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A SYSTEMS APPROACH TOWARDS DEVELOPING DESIGN
REQUIREMENTS FOR ACCIDENT DATA RECORDER SURVIVAL

By

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DECLARATION

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ABSTRACT

This research has been conducted with the primary aim of devising methods for increasing the probability of survival of the recording media used in aircraft accident data recorders. Survival, in this context, is defined as having been fully achieved when the intelligence on the record medium is recovered without the necessity of special recovery techniques having been brought into play to take account of deleterious effects due to the accident environment. A considerable amount of statistical material relating to previous accidents has been used in this study and, from this material, an analysis of the value of accident data recorders in those accidents has been made. From this analysis a minimum survival rate of 98 per cent has been determined as acceptable. From the large number of accident cases studied it has been shown also that this minimum survival rate has not so far been achieved.

The basic approach used in this research towards a solution of the above problem has been to derive a conceptual model of the total system in which two subsystems have been clearly identified and studied. The first of these, the environmental subsystem has provided a means of determining the main sources of insult likely to be produced and the probability and significance of such insults being applied to the record module through degradation of the structure. The second subsystem, the record protection subsystem, has provided an indication of how an injury to the record module is likely to be caused by the above insults and how such injuries may be minimised by improvements in the design and installation of the record module.

Recommendations are made relating to improved requirements for the protection of ADR against crushing forces and against the effects of fire. Among other recommendations directed towards an improvement in survivability are also ones calling for changes in the siting and restraint of the equipment.

LIST OF ABBREVIATIONS

ADR	Accident Data Recorder(s)
FDR	Flight Data Recorder(s)
CVR	Cockpit Voice Recorder(s)
UK	United Kingdom
USA	United States of America
NASA	National Aeronautics and Space Administration (USA)
CAB	Civil Aeronautics Board (USA)
TSO	Technical Standard Order
ANO	Air Navigation Order
O.R	Operational Requirement
Ps	Probability of Survival
Po	Probability of Occurrence
Fs	Significance Factor
Ws	Significance Weighting
Wr	Relative Weighting
DTD	Directorate of Technical Development
D.Eng RD	Directorate of Engineering Research and Development
AVGAS	Aviation Gasoline
BTM	Bromotriflouromethane
BCF	Bromochlorodiflouromethane
CBM	Chlorobromomethane
CAA	Civil Airworthiness Authority (UK)
FAA	Federal Aviation Agency (USA)
FAR	Federal Aviation Regulations
TWA	Total Weight Authorised
FM	Frequency Modulation
PCM	Pulse Code Modulation

1. INTRODUCTION

This thesis describes research carried out by the author into the problems of survival, in accident environments, of aircraft accident data recorders and it attempts to resolve some of those problems by means of systems analysis.

Throughout the years between the Second World War and the present day continuous advances have been made in the field of civil air transport particularly in relation to aircraft size, performance and passenger carrying capacity. These advances have been accompanied by a very great increase in aircraft and systems complexity, a complexity directly related to the higher standards of reliability and safety demanded of modern civil transport aircraft. It is beyond dispute that the design, development and operating standards of these aircraft have shown continuous improvement in recent years, as a result of which higher levels of safety have been achieved and accidents rates significantly decreased. However, despite these improving standards, accidents will inevitably occur in the future and when they do it will remain essential that the causes of such accidents are established to prevent recurrence from similar causes.

As a step towards assisting in the determination of the causes of aircraft accidents legislation has been introduced in many countries calling for the installation of crash protected flight data recorders (FDR) in certain categories of public transport civil aircraft. This legislation was brought into being following

pressure from the accident investigation and airworthiness authorities of the countries concerned and was intended to provide an investigating tool specifically to assist in the investigation of accidents. The requirement to fit crash-protected flight data recorders was followed by a further requirement to record audio information on the aircraft flight deck also for use in the event of an accident and, as a result of the latter requirement, the legislation was extended to include the mandatory provision of crash protected audio recorders, more generally known as cockpit voice recorders (CVR) on which a record of such audio information could be held. Both the crash protected flight data recorders and the crash protected audio recorders are categorised as accident data recorders (ADR) and will thus be collectively referred to in this paper. . An historical summary of the use of the two types of ADR and the related legislation is given in 2.2.

It soon became clear that the effort and expense of developing complex recording systems for the primary purpose of accident investigation would be nullified if the recorded data could not be recovered from the recording medium and validated to an acceptable standard subsequent to an accident. A further obvious requirement for such recording systems was that the recording medium should survive in the expected accident environment and, to this end, mandatory standards relating to survivability have been laid down for the equipment.

The problems inherent in ensuring effective data recovery and validation were highlighted during the earlier years in which the recordings were put to the test in accident situations and, following a series of early recording failures, considerable effort was put into devising effective methods for ensuring that any data recovered from accident data recording systems could be properly validated and effectively used for investigation purposes. The results of an extensive period of research by the author of this paper into this aspect of data recovery are given in a thesis (1) and in a subsequent paper (2) produced in 1970 and 1973 respectively. Both these papers include references to the obvious need for ensuring adequate survivability of the recording medium in the extreme conditions of the accident environment and, because an early survey (3) confirmed that there had been a considerable number of failures to survive, the need for further research into this particular aspect became evident. This need was re-inforced by the knowledge that very little research into this particular area had previously been undertaken and that the laid down standards for survival had been largely based on arbitrary data.

The present thesis is the result of such further research principally conducted during the years following publication of references (1) and (2). It involves a systems analysis of the problems relating to survivability and should be regarded as complementary to the work described in those earlier papers. The research deals with civil aircraft applications only but many of the problems apply equally to accident data recorder survival in the military sphere.

2. RESEARCH DATA

2.1 Research Objectives

This research is directed towards the overall objective of increasing the probability of post-accident survival of the recording media used in aircraft accident data recorders (ADR).

The principal aim is to establish whether the present requirements for the protection of accident data recording media are adequate to ensure a satisfactory recovery rate of the data and, should these prove to be inadequate, to specify additional requirements and/or propose means by which satisfactory protection and an adequate survival rate can be achieved. This principal aim embraces the following related objectives:-

- (1) To develop a systems approach towards assessing the survivability problems relating to ADRs
- (2) To determine a minimum acceptable survival rate for the record media
- (3) To determine the current survival rates of those media
- (4) To establish whether the presently laid down standards for recording media protection are adequate to ensure the survival rate in (2) above
- (5) To establish what shortcomings in survival capability are evident, if any
- (6) To determine what improvement in standards may be required

- (7) To provide information from which possible design and operational improvements may be made
- (8) To define those areas in which further research or effort is necessary to improve standards of survival.

2.2 History of, and Legislation relating to, Accident data Recorders

Accident data recording systems largely owe their present forms to the continuous development of in-flight recording techniques for flight test, airworthiness and operational purposes.

During the early days of test flying manuscript notes of the aircraft's performance, taken in flight, often provided the sole record of data available for ground analysis. With the rapid advance of aviation technology, however, involving higher flight speeds and more complex aircraft this method soon proved to be inadequate for the many coincident and precise measurements required and the development of automatic recorders followed. In the United Kingdom these initially took the form of oscillographic recorders in which indicated airspeed, normal acceleration levels and, later, barometric height were continuously recorded, together with various types of 'auto-observers' in which a camera produced a photographic record of 'paralleled' flight instrumentation. Although adequate for the flight testing of some of the larger aircraft during the Second World War, this latter method soon proved to be too bulky and of too limited capacity for the extensive developments of the post-war years. The introduction of long duration continuous trace recorders followed. These were a general purpose type of recorder principally using a photo-

sensitive paper as the recording medium and were used successfully not only for flight test purposes but for a variety of in-flight recording work until about the beginning of the present decade. Up to that time, also, considerable advances had been made in the development of electro-magnetic recording techniques and this latter method of recording has now been generally adopted for flight test work. It has led to the introduction of complex systems which are capable of recording many millions of discrete measurements throughout the entire period of a flight. These more advanced recording systems are now in general use during aircraft manufacturers flight test programmes and have been the means of advancing the development programmes of many aircraft during recent years. The value of flight data recorders for airworthiness and engineering research programmes and for the study of operational techniques has also become widely accepted. In the performance and operational analysis field some United Kingdom aircraft operators commenced serious recording in the mid-1950s firstly with a programme concerned with engine performance and systems evaluation and then with a much larger programme in which the monitoring of flight performance data contributed to a study of flight procedures over the operators routes. During this time also some recording of similar data had been undertaken on commercial aircraft in the USA for the purpose of acquiring statistical knowledge of aircraft performance and handling. This programme was sponsored by the National Aeronautics and Space Administration (N.A.S.A) (4) and was later extended to include a number of British-registered aircraft.

The need for the recording of flight data for accident investigation purposes had been evident to many investigating authorities from an early date. The first Government Regulation requiring the carriage of flight data recorders on civil aircraft became effective in the USA in April 1941. Because of war-time equipment supply difficulties, however, the compliance date was at first extended and later rescinded. A new requirement was adopted in the USA in September 1947 but in July 1948 the US Civil Aeronautics Board (C.A.B.) rescinded the requirement a second time. In that year the French Air Safety Commission developed an interest in flight data recorders and a requirement was issued in December 1948 which led to the installation of recorders on a non-mandatory basis in certain French registered aircraft.

The mandatory installation of flight data recorders in USA registered aircraft finally became law on 1st August 1958 (5). The requirement called for the carriage of recorders in all US air carrier aircraft of over 12500 lbs maximum weight and certificated for operation at altitudes above 25,000 feet. The parameters to be recorded were indicated airspeed, pressure altitude, vertical (normal) acceleration, magnetic heading and elapsed time. The relevant Technical Standard Order (6) laid down specific standards to be met in respect of performance, range, accuracy and crash protection. On 15th October 1958 the French authorities introduced statutory requirements for the carriage of flight data recorders and these requirements were amended by regulation on 4th October 1963 (7) to extend the general conditions. The parameters to be recorded were similar to those adopted in the United States except that,

in addition, the recording of certain radio navigational parameters was required. The Australian Government first called for the carriage of flight data recorders in particular transport aircraft in May 1959 and this requirement was made legally effective from 31st May 1962. The requirement was extended on 1st January 1965 (8) to include all transport aircraft over 12500 lb maximum weight certified after 1st May 1959. The Australian requirements (9) were similar in most detail to those of the United States except that 'cockpit voice' recording (10) was added to the requirements at an earlier stage. Both the US and the French requirements were amended from time to time, the former notably to include 'cockpit voice' recording with effect from 1st July 1966 and for the installation of the flight data record container as far aft as practicable with effect from 15th December 1967.

The first requirements for the carriage of flight data recorders in United Kingdom registered aircraft were introduced by an amendment to the Air Navigation Order 1960 (11). The first operative date for this legislation was 1st May 1965. Under the above Order carriage of recorders was mandatory to UK registered civil aircraft certified in the Transport category which were turbine-engine powered and over 12500 lb maximum weight or which were piston-engine powered of over 60,000 lb maximum weight. Details relating to the equipment were specified in an associated Operational Requirement (12), the parameters to be recorded being common to those specified in the US Regulations but, additionally, recording of the pitch attitude of the aircraft was required. Since they were first introduced the UK statutory requirements have significantly changed in terms of aircraft categories affected,

information required to be recorded and in crash protection standards. Details of the most important changes relating to aircraft categories and the required data for UK registered aircraft are summarised in Appendix E of Reference 1. A significant addition to the UK requirements occurred when, by an amendment to the Air Navigation Order 1972 (13) the mandatory installation of cockpit voice recorders was called for on certain UK registered aircraft. This requirement was amended to extend its compliance effectively from 1st January 1976 (14).

Many other countries have more recently introduced legislation requiring the carriage of FDR and CVR on aircraft registered in their territories, the requirements for their operation differing in some detail from country to country at the present time. Within the statutory requirements of all the countries requiring the carriage of ADR on their aircraft, however, the relevant regulations specify in detail crash protection requirements for the record media.

The first protection requirements laid down for the United Kingdom recorders stipulated that the recorded data shall be capable of intelligible analysis to within the overall specification requirements after the protection record medium has been subjected to each of the following tests:

- (a) An impact shock of 100 'g' applied at the attachment points
- (b) A static load of 1 ton applied in any direction
- (c) Exposure to flames of 800 deg C over 50 per cent of the surface area for a period of 15 minutes the recorder being allowed to cool naturally after such exposure.

Other protection requirements regarding resistance to water and other fluids were also laid down.

The initial protection requirements demanded in the USA (6) were more stringent than those of the UK, particularly with regard to the temperature test where the recorder had to be capable of being analysed after the recorder had been exposed to flames of 1100 C for a period, depending on recorder type, of up to 30 minutes, where impact shocks of 1000 'g' had to be sustained and where an additional penetration test had to be met.

Changes were subsequently introduced in the UK protection requirements for FDR bringing them more closely in line with those of the USA. The statutory protection requirements for CVR in the UK and USA differ, however, from those relating to FDR. The most recent US protection requirements have now been adopted by many countries as a general standard for their own legislation. Details of the current USA and UK statutory protection requirements are given in Appendix A.

It will be noted that the regulations referred to above lay down requirements for crash 'protection' ie the ADR is expected to survive the probable hostile environment of a crash as opposed to being provided with means to escape from it. The relative merits of these two alternative design philosophies will be discussed in ANALYSIS (3.1).

2.3 Types of Accident Data Recording Systems currently
in use

Three principal methods of recording have been employed in ADR systems up to the present time. They are:-

- (1) Photographic recording. With this method displacement of light beams, related to the data inputs, produces analogue traces on photo-sensitised paper.
- (2) Oscillographic engraving. In this type of recorder metal foil is used as the record medium on which electro-mechanically operated styli engrave either sampled or continuous traces representing each input measurement.
- (3) Electro-magnetic recording. This represents the most recent and advanced method of recording. In such systems both analogue and digital recording techniques are used. Of the former, frequency modulation (FM) methods are normally employed using plastic based magnetic tape as the recording medium. The earlier types of digital recording systems principally used pulse code modulation (PCM) techniques to produce digital data on steel wire although more recently developed digital systems use either steel or plastic based magnetic tape as the recording medium.

Most of the early ADR were of a long duration type which required removal and replacement of the record cassette when the data record became full. Later systems however, employ a recorder of the recycling type on which a constant amount of information is stored and on which continuous recording takes place concurrently with erasure or 'overwriting' of the

'first recorded' data. Many recycling types of data recording systems have a facility for parallel recording of the data on a second non crash-protected recorder from which the record medium may be readily removed for replay. The data capacities of all types of ADR systems are designed to ensure compliance with statutory data storage periods.

Of the above types of data recorder both the photographic types and those using metal foil have been in use for many years, many of the latter still giving wide service. Both types have a very limited development or expansion capability however, and most now be regarded as obsolescent. The more recently introduced electro-magnetic systems for accident data recording were first installed in British civil aircraft in 1965. Other countries, notably the USA, followed the UK lead some years later in adopting this method of recording for ADRs and it is now universally regarded as the most satisfactory basis for present and future systems. Such systems are complex and generally comprise a number of subsystems including sensors and transducers, power supplies, signal conditioning systems, multiplexing circuits, modulation and analogue to digital conversion stages and a recording system, the recording element of most electromagnetic systems being housed in a separately protected module. Recording of the output signals in these systems is carried out on a magnetic medium which, in the case of FM systems, is normally plastic based tape and, in the case of digital PCM systems, may also be plastic based tape or alternatively may be steel wire or steel tape. Changes in the design and operating requirements of ADR

systems have already become evident, much greater data capacity than hitherto called for now being required. Such changes often dictate the recording media required and the magnetic tapes, either steel or plastic based, have already superseded wire in many cases because of their greater data packing capability. The principal recording modules now in use in civil transport ADR contain the recording media either permanently installed on recycling spools or in removable cassettes. The former types are all electromagnetic systems and utilise either the plastic based tape, steel tape or steel wire as the recording medium having a recycling period of at least 25 hours. The types using removable cassettes include those using long duration steel wire (200-300 hours) and short and medium duration plastic based tape (7-125 hours) for electromagnetic recording, long duration metal foil (200-500 hours) for the oscillographic recorders and medium duration photosensitised paper (50-125 hours) for photographic trace recorders. The crash protected modules of CVRs also operate on the recycling principle, currently having a 30 minute recycling period only and utilising plastic based magnetic tape as the recording medium.

The design of the recorder module and the choice of recording medium used in ADR systems must be approached from two equally important points of view, firstly that of recording performance and secondly that of survival of the medium. The factors relating to recording performance have been

discussed in reference 1. The characteristics of the recording media and the present methods of module protection will now be examined.

2.4 Recording Media Used

As referred to earlier the media currently used for accident data recording falls into three main categories which are related to the three basic recording methods:

- (a) Photosensitised paper for photographic trace recording
- (b) Metal foil for electro-mechanical oscillographic recording
- (c) Steel wire, steel tape or plastic based tape for electro-magnetic recording

The first two types, being of an obsolescent nature, will only be considered in general terms because further developments of recorders using these media are unlikely.

The ADR using photosensitised paper as the basic recording medium were developed from similar types of recorder used for flight test purposes, the data image being formed by the application of light beams projected by galvanometer controlled mirrors on to the medium. The efforts to convert the initial flight test recorders into the ADR role at once highlighted the poor survival characteristics of the medium

and the difficulties of introducing adequate modifications to the recorders particularly in terms of fire protection. The photosensitised paper has very low resistance both to tearing and to moderately elevated temperature in addition to its requirement to be protected against the ingress of light. The inherent problems in using this medium for ADR has resulted in its extremely infrequent use for this purpose at the present time and for this reason it will be given limited further discussion.

The media used for electro-mechanical oscillographic recording take the form of metal foils stored on cassette reels within the ADR and which, by means of a time controlled transport mechanism, enable mechanical styli to impress input referenced data on to the surface of the medium. The metal foils used in these recorders fall into two categories, those using aluminium and those using forms of stainless steel as the basic material. The aluminium foils were introduced because their softness permitted continuous trace scribing to be easily achieved. The aluminium foil is normally approximately 57mm in width and 0.025mm thick with a melting point of approximately 640 ° C. Its vulnerability in crash situations was soon demonstrated, however, as its intolerance of high temperatures and its propensity to distort or tear makes it difficult to provide adequate protection. The relative plasticity of the material may also permit damage to the medium by the styli to take place due to applied accelerations during an accident sequence. The foils manufactured of alloy steel were developed because improved methods of recording using hardened styli which

indented the material by a 'pecked sampling' method enabled much harder materials to be employed. These foils are normally 125mm wide and of nominal 0.025mm thickness. They have a hardness of approximately 42.5 Rockwell and are considerably more resistant to impact damage than the aluminium foils although they remain vulnerable to tearing and, to a lesser degree, to acceleration damage. Their resistance to elevated temperature is very much greater than other oscillographic media, their melting point being approximately 1480 C. Because of the latter property ADR using this medium do not utilise additional fire protection material and are designed to rely entirely upon the fire resistant properties of the medium itself. As all types of oscillographic recorders are now becoming obsolescent for the purposes of accident data recording only limited further discussion of the media used in these types of ADR will be given.

Electro-magnetic methods of recording now predominate in most airborne data recording areas including that of ADR.

Stainless steel wire and, subsequently, stainless steel and other alloy metal tapes were initially introduced for the magnetic recording of digital data in ADR because their mechanical and temperature resistant properties are much superior to those of plastic based tape. The stainless steel wire currently used for magnetic recording is normally of between 0.05 and 0.75mm thickness. It has a Curie point of approximately 570 C and tests have shown that an acceptable signal is recoverable after the wire has been heated to

450 C. The metal tapes used for recording digital magnetic data are normally of stainless steel but some metal tapes are available which are alloys of vanadium, iron and cobalt. The metal tapes have an approximate thickness of 0.025mm and a width of 12.5mm. The steel wire and metal tape media have some distinct advantages from the point of view of resistance to damage in an accident environment but their recording characteristics are in many cases inferior to the plastic based tapes available. A comparison of some of these characteristics is given in reference 27. Although the metal alloy recording media are in wide use in present day ADRs, their limitation in terms of recording properties have brought a more general return to the use of plastic based tapes despite their greater vulnerability. The latter are almost universally used in CVR.

The plastic based magnetic tapes used in ADR are normally of 12.5mm width and although the base film thickness can vary between tapes of different manufacture it is normally about 0.035mm. The tapes commonly used in CVR are of the same width and of similar thickness. The tapes consist of a dispersion of magnetic oxide particles in a plastic binder system coated on to a flexible plastic substrate base. The most common magnetic material is gamma ferric oxide (Fe_2O_3) but chromium dioxide (CrO_2) is also frequently used. The latter material possesses superior magnetic properties giving a shorter wave length response and higher information packing density. It more rapidly loses its remanence at elevated temperature, however, and has a Curie point of approximately 125 C at which temperature total loss of signal

occurs. The base film materials used vary, derivatives of polyvinylchloride, polyimide and polyester are frequently met, the two last named being most common. Most of the polyester tapes are polyethylene terephthalates. The polyester tapes may be subclassified as tensilised or untensilised the latter being subjected to less stretching in the manufacturing process which provides a lower propensity to shrink when subjected to elevated temperature at or around 60 C. Polyimide tapes on the other hand only commence to shrink at or about 100 C.

2.5 Methods of Recorder Module Protection Currently employed

No specific requirements are laid down by regulation either regarding the nature of the recording media to be used in ADRs or of the methods to be used to achieve the levels of protection required. In consequence the basic protection philosophies employed in ADR module manufacture vary considerably. These variations are most evident in the design concepts employed to resist mechanical crushing and impact penetration, exposure to fire and elevated temperatures, and to immersion in, or contact with, contaminating fluids or other chemicals.

The recording medium is normally retained on some form of spooling device within the ADR and, as the medium is the sole element of the ADR required to survive, the protective element is in some cases confined to the medium only. Many oscillographic recorders which use stainless steel foil as the recording medium have heavily armoured casing for the foil spools only. As stated

earlier the fire protection aspect of these recorders relies entirely upon the fire resisting properties of the medium itself. Most ADR, however, have impact protection in the form of a strengthened outer case for the entire module, the armoured protection in many cases being of an alloy steel or titanium, a typical skin thickness of the latter material being about 3mm. The overall size and shape of the armoured element varies considerably and this has a strong bearing on survival in certain conditions. Protection against fire and elevated temperatures frequently takes the form of a thermal blanket enclosed within the armoured case, the material for the blanket varying from asbestos and laminated composites of that material to a number of commercially produced refractory materials. Material thickness of the blanket may vary between 2mm and 15mm. An alternative fire protection method more recently employed is the ablative method in which the medium is enclosed within a liquid jacket designed to be dissipated under controlled conditions at elevated temperatures. The liquid consists of water with certain additives and, under increased temperatures, steam is generated which, when released through blow-off plugs, progressively dissipates the high temperature.

In the past some manufacturers appear not to have taken the need for protection adequately into account during the early stages of module design. As a result protection consists, in many cases, of an outer envelope often of less than optimum size, shape or effectiveness. Other manufacturers, however, provide a module protective shell, frequently with a higher

shell/recorder volume ratio in which greater prominence has been given to the protective aspects at an early design stage. The relative merits of the differing protective methods will be discussed in 3.7.

2.6 Definition of Survival

Before an evaluation can be made of the ability of an accident data recorder medium to survive, it is necessary to define the term survival in the context of the use to which the medium is to be put.

The basic purpose of the medium is to provide a permanent record of intelligence and survival must therefore relate to the ability to achieve a defined measure of intelligence following specific accident circumstances. From this it follows that an acceptable level of intelligence must first be established. This acceptable 'defined measure of intelligence' could be either (a) that intelligence which is recoverable from the medium by normal processing methods or (b) that intelligence which is recoverable by specially developed recovery techniques.

The use of special recovery techniques may be necessary in one or other of the two following sets of circumstances.

- (1) Where the recorded information has been degraded because of some mechanical or electronic defect in the recording process.

- (2) Where the recorded information has been degraded because of some environmental influence associated with, or as a result of, the accident.

As (2) above is indicative of a failure or partial failure of the crash protection capability, whereas (1) above is not, the defined measure of intelligence acceptable in determining survival criteria will be expressed as :- 'That intelligence recorded on the medium which is either recoverable by normal processing methods or by such special techniques as may be devised to recover or reconstitute intelligence incorrectly recorded'. Survival may be considered complete therefore when the above defined measure of intelligence has been recovered from the record medium subsequent to an accident.

Although, in those cases where the recorded information has been degraded because of some environmental influence associated with the accident, every attempt would be made to recover the data by the most suitable method available, it must be accepted that the use of such special methods of recovery should not in any way influence the basic design criteria for survivability.

2.7 Acceptable Rates of Survival

Before standards for survival can be laid down and before design criteria for the protection module can be established it is necessary to consider what minimum rates of survival can be accepted. The following alternatives may first be considered:

- (1) Intelligence on the record medium should be recoverable following exposure of the protective module to a defined series of injury parameters.
- (2) Intelligence on the record medium should be recoverable following every conceivable accident circumstance ie Survival probability (P_s) = 1.
- (3) Intelligence on the record medium should be recoverable with a probability $P_s = a$ where a is a figure based on the probability b of the accident being in a category in which the aircraft sustains substantial damage.
- (4) Intelligence on the record medium should be recoverable with a probability $P_s = x$ where x is a figure based on the probability y of the data being of significant value to the investigation.

