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MIRACLE-ON-THE-HUDSON: QUANTITATIVE AFTERMATH

Application of the quantitative probabilistic risk management (PRM) concept should complement in various human-in-the-loop (HITL) situations, whenever feasible and possible, the existing vehicular psychology practices, which are typically qualitative a-posteriori statistical assessments. A PRM approach based on the double exponential probability distribution function (DEPDF) of the extreme value distribution (EVD) type is suggested as a suitable quantitative technique for assessing the probability of the human non-failure in an off-normal flight situation. The human capacity factor (HCF) is introduced in this distribution and considered along with the (elevated) short-term mental workload (MWL) that the human (pilot) has to cope with in an off-normal (emergency) situation. The famous 2009 US Airways «miracle-on-the-Hudson» successful landing (ditching) and the infamous 1998 Swiss Air «UN-shuttle» disaster are chosen to illustrate the usefulness and fruitfulness of the approach. It is shown that it was the exceptionally high HCF of the US Airways crew and especially that of its captain Sullenberger that made a reality what seemed to be, at the first glance, a «miracle». It is shown also that the highly professional and, in general, highly qualified Swiss Air crew exhibited inadequate performance (quantified in our analysis as a relatively low HCF level) in the off-normal situation they encountered with. The Swiss Air crew made several fatal errors and, as a result, crashed the aircraft. In addition to the DEPDF based approach, we show that the probability of safe landing can be evaluated by comparing the (random) operation time (that consists of the decision making time and the landing time) with the «available» time needed for landing. It is concluded that the developed formalisms, after trustworthy input data are obtained (using, e.g., flight simulators or applying Delphi method) might be applicable even beyond the vehicular domain and can be employed in various HITL situations, when a short term high human performance is imperative and therefore the ability to quantify it is highly desirable. It is concluded also that, although the obtained numbers make physical sense, it is the approach, not the numbers, that is, in the author's opinion, the main merit of the paper.

Keywords: *the concept of quantitative probabilistic risk management, double exponential probability distribution function, the human capacity factor, off-normal (emergency) situation in transport.*

Кількісна імовірнісна оцінка (КІО) ролі людського фактора в різних «людина-в-полі-зору» (ЛВПЗ) ситуаціях, де ця роль важлива, повинна доповнювати, коли це можливо і доцільно, існуючі методи психології

хології в задачах безпеки руху. Методи ці є, як правило, якісними статистичними методами, і застосовуються вони в більшості випадків «апостериорно», тобто коли подія вже відбулася. У даній статті пропонується підхід, заснований на методі кількісної апріорної ймовірнісної оцінки благополучного результату місії або події, пов'язаних з безпекою руху. Пропонований метод заснований на застосуванні функції розподілу ймовірностей типу «статистики екстремальних значень» і використовується для оцінки ймовірності безпомилкових дій пілота в Екстра-ординарних (незвичайних) умовах польоту. Знамените успішне «приводнення» літака компанії US Airways в 2009 р на Гудзоні («чудо-на-Гудзоні») і сумно-відома катастрофа швейцарського «Swiss Air 'UN-shuttle'», що відбулася в 2009 році, прийняті в якості ілюстрацій корисності і плідності підходу. Робиться висновок, що пропонований формалізм, після того як отримані досить достовірні вихідні дані (що може бути зроблено з використанням тренажера і / або на підставі відомого методу дельфійського оракула), може бути успішно застосований і за межами області безпеки руху транспортних засобів, в різних ситуаціях, коли дії людини в екстраординарних (незвичайних) умовах і їх кількісна оцінка вкрай важливі.

Ключові слова: *концепція кількісного імовірнісного управління ризиками, подвійна експоненціальна функція розподілу ймовірностей, фактор людського потенціалу, нештатна (аварійна) ситуація на транспорті.*

Количественная вероятностная оценка (КВО) роли человеческого фактора в различных «человек-в-поле-зрения» (ЧВПЗ) ситуациях, где эта роль важна, должна дополнять, когда это возможно и целесообразно, существующие методы психологии в задачах безопасности движения. Методы эти являются, как правило, качественными статистическими методами, и применяются они в большинстве случаев «апостериорно», т.е. когда событие уже произошло. В данной статье предлагается подход, основанный на методе количественной априорной вероятностной оценки благополучного исхода миссии или события, связанных с безопасностью движения. Предлагаемый метод основан на применении функции распределения вероятностей типа «статистики экстремальных значений» и используется для оценки вероятности безошибочных действий пилота в эктраординарных (необычных) условиях полёта. Знаменитое успешное «приводнение» самолёта компании US Airways в 2009 г. на Гудзоне («чудо-на-Гудзоне») и печально-знаменитая катастрофа швейцарского «Swiss Air 'UN-shuttle'», произошедшая в 2009 году, приняты в качестве иллюстраций полезности и плодотворности подхода. Делается вывод, что предлагаемый формализм, после того как получены достаточно достоверные исходные данные (что может быть сделано с использованием тренажёра и/или на основании т. н. метода дельфийского оракула), может быть успешно применён и за пределами *области безопасности движения транспортных средств, в различных ситуациях, когда действия человека в экстраординарных (необычных) условиях и их количественная оценка крайне важны.*

Ключевые слова: *концепция количественного вероятностного управления рисками, двойная экспоненциальная функция распределения вероятностей, фактор человеческого потенциала, нештатная (аварийная) ситуация на транспорте.*

Application of the quantitative probabilistic risk management (PRM) concept should complement in various human-in-the-loop (HITL) situations, whenever feasible and possible, the existing vehicular psychology practices, which are typically qualitative a-posteriori statistical assessments. A PRM approach based on the double exponential probability distribution function (DEPDF) of the extreme value distribution (EVD) type is suggested as a suitable quantitative technique for assessing the probability of the human non-failure in an off-normal flight situation. The human capacity factor (HCF) is introduced in this distribution and considered along with the (elevated) short-term mental workload (MWL) that the human (pilot) has to cope with in an off-normal (emergency) situation. The famous 2009 US Airways «miracle-on-the-Hudson» successful landing (ditching) and the infamous 1998 Swiss Air «UN-shuttle» disaster are chosen to illustrate the usefulness and fruitfulness of the approach. It is shown that it was the exceptionally high HCF of the US Airways crew and especially that of its captain Sullenberger that made a reality what seemed to be, at the first glance, a «miracle». It is shown also that the highly professional and, in general, highly qualified Swiss Air crew exhibited inadequate performance (quantified in our analysis as a relatively low HCF level) in the off-normal situation they encountered with. The Swiss Air crew made several fatal errors and, as a result, crashed the aircraft. In addition to the DEPDF based approach, we show that the probability of safe landing can be evaluated by comparing the (random) operation time (that consists of the decision making time and the landing time) with the «available» time needed for landing. It is concluded that the developed formalisms, after trustworthy input data are obtained (using, e.g., flight simulators or applying Delphi method) might be applicable even beyond the vehicular domain and can be employed in various HITL situations, when a short term high human performance is imperative and therefore the ability to quantify it is highly desirable. It is concluded also that, although the obtained numbers make physical sense, it is the approach, not the numbers, that is, in the author's opinion, the main merit of the paper.

Keywords: *the concept of quantitative probabilistic risk management, double exponential probability distribution function, the human capacity factor, off-normal (emergency) situation in transport.*

Introduction. Human error contributes to about 80 % of vehicular (avionic, maritime, railroad, automotive) casualties (see, e.g., [1-7]). Ability to understand their nature and minimize their likelihood is of obvious and significant importance. Considerable safety improvements in various off-normal vehicular situations can be achieved through better training, better ergonomics, better work environment, and other human psychology related means and efforts that directly affect human behavior and performance: psychological analysis of casualties, computer-aided simulations (including attempts to mimic the actual situation in an aircraft cockpit or in a space-shuttle cabin), and a-posteriori statistical analyses of the occurred casualties and accidents. There is also an opportunity (potential) for casualty reduction through better understanding the role that uncertainties of different nature play in the operator's world of work: uncertain environmental conditions; dependability and avai-lability of instrumentation and equipment; trustworthiness, consistency and user-friendliness of the obtained information; predictability and timeliness of the response of the object of control (aircraft, spacecraft, boat) to the navigator's actions; performance of the interfaces of these factors, etc. By employing quantifiable and measurable ways to assess the role of various critical uncertainties and by treating a HITL as a part (often as the most crucial part) of the complex «man-instrumentation-equipment-vehicle-environment» system, one could improve dramatically the human performance, and predict and minimize the probability of a mission failure [8-11].

PRM based concepts, methods, approaches and algorithms could and should be widely used, in addition to the psychological activities and efforts, when there is a need to evaluate, quantify, optimize and, when possible and appropriate, even specify the human ability (capacity) to cope with an elevated MWL. The following ten factors that affect mission success and safety in various HITL situations should be considered:

- human performance (capacity) factor;
- navigation, information and control instrumentation (equipment) factor;
- vehicle (object of control) factor;
- environmental factor;
- six interfaces between (interactions of) the above factors.

All these factors and their interfaces are associated with uncertainties that contribute to the cumulative probability that a certain pre-established safety criterion for a particular anticipated casualty or a mishap is violated. These uncertainties are characterized by their probability distributions, safety criteria, consequences of possible failure and the levels of the acceptable risk.

When adequate human performance in a particular critical HITL situation is imperative, ability to quantify the human factor is highly desirable. Such a quantification could be done particularly by comparing the actual or anticipated MWL with the likely («available») human capacity factor (HCF). The MWL vs. HCF based models and their modifications and generalizations can be helpful particularly, after appropriate algorithms are developed and extensive sensitivity analyses are carried out,

- to evaluate the role that the human plays, in terms of his/her ability (capacity) to cope with a MWL in various situations, when human factor, equipment/instrumentation performance and uncertain and often harsh environments contribute jointly to the success and safety of a task or a mission;
- to assess the risk of a particular mission success and safety, with consideration of the «human-in-the-loop» performance;
- to develop guidelines for personnel selection and training;
- to choose the appropriate simulation conditions; and/or
- to decide if the existing levels of automation and the employed equipment (instrumentation) are adequate in possible off-normal situations (if not, additional and/or more advanced and perhaps more expensive equipment or instrumentation should be developed, tested and installed).

