EMI, TWA 800 and Swissair 111

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Abstract

We refute Elaine Scarry's contentions, published in the New York Review of Books in September and October 2000, that external electromagnetic fields can have been major contributors to the accidents to TWA Flight 800 and Swissair Flight 111. The refutation for TWA 800 cites NASA research done in support of the investigation. The refutation for Swissair 111 is new here.

1 Introduction

Elaine Scarry has claimed in the New York Review of Books that the accidents to TWA Flight 800 on July 17, 1996 (B747-100 aircraft, registration N93119)[1] and Swissair Flight 111 on September 2, 1998 (MD-11 aircraft, registration HB-IWF) off the east coast of the United States have sufficient similarity that the possibility of a common cause or a common major causal factor should be more thoroughly investigated than it has been. In particular, she suspects electromagnetic interference (EMI) with aircraft electrical systems from high-intensity radiation fields (HIRF), which we shall call "external EMI"[2]

We refute Ms. Scarry's proposals of a common cause, and of significant EMI effects on either aircraft.

Section 2 states the propositions under discussion. Section 3 summarises the extensive research performed by NASA, its associates, the FAA, and others on

[1] One may distinguish between a flight, and the aircraft which conducts that flight. Although it is appropriate to talk of an accident to or a problem with Flight XXX, when one talks about physical features of the aircraft itself, it makes more sense to refer to the aircraft by its registration. We shall do so.

[2] External EMI is thereby distinguished from internal EMI, which would be EMI in aircraft systems caused by other aircraft systems or personal electronic devices (PEDs) inside the passenger cabin or in luggage. Although there are many anecdotes from reliable sources concerning internal EMI in flight, almost exclusively with navigation systems although occasionally with communication systems also, it is only recently that the existence of internal EMI with measurable functional effects has been demonstrated, by the U.K. CAA with mobile phones in an older aircraft.

aircraft wiring, and electromagnetic interference issues. Section 4 refutes the proposals presented by Ms. Scarry for the possibility of external EMI as a cause of the accidents to TWA Flight 800 and Swissair Flight 111.

There is technical merit in citing research results before one applies those results; thus in explaining the consequences of research by NASA, the FAA and others before we use it to assess Ms. Scarry's proposals. We follow that line.

2 Statement of the Technical Proposals

The main technical proposal in Ms. Scarry's 1998 article in the New York Review of Books (NYRB) [12] is that

(a): ignition of the central fuel tank under the mid-fuselage ("center wing tank" or CWT) of N93119 could have been caused by electrical activity generated by external EMI.

In her NYRB article of September 21, 2000 [13], Ms. Scarry suggests further that

(b): external EMI could be the cause of a communications blackout to Swissair 111, and

(c): external EMI could also be the cause of the electrical problems and fire that caused the accident to Swissair 111.

She suggests also that, because of a series of spatiotemporal coincidences,

(d): the accidents to TWA 800 and Swissair 111 may have had a common cause, namely external EMI from the same or similar source, produced for the same or similar reasons.

3 Results of NTSB, NASA and FAA Research

The details of the NASA and FAA research, as well as technical data from others, are necessary in order accurately to evaluate Ms. Scarry's suggestions. We summarise the salient details here before applying them in Section 4 to the evaluation of Ms. Scarry's proposals.

3.1 The NASA EMI study and TWA 800

NASA completed a significant study on the effects of EMI on electrical systems in the CWT of a B747-100 such as N93119. The research was reported in [5] and contained as an addendum to the Systems Group Chairmans's Factual Report [16] in the TWA 800 docket of the U.S. National Transportation Safety Board (NTSB) [1]. Further research is being conducted on more extensive questions about the effects of EMI on transport aircraft.

The NTSB has determined that the breakup of N93119 was initiated by ignition of flammable fuel vapors in N93119's CWT [16]. The question remains as to what the ignition source actually was. The NASA research looked at both external EMI, and internal EMI from PEDs.

3.1.1 Minimum Required Fuel-Vapor Ignition Energy

The NTSB System Group Chairman's Factual Report cites the minimum ignition energy requirement from American Petroleum Institute (API) Practice 2003 to be 0.25 milliJoules (mJ), and the Boeing specification for induced energy into the CWT wiring harness to be 0.02 mJ. In their investigation, the NTSB systems group succeeded in inducing 0.6 mJ, with transient voltage of over 1,000 volts (V), by creating a spark gap between the LO-Z terminal of an in-tank fuel probe and ground (the aircraft structure). Such a transient was "not found during normal conditions" [16, pages 8–9]. In a more detailed description [16, pages 105–6], the NTSB observed that "current analysis has not found coupling of CWT FQIS [Fuel Quantity Indication System] wires with a 75 foot source wire with the tested amount of inductive energy." They also note that Boeing questioned the accuracy of the results produced by this experiment.