In considering these alternatives it becomes clear that (1) above must be treated as a derivative of (2), (3) or (4) as the injury parameters can only be defined following an assessment of (2) or of the probabilities of (3) or (4).

In considering (2) above it is obvious that such a level of survivability ideally satisfies the requirements of an investigation and may well be used as a design objective. Nevertheless it must be recognised that such an ideal aim may never be achieved in practice and that some lower achieved level of survivability may be judged acceptable.

In considering (3) above it becomes clear that this is not an acceptable basis on which to determine survivability levels because by using this criteria the frequency of survival is not in any way related to the anticipated need to recover data. ADR are, in effect, tools designed to be used for a specific purpose and their efficiency, within which term survivability falls, should not depend upon their anticipated frequency of exposure to hostile environments.

In considering (4) above, the argument for requiring this level of survivability would at first sight appear to be sustainable in a generalised sense. However, it would seem that although very few cases can be quoted when the data recovered from ADR are of no value to the investigation there will be some instances in which the data will be a limited value only. These latter instances will nevertheless be infrequent and it is considered that the existence of this limited value data should not be used as an argument for lowering the probability of recovery in the predominantly more frequent cases when the data proves to be of higher significance. It is considered necessary, therefore, to include both the latter and the less significant data cases if this criterion is to be used and, if possible, to quantify these. Case (4) above would now realistically become 'Intelligence on the record medium should be recoverable with a probability $P_s = x$ where x is a figure based on the probability y of the data being of value (any value) to the investigation'. This level of survivability is proposed in this thesis as the most reasonable basis from which to develop a design philosophy relating to survivability. Furthermore based on the statistics

later examined it applies much more stringent criteria than any alternative related to the frequency of aircraft damage. From this the fundamental question is raised: "How many instances are likely to occur in which the data will have no value?". This question has been examined in relation to all the accidents in Group A of section 2.11 and it is concluded that in 4 per cent of the accident cases examined the recorded information would reasonably not have been required. From this a minimum acceptable survival probability level $P_s = 0.98$ may be derived where $x = y^{\frac{1}{2}}$. At first sight this is a very demanding standard and one which clearly approaches the ideal design objective in (2) above. It is considered, therefore, that the latter objective should still be regarded as a design aim with the survival probability level of $P_s = 0.98$ being retained as a minimum acceptable standard. Having established a minimum acceptable level it will be necessary to define the nature and limits of the injury parameters to be used for acceptance purposes to ensure that this required survival level is achieved. This is later discussed in 3.7.2 and the associated following sections.

2.8 Requirement for a Systems Evaluation

Every aircraft accident is a unique occurrence and, in itself, consists of a series of events during which the aircraft structure is transformed from its initial designed state to one of lesser integrity which may vary from a post-crash condition involving minimal damage to one of total disintegration. The forces and interactions introduced during the crash sequence, therefore, are often too complex to quantify in anything but a limited and generalised way and consequently any attempt to

establish in numerical terms the levels of these interactions and their effect on an ADR protective module is likely to prove impossible on all but some limited number of occasions involving 'simple' accident sequences. In order to assist towards improving the design capability of ADRs to survive the foreseeable crash environments it was considered, therefore, that a more generalised approach involving some form of systems analysis of the total crash environment might well provide information from which useful progress could be made. This generalised study would include a comprehensive view of all the interacting elements and from this it was hoped to identify and explore those areas requiring further investigative or experimental effort so that future design parameters could be more soundly based.

2.9 Methodology

Before developing this systems study it was necessary to consider the methodology to be adopted in the evaluation of ADR survival problems. A first consideration of the factors involved showed a need to identify the major elements of the crash environment and to develop an appreciation of their combined effect on the aircraft structure within which the ADR is housed. The following alternative approaches were considered:

(a) Mathematical approach

An initial examination indicated that it would not be possible to construct a mathematical model to satisfactorily represent the conditions relating to this problem. The mechanics of failure of an aircraft structure in the accident situation are

both highly complex and unique to the particular accident. Once failure of a primary structural element or elements has occurred the complexity of the stress paths in the structure in a uniquely loaded condition prevent any normal failure theories from then being applied. Furthermore, as any failure theories would be invalid once an element has yielded, calculation of element stresses would only be of value in identifying the initial points of failure. Although mathematical techniques have been applied in the past for examining the most basic forms of cabin crushing dynamics and for making assessments of passenger cabin integrity in crash situations (15) (16), a simplistic view had to be taken in these cases, all of which relate to low speed impact conditions. In attempting to apply mathematical techniques, however, to the problems of ADR survival in higher speed impact situations often involving complex break-up of the aircraft, the structure would need to be idealised to such an extent and the determination of the combined stresses in the related elements simplified to such a degree that the results would clearly remain unrealistic. It was considered, therefore, that mathematical techniques could not reasonably be developed for use in this systems study.

(b) Conceptual Approach

A conceptual approach was considered to be very valuable in identifying the most significant elements of the system. It appeared reasonable in this instance, therefore, to produce a conceptual model of the crash environment from which the

predominant factors could be isolated for further study. Such a study would enable the interdependence of these factors to be more fully assessed and, given adequate data, for a statistical evaluation of their relative importance to be undertaken.

A conceptual model has been developed, therefore, to be used as a central part of this research.

(c) Experimental Methods

Experimental methods have been used on a limited scale in the past (17) (18) to obtain crash environmental data. Such tests have necessarily been restricted to certain simulated flight and crash conditions and have sought to obtain information relating to fuel containment, flight deck environmental data, cabin seating and restraint data and other occupant survival parameters. As such they provide a useful insight into low speed impact conditions, the structural outcomes in the experimental cases being not dissimilar to the low speed impact examples within the Group A accidents studied (paragraph 2.11).

(d) Use of factual data

The data in this study have two main elements. The first element consists of statistical data derived from recognised authoritative sources and the second includes data directly derived from actual investigative experience in which the author has been involved. In many cases the data used is common to both categories.

Although any statistical approach has limitations, such an approach is often useful in exploring the predominant areas of a problem. A statistical approach, however, can only be valid if the statistics used are adequate both in terms of

numerical samples and in information content. It has been difficult for some researchers in the past to use statistical data relating to aircraft accidents principally because the general statistics then available did not contain sufficient detailed information for their needs. This difficulty arose when the initial standards for survival of ADRs to be used in the United Kingdom (12) were drawn up. However, very considerable experience has been gained during the past ten years relating to this question, experience which can provide additional data for evaluation. Much of this additional information has been used to provide statistical data for this paper.

As indicated above, experience in the use of ADR has increased very greatly over the past decade. The use of data derived from the investigation of aircraft accidents enables the effects of those accidents on the ADR to be directly assessed. Additionally the information recorded on the ADR can be used to advantage by providing a more comprehensive picture of the impact circumstances involved in terms of time, impact speeds, impact angles and attitude changes. This unique facility whereby the equipment can monitor and record parameters relating to its own survival capability is considered to be of extreme benefit in this type of study and has been extensively used.

(e) Independent Critical Appraisal

Although the value of an intuitive approach must remain doubtful in many cases, the benefit of independent critical judgement must be recognised in those instances where the level of experience is high. On this occasion the level of experience of the

author in this specialised field is very extensive having not only included direct responsibility for the recovery of information from ADR in 78 cases of civil aircraft accidents since their fitment became a statutory requirement in the United Kingdom in 1966 but has also included responsibility for the total wreckage analysis activity in some hundreds of aircraft accidents on a world wide basis during the last 25 years. Therefore, although the use of independent judgement would not be considered reasonable as a primary method, it has been extensively drawn upon, because of the author's particular experience, as a supplementary approach in this paper.

(f) Method Adopted

Having considered the alternative approaches available for this study it appeared clearly beneficial to adopt a multiple approach to the problem. It was decided, therefore, to derive a conceptual model of the system and by developing this further using factual data, both direct and statistical, to determine those elements which predominate in the system. From such a basis it was deemed possible, by using critical judgement, to determine the relationship between significant inputs in the form of 'insult' parameters and the system 'outcomes' both in terms of structural degradation and ADR injury so that those areas demanding improvement in standards or design could be identified and, where possible, practical solutions developed. Experimental data and other supporting information have also been used where appropriate. The direct data used are taken from accident cases with which the author has been either associated or directly involved. The remaining statistical

data are drawn from a wider field and are more fully identified in 2.11 and Appendix B.

2.10 Conceptual Model of the System

A conceptual model of the Crash Environment System for accident data recorders is shown in Figure 1. This figure is drawn non-conventionally with some of the active elements 'boxed'. This form of presentation more clearly indicates the dynamic elements involved. Other figures referred to in this paragraph will be drawn conventionally. From Figure 1 most of the significant variables in the crash system are readily identifiable and the general concept of their interaction becomes apparent.

Having identified the significant influences in the system it is necessary to classify the variables involved. Because the data examined involves a variety of aircraft types, such factors as aircraft mass volume and disposition of high mass items have been categorised as discrete variables instead of initial states. Likewise, as the types of recorder being used and their location features are not standardised, these will also be treated as discrete variables in the system. The variables are classified as follows:-

(a) External independent variables:

- | | |
|----------------------|-----------------------------------|
| Continuous variables | - Initial velocity |
| | - Angle of Impact. |
| Discrete variables | - Characteristics of
Terrain:- |

Presence of Obstacles
Penetration Potential.

(b) Internal independent
variables:

Continuous variables - Initial total energy of
the aircraft related to
potential and kinetic
energies

Supplemental energy due to
explosive release

Discrete variables

(Non-controllable)

- Aircraft mass volume

Disposition of items of high
mass

Type, quantity and disposition
of fuel

Sources of ignition

Discrete variables

(Controllable)

- General location of recorder
unit

Location of recorder relative
to other items

Restraint of recorder

Recorder protection
capability

(c) Dependent Variables

- Deceleration of structure
along axis of impact

Structural distortion

Structural disintegration

Acceleration and/or deceleration of released items

Acceleration and/or deceleration of recorder

Release of fuel

Ignition of fuel

Location, extent and duration of fire.

Examination of the above factors and their inter-relationships shows that the products of the crash system are largely reflected in the dependent variables. Additionally, many of the factors affecting the impact injury case may be substantially separated from those affecting the fire injury case. However the central presence of the acceleration/deceleration variable in the system shows that this variable has a strong influence in both these cases. Furthermore this dependent variable is so related to the independent variables of velocity, impact angle and total energy as to make those parameters ones worthy of primary study. Whereas the total energy of the aircraft in the pre-impact situation is a summation of its kinetic energy related to velocity and its potential energy related to height, the post impact situation may well be modified by a change in total energy due to the effects of fuel explosion at any point in the crash system. This inter-relationship demands that the factors associated with ignition and fire development are also considered of primary importance.

An examination of the model shows that circumstances may occur where the record medium is never recovered. This may be because the recorder is not retrieved from the accident site or because the aircraft itself is totally lost. An example of the latter case is where an aircraft is not recovered from the sea. This aspect of total loss will be referred to later in 3.7.2.4.

The conceptual presentation in Figure 1 provides a means whereby the uncontrolled influences, as far as ADRs are concerned, may be separated from those which are controllable and thereby enables an aircraft environment subsystem and a record protection subsystem to be individually identified. These subsystems are shown in Figures 2 and 3 respectively. It will be seen from these figures that a number of variables are of a dichotomous nature so that a binary output can be presented in such cases. This presentation more readily enabled a statistical analysis to be applied to these variables and their significance to be more clearly studied.

2.11 Use of Statistical Data

Three main groups of statistical data have been used in this analysis. They comprise information obtained from:-

Group A - A group totalling 954 accidents involving United Kingdom registered aircraft in the period August 1971 to November 1976.

Group B - A group totalling 62 accidents to large public transport aircraft in the period May 1966 to October 1976 in which the United Kingdom authorities either controlled or participated in the investigation.

Group C - A further group totalling 78 other accidents to large public transport aircraft in the period October 1965 to December 1977 in which the United Kingdom authorities either controlled or participated in the investigation and were responsible for recovering the data from the ADR.

The above statistical groups are identified in Appendix B. The information derived from them comprised the following:-

Group A provided information concerning the nature of the impacts involved and the structural outcome together with an assessed value of an ADR to the investigation, whether or not one was fitted to the aircraft.

Group B involved accidents to large aircraft in which more information relating to the input parameters and structural outcomes was available for study in greater depth.

Group C provided the most detailed and most significant data in that almost all the parameters of the conceptual model were available for analysis.

2.12 Relationship of Conceptual Model to Statistical Evaluation

An examination of the influences within the conceptual model enabled the most significant requirements of the statistical

evaluation to be determined. In general terms it was found necessary to examine the many variables involved and to evaluate the extent of their influence on the insults applied and the injuries sustained firstly to the aircraft structure and secondly to the protected recorder module. An evaluation of the independent variables previously identified comprised the basic data used for an analysis of the inputs to the system. The products of the crash system are, as described earlier, largely reflected in the dependent variables. The values of those variables were, therefore, further elements of the statistical data necessarily required. The discrete variables were found to provide a number of influences within the system. Many of these influences are non-controllable in that they are either influences external to the aircraft or, where they are not, they are fixed in relation to the aircraft type. The influence of these discrete variables has been separately considered.

3 ANALYSIS

3.1 Basic Approach to survival of ADR media

Before design standards for ADRs can be laid down it is necessary to consider the two basic approaches which may be applied to accident data recorder media survival and to decide which approach provides the greater advantages from the viewpoints of safety, efficiency and cost. As indicated in section 2.2 all civil legislation relating to ADR calls for resistance of the module to specified environmental hazards from which the present designed standards of protection are derived. Consequently all ADR for current use in civil aircraft have been developed within the protection concept. However,

in earlier days of civil ADR development and, in some instances, in the current military sphere the concept of ADR escape from the hazardous environment of an aircraft accident site has been utilised. The escape philosophy was first advanced in civil usage by developing some form of ejection system for the ADR module so that the recording medium could be thrown sufficiently clear of the crash site to ensure survival. Early designs used an explosive ejection system for this purpose. Explosive ejection systems, however, do not meet the general airworthiness standards laid down by regulatory authorities because of the inherent risks of inadvertent or otherwise faulty operation and the development of such systems has now been discontinued. Concurrently with the above some design work took place towards providing release of the ADR module from the aircraft in circumstances where the aircraft crashes into the sea. One such system involved the use of a pressure controlled pneumatically operated ejection mechanism but the problems of structural distortion in conditions of sea impact prevented development of a satisfactory system. Likewise another system in which the ADR module was designed to be mechanically released from the extremity of the aircraft tail made no significant advance and all the above types of system involving either explosive ejection or underwater release have now been abandoned for civil use.

One further type of escape system has reached a significantly advanced state of development, however, and is in current use in certain military aircraft. This is known as the aerofoil

separation system. It operates on the following principle: A data recording module is fitted within an aerofoil package installed on, or flush with, the rear fuselage or tail structure of the aircraft. The aerofoil is designed with a lift/drag performance aimed at ensuring that the aerofoil is carried away from the aircraft under aerodynamic loads following initial ground impact of the aircraft structure. The aerofoil is designed to be released by sensors fitted to the forward extremities of the aircraft, the forward velocity of the aerofoil being derived from the residual velocity of the rear of the aircraft structure following initial impact. The aerofoil is intended to follow a curving path after release to assist it to escape from the main wreckage environment. Although aerofoil separation systems are currently being designed for use in military aircraft there are a number of serious drawbacks to these systems particularly in relation to their possible use in civil transport aircraft. These drawbacks include the following:

- (a) Near vertical impacts prejudice the chances of the package being carried out of the immediate crash area.
- (b) At the low impact speeds that form a significant proportion of civil aircraft accidents the residual velocities and the air loads induced are insufficient to project the package an adequate distance after release.
- (c) The aerofoil area/payload ratio is such that a very large aerofoil would be required to carry a record module of civil ADR standard.

(d) The necessary complexity of triggering systems and the small time window available for operation of the device limits the likelihood of a successful release.

(e) The possibility of inadvertent release imposes an additional safety hazard.

(f) Boundary layer effects may degrade the efficiency of aerofoil release under certain flight conditions where a thick boundary layer exists in the region of the aerofoil.

(g) The installation and maintenance costs are higher than those of alternative concept systems.

In view of the many difficulties associated with the escape philosophy for ADR together with the attendant hazard to safety it is believed that further development of such systems for civil transport aircraft would be not only unproductive but unacceptable from the airworthiness point of view. It is considered, therefore, that the legislative decision to require appropriate crash protection for ADR was a correct one and all further discussion in this thesis will be centred upon the protection concept.

3.2 Predominant Outcomes of the Crash Environment Subsystem

Accepting that the philosophy of protecting the record medium against the adverse factors of the accident environment is preferable to providing an escape facility for the medium, it is firstly necessary to consider the possible injuries that the ADR medium might suffer in that environment and determine the aircraft structural outcomes that might cause those injuries to be

produced. The possible injuries fall almost entirely into one or more of the following categories:- (a) Impact and/or deceleration damage, (b) Damage by fire and exposure to high temperatures and (c) Exposure to chemical and other contaminants. These, individually, might result from one of the following outcomes to the aircraft structure:

- (1) High deceleration levels of structure causing deceleration damage to the recorder medium.
- (2) High levels of structural disruption permitting crushing, penetration or release of recorder.
- (3) Structural disruption permitting release and ignition of fuel followed by exposure of recorder to high temperature.
- (4) Structural disruption causing release of chemical contaminants in vicinity of recorder.
- (5) Immersion of structure in sea water.

Of these outcomes items (1) and (5) are frequently accompanied by high levels of structural distortion whilst items (2), (3) and (4) pre-suppose structural disruption in every case.

Structural disruption of varying degree is seen, therefore, to be the one uncontrolled variable common to almost every instance of recorder injury. The outcome involving structural disruption forms part of the environmental subsystem of the conceptual model and, as such, comprises a highly significant, albeit uncontrollable, influence within the system. Before

proceeding to analyse the possible recorder injuries and the controllable influences within the record protection subsystem of the model, therefore, it was desirable to study, statistically, the uncontrolled influences within the environmental subsystem to establish, where possible, which of those influences predominate in cases of structural disruption. This took the form of a structural outcome study.

3.3 Structural Outcome Study

The major elements of the Environmental Subsystem of the model were examined as follows:-

Frequency Distributions were derived for each of the following parameters in respect of (a) all accidents in Groups B and C and (b) all catastrophic accidents: (1) Impact Velocity and (2) Impact Angle. For reasons given in 3.6.1 Frequency Distributions could not be derived for Longitudinal Acceleration data.

Probability of Occurrence (PO) Values, Significance factors (Fs) and Significance weightings (Ws) (see Appendix C) were derived in respect of the following variables: (3) Terrain Penetration Potential, (4) Presence of Obstacles, (5) Development of Multiple Impacts, (6) Release of Fuel, (7) Ignition of Fuel, (8) Proximity of Primary Ignition Sources to Fuel, (9) Type of Fuel involved, (10) Release of Components of High Mass and (11) Generation of Explosive Disruptive Energy. Po values were derived in respect of (a) all accidents in Groups B and C for variables (3), (4), (5), (6), (7) and (9). Po values

were derived in respect of all catastrophic accidents for all the above variables and Fs and Ws values were derived in respect of catastrophic accidents for all variables except (8) and (9). Additionally two further elements of the Environmental Subsystem were examined. These were: (12) Positions of Components of High Mass and (13) Aircraft Mass Volume. These two further elements were studied, however, not for the purpose of determining their effect upon the general structural outcome but for their more specific and local effect upon ADR survival. As such they will be later discussed in relation to the elements of the Protection Subsystem. Frequency distribution curves for impact velocity and impact angle are shown in Figures 4 and 5. Detailed results of the structural outcome analysis are given in Appendix C.

3.4 Protection Statistical Study

Following upon the structural outcome study it became necessary to undertake a parallel study of the elements of the Protection Subsystem so that the interactions of the two subsystems could be established. A statistical study of those elements was made, therefore, in relation to recorder injury and, in addition to the two elements (12) and (13) of the Environment Subsystem previously referred to, the following elements were examined: (1) Impact insult applied, (2) Fire insult applied, (3) Chemical insult applied, (4) Recorder siting and (5) Recorder restraint. Probability of Occurrence (Po) values were derived for all accidents in which an ADR was fitted and the results are given in Appendix C.

3.5 Critical Paths within Model

From the study made in 3.3 it was possible to determine Probability of Occurrence (Po) paths indicating the frequency at which a particular outcome to the aircraft structure has been shown to occur. However the frequency of outcome must be related to the significance of that outcome in relation to the outcome to the ADR module. From the two studies in 3.3 and 3.4, therefore, it is possible to draw up Significance Weighting (Ws) paths which more nearly reflect the influences likely to cause damage to the module. Figures 6 and 7 show the paths derived from the study of the two subsystems. The Ws values, being products of the Po values and the Significance factors (Fs), are considered to be the critical paths from the point of view of ADR module design and are thus marked in Figures 6 and 7.

3.6 Relationship of Structural Outcomes to ADR Injury

This critical path analysis may now be used to examine the relationship between the types of structural outcome that may affect the protected module and the three broad categories of adverse outcome that the module may suffer. The former are: (a) major disruption of the aircraft structure, (b) outbreak of fire within or around the aircraft structure and (c) disruption of aircraft systems causing release of chemical contaminants or immersion in other liquids such as sea water. These structural outcomes can be respectively identified with the following outcomes to the ADR module: (a) mechanical damage to the module, (b) exposure of the module to high temperature and (c) exposure of the module to chemical contaminants. The above aspects will now be separately considered.

3.6.1 Structural Aspects

The possibility of the ADR module suffering insult under any of the above circumstances is primarily related to the severity of injury sustained by the aircraft structure and this normally reflected in the extent of structural break-up. A study of the conceptual model and its critical paths shows that to achieve any of the known insults to the module a degree of structural deceleration and, in most cases, a large element of structural disruption is necessary. Deceleration is rarely the sole cause of injury to an ADR module although an instance of deceleration injury to a recording medium has occurred without displacement of the ADR module. This aspect is further discussed in 3.6.2. The structural deceleration levels are never constant in an accident sequence and many peak variations occur before the structure comes to rest. Longitudinal acceleration is not a parameter normally recorded in ADR and was not recorded in any of the aircraft that were the subject of this research. Data concerning the mean deceleration of the structure as a whole were obtained, however, from velocity and distance measurements and from these measurements it could be deduced that mean decelerations on the subject aircraft involved in catastrophic accidents ranged from 200 m/sec^2 to 1500 m/sec^2 . No means were available, however, to establish the peak acceleration levels, to separate the differing levels of deceleration sensed by individual areas of the structure or to derive frequency distributions in respect of acceleration levels in the subject accidents.

The severity of insult to the aircraft structure is principally related to the external inputs to the crash system in terms of impact velocity, aircraft attitude, impact angle and other

deceleration factors such as the presence of obstacles and the penetration potential of the impact surface. The probability of structural break-up is often decreased if the flight path of the aircraft and its traverse path throughout the crash sequence is coincident with its longitudinal axis. Any significant deviation of the longitudinal axis from the traverse path will increase the probability of break-up and this can frequently be seen in those cases of low angle impacts where 'skip' conditions exist and multiple impacts occur. Where large angles between the longitudinal axis and the traverse path occur the possibility of 'tumbling' or 'cartwheeling' of the structure becomes likely accompanied by a high probability of extensive structural break-up. At very high angles of impact and/or when high impact speeds exist disintegration of the structure by progressive crushing is more likely. In any or all of the above conditions deceleration levels may vary considerably throughout the crash sequence with one or more acceleration peaks occurring through the dynamic period. The derivation of mean deceleration levels, therefore, can in no way reflect the peak values which may have obtained and are, therefore, of very limited value in this type of structural analysis.

Examination of the critical paths within the crash environment subsystem shows that the following elements are the most critical in relation to structural disruption by impact: Impact velocity; the presence of obstacles; the development of multiple impacts. Impact velocity is related to the total

energy to be dispersed throughout the structure at impact and as impact velocities increase the energy absorbed by the structure becomes exponentially higher. Impact angles have a slightly less predominant bearing on structural disruption although low impact angles of about 15 degrees appear to increase the possibility of multiple impacts developing.

One of the most significant features of major structural disruption by impact is that it almost invariably permits fuel to be released, as a result of which a high probability of fuel ignition exists. In those instances of limited structural disruption where fuel is not released fire rarely occurs. The high probability of ignition of fuel and destruction of the structure by fire in catastrophic accidents is shown by the probability path analysis in Fig 6. One further significant internal variable is that of the disruptive energy generated in those instances where fuel explosion occurs. Fig 6 also shows the high probability of structural disruption from this cause.