In the analysis that follows the DEPDF based model is applied for the evaluation of the likelihood of a human non-failure in an emergency vehicular mission-success-and-safety situation. The famous 2009 «miracle-on-the-Hudson» event and the infamous 1998 «UN-shuttle» disaster are used to illustrate the substance and fruitfulness of the approach. We try to shed «probabilistic light» on these two well-known events. As far as the «miracle-on-the-Hudson» is concerned, we intend to provide quantitative assessments of why such a «miracle» could have actually occurred, and what had been and had not been indeed a «miracle» in this incident: a divine intervention, a perceptible interruption of the laws of nature, or «simply» a wonderful and rare occurrence that was due to a heroic act of the aircraft crew and especially of its captain Sullenberger, the lead «miracle worker» in the incident. As to the «UN-shuttle» crash, we are going to demonstrate that the crash occurred because of the low HCF of the aircraft crew in an off-normal situation that they had encountered and that was, in effect, much less demanding than the «miracle-on-the-Hudson» situation. Some other reported water landings (ditchings) of passenger airplanes are listed in Appendix A. Some of them have ended successfully.

PRM-based HCF vs. MWL approach: «ten commandments». Here are the major principles («ten commandments») of our PRM-based approach:

1. HCF is viewed as an appropriate quantitative measure (not necessarily and not always probabilistic though) of the human ability to cope with an elevated short term MWL;
2. It is the relative levels of the MWL and HCF (whether deterministic or random) that determine the probability of human non-failure in a particular HITL situation;
3. Such a probability cannot be low, but need not be higher than necessary either: it has to be adequate for a particular anticipated application and situation;
4. When adequate human performance is imperative, ability to quantify it is highly desirable, especially if one intends to optimize and assure adequate HITL performance;

5. One cannot assure adequate human performance by just conducting routine today's human psychology based efforts (which might provide appreciable improvements, but do not quantify human behavior and performance; in addition, these efforts might be too and unnecessarily costly), and/or by just following the existing «best practices» that are not aimed at a particular situation or an application; the events of interest are certainly rare events, and «best practices: might or might not be applicable»;
6. MWLs and HCFs should consider, to an extent possible, the most likely anticipated situations; obviously, the MWLs are and HCFs should be different for a jet fighter pilot, for a pilot of a commercial aircraft, or for a helicopter pilot, and should be assessed and specified differently;
7. PRM is an effective means for improving the state-of-the-art in the HITL field: nobody and nothing is perfect, and the difference between a failed human performance and a successful one is «merely» in the level of the probability of non-failure;
8. Failure oriented accelerated testing (FOAT) on a flight simulator is viewed as an important constituent part of the PRM concept in various HITL situations: it is aimed at better understanding of the factors underlying possible failures; it might be complemented by the Delphi effort [12];
9. Extensive predictive modeling (PM) is another important constituent of the PRM based effort, and, in combination with highly focused and highly cost effective FOAT, is a powerful and effective means to quantify and perhaps nearly eliminate human failures;
10. Consistent, comprehensive and psychologically meaningful PRM assessments can lead to the most feasible HITL qualification (certification) methodologies, practices and specifications.

Most likely (normal) mental workload (MWL). Our HCF vs. MWL approach considers elevated (off-normal) random relative HCF and MWL levels with respect to the ordinary (normal, pre-established) deterministic HCF and MWL values. These values could and should be established on the basis of the existing human psychology practices.

The interrelated concepts of situation awareness and MWL («demand») are central to the today's aviation psychology. Cognitive (mental) overload has been recognized as a significant cause of error in aviation. The MWL is directly affected by the challenges that a navigator faces, when controlling the vehicle in a complex, heterogeneous, multitask, and often uncertain and harsh environment. Such an environment includes numerous different and interrelated concepts of situation awareness: spatial awareness for instrument displays; system awareness for keeping the pilot informed about actions that have been taken by automated systems; and task awareness that has to do with the attention and task management. The time lags between critical variables require predictions and actions in an uncertain world. The MWL depends on the operational conditions and on the complexity of the mission. MWL has to do therefore with the significance of the long- or short-term task. The long-term MWL is illustrated in Figure 1.

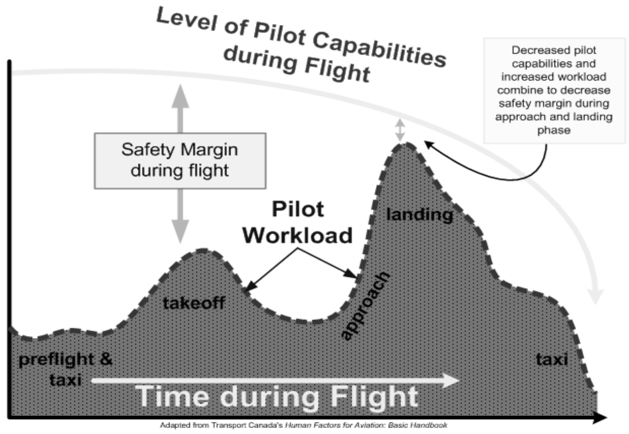


Fig. 1. Long-term (pilot capabilities) HCF vs. MWL (pilot workload)

Task management is directly related to the level of the MWL, as the competing «demands» of the tasks for attention might exceed the operator's resources – his/her «capacity» to adequately cope with the «demands» imposed by the MWL.

Measuring the MWL has become a key method of improving aviation safety. There is an extensive published work in the psychological literature devoted to the measurement of the MWL in aviation, both military and commercial. Pilot's MWL can be measured using subjective ratings and/or objective measures. The subjective ratings during FOAT (simulation tests) can be, e.g., after the expected failure is defined, in the form of periodic inputs to some kind of data collection device that prompts the pilot to enter a number between 1 and 10 (for example) to estimate the MWL every few minutes. There are some objective MWL measures, such as, e.g., heart rate variability. Another possible approach uses post-flight paper questionnaires. It is easier to measure the MWL on a flight simulator than in actual flight conditions. In a real aircraft, one would probably be restricted to using post-flight subjective (questionnaire) measurements, since one would not want to interfere with the pilot's work.

Given the multidimensional nature of MWL, no single measurement technique can be expected to account for all the important aspects of it. In modern military aircraft, complexity of information, combined with time stress, creates difficulties for the pilot under combat conditions, and the first step to mitigate this problem is to measure and manage the MWL. Current research efforts in measuring MWL use psycho-physiological techniques, such as electroencephalographic, cardiac, ocular, and respiration measures in an attempt to identify and predict MWL levels. Measurement of cardiac activity has been a useful physiological technique employed in the assessment of MWL, both from tonic variations in heart rate and after treatment of the cardiac signal.

Most likely (normal) human capacity factor (HCF). HCF includes, but might not be limited to, the following major qualities that would enable a professional human to successfully cope with an elevated off-normal MWL:

- psychological suitability for a particular task;
- professional experience and qualifications;
- education, both special and general;
- relevant capabilities and skills;
- level, quality and timeliness of training;
- performance sustainability (consistency, predictability);
- independent thinking and independent acting, when necessary;
- ability to concentrate;
- ability to anticipate;
- self control and ability to act in cold blood in hazardous and even life threatening situations;
- mature (realistic) thinking;
- ability to operate effectively under pressure, and particularly under time pressure;
- ability to operate effectively, when necessary, in a tireless fashion, for a long period of time (tolerance to stress);
- ability to act effectively under time pressure and make well substantiated decisions in a short period of time;
- team-player attitude, when necessary;
- swiftness in reaction, when necessary.

These and other qualities are certainly of different importance in different HITL situations. It is clear also that different individuals possess these qualities in different degrees. Long-term HCF is illustrated by Figure 1. It could be time-dependent. In order to come up with a suitable figures-of-merit (FOM) for the HCF, one could rank, similarly to the MWL estimates for particular situations or missions, the above and perhaps other qualities on the scale from, say, one to four, and calculate the average FOM for each individual and particular task (see, e.g., Tables 5, 6 and 8 below).

Double-exponential probability distribution function (DEPDF). Different PRM approaches can be used in the analysis and optimization of the interaction of the MWL and HCF. When the MWL and HCF characteristics are treated as deterministic ones, a high enough safety factor $SF = \frac{HCF}{MWL}$ can be used. When both MWL and HCF are random variables, the safety factor can be determined as the ratio $SF = \frac{\prec SM \succ}{S_{SM}}$ of the mean value $\prec SM \succ$ of the random safety margin $SM = HCF - MWL$ to its standard deviation S_{SM}. When the capacity-demand («strength-stress») interference model is used (Figure 2) the HCF can be viewed as thecapacity (strength) and the MWL as the demand (stress), and their overlap area could be considered as the potential (probability) of possible human failure.