NASA commissioned a report by Frank Fisher of Lightning Technologies, Inc on fuel ignition [8]. This report cites the "widely accepted minimum guideline for aircraft fuel-vapor ignition" [8, page 1; also page 21] as 0.2 mJ. It points out that the actual ignition energy required depends on the richness of the fuel-air mixture [8, page 21]; that there are a number of intermediate factors coming between source power levels and energy available to the "spark" (or equivalent electrical energy discharge), all of which serve to reduce the energy available to the spark, some significantly [8, Section 4]; and that the power levels cited in studies of ignition as a function of power levels "do not refer to the power or energy delivered to the sparking contact or the fuel-air mixture in which the break spark mechanism is immersed" [8, Section 4.2, point (b)]. The report considers that, although much work has been done on EM-induced ignition of flammable vapors, most of this work has not been at the frequencies relevant for HIRF effects on aircraft, nor on aircraft structures, nor specifically on aircraft fuels [8, Section 4, page 25; Section 5, p34].

3.1.2 Energy Provided by External Emitters

The salient characteristics of the dominant electromagnetic (EM) transmitters present in the general vicinity of N93119's breakup were provided to NASA and the NTSB by the DoD's Joint Spectrum Center (JSC). All of those transmitters were radio frequencies: GigaHerz (GHz)-frequency waves with a wavelength in terms of millimeters.

NASA developed a new code[3], which they call the Modal/Method-of-Moments

[3] A *code* is a computer program for performing accurate numerical-analytical calculations of mathematical or physical problems, usually of the form of propagating waves or other phenomena inside given boundaries. The waves may reflect off parts of the boundaries, which may

(Modal/MoM) code[4], for analysing the EM available to the CWT FQIS wiring based on the data on external EMI supplied by the JSC. The external energy affects the internal state of the aircraft primarily through the apertures, i.e., the windows. The aircraft body effectively shields the internal systems from external EM and the energy gets in to the interior through the holes in this cage: the windows. The Modal/MoM code was validated against other calculations on known configurations, all pertinent to, but not sufficient for, solving the equations for the shape with apertures that sufficiently approximates a B747. All the assumptions explicitly made in estimations were conservative; in particular, the FQIS wire length was chosen to maximise the energy available in the FQIS wire for a given EM situation within the airframe hull (called the "cavity" in the NASA study). The NASA study estimated that "For an external source of 1 V/cm [volt per centimeter], the energy delivered to the CWT load was found to be ... 1.4839×10^{-9} J [Joules]..... the total energy delivered to the CWT due to field strength of 17.921 V/m [volts per meter] was calculated as ... $(0.17921)^2 \times 1.4839 \times 10^{-9}$ J." [5, page 35]. This cited figure is equal to 4.766×10^{-11} J., to the first four significant figures.

NASA points out here what the Fisher report also noted, that Event Power ("the minimum RF power required at the FQIS connector for ionisation/heating event") and Source Power ("Worst-case EM emission threat") and Path Factor ("Worst-case coupling factor from source power to FQIS coupled power") are "independent variables" [5, Section 3.6, page 32]. To get an ignition event, the source power multiplied by the path factor has to be larger than the event power. The source power came from the JSC [5, Table 3.3.1-1, page 16]; the event power from the fuel ignition study [8] and elsewhere. The NASA research focused on developing techniques for estimating the path factor, which is dependent on the size and shape of the "cavity" and the "apertures" (the windows). That is what the Modal/MoM code is for.

NASA summarises two calculations that were performed. First, "The total available energy inside the aircraft cabin from the maximum dominant emitter .... was found to be less than 0.1 mJ [milliJoules]. Even if this total energy could have been focused into a single discharge event, it was still below the generally accepted estimate of the minimum energy level (0.2 mJ) required to achieve ignition" [5, page 39]. Second, the more accurate estimate of how much energy from that available could actually be coupled to the FQIS wiring, for which they used the Modal/MoM numerical modelling technique. They found that "When applied to the energy from the 1.294 GHz emitter source [one of those cited by the JSC], the [numerically estimated] energy levels were several orders of magnitude[5] ((1to 30) $\times 10^{-4}$) less than the maximum available energy." [5,

also be irregular, making the purely analytical solution of the equations next to impossible.

[4] In the Method of Moments, the partial differential wave equations are solved numerically by first formulating the solution as a sum of waveforms which fulfil the boundary conditions on the conducting planes, called a Fourier series, with certain undetermined constants per waveform, called the Fourier coefficients, then determining the coefficients by considering the initial state of the system, and finally focussing on the most significant waveforms in the series in terms of contribution to the whole field.

[5] "Order" or "order of magnitude" means a power of ten. So "one order of magnitude less"

Section 3.7, page 39]. That is, the energy available to the FQIS wiring was estimated by the Modal/MoM technique to be 330 to 10,000 times less than the maximum energy available to the hull (estimated at less than 0.1 milliJoules from the most significant emitter)[6].

