CVR Recordings of Explosions and Structural Failure Decompressions

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Abstract

Rapid identification of the cause of failure is a high priority in the immediate aftermath of a major civil aircraft accident. Attention is often focused on the two recorders, the Cockpit Voice Recorder (CVR) and flight data recorder. In the event of sudden, catastrophic loss of an aircraft through explosions or structural failure decompressions, the recordings are seen as even more important. Yet these recorders are not designed to record such events with great fidelity and the ability of accident investigators to interpret such recordings has been severely tested in several major accidents in the past thirty years; comparisons between accident recordings have not been able to produce conclusive results. This paper reports on a programme investigating CVR recordings of explosions and rapid decompressions on a variety of aircraft from trials in several countries. In particular we show that CVR recordings are generally unable to discriminate between explosions and structural failure decompressions and we explain why this is so. We shall also put forward practical suggestions for systems that may be able to record these events with greater fidelity and which would provide investigators in the future with tools to locate the seat of the failure.

Introduction

The AAIB report [1] on the Pan-Am Lockerbie accident in December 1998 identified a loud sound lasting 170ms on the cockpit area microphone (CAM) track at the end of the recording. The sound occurred while the crew were copying their transatlantic clearance from Shanwick ATC. A very large volume of forensic material arising out of Lockerbie indicated that detonation of an improvised explosive device led directly to the destruction of the aircraft. While it is reasonably inferred that the 'loud sound' is related in some way to the detonation of the explosive device, the official report into the accident conceded "analysis of the flight recorders … did not reveal positive evidence of the explosion event." Moreover a safety recommendation arising out of the investigation was that "a method should be devised of recording positive and negative pressure pulses, preferably utilising the aircraft's flight recorder systems." Since the publication of this report a study into the CVR/CAM response to explosions and structural failure rapid decompressions has taken place and has been reported widely to Working Groups, such as ISASI WG50, EUROCAE ED-56, at conferences [2, 3] and to an ISASI Seminar [4]. More recently a loud sound at the end of the TWA 800 recording was subject to detailed and meticulous analysis by the NTSB but did not reveal the cause of the accident and was therefore of little diagnostic value. This aim of this paper is to explain why these recordings do not lead to useful forensic evidence and to consider what systems would be necessary to discriminate between explosions and structural failure decompressions and to locate the seat of the hull loss.

CAM/CVR recordings of explosions

Figure 1 (reproduced from reference [4]) shows the CVR and instrumentation signatures for an explosion event conducted on the ground in an ex-service BAe Trident aircraft. The plot shows the CAM channel of each of three tape-based CVR systems together with an accelerometer (vibration sensor) and a microphone (pressure sensor) installed close to the CAM for the trials. All sensors were in close proximity to each other in the cockpit and the explosion was approximately 9.4m aft of the sensor position. Time zero is the time of detonation of the explosive device – obviously this reference would not be available on an accident recording but is helpful here in the determination of the cause of epochs within the recording.

Several features are striking about this figure. First, the three CAM signatures have some similar features but are certainly not identical. The features that they share include a response commencing before 0.01s with a low amplitude and low frequency range (the graph is fairly smooth). All of them change character at around 0.025s increasing in amplitude and frequency range (the graph becomes more spiky). Interestingly the vibration record is similar although the vibration response amplitude falls soon after 0.035s whereas the record for CVR system 1 remains at a high level until 0.06s and high for the whole of the record for CVR 2, suggesting a possible saturation of the tape dynamic range. The pressure record differs from the others in that it only commences at 0.025s.

Similar results have been obtained from very many trials with explosive devices at many locations on several aircraft and the following explanation of the records described above may be inferred. First the blast wave from the explosion source impinges on the structure and a shock wave is then transmitted through the structure at a speed of 4000 to 5000 m/s. The CAM is sensitive to vibration and responds to the arrival of the structure-borne shock wave. Meanwhile the air-blast wave travels through the fuselage and eventually arrives in the cockpit. The speed of this wave is dependent upon the yield of the explosion but can be taken as the speed of sound in air of 340 m/s where distances are relatively large and yields are quite small. On arrival in the cockpit, the blast produces both a pressure response from the CAM but also produces further local vibration (as seen by the accelerometer) to which the CAM is also sensitive. The instrumentation microphone (bottom graph) responds only when the pressure wave arrives at the CAM and is designed to have very low vibration sensitivity.