An analysis of all the cases in which major structural disruption has occurred from any of the above causes shows that in a high percentage of the cases the tail unit of the aircraft, often including the extremity of the rear fuselage, survives the impact and any subsequent fire as a relatively intact unit. Of the 140 cases examined in the structural outcome study 59 instances involved catastrophic destruction of the structure. Of these latter cases the tail unit was totally destroyed on 9 occasions only. This is considered to be a highly relative finding and will be referred to later

Plates 1 to 6 illustrate many of the above points.

3.6.2 Mechanical Damage to ADR

Mechanical damage to an ADR may be caused either by crushing, penetration, or by impact deceleration. The degree of any mechanical damage likely to be sustained will be dependent upon the severity of, and the module resistance to, the above influences. The severity of insult to the module is affected not only by the external inputs to the crash system but may also be affected by influences internal to the aircraft such as aircraft mass volume, local position of the ADR module, extent of ADR restraint and the relative positions of items of high mass.

The external influences are usually of greater significance in cases of severe structural disintegration particularly where break-up occurs early in the accident sequence before the major items of wreckage have decelerated significantly. Impact with moderately light obstacles such as small trees at high speed is one example where this may occur. In such cases the ADR is often released at an early point in the impact sequence and if projected forward with the heavier items of wreckage it may well suffer extensive crushing injury. Plate 7 shows an example of this: The mass volume of larger aircraft often has a beneficial effect in cases where slow impact conditions prevail because the structural break up is frequently less than total and the large volume fuselage together with its payload can act as a decelerating cushion. Both the general and local siting of the ADR are of high significance in respect of possible mechanical injury. UK regulations call for fitting the ADR as far to the rear of the

aircraft as possible consistent with reasonable maintenance access and the results of this research show that the probability of survival of those ADR fitted forward of the rear fuselage and tail unit is significantly lower than those fitted in or near the tail unit. Furthermore, as will be explained in 3.7.1, there are strong grounds for fitting the ADR aft of the rear pressure bulkhead. With regard to local conditions of siting it is important to locate the ADR aft of or away from items of high mass such as rear mounted engines or heavy structural items. The question of ADR restraint is considered to be of highest significance in relation to survival and will be discussed further in 3.7.1 and 3.7.2.

3.6.3 Exposure of ADR module to high temperature

The effects of minor temperature changes on the ADR medium due to variations expected under normal operating conditions of the ADR must necessarily be considered at the design stage. However, the possibility of severe temperature changes taking place at the external surface of the ADR module due to the generation of high temperatures in the crash environment must also be a central consideration in the module design. These latter temperatures arise from two broad categories of fire which are; firstly, the development of a widely spread, all enveloping, flash fire of comparatively short duration, and/or, secondly, a larger duration and more intense localised fire. The former is likely to occur when the crash environment permits wide dispersal of the fuel at the time of initial impact. The latter may take place where less severe structural

break-up permits more localised containment of the fuel. In the latter instances the time/temperature profile of the burning fuel will be a significant factor in relation to medium survival in those cases where the ADR is in close proximity to the locus of the fire.

The factors relating to fuel ignition must also be considered in assessing the risk of fire development and, of these factors, the following predominate; type and quantity of fuel carried, degree of fuel containment, sources of ignition and proximity of such sources to dispersed or contained fuel. The most common sources of fuel ignition are contact with high temperature components such as power units, electrical arcing due to short circuits produced in the crash sequence and generation of sparks caused by friction between parts of the decelerating wreckage and the surface of the crash site. The first mentioned source of ignition is much the predominant one.

The flash fire flame is a diffusion flame, whose temperature varies, in the predominantly used case of kerosene, from 980^o to 1100^o C depending upon the wind conditions, a moderate wind producing a higher temperature (19). The fuel configuration and aircraft deceleration conditions will determine the nature of the fuel spread. High deceleration conditions cause forward and possible span-wise distribution of fuel. High sustained speeds during the impact sequence, however, cause aftwise distribution of fuel. The boundaries of the fire, therefore, will vary according to the impact conditions, being generally aft of the aircraft structure during high speed impact phases and forward

of or more centrally disposed around, the aircraft structure at lower speeds or in high deceleration conditions. During this dynamic decelerating period fuel spreads either as liquid or as droplet mist, fuel vapours adding little to the combustible environment. Fuel volatility, therefore, plays only a secondary role during this dynamic period.

The nature of longer duration more localised crash fires are dependent upon a variety of factors including fuel type, quantity, disposition, ventilation and ambient conditions. The duration of high temperature localised fires vary widely and can be a major factor in ADR survival. Only limited data is available concerning the time/temperature profiles of many accidents but some major post-crash fires have been known to persist for more than an hour and the maximum temperatures at the seat of some fires had been assessed as approximately 1200 C.

Although time/temperature profiles of accidents are not fully available some experimental work has been undertaken in this area by N.A.S.A (20). An example of a time/temperature profile based on such data is shown in Fig 8. This profile relates only to burning fuel, however, and in the absence of wreckage residue is not considered to be representative of wreckage temperature conditions.

3.6.4 Other forms of injury to ADR module

Although less common than damage by impact or fire the possibility of chemical contamination of the ADR exists

in those areas where extensive structural break-up occurs. Such break-up of the structure may well disturb many of the aircraft systems and release fluids such as aircraft fuel, lubricating oils, hydraulic and anticing fluids, fire extinguishants and other chemicals in the vicinity of the ADR. The following are among the most common chemicals likely to be involved and should be taken into account in determining protection requirements.

Aircraft fuels (Kerosene JP1, JP4, Gasoline (AVGAS).
Engine lubricating oils (D. Eng R.D. 2487.)
Hydraulic fluids (DTD 585, DTD 900/4081, Skydrol 500)
Fire extinguishants (Water Glycol solution, Co2 foam,
Methyl bromide, Freon 12, BTM, BCF, CBM.)

Additionally the possibility of injury due to the chemical effects of fumes in a burning environment must be borne in mind. Plate 8 shows an example of chemical attack on a metal foil medium due to the effects of burning butyl rubber adjacent to the outer case of the ADR. The other possible type of attack which must be considered is the immersion of the ADR in sea water. On occasions such immersion is likely to be for a comparatively long period ie until such time as the wreckage is located and salvaged. It is necessary, therefore, that resistance to sea water is included in the specification for the medium and in the design parameters of the ADR.

3.7 Discussion

The statistical examination carried out into 140 large public transport accidents in Groups B and C, including 59 catastrophic accidents, clearly shows that two forms of damage to ADRs are likely to predominate namely those related to impact and those related to fire injury. These two types of damage, together with the less common type of damage due to chemical contamination, normally occur only when a degree of structural disruption has taken place. Such disruption may permit mechanical damage to the ADR to occur due to crushing, impact by other objects or by deceleration after being thrown from its mounting and/or cause exposure of the ADR to high temperatures due to an outbreak of fire following release of fuel from the degraded structure. Exposure of the ADR to chemical contaminants is usually related to the release of fluids due to structural disruption. A study of the data indicates that collision with obstacles and/or multiple impact conditions have a greater effect on the probability of structural break-up than do high levels of velocity or high angles of impact at the time of striking the ground. More detailed study of the data shows also that certain features have a predominant effect on the likely outcome to the ADR. These are: the retention or release of the recorder from its installed position, the location of the recorder in the aircraft and the survival of the tail unit as an entity. These three factors will now be examined in more detail.

3.7.1 Secondary Envelope Concept

Of the 59 cases of catastrophic accident referred to in the previous paragraph, 39 were instances in which an ADR was being carried and in 29 of those instances the ADR module was mounted in the tail unit of the aircraft aft of the fuselage rear pressure bulkhead. Because of its type of construction the latter bulkhead forms a natural location at which the fuselage structure is likely to separate when extensive structural disruption occurs during an impact sequence. In 23 of the above 29 instances the tail unit survived the impact as a single unit. In 19 of those cases the ADR module remained in its installed position and on each of those occasions the ADR module survived without impact damage. Minor fire exposure occurred in 4 instances only. Of the remaining cases in which either the tail unit itself suffered extensive disruption and/or the ADR module was released from its mounting, the ADR suffered impact and/or fire injury in every instance.

From the data it can be said that in every case where the tail unit of the aircraft survived as a relatively whole unit and where the ADR module remained in position within the tail unit no significant injury to the module was sustained. The tail unit structure, in each instance, acted as a further protective barrier to the ADR module both against impacts from other parts of the wreckage and, because of the firewall effect of the rear pressure bulkhead, also against the major effects of fire. On those occasions when the ADR module was released from the tail unit, however, including those instances where the tail unit remained relatively intact, damage to the ADR module occurred.

It can be stated, therefore, that if the ADR module is installed aft of the rear pressure bulkhead and means are provided whereby it is restrained from being projected out of the tail unit, whether or not the latter is damaged, a very high probability will exist of the module being screened from most if not from all the effects of impact and fire. If this secondary protection envelope formed by the tail unit is largely preserved throughout the crash sequence and the ADR module can be restrained within it, then the module, with its primary impact and fire protection elements more highly preserved, should achieve a much higher probability of survival even when the remaining structure is subjected to total disintegration.

From the above it is proposed, therefore, that a dual approach should be made to the problem of ADR survival: firstly the design aspects providing for protection of the module against the effects of impact, fire and chemical contaminants should be improved and, secondly, that the equally important aspects of ADR location and restraint should be taken into account both by regulation and design.

3.7.2 Module Design

No requirements are laid down concerning the basic design for ADR modules either in terms of general concept, size, shape, configuration or materials to be employed. The only criteria are that the module must meet, in addition to certain performance standards, the requirements in terms of crash resistance laid down by Government regulation.

The general concepts of ADR modules have already been referred to in section 2.5 and it will now be useful to compare the various methods employed and to consider whether and in what area improvements may be necessary. This comparison will deal separately with each crash protection requirement and will take into account any UK regulations that may apply.

3.7.2.1 Mechanical Protection of ADR

The mechanical protection requirements include protection against impact, penetration and crush forces.

A serious anomaly exists between the crash protection test requirements laid down both in the USA and UK regulations for FDR and CVR. The requirements are much less stringent for the latter in both instances as may be seen by reference to Appendix A. There are no technical grounds for this anomaly and it is strongly recommended that the crash protection requirements for CVR are uprated to the same standard as those laid down for FDR.

It is considered that the impact and penetration tests called for by the requirements for FDR in Appendix A provide reasonable safeguards against the levels of such insults likely to be experienced in an accident environment. The impact requirements call for an FDR medium to withstand accelerations of the recorder up to peak values of 1000 g for 5 milliseconds. Whereas high levels of acceleration up to this maximum do not normally affect most ADR media, certain cases of acceleration

damage to a medium have occurred in particular recording modules where design shortcomings have been apparent. Two examples are shown in Plates 9 and 10. In the first example accelerations applied to a recording stylus caused damage to the aluminium foil medium of an oscillographic recorder. In this instance a series of impact accelerations was applied to the stylus against which it was not protected. In the second example impact accelerations applied to a plastic based tape of a CVR caused severe displacement of the medium. The tape deck of this CVR is designed on the random bin principle and the recording tape suffered extensive creasing due to its displacement. This latter example is of significance in that random spooling of plastic based tape is a widely used method in present day CVR and is clearly an unsatisfactory design concept. The penetration requirements call for the FDR to be subjected to an impact force equal to a 500 lb steel bar dropped from a height of 10 feet on to the most critical plane of each of its sides. The detail design of many ADRs could be improved both in relation to this requirement and to the requirement relating to crush resistance. The design of many modules produced to date appear to have been evolved by treating the recording process as the primary feature and permitting the design of the protective element to be secondary to it. As a result, protection has often been provided by the addition of an armoured package to suit the size and shape of the recording device. In other cases, however, the designer has considered the protective element within the initial design concept and, as a result, a better protective barrier has

resulted. In designing ADR for public transport aircraft, volume and weight are not significant constraints.

The external shape of the ADR module can therefore be defined at initial design and from the point of view both of penetration and crush injuries a spherical shape should be the primary aim. Such a shape more readily provides a deflective surface to impacting objects and also provides compressive resistance to crushing forces. At least two types of currently used ADR are of spherical shape. Plate 11 shows one such example.

The requirements for FDR in Appendix A for protection against crushing forces are considered to be inadequate. On many occasions FDR which have been subjected to and have satisfied the tests involving static crush forces laid down by the above regulations have had their recording media severely damaged in accident environments. Plate 7 shows an example of an ADR subjected to external crushing forces in an accident and in which the medium suffered heavy damage. Clearly, therefore, the protection requirements in respect of crush forces are insufficient to ensure survival and require to be upgraded. Many large items of wreckage can impart crush injuries to an ADR. However, the high mass items likely to produce the greatest injury, in the event of their impacting an ADR following their displacement in the wreckage, are the power units. Power unit installations are designed to be restrained up to loadings of 88 m/sec². In a moderately severe wreckage break-up, therefore, where the above accelerations are exceeded a medium size power unit of about 1025 kg dry weight could provide a crush

force of over 9000 kg if displaced from its mountings. Although in some circumstances the loads involved could be greater than the above figure, and in some particular cases less, the above example would seem a reasonable basis for establishing the maximum crash loads to be accepted, albeit at a low probability level. Such a requirement would entail an increase in the crush force test requirement to a figure of 20,000 lbs (9090 kg). Although the possibility of a power plant crushing an ADR can be considered remote, the increased requirement would most probably prevent all crushing injury from other causes. It should not be a difficult requirement to meet even using conventional materials referred to in section 2.5, as certain current designs of FDR module have already been shown to meet such crush resistance levels.

3.7.2.2 Fire Protection of ADR

FDR are designed to meet the statutory requirements to preserve the record on the medium following exposure of the ADR to flames of 1100 C over one half its outside surface area for a period of 30 minutes. It is known that this requirement was arbitrarily drawn up in the absence of data relating to the time/temperature profiles of accident fires. Although many current designs of ADR have survived the fire environment of major accidents without damage to the medium, others have not done so. In the latter cases it is known that the above fire test requirements were met and it must be concluded, therefore, that the test environment was less severe than that experienced in the accident case.

In attempting to produce a realistic fire protection requirement it is at first necessary to define a representative crash fire envelope for those types of aircraft generally equipped with ADR. Despite a detailed study into all the accident cases related to this research no extensive data concerning the time/temperature profiles of many of the cases in which fire occurred are available. In particular there is no direct knowledge of the duration of many fires which have occurred at locations away from airports. Where specific times have been recorded the duration of the most intense fires extended for periods of between 4 and 18 minutes. However, it is believed that some fires have persisted for periods of over 1 hour (some reports give much longer times) and that areas of the wreckage have been at high temperature conditions for much longer periods. The nature of any ground fire depends largely upon the characteristics of the impact and the extent of fuel spillage and wreckage spread. In conditions where the wreckage is widely spread the duration of any ground fire is frequently low but where the wreckage is less dispersed pockets of fuel often remain and may burn for an extended time. In cases where the fuel retains a 'high pool depth' burning may persist over a very long period of time. Often this will occur when the impact terrain has deep pockets or craters to retain the fuel, a situation predominant in high angle impact conditions. The maximum burning (regression) rate of an open pool of predominantly used kerosene has been calculated to be approximately 8.9 mm/min (21). Experimental work (22) has shown slower burning rates of about 2.54 mm/min, however. A kerosene pool depth of 300 mm, therefore, could, on the basis of the above, permit burning to persist for at least 34 minutes and possibly up to 2 hours with a flame

temperature of approximately 1000 C. In flash fire conditions where this fuel is used the surface temperature of an exposed ADR may reach 1200 C for a period of a few seconds. The temperature inertia is such, however, that the internal temperature of the ADR would make no significant rise within such a short time. The time of exposure at high temperature, not the maximum temperature achieved, is the most significant factor, therefore, and this must be the central design consideration in the protection of an ADR medium against fire. An indication of the maximum temperature conditions can often be established by examining the post-fire state of the wreckage. In many instances in this research melting of aluminium alloys showed that an intense fire with a temperature in excess of 640 C took place. However no cases were found of the melting of steel or its alloys showing that the temperature of the relevant areas did not exceed 1380 C for any length of time. In some instances magnesium fires took place due to the burning of magnesium alloys found in the aircraft landing gear, thus generating temperatures above 680 C but such fires were always localised and are not considered to be a major hazard to ADR. The possibility exists of oxygen fed fires occurring in burning aircraft wreckage due to the disruption of an oxygen system thereby increasing the stabilised temperature at the seat of the fire. Such fires are normally very localised and would not be expected to significantly increase the fire hazard to an ADR module. One such instance of an oxygen fed fire affecting an ADR module is known, however (26). The fire damage occurred because the module was mounted in close proximity to the passenger oxygen system

cylinders which released a stream of oxygen directly at the recorder module after fire had disrupted the oxygen system pipework. No instances of titanium fires were found. Such fires in power plant components are not unknown and can give temperatures well in excess of 1700 C. However, these fires are most frequently generated in airborne conditions and being again very localised and sufficiently rare, they are not considered significant in the context of ADR protection.

In the light of the above the test temperature in the current requirements is considered to be a realistic figure. However, the 30 minute exposure period followed by natural cooling is not considered sufficient to take account of a prolonged heat soakage to which an ADR can be exposed in an accident environment. Whilst the burning of fuel may be completed within a 30 minute period the temperature conditions of the wreckage residue may considerably extend the heat soak time of an ADR within it. It is considered that an exposure time of 1 hour to the test temperature, followed by natural cooling, is the minimum figure likely to satisfactorily represent extreme conditions. With this increased exposure time the half-surface exposure condition in the test requirements is thought to be realistic.

In establishing design parameters to meet the proposed fire protection requirements for the ADR the nature of the medium to be used will dictate the permissible internal temperatures of the recording module. In many current designs using plastic based tape this means that internal temperature must be kept below 100 C during a crash to ensure effective data recovery. The stainless steel magnetic media can accept temperatures

approaching 400 C without loss of data. Plate 12 provides an example of digital signal recovery from stainless steel wire after heating the medium up to temperatures of 450 C. Many commercial materials are available to provide temperature insulation of the medium the efficiency of which will depend considerably upon the methods and the material thickness employed. Figure 9 indicates the internal temperature profile during test exposures of an ADR module to high temperature using a 17mm blanket of commercial 'Min K' insulant as a protective barrier for the medium. A recently developed method of ablative fire protection has been previously referred to in section 2.5. With this method a liquid impregnated thermal protection shield releases vapour at a controlled rate when exposed to high external temperatures thus maintaining the medium at a lower temperature during the process. All the ADR studied in this research which used this method of fire protection and which were exposed to fire had a 100% data recovery rate. A supplementary method of temperature protection which may readily be applied to many recording modules lies in the use of an intumescent coating to the exterior surface. The need for adequate fire protection is normally realised once only in the life of an ADR and such coatings, therefore, ideally suit the needs of crash fire protection. Such coatings are formulated from resins which on heating will soften and, as a result of internal generation of gases, expand to form a low density carbonaceous char which can act as a thermal barrier. Many such resin formulations have been evaluated for fire protection purposes (23) and it is believed that their use as a supplementing element in thermal protection systems for ADR should be further explored.

3.7.2.3 Other Protection Requirements

Paragraph 3.6.4 gives an indication of the possible forms of insult to the ADR additional to those of impact and fire. The present UK requirements call for the medium itself to be immune to the action of chemical contaminants. The most common liquid contaminants to which the medium is likely to be exposed are aircraft fuel and sea water. It has been demonstrated that the data on most currently used magnetic media are preserved even after total immersion in either of these two fluids and in the chemicals referred to in 3.6.4. The media meet, therefore, the current requirements in this particular respect. However, should such contamination take place in an accident environment, the subsequent processes of data recovery cannot proceed until the medium concerned has been effectively cleared of contaminant. In the case of sea water this entails a prolonged period of washing in distilled water and in the case of other liquids and chemicals an equivalent decontamination delay. Such a delay in the data recovery process is undesirable and it is considered, therefore, that the need for such sealing of the medium as is possible should be introduced at the design stage bearing in mind the additional insults that may accompany the chemical attack.

3.7.2.4 Precautions against total loss

In all of the cases examined in this research in which the wreckage was recovered the ADR module was also retrieved. Only one such instance is known (24) where this was not so. On that occasion failure to retrieve the record module was attributed to the extensive distribution of the wreckage in a mountainous area. A more frequent cause of loss of an ADR module, however, is failure to recover the aircraft wreckage, the most frequent cases

of this being those instances in which the aircraft crashes into deep water. A certain amount of research has been directed towards providing a release and flotation capability for the record module in such circumstances and development of a project towards this end (25) was commenced in the UK in 1968. As stated in 3.1, however, the difficulties of ensuring satisfactory release in conditions in which the aircraft structure would probably sustain considerable disruption prevented successful development of a system, and all proposals for underwater release of ADR fitted to civil aircraft have now been abandoned.

On the occasions in which aircraft crash into deep water reliance has to be placed on the ability to locate the aircraft so that salvage of the wreckage may be undertaken and many large aircrafts are now fitted with acoustic beacons to facilitate location. UK regulations now call for sonar locator beacons to be fitted to aircraft above 230,000 kg max TWA (Total Weight Authorised) with a type certificate first issued on or after 1st January 1970. It is considered that the fitment of such locator beacons should be made mandatory on all aircraft fitted with ADR.

3.7.3 Installation of ADR

This research has confirmed that the installation features of the recording module constitute a highly significant factor in respect of its survival. The UK requirements call for the ADR to be installed as far to rear of the aeroplane as possible

consistent with reasonable maintenance access, in a position which minimises the possibility of damage in the event of an accident. As shown in paragraph 3.7.1 the tail unit can be expected to survive as an entity in all but the most severely disintegrated wreckages and, provided the ADR is sensibly sited and retained within the tail unit during the impact sequence, the possibility of substantial damage to the ADR is low, particularly when the structural damage is not accompanied by fire. In the most severe cases of disintegration the possibility of damage will be minimised if the local siting of the ADR avoids a position immediately forward of an item of high mass. Plate 13 shows an example of poor positioning of an ADR immediately forward of a tailplane main spar and Plate 14 shows the extensive damage to the wire medium of the same recorder due to crushing by the tailplane spar at the time of ground impact.

In the less severe cases of break-up, in which the tail unit survives, the probability of damage to the ADR is very considerably reduced if the ADR is restrained within the tail unit. This feature is considered to be a most significant finding of this research and it is proposed that a requirement should be introduced to provide some degree of restraint by means of a lanyard attaching the ADR to an appropriate anchor point within the tail unit structure. It is proposed that this lanyard and its attachments should be stressed to restrain the ADR up to loadings of 500m/sec^2 . The introduction of such a requirement would, without doubt, increase the probability of survival by reducing the possibility of damage due to ballistic throw, penetration, crushing and the effects of fire.

3.7.4 Examination of Objectives

It is now appropriate to examine the objectives laid down in 2.1 in order to establish to what degree those objectives have been attained. It can reasonably be said that some have been fully achieved whereas, in others, certain areas remain unresolved. Viewed separately, comments relating to the objectives in the subheadings can be made as follows:

(1) A systems approach has provided a useful method of examining the many variables involved in a crash environment situation and has enabled relative degrees of significance to be applied to each of the major elements contained within the overall problem. The approach has not provided a precise solution to all the problems of survival but it has enabled certain recommendations to be put forward which should enable designers of ADR and aircraft manufacturers to jointly achieve a much higher rate of survival than hitherto.

(2) Minimum survival rates have not previously been laid down for ADR. A minimum survival rate of 98% has been proposed which is considered to be both achievable and acceptable from the accident investigation viewpoint.

(3) The survival rate of the media examined during this research is 36.25 per cent of the total number of accidents examined and only 73.8 per cent of the total number of catastrophic accidents. These figures do not approach the criterion in (2) above and are not acceptable by any reasonable standard. They clearly demonstrate both the need for this research and for improvement in standards to be sought.

(4) The presently laid down requirements for recording medium protection are inadequate to achieve the minimum survival rate in (2) above.

(5) Shortcomings in protection of the recording module against crushing injuries have been clearly shown together with inadequate protection against high temperature conditions in which the time period of the heat soak has been extensive. A number of instances of unsatisfactory installation conditions for the ADR module have also been apparent.

(6) Recommendations have been drawn up covering improvements in the standards of protection which are considered necessary to achieve the survival rate called for in (2) above. These recommendations are related to the survival failure areas given in (5) above and principally involve higher standards of protection against impact crushing, extended temperature profiles and the adverse effects of poor installation of the module.

(7) This research has highlighted certain areas where design improvements can be made. They principally relate to the requirements of (6) above and include suggestions to improve the penetration resistance of ADR modules, to improve resistance to high temperatures over a greater time period and to ensure retention of the module within that part of the aircraft most likely to provide a protected environment during the impact sequence.

(8) Further effort is clearly necessary to obtain more detailed information relating to the temperature conditions of aircraft wreckage in which an outbreak of fire occurs. Insufficient investigation of this aspect has been made in the past and inadequate records have been kept as a result of which no statistics exist of the precise time/temperature profiles of many accidents. The profiles used in drawing up present-day requirements have clearly been inadequate and in the absence of more precise knowledge the more stringent requirements necessary must be arbitrarily assessed.