3.1.3 Comparison with Other External EM Environments

NASA also indicated that certification guidance and methods regarding operation of electrical and electronic systems on an aircraft exposed to external HIRF is being developed in Advisory Circular/Advisory Material Joint (AC/AMJ) document 20.1317, by a group of US and European engineers. By comparing data from AC/AMJ 20.1317 and that available from the JSC [5, Figure 3.3.2-1, page 17], NASA observed that "the JSC-derived TWA-800 environment was far less severe than that encountered in routine departure and arrival operations." [5, Section 3.3.2, page 17]. At breakup, N93119 was operating in a field that was far less severe than that in the vicinity of the most high-density commercial airports.

3.2 Swissair 111 and FAA Wiring Research

Let us move now to the situation concerning Swissair 111. Unprotected electrical conductors in the presence of a highly flammable fuel-air mixture, as in the case of TWA 800, do not appear to be relevant to the Swissair 111 case. A location of significantly burned material, including wiring showing signs of arcing and other deterioration, has been identified in the area where a fire is believed to have started, in or near the cockpit/cabin dividing partition.

3.2.1 Ticking Faults and Their Consequences

It appears in this case that we are considering insulated wiring in the presence of air or, possibly but exceptionally, some fluid such as condensation moisture or blue toilet fluid. Insulation can burn; indeed it has been shown that short circuits can bring it to do so [3]. So-called "ticking faults" appear to be particularly consequential. Ticking faults can be described as intermittent arcing or short circuits, in which an arc or short circuit is created for a period of time of the order of fractions of a second up to seconds, then ceases, then recurs, and so on continuously. Although standard 7.5 amp (A) aircraft circuit breakers often

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means between 5 and 50 times less; "two orders of magnitude less" means between 50 and 500 times less; "three orders of magnitude less" means between 500 and 5,000 times less, and so on.

[6] There appears to be some inconsistency between this figure here, of a factor of between 330 and 10,000, and the statement in [5, Section 3.6.4, page 35], repeated in [5, Table 3.6.4-2, page 36], of the energy delivered by one significant emitter. This latter delivered energy of between 10^{-10} and 4.47×10^{-9} Joules for different wire lengths, according to [5, Table 3.6.4-2, page 36], and this is more than a factor of 10,000 smaller than the maximal available energy quoted as 0.097 mJ on [5, Section 3.3.1, page 15]. Pending a clarification, we use in our argument the factor which is the more conservative for the calculations, namely the factor of between 330 to 10,000 times smaller.

tripped during a discharge occurrence in the FAA tests, they did not invariably do so. Further, despite FAA efforts to inform the aviation community, it is suspected that many commercial pilots are still in the habit of resetting tripped circuit breakers once, or even repeatedly, when the trip does not immediately recur. In the case of a ticking fault with certain types of wiring (wiring is classified by gauge and by the kind of insulation it uses), rapid deterioration of the insulation leading to massive arcing has been observed in tests. The procedures to use in the case of a tripped circuit breaker (basically, don't reset it and don't use the circuit until it has been determined what caused the trip) have been summarised recently in an FAA Safety Bulletin [7]. Industry has developed circuit breakers which contain electronics to detect arcing (so-called "arc fault detection" technology) and which trip on the occurrence of arcing. One such has been developed by ETA Technologies in Germany (which amongst other things provides circuit breakers for European military aircraft) [14, 11]. Other detectors have been developed by the company Square D for home use [15], and Eaton Corp has patented arc fault detection technology suitable for aviation [10]. The issues of faulty and deteriorated wiring have attracted the attention of US Congressional committees.

3.2.2 Summary of the FAA Research

It is worthwhile to summarise briefly some of the tests that have been conducted and whose information is public. In a series of investigations at the FAA Technical Center in Atlantic City, New Jersey in 1988 through 1995, Patricia Cahill tested aircraft wiring under arcing to destruction, namely when the wire caught fire [4, 2, 3]. Tests on both dry and "wet" wire were performed ("wet" refers to fluids such as used in aircraft toilets, and not necessarily water). In all these tests, a generator rated at 18.75 kiloVolt-Amps (kVA) was used as the power source. 18.75 kVA is a power rating of 18,750 Joules per second. The dry arc-tracking tests were performed by stripping 3/16" of insulation from the ends of each wire in a seven-wire bundle, splaying out the exposed ends of the wiring so that adjacent wires intermingled, and applying powdered graphite to the ends to insure that an arc was struck. Each wire was attached to a 7.5A circuit breaker. Various wire types were then exposed to the short circuits, the effects on the insulation were measured, circuit breakers reset if necessary, and current applied again. Arcing on various wires was mild to moderate to massive. On the massive arcing, associated with wiring insulated with aromatic polyimide (Kapton$^{\text{tm}}$), 4 to 6 of the circuit breakers tripped with each initial arc.