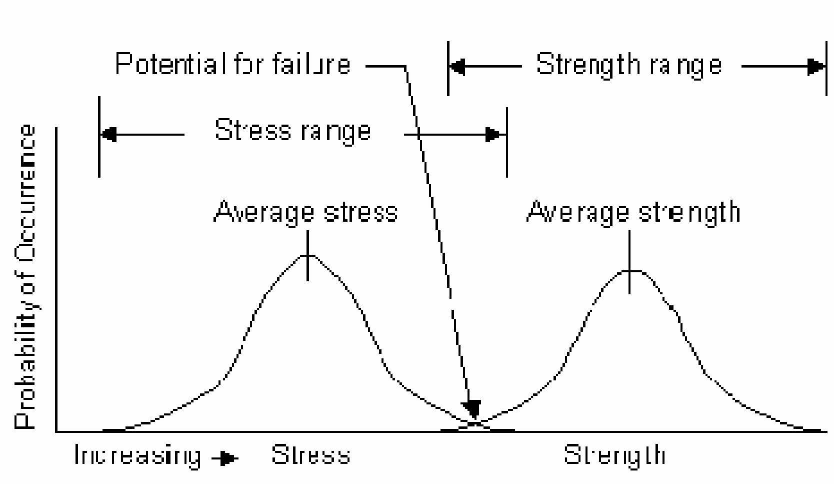


Fig. 2. Capacity-demand (strength-stress) interference model

The capacity and the demand distributions can be steady-state or transient, i.e., their mean values can move towards each other when time progresses, and/or the MWL and HCF curves can get spread over larger areas. Yet another PRM approach is to use a single distribution that accounts for the roles of the HCF and MWL, when these (random) characteristics deviate from (are higher than) their (deterministic) most likely (regular) values. It is this approach that is used in the analysis below.

A double-exponential probability distribution function (DEPDF)

$$P_h(G,F) = P_0 \exp\left[\left(1-\frac{G^2}{G_0^2}\right)\exp\left(1-\frac{F^2}{F_0^2}\right)\right], G \ge G_0, F \ge F_0 \tag{1}$$

of the extreme value distribution (EVD) type (see, e.g., [8]) can be used to characterize the likelihood of a human non-failure to perform his/her duties, when operating a vehicle [10; 11]. Here $P_h(G,F)$ is the probability of non-failure of the human performance as a function of the off-normal mental workload (MWL) G and outstanding human capacity factor (HCF) F, P_0 is the probability of non-failure of the human performance for the specified (normal) MWL $G = G_0$ and the specified (ordinary) HCF $F = F_0$. The specified (most likely, nominal, normal) MWL and HCF can be established by conducting testing and measurements on a flight simulator. The calculated probabilities

$$p = \frac{P_h(G,F)}{P_0} = \exp\left[\left(1-\frac{G^2}{G_0^2}\right)\exp\left(1-\frac{F^2}{F_0^2}\right)\right], G \ge G_0, F \ge F_0 \qquad (2)$$

(that are, in effect, ratios of the probability of non-failure in the off-normal conditions to the probability of non-failure in the normal situation) are shown in Table 1.

Table 1

Calculated probability ratios of human non-failure

<table>
<tr><td>G/G_0</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>8</td><td>10</td><td>∞</td></tr>
<tr><td>F/F_0</td><td>x</td><td>x</td><td>x</td><td>x</td><td>x</td><td>x</td><td>x</td><td>x</td></tr>
<tr><td>1</td><td>1</td><td>4.979E-2</td><td>3.355E-4</td><td>3.059E-7</td><td>3.775E-11</td><td>4.360E-28</td><td>1.011E-43</td><td>0</td></tr>
<tr><td>2</td><td>1</td><td>0.8613</td><td>0.6715</td><td>0.4739</td><td>0.3027</td><td>0.0434</td><td>0.007234</td><td>0</td></tr>
<tr><td>3</td><td>1</td><td>0.9990</td><td>0.9973</td><td>0.9950</td><td>0.9920</td><td>0.9791</td><td>0.9673</td><td>0</td></tr>
<tr><td>4</td><td rowspan="5" colspan="7">1.0000</td><td>0</td></tr>
<tr><td>5</td><td>0</td></tr>
<tr><td>8</td><td>0</td></tr>
<tr><td>10</td><td>0</td></tr>
<tr><td>∞</td><td>1.0000</td></tr>
</table>

The following conclusions can be drawn from the table data:

- At normal (specified, most likely) MWL level ($G = G_0$ and/or at an extraordinary (exceptionally) high HCF level $(F \to \infty)$ the probability of human non-failure is close to 100%.
- The probabilities of human non-failure in off-normal situations are always lower than the probabilities of non-failure in normal (specified) conditions.
- When the MWL is extraordinarily high, the human will definitely fail, no matter how high his/her HCF is.
- When the HCF is high, even a significant MWL has a small effect on the probability of non-failure, unless the MWL is exceptionally high. For high HCFs the increase in the MWL has a much smaller effect on the probabilities on failure than for relatively low HCFs.
- The probability of human non-failure decreases with an increase in the MWL, especially at low MWL levels, and increases with an increase in the HCF, especially at low HCF levels.

These intuitively more or less obvious conclusions are quantified by the Table 1 data. These data show also that the increase in the probability ratio above 3.0 («three is a charm») has a minor effect on the probability of non-failure. This means particularly that the navigator (pilot) does not have to be trained for an unrealistically high MWL, i.e., does not have to be trained by a factor higher than 3.0 compared to a navigator of ordinary capacity (skills, qualification). In other words, a pilot does not have to be a superman to successfully cope with a high level MWL, but still has to be trained in such a way that, when there is a need, he/she would be able to cope with a MWL by a factor of 3.0 higher than the normal level, and his/her HCF should be by a factor of 3.0 higher than what is expected of the same person in ordinary (normal) conditions. Of course, some outstanding individuals (like Captain Sullenberger, for instance) might be characterized by the HCF that corresponds to MWL's somewhat higher than 3.0 (see Table 5).

Physical meaning of the DEPDF. From (2) we find, by differentiation

$$\frac{dp}{dG} = -2\frac{H(p)}{G}\frac{1}{1-\frac{G_0^2}{G^2}} \tag{3}$$

where $H(p) = -p\ln p$ is the entropy of the distribution of the relative probability of the human non-failure in extraordinary (off-normal) operation conditions. When the MWL G is significant, the formula (3) can be simplified

$$\frac{dp}{dG} = -2\frac{H(p)}{G}. \tag{4}$$

This result explains the physical meaning of the distribution (2): the change in the probability of human non-failure (provided that the probability of non-failure in normal conditions is simply 100 %) with the change in the MWL is, for large MWL levels, proportional to the uncertainty level that is defined by the entropy of the distribution in question and is inversely proportional to the MWL level. The right part of the formula (4) can be viewed as a kind of coefficient of variation (COV), where the role of the uncertainty level in the numerator is played by the entropy, rather than by the standard deviation, and the role of the stress (loading) level in the denominator is played by the MWL rather than by the mean value of the random characteristic of interest.

From (2) one could find also

$$\frac{dp}{dF} = 2\frac{H(p)F}{F_0^2}. \tag{5}$$

When the random HCF F is equal to its nominal value F_0, this formula yields

$$\frac{dp}{dF} = 2\frac{H(p)}{F_0}. \tag{6}$$

This result can also be used to interpret the physics underlying the DEPDF (2): the change in the probability of human non-failure with the change in the HCF at its nominal (normal) level is proportional to the entropy of the distribution (2) and is inversely proportional to the nominal HCF.

HCF needed to satisfactorily cope with a high MWL. From (2) we obtain

$$\frac{F}{F_0} = \sqrt{1 - \ln\left(\frac{\ln}{1 - \frac{G^2}{G_0^2}}\right)}. \qquad (7)$$

This relationship is tabulated in Table 2. The following conclusion can be drawn from the computed data:

- The HCF level needed to cope with an elevated MWL increases rather slowly with an increase in the probability-of-non-failure, especially for high MWL levels, unless this probability is very low (below 0,1) or very high (above 0,9);
- In the region $p = 0{,}1 \to 0{,}9$ the required high HCF level increases with an increase in the MWL level, but this increase is rather moderate, especially for high MWL levels;
- Even for significant MWLs that exceed the normal MWL by orders of magnitude the level of the HCF does not have to be very much higher than the HCF of a person of ordinary HCF level. When the MWL ratio is as high as 100, the HCF ratio does not have to exceed 4 to assure the probability of non-failure of as high as 0,999.

Table 2

Relative HCF F/F_0 vs. relative probability of non-failure and relative MWL

p	E-12	E-3	E-2	0,1	0,5	0,9	0,99	0,9999
G/G_0	x	x	x	x	x	x	x	x
5	1,0681	1,4985	1,6282	1,8287	2,1318	2,5354	2,9628	3,6590
10	1,5087	1,9138	2,0169	2,1820	2,4416	2,8010	3,1930	3,8478
100	2,6251	2,8771	2,9467	3,0621	3,2522	3,5300	3,8484	4,4069
1000	3,3907	3,5893	3,6453	3,7392	3,8964	4,1311	4,4063	4,9016
10000	4,0127	4,1819	4,2301	4,3112	4,4483	4.6552	4,9011	5,3508

Different approach: operation time vs. «available» landing time. The above time-independent DEPDF based approach enables one to compare, on the probabilistic basis, the relative roles of the MWL and HCF in a particular off-normal HUTL situation. The role of time (e.g., swiftness in reaction) is accounted for in an indirect fashion, through the NCF level. In the analysis that follows we assess the likelihood of safe landing by considering the roles of different times directly, by comparing the operation time, which consists of the decision making time and actual landing time, with the «available» landing time (i.e., the time from the moment when an emergency was determined to the moment of landing). Particularly, we address the item 10 of Table 4, i.e., the ability of the pilot to anticipate and to make a substantiated and valid decision in a short period of time («We are going to be in the Hudson»). It is assumed, for the sake of simplicity, that both the decision making and the landing times could be approximated by the Rayleigh's law, while the available time, consi-dering, in the case of the «miracle-on-the-Hudson» flight) the glider conditions of the aircraft, follows the normal law with a high ratio of the mean value to the standard deviation. Safe landing could be expected if the probability that it occurs during the «available» landing time is sufficiently high. The formalism of such a model is similar to the helicopter-landing-ship (HLS) formalism developed earlier [9].

