risky parts of a filmstar's role from which the latter shrinks back or for which he doesn't have the aptitude - and when he gets wounded it is considered more or less to be all in the game. The death of a drunken car driver who kills himself in an accident is nearly insignificant compared to the unacceptability of the death of the child which was killed by the same accident.
As to the emotional, irrational and political factors that influence the unacceptability of a risk, one may think of feelings of horror, of impressive human suffering and of matters like fear of flying, prejudices and again also the scale of an accident. All this is influenced to a large extent by the publicity which increases disproportionately with the scale and which has great influence on political decision making.

ad 3: The third type of reason for taking safety measures depends on the extent and the ways the risk can be influenced. For instance it is not possible to reduce the chance that certain natural disasters like an earthquake will happen, but it is quite feasible to keep away from areas which are prone to such disasters, or to build houses in such a way that they can withstand severe earthquakes or hurricanes. But there exists no remedy against a meteor falling on a house. So in certain cases it is feasible to attack the chance that something disastrous will happen, and in other cases it is better to take measures in order to reduce the possible damage of a dangerous event and in a few cases there is no reasonable way to reduce a specific risk at all and one simply has to live with it.

ad 4: As to the economic reasons to take or to leave safety measures there is always a balance between the value of the dangerous activity and the cost of the appropriate or applicable safety measures. If the activity has a great value for someone, then he or she will be inclined to take a certain risk for granted, when diminishing the risk impairs the value of the activity. The motorcyclist who enjoys the fun of riding on a motorbike much more than driving in a car, which is undoubtedly safer, apparently takes the greater risk for granted. And what to say about the preference of most people to ride forward facing in a car, bus, train or airplane? Can you imagine an aircraft manufacturer who for safety reasons puts all the seats in his aircraft backward facing, or who also for safety reasons gets rid of all those construction weakening windows in the passenger cabin? (As a matter of fact, the original Tridents had backward facing seats, but people did not like it).

But economic factors can also yield a strong motive to enhance safety, for instance the possibility of liability claims and the adverse publicity of a bad safety image caused by avoidable or reproachable incidents and accidents. And of course the cost of any safety measure also constitutes a powerful economic factor in the decision whether to implement it or not. On this matter of cost-effectivity I will later elaborate further.

With all these different types of reasons in mind you can easily determine that there are strong motives to work on amelioration of aviation safety, especially in the area of public transport.
Apart from the still existing and not to be neglected unsafety, which in itself is already a good motive, the following reasons are evident:

- The unacceptability of aircraft accidents is always extremely high because of the scale of the accidents and the serious and abhorrent consequences. This in particular is a strong motive to pay very much attention to fire safety.
- As in all public transport, the risk comes to the passenger in an unvoluntary and hardly realized way.
- The emotional, irrational and political factors are, although perhaps not quite reasonable, a very strong reality.
- With respect to the possibility to influence the risk of aircraft accidents, much has already been done successfully in the area of reducing the chances that an accident will happen. Although with gradually diminishing results, work is going on in this area.
- Limiting the adverse consequences of aircraft accidents is still a very fertile area for enhancing safety, which to a certain extent already can be concluded from the high lethality of these accidents compared to other types of traffic accidents.
- Finally the economical factors connected with aircraft accidents often are important stimulators to enforce safety measures. Among other things there are the enormous liability claims which may result from an accident and also you may think of the economical result of a decrease in the number of passengers when fear of flying is stirred up by accidents or terrorism (or even by remote causes like the Tsjernobyl disaster). Negative economical factors are of course the enormous cost of safety measures in aviation, especially when it is a matter of retrofit.

WHY SO MUCH EMPHASIS ON CABIN SAFETY AND FIRE SAFETY?

From the foregoing it is quite clear that there are strong reasons for continuously trying to ameliorate safety in transport aviation, which leads to the question: "How?"

As previously mentioned, risk is a directly proportional to the product of chance times consequences of an accident. Therefore, diminishing risk can principally be achieved in two ways, either by limiting the chances of some accident to happen, or by reducing the possible damage that may result from it.
Or, in other words, one has the choice whether to direct one's attention to <u>prevention</u>, or to <u>survival</u> of accidents.