It is concluded that:

A systems analysis approach using a conceptual module provides a practical means of evaluating the survival aspects of an ADR module in the extreme and varying conditions of an aircraft accident environment. From such an approach it is possible to attach values of significance to each of the inputs to the system thus enabling the mechanisms of the environment to be more clearly understood, the major problem areas to be identified and broad solutions to those problems to be formulated. The research has enabled acceptable survival rates for ADR to be established and recommendations to be made in respect of revised protection standards from which significantly improved levels of protection should be achieved.

RECOMMENDATIONS

The following recommendations are made as a result of this research:-

- (1) The crash protection requirements for all type of civil ADR should be identical and the stringency of the crash protection test procedures for CVR should be increased to that for FDR to achieve this.

- (2) The protection of ADR against crushing forces should be improved by increasing the crush force test requirement laid down by regulation to a figure of 9900 kg (20,000 lbs).

- (3) The duration of the fire test laid down by regulation to satisfy resistance of the ADR to the effects of high temperatures should be increased from 30 minutes at maximum temperature to one hour at maximum temperature, the remainder of the temperature profile and conditions to remain as at present.

- (4) The installation location of ADR fitted to pressurised aircraft should, where ever possible, be aft of the pressure cabin rear bulkhead.

- (5) The ADR should be restrained by a lanyard attached to an appropriate anchor point on the aircraft structure. The lanyard and its attachment points should be capable of restraining the ADR against acceleration minima of 500 m/sec².

(6) ADR should be so constructed as to be leakproof in their undamaged state in order to isolate the medium as far as possible from the ingress of fluids and other contaminants.

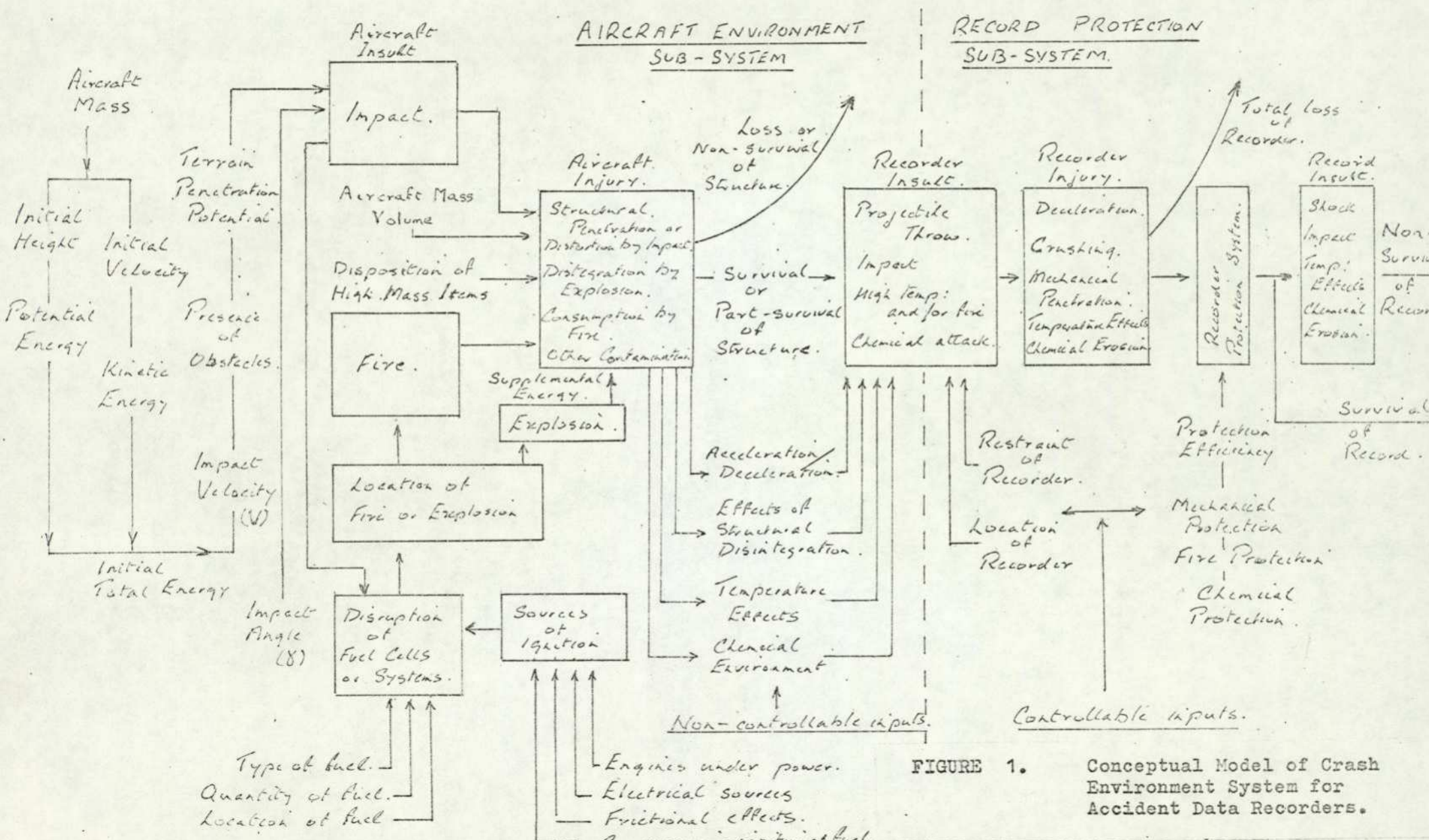


FIGURE 1. Conceptual Model of Crash Environment System for Accident Data Recorders.

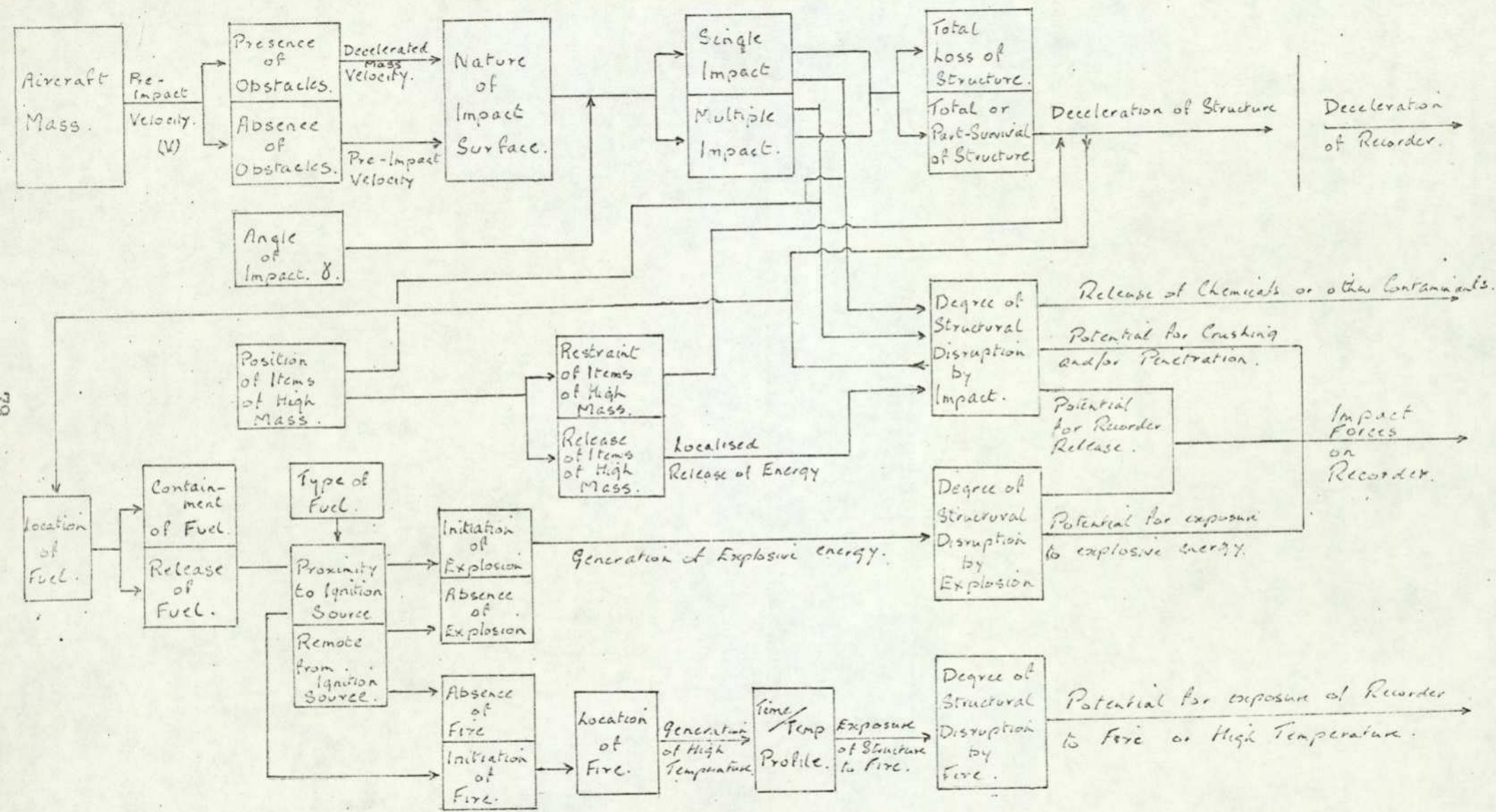


FIGURE 2. Aircraft Environment Subsystem.

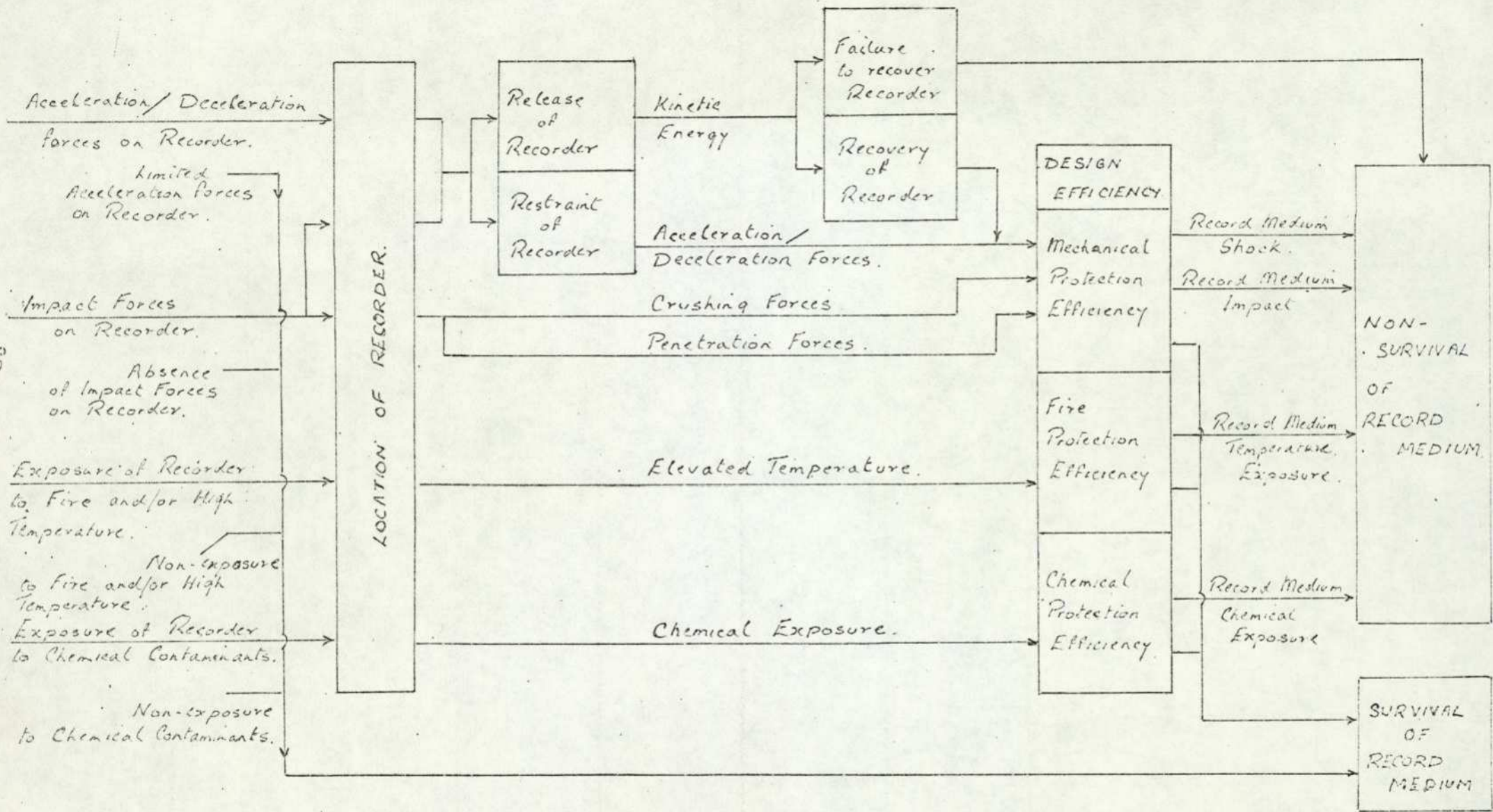


FIGURE 3. Record Protection Subsystem.

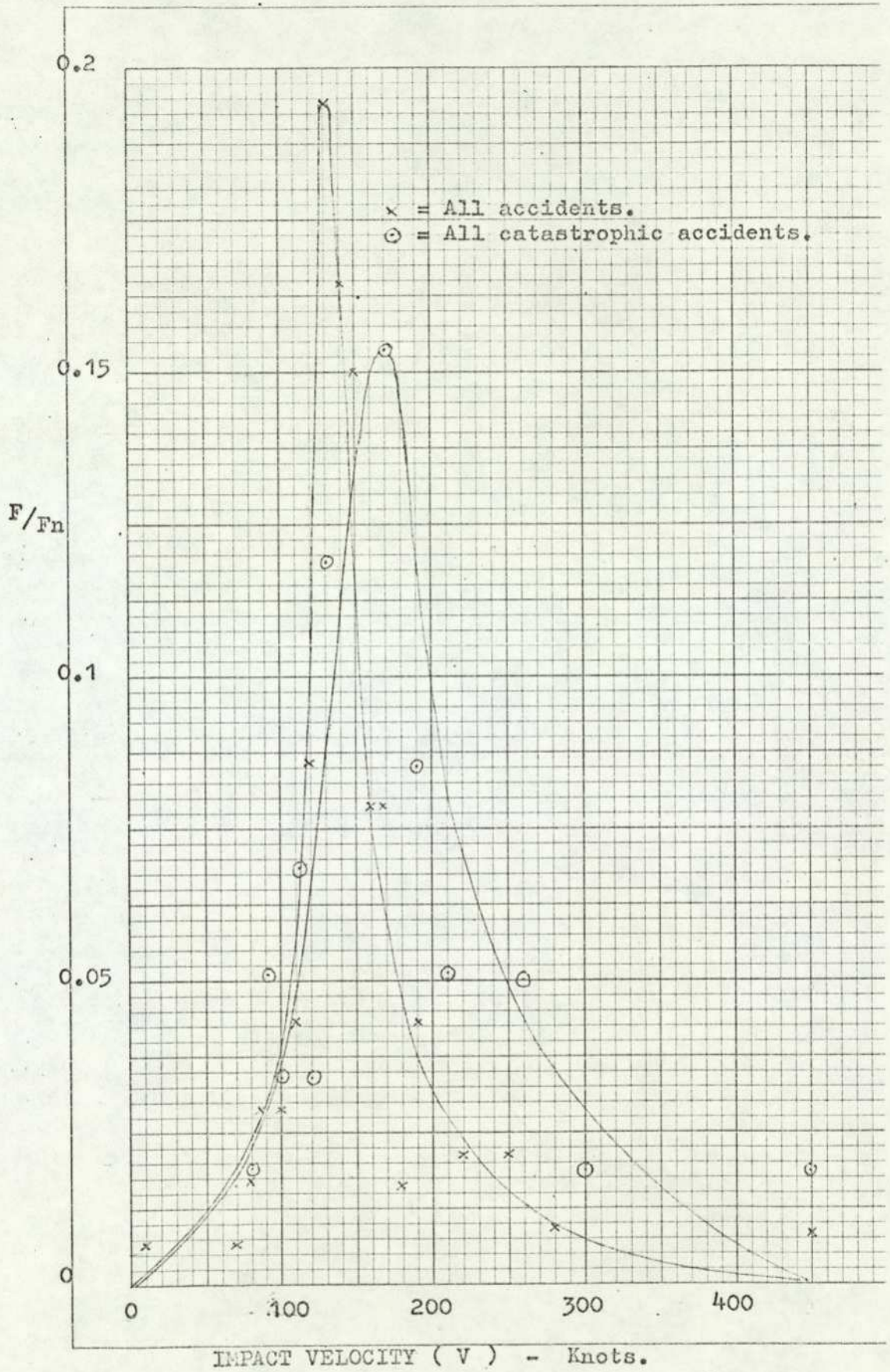


FIGURE 4.

Impact Velocity Frequency Distribution Curve.

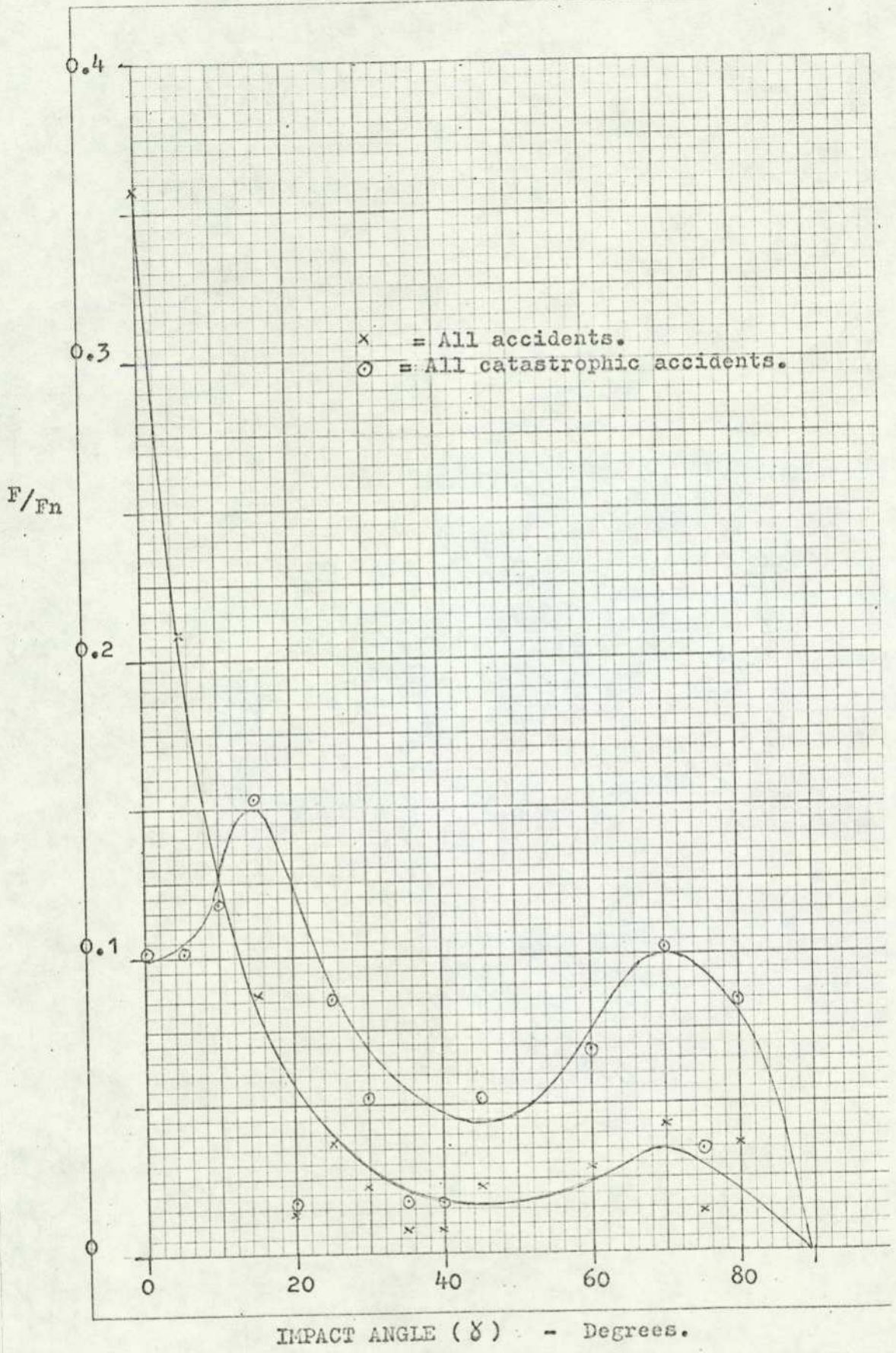


FIGURE 5.

Impact Angle Frequency Distribution Curve.

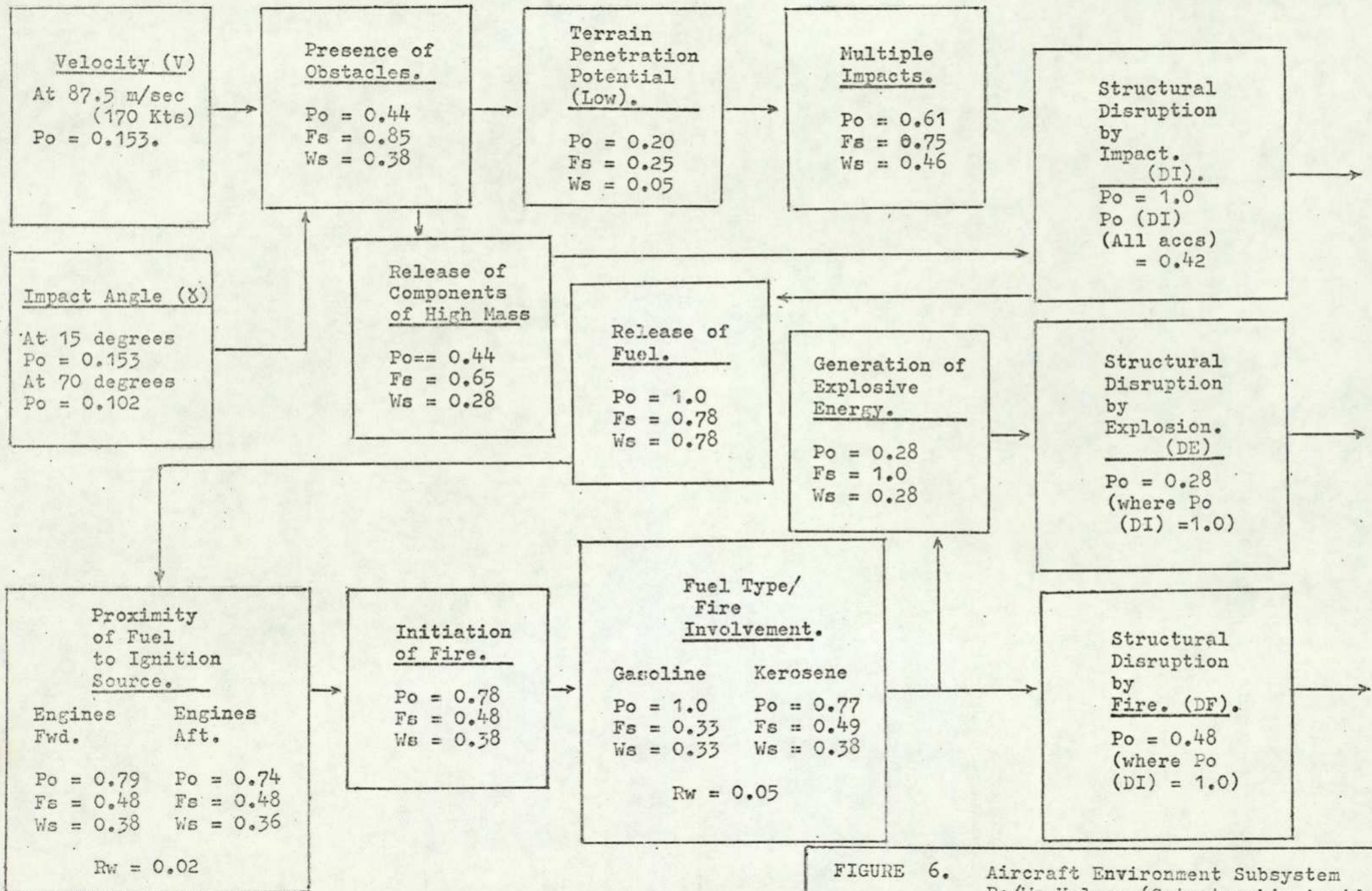


FIGURE 6. Aircraft Environment Subsystem P_o/W_s Values (Catastrophic Accidents).