Probability that the operation time exceeds a certain level. If the (random) sum, $T = t + \theta$, of the (random) decision making time, t, and the (random) time, θ, needed to actually land the aircraft is lower, with a high enough probability, than the (random) duration, L, of the available time, then safe landing becomes possible. In the analysis that follows we assume the simplest probability distributions for the random times of interest. We use the Ray-leigh's law

$$f_t(t) = \frac{t}{t_0^2}\exp\left(-\frac{t^2}{2t_0^2}\right),\ f_\theta(t) = \frac{\theta}{\theta_0^2}\exp\left(-\frac{\theta^2}{2\theta_0^2}\right) \tag{8}$$

as a suitable approximation for the random times t and θ of decision making and actual landing, and the normal law

$$f_l(l) = \frac{1}{\sqrt{2\pi\sigma}}\exp\left(-\frac{(l-l_0)^2}{2\sigma^2}\right),\ \frac{l_0}{\sigma} \geq 4.0 \tag{9}$$

as an acceptable approximation for the available time, L. In the formulas (8) and (9), t_0 and θ_0 are the most likely times of decision making and landing, respectively (in the case of a Rayleigh law these times coincide with the standard deviations of the random variables in question), l_0 is the most likely (mean) value of the available time, and σ is the standard deviation of this time. The ratio $\frac{l_0}{\sigma}$ («safety factor») of the mean value of the available time to its standard deviation should be large enough (say, larger than 4), so that the normal law could be used as an acceptable approximation for a random variable that, in principle, cannot be negative, as it is the case when this variable is time.

The probability, P_*, that the sum $T = t + \theta$ of the random variables t and θ exceeds a certain time level, $\hat{T}$, can be found on the basis of the convolution of two random times distributed in accordance with the Rayleigh law as follows:

$$P_* = 1 - \int_0^{\hat{T}} \frac{t}{t_0^2} \exp\left(-\frac{t^2}{2t_0^2}\right)\left[1 - \exp\left(-\frac{(T-t)^2}{2\theta_0^2}\right)\right] dt = \exp\left(-\frac{\hat{T}^2}{2t_0^2}\right) +$$
$$+ \exp\left[-\frac{\hat{T}^2}{2(t_0^2+\theta_0^2)}\right] \times \left\{\frac{\theta_0^2}{t_0^2+\theta_0^2}\left[\exp\left[-\frac{t_0^2\hat{T}^2}{2\theta_0^2(t_0^2+\theta_0^2)}\right]\right] - \right.$$
$$\left. \times - \exp\left[-\frac{\theta_0^2\hat{T}^2}{2\theta_0^2(t_0^2+\theta_0^2)}\right]\right\} + \sqrt{\frac{\pi}{2}} \frac{\hat{T} t_0 \theta_0}{(t_0^2+\theta_0^2)^{3/2}} \exp\left[-\frac{\hat{T}^2}{2(t_0^2+\theta_0^2)}\right] \times$$
$$\times \left\{\left[erf\left[-\frac{t_0\hat{T}}{\theta_0\sqrt{2(t_0^2+\theta_0^2)}}\right]\right] + erf\left[-\frac{\theta_0\hat{T}}{t_0\sqrt{2(t_0^2+\theta_0^2)}}\right]\right\}, \tag{10}$$

where

$$erf(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-z^2} dz \tag{11}$$

is the error function. When the most likely duration of landing, θ_0, is very small compared to the most likely decision making time, t_0, the expression (10) yields

$$P_* = \exp\left(-\frac{\hat{T}^2}{2t_0^2}\right) \tag{12}$$

i.e., the probability that the total time of operation exceeds a certain time duration, $\hat{T}$, depends only on the most likely decision making time, t_0. From (12) we obtain

$$\frac{t_0}{\hat{T}} = \frac{1}{\sqrt{-2\ln P_*}} \tag{13}$$

If the acceptable probability, P_*, of exceeding the time, $\hat{T}$ (e.g., the available time, if this time is treated as a non-random variable of the level $\hat{T}$), is, say, $P = 10^{-4} = 0.01\%$, then the time of making the decision should not exceed 0.2330 = 23.3% of the time, $\hat{T}$ (expected available time), otherwise the requirement $P \le 10^{-4} = 0.01\%$ will be compromised. If the available time is, say, 2 min, then the decision making time should not exceed 28 sec, which is in good agreement with Capt. Sullenberger's actual decision making time. Similarly, when the most likely time, t_0, of decision making is very small compared to the most likely time, θ_0, of actual landing, the formula (10) yields

$$P_* = \exp\left(-\frac{\hat{T}^2}{2\theta_0^2}\right) \tag{14}$$

i.e., the probability of exceeding a certain time level, $\hat{T}$, depends only on the most likely time, θ_0, of landing.

As follows from the formulas (8), the probability that the actual time of decision making or the time of landing exceed the corresponding most likely times is expressed by the formulas of the types (12) and (14), and is as high as $P_* = \frac{1}{\sqrt{e}} = 0{,}6065 = 60{,}6\%$. In this connection we would like to mention that the one-parametric Rayleigh law is characterized by a rather large standard deviation and therefore might not be the best approximation for the probability density functions for the decision making time and the time of landing. A more «powerful» and more flexible two-parametric law, such as, e.g., the Weibull law, might be more suitable as an appropriate probability distribution of the random times, t and θ. Its use, however, will make our analysis unnecessa-rily more complicated. Our goal is not so much to «dot all the i's and cross all the t's», as far as modeling of the role the human factor in the problem in question is concerned, but rather to demonstrate that the attempt to use PRM me-thods to quantify the role of the human factor in avionics safety and similar problems might be quite fruitful. When developing practical guidelines and recommendations, a particular law of the probability distribution should be established based on the actual statistical data, and employment of various goodness-of-fit criteria (Pierson's, Kolmogorov's, etc.) might be needed in detailed statistical analyses.

When the most likely times t_0 and θ_0 required for making the go-ahead decision and for the actual landing, are equal, the formula (10) yields:

$$P_* = P_*\left(\frac{t_0}{\hat{T}}, \frac{\theta_0}{\hat{T}}\right) = \exp\left(-\frac{\hat{T}^2}{2t_0^2}\right)\left[1 + \sqrt{\pi}\,\frac{\hat{T}}{2t_0}\exp\left(\left(\frac{\hat{T}}{2t_0}\right)^2\right) erf\left(\frac{\hat{T}}{2t_0}\right)\right] \tag{15}$$

For large enough $\frac{\hat{T}}{t_0}$ ratios $\left(\frac{\hat{T}}{t_0} \geq 3\right)$ of the critical time $\hat{T}$ to the most likely decision making or landing time, the second term in the brackets becomes large compared to unity. The calculated probabilities of exceeding a certain time level, $\hat{T}$, based on the formula (15), are shown in Table 3. In the third row of this table we indicate, for the sake of comparison, the probabilities, P°, of exceeding the given time, $\hat{T}$, when only the time t_0 or only the time θ_0 is different from zero, i.e., for the special case that is mostly remote from the case $t_0 = \theta_0$ of equal most likely times. Clearly, the probabilities computed for other possible combinations of the times t_0 and θ_0 could be found between the calculated probabilities P_* and P°. The following conclusions can be drawn from the Table 3 data:

- The probability that the total time of operation (the time of decision making and the time of landing) exceeds the given time level $\hat{T}$, thereby leading to a casualty, rapidly increases with an increase in the total time of operation;

The probability P_* that the operation time exceeds a certain time level $\hat{T}$ vs the ratio $\hat{T}/t_0$ of this time level to the most likely time t_0 of decision making for the case when the time t_0 and the most likely time θ_0 time of landing are the same. For the sake of comparison, the probability P° of exceeding the time level $\hat{T}$, when either the time t_0 or the time θ_0 is zero, is also indicated.

Table 3

$\hat{T}/t_0$	6	5	4	3	2
P_*	6.562E-4	8.553E-3	6.495E-2	1.914E-1	6.837E-1
P°	1.523E-8	0.373E-5	0.335E-3	1.111E-2	1.353E-1
P_*/P°	4.309E4	2.293E3	1.939E2	1.723E1	5.053

- The probability of exceeding the time level $\hat{T}$ is considerably higher, when the most likely times of decision making and of landing are finite and especially when they are close to each other, in comparison with the situation when one of these times is significantly shorter than the other, i.e., zero or next-to-zero. This is particularly true for short operation times, like in the situation in question: the ratio P_* / P° of the probability P_* of exceeding the time level $\hat{T}$ in the case of $t_0 = \theta_0$ to the probability P° of exceeding this level in the case $t_0 = \theta_0$ or in the case $\theta_0 = 0$ decreases rapidly with an increase in the time of operation. There exists therefore a significant incentive for reducing the operation time. The importance of this intuitively obvious fact is quantified by the table data.

- Another useful information that could be drawn from the data of the type shown in Table 3 is whether it is possible at all to train a human to react (make a decision) in just a couple of seconds. It took Capt. Sullenberger about 30sec to make the right decision, and he is an exceptionally highly qualified pilot, with an outstanding HCF. If a very short-term decision could not be expected, and a low probability of human failure is still required, then one should decide on a broader involvement of more sophisticated, more powerful and more expensive equipment and instrumentation to do the job. If pursuing such an effort is decided upon, then probabilistic sensitivity analyses of the type developed above will be needed to determine the most promising ways to go. It is advisable, of course, that the analytical predictions are confirmed by computer-aided simulations and verified by highly focused and highly cost effective FOAT conducted on flight simulators.