In aviation for a long period the rule applied that "prevention is better than cure" and in former days aviation safety people mostly concentrated their attention on preventive measures. It is obvious that much was to be achieved in this area, in the early days of aviation.
Accordingly, as aircraft became more complicated, larger and at the same time safer, it became more and more difficult to achieve significant improvements. For obvious reasons the most important causes for accidents were attacked first and in the course of years the attention therefore shifted gradually to the numerous remaining causes of less and even little importance, with the result that the effect on safety of possible safety measures in this area is diminishing continuously. Also at the same time the number of possible accident-causes increased because of the increase of the number and intricacy of aircraft systems and that too is a reason for the diminishing effect of preventive safety measures. Meanwhile in due time it was realized more and more that even aircraft accidents can be survived. That survivability in a certain way was even enhanced by the fact that the average size of transport airplanes increased gradually, for a large aircraft usually endures a lower deceleration during a crash, than a smaller one.
For all these reasons the attention to new rulemaking in the field of aviation safety gradually shifted from prevention to survival. Of course also in the past, one endeavoured to ameliorate survival chances, remember for instance the use of parachutes, and also at this moment preventive measures are not being neglected. But it makes clear why especially in recent years attention is so much focussed on cabin safety and fire safety, because the regarding safety measures to a large extent are aimed at limiting the harmful effects of aircraft accidents as much as possible and to increase survivability.

WHAT CAN HAPPEN IN AN AIRCRAFT CABIN DURING AN ACCIDENT AND TO WHAT SAFETY MEASURES DOES THIS LEAD?

The passenger cabin in a transport aircraft may be considered as a cocoon, to be transported by the aircraft which also serves as a protective cage for its occupants. By looking at a number of specific accident scenarios it can be concluded which life threatening events may happen within and with that cocoon. This in turn can give rise to insight in the nature of possible safety measures, that can limit the harm to occupants and enhance survivability. The chosen division of the scenarios is not complete and also not fully consistent, because some of the scenarios overlap or flow over into each other.
A distinction is made between the accidents that can happen during free flight (climb, cruise and approach) and accidents that can happen during take-off and landing and which take place close to or in contact with the earth surface.

For the sake of completeness, all types of accidents are mentioned, even the ones which never or seldom end in a post-crash fire, and a post-crash fire is separately mentioned although it is not a generic type of accident, but always a result of something else.

In free flight:
- Decompression
- Explosion
- In-flight fire
- Collision
- Clear air turbulence and other adverse weather phenomena.

Near the earth surface:
- Ditching: controlled touch-down at a water surface
- Collision with obstacles and mountains
- Failed take-off, failed landing
- Post-crash fire

DECOMPRESSION

At a normal cruise level of 30,000 ft (Flight Level 300) the prevailing outside air pressure is about 300 mb, some three tenths of the barometric pressure at sea level. At that low pressure outside the aircraft cabin a human being cannot live without extra supply of oxygen, so there is a need for pressurization of the cabin. Within a pressurized cabin the pressure at cruise level is maintained at about 800 mb, which is equal to the atmospheric pressure at an altitude of some 5000 ft. When - by whatever cause it may be - the cabin wall is damaged and the pressurized cabin is perforated, then in a very short time, for instance 10 seconds, the pressure difference of 500 mb will disappear because the air in the cabin will blow out. Near the gap there will be the full pressure difference at first, which equals 5 N per square centimeter. Should the frontal surface of a human being be exposed to such a pressure difference, then this would exert a force of some 30,000 N, say about 6500 lbs. In reality it is not that bad, the real forces will be a fraction of this value, because as the distance to the gap is larger and the gap is smaller, these forces diminish quickly. Still these forces, which manifest themselves as airforces with corresponding high airspeeds, are very large and dangerous. It happened at decompressions that passengers were literally blown out of the aircraft. This for instance occurred in a Lockheed Tristar to two children, and also at a terrorist action when a bomb damaged the fuselage of an American aircraft and a passenger lost his life when he was hurled out through the resulting hole.
Even when a decompression occurs at a much lower altitude than cruise level, the results can be devastating. When recently a cargo door of a B747 which apparently was not properly locked, was blown out and took with it a part of the passenger cabin wall, several passengers were blown out with their seats, and others in the neighbourhood of the hole were lucky that the belts were fastened while the airplane was still in its climb and far below cruise level.
Because of such a sudden pressure reduction the air temperature falls till far below the freezing point and as a consequence, the watervapour in the relatively damp cabin condenses and causes a sudden and very dense fog.
The quantity of oxygen in the rarefied air after the decompression is so low that shortage of oxygen within a minute can lead to unconsciousness of occupants. At longer exposure to such a low pressure or at still higher cruise levels, as with the Concorde, there is the danger of vapor-bubbles forming in the blood, the same phenomenon as caisson-disease of divers, who rise too quickly.
Finally also the very low temperature in itself is already a danger and the structural weakening of the fuselage by the damage may threaten the integrity of the aircraft. In a certain sense it may be a good thing that the pressure difference between the inside and the outside of the cabin is leveled when the fuselage is seriously damaged because it decreases the loads considerably.

