No. 9

British European Airways Corporation, Trident Series 1, G-ARPY,
accident 1 mile SSW of Felthorpe, near Norwich, Norfolk,
United Kingdom, on 3 June 1966.   Civil Accident Report EW/C/0130,
dated June 1968, released by the Board of Trade, United Kingdom, C.A.P. 311

1. - Investigation

1.1 History of the flight

        The aircraft took-off from Hatfield at 1652 hours to carry out the first of
a series of production test flights for the purpose of qualifying for a Series Certificate
of Airworthiness.   The schedule for the flight called for stalling tests should the air-
craft and the flight conditions be suitable.

        After take-off the aircraft climbed towards the north-east and at about
1830 hours, after completing the greater part of the flight test schedule, the stalling
tests were begun.   Three approaches to the stall were made in order to check the aircraft's
stall warning and stall recovery systems and the flight engineer's log shows that with the
aircraft in the landing configuration the stick shaker operated at 102 kt and the stall
recovery system at 93 kt.   The fourth stalling run was made at a height of 11 600 ft with
the aircraft still in the landing configuration but, in accordance with the requirements
of the test schedule, the stall warning and stall recovery systems had been made inoperative.

        Radio telephony communication with the aircraft consisted only of routine
messages until at 1834 hours when the pilot-in-command reported "We are in a superstall at
the moment".   This was the last radiocommunication received.

        At about this time the aircraft was seen over Felthorpe flying very slowly
heading south-west at about 10 000 ft.   The nose was seen to go up 30 to 40 degrees and
the aircraft began to turn to port; the starboard wing then dropped sharply and, following
a short burst of engine power, the aircraft went into a flat spin to starboard.   The spin
continued, the aircraft turning once every 6 to 8 seconds until it reached the ground about
a minute and a half later.

1.2 Injuries to persons

Injuries	Crew	Passengers	Others
Fatal	4		
Non-fatal			
None			

1.3 Damage to aircraft

          Destroyed.

1.4 Other damage

          Growing crops were damaged by the wreckage, rescue personnel and equipment.

1.5 Crew information

          Mr. Peter Barlow, aged 39, held a valid commercial pilot's licence endorsed in Part 1 for HS 104, HS 125, Comet and Trident aircraft. He qualified as a pilot in the Royal Navy in 1949 and in 1953 completed a course at the Empire Test Pilot's School; he served with the Naval Test Squadron until 1958, and then joined the de Havilland Aircraft Company as a development test pilot on Sea Vixens. He joined the Trident development programme in 1962 and later assisted Iraqi Airways and Kuwait Airways with Trident 1E crew training. His total flying experience amounted to about 4 500 hours including about 1 600 hours test flying of the Trident. He first flew as test pilot-in-command of the Trident after 80 flights as co-pilot and two flights in command under supervision with the chief test pilot. Since then he had made 416 test flights in command of Trident 1 aircraft and 52 in command of Trident 1E aircraft. He had taken part in about 2 195 stalls on the Trident in various configurations including 750 as pilot-in-command.

          Mr. G.B.S. Errington, OBE, aged 64, had held a valid private pilot's licence since 1930. He had qualified as a ground engineer in 1932. In 1935 he joined Airspeed Limited as a test pilot and became chief test pilot in 1939. In 1949 he undertook the development and production test flight programmes for the Airspeed Ambassador. At Hawker Siddeley he was responsible for operations liaison with airlines flying Comets and Tridents and helped as required on test work at Hatfield. At the time of the accident his licence was endorsed for group A and B aircraft and he had accumulated a total of 6 800 flying hours.

          Mr. E. Brackstone-Brown, aged 47, was chief flight test engineer with Hawker Siddeley Aviation at Hatfield and had been in charge of flight engineering in the flight test department from 1949. Since that time he had flown over 2 000 hours on development and production testing in Comet and Trident aircraft.

          Mr. G.W. Patterson, aged 43, joined the de Havilland Flight test department as a radio navigator in 1958 after eleven years as a radio officer in BOAC. His flying experience in Trident aircraft amounted to 57 hours.

1.6 Aircraft information

Trident G-ARPY

          The Trident 1 is a turbine-powered rear-engined, swept-wing, high-tail transport aircraft fitted with adjustable high lift devices including a droop leading edge. The flying controls are hydraulically operated, and the tail plane is all moving, with a geared elevator to improve its effectiveness. G-ARPY was the twenty-third production Trident 1 aircraft. It was a standard aircraft with standard equipment, except that a specially calibrated airspeed indicator was fitted to assist the pilot to control

the airspeed accurately during the stalling tests. At the time of the accident its weight was approximately 32 800 kg and the centre of gravity was at 0.246 mean aerodynamic chord (MAC), the normal position for these tests. The fuel was standard aviation kerosene.

Development testing

Part of the intensive pre-production test programme for the Trident was devoted to examining the stalling characteristics. Ideally there should be a clear warning of an imminent stall; at the stall an aircraft should pitch nosedown so strongly that the pilot cannot keep the wing stalled by applying nose-up elevator and there should be no tendency for a wing to go down. Such characteristics are diff ult to achieve with aircraft of the physical shape of the Trident. High lift devices and a powerful tail plane increase the difficulty.