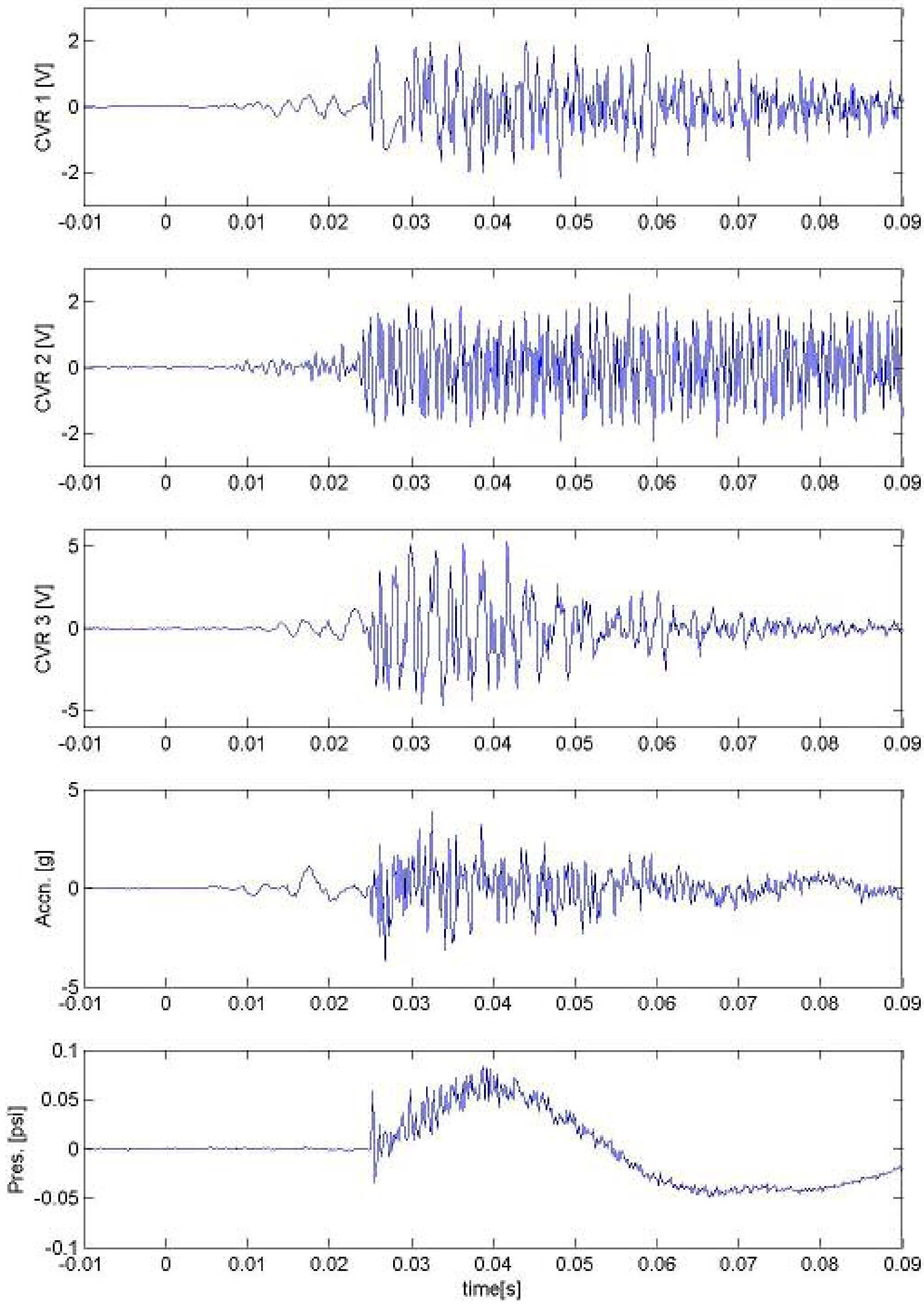

Figure 1: CVR and instrumentation signatures for an explosive device

Vibration Sensitivity

It is interesting that the CAM is quite sensitive to vibration. This phenomenon has been exploited in the past with helicopter gearbox investigations, yet the CAM is intentionally vibration isolated from the structure. The reason is simply that the vibration levels of a few 'g' are themselves quite high, not that the CAM or vibration isolation are poorly designed.