From this description the nature of the appropriate measures can be deduced. There is an immediate need for oxygen for all the occupants, an emergency descent (which may last for some ten minutes) should be started immediately and adequate training of the cabin staff is a prerequisite.

EXPLOSION DURING FLIGHT

Apart from explosions as a consequence of terrorist activity - outside the scope of this paper - explosions on board nowadays are an extreme rarity. In the past it sometimes happened that an explosion was caused by a lightning strike, but by appropriate measures of a technical nature and in the area of fuel composition, this danger has been practically overcome. But when an explosion on board still occurs, and the aircraft desintegrates in the air, the results will be fatal.

IN-FLIGHT FIRE

It is estimated that yearly some 500 or 600 in-flight fires happen in the USA, so worldwide this number will even be much greater. From that large number it can be deducted that such usually small fires, apparently can be contended with very effectively using the fire-fighting equipment available on board. A necessary condition therefore is that such a fire is perceived in an early stage. The present safety measures therefore are directed at timely detection and extinguishing. This holds especially for the so called "hidden fires", fires at places where they cannot be perceived easily, like in the cargo-holds, in lavatories, behind wallpanels and in similar places.
Fire detection and alarming in lavatories, and automatic fire extinguishers in waste-boxes

of lavatories, are typical actual examples of this type of preventive and suppressive measures. When a fire on board is not detected in time, the danger arises that extinguishing becomes impossible with the available equipment. That is a very dangerous situation which luckily very seldom occurs. The most imminent danger in that situation is poisoning and suffocation by smoke and gaseous combustion products. Additional dangers are the reduced visibility caused by the dense smoke and in a later stage physical burning. Only when the aircraft succeeds in reaching an airport before the fire reaches that stage, there may be hope of survival, but an emergency landing somewhere else in these circumstances will certainly be fatal.
Besides measures directed at fire-fighting and fire-detection, also measures are applicable which are aimed at retarding expansion of the fire or at diminishing such an expansion. This approach comprises of the use of fire-delaying an fire-extinguishing materials that develop only very little or no smoke and poisonous vapors when heated or burning. The recently introduced "heat release" requirements will be beneficial to this purpose, although their main objective is to prevent a flash-over condition. In the United Kingdom research is going on concerning the possibilities of the use of smoke hoods, individually used protection hoods of transparant heat resistant material, some with a built-in oxygen supply. It goes without saying that adequate training of cabin attendants, especially in fire prevention, fire detection and fire-fighting is an all important requirement.

MID-AIR COLLISION

On september 10, 1976, near Zagreb in Yougoslavia, a DC-9 and a Trident collided. All 176 occupants perished. A few years ago a light aircraft, flying over the outskirts of Los Angeles collided with the tail of a DC-9. Not only all occupants from both aircraft perished, but so did 15 persons who were in the houses that were hit by the fragments.
For this type of accidents, only preventive measures of operational nature are applicable. In the unfortunate case of a mid-air collision, mostly it is a lost case for all of the occupants.

CLEAR AIR TURBULENCE (CAT)

Large airspeed changes within short distances, which can occur near "jetstreams" in the atmosphere at high altitude can cause sudden vehement movements of an aircraft, during which accelerations and decelerations of the magnitude of for instance half a g can occur. This so called Clear Air Turbulence which happens fairly often, usually does not have very serious consequences. Mostly they are limited to injuries caused by loose objects or by hot liquids and injuries of free walking persons.
Early detection and warning is effected by means of advanced equipment (which is still in the development phase) and by means of communication (warnings for the presence of CAT in certain areas to other aircraft by aircraft which encountered it). In the passenger cabin it makes sense to promote that passengers leave their seats as little as possible and keep their belts on also when that is not compulsory.

OTHER ATMOSPHERIC INFLUENCES

Within the troposphere, which for most jet transport aircraft is below cruise level, processes and occurrences can happen which may give rise to disastrous circumstances for aircraft, like extremely heavy turbulence, very severe hail and lightning strikes. A clear example was the accident of a Fokker F28 "Fellowship" which encountered an extraordinary heavy turbulence somewhere over the south part of the Netherlands. This caused a heavy overload on the wing, far above its design-strength until it eventually collapsed. The wreckage fell down and was totally destroyed; all occupants were killed.
Also for this type of accident it applies that the only remedies can be found in preventive measures during design and during operations. There is no real way to enhance survivability once the structural integrity of the aircraft is lost while still airborne.