In spite of a programme of over 3 000 stalls and much wind tunnel testing it was not found possible to produce the ideal stalling characteristics in the Trident aero-dynamically and an electrically operated stall warning system (stick shaker) was therefore incorporated to comply with British Civil Airworthiness Requirements. As the natural nose-down pitch of the aircraft could only be detected by very careful handling and as the tail plane was powerful enough to permit the pilot to overcome this nosedown pitch, a stall recovery system was installed. This consisted of a pneumatic stick-pusher triggered by the same incidence detecting system as the stall warning device, to push the control column forward and pitch the aircraft nosedown before the wing became fully stalled. It included compensation for the rate of change of pitch attitude.

Production flight tests

It was agreed between the constructor and the Air Registration Board that before any newly constructed Trident was delivered to the operator it would undergo a series of flights covered by a Production Flight Test Schedule. During these flights, checks were made to ascertain, among other things, that the stall warning and stall recovery systems worked as intended. After one or two of the first batch of aircraft had shown that a wing-drop might be encountered at or near the stick-push, a further stall check was added to ensure that the aircraft would remain reasonably level laterally through the stall. When the stall warning and recovery systems had been found to operate satisfactorily, and at the right speeds, the pilot was required by the test schedule to switch them off and, using as datum the airspeed at which the stall recovery system had operated, to explore the speeds between the onset of the stall and the speed at which the greatest permissible deployment of the stall over the wing occurred.

Many hundreds of tests on the final Trident 1 configuration, including a series flown by Mr. Barlow to investigate detail problems on production aircraft, had shown that the normal breakdown of flow at the stall took 3 or 4 kt (of pilots' ASI reading) to spread from the initial small local area over the whole of the inner wing. This spread was always accompanied by a sharp increase in buffet in a lag stall. A wing-drop could result from either a delay in the matching of the spread of the stall on both inner wings or from a premature loss of lift over one tip section; in the latter case the buffet was usually not so marked.

For performance purposes the operation of the stick-pusher at low rates of approach to the stall had been accurately tied, in terms of incidence, to the peak of the lift curve and hence the start of the development of the stall. There was agreement between the manufacturer and the ARB that there should be a small margin beyond this point which provided a safeguard against an uncontrollable wing drop developing as a result of a delayed stick-push.

When the additional check on the stall was added to the test schedule there was no simple readily available means of incidence presentation for production Trident 1 aircraft and, as later versions of the aircraft with a leading edge slat had regularly operated to much higher incidences without problems, an incidence meter was not considered necessary. Instead a specially calibrated airspeed indicator was fitted. In view of the extensive development experience it was considered a safe test flying technique first to make an accurate correlation of airspeed and incidence during a stall with the stick-pusher operating and then to switch it off and to reduce this speed by the 3 to 4 kt margin established for the deployment of flow separation. As flow separation developed, it produced a sharp increase in buffet and as an additional safeguard the pilots were told to recover immediately any buffet was felt regardless of the ASI reading. This additional check was carried out by the manufacturers only and was not to be repeated in the service life of the aircraft.

Examination of the flight engineer's log for the subject flight shows that the test had followed the standard procedure. The recorded speeds for the operation of the stick shakers and stick-pusher were normal for the weight and configuration of the aircraft. Additional data for the flight is contained in Section 1.11.

The superstall

With the aim of making recovery from the stall a natural characteristic of a swept-wing aircraft the wing is usually designed so that as its incidence increases to the critical stalling angle, the root (forward) portion stalls first thereby producing a nose-down pitching moment. However, to appreciate what happens to the overall aircraft pitching moment it is necessary to consider contributions arising from the fuselage and tail plane. A large fuselage with appreciable forward overhang generates a nose-up contribution to the pitching moment as incidence is increased. Below stalling incidence the tail plane contribution, which increases with incidence, is sufficient to overcome the unstable nature of the pitching moment arising from the wing-fuselage combination.

However, it is inherent in a high-tail design that at angles of incidence appreciably above the stall the tail plane will be in the wake behind the wing. At these angles of incidence the velocity of the airflow in the wake is low and this seriously reduces the efficiency of the tail plane. The tail plane contribution to the overall pitching moment can also be adversely affected by changes in flow direction. Thus, while the tail plane contribution may still be in a nosedown sense, it will be much reduced. In addition, the contribution from the wing may have been made less nosedown by the spread of the stall over the entire wing. The combined effects of wing and tail plane can then be insufficient to overcome the large fuselage contribution and, when incidence is increased appreciably beyond the stall, the nosedown pitching moment can give way to a marked nose-up tendency.

Loss of lift resulting from the development of the stall causes the aircraft to sink and this further increases the incidence to the relative airflow so that the situation becomes unstable. Also a long rear-engined layout implies large inertia in pitch and so results in a tendency to overswing, thereby aggravating the effect of the unstable aerodynamic situation. In these circumstances great care has to be exercised to avoid too deep a penetration into the post-stall regime.