Probability that the landing time exceeds the «available» time. Since the «available» time *L* is assumed to be a random normally distributed variable, the probability that this time is found below a certain level $\hat{L}$ is

$$P_l = P_l\left(\frac{\sigma}{\hat{L}}, \frac{l_0}{\hat{L}}\right) = \int_{-\infty}^{\hat{L}} f_l(l)dl = \frac{1}{2}\left[1 + erf\left(\frac{\hat{L} - l_0}{\sqrt{2}\sigma}\right)\right] = \left[1 + erf\left(\frac{1 - \frac{l_0}{\hat{L}}}{\sqrt{2}\frac{\sigma}{\hat{L}}}\right)\right]. \tag{16}$$

The probability that the available time is exceeded can be determined by equating the times $\hat{T} = \hat{L} = T$ and computing the product

$$P_A = P_*\left(\frac{t_0}{T}, \frac{\theta_0}{T}\right) P_l\left(\frac{\sigma}{T}, \frac{l_0}{T}\right) \tag{17}$$

of the probability, $P_*\left(\frac{t_0}{T}, \frac{\theta_0}{T}\right)$, that the time of operation exceeds a certain level, T, and the probability, $P_l\left(\frac{\sigma}{T}, \frac{l_0}{T}\right)$, that the available time is shorter than the time T. The formula (17) considers the roles of the most likely available time, the human factor, t_0 (the most likely time required for the pilot to make his/her go-ahead decision), and the most likely time, θ_0, of actual landing (which characterizes both the qualification and skills of the pilot and the qualities/behavior of the flying machine) on the probability of safe landing. Carrying out detailed computations based on the formulas (10), (16) and (17) is, ho-wever, beyond the scope of the present article.

«Miracle-on-the-Hudson»: incident. US Airways Flight 1549 was a domestic passenger flight from LaGuardia Airport (LGA) in New York City to Charlotte/Douglas International Airport, Charlotte, North Carolina. On January 15, 2009, the Airbus A320-214 flying this route struck a flock of Canada Geese during its initial climb out, lost engine power, and ditched in the Hudson River off midtown Manhattan. Since all the 155 occupants survived and safely evacuated the airliner, the incident became known as the «Miracle on the Hudson» [13; 14].

The bird strike occurred just northeast of the George Washington Bridge (GWB) about three minutes into the flight and resulted in an immediate and complete loss of thrust from both engines. When the crew determined that they would be unable to reliably reach any airfield, they turned southbound and glided over the Hudson, finally ditching the airliner near the USS *Intrepid* museum about three minutes after losing power. The crew was later awarded the Master's Medal of the Guild of Air Pilots and Air Navigators for successful «emergency ditching and evacuation, with the loss of no lives… a heroic and unique aviation achievement…the most successful ditching in aviation history.» The pilot in command was 57-year-old Capt. Chesley B. «Sully» Sullenberger, a former fighter pilot who had been an airline pilot since leaving the United States Air Force in 1980. He is also a safety expert and a glider pilot. The first officer was Jeffrey B. Skiles, 49. The flight attendants were Donna Dent, Doreen Welsh and Sheila Dail (Figure 3).

The aircraft was powered by two GE Aviation/Snecma-designed CFM56-5B4/P turbofan engines manufactured in France and the U.S. One of 74 A320s then in service in the US Airways fleet, it was built by Airbus with final assembly at its facility at Aéroport de Toulouse-Blagnac in France in June 1999 and delivered to the carrier on August 2, 1999.

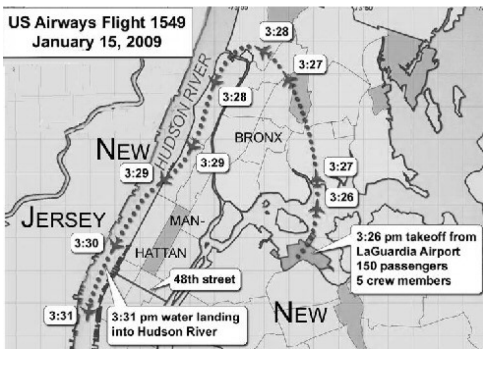
Fig. 3. Captain Sullenberger and his magnificent crew

The Airbus is a digital fly-by-wire aircraft: the flight control surfaces are moved by electrical and hydraulic actuators controlled by a digital computer. The computer interprets pilot commands via input from a side-stick, making adjustments on its own to keep the plane stable and on course. This is particularly useful after engine failure by allowing the pilots to concentrate on engine restart and landing planning. The mechanical energy of the two engines is the primary source of electrical power and hydraulic pressure for the aircraft flight control systems. The aircraft also has an auxiliary power unit (APU), which can provide backup electrical power for the aircraft, including its electrically powered hydraulic pumps; and a ram air turbine (RAT), a type of wind turbine that can be deployed into the airstream to provide backup hydraulic pressure and electrical power at certain speeds. According to the NTSB [14], both the APU and the RAT were operating as the plane descended into the Hudson, although it was not clear whether the RAT had been deployed manually or automatically. The Airbus A320 has a «ditching» button that closes valves and openings underneath the aircraft, including the outflow valve, the air inlet for the emergency RAT, the avionics inlet, the extract valve, and the flow control valve. It is meant to slow flooding in a water landing. The flight crew did not activate the «ditch switch» during the incident. Sullenberger later noted that it probably would not have been effective anyway, since the force of the water impact tore holes in the plane's fuselage much larger than the openings sealed by the switch.

First officer Skiles was at the controls of the flight when it took off at 3:25 pm, and was the first to notice a formation of birds approaching the aircraft about two minutes later, while passing through an altitude of about 2,700 feet (820 m) on the initial climb out to 15,000 feet (4,600 m). According to flight data recorder (FDR) data, the bird encounter occurred at 3:27:11, when the airplane was at an altitude of 2,818 feet (856m) above ground level (agl) and at a distance of about 4.5 miles north-northwest of the approach end of runway 22 at LGA. Subsequently, the airplane's altitude continued to increase while the airspeed decreased, until 3:27:30, when the airplane reached its highest altitude of about 3,060 feet (930 m), at an airspeed of about 185 kts calibrated airspeed (KCAS). The altitude then started to decrease as the airspeed started to increase, reaching 210 KCAS at 3:28:10 at an altitude of about 1,650 feet (500 m) The windscreen quickly turned dark brown and several loud thuds were heard. Capt. Sullenberger took the controls, while Skiles began going through the three-page emergency procedures checklist in an attempt to restart the engines.

At 3:27:36 the flight radioed air traffic controllers at New York Terminal Radar Approach Control (TRACON)»Hit birds. We've lost thrust on both engines. We're turning back towards LaGuardia» Responding to the captain's report of a bird strike, controller Patrick Harten, who was working the departure position told LaGuardia tower to hold all waiting departures on the ground, and gave Flight 1549 a heading to return to LaGuardia. Sullenberger responded that he was unable.

Sullenberger asked if they could attempt an emergency landing in New Jersey, mentioning Teterboro Airport in Bergen County as a possibility; air traffic controllers quickly contacted Teterboro and gained permission for a landing on runway 1. However, Sullenberger told controllers that «We can't do it», and that «We're gonna be in the Hudson», making clear his intention to bring the plane down on the Hudson River due to a lack of altitude. Air traffic control at LaGuardia reported seeing the aircraft pass less than 900 feet (270 m) above GWB. About 90 seconds before touchdown, the captain announced, «Brace for impact», and the flight attendants instructed the passengers how to do so. The plane ended its six-minute flight at 3:31 pm with an unpowered ditching while heading south at about 130 knots (150 mph; 240 km/h) in the middle of the North River section of the Hudson River roughly abeam 50th Street (near the Intrepid Sea-Air-Space Museum) in Manhattan and Port Imperial in Weehawken, New Jersey (Figure 4). Sullenberger said in an interview on CBS television that his training prompted him to choose a ditching location near operating boats so as to maximize the chance of rescue. After coming to a stop in the river, the plane began drifting southward with the current.



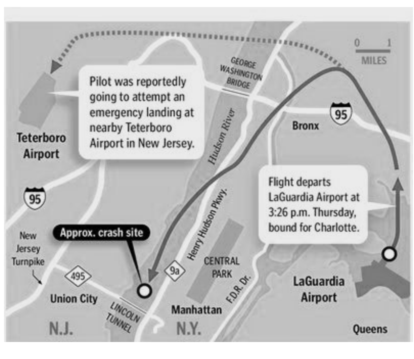


*Fig. 4. Flightpath flown (**___**). Alternative trajectories to Teterboro (**.....**) and back toward La Guardia were simulated for the investigation*

National Transportation Safety Board (NTSB) Member Kitty Higgins, the principal spokesperson for the on-scene investigation, said at a press conference the day after the accident that it «has to go down [as] the most successful ditching in aviation history… These people knew what they were supposed to do and they did it and as a result, nobody lost their life» (Figure 5). The flight crew, particularly Captain Sullenberger, were widely praised for their actions during the incident, notably by New York City Mayor Michael Bloomberg and New York State Governor David Paterson, who opined, «We had a *Miracle on 34th Street.* I believe now we have had a *Miracle on the Hudson*» Outgoing U.S. President George W. Bush said he was «inspired by the skill and heroism of the flight crew», and he also praised the emergency responders and volunteers. Then President-elect Barack Obama said that everyone was proud of Sullenberger's «heroic and graceful job in landing the damaged aircraft», and thanked the A320's crew.

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Fig. 5. «Miracle-on-the-Hudson»: ditched aircraft

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responders and volunteers. Then President-elect Barack Obama said that everyone was proud of Sullenberger's «heroic and graceful job in landing the damaged aircraft», and thanked the A320's crew.

The NTSB ran a series of tests using Airbus simulators in France, to see if Flight 1549 could have returned safely to LaGuardia. The simulation started immediately following the bird strike and «...knowing in advance that they were going to suffer a bird strike and that the engines could not be restarted, four out of four pilots were able to turn the A320 back to LaGuardia and land on Runway 13» When the NTSB later imposed a 30-second delay before they could respond, in recognition that it wasn't reasonable to expect a pilot to assess the situation and react instantly, all four pilots crashed.

On May 4, 2010, the NTSB released a statement which credited the accident outcome to the fact that the aircraft was carrying safety equipment in excess of that mandated for the flight, and excellent cockpit resource management among the flight crew. Contributing factors to the survivability of the accident were good visibility, and fast response from the various ferry operators. Captain Sullenberger's decision to ditch in the Hudson River was validated by the NTSB. On May 28, 2010, the NTSB published its final report into the accident [14]. It determined the cause of the accident to be «the ingestion of large birds into each engine, which resulted in an almost total loss of thrust in both engines».