DITCHING

When for some reason, for instance because of fuel starvation or engine trouble, the remaining engine power is not enough to reach the nearest airport, over sea the only recourse is trying to touch-down on the surface of the sea. The direct purpose of such a "ditching" is to take care that the fuselage remains intact and keeps floating in a horizontal position long enough to enable the occupants to leave the cabin and take their place in the life rafts. The risk of failure of an emergency "landing" like this is considerable, especially when the waves are high. Most aircraft have not been built to withstand a ditching and the probability is high that the aircraft will break to pieces at the moment it touches the water surface. When that happens, the survivability is very low, for not only the broken parts will not float, and certainly will not stay in a horizontal position, but the impact velocity on the water is so high that people may be killed by it. Besides, undercooling of a floating person happens very quick, especially in cold seawater (think of polar flights): survivability in May in the North Sea usually is not much more than five minutes if no special protective clothing is available. Therefore, the applicable measures are mainly directed at survival after a succesfull ditching. They are:

- Life-jackets, with of course a good instruction for donning and using them
- Life-rafts and slide-rafts, slides which also function as a life-raft
- Emergency signals and beacons
- Special training for aircraft crews.

At a ditching which, incidentally, hardly ever happens, there are a few small but still important bright spots: the preparation time usually is adequate and there is not much chance of a post-crash fire.

COLLISION WITH THE SURFACE OF THE EARTH

If due to a navigation error an aircraft collides with the surface of the earth, the velocity at the moment of impact normally is much higher than during take-off or landing, because the aircraft is not in a landing configuration. Mostly the aircraft will be totally destroyed, even if the touch-down area is more or less level and often there will be a post-crash fire. When the place of the accident is in an inaccessible area and not very near to an airport, then external first-aid will certainly be too late.
In november 1979 a New Zealand DC-10 flew into an incline near Mount Erebus in Antarctica, due to a navigation error caused by a wrongly programmed computer. All 257 occupants perished. In august 1985 a B747 flew into the ground in a hilly and mountainous region some 60 miles north of Tokio when due to a decompression, it had become totally uncontrollable. Except for four survivors, all 524 occupants perished.

FAILED TAKE-OFF OR LANDING

Three quarters of all accidents with transport aircraft occur at, or within a distance of a few miles from an airport. It is then always a take-off or landing where something has gone wrong.
The initial speed at impact in such a case is not so very high, not even for a jet aircraft, namely some 140 or 150 knots. Also the angle with which the aircraft touches the ground, usually is not so steep. Mostly it is something like the normal glide angle during approach, about three degrees. Therefore the average decelerations at impact need not be so very high. This can be elucidated with a very simple calculation. At an initial velocity of about 140 knots and a constant deceleration of 6 g's - which is survivable - the speed is reduced to zero in about one second and the "braking" distance is no more than about 100 ft. Should a large aircraft like a B747 collide with a wall or a mountain with this speed, then the occupants in the back could survive even this extreme case, provided the deceleration was constant and there were no other adverse circumstances. Alas, the deceleration is far from constant and during the random movements of the airplane during the crash and due to collisions with obstacles there are usually peak values in the deceleration of about 15 to 25 g's. But these peak values have a very short duration.
Human tolerance for acceleration and deceleration forces however is enough to withstand such short peak values. This tolerance is very much dependent on the duration of the peaks. There are known cases that persons have been submitted to peak values of 40 and 50 g's, without injuries of any importance. Sustained g-values of about 10 g's are easily survivable, although mostly in a black-out condition.
It is clear that the human body can withstand much more than the average g-forces that occur during a crash at take-off or landing. Furthermore, from analyses of accidents it is apparent, that also the fuselage normally remains intact, although often heavily damaged, and therefore really can be considered as a protective cage for the occupants. And still such an impact causes many serious and often even deadly injuries.
The reason for that is illustrated by the following table, in which are put together the requirements which are in force for the strength of the "furniture" in the cabins of existing transport aircraft and what g-forces are considered to be survivable for a human. These latter figures are valid when hip-belts are used: when also a shoulder harness is used, the applicable values are even considerably higher.

DISCREPANCY BETWEEN STRENGTH REQUIREMENTS AND THE HUMAN TOLERANCE FOR G-FORCES

DIRECTION	REQUIREMENTS	SURVIVABLE
FORWARD	9 g	20-25 g
DOWN	4.5 g	15-20 g
SIDEWARD	1.5 g	10-15 g
UPWARD	2 g	20 g

It is very clear that the requirements for the strength of the cabin furniture, which date from the beginning of the years '50, are far behind to what a human being can withstand. It is no wonder therefore that the FAA last year introduced new requirements. These however will only apply for new aircraft designs. Although they are a significant improvement especially because also the behavior under dynamic conditions is addressed by the new rules, it still seems that the human being can withstand considerable larger impact forces than the seat he is placed on. The dangerous results of an impact at a crash therefore differ from what they usually are supposed to be. What in fact happens is:
- seats collapse, with the result that people become trapped or injured;
- safety belts tear to pieces;
- luggage bins become loose;
- nonrestrained people and loose objects fly through the cabin with very high relative velocities;
- aisles and emergency exits become blocked.