For certain aft positions of the centre of gravity the overall pitching moment can be nose-up over a certain range of incidence angles even with the control column fully forward. The aircraft then will tend towards and stay in the neighbourhood of the upper limit of this incidence range and, as simple nosedown application of control will have a negligible effect, is said to be "locked in" a stalled condition, or to be "superstalled". It can only be brought back into the normal flying regime by means of an additional device such as a tail parachute. G-ARPY was not fitted with such a device and at the time of the accident its centre of gravity was within the critical range.

On the Trident 1, at the rate of approach to the stall of 1 kt per second specified in the test schedule, the incidence for stick-pusher operation was $17\frac{1}{2}^{\circ}$. During the reduction in airspeed of 3-4 kt the incidence could rise to $19\frac{1}{2}^{\circ}$ to $20\frac{1}{4}^{\circ}$ depending on the pilot's technique. Although no firm figures of maximum permissible incidence to avoid a superstall had been quoted before the accident, values of 22° to 23° were seen on occasions on the Trident 1E development aircraft.

Although it was appreciated that a more forward C of G would give greater safety in the event of late recovery action, in view of the considerable background experience the manufacturer and the ARB considered that the tests with the stick-pusher inoperative could be safely undertaken at the C of G position obtained on an empty aircraft without ballast. This C of G position was still well forward of the aft limit.

1.7   Weather

An anticyclone over southern England was declining slowly; the weather was fine with little or no cloud with the wind from the WSW at 6-12 kt. The weather had no bearing on the accident.

At the time of the accident the sun was in the west and should not have caused the pilots any inconvenience.

1.8   Aids to navigation

Not relevant to this accident.

1.9   Communications

Communications with various stations by R/T or VHF were normal and suggest that the flight was without significant incident until about 1833 hours.

1.10   Aerodrome and ground facilities

Not relevant to this accident.

1.11   Flight recorder

The aircraft was fitted with a Plessey-Davall type PV 710 Flight Data Recorder System. This was a digital type system using pulse code modulation on an electric magnetic wire. In addition to a time scale, the parameters recorded were as follows:

            Indicated air speed   -   1 sample per second

            Pressure altitude   -   1 sample per second

            Heading   -   1 sample per second

            Normal acceleration   -   5 samples per second

            Pitch attitude   -   5 samples per second

The recorder was installed in the aircraft above the centre engine at the base of the fin. It sustained only slight damage in the accident. Play-back was achieved without difficulty and this showed that information had been recorded throughout the accident flight with the exception of the take-off and a period immediately prior to the crash when it had been switched off by the airspeed switch.

The time history of the flight parameters for the last three minutes of recorded flight is contained at Appendix A. The stalling tests begin at a height of 15 700 ft which agrees with the flight engineer's log. At this time the aircraft was in almost level flight at a speed of 130 kt. A gradual nose-up pitch accompanies the steady decrease in airspeed towards the stall, while normal acceleration changes very little. This first "stall" which occurs at about two minutes before the end of the record was straightforward and recovery was made with the stick-pusher system fully operative. There followed a second and then a third approach to the stall; these were designed to check the functioning of the duplicated parts of the stick-pusher system. Finally, towards the end of the record, the aircraft levels out at 11 600 ft and the fourth stalling run is started. After the stall the aircraft starts to pitch nosedown and speed falls off rapidly. Then for about 5 seconds the nosedown pitching motion ceases indicating that the aircraft was tending towards a superstalled condition. At the same time the heading changes, the aircraft turning to port at the rate of 8° per second.

The rate of decay of airspeed during this last stalling run averaged at about $1\frac{1}{2}$ kt per second - but the rate was increasing towards the end of the run.

1.12 Wreckage

On-site examination showed that the aircraft had struck the ground in a flat attitude with little forward speed and a high rate of descent while spinning to the right. The fuselage was grossly flattened in the impact and the tail unit, which had rolled and skidded to port, had detached at the rear pressure dome. The engine installation and rear equipment bay had been demolished. A localized ground fire which had been initiated in the region of the centre engine on impact had affected the No. 1 engine.

The main planes, particularly the port, had broken up in the violent impact with the ground. It was concluded that the aircraft was complete at impact and that its configuration was:

> Landing flaps   - UP
>
> Undercarriage   - UP
>
> Airbrakes/spoilers
>   and lift dupers   - IN
>
> Droop leading edge - DROOPED

It was considered that all three Rolls Royce engines had been running, the centre (No. 2 engine) at a higher speed than the other two engines which were probably throttled to flight idle.

The wreckage was dismantled and transported to Hawker Siddeley Aircraft Ltd. premises at Hatfield where it was further examined in conjunction with the company.

The following were examined in detail, certain items being examined at the supplier's works.

Pitch controls

The tail plane circuit in the fin was virtually undamaged. A check of the rigging and operation of this assembly proved satisfactory. Subsequent test and examination of the tail plane operating jacks proved these to be normal and satisfactory. Fore and aft trim was established as slightly aft of neutral.