3.2.3 The Possibility of Arcing from External Fields

There are two issues involved in analysing the question whether arcing can have brought down Swissair 111 by causing the fire damage seen in the wreckage. First is the question whether arcing in aircraft wiring can be caused by external EMI at all. Second would be the question whether, if so, enough energy could be contained in the spark to cause the insulation to burn.

A field intensity of approximately 30 kilovolts per centimeter (kV/cm) is required to cause arcing between two conductors at sea-level pressure. This varies approximately linearly with air pressure. The air pressure in the "International Standard Atmosphere[7]" is 1013.2 hectoPascal (hPa) at sea level, and varies very roughly linearly with altitude up to 15,000 ft or 20,000 ft or so, decreasing by about 1 hPa per 30 ft altitude (standard aviation calculations regard this linear relationship as accurate up to 5,000 ft or so). Thus one can expect the field intensity required for arcing to be about 15 kV/cm at 15,000 ft. This is a value of 1.5 million volts per meter (V/m). This required field intensity for arcing is many orders of magnitude larger than the intensities of between 3.773 V/m and 32.713 V/m available to the outside of the hull of TWA 800 [5, Table 3.3.1-1, page 16].

However, an arc that burned for tiny fractions of a second would not by itself have enough energy to start an insultation fire. We now turn to calculating a lower bound for that amount of energy.

3.2.4 Consequences of the NASA, FAA and Other Research for Swissair 111

Consider first a wire protected by a circuit breaker rated at 7.5A which is under load and supplied from a 115 Volt (V) power source. It can take power of at least (115×7.5) VA [8]. This load figure represents power of 862.5 Joules per second. Let us use a lower, rounder figure of 850W, that is, 850 Joules per second, for maximal continuous load. Note that this estimate is conservative, since all assumptions are conservative.

Breakers do not trip instantaneously. Standard aviation circuit breakers are composed of a bimetallic strip which bends under the temperature changes generated by heat energy which is itself generated by an electrical overload. A certain amount of energy is necessary to move the breaker. This energy may be calculated from the characteristics of the breaker, and is dependent upon ambient temperature. A typical breaker will trip at overloads of 1000% (that is, a factor of 10) at between 0.08 seconds minimum (at 121 deg C) and 0.8 seconds maximum (at -54 deg C). The usual range is at an ambient temperature of 25 deg C and takes between 0.1 and 0.5 seconds [10, Figure 8, page 216]. (In contrast, a spark can be generated in 10 nanoseconds, and ticking faults, with the associated current waveform, can be very hard to distinguish from transient waveforms associated with starting a motor, or turning on other electrical loads.) At just over 100% of rated load (that is, at almost exactly but just over rated load) a breaker will trip in a minimum of 300 seconds in worst-case temperature (121 deg C). The minimum trip time curve at this temperature passes through 1 second at 250%, and 5 seconds at 165% [10, Figure 8, page 216]. So the

[7] The pressure and temperature at particular altitudes varies constantly at a particular location on the globe, with weather systems, seasons and other local and not-so-local variations. However, one needs a "standard" set of values for various scientific and technical purposes, hence the International Standard Atmosphere.

[8] which is one Joule of energy per second

minimum value of the quantity (overload factor $\times$ time) is reached at 1000% and 0.08 seconds. That is, ten times rated load for 0.08 seconds. Let us use this value.

One may then conservatively calculate the minimal energy needed to trip a circuit breaker as (power $\times$ time), which is 850 multiplied by a factor of ten for 0.08 second, i.e., $850 \times 10 \times 0.08$ Joules, or 680 Joules.

In Ms. Cahill's tests, the worst case, in which the wiring insulation caught fire very quickly, was accompanied by at least one trip and reset of the 7.5A circuit breakers on the wiring. This represents then a minimum energy of 680 Joules per wire before the insulation caught fire, in the least-favorable case. We may then take this figure of 680 Joules as representing the minimum energy that must be available in order to ignite insulation under arcing. This is a very conservative estimate – the true figures would seem to be far higher.

If we are to say that the required energy comes from external EMI, this entails that at least this amount of energy, 680 Joules, must have been available outside the aircraft from EM fields. In reality, as with NASA's best estimate of energy available at the wiring, which was some orders of magnitude lower than the total energy available at the location, it is probable that this figure is too low. However, it is a lower bound, and will suffice for the rest of the argument.

This figure of 680 Joules compares with the 0.1 mJ available to TWA 800 [5, Section 3.3.1, page 15]. Thus, we are talking about energy available from EM fields that would have to be 6.8×10^6 greater, that is, 6.8 million times, or seven orders of magnitude greater (6.8×10^6 is considered as 0.68×10^7 for an order-of-magnitude assessment). And it may well be some orders of magnitude greater than this, if a similar relation were found to hold between the energy induced in the wiring and the available external energy as was found with TWA 800.