Besides, the dynamic circumstances during an impact, when combined loads and unforeseen

deformations occur, often cause collapsing of seats and other aircraft parts at lower load values than the static loads that these parts according to the requirements should be able to withstand. This was the reason why in the new rules also dynamic conditions are addressed. It is utterly important that the occupants are very well fastened to the aircraft fuselage by means of their safety belts. This was clearly demonstrated when at an otherwise succesfull ditching, one of the cabin attendants was in the back of the aircraft without having fastened her safety belt. All occupants survived the ditching, but for this one cabin attendant who during the ditching itself was hurled through the cabin and finally smashed through a cabin wall with a velocity of some 120 miles per hour.
Even having the safety belts not tightened properly can bring about much higher g-force peak values than those which the fuselage itself undergoes, especially when the crash sets in with a g-force peak value instead of with a gradually increasing or just moderate deceleration.
The possible safety measures are obvious and part of them are recently introduced or under discussion. Several of them however are not easy to implement or are not feasible because of economic restrictions or unacceptability with a view on passenger comfort. Examples of such measures are:

- increase of the strength requirements and test requirements that include testing in dynamic load conditions and combined loads;
- application of energy absorbing constructions for smoothing peak load values;
- facilitating free movement through the aisles and improving the accessibility of emergency exits;
- restrictions with respect to hand carried luggage;
- better safety belts and safety belt fastening;

With regard to this latter point it can be remarked that the requirements for safety belts in American cars are based on a load of 60 g. Compared with this value, the applicable requirement of 9 g for aircraft safety belts makes a poor show. A higher safety factor would substantially increase cabin structural weight, though.

It is obvious, that in the area of increasing the survivability of crashes during take-off and landing, much can still be done.

POST-CRASH FIRES

The same remark is applicable to "post-crash fires". Fire after a crash, as a result of that crash, occurs at more than 40% of the fatal aircraft accidents and is the most important direct cause of death at accidents with transport aircraft.
Such fires originate when fuel tanks or fuel lines during impact are damaged and the spilled fuel is ignited by contact with heated engine parts or for instance by electrically or mechanically caused sparks. These fires nearly always are very extensive and intense and cannot be extinguished before heavy damage has already occurred. The fighting of such a fire therefore concentrates first on limiting its propagation and enabling the occupants to leave the aircraft safely.
Burn-through of the cabin wall from the outside normally takes hardly more than a minute. Within the cabin the temperature rises quickly and a dense smoke can develop. Two, three or four minutes after the fire has burnt through into the cabin, a "flash-over fire" can occur. This is a more or less explosive expansion of the fire, which takes place when through the heating of the cabin materials enough combustible gases have developed. Once this flash-over fire occurs the situation in the cabin is unsurvivable.
The direct life-threatening dangers at a post-crash fire are:

- suffocation by lack of oxygen
- intoxication by the fumes
- burning by heat radiation
- burning by molten, burning material
- burning by burning clothes and luggage
- decreased visibility because of smoke and because the eyes are irritated by the fumes
- panic.

The safety measures which deserve consideration, are aimed at preventing or diminishing these dangers, to postpone exposure to them and to enable the occupants of the aircraft to escape in time.
With regard to the fire itself, there are in the first place possibilities for preventive measures, which are outside the scope of this paper, as for instance the possible use of an anti-misting additive in the fuel (fuel with such an additive, the so-called anti-misting-kerosene AMK is much less inclined to vaporize, which diminishes the chances of ignition. Unfortunately vaporization is required in the combustion chamber of the engine, so it introduces new problems also).
Furthermore there are possibilities to delay the burn-through of the cabin wall, by using fire-retarding and fire-blocking materials. An interesting example is the use of a special swelling paint on the cabin outside, which when exposed to fire, swells and transforms in a fire-retarding layer. Also within the cabin itself a suitable application of special materials can contribute much to limit the speed of propagation of a fire, to delay or even prevent a flash-over fire and to diminish the development of fumes. Very important are the recently introduced requirements with regard to "heat release" of furnishing materials. Their purpose is to postpone or even totally prevent the flash-over fire.
Together with this last item attention is also given to reducing the toxicity of those combustion products. Measures which are directly related to the occupants are among other things the provision of sufficient oxygen supply: it has happened that when a cabin fire occurred the airconditioning was shut off in order not to stir up the fire, but with the sad result that the passengers suffocated. Also, there exist individual means for occupants enabling them to keep respirating also in a very poisonous and bad atmosphere. Especially in the U.K. there has been a lot of attention in this area lately. This concerns the use