Main plane droop leading edge and kruger flaps

It was confirmed that the main plane leading edge had been in the drooped position at impact. All failures and disconnections are attributable to overstressing in the crash impact. Examination of the leading edge sealing and vortex generators has shown these to be of normal and satisfactory standard.

Pitot static system

Wind tunnel calibration of the Pitot heads showed that these conformed to standards within the applicable range of incidence. In so far practicable the Pitot and static system pipelines were tested. All fractures and leaks, with two exceptions, were attributable to the crash impacts. The exceptions were small leaks in the No. 1 Pitot and No. 2 static systems, which were reported by the flight crew prior to take off.

Stall warning and recovery system

The damage to the circuit breakers rendered it impossible to determine whether the system was switched ON or OFF.

Impact marks in the airstream detectors showed that these had responded to the upward air flow of the high angle of attack associated with a stalled condition.

The stick-pusher jack was found jammed by impact in the non-operated setting. Examination of all components and details of the system produced no evidence that, had it been switched ON, it would not have operated correctly.

Airspeed indicators

No defects found.

Flight attitude indicator system

The captain's flight attitude indicator and associated components were examined for evidence of pre-crash failure and/or malfunctioning. Inspection showed that the vertical gyro rotor had been rotating at impact.

Standby horizon

This instrument had been operating satisfactorily at impact.

General

The detailed examination served to confirm the findings of the on-site inspection. All control separation and disconnections and damage to instruments and equipment are, with the exceptions of the leaks in the Pitot/static systems, attributable to the crash impact.

1.13   Fire

A small fire broke out in the vicinity of No. 2 engine at or shortly after impact. It did not spread and caused little damage. It was brought under control by fire appliances from RAF Coltishall.

1.14 Survival aspects

        The impending crash was reported by RAF personnel living in the vicinity.
RAF Coltishall dispatched fire and rescue appliances and called up helicopters from RAF
Manston. Norwich Fire Service also attended and removed the bodies of the crew members.
The injuries to the occupants of the aircraft could not have been prevented by anything
in the nature of safety equipment or stronger seats or flight deck structure. The accident
is therefore classified as non-survivable.

1.15 Test and research

        After the accident further studies were made using the flight simulator at
Hatfield. These examined in detail the relationship between rate of approach to the stall,
recovery action and the probability of the occurrence of a superstall. The studies showed
that with the stick-pusher inoperative the safety margins were not large. In addition to
these studies the Royal Aircraft Establishment undertook a more specific investigation which
aimed at computing an approximate history of the tail plane deflection that occurred on the
fatal test. For this investigation the aerodynamic and other characteristics of the aircraft
were taken to be the same as those used in the simulator. The history of the pitch attitude
was also assumed to be known and to be given by the recorded data corrected for instrument
error. On this basis it was possible to deduce the other flight parameters and the tail
plane angle. This was not, however, a simple matter of inverting the calculation procedures
since the accuracy of the recorded data was not such as would permit successive differentia-
tion of the attitude angle with respect to time. The situation was further complicated by
the fact that no information was available on the level of engine thrust being used at various
stages of the test. This again made it necessary to do additional exploratory calculations
to assess the most plausible assumption on which to proceed. A detailed account of the RAE
study is at Appendix B.

2. - Analysis and Conclusions

2.1 Analysis

        It was apparent at the start of this investigation that the accident had
resulted from a deep pentration into the post-stall regime and that a superstall had
occurred from which recovery was not possible. During an extensive examination of the
wreckage particular attention was paid to possible defects which could have affected the
handling of the aircraft and its stalling characteristics. None were found. The investiga-
tion then sought to determine the speed at which recovery action was initiated by the
pilots.

        Control surface movement was not measured by the flight recorder and con-
sequently considerable work was necessary before a reasonable assessment of the pilot's
actions could be made. On the basis of the data derived from the flight recorder and
from a knowledge of the static aerodynamic characteristics of the aircraft obtained from
wind tunnel tests, an attempt was made to reconstruct the aircraft's motion up to the
penetration into the superstall (Appendix B). From this it appears that recovery action
was not taken until the speed had dropped to about 8 kt below the stick-pusher datum and
that the control movement was insufficient to arrest the development of the stall. The
reason why the pilot delayed recovery action is not known. It may be that with his very
considerable experience of stalling the Trident he expected to detect the true stall or
alternatively, to initiate recovery at a wing drop which did not occur on this occasion.
On the other hand, his hesitation after moving the controls most probably resulted from
an impression that the nosedown pitch was providing effective recovery but at that time
the rate of sink was increasing and its effect was to cause a rapid increase in incidence
to a superstall.