The results of all these trials appeared to show that locating the seat of an explosion event should be rather straightforward. One simply took the difference in arrival times of the structure-borne and air-borne shock waves and computed distance from this difference using values for the two propagation velocities. Formulae for this were given in [4] taking into account the possible delay caused by the propagation of an air-blast wave across the fuselage for a device not attached to the outer skin, so providing lower and upper bounds for the distance from the cockpit to the seat of the explosion.

However, accident recordings did not appear to show these two epochs with any distinction, so determination of axial location using direct application of this method was not possible. Moreover some trials with larger explosion yields also did not show the two epochs; the explosion response simply arrived and then decayed with time without distinct change in bandwidth or amplitude after the start. Analysis of the influence of explosion yield on the response components helps to explain why this is so.

CVR output related to explosion yield

Trials were conducted on a Boeing 747 aircraft using small yield explosions. The response was measured with five widely used commercial aircraft CVR systems including four tape-based systems and one solid-state recorder. For one series of firings the same source location was used each time but the mass of explosive was increased linearly from one unit to five units. The results, sets of time series, resembled the time series given in figure 1 so are not reproduced here. Instead, in figure 2, we show the peak-to-peak values for the two components in each of the recordings. Suppose we denote the time of arrival of the structure borne wave by t1 and the time of arrival of the air-borne wave by t2. Figure 2 shows the CVR/CAM response amplitude for $t1<t<t2$, i.e. the response due exclusively to the structure-borne shock. The figure shows that an increase in yield generally produces a greater CVR/CAM output.

Figure 3 shows the results for $t>t2$, i.e. the response after the arrival of the airborne blast wave including both sound and vibration. We observe that the amplitude of this response is not only greater than for the phase $t1<t<t2$ but is independent of the explosion yield. This implies that the physical parameter variation is greater than the

dynamic range of the recorder or that the sensors are overloaded and that the recording is saturated and probably highly distorted.

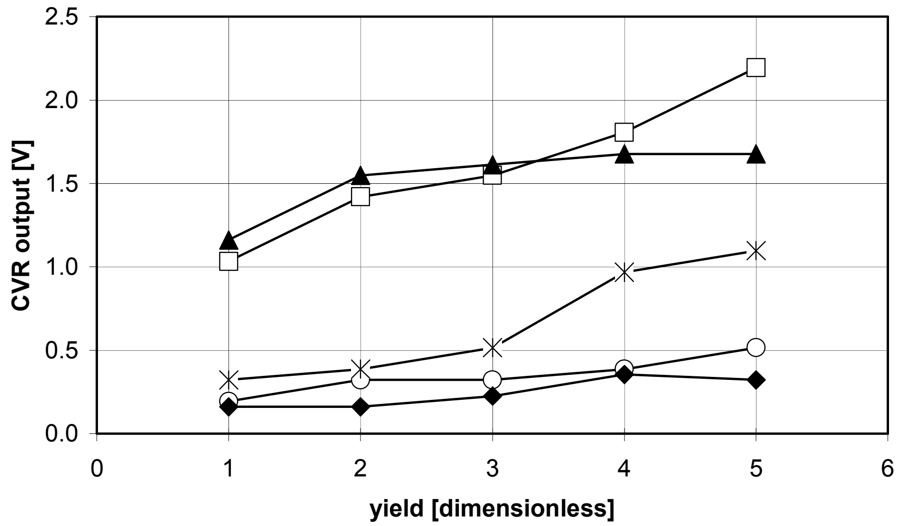

Figure 2: Variation in CVR output with explosion yield for t1<t<t2 for five different CVR/CAM systems. Each symbol represents one CVR type