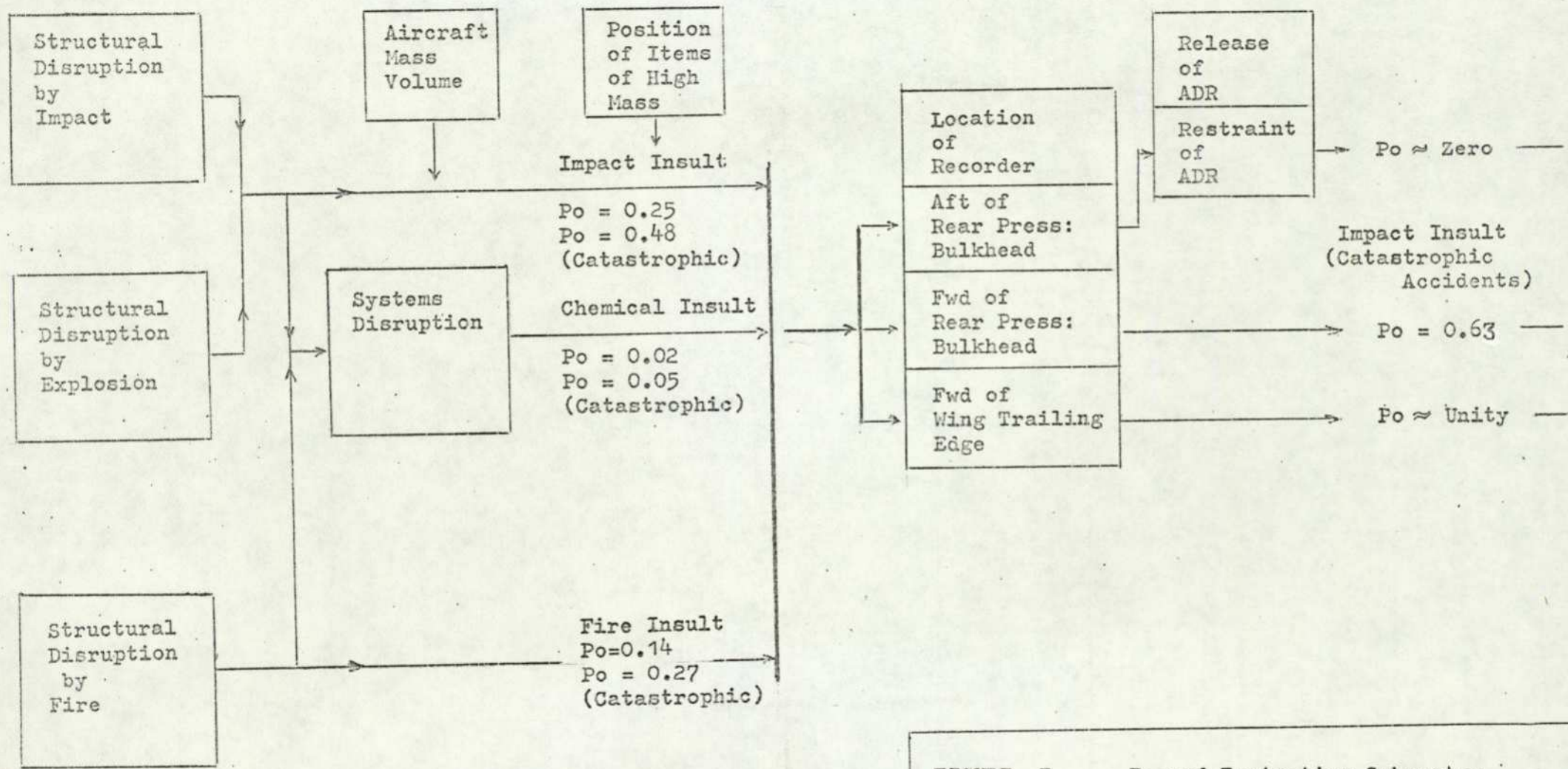


FIGURE 7. Record Protection Subsystem Po Values (Catastrophic Accidents).

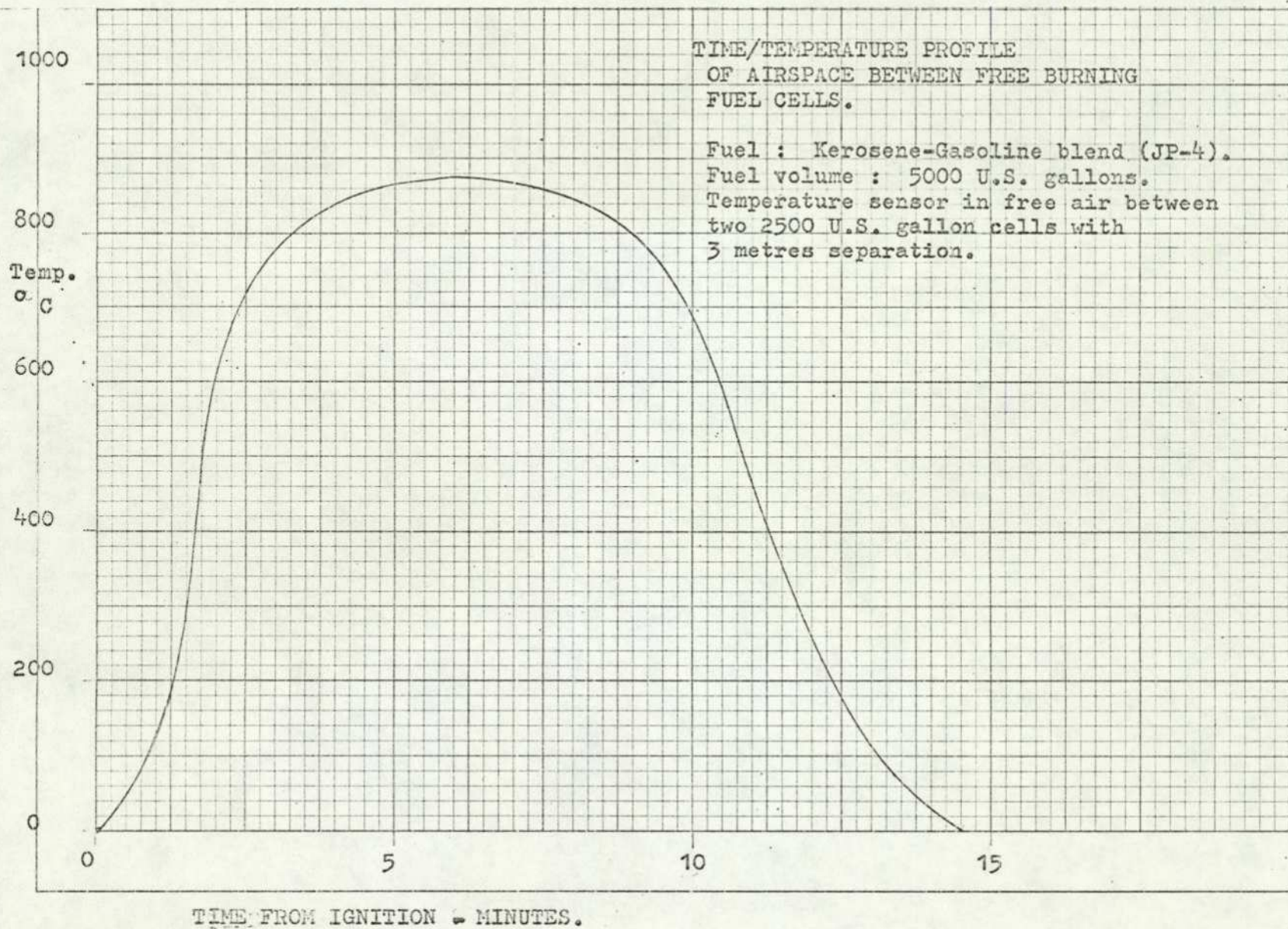


FIGURE 8. Fuel Fire Time/Temperature Profile.

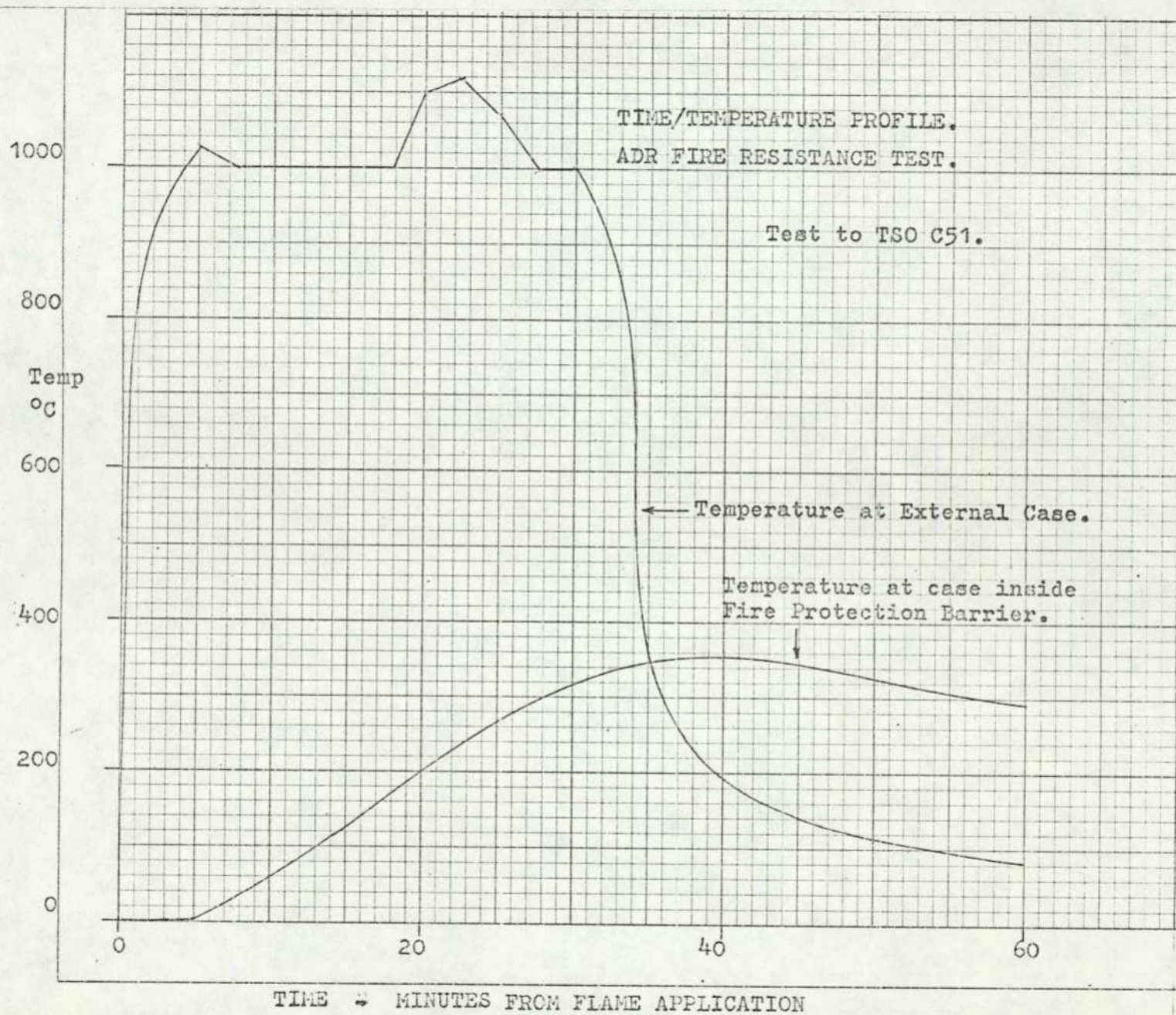


FIGURE 9. Time/Temperature Profile - ADR Fire Resistance Test.

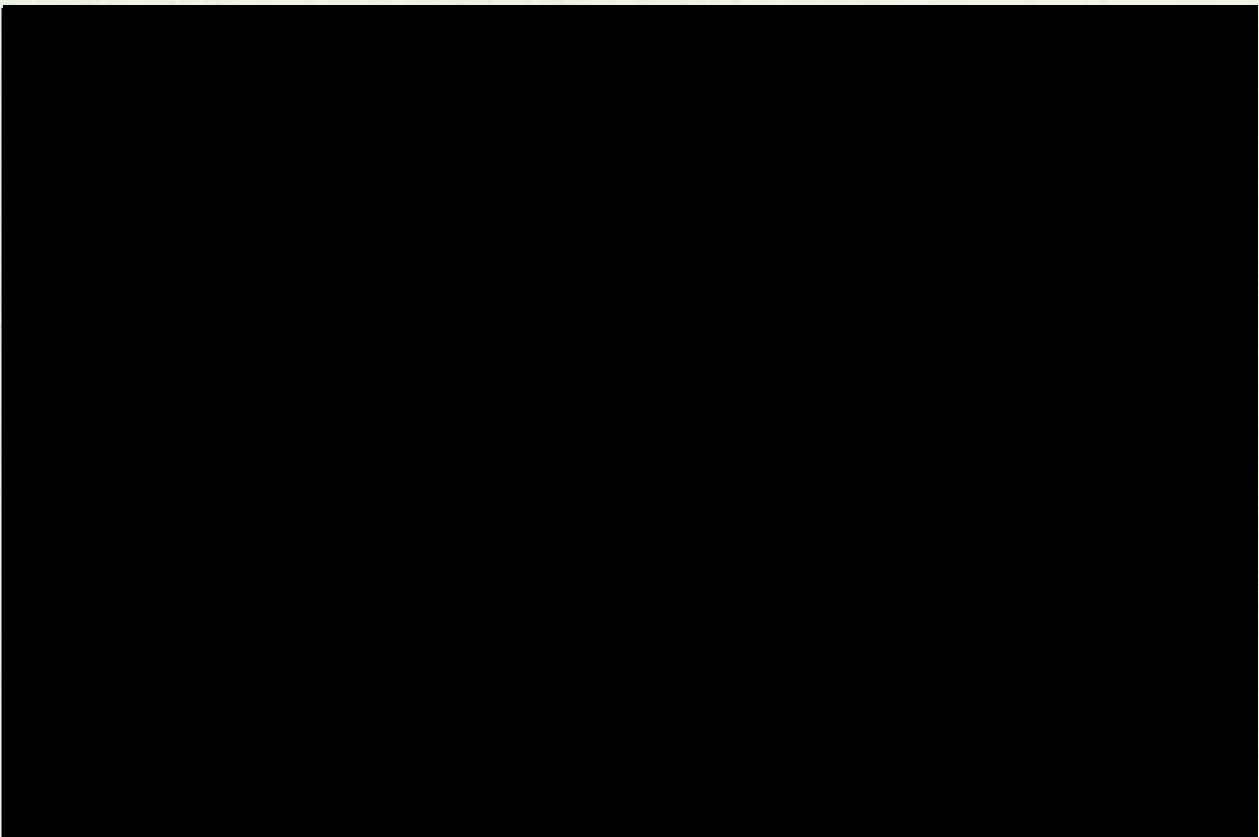


PLATE 1. Low velocity, medium angle impact
without obstruction.



PLATE 2. Survival of main structure of tail unit
after medium velocity, low angle impact
with trees.

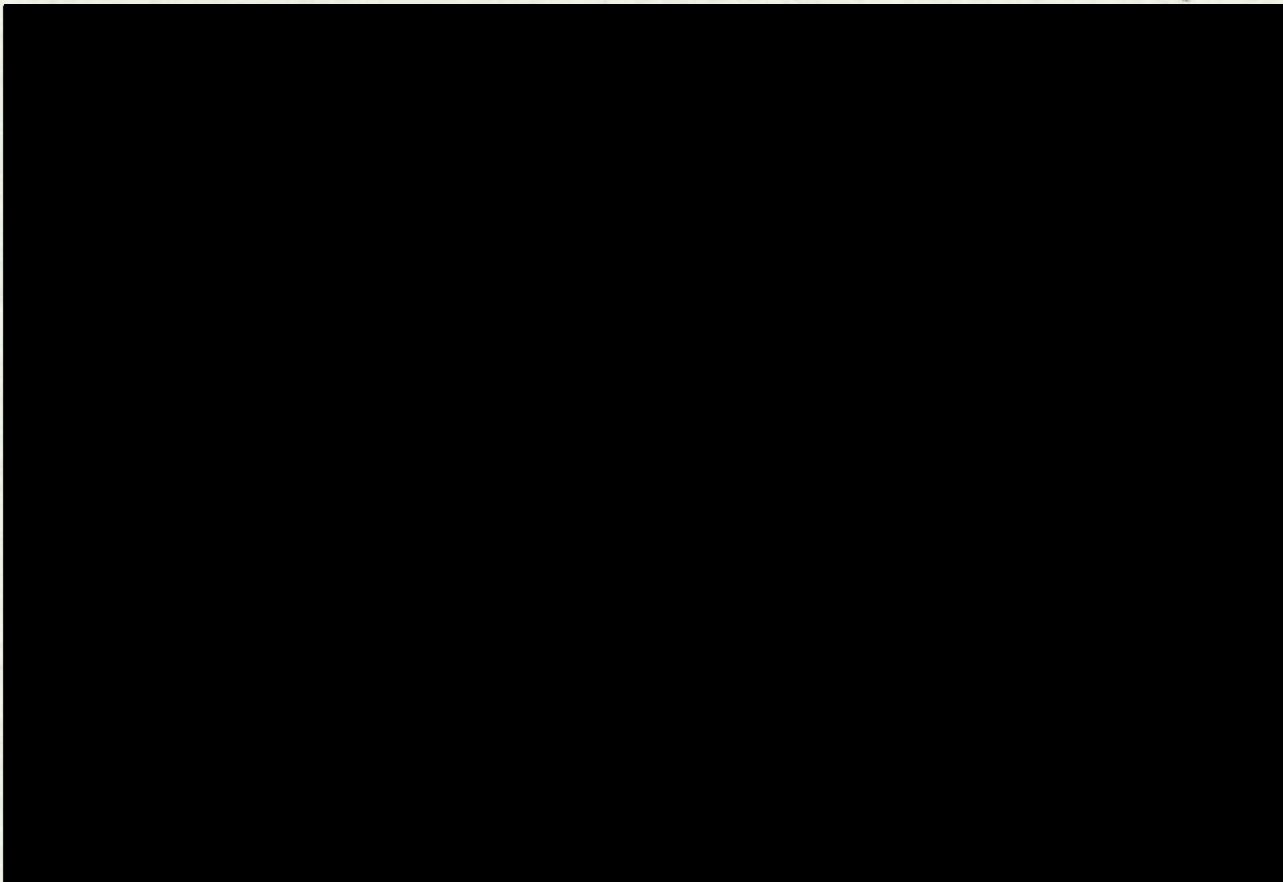


PLATE 3. Site of medium velocity, steep angle impact from which tail unit survived.

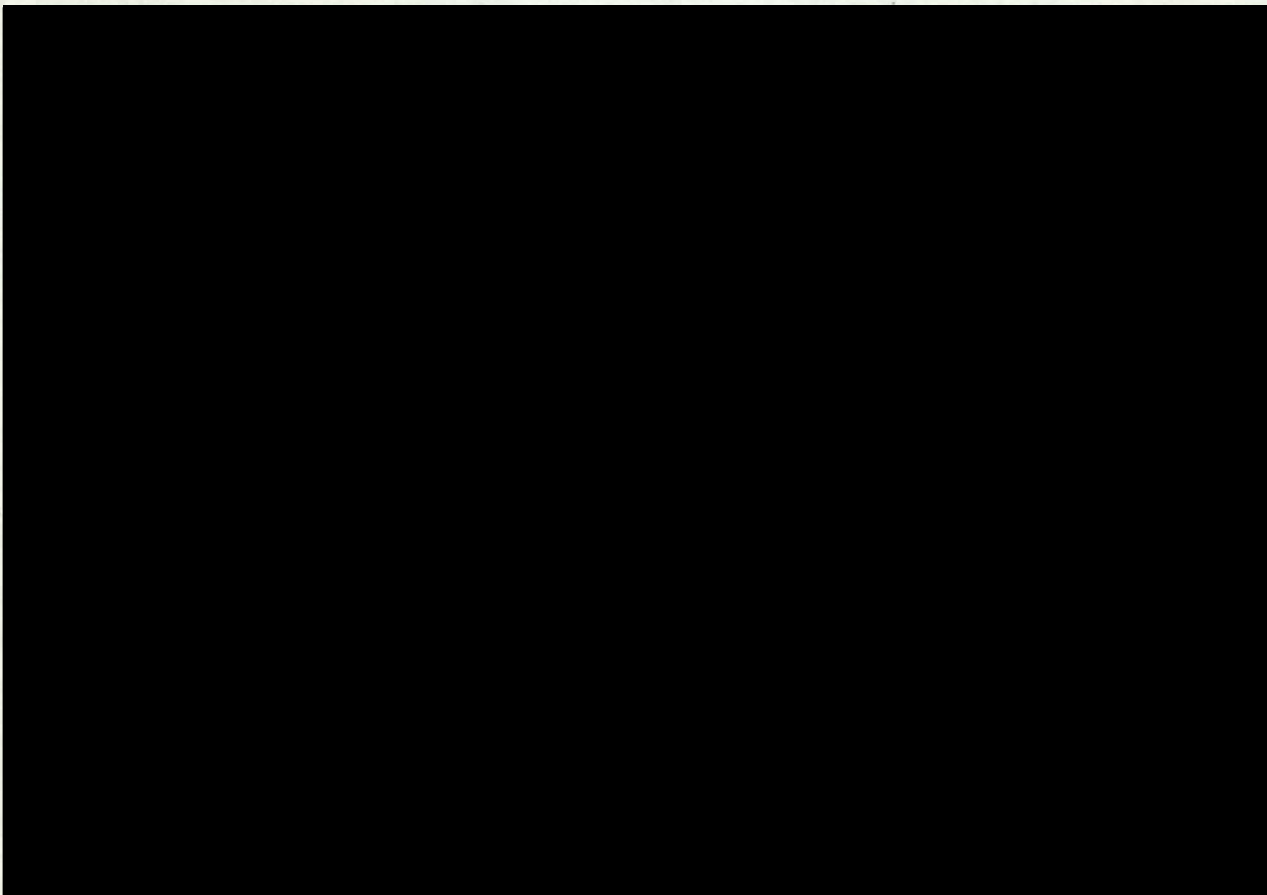


PLATE 4. Tail unit at accident site shown on Plate 3.

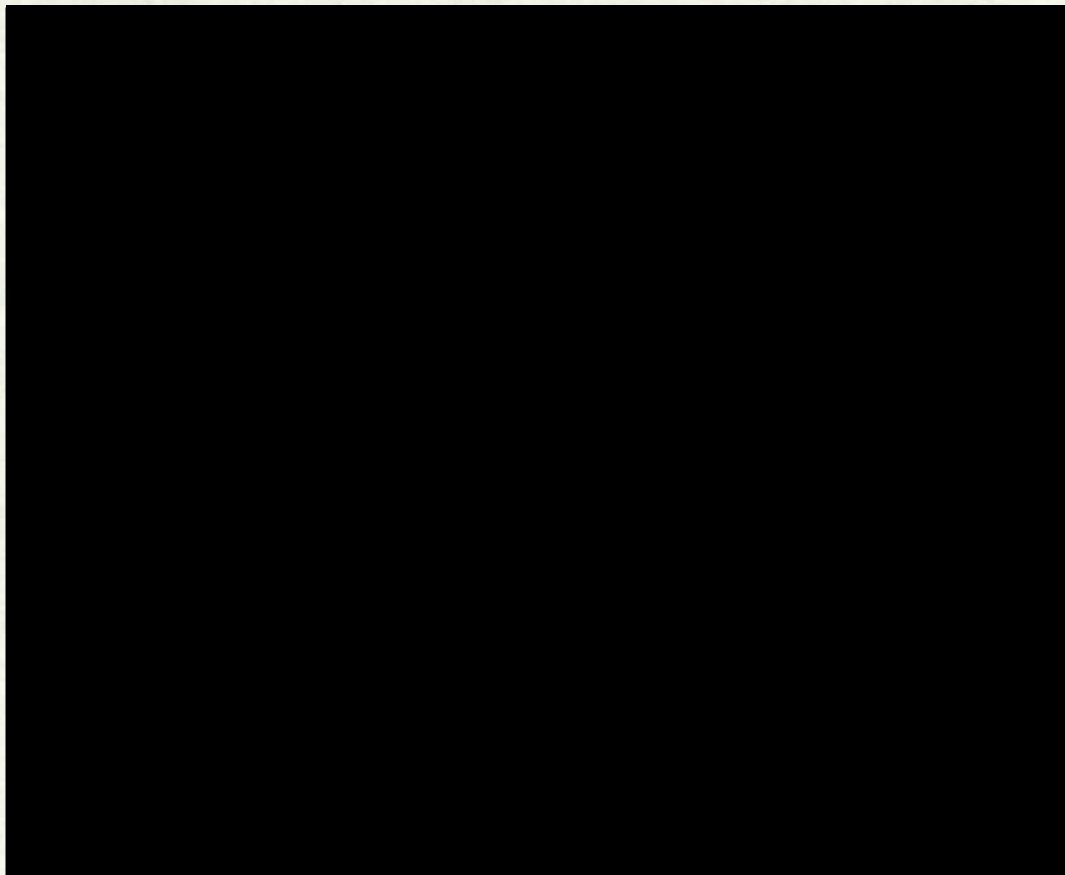


PLATE 5. Site of high velocity, steep angle impact from which large elements of tail unit survived.