of the already mentioned smoke-hoods on which a lot of development work and research is going on. It might be possible that having a smoke-hood on board for every passenger would have much more influence on enhancing safety, than the life jackets, which have been obligatory for a long time on long overwater flights.
Also the development of a water mist spray system, looks very promising although its evaluation is not yet finished.
Furthermore good training of cabin attendants is required to enable them to help passengers in the frightening circumstances of a post-crash fire. Very important in those circumstances is preventing panic, also negative panic, which is the phenomenon that some people become totally inactive by the shocking experiences of a crash and therefore deliberately have to be activated.
For a quick evacuation the aisles have to be passable and stay so, which often is impeded by pieces of luggage and other objects that are hurled around at a crash. Emergency exits have to be accessible and easy to open, also when people are pushing and crowding in front of them. The emergency lighting has to be effective, which among other things means that the lights remain well visible also when a dense smoke is generated. This requirement was the inducement for the regulation that emergency lighting should be fitted on or near to the floor. The visibility below at the cabin floor is diminished the least because the hot smoke rises first to the ceiling.
Escape slides, which are very important for a quick evacuation of the occupants, must be reliable and should not be too vulnerable to heat radiation and mechanical damage.
Markings and other signals, that indicate the emergency exits or in another way serve to help occupants to find the right direction to the most appropriate emergency exits, should be clear and unambiguous.
Finally there is another important area in which safety measures with respect to post-crash fires are appropriate: the equipment of airports. This concerns of course the availability of a quick and efficient fire brigade and medical provisions. Also a pre-planned scenario for taking action in case a disaster occurs should be available.

CLASSIFICATION OF SAFETY MEASURES

In the foregoing it is described which types of safety measures come into consideration for several types of occurrences. Via another approach I will now make a division of types of safety measures in order to indicate their mutual relation.
It was argued that safety can be improved by fighting risk, and that risk is proportional to the chance that something will happen, times the extent of its possible consequences. This indicates that there are two principally different ways to fight risk: to prevent something from happening and to improve survivability when something has happened. But in reality most safety measures are a mixture of both. In a way every safety measure is to some extent preventive, since its purpose is always to make the best out of an existing situation and so to prevent worsening the consequences.
So there seems to be a continuous scale of possible safety measures ranging from pure prevention to measures solely aimed at improving survivability. This scales runs remarkably parallel to a timescale which represents the time that the safety measures come into effect with respect to the occurrences at which they are directed.
In order to give a further explanation of the characteristics of the safety measures along these scales I have quite arbitrarily divided the combined scale in five areas which shade off into one another. For ease of understanding I have depicted the scale with these five areas and in each area I have mentioned one more or less characteristic safety measure.

PREVENTION ←		→		SURVIVABILITY
1	2	3	4	5
Quality	Redundancy	Fire extinguishing	Escape	First Aid
BEFORE ←		→ DURING ←		AFTER

DESCRIPTION OF THE SAFETY MEASURE AREAS

1. <u>Pure prevention</u>
The first area is that of pure prevention. In a way one can hardly consider the measures in this area to be safety measures because safety measures are aimed at abnormal occurrences, while pure prevention is directed at a situation in which no abnormal occurrences arise. In a perfect aircraft pure prevention takes care that no foreseeable accident or incident can happen. Only force majeure can still cause an accident but all other causes have been prevented by sheer quality. So pure prevention is achieved by quality. Quality of design, of operations, of procedures, of materials, of training, of maintenance and so on.
It is interesting to realise that a lot of safety measures start as a remedy against some shortcoming in design, operations, procedures, materials etc., and that in due time these safety measures are incorporated into quality standards. For example the recent requirements on heat release properties of furnishing materials, which undoubtedly can be considered as a safety measure, will be considered in the future as a quite normal standard for the choice of high quality materials. Also when you consider redundancy measures as a safety measure, the fail safe concept is one way how it can be translated into quality standards for design.
So there appears to be a gradual shift in safety measures. Either they themselves may in due time be transformed to quality standards, or related quality standards are gradually deve-

loped, which replace the safety measures or make them less important.
As for the time scale, preventive measures aim to be indefinitely remote from the occurrences they should prevent.