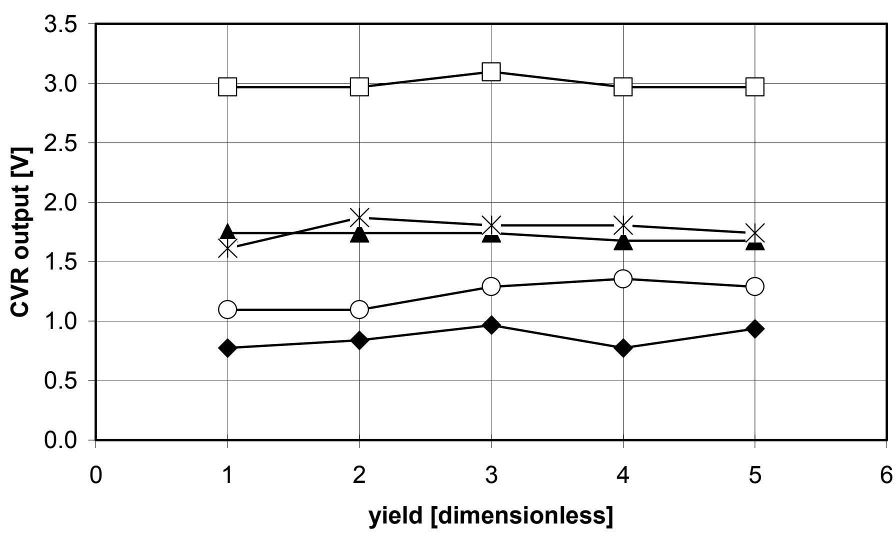

Figure 3: Variation in CVR output with explosion yield for t>t2 for five different CVR/CAM systems.

Figure 4 shows a CAM time history for a high-yield explosion on a pressurised Boeing 727 aircraft. The charge was approximately 8.1m aft of the cockpit; the explosion ruptured the skin of the aircraft. Clearly the CAM does not show a transition at t2. The time taken for sound to travel from the seat of the explosion to the cockpit is approximately 0.024s and the response clearly begins significantly before this. We infer that the response begins ostensibly at t1 but the magnitude already exceeds the dynamic range of the CAM/CVR so no change in signal magnitude is visible at t2. The record is therefore unable to show the axial location of the charge as was the case for smaller, non-destructive tests.