For electrical fields at a distance of many times wavelength (and we are talking of wavelengths of the order of millimeters and transmitters miles away), we may assume that the energy density may be calculated as the square of the field intensity in Volts per meter, divided by the characteristic impedance in air (which is a constant) of about 377 ohms. This is the formula that NASA used to calculate the energy density outside TWA 800 from the emitter table [5, Section 3.3.1, page 15], and it is always valid in the far-field region, that region at some distance from the emitting antenna. This figure for energy density is then multiplied by the surface area of the body to obtain the total energy available to the aircraft from the influence of the EM field. In order to calculate the required energy density that must have been available to Swissair 111 for an EM field to generate an insulation fire, then, we take the total energy, 680 Joules, and divide by the surface area of HB-IWK. The surface area of HB-IWK is less than that of N93119, so if use the same figure as for N93119, this will give us a conservative estimate of the required energy density. This conservative estimate is still, however, 6.8 million times greater than the energy density associated with TWA 800, because one is simply taking the total energy figure for each and then dividing by the same number (the total surface area of N93119).

If we want to compare the situation with regard to the Swissair wiring fire energy, then, with that pertaining to TWA 800 fuel tank ignition, there are two ways to do so.

- One may consider stronger transmitters at the similar distances, or
- one may consider similar-strength transmitters that are closer

3.2.5 Stronger Transmitters at Similar Distances

It is hard to get too close by land or sea to an aircraft that is already flying miles high. So it makes sense to consider stronger transmitters. We have calculated that the energy available to a similar-shaped body at a similar distance must be 0.68×10^7 times greater, at a minumum, to cause insulation fires through induced currents than it must have been in the vicinity of TWA 800, which was an unusually dense emissions environment at that altitude according to estimates, although still less than that available around many airports during take-off and landing operations [5, Section 3.3.2, pages 16–17]. However, to produce energy that is 0.68×10^7 times greater, one must put that amount of energy in; energy generation is after all only a lossy transformation process. So any stronger transmitter at similar distances must have been 6.8 million times as powerful (power is energy per unit time).

3.2.6 Similar Strength at Closer Distances

By contrast, one can increase the energy strength considerably by reducing the distance. In the normal case, the energy density of an electromagnetic field will vary as the square of the distance from the source. Now $(0.68 \times 10^7) = approx\ (2,600)^2$. We can conclude that any similar source would have to be 2,600 times closer to obtain the energy density we have calculated as a lower bound on the minimal requisite density.

3.2.7 Higher Strengths at Closer Distances

Finally, we may consider some combination of more powerful transmitters with closer distances. It will be appropriate to keep in mind that ground-based sources can have achieved a proximity of no closer than about 3 miles to the aircraft, for this is the minimum altitude during the flights at which electromagnetic events were suspected by Ms. Scarry's proposals to have occurred. Similarly, the proximity of airborne sources is limited by air traffic control and military distancing procedures.

3.3 U.S. Air Force Experiments on Electromagnetic Pulses

It is well to emphasise that the figure with which we worked, 680 Joules, is not a realistic estimate of the energy that may be required to ignite wiring insulation inside an aircraft. It was a number which can be shown to be a lower bound by a train of (hopefully) rigorous logical and physical reasoning from existing evidence. As we have noted, realistic estimates depend on the current density in the wiring and are likely to be significantly greater.

One way in which one could obtain more realistic physical estimates is by considering the results of some research of the U.S. Air Force. The U.S.A.F. conducted extensive empirical research into the effects of nuclear explosions on aircraft electronic systems. They were concerned to know about the effects of the electromagnetic pulse, caused when a nuclear weapon explodes, on the avionics. A nuclear explosion generates an electromagnetic field much larger that anything that could be supposed in the case of TWA 800 or Swissair 111. The Air Force experiments involved taking real airplanes, putting them in the near vicinity of ("zapping them with" would probably be a more appropriate expression) extremely powerful EM generators, and measuring the internal fields. Damage to electronics occurs much sooner than electrical fires [9].

One might think of developing usable military equipment based on such very-high-power transmitters. Such proposals are, however, technically limited by the problem that the source, one's own personnel and equipment, tends to be much closer than the target, and thus one tends to "fry" one's own resources rather than those of the target [9]. This suggests that thinking of transmitters of the order of seven million times more powerful than those already identified by the JSC is somewhat far-fetched.

Capt. Zimmerman mentioned no problems with any of the extensive and sensitive electronics, including electronic displays, on board Swissair 111 up until the time the fire emergency had already commenced.