The general nature of the superstall problem was widely known at this time both from accidents which had occurred on other aircraft and also from theoretical and flight simulator investigations undertaken on the Trident at Hatfield. These had been discussed in reports circulated to the pilots and the flight test and design teams. Early in 1965 Mr. Barlow had taken part in simulator studies of the Trident 1C and Trident development including stall investigation. This was in addition to his experience of stalls during the development flying. However, it is apparent that the danger does not only arise from a lack of awareness of the problem but from the circumstance that the time the aircraft takes to pass from the stalling incidence to the entry into a superstall is very short and small delays have a major influence on the outcome. The greater the rate of decay of airspeed during the approach to the stall the less time is available for recovery action and in addition the extra inertia results in a considerable overswing in incidence before the pilot's control movement can be effective. Therefore, bearing in mind the very short margin by which the pilot missed retaining control, consideration was given to whether the addition of an incidence meter might have enabled him to have carried out the test in greater safety; no definite conclusion could be reached. However, if the flight region beyond the stick-pusher datum (i.e. $17\frac{1}{2}°$ in this case) is to be explored there is a greater need for information on incidence; this becomes the only means by which the pilot can assess the flight condition as the usual relationship between airspeed and incidence has become invalid. On this occasion, if an incidence meter had been provided the rapid increase in incidence that occurred below 90 kt might have impressed upon the pilot the need for quick and decisive recovery action. On the other hand it must be stated that if the approach to the stall had been carried out by reducing speed at 1 kt per second and particularly, if the test had been terminated by decisive recovery action by the time the ASI was reading 4 kt below the stick-pusher datum, the specially calibrated airspeed indicator that had been fitted should have provided sufficient information. The onset of buffet at this point is common to this type and should also have provided a positive recovery cue. Therefore, although the provision of an incidence meter would have been prudent, it is considered that the accident indicates that a greater contribution to safety would have been made if a suitable "backing up" system had been devised as a safeguard for the occasion when a pilot might fail to take prompt action. In this respect it is understood that since the accident, tests on this type of aircraft are carried out only with the stick-pusher operating and with additional safety measures to reduce the possibility of failure following a single fault, and includes the fitting of incidence meters.

2.2 Conclusions

(a) Findings

The documentation of the aircraft was in order.

The flight was being conducted in accordance with an agreed test schedule.

No evidence of pre-crash failure of the aircraft has come to light.

During the final stalling run speed was reduced at a rate greater than 1 kt per second and recovery action was not initiated until the speed had fallen beyond the limit set by the test schedule.

(b) Cause or Probable cause(s)

During a stalling test decisive recovery action was delayed too long to prevent the aircraft from entering a superstall from which recovery was not possible.
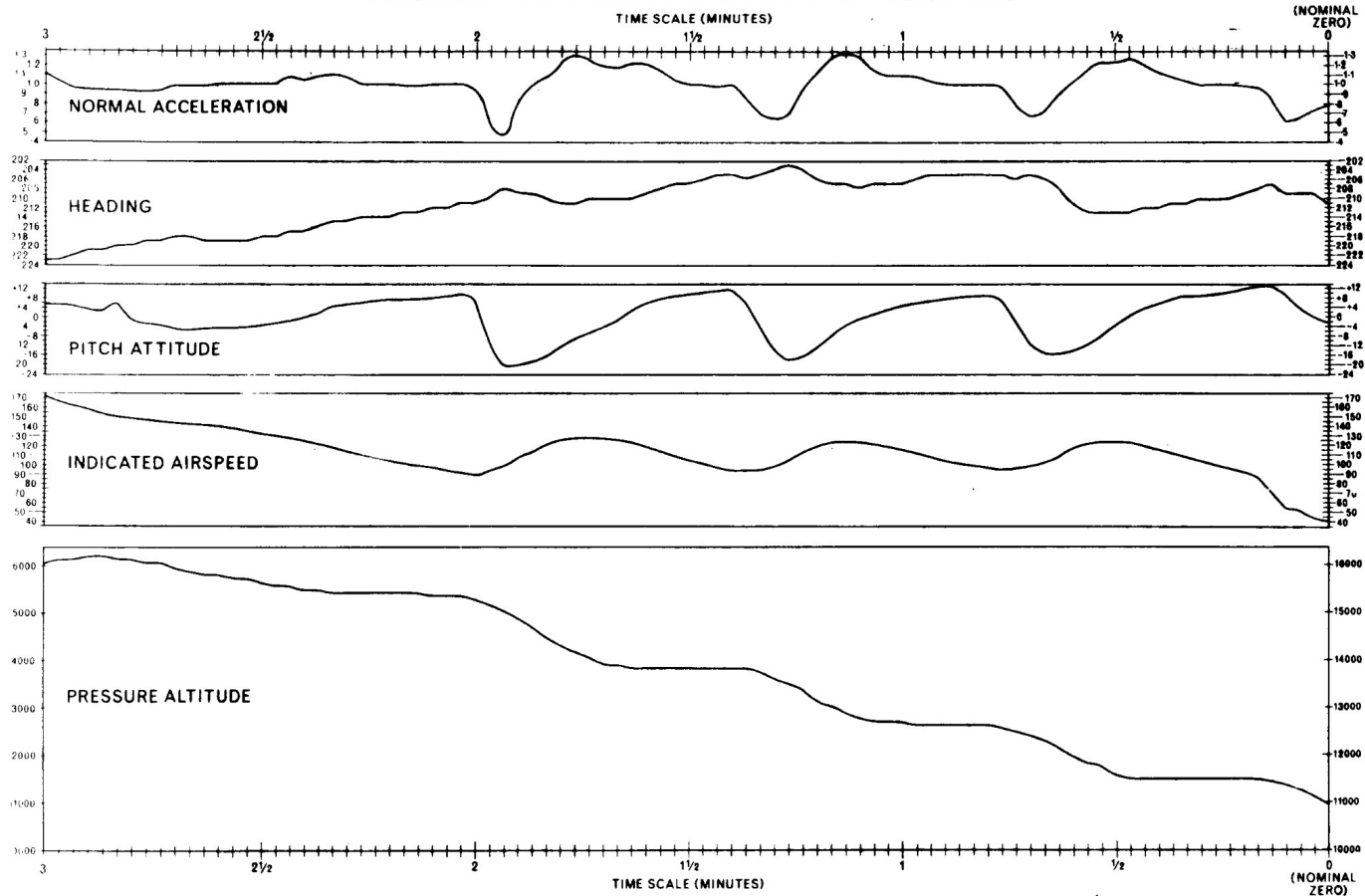
3. - Recommendations