«Miracle-on-the-Hudson»: flight segments (events). The US AW Flight 1549 events (segments) and durations are summarized (listed) in Table 4. It took only 40sec for the Captain Sullenberger to make his route change decision and another 2min to land the aircraft.

Table 4

US AW Flight 1549, January 15, 2009 (Wikipedia)

Flight segment	Time (EST)	Duration, sec., %	Altitude	Speed	Event
1	3:25:00 pm	60.00 (16.6667)	0	279.6 km/h	Aircraft took off LGA and started climbing out. First officer Skiles runs the aircraft
2	3:26:00 pm	71.00 (19.7222)	820 m	-	Skiles noticed a flock of birds
3	3:27:11 pm	19.00 (5.2778)	856 m	322.2 km/h	Bird strike (North-East of GWB, NYC)
4	3:27:30 pm	6.00 (1.6667)	930 m	342.6 km/h	Highest altitude reached
5	3:27:36 pm	24.00 (6.6667)	-	359.3 km/h	Radioed TRACON traffic controllers: «Hit birds. Lost thrust on both engines.

					Turning back towards LGA»
6	3:28:00 pm	10.00 (2.7778)	609 m	374.1 km/h	Complete loss of thrust (engine power)
7	3:28:10 pm	30.00 (8.3333)	500 m	388.9 km/h	Sullenberger takes over control
8	3:28:40 pm	20.00 (5.5555)	500 m	388.9 km/h	Sullenberger makes route change decision and turns southbound
9	3:29:00 pm	10.00 (2.7778)	396 m	353.7 km/h	Started gliding over Hudson River
10	3:29:10 pm	90.00 (25.0000)	-	-	«Brace for impact» command
11	3:30:40 pm	20.00 (5.5555)	0	240 km/h	Touch down (ditching) Hudson River
12	3:31:00 pm	-	0	0	Full stop, start drif-ting

«Miracle-on-the-Hudson»: quantitative aftermath. In this section we intend to demonstrate how the «miracle-on-the-Hudson» event could be quantified using the DEPDF based evaluations.

Sullenberger's HCF. Sullenberger's HCF is computed in Table 5. The calculations of the probability of the human non-failure are carried out using formula (2) and are shown in Table 6.

Table 5

Sullenberger's HCF

№	Relevant qualities	Relative HCF Rating $\left(\frac{F^*}{F_0}\right)$	Comments
1	psychological suitability for the given task;	3.2	1) 57 years old former fighter pilot who had been a commercial airline pilot since leaving the US Air Force in 1980. He is also a safety expert and a glider pilot [7]. See also Appendix B. «I was sure I could do it». «The entire life up to this moment was a preparation for this moment». «I am not just a pilot of that flight. I am also a pilot who has flown for 43 years…» 2) Probability of human non-failure in normal flight conditions is assumed to be 100 % 3) The formula $p=\exp\left(1-\frac{G^2}{G_0^2}\right)$
2	professional qualifications and experience;	3.9	
3	level, quality and timeliness of past and recent training;	2.0	
4	mature (realistic) and independent thinking;	3.2	
5	performance sustainability (predictability, consistency)	3.2	
6	ability to concentrate and act in cold blood («cool demeanor») in hazardous and even in life threatening situations;	3.3	
7	ability to anticipate («expecting the unexpected»);	3.2	

<table>
<tr><td>8</td><td>ability to operate effectively under pressure</td><td>3.4</td><td rowspan="4">would have to be used to evaluate the probability of non-failure in the case of a pilot of ordinary skills.
The computed numbers are shown in parentheses.
The computed numbers show that such a pilot would definitely fail in the off-normal situation in question</td></tr>
<tr><td>9</td><td>self-control in hazardous situations</td><td>3.2</td></tr>
<tr><td>10</td><td>ability to make a substantiated decision in a short period of time («we are going to be in the Hudson»)</td><td>2.8</td></tr>
<tr><td></td><td>Average FOM</td><td>3.14</td></tr>
<tr><td colspan="4">*)This is just an example that shows that the approach makes physical sense. Actual numbers should be obtained using FOAT on a simulator and confirmed by an independent approach, such as, say, Delphi method: http://en.wikipedia. org/ wiki/ Delphi_method [12]</td></tr>
</table>

Table 6

Computed probabilities of human non-failure (Captain Sullenberger)

G/G_0	5	10	50	100	150
p	0.9966	0.9860	0.7013	0.2413	0.0410

We did not try to anticipate and quantify a particular (most likely) MWL level, but rather assumed different MWL deviations from the most likely level. A more detailed MWL analysis can be done using flight simulation FOAT data. The computed data indicate that, as long as the HCF is high (and Capt. Sullenberger's HCF was/is exceptionally high), even significant relative MWL levels, up to 50 or even higher, still result in a rather high probability of the human non-failure.

Capt. Sullenberger's HCF is/was extraordinarily, exceptionally high. This was due to his age, old enough to be an experienced performer and young enough to operate effectively in a cool demeanor under pressure and possess other qualities of a relatively young human. As evident from the computed data, the probability of human non-failure in off-normal flight conditions is still relatively high, provided that the HCF is significantly higher than that of a pilot of normal skills in the profession and that the MWL is not extraordinarily (perhaps, unrealistically) high. So, the actual «miraculous» event was due to the fact that a person of extraordinary abilities (measured by the level of the HCF) turned out to be in the driving chair at the critical moment. Other favorable aspects of the situation were high HCF of the crew, good weather and the landing site, perhaps the most favorable one could imagine. As long as this miracle did happen, everything else was not really a miracle. Captain Sullenberger knew when to take over control of the aircraft, when to abandon his communications with the (generally speaking, excellent) ATCs and to use his outstanding background and skills to land (ditch) the plane: «I was sure I could do it…the entire life up to this moment was a preparation for this moment…I am not just a pilot of that flight. I am also a pilot who has flown for 43 years…» Such a «miracle» does not happen often, of course, and is perhaps outside any indicative statistics.

Flight attendant's HCF estimate: example. The HCF of a fligh-tattendant is assessed in Table 7, and the probabilities of his/her non-failure are shown in Table.8. The qualities expected from a flight-attendant are, of course, quite different of those of a pilot. As evident from the obtained data, the probability of the human non-failure of the airbus A-320 flight attendants is rather high up until the MWL ratio of 10 or even slightly higher.

Although we do not try to evaluate the first officer's Skiles' HCF, we assume that his HCF is also high, although this did not manifest itself during the event. It has been shown elsewhere [10] that it is expected that both pilots have high and, to an extent possible, equal qualifications and skills for a high probability of a mission success, if, for one reason or another, the entire MWL is taken by one of the pilots. In this connection we would like to mention that, even regardless of the qualification, it is widely accepted in the avionic and maritime practice that it is the captain, not the first officer (first mate) gets in control of a dangerous situations, especially life threatening ones. It did not happen, however, in the case of the Swiss-Air «UN-shuttle» last flight addressed in the next section.

«UN-shuttle» flight: crash. For the sake of comparison of the successful miracle-on-the-Hudson case with an emergency situation that ended up in a crash, we have chosen the infamous Swiss Air September 2, 1998, Flight 111, when a highly trained crew made several bad decisions under considerable time pressure [15] that was, however, not as severe as in the miracle-on-the-Hudson case. Swissair Flight 111 was a McDonnell Douglas MD-11 on a scheduled airline flight from John F. Kennedy (JFK) International Airport in New York City, US to Cointrin International Airport in Geneva, Switzerland. On Wednesday, September 2, 1998, the aircraft crashed into the Atlantic Ocean southwest of Halifax International Airport at the entrance to St. Margaret's Bay, Nova Scotia. The crash site was just 8 km (5.0 nm) from shore. All 229 people on board died − the highest death toll of any aviation accident involving a McDonnell Douglas MD-11. Swissair Flight 111 was known as the «U.N. shuttle» due to its popularity with United Nations officials; the flight often carried business executives, scientists, and researchers.

Table 7

Flight attendant's HCF

№	Relevant qualities	Relative HCF $\left(\frac{F^*}{F_0}\right)$
1	psychological suitability for the task	2,5
2	professional qualifications and experience	2,5
3	level, quality and timeliness of past and recent training	2,5
4	team-player attitude	3,0
5	performance sustainability (consistency)	3,0
6	ability to perform in cold blood in hazardous and even in life threatening situations	3.0
7	ability and willingness to follow orders	3,0
8	ability to operate effectively under pressure	3,4

	Average FOM	2,8625
***)** It is just an example. Actual numbers should be obtained using FOAT on a simulator and confirmed by an independent method, such as, say, Delphi method: http://en.wikipedia.org/wiki/Delphi_method [12]		

Table 8

Estimated probabilities of non-failure for a flight attendant

G/G_0	5	10	50	100	150
p	0.9821	0.9283	0.1530	5.47E-4	4.57E-8

The initial search and rescue response, crash recovery operation, and resulting investigation by the Government of Canada took over four years. The Transportation Safety Board (TSB) of Canada's official report stated that flammable material used in the aircraft's structure allowed a fire to spread beyond the control of the crew, resulting in the loss of control and crash of the aircraft. An MD-11 has a standard flight crew consisting of a captain and a first officer, and a cabin crew made up of a maître-de-cabine (M/C − purser) supervising the work of 11 flight attendants. All personnel on board Swissair Flight 111 were qualified, certified and trained in accordance with Swiss regulations, under the Joint Aviation Authorities (JAA).