4 Evaluation of Ms. Scarry's Proposal

Two of Ms. Scarry's proposals are straightforward to refute. NASA research refutes the claim that external EMI could have been the ignition source of the CWT fire in TWA 800, as explained in Section 4.1. This refutes a fortiori the claim that external EMI could have been a common cause for the accidents to both TWA 800 and Swissair 111, noted in Section 4.2. Section 4.3 discusses the relevance of possible disturbance to communications or navigation signals to the major proposals under consideration. The proposal, that external EMI could have been the cause of the electrical damage to HB-IWK, is refuted in Section 4.4, based on the observations in Section 3.

4.1 Refutation of Proposal (a)

We summarise the NASA findings. The NASA study concluded that at most 0.1 mJ of energy was available at the location of TWA 800 from a single dominant transmitter, outside the aircraft but in the space which it occupied. This energy total, available over the entire outside of the aircraft, was at most one-half of the minimal energy required in the CWT to ignite the fuel vapors. The best estimate of the amount of energy generated by external EMI that was actually available inside the CWT in the CWT wiring, generated by the emitter that was strongest at that location, was 333 times to 10,000 times less than that[9]. Fisher cited 0.2 milliJoules at the CWT electrics needed for ignition as the "widely accepted minimum". That is: 666 to 20,000 times the amount of energy would be needed to cause an electrical discharge capable of igniting the vapors, as was identified as present from the strongest emitter. Whatever that emitter was, P3 or Aegis cruiser, you would need 666 to 20,000 of them to cause ignition of the CWT vapors. We conclude that proposal (a) has been refuted by the NASA study.

4.2 Refutation of Proposal (d)

This reasoning also refutes proposal (d): what is not a cause of one accident cannot be a common cause of both. Ms. Scarry cites coincidences as potential evidence of common causality. But where there can be no common causality, coincidences cannot be evidence of it.

4.3 Discussion of Proposal (b)

In support of (b), Ms. Scarry has identified a potential source. Using the U.S. Freedom of Information Act, she discovered that a "eavesdropping" P3 of Squadron 26 suffered severe radiocommunications disruption because of the presence of a P3 of Squadron 10 in the same Warning Area. This incident took place in the vicinity of TWA 800's and Swissair 111's route of flight, in the same time frame but not at the same time as Swissair 111's accident flight.

Disturbance to communications and navigation electronics is an unusual but known event, which has no known role as an indicator of major aircraft problems, such as those sufficient directly to cause an aircraft accident through wiring fires.

First, navigation and communication signals are high-information-content signals which are transmitted as modulations – variations – on an underlying waveform, which is usually identified by its frequency. These modulations may be changes in the amplitude of the waveform ("amplitude modulation" or AM), or slight changes in the frequency ("frequency modulations" or FM). Which of these is chosen is a matter of system design. The signals are picked up by an external antenna, and then pass through a series of amplifiers (which we shall call the "amplification chain"), which add power to the signal, before being presented to a device which interprets this signal (speakers for communications, for example, or navigation display information for cockpit instruments). It is important to realise that external fields can distort the signal at the antenna, but that the amount of power added to the signal by the end of the amplification chain remains the same. The distortions are amplified along with the rest of the signal and cause problems at the interpretation end. But external signals cannot cause any increase in power at the end of the amplification chain itself.

[9]Recall that his factor is conservative, and that the detailed NASA calculations suggest a figure of hundreds of thousands of times less.

Everyone who has run a household vacuum cleaner at the same time as a television set has seen how easy it is to disturb the signal enough at the antenna to distort significantly the data presented at the other end of the system. The electric motor in a vacuum cleaner continually produces sparks, EM emissions containing all frequencies. Certain frequencies in the emissions are sensed by the antenna and are included along with the signal and sent through the amplification chain to the screen and speakers of the television. So the effect on the screen and speakers is significant. However, this effect is caused purely through modification of the signal at the antenna. If the antenna itself is shielded against the local environment, the effect disappears.

Any proposed disturbance in the amplification chain itself from external EMI is a very different proposition from disturbing the signals themselves and would be subject to the considerations we offer in Section 4.4 as refutation of Ms. Scarry's proposal (c).

Second, other electronic warfare devices target radars and other sensors. But, to use an analogy, one doesn't have to have a loud voice to deafen Granny by shouting into her ear trumpet.

Finally, in contrast with these situations, Ms. Scarry's other proposals are considering changes of electric current, sufficient to cause insulation to ignite, inside the aircraft. That is a very different kettle of fish altogether. The aircraft hull is an excellent shield against EM radiation, a so-called "Faraday cage". EMI fields external to the "cage" generate internal fields primarily through the window apertures. There is no correlation between EMI energy sufficient to cause communications disruption and electromagnetic energy sufficient to cause a discharge event in an electrical system inside the aircraft hull, as the NASA study on (a) established. The former are relatively common events; the latter are unknown even in designed tests, except in circumstances which could not occur in a commercial aircraft in flight. It is gratuitous to suggest a causal connection, as Ms. Scarry does, between types of events of which the evidence shows there isn't any in general.