Very shortly after the accident occurred, the manner of the conduct of Trident tests was discussed with the Air Registration Board and the aircraft manufacturer and the view was put forward by the Chief Inspector of Accidents that, if the type of stalling test in which the accident was involved was to continue, incidence meters should be provided. Following these discussions it was decided by the Board that, for test flights and training flights involving deliberate approach to the stall, the stick-pusher system must have a survival capability and additionally the crew must be provided with dual incidence indicators independent of the stick-push incidence sensors. This requirement is applied to all aeroplanes fitted with stick-pushers and therefore no specific recommendation for this is required.

ICAO Ref: AR/015/66

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Test
En route
Stall
Pilot - improper flight planning
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ACCIDENT TO TRIDENT I G-ARPY. 3RD. JUNE 1966

TIME SCALE (MINUTES)

(NOMINAL
ZERO)

NORMAL ACCELERATION

HEADING

PITCH ATTITUDE

INDICATED AIRSPEED

PRESSURE ALTITUDE

TIME SCALE (MINUTES)

(NOMINAL
ZERO)

TIME HISTORY OF LAST 3 MINUTES OF FLIGHT RECORDER DATA

C A Dept C OPS 10 D.O.Drg.No.5312 28-2-68

ICAO Circular 88-AN/74

APPENDIX A

APPENDIX B

ROYAL AIRCRAFT ESTABLISHMENT - FARNBOROUGH

An attempt to reconstruct the history of the 'superstall' of the Trident G-ARPY

Introduction

The nature of the test being conducted, the pilot's report that the aircraft was in a superstalled condition and the recorded data all fairly clearly indicate that the most likely primary cause of the accident was a deep penetration into the post-stall regime, which resulted in a superstalled condition. Since the centre of gravity of the aircraft was at its aft position, recovery from such a flight condition is extremely unlikely. Accordingly, there is little to explain in relation to what was broadly the cause of the accident. Nevertheless it would be wholly unsatisfactory if the matter were allowed to rest there.

It is, in fact, necessary to examine the background of the test, the conditions governing the conduct of the test as laid down by the firm and finally to assess the actions of the pilot in this case.

A background knowledge of the sensitivity of the behaviour of this class of aircraft, particularly the way this depends on the centre of gravity location, was available to the firm from its own researches and other sources. This is discussed in other sections of the report.

This appendix, on the other hand, attempts a reconstruction of the history of the aircraft's motion, up to the time it ceased to be essentially confined to the longitudinal plane, with the object of defining, as clearly as possible, the actions of the pilot during the manoeuvre.

After ascertaining the pilot's actions which best correlate with the recorded flight data, the former are then examined to see how far they are in line with the conditions laid down for the test procedure, how far they are conditioned by motion cues and finally how sensitive the aircraft's behaviour is to the pilot's input.

The required matching of the response and input could be sought along a number of different lines of approach. With high grade data it might be tempting to try to use as much of these directly and deduce the unknown variables from the equations of motion. It is doubtful whether circumstances such as prevail in the particular problem considered here will yield data of sufficiently high quality to admit of the necessary smoothing and repeated differentiation. Furthermore corrections, which are functions of the unknown angle of attack, have to be applied to the airspeed and the apparent normal acceleration to yield the true normal acceleration. This would have had to be done on an iterative basis.

Yet a third approach, and the one chosen here because it enabled an existing computer programme to be used, is to compute the response to an input which might be expected to yield something close to the assumed (or given) response. The small adjustment necessary to produce a specified closeness of fit with the known response for one of the motion variables can be estimated on some approximate basis from the discrepancy between the recorded data and the initially computed response.