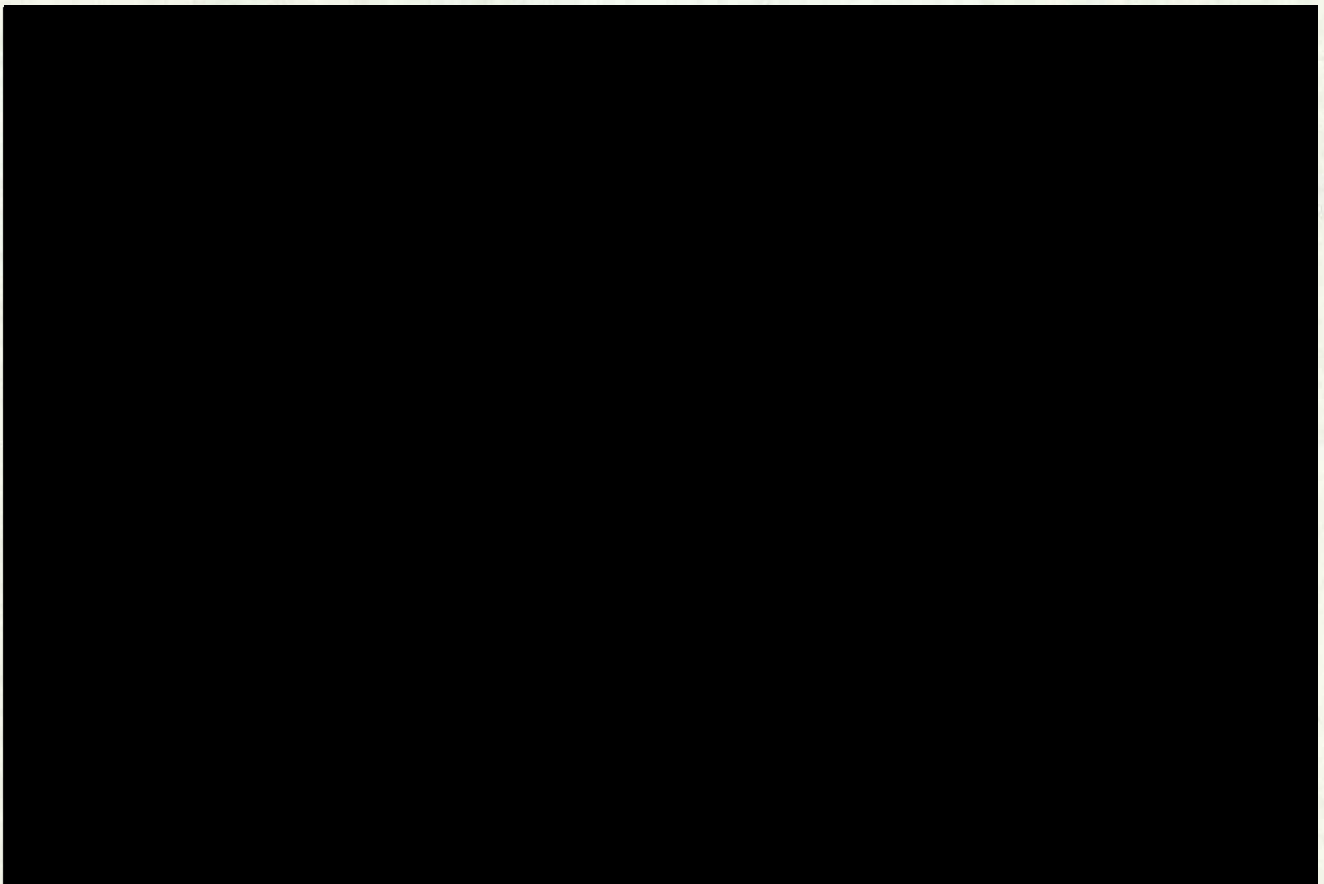


PLATE 6. Site of accident involving major fire showing partial survival of tail unit.

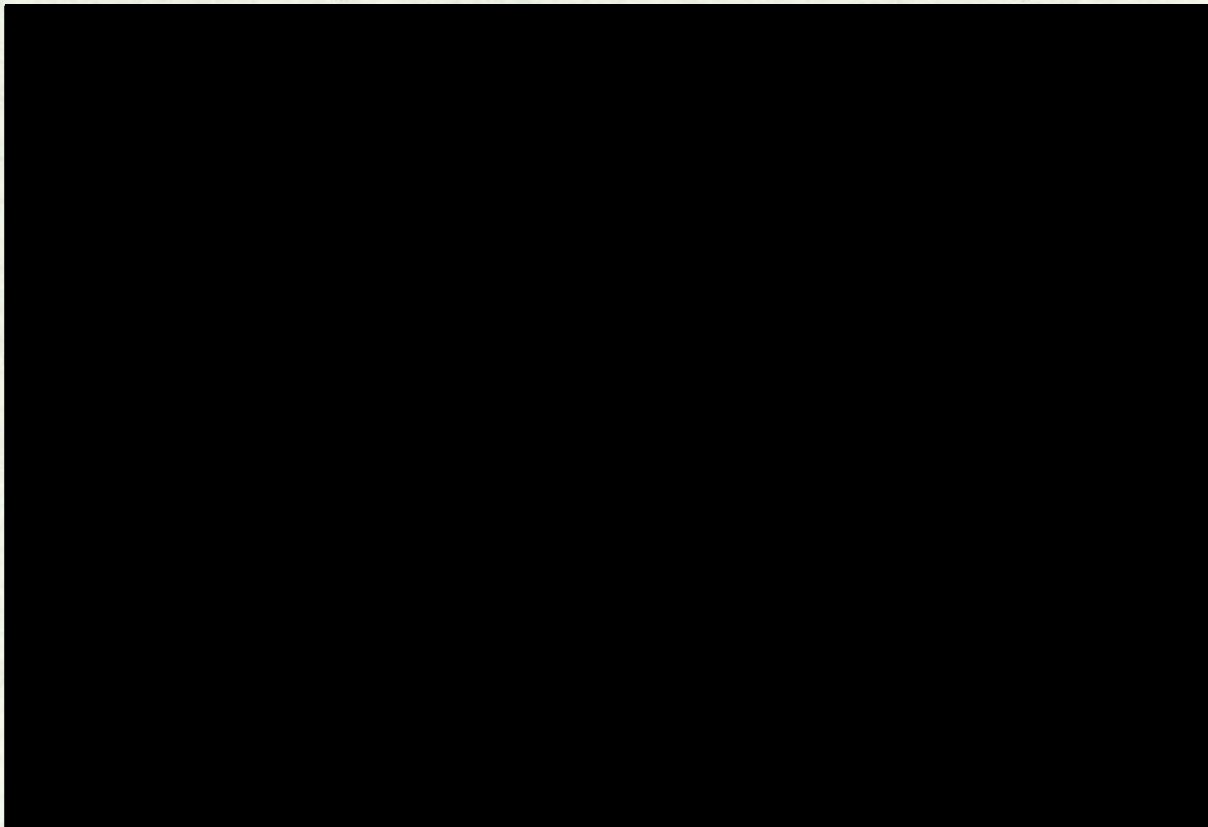


PLATE 7. Impact damage to foil medium of ADR after being released and thrown from installed position.

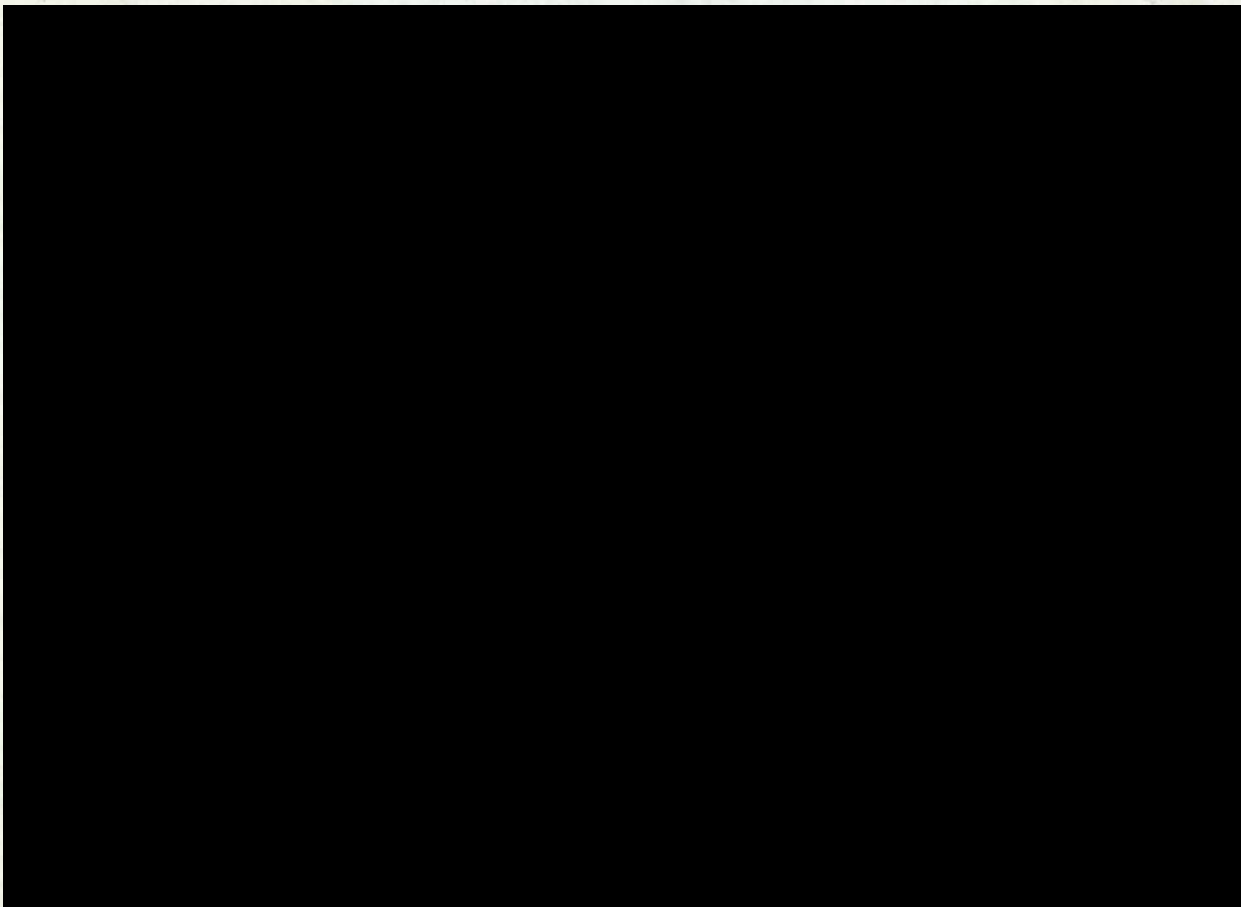


PLATE 8. Damage to foil medium due to combined effects of high temperature and chemical attack.

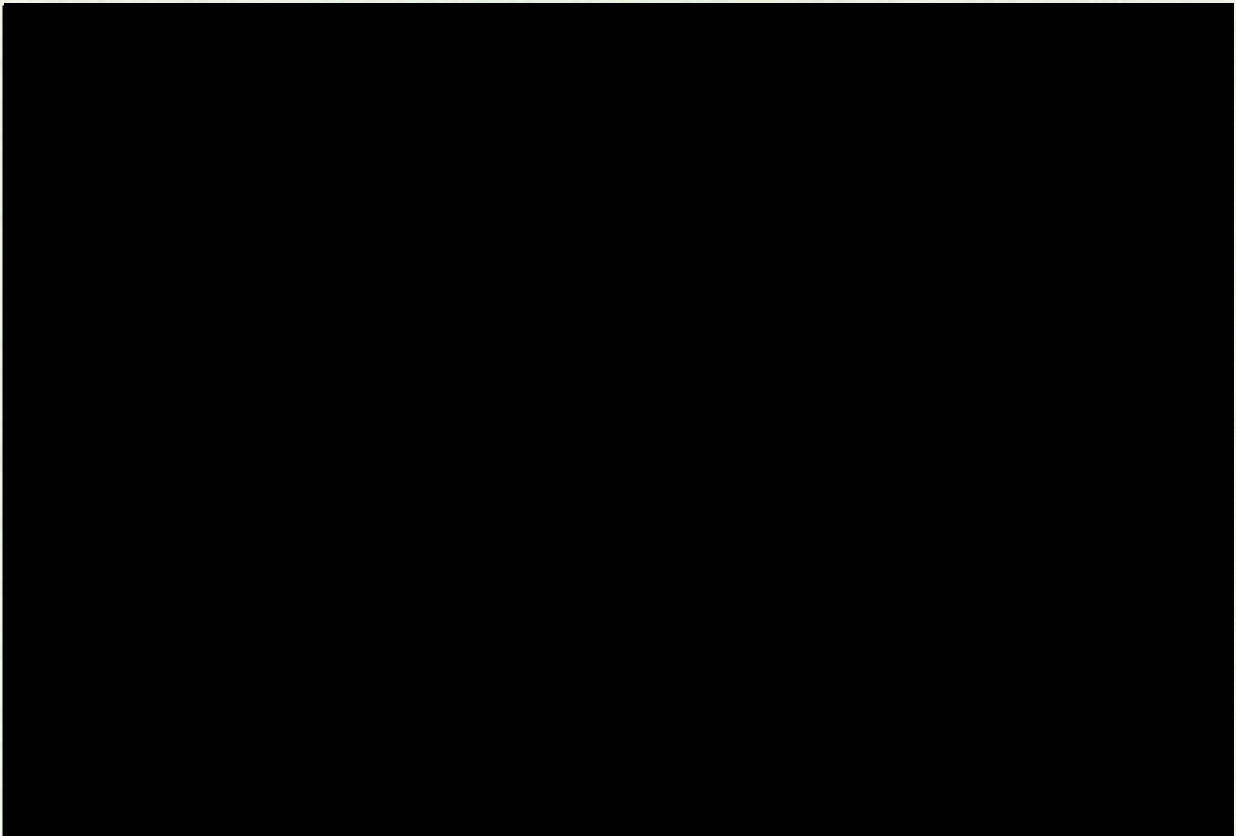


PLATE 9. Acceleration damage to aluminium foil medium.

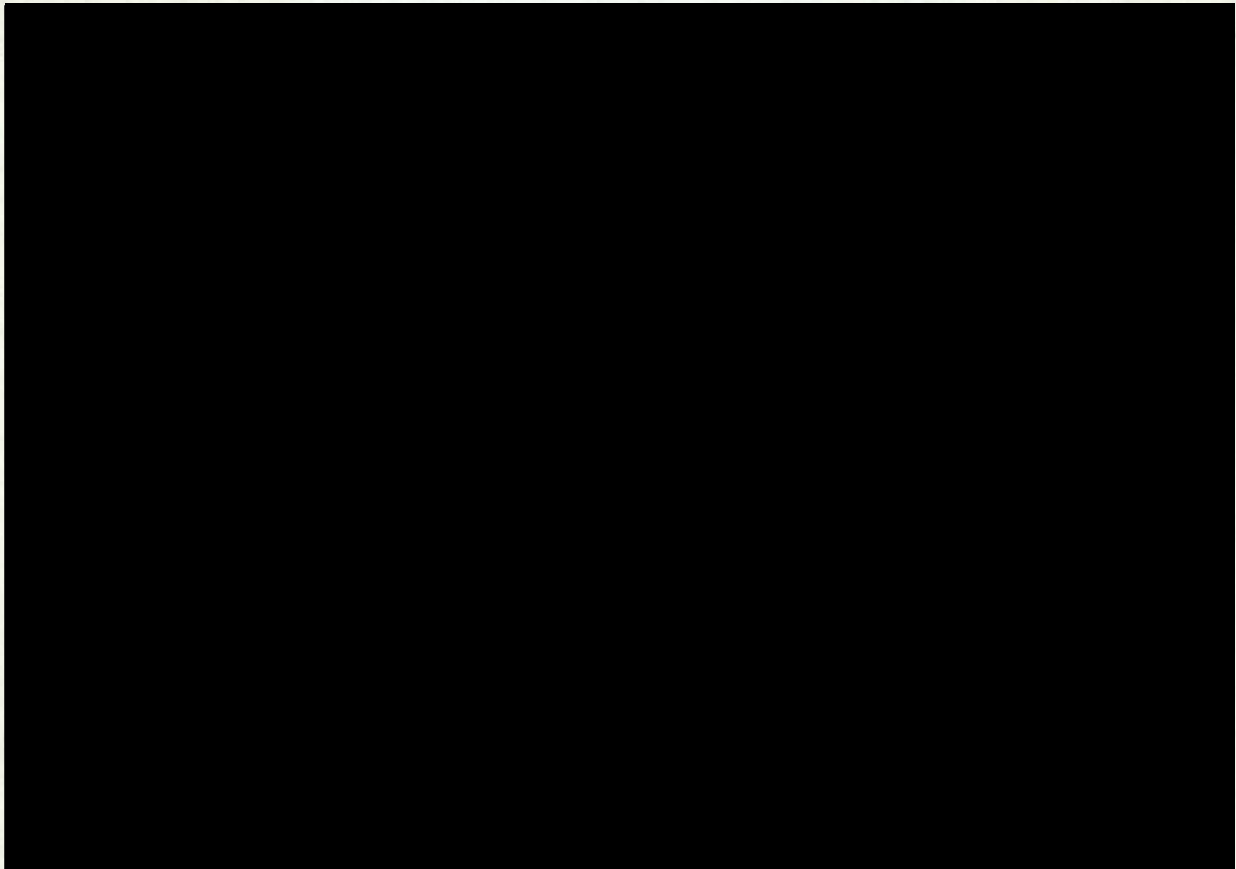


PLATE 10. Acceleration damage to plastic based tape medium.

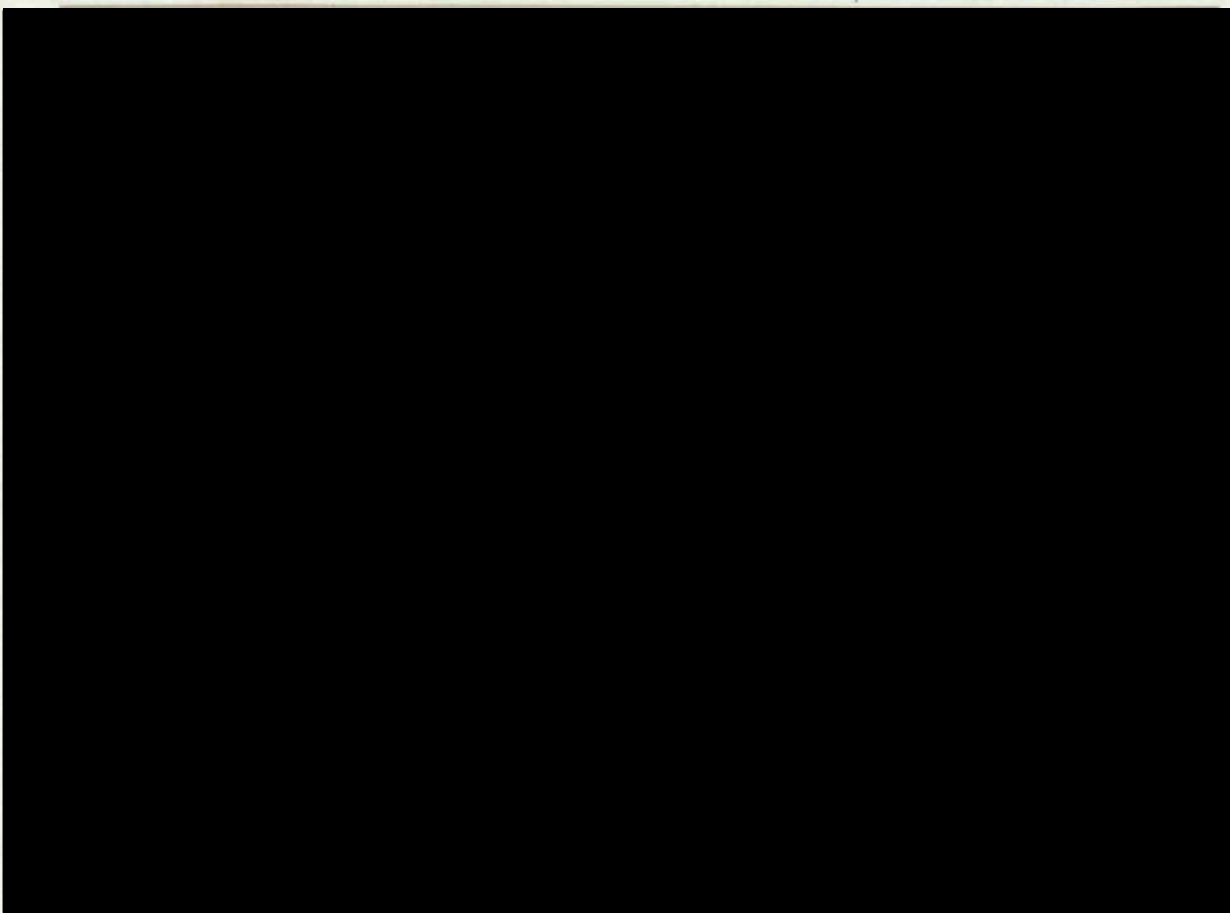


PLATE 11. Example of ADR constructed with spherical
outer case.

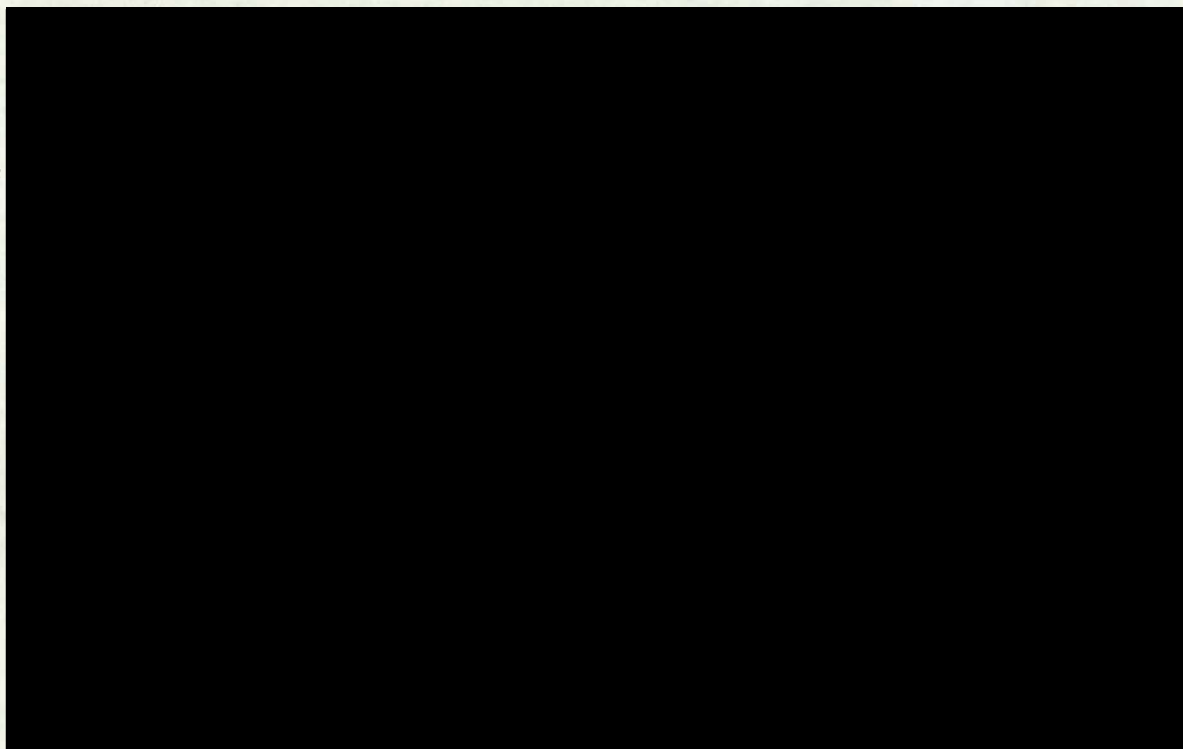


PLATE 12. Digital data signal recovered with low noise
after heating stainless steel wire medium
to 450° C

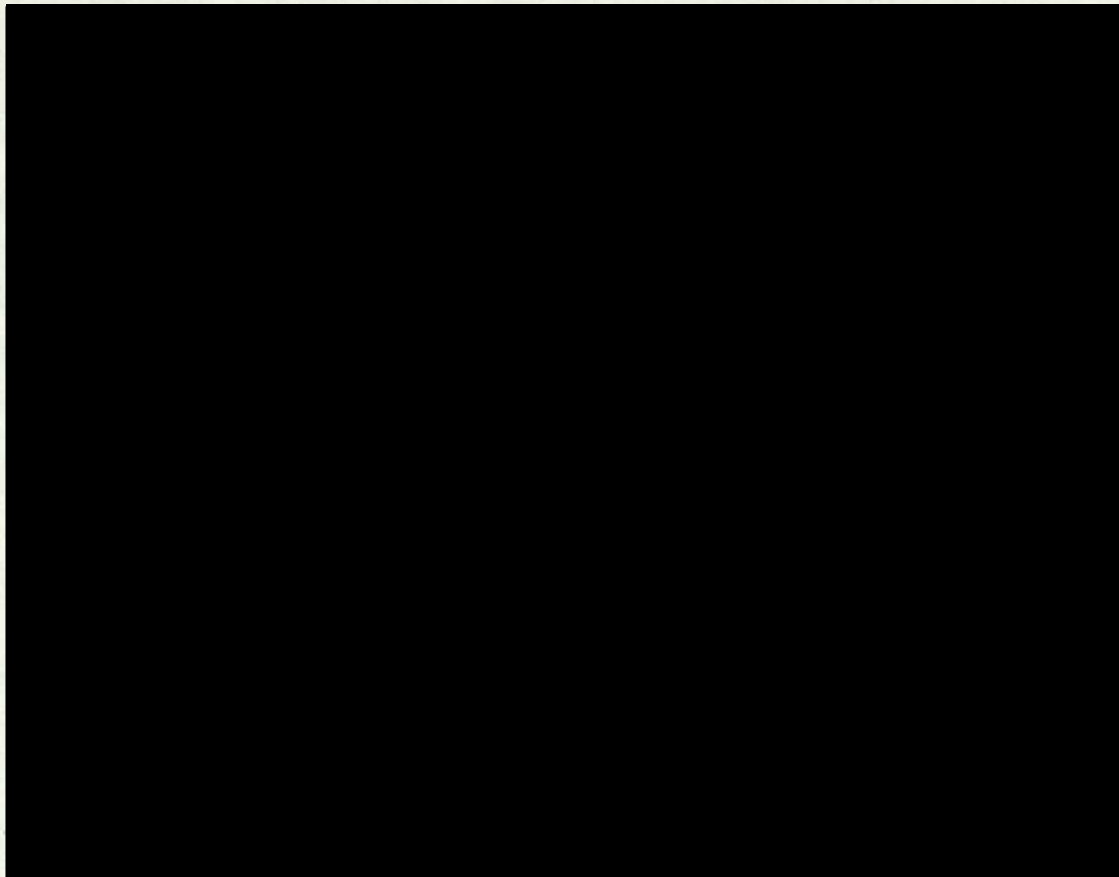


PLATE 13. ADR mounted in vulnerable position immediately forward of tailplane main spar.