The Canadian Transportation Safety Board has said that the Flight Data Recorder of HB-IWK showed no anomalies during the period of the communications interruption, and the transponder, a radio receiver/transmitter used for automatic identification and altitude reporting of civil aircraft, was functioning normally during this period [6]. It should be remarked here, though, that some signal forms are robust against interference, and some not[10]. The important parameters are the modulation form and the redundancy. It is perfectly possible for outside interference to disturb communications while leaving the transponder functioning.

4.4 Refutation of Proposal (c)

The accident airplane HB-IWF in the Swissair Flight 111 accident was a relatively new MD-11, 7 years old, with a third the number of hours and number

[10] We are grateful to Hal Lewis for this observation.

of takeoffs and landings (called "cycles"[11]) as N93119[12]. Wiring weaknesses due mainly to age are correspondingly less likely although not impossible; the mechanical, chemical or thermal deterioration of wiring insulation which may allow discharge events, and the origin of the voltage leading to such discharges, are being investigated.

A leading candidate for cause is some kind of wiring discharge that initiated an electrical system fire in the region of the cockpit/cabin divider. Ms. Scarry's proposal is consistent with this hypothesis, but suggests a cause for the discharge. The question before us is thus: what caused the discharge?

Defective wiring has been found; 20 wires or so have significant arcing or insulation damage, although it has not been determined which damage, if any, was causative and which was a consequence of the fire. In this area there runs avionics wiring, as well as electrical system wiring, and wiring for the in-flight entertainment system, which was installed post-manufacture [11].

Damage to wiring may occur through faulty wiring system design, faulty installation, mechanical deterioration, or chemical deterioration of the insulation, through use or age or both. If wiring is routed through a bend, then a factor of two in the radius of the bend can increase the deterioration of the wiring insulation with age by an order of magnitude or more. Similar effects occur if the wire is under tension for some reason, for example from improper installation[13].

If defective wiring was involved, then Ms. Scarry's suggestion, that external EMI caused the event, is at best misleading. At most, one could say that external EMI *together with defective wiring* could have caused the event.

With this modification of the proposal, we have calculated in Section 3.2.4 that any transmitter capable of causing electrical discharge sufficient to start an insulation fire must have been 6.8 million times as powerful as any in the vicinity of TWA 800 or 2,600 times closer, or some combination of both. And it is plausible that it would have had to have been some orders of magnitude more powerful even than this.

The dominant transmitters in the vicinity of TWA 800 have been determined by the Joint Spectrum Center in order of contributed energy to be transmitters at 15.7 miles, 112 miles, 2.93 miles, 156.3 miles, 13.1 miles and 17.1 miles [5, Table 3.3.1-1, page 16]. Let us consider how close such transmitters could theoretically have gotten to an airplane at an altitude of 16,000 feet, or 3 miles. Ground-based transmitters cannot have gotten closer than 3 miles; air-based not

[11] The term "cycles" stands for pressurisation cycles: the event of pressurising and depressurising an aircraft hull once, as in a single trip from takeoff to landing. A pressurisation cycles causes stress to the airframe and is counted as a significant measure of use along with total hours in flight.

[12] N93119 was a Boeing 747-131 aircraft built in 1971 with 93,303 total hours in flight and 16,869 cycles at the time of the accident. HB-IWK was a McDonnell-Douglas (now Boeing) MD-11 built in 1991 with 35,000 hours and 6,400 cycles. This information courtesy of `www.aviation-safety.net`.

[13] Hal Lewis relates a story of a coaxial cable on his ship in WWII, which led to the air defense radar antenna, shorting out, having been bent too sharply around a yardarm during installation. He had it repaired at Pearl Harbor, and the installers replaced it, bending it around the yardarm as before.......

closer than a mile. This yields (whole-number) physical distance limitations of factors of 5, 37, 3, 52, 4 and 6, respectively; that entails factors of 25, $1,369$, 9, $2,704$, 16 and 36 respectively in the increase of energy density at the location of the aircraft, were they to be as close as they could physically come. Compare these physical limitations with the required increase in field strength of 0.68×10^7. This yields required increases in transmitter strength of 2.72×10^5, 4.93×10^3, 0.756×10^6, 2.52×10^3, 4.25×10^5, and 1.89×10^5 respectively.

The only even faintly plausible possibilities for significant increases in transmissive capability lie with the types of transmitters at 112 miles and 156 miles from TWA 800. These are already known to be exceptional transmitters of significant military worth. First, they would have had to have been directly under the route of Swissair Flight 111, and, second, they would have to have been 5,000, respectively 2,500, times as powerful as they were in 1996. No such significant military transmitters have been identified anywhere in the vicinity of Swissair 111, and the installed transmitters on board the relevant ships have not become those many thousands of times more powerful in the two years between 1996 and 1998.