The flight details are shown in Table 9. The flight took off from New York's JFK Airport at 20:18 Eastern Standard Time (EST). Beginning at 20:33 EST and lasting until 20:47, the aircraft experienced an unexplained thirteen-minute radio blackout. The cause of the blackout, or if it was related to the crash, is unknown. At 22:10 Atlantic Time (21:10 EST), cruising at FL330 (approximately 33,000 feet or 10,100 meters), Captain Urs Zimmermann and First Officer Stephan Loew detected an odor in the cockpit and determined it to be smoke from the air conditioning system, a situation easily remedied by closing the air conditioning vent, which a flight attendant did on Zimmermann's request. Four minutes later, the odor returned and now smoke was visible, and the pilots began to consider diverting to a nearby airport for the purpose of a quick landing. At 22:14 AT (21:14 EST) the flight crew made a radio call to air-traffic control (ATC) at Moncton (which handles trans-atlantics air traffic approaching or departing North American air space), indicating that there was an urgent problem with the flight, although not an emergency, which would imply immediate danger to the aircraft. The crew requested a diversion to Boston's Logan International Airport, which was 300 nautical miles (560 km) away. ATC Moncton offered the crew a vector to the closer, 66 nm (104 km) away, Halifax International Airport in Enfield, Nova Scotia, which Loew accepted. The crew then put on their oxygen masks and the aircraft began its descent. Zimmermann put Loew in charge of the descent, while he personally ran through the two Swissair standard checklists for smoke in the cockpit, a process that would take approximately 20 minutes and become a later source of controversy.

Table 9

Swiss Air Flight 111, September 2, 1998 (Wikipedia)

Flight segment	Time (EST)	Event
1	20:18:00	Aircraft took off JFK airport. First officer Stephan Loew runs the aircraft
2	20:33-20:47	Radio blackout
3	21:10	Captain Urs Zimmermann and first officer Stephan Loew detected an odor in the cockpit and determined it to be smoke from the air conditioning system, a situation easily remedied by closing the air conditioning vent, which a flight attendant did on Zimmermann's request

Table 9. Continuid

4	21:14	Odor returned and smoke became visible. The crew called ATC Moncton indicating an urgent, but not an emergency, problem, and requested a diversion to Boston's Logan Airport, which was 300 nm (560 km) away. ATC Moncton offered a vector to the closer Halifax Airport in Enfield, Nova Scotia, 66 nm (104 km) away, which Loew accepted.
5	21:14-21:34	The crew put on oxygen masks and the aircraft began to descent. Zimmermann put Loew in charge of the descent, while he ran through the Swissair checklists for smoke in the cockpit, a process that become later a source of controversy.
6	21:18	ATC Moncton handed over traffic control of Swissair 111 to ATC Halifax.
7	21:19	The plane was 30 nm (56 km) away from Halifax Airport, but Loew requested more time to descend the plane from its altitude of 6,400 m.
8	21:20	Loew informed ATC Halifax that he needed to dump fuel. ATC Halifax said later it was a surprise, because the request came so late. Dumping fuel was a fairly standard procedure early on in nearly any «heavy» aircraft urgent landing scenario. Subsequently, ATC Halifax diverted aircraft toward St. Margaret's Bay, where they could more safely dump fuel, but still be only around 30 nm (56 km) from Halifax.
9	21:24:28	In accordance with the Swissair «In case of smoke of unknown origin» checklist, the crew shut off the power sup ply in the cabin. This caused the re-circulating fans to shut off. This caused a vacuum, which induced the fire to spread back into the cockpit. This also caused the autopi-

		lot to shut down. Loew informed ATC Halifax that «we now must fly manually.»
10	21:24:45	Loew informed ATC Halifax that «Swissair 111 is declaring emergency»
11	21:24:46	Loew repeated the emergency declaration one second later, and over the next 10 seconds stated that they had descended to «between 12,000 and 5,000 feet» and once more declared an emergency.
12	21:25:40	The flight data recorder stopped recording, followed one second later by the cockpit voice recorder.
13	21:25:50–21:26:04	The doomed plane briefly showed up again on radar screens. Its last recorded altitude was 9,700 feet. Shortly after the first emergency declaration, the captain could be heard leaving his seat to fight the fire, which was now spreading to the rear of the cockpit.

At 22:18 AT (21:18 EST), ATC Moncton handed over traffic control of Swissair 111 to ATC Halifax, since the plane was now going to land in Halifax rather than leave North American air space. At 22:19 AT (21:19 EST) the plane was 30 nautical miles (56 km) away from Halifax International Airport, but Loew requested more time to descend the plane from its altitude of 21,000 feet (6,400 m). At 22:20 AT (21:20 EST), Loew informed ATC Halifax that he needed to dump fuel, which ATC Halifax controllers would say later, was a surprise considering that the request came so late; dumping fuel is a fairly standard procedure early on in nearly any «heavy» aircraft urgent landing scenario. ATC Halifax subsequently diverted Swissair 111 toward St. Margaret's Bay, where they could more safely dump fuel, but still be only around 30 nautical miles (56 km) from Halifax.

In accordance with the Swissair checklist entitled «In case of smoke of unknown origin», the crew shut off the power supply in the cabin, which caused the re-circulating fans to shut off. This caused a vacuum, which induced the fire to spread back into the cockpit. This also caused the autopilot to shut down; at 22:24:28 AT (21:24:28 EST), Loew informed ATC Halifax that «we now must fly manually». Seventeen seconds later, at 22:24:45 AT (21:24:45 EST), Loew informed ATC Halifax that «Swissair 111 heavy is declaring emergency», repeated the emergency declaration one second later, and over the next 10 seconds stated that they had descended to «between 12,000 and 5,000 feet» and once more declared an emergency. The flight data recorder stopped recording at 22:25:40 AT (21:25:40 EST), followed one second later by the cockpit voice recorder. The doomed plane briefly showed up again on radar screens from 22:25:50 AT (21:25:50 EST) until 22:26:04 AT (21:26:04 EST). Its last recorded altitude was 9,700 feet. Shortly after the first emergency declaration, the captain could be heard leaving his seat to fight the fire, which was now spreading to the rear of the cockpit. The Swissair volume of checklists was later found fused together, as if someone had been trying to use them to fan back flames. The captain did not return to his seat, and whether he was killed from the fire or asphyxiated by the smoke is not known. However, physical evidence provides a strong indication that First Officer Loew may have survived the inferno only to die in the eventual crash; instruments show that Loew continued trying to fly the now-crippled aircraft, and gages later indicated that he shut down engine two approximately one minute before impact, implying he was still alive and at the controls until the aircraft struck the ocean at 22:31 AT (21:31 EST). The aircraft disintegrated on impact, killing all on board instantly.

The search and rescue operation was launched immediately by Joint Rescue Coordination Centre Halifax (JRCC Halifax) which tasked the Canadian Forces Air Command, Maritime Command and Land Force Command, as well as Canadian Coast Guard (CCG) and Canadian Coast Guard Auxiliary (CCGA) resources. The first rescue resources to approach the crash site were Canadian Coast Guard Auxiliary volunteer units-mostly privately owned fishing boats − sailing from Peggy's Cove, Bayswater and other harbors on St. Margaret's Bay and the Aspotogan Peninsula. They were soon joined by the dedicated Canadian Coast Guard SAR vessel CCGS *Sambro* and CH-113 Labrador SAR helicopters flown by 413 Squadron from CFB Greenwood.

The investigation identified eleven causes and contributing factors of the crash in its final report. The first and most important was: «Aircraft certification standards for material flammability were inadequate in that they allowed the use of materials that could be ignited and sustain or propagate fire. Consequently, flammable material propagated a fire that started above the ceiling on the right side of the cockpit near the cockpit rear wall. The fire spread and intensified rapidly to the extent that it degraded aircraft systems and the cockpit environment, and ultimately led to the loss of control of the aircraft».

Arcing from wiring of the in-flight entertainment system network did not trip the circuit breakers. While suggestive, the investigation was unable to confirm if this arc was the «lead event» that ignited the flammable covering on MPET insulation blankets that quickly spread across other flammable materials. The crew did not recognize that a fire had started and were not warned by instruments. Once they became aware of the fire, the uncertainty of the problem made it difficult to address. The rapid spread of the fire led to the failure of key display systems, and the crew were soon rendered unable to control the aircraft. Because he had no light by which to see his controls after the displays failed, the pilot was forced to steer the plane blindly; intentionally or not, the plane swerved off course and headed back out into the Atlantic. Recovered fragments of the plane show that the heat inside the cockpit became so great that the ceiling started to melt.

The recovered standby attitude indicator and airspeed indicator showed that the aircraft struck the water at 300 knots (560 km/h, 348 mph) in a 20 degrees nose down and 110 degree bank turn, or almost upside down. Less than a second after impact the plane would have been totally crushed, killing all aboard almost instantly. The TSB concluded that even if the crew had been aware of the nature of the problem, the rate at which the fire spread would have precluded a safe landing at Halifax even if an approach had begun as soon as the «pan-pan-pan» was declared. The plane was broken into two million small pieces by the impact, making this process time-consuming and tedious. The investigation became the largest and most expensive transport accident investigation in Canadian history.

Swiss Air Flight 111: segments (events) and crew errors. The Swiss Air Flight 111 events (segments) and durations are summarized in Table 9. The following more or less obvious errors were made by the crew:

- At 21:14 EST they used poor judgment and underestimated the danger by indicating to the ATC Moncton that the returned odor and visible smoke in the cockpit was an urgency, but not an emergency problem. They requested a diversion to the 300 nm (560 km) away Boston Logan Airport, and not to the closest 66nm (104 km) away Halifax Airport.

- Captain Zimmermann put first officer Loew in charge of the descent and spent time for running through the Swissair checklist for smoke in the cockpit.
- At 21:19 EST Loew requested more time to descend the plane from its altitude of 6,400 m, although the plane was only 30 nm (56 km) away from Halifax Airport.
- At 21:20 EST Loew informed ATC Halifax that he needed to dump fuel. As ATC Halifax indicated later, it was a surprise, because the request came too late. In addition, it was doubtful that such a measure was needed at all.
- At 21:24:28 the crew shut off the power supply in the cabin. That caused the re-circulating fans to shut off and caused a vacuum, which induced the fire to spread back into the cockpit. This also caused the autopilot to shut down, and Loew had to «fly manually». In about a minute or so the plane crashed.