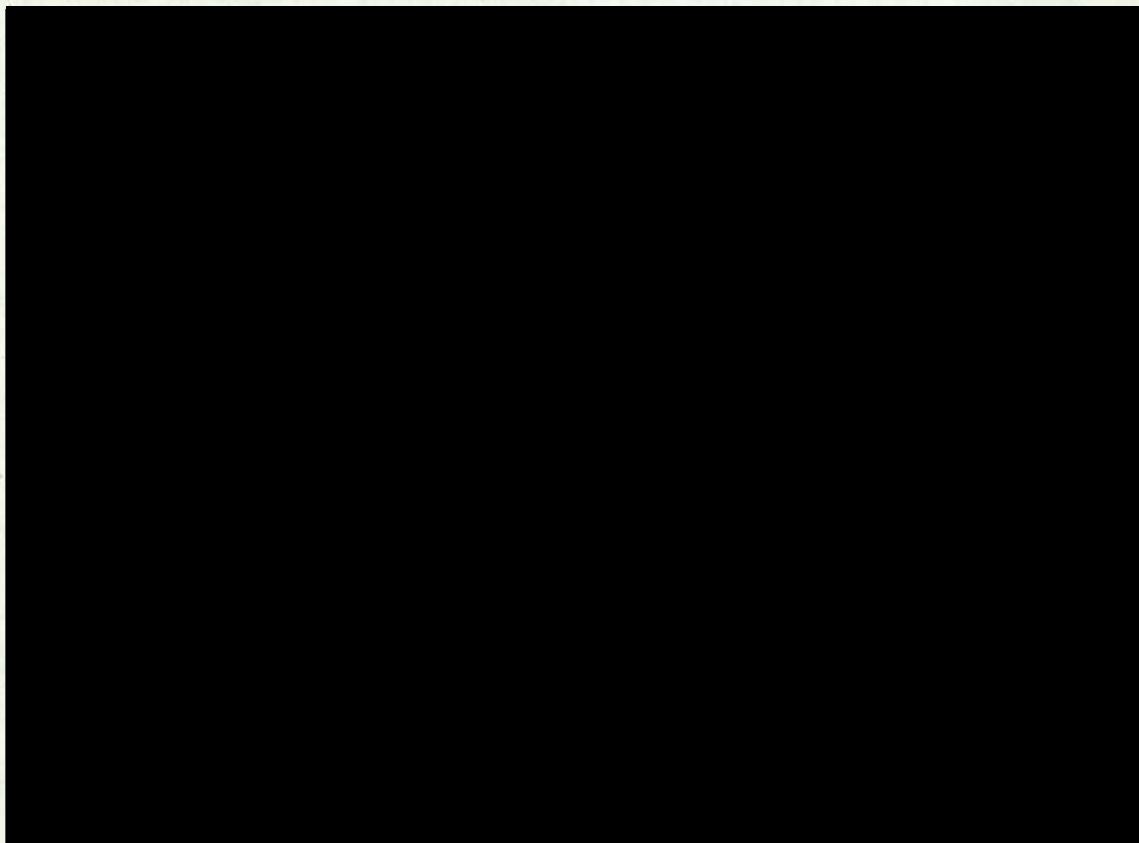


PLATE 14. Extensive impact damage to wire medium from ADR installed as in Plate 13.

APPENDIX A

This Appendix defines the equipment test procedures necessary to satisfy the present crash protection requirements for FDR and CVR installed in United Kingdom and United States registered aircraft as laid down by the respective airworthiness authorities of the two States. The airworthiness authorities of many other countries also base their requirements for crash protection upon one or other of the following standards. Details of the associated requirements and specifications may be found under the references quoted.

1 Flight Data Recorders - United Kingdom (Reference 29)

Crash Protection Requirements

The record shall be capable of analysis by normal playback techniques after a flight recorder(s) has been subjected to the following sequence of tests:-

- (i) Impact, penetration, crush, fire and fluids, excepting sea water.
- (ii) Impact, penetration, crush and sea water.

At the start of the fire tests the recorder shall be at its normal maximum internal working temperature, and shall be allowed to cool naturally after the test.

Test Procedures

- (a) Impact. The recorder shall be subjected to half sine wave impact shocks applied to each of the three axes in the most critical direction, and having a peak acceleration of 1,000 'g' for at least 5 milliseconds.
- (b) Penetration Resistance. The recorder shall be subjected to an impact force produced by a 226 kg (500 lb) steel bar which is dropped from a height of 3m (10 ft) on to the weakest face of the recorder in the most critical plane. The point of contact of the bar shall have an area no greater than 32mm^2 (0.05 in^2). The longitudinal axis of the bar shall be vertical at the time of impact.
- (c) Static Crush. The recorder shall be subjected to a static crush force of 22.25 kN (5,000 lbf) applied continuously but not simultaneously to each of the three axes in the most critical direction, for a period of 5 minutes.
- (d) Fire. At least 50% of the outside area of the recorder shall be subjected to flames of at least 1100 C for a period of 30 minutes.
- (e) Fluids (excepting seawater). The recording medium shall be immersed for 24 hours in each of the following fluids:-

Aircraft fuel - J.P.1 (Kerosene)
J.P.4

Lubricating Oil - D.Eng. RD2487

Hydraulic Fluid - DTD 585
Phosphate ester
based fluid

Fire Extinguishing Fluids - Water glycol + 62% water,
CO foam, methyl bromide,
2
freon 12, standard foam
liquid, dry powder, CTC,
BTM, BCF.

(f) Sea Water. The recorder or the recording medium shall be immersed in sea water for 30 days.

NOTE: Where the recording medium is immersed in sea water the recorder need not be subjected to the tests specified in (ii).

2 Flight Data Recorders - United States of America (Reference 30)

Crash Protection Requirements

(a) Impact. The intelligence on the record medium shall be capable of being analysed after the recorder has been subjected to the following impact shock: Types I and II - Half sine wave impact shocks applied to each of the three main orthogonal axes and having a peak acceleration magnitude of 1,000 g with a time duration of at

least 5 milliseconds. Type III - Acceleration not less than the shocks developed on contact with a horizontal rock surface, considering the direction of ejection and any provisions for alleviation of shock. With regard to the former, the aircraft shall be assumed to be tilted at least 30 degrees from horizontal in the most critical direction.

(b) Penetration resistance (Type I and II recorders only). The intelligence on the record medium shall be capable of being analyzed after the recorder has been subjected to an impact force equal to a 500-pound steel bar which is dropped from a height of 10 feet to strike each side of the enclosure in the most critical plane. The point of contact on the bar shall have an area that is no greater than 0.05 square inches. The longitudinal axis of the bar shall be vertical at the time of impact. NOTE: The objective of this test is to achieve protection of the record medium from possible damage caused by airframe structural members striking the recorder case during crash impact.

(c) Static crush (Type I and II recorders only). The intelligence on the record medium shall be capable of being analyzed after the recorder has been subjected to a static crush force of 5,000 pounds applied continuously, but not simultaneously to each of the three main orthogonal axes for a test period of 5 minutes.

(d) Fire protection. The record medium shall remain intact so that the intelligence can be analyzed after the recorder is exposed to flames of 1100 °C enveloping at least 50 percent of the outside area of the case for the following periods of time: Type I-30 minutes; Type II - 15 minutes; Type III - 15 minutes.

(e) Water protection. The intelligence on the record medium shall be capable of remaining permanent and reproducible after the record medium has been immersed in seawater for 36 hours.

3 Cockpit Voice Recorders - United Kingdom (Reference 31)

Crash Protection Requirements. The output level and distortion characteristics of a 1000 Hz signal previously recorded on each channel shall not have changed by more than 2 dB when the recording medium is played back after the voice recorder has been subjected to the tests of (1) and the recording medium to test of (2).

(1) Impact, shock and fire, (in this order).

(2) Sea water immersion.

Test Procedures

(a) Impact Shock. The recorder shall be subjected to an impact shock having a peak acceleration of at least 100 'g' and a time duration of at least 11 ms. The force shall be applied in the direction of the longest diagonal line that can be drawn through the recorder under tests.

(b) Fire

(1) At least 50% of the outside surface of the recorder shall be subjected to flames of not less than 1100 C for a minimum of 30 minutes.

(2) At the start of the fire tests the recorder shall be at its normal maximum internal working temperature and shall be allowed to cool naturally after the test.

(c) Sea Water Immersion. The recording medium shall be immersed in sea water for 48 hours.

4 Cockpit Voice Recorders - United States of America (Reference 32)

Crash Protection Requirements

(a) Impact Shock and Fire Protection Test.

(1) Apply to each of the four required recording channel inputs and input signal of 1,000 c.p.s. having a level within the range for which the equipment is designed for a period of 30 minutes.

(2) Remove the recording medium from the equipment and play it back on a suitable play-back equipment and determine the output level and distortion characteristic of the 1,000 c.p.s. signal on each channel using appropriate measuring equipment. Note the volume and tone control (if any) settings of the play-back equipment during this portion of the test and also the input power voltage.

(3) Replace the recording medium in the equipment under test in its normal location and subject that major component of the equipment under test which contains the recording medium, the recording mechanism, and such recording medium spools, conveyors and storage devices as may be parts of the equipment to an impact shock having a peak acceleration

of at least 100G and a time duration of at least 11 milliseconds.

If the shape of the equipment under test is other than spherical, the impact shock force shall be applied in the direction of the longest diagonal line that can be drawn through the equipment under test.

(4) Without making any repairs or alterations to that major component of the equipment which was subjected to the impact shock test in subparagraph (3) subject it to fire of at least 1,100^o C. The flames of the fire shall envelope at least 50 per cent of the outside area of the equipment under test for a continuous and uninterrupted period of at least 30 minutes. If, subsequent to the impact shock test in (3), a visual inspection of the outside of the equipment under test reveals areas of cracks, holes or other openings not existant prior to the impact shock test, these areas shall be included to the greatest extent possible in the required 50 percent of the outside area of the equipment that is enveloped by flames. Allow the equipment under test to cool naturally without the aid of water or other forced cooling.

(5) Remove the recording medium from the equipment which has been exposed to impact shock and fire and, using the same play back equipment, measuring equipment and control and input power voltage settings used in (2), play-back the recording medium and determine the output level and distortion characteristics of the 1,000 c.p.s signal on each channel. There shall be no more than a 2 db change from that previously measured in b, for either of these performance parameters and the recording medium shall be intact at the completion of the play-back.

(b) Water Immersion Test.

- (1) Apply to each of the four required recording channel inputs an input signal of 1,000 c.p.s having a level within the range for which the equipment is designed for a period of 30 minutes.
- (2) Remove the recording medium from the equipment and play it back on a suitable play-back equipment and determine the output level and distortion characteristics of the 1,000 c.p.s signal on each channel using appropriate measuring equipment. Note the volume and tone control (if any) settings of the play-back equipment during this portion of the test and also the input power voltage.
- (3) Remove the recording medium from the play-back equipment and completely immerse it in sea water at ambient room temperature for a period of at least 48 hours. During this portion of the test, the recording medium shall be normally mounted with respect to the recording mechanism, and such recording medium spools, conveyors and storage devices as may be a part of the equipment under test.
- (4) Remove the recording medium from the sea water and dry it using drying techniques suitable to the particular recording medium material.
- (5) Using the same play-back equipment, measuring equipment, and control and input power voltage settings used in (2), play back the recording medium and determine the output level and distortion characteristics of the 1,000 c.p.s signal on each channel. There shall be no more than a 2 db change from that previously measured in (2), for either of these performance parameters and the recording medium shall be intact at the completion of the play-back.

APPENDIX B

IDENTIFICATION OF ACCIDENT DATA

This Appendix provides a reference to the accident data used in this research and is subdivided into the groups referred to in paragraph 2.11.

- 1 Group A. This group comprised 954 accidents.
The accidents are not separately identified in this Appendix but they include all fixed wing aircraft accidents recorded in reference 28. between August 1971 and November 1976.

- 2 Group B. This group comprised 62 accidents each of which is separately identified as follows: Three groups of two digits representing the day, month and year of the accident is followed by a combination of letters or numbers which identifies the State in which the accident occurred by using the aircraft nationality marks of that country. (IW = International Waters). This combination is followed by the nationality mark of the aircraft and the last two letters or numbers of the aircraft's registration.

- 3 Group C. This group comprised 78 accidents each of which is separately identified in the same manner as those in Group B.

**Group B and Group C
identifiers (pp. 103-106)
have been removed**

APPENDIX C

This Appendix summarises the results of the Structural Outcome Analysis (paragraph 2.11 and 3.3) and of the Protection Statistical Study (paragraph 3.4).

For the 954 aircraft in Group A the analysis involved two assessments. The first assessment aimed to establish the probability of value of an ADR, whether or not one was fitted, to the investigation of each accident, the assessment being based solely upon investigative experience. The results of this assessment were used in determining the minimum acceptable survival rate for ADR (paragraph 2.7). The second part of the assessment was undertaken to provide broad structural outcome data with which to compare, on a greater statistical basis, the more detailed analyses of the accidents in Groups B and C.

The structural outcome study referred to in paragraph 3.3 involved all aircraft in Groups B and C. All the parameters enumerated in paragraph 3.3 were studied using established data from each accident case supported, in the cases of aircraft in Group C, with data recovered from the ADR. In the accident cases in these two Groups parts of the analyses were subdivided to separately reflect the outcome to aircraft which received catastrophic damage in the accident so that those results could then be compared with the groups as a whole. In this context the accident was deemed to be catastrophic if major disruption of the structure or separation of one or more major structural items took place or if an outbreak of fire occurred of such severity as to engulf a larger proportion of the aircraft. A probability of occurrence (P_o) value was derived for each of the

parameters. A significance factor (Fs) was then established for each parameter on the basis of investigative experience from which a significance weighting (Ws) was then derived (Ws being the product of Po and Fs). The Ws value was considered to be the most reasonable basis for establishing the relative importance of each parameter in the context of protection provision.

Structural Outcome Analysis

Group A. The results of the analysis of the structural outcomes to aircraft in Group A showed that neither structural dimensions nor mass volume of the aircraft had a significant effect upon the general structural outcome. The effect of the other variables, however, appeared to have a significance in this group generally similar to that in the other Groups.

Groups B and C. An analysis of the results of the structural outcome study relating to the accidents in Group B and C, under the headings of the individual variables examined - see paragraph 3.3, is summarised below.

(1) Impact Velocity

Impact velocity frequency distribution curves derived from a study of all accidents in Groups B and C and of all catastrophic accidents in those groups are shown in Figure 4. The disposition of the curves show that impact velocity may have played a significant part in determining whether or not of the accidents became catastrophic.

(2) Impact angle

Impact angle frequency distribution curves derived from the same accidents in (1) above are shown in Figure 5. These curves suggest that impact angles have a significant but not predominant effect upon structural outcome. The curves show

that at large impact angles the structural outcome is more likely to be catastrophic whilst a peak at about 15 degrees reflects the low impact angles at which multiple impacts were initiated.

(3) Terrain Penetration Potential

Terrain categorised as follows:-

Category (a) - High resistance to penetration (low penetration potential) - Runway Tarmac, Concrete Surface, Solid Buildings, Hard Rock.

Category (b) - Lower resistance to penetration (High penetration potential) - Sea or lakes, Wooded areas, Fields or other areas with growth (crops etc)

Total number of accidents examined - 140
 Total number of catastrophic accidents examined - 59
 The probability of any one of the accidents examined having a site with a low penetration potential - $P_o = 0.56$.
 The probability of any one of the accidents examined having a site with a low penetration potential and having a catastrophic outcome. - $P_o = 0.20$
 Total number of catastrophic accidents examined which terrain low penetration potential significantly affected the structural outcome - 3. $F_s = 0.25$
 $W_s = 0.05$

(4) Presence of Obstacles

Total number of accidents examined - 140.
 Total number of accidents in which obstacles were involved in initial impact - 34. $P_o = 0.24$
 Total number of catastrophic accidents examined - 59
 Total number of catastrophic accidents examined in which obstacles were involved in initial impact - 26 $P_o = 0.44$
 Total number of catastrophic accidents in which obstacles had significant effect upon structural outcome - 22 $F_s = 0.85$
 $W_s = 0.38$

(5) Development of Multiple Impacts

Total number of accidents examined - 140
 Total number of accidents in which multiple impacts developed - 50 $P_o = 0.38$
 Total number of catastrophic accidents examined - 59
 Total number of catastrophic accidents in which multiple impacts developed - 36 $P_o = 0.61$
 Total number of catastrophic accidents in which multiple impacts had significant influence upon structural outcome - 27 $F_s = 0.75$
 $W_s = 0.46$

(6) Release of Fuel

Total number of accidents examined	- 140	
Total number of accidents in which fuel was released	- 64	Po = 0.46
(These included all catastrophic accidents plus those in which minor fire and less significant damage occurred)		
Total number of catastrophic accidents examined	- 59	
Total number of catastrophic accidents in which fuel was released	- 59	Po = 1
Total number of catastrophic accidents in which fuel release affected outcome (ie fuel release resulted in an outbreak of fire)	- 46	Fs = 0.78 Ws = 0.78

(7) Ignition of Fuel

Total number of accidents examined	- 140	
Total number of accidents in which fire occurred	- 53	Po = 0.38
Total number of catastrophic accidents examined	- 59	
Total number of catastrophic accidents in which fire occurred	- 46	Po = 0.78
Total number of catastrophic accidents in which fire significantly affected the structural outcome	- 22	Fs = 0.48 Ws = 0.38

(8) Proximity of Primary Ignition Source to Fuel

Total number of catastrophic accidents examined	- 59	
Total number of aircraft involved in catastrophic accidents with all power units mounted at rear	- 19	
Total number of aircraft involved in catastrophic accidents with all power units at rear and in which fire occurred.	- 14	Po = 0.74
Total number of aircraft involved in catastrophic accidents with all power units fitted forward of the wing trailing edge	- 39	
Total number of aircraft involved in catastrophic accidents with all power units fitted forward of the wing training edge and in which fire occurred	- 31	Po = 0.79
Total number of aircraft involved in catastrophic accidents with one but not all power units fitted at rear	- 1	
Total number of aircraft involved in catastrophic accidents with one but not all power units fitted at rear and in which fire occurred	- 1	

The similarity of the P_o values above (0.74 in the rear power unit cases and 0.79 in the cases of power units forward of the wing trailing edge) permits a conclusion that the position of the power units is not of high significance in respect of the possibility of an outbreak of fire. The small sample (1) of the mixed power unit position case renders it of no significance in this assessment.

(9) Type of Fuel involved

Total number of accidents examined	- 140	
Total number of accidents in which fire occurred	- 53	
Total number of catastrophic accidents examined	- 59	
Total number of catastrophic accidents in which an outbreak of fire occurred	- 46	
Total number of accidents involving gasoline fuel	- 11	
Total number of accidents involving gasoline fuel and in which fire occurred	- 4	$P_o = 0.36$
Total number of catastrophic accidents involving gasoline fuel	- 3	
Total number of catastrophic accidents involving gasoline fuel and in which fire occurred	- 3	$P_o = 1$
Total number of catastrophic accidents involving gasoline fuel and in which fire had significant effect upon structural outcome	- 1	$F_s = 0.33$ $W_s = 0.33$
Total number of accidents involving kerosine fuel	- 129	
Total number of accidents involving kerosine fuel and in which fire occurred	- 49	$P_o = 0.38$
Total number of catastrophic accidents involving kerosine fuel	- 56	
Total number of catastrophic accidents involving kerosine fuel and in which fire occurred	- 43	$P_o = 0.77$
Total number of catastrophic accidents involving kerosine fuel in which fire significantly affected the structural outcome	- 21	$F_s = 0.49$ $W_s = 0.38$

The similarity of the W_s values above suggests that the probable effect upon the structural outcome from fires in which gasoline is the fuel is not likely to be significantly different from those instances in which kerosine has been used.

(10) Release of Components of High Mass

Total number of catastrophic accidents examined	- 59	
Total number of catastrophic accidents in which power units tore away at early stage of impact sequence	- 26	Po = 0.44
Total number of catastrophic accidents in which power units tore away at early stage of impact sequence and had significant effect upon structural outcome	- 17	Fs = 0.65 Ws = 0.28

(11) Generation of Explosive Disruptive Energy

Total number of catastrophic accidents examined	- 59	
Total number of catastrophic accidents in which fire occurred	- 46	
Total number of catastrophic accidents in which fire occurred and explosive disruptive energy was generated	- 17	Po = 0.28
Total number of catastrophic accidents in which the explosive disruptive energy generated had significant effect upon structural outcome	- 17	Fs = 1.0 Ws = 0.28

Protection Subsystem Analysis

(1) All accidents examined

Total number of accidents examined involving aircraft carrying ADR	- 78	
Total number of ADR fitted to those aircraft (some aircraft carried both FDR and CVR)	- 91	
Total number of ADR recovered	- 91	
Total number of ADR damaged by impact	- 23	Po = 0.25
Total number of ADR damaged by fire	- 13	Po = 0.14
Total number of ADR damaged by impact and fire	- 6	Po = 0.06
Total number of ADR that suffered chemical attack	- 2	Po = 0.02
Total number of ADR undamaged	- 61	Po = 0.67

(2) Retention/release of ADR

Total number of ADR released from installed location by impact	- 20	
Total number of ADR released and damaged by impact	- 18	Po = 0.90
Total number of ADR released and damaged by fire	- 6	Po = 0.30
Total number of ADR released and damaged by impact and fire	- 4	Po = 0.20
Total number of ADR released and undamaged	- None	

Total number of ADR remaining in situ	- 71	Po = 0.76
Total number of ADR remaining in situ and damaged by impact	- 6	Po = 0.08
Total number of ADR remaining in situ and damaged by fire	- 7	Po = 0.09
Total number of ADR remaining in situ and damaged by impact and fire	- 2	Po = 0.03
Total number of ADR remaining in situ and not damaged	- 60	Po = 0.85

(3) Siting of ADR (Catastrophic accidents)

Total number of ADR recovered from catastrophic accidents	- 48	
Total number of ADR sited forward of wing trailing edge	- 3	
Total number of ADR sited forward of tailcone/rear pressure bulkhead but aft of wing trailing edge	- 16	
Total number of ADR sited forward of wing trailing edge and damaged by impact	- 3	
Total number of ADR sited forward of wing trailing edge and damaged by fire	- 2	
Total number of ADR sited forward of tailcone but aft of wing trailing edge and damaged by impact	- 10	Po = 0.63
Total number of ADR sited forward of tailcone but aft of wing trailing edge and damaged by fire	- 5	Po = 0.31
Total number of ADR sited forward of wing trailing edge and released at impact	- 1	Po = 0.33
Total number of ADR sited forward of tailcone but aft of wing trailing edge and released at impact	- 10	Po = 0.63

(4) Catastrophic accidents examined

Total number of catastrophic accidents examined	- 59	
Total number of catastrophic accidents examined from which one or more ADR were recovered	- 39	
Total number of ADR carried in the catastrophic accidents examined	- 48	
Total number of ADR involved in the catastrophic accidents in which ADR suffered impact damage	- 23	Po = 0.48
Total number of ADR involved in the catastrophic accidents in which ADR suffered fire damage	- 13	Po = 0.27
Total number of ADR involved in the catastrophic accidents in which ADR suffered impact and fire damage	- 5	Po = 0.10
Total number of ADR involved in catastrophic accidents where ADR was mounted behind rear pressure bulkhead	- 29	
Total number of catastrophic accidents where ADR was mounted behind rear pressure bulkhead and tail unit survived as a single unit	- 23	
Total number of catastrophic accidents in which ADR was mounted aft of the rear pressure bulkhead and remained in situ	- 19	

Total number of catastrophic accidents in which the tail unit survived and the ADR, mounted aft of the rear pressure bulkhead, remained in situ and was:

damaged by impact	- None
damaged by fire	- 4

(5) Relationship of rear-mounted power units to ADR damage

Total number of catastrophic accidents involving aircraft with rear-mounted power units	- 21
Total number of catastrophic accidents involving aircraft with rear-mounted power units in which ADR were carried	- 13
Total number of ADR carried in above aircraft	- 16
Total number of above ADR released from installed location at impact	- 8
Total number of above ADR released from installed location and damaged by impact	- 6 Po = 0.75
Total number of above ADR retained in situ	- 8
Total number of above ADR retained in situ and damaged by impact	- 3 Po = 0.38

Note: The above ADR were installed in various locations in the aircraft. However, the higher damage probability value, $P_o = 0.38$, for the above ADR retained in situ compares unfavourably with the corresponding value, $P_o = 0.08$, which applies both to all accidents and to all catastrophic accidents examined. Although the statistical sample is small this suggests that the installed position of the power units may have been a factor in respect of the damage sustained.