Outline of the calculation procedure

An outline of the procedure just hinted at follows and the first step is to establish the initial conditions. In order to avoid unduly lengthy calculations these are chosen to correspond to an instant during which the aircraft is already decelerating towards the stalling speed. Since various corrections to quantities V_i, V_i, h_i and n_i depend on the incidence, some integration is necessary. The form of the θ curve in the neighbourhood of the chosen instant is used to determine the out-of-trim tail plane setting implicit on the initial conditions. The best fit to the initial conditions is obtained by assuming the error in θ to be 1.6°. It has been established separately that an instrument error of between 1° and 2° would be expected. The record showed that an error of $+ 0.03$ was present in the apparent normal acceleration.

It is of interest to note that the estimated initial value of thrust was higher than that normally used in stalling tests.

As indicated earlier the assumed elevator input (elevator is used to denote longitudinal control, which in this case was an all-moving tail plane with geared flap) for the first stage of the calculating that is in the approach to the stall, has the form $n_T = n_{Ttrim} + \Delta n_T$. The increment over the trimmed value is subject to adjustment, on a step-wise basis, so as to maintain good correlation with the observed pitch attitude. Thus the reduced steepness of the θ curve at about 4 sec. (on time scale used here) and again around 6 sec. is reflected in the two small steps in the elevator angle, see figs. 9-1 and 9-3

In the neighbourhood of the stall, in order to maintain the same high standard of correlation with respect to the maximum value of the pitch attitude angle, the sharpness of the break in the normal acceleration curve as well as the speed loss, it proves necessary to make some further assumption. Since no a priori case exists for assuming the aerodynamic data to be in error and the fact that little rational basis exists on which changes could be introduced, attention is directed to the assumption concerning thrust. It has already been noted that more than usual thrust seems to have been used in the approach. It is, therefore, all the more plausible that a reduction was made.

Calculations using different levels of thrust show that a reduction to a sixth of the initial value at 6 sec. yields the best speed correlation. Correlation of the calculated and measured values of other parameters were also improved slightly. It is noteworthy that the changes in the estimated control input associated with the different levels of thrust are trivial.

Exploratory calculations assuming the stick held constant, moved forward step fashion or gradually in a linear manner at around 9 secs. show an optimum correlation of measured and calculated θ values, when the stick is moved forward at a slow rate corresponding a rate of change of tail plane angle of $0.25^{\circ}/sec$.

This is taken to indicate that the recovery attempt is imminent. Accordingly the assumed form of control input is changed to a polygonal form. The slope of each segment is adjusted so that the pitch attitude is faithfully reproduced. It is of interest that the sensitivity of the pitch attitude to small changes is higher than that of the other parameters.

In this way the curves shown in figs. 9-1, 9-2 and 9-3 are obtained. The estimation of both the indicated airspeed showing on the recorder and the indicated airspeed of the pilot's instrument involved large corrections for instrument and position errors.

In fact with the suggested extrapolation of the pitch and static errors beyond an incidence of about 30° (i.e. beyond a time of 16.5 sec) the corrections become meaningless. This may account for the rather poorer correlation of airspeed as compared with all other measured quantities. For these the measured and recorded values agree within acceptably small limits. On this high degree of correlation rests the assertion that notwithstanding its somewhat unrealistic character the calculated input must approximate closely the pilot's action. The only doubt concerns the aerodynamic data used in the calculations and it is scarcely conceivable that these can be materially in error in view of the results.

At 20.5 secs the calculation has been terminated, since the recorded data show that at this time a small change of heading is taking place. It is, therefore, inferred that the motion is no longer confined to the longitudinal plane and account must be taken of the lateral motion if the correlation were to be taken further, which seems an exercise of little profit or hope of success in the absence of fuller lateral motion data.

Interpretation of the results

If it is accepted, on the basis of the above argument, that the input history shown in fig. 9-3 closely approximates the tail plane movements made by the pilot then it remains to interpret these as far as it is possible to do so.

It is essential to this part of the investigation to consider what airspeed reading was displayed to the pilot. His instrument is subject to entirely different corrections as compared with those of the recorder equipment, c.f. figs. 9-2 and 9-3. Estimates of the readings of the pilot's airspeed indicator can be obtained in two ways. In the first of these the calculated equivalent airspeed is converted into a pilot's instrument reading. This yields the curve marked 'estimated V_{ip}' in fig. 9-3. In the second method the recorded airspeed (corrected for instrument error) is multiplied by a factor, which accounts for the different position errors. This gives the curve marked 'derived V_{ip}'. In the range of speeds covered by the 'estimated V_{ip}' instrument corrections are small and no account is taken of them. Although the values obtained by the two methods are quite different beyond about 10 secs, both curves indicate that a flattening off or even an increase of speed occurs at around 13 secs.

Examination of the behaviour of the various motion parameters shows that having brought the aircraft down to 'stick-pusher' speed, or strictly a somewhat slower speed, the pilot eases the stick forward. During the phase he could have been awaiting the occurrence of the buffet and would have noted the change to a mild nosedown rotation, which results mainly from the inherent pitching moment characteristics of the aircraft and partly from his action. This latter hardly merits being called a recovery action and might rather have been an attempt to hold a given flight condition. A plausible reason for doing so is that the pilot was not convinced that he had achieved the objective of the test, namely to explore the aircraft's behaviour to the buffet or the overriding speed limit.