Theses errors are reflected in the Table 10 score sheet and resulted in a rather low HCF and low probability of the assessed human non-failure.

Table 10

Flight 111 pilot's HCF

№	Relevant qualities	HCF $\left(\frac{F^*}{F_0}\right)$
1	psychological suitability for the given task;	3.0
2	professional qualifications and experience;	3.0
3	level, quality and timeliness of past and recent training;	2.0
4	mature (realistic) and independent thinking;	1.0

5	performance sustainability (consistency)	2.0
6	ability to concentrate and to act in cold blood in hazardous situations;	1.5
7	ability to anticipate ("expecting the unexpected");	1.2
8	ability to operate effectively under pressure	1.5
9	self-control in hazardous situations	2.0
10	ability to make a substantiated decision in a short period of time	1.2
	Average FOM	1.84
*) It is just an example. Actual numbers should be obtained using FOAT on a simulator and confirmed by an independent method, such as, say, Delphi method: http://en.wikipedia.org/wiki/Delphi_method [12]		

Flight 111 pilot's HCF. Flight 111 pilot's HCF and the probability of human non-failure are summarized in Table 10. The criteria used are the same as in Table 5 above. The probabilities of human non-failure are shown in Table 11.

Table 11

Computed probabilities of human non-failure (Swiss Air pilot)

G/G_0	5	10	50	100
p	0.1098	1.1945E-4	0	0

The computed probability of non-failure is very low even at a non-very high MWL levels. Although the crew's qualification seems to be adequate, the qualities № 4, 6, 7, 8 and 10, which were particularly critical in the situation in question, turned out to be extremely low. No wonder that it led to a crash.

Conclusions

- Application of quantitative probabilistic risk management (PRM) approach should complement, whenever feasible and possible, the existing vehicular psychology practices that are, as a rule, qualitative assessments of the role of the human factor when addressing the likelihood of success and safety of various vehicular missions and situations.
- It has been the high human capacity factor (HCF) of the aircraft crew and especially of Capt. Sullenberger's that made a reality what seemed to be a «miracle». The carried out PRM-based analysis enables one to quantify this fact. In effect, it has been a «miracle» that an outstanding individual like Capt. Sullenberger turned out to be in control at the time of the incident and that the weather was highly favorable. As long as this took place, nothing else could be

considered as a «miracle»: the likelihood of safe landing with an individual like Capt. Sullenberger in the cockpit was rather high.

- The taken PRM based approach, after the trustworthy input information is obtained using FOAT on a simulator and confirmed by an independent approach, such as, say, Delphi method, is applicable to many other human-in-the-loop (HITL) situations, well beyond the situation in question and perhaps even beyond the vehicular domain.
- Although the obtained numbers make physical sense, it is the approach, not the numbers that is, in the author's opinion, the merit of the paper.

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Appendix A
Other reported water landings (ditchings) of passenger airplanes

- On 11 July 2011, Angara Airlines Flight 5007 (an Antonov An-24) ditched in the Ob River near Strezhevoy, Russia, after an engine fire. Upon water contact the tail separated and the burnt port engine became detached from its mounts. Otherwise the plane remained intact, but was written off. Out of 37 people on board, including four crew and 33 passengers, 7 passengers died. Of the survivors, at least 20 were hospitalized with various injuries.
- On 6 June 2011, a Solenta Aviation Antonov An-26 freighter flying for DHL Aviation ditched in the Atlantic Ocean near Libreville, Gabon. Three crew and one passenger were rescued with minor injuries.
- On 22 October 2009, a Divi Divi Air Britten-Norman Islander operating Divi Divi Air Flight 014 ditched in off the coast of Bonaire after its starboard engine failed. The pilot reported that the aircraft was losing 200 feet per minute after choosing to fly to an airport. All 9 passengers survived, but the captain was knocked unconscious and although some passengers attempted to free him, he drowned and was pulled down with the aircraft.
- On 6 August 2005, Tuninter Flight 1153 (an ATR 72) ditched off the Sicilian coast after running out of fuel. Of 39 aboard, 23 survived with injuries. The plane's wreck was found in three pieces.
- On 16 January 2002, Garuda Indonesia Flight 421 (a Boeing 737) successfully ditched into the Bengawan Solo River near Yogyakarta, Java Island after experiencing a twin engine flameout during heavy precipitation and hail. The pilots tried to restart the engines several times before making the decision to ditch the aircraft. Photographs taken shortly after evacuation show that the plane came to rest in knee-deep water· Of the 60 occupants, one flight attendant was killed.

- On 23 November 1996, Ethiopian Airlines Flight 961 (a Boeing 767-260 ER), ditched in the Indian Ocean near Comoros after being hijacked and running out of fuel, killing 125 of the 175 passengers and crew on board. Unable to operate flaps, it impacted at high speed, dragging its left wingtip before tumbling and breaking into three pieces. The panicking hijackers were fighting the pilots for the control of the plane at the time of the impact, which caused the plane to roll just before hitting the water, and the subsequent wingtip hitting the water and breakup are a result of this struggle in the cockpit. Some passengers were killed on impact or trapped in the cabin when they inflated their life vests before exiting. Most of the survivors were found hanging onto a section of the fuselage that remained floating.
- On 2 May 1970, ALM Flight 980 (a McDonnell Douglas DC-9-33CF), ditched in mile-deep water after running out of fuel during multiple attempts to land at Princess Juliana International Airport on the island of Saint Maarten in the Netherlands Antilles under low-visibility weather. Insufficient warning to the cabin resulted in several passengers and crew still either standing or with unfastened seat belts as the aircraft struck the water. Of 63 occupants, 40 survivors were recovered by U.S. military helicopters.
- On 21 August 1963, an Aeroflot Tupolev Tu-124 ditched into the Neva River in Leningrad (now St. Petersburg) after running out of fuel. The aircraft floated and was towed to shore by a tugboat which it had nearly hit as it came down on the water. The tug rushed to the floating aircraft and pulled it with its passengers near to the shore, where the passengers disembarked onto the tug; all 52 on board escaped without injuries.
- On 23 September 1962, Flying Tiger Line Flight 923, a Lockheed 1049H-82 Super Constellation N6923C, passenger aircraft, on a military (MATS) charter flight, with a crew of 8 and 68 U.S. civilian and military (paratrooper) passengers ditched in the North Atlantic about 500 miles west of Shannon, Ireland after losing three engines on a flight from Gander, Newfoundland to Frankfurt, West Germany. 45 of the passengers and 3 crew were rescued, with 23 passengers and 5 crew members being lost in the storm-swept seas. All occupants successfully evacuated the airplane. Those who were lost succumbed in the rough seas.
- In October 1956, Pan Am Flight 6 (a Boeing 377) ditched northeast of Hawaii, after losing two of its four engines. The aircraft was able to circle around USCGC *Pontchartrain* until daybreak, when it ditched; all 31 on board survived.
- In April 1956, Northwest Orient Airlines Flight 2 (also a Boeing 377) ditched into Puget Sound after what was later decided to be caused by failure of the crew to close the cowl flaps on the plane's engines. All aboard escaped the aircraft after a textbook landing, but four passengers and one flight attendant succumbed either to drowning or to hypothermia before being rescued.
- On 26 March 1955, Pan Am Flight 845/26 ditched 35 miles from the Oregon coast after an engine tore loose. Despite the tail section breaking off

during the impact the aircraft floated for twenty minutes before sinking. Survivors were rescued after a further 90 minutes in the water.

- On 19 June 1954, Swissair Convair CV-240 HB-IRW ditched into the English Channel because of fuel starvation, which was attributed to pilot error. All three crew and five passengers survived the ditching and could escape the plane. However, three of the passengers could not swim and eventually drowned, because there were no life jackets on board, which was not prescribed at the time.
- On 3 August 1953, Air France Flight 152, a Lockheed L-749A Constellation ditched 6 miles from Fetiye Point, Turkey 1,5 miles offshore into the Mediterranean Sea on a flight between Rome, Italy and Beirut, Lebanon. The propeller had failed due to blade fracture. Due to violent vibrations, engine number three broke away and control of engine number four was lost. The crew of eight and all but four of the 34 passengers were rescued.
- On 16 April 1952, the de Havilland Australia DHA-3 Drover VH-DHA operated by the Australian Department of Civil Aviation[26] with 3 occupants was ditched in the Bismarck Sea between Wewak and Manus Island. The port propeller failed, a propeller blade penetrated the fuselage and the single pilot was rendered unconscious; the ditching was performed by a passenger.
- On 11 April 1952, Pan Am Flight 526A ditched 11.3 miles northwest of Puerto Rico due to engine failure after take off. Many survived the initial ditching but panicking passengers refused to leave the sinking wreck and drowned. 52 passengers were killed, 17 passengers and crew members were rescued by the USCG. After this accident it was recommended to implement pre-flight safety demonstrations for over-water flights.

Appendix B
Captain Sullenberger

Sullenberger was born to a dentist father – a descendant of Swiss immigrants named Sollenberger − and an elementary school teacher mother. He has one sister, Mary Wilson. The street on which he grew up in Denison, Texas, was named after his mother's family, the Hannas. According to his sister, Sullenberger built model planes and aircraft carriers during his childhood, and might have become interested in flying after hearing stories about his father's service in the United States Navy. He went to school in Denison, and was consistently in the 99th percentile in every academic category. At the age of 12, his IQ was deemed high enough to join Mensa International. He also gained a pilot's license at 14. In high school he was the president of the Latin club, a first chair flute, and an honor student. His high school friends have said that Sullenberger developed a passion for flying from watching jets based out of Perrin Air Force Base.

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