(6) Relationship of aircraft mass volume to ADR damage

Total number of wide-bodied aircraft carrying ADR	- 8
Total number of wide-bodied aircraft carrying ADR: in which ADR was released at impact	- 1
in which ADR was released and damaged by impact	- 1
in which ADR were retained and remained undamaged	- 7

Note: In the 7 instances above in which the ADR were retained only 1 instance involved a catastrophic accident. The single instance in which the ADR was released also involved a catastrophic accident.

(7) Damage to recording media.

Total number of ADR recovered	- 91
Total number of ADR media recovered	- 91
Total number of media damaged	- 12
Total number of media damaged by impact	- 6
Total number of media damaged by fire	- 5
Total number of media chemically affected	- 2
Total number of media damaged by impact and fire	- None
Total number of media damaged by fire and chemical attack	- 1
Total number of media damaged by impact and chemical attack	- None

(8) Details of media damaged

Case 1. Medium - Stainless steel wire. ADR released. ADR sited aft of rear pressure bulkhead. ADR damaged by fire and impact. Heavy impact with some fire damage. Medium affected by high temperature. $V = 62$ m/sec $\gamma = 25$ deg

Case 2. Medium - Photosensitised paper. ADR retained. ADR sited forward of wing trailing edge. ADR damaged by fire and impact. Considerable fire damage in locality of ADR. Medium affected by high temperature. $V = 93$ m/sec $\gamma = 30$ deg

Case 3. Medium - Aluminium foil. ADR retained. ADR sited forward of wing trailing edge. ADR suffered minor external damage due to impact. No fire damage in spite of severe aircraft fire. Medium suffered damage due to acceleration forces on styli. $V = 61$ m/sec $\gamma = 10$ deg.

Case 4. Medium - Stainless steel foil. ADR released. ADR sited forward of wing trailing edge. ADR suffered external crushing after being projected through wreckage trail. Medium damaged by tearing. $V = 140$ m/sec $\gamma = 3$ deg.

Case 5. Medium - Stainless steel foil. ADR released. ADR sited in aft fuselage. ADR suffered fire and impact damage following aircraft collision with building. Medium damaged by tearing. $V = 72$ m/sec $\gamma = 10$ deg.

Case 6. Medium - Stainless steel wire. ADR released. ADR sited aft of rear pressure bulkhead. ADR suffered severe impact damage by crushing by tailplane spar. ADR medium completely fragmented. $V = 103$ m/sec $\gamma = 25$ deg.

Case 7. Medium - Stainless steel foil. ADR retained. ADR sited aft of rear pressure bulkhead. ADR exposed to heat and chemical fumes from burning butyl rubber within own pressurised container. Medium discoloured by heat and chemical attack. $V = 78$ m/sec $\gamma = 10$ deg.

Case 8. Medium - Photosensitised paper. ADR released. ADR sited in aft portion of cabin. ADR exposed to flash fire and high temperature. No impact damage. Photosensitised paper completely charred. $V = 57$ m/sec $\gamma = 2$ deg.

Case 9. Medium - Stainless steel foil. ADR released. ADR sited in pressurised container aft of rear pressure bulkhead. ADR suffered severe structural distortion due to impact. Medium damaged by tearing. $V = 87$ m/sec $\gamma = 70$ deg.

Case 10. Medium - Plastic based tape. ADR sited in starboard rear toilet area. ADR released. ADR suffered extensive exposure to fire and high temperature. Medium completely charred. $V = 82$ m/sec $\gamma = 15$ deg.

Case 11. Medium - Stainless steel foil. ADR sited above rear galley forward of rear pressure bulkhead. ADR severely crushed by impact. Medium distorted and torn by impact. ADR released. $V = 129$ m/sec $\gamma = 70$ deg.

Case 12. Medium plastic based tape. ADR sited in baggage hold forward of rear pressure bulkhead. ADR released. ADR crushed severely. Medium soaked with kerosine aircraft fuel.

V = 129 m/sec $\delta = 70$ deg.

Case 13. This case occurred after the general analysis in paragraph 3.3 had been completed. It is not included in the statistics but is significant to this research. It provides an example of deceleration damage to a plastic based medium, referred to in paragraph 3.7.2.1 and shown in Plate 10. The following details have been established:

Medium - plastic based tape. ADR sited forward of rear pressure bulkhead. ADR released. ADR crushed externally. No fire damage. Medium damage by deceleration forces.

V = 144 m/sec $\delta = 45$ deg.

APPENDIX D

This Appendix includes a summary of the assessments made of the value of an ADR to those accidents in Group A and of the impact and damage data relating to all multi-engined aircraft within that group. It also records basic data in either quantitative or state form in respect of the primary parameters examined during the structural damage and ADR survival assessments relating to those aircraft examined in Groups B and C. The detailed evaluations made in each case and the study of associated data in these groups could not be incorporated into the tabulated presentation. This Appendix cannot reflect, therefore, the subjective assessments made in each case.

D.1. Summary of ADR value and damage assessments
for Group A accidents.

Number of accidents in Group A - 954.

Number of multi-engined aircraft accidents in Group A - 193.

Number of accident cases in Group A where an ADR, if fitted, would reasonably have been considered of nil value - 37.

Number of accident cases involving multi-engined aircraft in Group A where an ADR, if fitted, would reasonably have been considered of nil value - 7.

Number of multi-engined aircraft in Group A that received significant damage with potential for the accident to have been more serious - 157.

Of these 157 accidents :-

128 involved low angle impact (≤ 15 deg) without structural break-up.

9 involved low angle impact (≤ 15 deg) with structural break-up.

1 involved higher angle impact (> 15 deg) without structural break-up.

19 involved higher angle impact (> 15 deg) with structural break-up.

D.2. Data relating to the primary parameters examined during structural damage assessments for accidents in Groups B and C.

The following key applies to the data headings in this section. X denotes applicable state.

- A. - Accident reference number.
- B. - Impact angle. Final flight path relative to terrain surface.
- C. - Impact velocity. Metres/sec.
- D. - Accidents in which structural damage was catastrophic.
- E.1. - Terrain penetration potential low.
- E.2. - Catastrophic accidents in which terrain penetration potential low.
- E.3. - Catastrophic accidents in which low terrain penetration potential significantly affected structural outcome.
- F.1. - Obstacles involved in initial impact.
- F.2. - Catastrophic accidents in which obstacles initially involved.
- F.3. - Catastrophic accidents in which obstacles had significant influence upon structural outcome.
- G.1. - Accidents involving multiple impacts.
- G.2. - Catastrophic accidents involving multiple impacts.
- G.3. - Catastrophic accidents in which multiple impacts had significant effect upon structural outcome.
- H.1. - Accidents in which fuel released.
- H.2. - Catastrophic accidents in which fuel released.
- H.3. - Catastrophic accidents in which released fuel resulted in fire.

- J.1. - Accidents in which fire occurred.
- J.2. - Catastrophic accidents in which fire occurred.
- J.3. - Catastrophic accidents in which fire significantly affected structural outcome.
- K.1. - Catastrophic accidents with power units installed in forward position.
- K.2. - Catastrophic accidents with power units installed in rear position.
- K.3. - Catastrophic with one but not all power units installed in rear position.
- L.1. - Accidents in which aircraft had power units fuelled by gasoline.
- L.2. - Catastrophic accidents in which aircraft had power units fuelled by gasoline and in which fire occurred.
- L.3. - Catastrophic accidents in which aircraft had power units fuelled by gasoline and in which fire had significant effect upon structural outcome.
- L.4. - Catastrophic accidents in which aircraft had power units fuelled by kerosine and in which fire had significant effect upon structural outcome.
- M. - Catastrophic accidents in which fire occurred and explosive disruptive energy was generated.
- N.1. - Catastrophic accidents in which power units tore away at early stage of impact.
- N.2. - Catastrophic accidents in which power units tore away at early stage of impact and had significant effect upon structural outcome.

APP. D.2.

A	B	C	D	E.1	E.2	E.3	F.1
1	25	62	X	X	X		
2	80	93	X				
3	3	41					
4	70	44	X				
5	60	77	X				
6	3	62		X			
7	80	93	X				
8	60	72	X				X
9	3	77		X			
10	3	72		X			
11	5	77	X	X	X		X
12	3	72		X			
13	3	57		X			
14	10	62	X				X
15	60	88	X				X
16	20	47	X	X	X	X	X
17	10	82	X				
18	3	62					
19	3	62					
20	3	59		X			
21	6	62		X			
22	3	51		X			
23	10	62		X			
24	80	77	X				
25	3	140	X				X
26	3	72		X			
27	5	82		X			X
28	10	72	X				X
29	15	37	X				
30	5	67		X			
31	70	51	X				
32	5	67	X	X	X		
33	3	34		X			X
34	5	62		X			
35	5	64		X			
36	15	62	X	X	X	X	X
37	5	129	X				X
38	25	103	X				
39	3	62		X			
40	3	67		X			

A	B	C	D	E.1	E.2	E.3	F.1
41	5	67		X			
42	3	72		X			
43	5	77		X			
44	10	51		X			X
45	10	78	X	X	X	X	X
46	15	59	X				
47	10	64		X			
48	10	64	X	X	X		
49	30	51	X				
50	12	64		X			
51	3	59		X			
52	3	64					
53	3	67		X			
54	3	62		X			
55	5	83	X				X
56	15	75	X				
57	10	77		X			
58	25	88	X				
59	3	64	X	X	X		
60	5	104	X				X
61	40	93	X				
62	10	77	X	X	X		
63	5	67					
64	5	67		X			
65	5	57		X			
66	5	67					
67	3	62		X			
68	3	72		X			
69	8	82	X				X
70	3	82		X			
71	5	72		X			
72	3	82	X				
73	3	77		X			
74	3	72		X			X
75	15	62	X				
76	5	72					
77	3	72		X			
78	60	129	X				
79	3	69		X			
80	5	67					

	A	B	C	D	E.1	E.2	E.3	F.1
	81	25	72	X				
	82	5	62		X			
	83	8	67		X			
	84	4	72		X			
	85	7	75		X			
	86	15	62	X	X	X		
	87	80	51	X				
	88	75	46	X				
	89	2	57	X				X
	90	2	62					
	91	70	44	X				
	92	45	51	X				X
	93	10	59		X			
	94	3	67		X			
	95	15	93					
	96	15	72	X				X
	97	3	72		X			
	98	3	69		X			
	99	5	67		X			
	100	2	3		X			
	101	5	72		X			
	102	10	62					X
	103	15	218	X				X
	104	20	46		X			X
	105	10	67		X			
	106	2	62		X			X
	107	3	67		X			
	108	80	80		X			X
	109	5	67		X			
	110	2	57		X			
	111	30	51	X				
	112	3	62		X			
	113	5	57					
	114	15	38		X			
	115	3	67		X			
	116	3	67		X			
	117	5	69		X			
	118	10	55		X			
	119	6	64		X			
	120	3	57		X			

APP. D.2.

A	B	C	D	E.1	E.2	E.3	F.1
121	2	15		X			
122	3	44	X				X
123	70	77	X				
124	3	67		X			
125	75	93	X				X
126	80	93	X				X
127	45	103	X				
128	5	78					X
129	3	64					
130	35	82	X	X	X		X
131	3	49		X			
132	3	57	X				X
133	5	73	X	X	X		
134	10	62		X			
135	70	87	X				
136	45	77	X				
137	30	82	X				X
138	25	67	X				X
139	15	82	X				X
140	70	129	X				

A	F.2	F.3	G.1	G.2	G.3	H.1	H.2
1			X	X	X	X	X
2						X	X
3							
4						X	X
5						X	X
6							
7						X	X
8	X	X	X	X	X	X	X
9							
10							
11	X	X	X	X	X	X	X
12							
13							
14	X		X	X		X	X
15	X	X	X	X	X	X	X
16	X	X	X	X	X	X	X
17						X	X
18							
19							
20							
21							
22							
23							
24						X	X
25	X	X	X	X	X	X	X
26							
27			X				
28	X	X	X	X		X	X
29			X	X	X	X	X
30							
31						X	X
32						X	X
33	X	X	X				
34			X				
35							
36	X	X	X	X	X	X	X
37	X	X	X	X	X	X	X
38			X	X		X	X
39							
40							

A	F.2	F.3	G.1	G.2	G.3	H.1	H.2
41							
42							
43							
44			X				
45	X	X	X	X		X	X
46						X	X
47							
48						X	X
49						X	X
50							
51							
52						X	
53							
54							
55	X	X	X	X	X	X	X
56			X	X	X	X	X
57			X				
58						X	X
59						X	X
60	X	X	X	X	X	X	X
61						X	X
62			X	X	X	X	X
63							
64							
65							
66							
67							
68							
69	X	X	X	X	X	X	X
70							
71							
72			X	X	X	X	X
73							
74							
75			X	X	X	X	X
76							
77							
78						X	X
79							
80							

A	F.2	F.3	G.1	G.2	G.3	H.1	H.2
81						X	X
82							
83			X				
84						X	
85							
86			X	X	X	X	X
87						X	X
88						X	X
89	X	X	X	X	X	X	X
90			X				
91			X	X		X	X
92	X		X	X		X	X
93							
94							
95							
96	X	X	X	X	X	X	X
97							
98							
99			X				
100							
101							
102							
103	X	X	X	X	X	X	X
104			X				
105			X				
106							
107							
108							
109							
110						X	
111			X	X	X	X	X
112							
113			X			X	
114			X				
115							
116							
117							
118							
119							
120			X				

A	F.2	F.3	G.1	G.2	G.3	H.1	H.2
121						X	
122	X	X	X	X	X	X	X
123						X	X
124							
125	X	X	X	X		X	X
126	X	X	X	X		X	X
127						X	X
128							
129							
130	X	X	X	X		X	X
131							
132	X		X	X	X	X	X
133			X	X	X	X	X
134			X				
135						X	X
136						X	X
137	X	X	X	X	X	X	X
138	X		X	X	X	X	X
139	X	X	X	X	X	X	X
140						X	X

A	H.3	J.1	J.2	J.3	K.1	K.2	K.3
1	X	X	X	X	X		
2	X	X	X	X	X		
3							
4							X
5	X	X	X	X			X
6							
7	X	X	X	X			X
8	X	X	X		X		
9							
10							
11	X	X	X	X	X		
12							
13							
14	X	X	X	X	X		
15	X	X	X		X		
16	X	X	X	X	X		
17							X
18							
19							
20							
21							
22							
23							
24						X	
25	X	X	X	X			X
26		X					
27							
28	X	X	X	X			X
29	X	X	X		X		
30							
31						X	
32	X	X	X	X	X		
33							
34							
35							
36	X	X	X		X		
37	X	X	X		X		
38	X	X	X		X		
39							
40							

A	H.3	J.1	J.2	J.3	K.1	K.2	K.3
41							
42							
43							
44							
45	X	X	X	X			X
46							X
47							
48						X	
49	X	X	X		X		
50							
51							
52		X					
53							
54							
55	X	X	X				X
56	X	X	X				X
57							
58	X	X	X				X
59	X	X	X			X	
60	X	X	X	X		X	
61						X	
62	X	X	X				X
63							
64							
65							
66							
67							
68							
69							X
70							
71							
72	X	X	X	X	X		
73							
74							
75						X	
76							
77							
78	X	X	X			X	
79							
80							

A	H.3	J.1	J.2	J.3	K.1	K.2	K.3
81					X		
82							
83							
84		X					
85							
86	X	X	X	X		X	
87	X	X	X		X		
88						X	
89	X	X	X	X		X	
90							
91	X	X	X		X		
92	X	X	X		X		
93							
94							
95							
96	X	X	X	X	X		
97							
98							
99							
100							
101							
102							
103	X	X	X				X
104							
105							
106							
107							
108							
109							
110		X					
111	X	X	X	X	X		
112							
113		X					
114							
115							
116							
117							
118							
119							
120							

A	H.3	J.1	J.2	J.3	K.1	K.2	K.3
121		X					
122	X	X	X			X	
123	X	X	X		X		
124		X					
125						X	
126	X	X	X			X	
127	X	X	X	X		X	
128							
129							
130	X	X	X		X		
131							
132					X		
133	X	X	X	X	X		
134							
135	X	X	X		X		
136	X	X	X	X	X		
137	X	X	X	X	X		
138	X	X	X		X		
139	X	X	X	X	X		
140	X	X	X			X	

A	L.1	L.2	L.3	L.4	M	N.1	N.2
1				X	X	X	X
2				X			
3	X						
4						X	
5				X	X		
6	X						
7				X			
8						X	X
9							
10							
11				X			
12							
13							
14				X			
15	X	X				X	X
16	X	X	X		X	X	
17							
18							
19							
20							
21							
22	X						
23							
24							
25				X	X	X	X
26							
27							
28				X	X		
29							
30							
31							
32				X	X	X	X
33							
34							
35							
36	X	X				X	X
37						X	X
38					X	X	X
39	X						
40							

A	L.1	L.2	L.3	L.4	M	N.1	N.2
41							
42							
43							
44							
45				X	X	X	X
46							
47							
48							
49							
50							
51	X						
52							
53							
54							
55					X	X	X
56							
57							
58							
59							
60				X		X	
61							
62							
63							
64							
65							
66							
67							
68							
69							
70							
71							
72				X			
73							
74							
75							
76	X						
77							
78							
79							
80							

A	L.1	L.2	L.3	L.4	M	N.1	N.2
81							
82							
83							
84							
85							
86				X	X	X	X
87						X	
88							
89				X	X	X	
90							
91						X	X
92							
93							
94							
95							
96				X		X	X
97							
98							
99							
100							
101							
102							
103					X	X	X
104	X						
105							
106							
107							
108							
109							
110	X						
111				X			
112							
113							
114							
115							
116							
117							
118							
119							
120							

A	L.1	L.2	L.3	L.4	M	N.1	N.2
121							
122							
123							
124							
125							
126					X		
127				X	X	X	X
128							
129							
130						X	
131							
132							
133				X			
134							
135					X	X	
136				X	X	X	
137				X		X	X
138							
139				X	X	X	
140						X	X

D.3. Data relating to the primary parameters examined during the ADR survival assessments for accidents in Group C.

The following key applies to the data headings in this section. X denotes applicable state.

- A. - ADR reference number.
- B. - Accident reference number. Note: some aircraft had more than one ADR installed.
- C. - Accidents in which structural damage was catastrophic.
- D. - Accidents in which structural damage was catastrophic but tail unit survived as an entity.
- E. - Installed position of ADR in catastrophic accidents.
 - E.1. - Tailcone/aft of rear pressure bulkhead.
 - E.2. - Forward of tailcone/rear pressure bulkhead but aft of wing trailing edge.
- F. - ADR released from installed position at impact.
- G. - ADR externally damaged by impact.
- H. - ADR externally damaged by fire.
- J. - ADR medium involved in catastrophic accidents.
 - J.1. - Steel wire, steel tape or steel foil.
 - J.2. - Plastic based tape.
 - J.3. - Aluminium foil or photosensitised paper.
- K. - Medium damaged by impact.
- L. - Medium damaged by fire.
- M. - Medium damaged by chemical attack.

A	B	C	D	E.1	E.2	F	G
1	1	X		X		X	X
2	2	X					X
3	4	X	X	X		X	X
4	9						
5	10						
6	13						
7	14	X	X				X
8	15	X	X	X		X	X
9	16	X	X	X			
10	18						
11	19						
12	20						
13	21						
14	25	X				X	X
15	27						
16	28	X		X		X	X
17	29	X			X		
18	30						
19	32	X	X	X			
20	33						
21	34						
22	35						
23	38	X		X		X	X
24	41						
25	42						
26	43						
27	44						
28	45	X	X	X	X		
29	45	X	X			X	X
30	46	X	X	X			
31	48	X	X	X			
32	49	X	X	X			
33	53						
34	55	X		X			X
35	56	X		X			X
36	60	X	X	X			
37	66						
38	68						
39	69	X	X	X			
40	70						

A	B	C	D	E.1	E.2	F	G
41	71						
42	72	X	X	X			
43	75	X	X	X			
44	78	X		X		X	X
45	83						
46	85						
47	86	X	X	X			
48	88	X	X	X			
49	89	X			X	X	
50	90						
51	91	X			X		X
52	92	X	X	X			
53	95						
54	96	X	X	X			
55	103	X			X	X	X
56	103	X			X	X	X
57	104						
58	104						
59	106						
60	108						
61	109						
62	111	X	X	X	X		
63	111	X	X				
64	113						
65	113						
66	114						
67	115						
68	117						
69	118						
70	120						
71	125	X	X	X			
72	125	X	X		X	X	X
73	128						
74	128						
75	129						
76	130	X	X		X	X	X
77	131						
78	132	X	X	X			
79	133	X	X	X			
80	133	X	X		X		

A	B	C	D	E.1	E.2	F	G
81	134						
82	134						
83	135	X	X	X		X	X
84	135	X	X		X	X	X
85	137	X	X	X		X	X
86	137	X	X		X	X	X
87	138	X			X		
88	139	X	X	X			
89	139	X	X		X	X	
90	140	X			X	X	X
91	140	X			X	X	X

A	H	J.1	J.2	J.3	K	L	M
1	X	X				X	
2	X			X		X	
3		X					
4							
5							
6							
7	X			X	X		
8		X					
9			X				
10							
11							
12							
13							
14		X			X		
15							
16	X	X			X		
17		X					
18							
19	X	X					
20							
21							
22							
23		X			X		
24							
25							
26							
27							
28	X	X				X	X
29	X		X				
30		X					
31			X				
32			X				
33							
34		X					
35		X					
36	X		X				
37							
38							
39		X					
40							

	A	H	J.1	J.2	J.3	K	L	M
T	41							
	42			X				
	43		X					
	44		X					
	45							
	46							
	47		X					
	48		X					
	49	X			X		X	
	50							
	51		X					
	52		X					
	53							
	54			X				
	55		X					
	56			X				
	57							
	58							
	59							
	60							
	61							
	62		X					
	63			X				
	64							
	65							
	66							
	67							
	68							
	69							
	70							
	71		X					
	72			X				
	73							
	74							
	75							
	76		X					
	77							
	78		X					
	79	X	X					
	80	X		X				

A	H	J.1	J.2	J.3	K	L	M
81							
82							
83		X			X		
84			X				
85		X					
86	X		X				
87			X				
88		X					
89	X		X			X	
90		X			X		
91			X				X

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ADDENDUM

Since this research was commenced a change in the mandatory installation requirements for ADR subject to French legislation has been introduced by the French authorities. The amended requirements, issued by the French Secretariat D'Etat aux Transports, include the mandatory provision of two independent means of attachment of the ADR to the aircraft structure. This requirement was introduced because of the failure to recover the ADR involved in the accident at reference 24. Although the reason for the introduction of this change is not the same as that for which Recommendation 5 of this thesis was introduced, the objective of close retention of the ADR within the aircraft structure is the same in both cases.