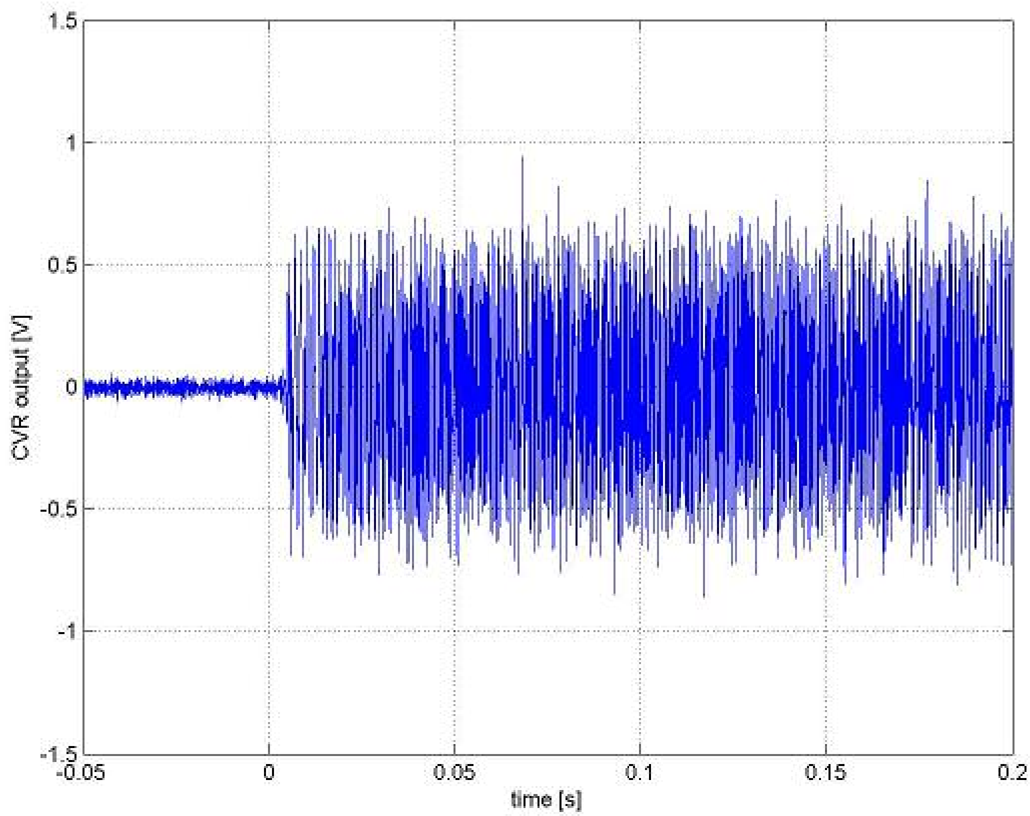

Figure 4: CAM time history for a high yield explosion
on a Boeing 727 aircraft.

The yields of all the explosions analysed in figures 2 and 3 are below the yield that might be expected from a terrorist device. If results from increased yield were produced, the response for $t1<t<t2$ for all recorder types would exceed the dynamic range and the recordings would be saturated as was the case in figure 4. There would then be no discrimination between the two phases of the response recording and the

section for $t>t2$ would be indistinguishable from $t<t2$. It is therefore not possible to use the method described above to locate the source for accident recordings.

One extensive study [5-8] has attempted to locate the seat of an explosion using the spectrogram of the CVR recording. The basis of the method is that the structural shock transmission is dispersive, i.e. different frequencies propagate at different velocities. However, the nature of the explosion source and complex multiple transmission paths severely limit the applicability of the theoretical basis. Operationally, the method required placement of a series of curves on an accident recording spectrogram with the intention that their curvature would indicate distance from the source to the CAM. Investigators found this aspect particularly problematic as several sets of curves could be drawn on any given spectrogram leading to ambiguous results. In one part of the study, spectrograms of several accidents were analysed in a blind test but were not able to confirm the validity of the approach. A recommendation arising from a review [9] at the end of the study was that the method should not be used in accident investigation.

The interval $t1<t<t2$ is due to structure-borne vibration which is likely to be produced at very high levels under both structural failure and explosion-generated conditions. In the case of an explosion, t2 is the arrival time of the blast wave at the CAM and in the case of a structural failure t2 is the arrival of the decompression wave at the CAM. Decompression waves travel at the speed of sound as with blast waves but are obviously of opposite polarity. Their propagation velocity and arrival at the CAM has been observed in various decompression trials. For both explosions and decompressions the CVR records are not high fidelity recordings of vibration as (i) the CAM is not designed as a vibration sensor but merely exhibits vibration sensitivity (which may be frequency dependent, non-linear and directionally dependent) and (ii) because the limited dynamic range of the recording medium and sensor are both (considerably) exceeded. Thus, the CVR/CAM combination is unable to locate the source of a decompression and seems to be unable to discriminate between explosions and structural failure decompressions.

Other transducers to detect explosions/structural failure decompressions

Among the instrumentation deployed in some trials were arrays of pressure transducers. These are effectively very low sensitivity microphones with corresponding low vibration sensitivity. Figure 5 shows the output of two transducers placed on either side (axially) of an explosion in a pressurised fuselage. Several features in these time histories are noteworthy. First both records commence with a pressure rise. The magnitude of an air-blast pressure rise is a function of explosion yield and distance from the charge and is widely tabulated [10,11]. The pressure rises occur at different times because the transducers are at different distances from the explosion source. The transducer closest to the charge shows the earliest and greatest pressure rise. The time delay between the two pressure rises can be used to determine the axial location of the device to within 0.5m. Secondly, both transducers show a pressure fall to a value significantly below the original ambient conditions. This is due to the breach of the pressurised fuselage. The rate of depressurisation indicates the size of the hole through which cabin pressure is venting. The precise form of the pressure curve (a series of pressure drops between short periods of relatively constant pressure producing a step-like appearance) has been explained by reference to one-dimensional flow models [2].