2. Suppressive measures
The second area, for which redundancy is representative, consists of safety measures, which come into effect when something potentially dangerous occurs. The measures are aimed at supressing the danger in a phase and in a manner that normal operation of the aircraft is not hampered. Often the passengers and sometimes even the crew need not become aware of what has happened. To this area belong measures like:
-redundancy requirements for structures and systems;
-fire detection systems in combination with:
-emergency procedures for specific events;
-automatic fire extinguishers as for instance within waste boxes in lavatories, or in cargo holds;
-the use of fire-extinguishing materials, which for instance prevent a burning cigarette butt to start a fire;
-quite a lot of operational procedures like requirements for fuel reserves and so on.
In an advanced transport aircraft even the function of the pilot from a safety point of view, may be considered as a safety measure in this area: the aircraft is quite capable to fly itself automatically most of the time, so the monitoring function of the pilot is comparable with a redundancy measure! (which of course does not mean that he is redundant).
On the time scale safety measures of this type come into effect in a very early stage of some developing danger.

3. Fighting the hazards
The third group of safety measures consists of measures, equipment and procedures that come into effect when some danger is so serious or is already so much developed that it will soon be a threat to the lives of the occupants.
To the safety measures in this area belong all measures which are aimed at minimalizing the adverse results of the probably coming disaster. The cabin should be constructed an equipped to act as a protective cage for the occupants. The crew should have the appropriate training to prepare the passengers for an emergency. Seats and safety belts should be strong enough. Luggage should be properly stowed. Fire extinguishers should be available to the crew and so on.
On the time scale these measures come into effect immediately before, or during the climax of the accident and anyhow in a phase that serious damage and harm seem unavoidable or at least probable.

4. Escape measures
In the fourth category the actual crash has already happened. Probably a fire has started as a result of the crash or at least there is a grave danger that a post-crash fire can still arise. The main point is now to make escape as easy and quick as possible. Quite a lot of safety measures are aimed at this purpose, for example:
- emergency lighting, like the recently introduced "Floor Proximity Emergency Escape Path Lighting", provides effective guidance for the occupants to the emergency exits and is located in a way that it will stay visible as long as possible;
- smoke hoods, aimed at giving the occupants protection against intoxication by poisonous fumes and at providing oxygen against the danger of suffocation. Discussions about the balance between advantages and disadvantages, benefit and cost, have not yet died down. Although for certain circumstances the use is undeniable, up till now the available types of smokehoods are not yet considered good enough to warrant general application for passengers;
- emergency exits which are sufficient in number, easily accessible and openable and which should be within reasonable reach of any occupant;
- the newly developed water mist spray system, to mention a promising new safety measure in this area;
- crash-axes for the crew in order to clear obstructions;
- slides at every exit, in order to bridge the distance between the exit and the ground, and to enable the passengers to clear the exit-opening as quickly as possible.

5. Post-crash measures
The last area includes equipment and services which are aimed at improving survival in the final stage of an accident. It comprises as well equipment on board the aircraft itself as equipment or services from elsewhere, that can be brought into action for this purpose.
Measures within, or connected with the aircraft are for example:
- life rafts;
- life jackets;
- emergency locators;
- survival kits.

Other measures and services in this area are mostly connected with airports, and are for instance:
- fire brigades;
- first aid services;
- emergency schemes.

THE FUTURE OF SAFETY IN CIVIL AVIATION AND THE ROLE OF THE REGULATORY AUTHORITIES

Based on the foregoing it is possible to make some interesting or even intriguing statements concerning the future developments in safety of civil aviation and about what the role of the regulatory and surveying authorities can be in this area.

WHAT SHOULD BE THE GOAL?

In how far should safety be considered a necessity and where does it start to be a luxury? There is not an exact answer to this question, because there are too many ethical, political and economical factors which have an influence. But the approach to consider commercial air transportation as just another human activity might provide something like a reasonable answer.
Clearly it is not possible to evade all risk: force majeure will always remain possible. But it can be argued that risk should be fought as long as it surpasses the average risk of life. Of course there can be very good reasons for a person to accept a higher risk, but for public transportation it is quite another matter to submit passengers to a higher risk than they run in average. On the other hand, it is hardly worthwile to fight risks for activities that are safer than the average risk of life, because then there are good reasons to spend money and energy to improving safety on other activities which not yet have reached such a level. Therefore a very viable and at the same time challenging goal for the safety of civil aviation could be formulated as follows:

"Living in an aeroplane shall be as safe as living anywhere else".

It will be clear that there is still a long way to go to reach such a reassuring level.

THE PERFECT AEROPLANE

Working on safety means to reduce risks. It is senseless to reduce one or two risks to zero while leaving other risks at an unacceptable level. Like the chain which is not stronger than its weakest link, the worst risks have the most influence on the overall safety. Therefore fighting risks should be done on many fronts at the same time. Continuous monitoring of all possible risks is necessary to keep aware of which are the worst risks in civil aviation. At present fire risks score high on the list of potential dangers, so much attention should be directed to reduce these risks, by means of safety measures. In the long run safety measures may turn into quality standards or may be made unnecessary because of related quality measures. For in principle it might be possible to prevent all foreseeable accidents by a perfect quality. In theory in such a perfect aeroplane, there is no need for any safety measure apart from a superb level of quality that in itself can provide the desirable level of safety. Whether we ever can reach that level is questionable but it is useful to realize that safety measures should not be considered as unassailable, because safety measures nearly always have important disadvantages. Not only disadvantages of cost and weight penalties, but sometimes even disadvantages in another area of safety, or disadvantages of discomfort to the passengers.