Thus is Ms. Scarry's proposal (c) refuted.

One should also keep in mind that these figures represent the figures obtained by an argument from existing data in which each step was (supposed to be) incontrovertible. More realistic estimates of required energy density outside the aircraft are likely to be significantly greater.

4.5 Other Potential Causes

Let's consider briefly two potential causes:

(e): internal wiring problems in N93119 caused current sufficient to ignite vapors to pass through exposed CWT conductors;

(f): arcing caused by mechanical, chemical or electrical defects in HB-IWF's wiring caused the electrical fire which led to the accident.

In contrast to the Ms. Scarry's proposed phenomena, the phenomena in (d) and (e) were both known to be present and are known to be sufficient to be contributory causes of both accidents. In fact, (e) has been identified as the most likely candidate by the NTSB TWA 800 investigators [16].

However, in neither case can these phenomena be the sole cause of the accident. In the case of TWA 800, the CWT eruption needed a combustible vapor with sufficient oxygen, a sufficient temperature to sustain burning, and an ignition source. The ignition source mooted in proposal (e) is only one of three joint causes. In the case of Swissair 111, electrical arcing is alone sufficient to have caused the fire that directly led to the accident. However, the cause of that arcing would not just be wiring defects, but whatever caused these defects: improper design, installation or maintenance, or a combination of all three.

Properly designed, installed and maintained aircraft wiring of that age and use factor should not be expected to exhibit defects.

Could it nevertheless be that external EMI, while not the cause of either of the accidents, was a contributory factor? Physically speaking, we can trivially observe that some influence is certain: any electrical field of any strength whatever contributed to whatever was going through the wires of N93119 and HB-IWK at the time. But little need be made of this, if the influence is negligible. Consider the following analogy. One can observe that a passing truck may influence our motion as we step off the sidewalk to cross the road. The truck has a gravitational field, which moves with it, and that gravitational field must have some tiny effect on our motion, but it would be foolish to consider it a factor in any misstep.

4.6 Summary

We have summarised JSC data, and NASA calculations, to explain NASA's refutation of Ms. Scarry's proposal (a), and a fortiori also (d). We then used this same data and analysis, along with data from a variety of other sources, to argue that external EMI did not cause the events known to have occurred to Swissair 111, via rigorous but highly conservative arguments. This refuted Ms. Scarry's proposal (c). We observed that the estimates of quantities used in this reasoning are likely to be some orders of magnitude different from reality in the conservative direction, just as NASA's best estimate for the induced field in the CWT FQIS wiring is some orders of magnitude different from their rough calculation based on bounding the total energy available at the location. These figures should therefore not be used as a realistic estimate of any sort of either the electromagnetic environment surrounding Swissair 111 or the size of that field needed to cause insulation fires in internal wiring.

5 Further Work

If better estimates of these quantities are needed, the following must be done:

- the available electromagnetic field environment in the vicinity of Swissair 111 should be requested from and determined by the appropriate military authorities;

- Experiments on wiring similar to those performed by Ms. Cahill should be run in order to determine what amount of energy is required to start an insulation fire in wiring bundles of the sort present in HB-IWK.

- Codes similar to those used by NASA should be run using dimensions and modes appropriate for the emitters identified, and an appropriately placed conductor in the model, to determine realistic values of the fields inside the hull;

Such models as one might obtain from such coding effort allow one to solve for different field strengths and different frequencies. When the coding has been accomplished and validated, one may then ask, on the basis of the results of the wiring experiments, what field strengths would be required to cause insulation fires. Only after this information is obtained would it make sense to go looking for those fields.

Those who are sceptical of obtaining correct information about transmitters may want to go looking for them, as Ms. Scarry proposes. But this has no pertinence to determining the causes of TWA 800's tank ignition and Swissair 111's wiring fire unless one knows what one is looking for; unless one knows the field strengths realistically sufficient to cause those phenomena. These calculations should be performed first. Then one can go looking for strong fields only if there remains any possibility that fields of the necessary strengths could exist.

A final point. The NTSB and FAA know they need to think long and hard about aircraft wiring, as a consequence of TWA 800 and Swissair 111. This is so, no matter what the causes of the suspected overloads that are the main causal candidates for TWA 800's and Swissair 111's accidents. This is a matter of urgency, affecting a significant portion of the worldwide commercial aircraft fleet. Please let us not distract this investigation.

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Some years ago, he numerically analysed the electromagnetic fields in the neighborhood of the laboratories in Bielefeld to gauge the effect of the proposed tramway to the university that is being built. The high-frequency fields are generated by the spark discharge often observed between the overhead wires and the current collector on the tram, and such fields can disturb measurement apparatus such as scanning electron microscopes and magnetic resonance spectrometers. As a result of his calculations, another configuration of the conductors was suggested and implemented, with the result that the fields can be compensated by a factor of 10 below 50nT.