Interpretation of the results in figure 5 indicates that recordings of pressure from either side of an event appear to offer everything the investigator would seek namely:

- the location of the source (from the difference in arrival times)
- the presence of any explosion (indicated by an initial pressure rise)
- any decompression (indicated by a pressure fall)

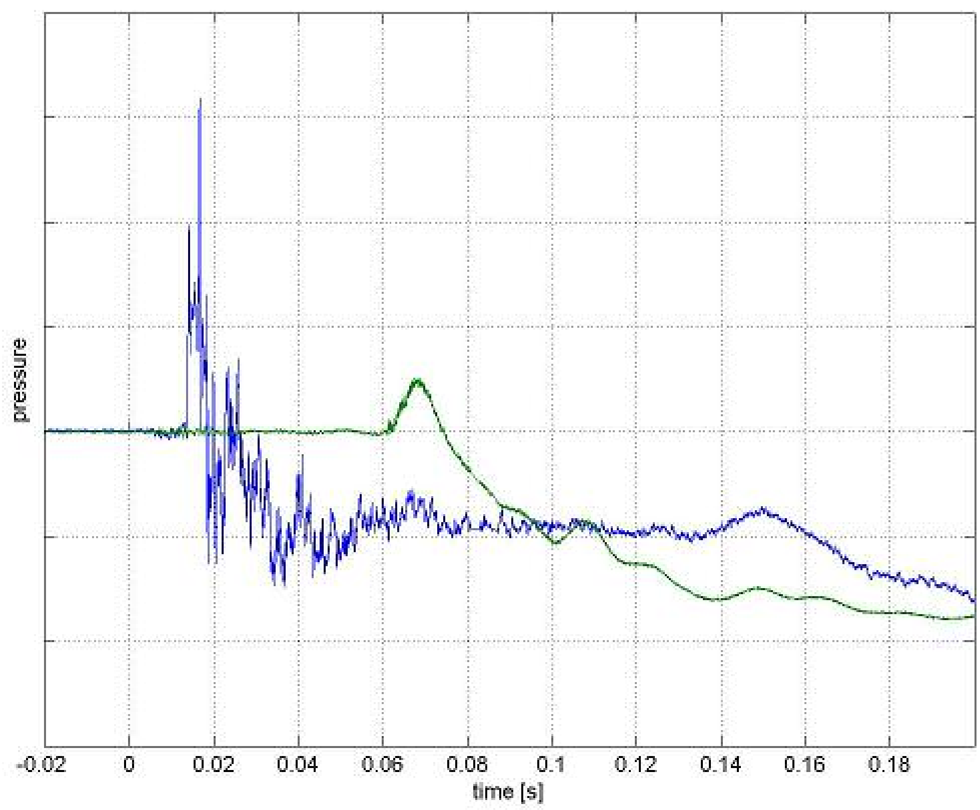

Figure 5: Recordings from pressure transducers placed on either side of an explosion in a pressurised fuselage.

Although this single result suggests that pressure transducer based systems may be widely applicable, trials are needed to consider the effect of baggage in the immediate vicinity of the explosive device, and of baggage and other barriers between the source and sensors. While vibration has the advantage that it is inevitably transmitted to all parts of the aircraft, it is ostensibly more difficult to analyse vibration records to locate sources. The likelihood of discriminating between explosions and structural failure decompressions from vibration records alone is not fully researched and certainly appears more difficult than the interpretation of pressure records.

Summary

We have seen that CVR/CAM records exhibit vibration sensitivity and that vibration is transmitted from the seat of an explosion/structural failure to the CAM. However, the level of vibration produced in accidents is so high that the dynamic range of the CAM/CVR is likely to be exceeded thereby masking the arrival of the explosion blast wave or decompression rarefaction wave in the cockpit.

It is appropriate to review all CVR recordings (of established provenance) of known explosions and structural failure decompressions. Such a review could confirm (or refute) the assertion that no transition at candidate values of t2 is visible. That is, the accident recordings correspond exclusively to vibration and not to pressure/sound. If so, accident investigators should be relieved to learn that the inability to obtain useful forensic information from the CVR in these cases is not a failing on their part but simply an equipment limitation.

The industry needs to consider if explosion/structural failure decompression sensors are required. If so, there is a need to invest in research to determine the most suitable sensor(s) and appropriate means of recording, possibly exploiting the flexibility now available through solid-state recording media.

Preliminary research suggests that pressure-based systems may be ideal in sudden catastrophic loss incidents, but trials are needed to consider the effect of baggage and other barriers between the source and sensor(s).

Acknowledgement

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