COST-BENEFIT ANALYSES

Most new safety measures are submitted to thorough cost-benefit analyses and they should be, because although it is not always clear who will carry the cost burden of safety, it is sure that there is not a limitless safety budget and it is equally sure that in the end, the passenger will pay the bill. So it is a necessity to evaluate whether a proposed measure is worth its cost. An absolute determination of its value is clearly impossible: therefore there are too much imponderables like for example the value of human life. Yet it is very wise to arbitrarily put some price tag to the economical value of a human live, like the US government does, in order to enable cost-benefit analyses. In this way, although it does not give an absolute measure, a comparison of the effectiveness of safety measures becomes possible.
Not only for new safety measures such cost-benefit analyses are useful. As I have outlined, there is a gradual shift from safety measures to quality standards and also the circumstances change in the course of the years. Therefore it may be quite well possible that well-established safety measures which were initiated long ago in quite different circumstances, gradually lose their effectiveness or even become unwanted.
An example is the requirement to have a crash-axe within the passenger cabin. Only recently the European Civil Aviation Committee decided to discard this requirement because the risk that a passenger might use such an axe as a weapon was considered to be more important than its benefit when a crash occurred.

THE ROLE OF AVIATION AUTHORITIES WITH REGARD TO SAFETY IN COMMERCIAL AIR TRANSPORTATION.

Often a Civil Aviation Authority like RLD is considered to be an awkward snooper and it is a rightful question what is the use of such an authority related to - in this case - fire safety, or to safety of aviation in general. To answer that, it is useful to realize what the influence on safety would be when there would not be any supervision by authorities on safety-matters in aviation. In that case safety would undoubtedly at best become a competition-item between airlines and between aircraft-manufacturers. And because safety costs a lot of money and the benefits are not easily perceptible, it might easily degrade in many cases to a balance post on the budgets. Less scrupulous manufacturers and airlines could offer lower prices and fares and for the guileless air traveler the temptation is great to give preference to a tangible discount above something elusive as safety. Accident rates are so low that the occurrence of accidents is no suitable means to distinguish between

"safe" and "unsafe" airlines or aircraft types (although sometimes publicity media create that impression). Cooperation on safety-matters between manufacturers and between airlines would be hampered because safety soon would be drawn into the area of competition. Presumably a new equilibrium of safety would emerge on a much lower level which would be determined by the amount of damage to be expected and liability claims to insurance companies, or by unions of aviation personnel that would boycott or put pressure on companies with a bad safety record.
In this view the existence of an aviation authority as a watchdog on safety is not only meaningful for the citizens because it ensures a reasonable high level of safety to which each manufacturer or airline has to confirm. But also it is highly important for the manufacturers and airlines either who in good faith want to deliver safe products and safe services, because it enhances their chances for survival against other companies that would otherwise be inclined to compromise on safety matters in order to increase their revenues.
From this point of view it emerges that for the authorities to function properly they have to pursue:

- International harmonisation of regulations;
- Continuous adaptation of regulations to the actual state of technical achievements;
- Regulations which are formulated in such a manner that the put no unnecessary and unwanted impediments to technical progress, but on the contrary stimulate developments;
- Great care at the introduction of new safety measures, especially with regard to retro-fit;
- Continuous orientation with regard to the social and technical developments which have impact on aviation;
- Understanding for the very divergent interests in the various branches of aviation.

CONCLUSIONS

At the end of this paper it seems meaningful to summarize a few conclusions:

- Although commercial air transport is already fairly safe, it is desirable to improve its safety much further.
- Aviation accidents are to a very high degree unacceptable.
- The possibilities to enhance safety are not exhausted by any means, especially not in the area of improving survivability, which for a large share is determined by fire safety.
- Quality can be considered as a superior way to achieve safety. In the long run specific safety measures may turn into quality standards or may become unnecessary because of related quality standards.
- Evaluation by means of cost-benefit analyses is a must for new measures and may also be very useful for existing measures and rules in order to test their actual effectiveness.
- The task of the civil aviation authorities is to stimulate activities directed at improving safety, to prevent safety from being degraded to a competition item at the cost of a good safety level, and to provide for a realistic rulemaking.
- International cooperation and harmonization is to this purpose a necessity.