There is no means of resolving this particular problem, but whatever the reason it would seem that no forcible recovery action was taken till about 12.5 secs on the present time scale. After applying the 'elevator' control at a fairly fast rate in the nosedown sense for about half a second there now seems to follow another interval during which the rate of application of the tail plane is much reduced. This hesitation may be related to the pilot's assessment of the situation, in particular the apparent deceleration, as has been demonstrated, exhibits a marked falling off, if not reversal. It also seems possible that a further apparent drop in speed alerted him to the true situation and resulted in the final push forward of the stick.

The calculations thus give clear indications that in the absence of lateral motion the aircraft would have 'superstalled' or penetrated so deeply into the post-stall regime that recovery by longitudinal control would have been impossible. Evidence is given elsewhere that the flight condition was so diagnosed by the pilot and that he sought to increase the chances of regaining control by use of thrust and possibly by putting the aircraft into a turn.

Some general remarks

The present investigation raises a number of points of more general interest. When data of the type used herein are recorded, whether in flight testing or operationally, two requirements have to be borne in mind. These are:

(a) the provision of as much data as possible from which the flight conditions can be directly and unambiguously interpreted, and the nature of an incident, if any, directly determined.

(b) that the data are such as permit correlative calculations to be most easily and reliably undertaken.

To meet these in flight testing is perhaps somewhat easier, since the purpose of the test often provides an indication of those parameters that are more critical. For instance, in the tests being analysed here it would have been extremely valuable to have had incidence measured.

Apart from this there is generally a strong case for recording the pilot's inputs (as elevator deflections etc.), since the calculation of the corresponding response of the aircraft is then a relatively straightforward calculation as compared with the one outlined above.

In the particular test under consideration it is of interest to see whether a situation could have arisen in which recovery would have proceeded without mishap and yet there would be little evidence immediately available to someone examining the recorded data, much less to the pilot, of how narrowly disaster had been avoided. From among a number of calculations made to test the sensitivity of the deteriorating situation to the pilot's action, as well as the sensitivity of the calculation process to the tightness of the correlation tolerance allowed between calculated and measured pitch attitude angle, one was chosen which illustrates this point well. In this calculation the pilot is assumed to start his final push forward of the stick half a second earlier than he seems to have done in reality.

The effect of such a change in input on the history of the variables recorded is shown in figs. 9-4, 9-5, 9-6. Up to 15 secs the curves marked (1) and (2) are, of course, identical. Beyond this there is some gradual divergence of the curves, but the significance of this could easily be overlooked in a casual examination of the recorded data. It is difficult to see how the pilot could distinguish between these two situations with any certainty. On the other hand it is clear that such diffe.··ces are significant in terms of the present analysis.

If, however, the angle of a·'·ck (2) is available it can be seen from fig. 9-4 that not only are the two cases more readily distinguished but also the maximum value of the angle (29°) indicates how dangerously near the manoeuvre would have been to one from which recovery would have been impossible. Th:·· fact would have been much less evident to a pilot using airspeed and altitude angle as hi· ·:mary cues.

To put these marginal cases into perspective the effect of continuing the rapid forward movement of the stick at 12.5 secs until 5° (trailing edge down) tail plane angle had been reached, is also shown on the same set of figures (figs. 9-4, 9-5, 9-6.) Even in this case the progress of the recovery is not easy to assess from any of the resulting responses except that for the angle of attack. In all three cases there is only a very narrow margin of speed of about 2 kt (EAS) below the stalling speed for which speed continues to decrease as incidence increases. Thereafter speed is not a reliable indicator of the aircraft's incidence. It is worth noting, however, that the instrument and position errors are such that the indicated airspeed might be a somewhat better guide for a wider range of incidence. However it must be stressed that at speeds just below the limit set the indicated airspeed may vary so slowly with increase in incidence that, having in mind the inevitable fluctuations of the instrument reading, it is questionable whether the airspeed is an acceptable indication of the situation.

Conclusions

With reference to the specific circumstances of the accident it can be concluded from the calculations described above that:

(1) the recovery action taken, if indeed it can be classed as such at this stage, was tentative up to 12.5 secs (on the time scale used here) by which time the pilot's airspeed indicator would have shown a speed of 85 kt or less.

(2) a late, but more forceful, recovery action follows, but this was soon eased off possibly due to the manner in which the pilot's airspeed indicator would be behaving.

(3) it is possible that a reappraisal of the situation led to a final push forward of the stick, which came too late to prevent the aircraft superstalling.

(4) apart from rapid recoveries made in that narrow band of incidence above that at which the stick-pusher is activated and within which speed may be taken to give a reliable indication of incidence, the addition of an incidence meter would be a valuable aid to the pilot. However, since the rate of change of incidence is an equally important factor use of an incidence meter would not, in itself, render the test safe.
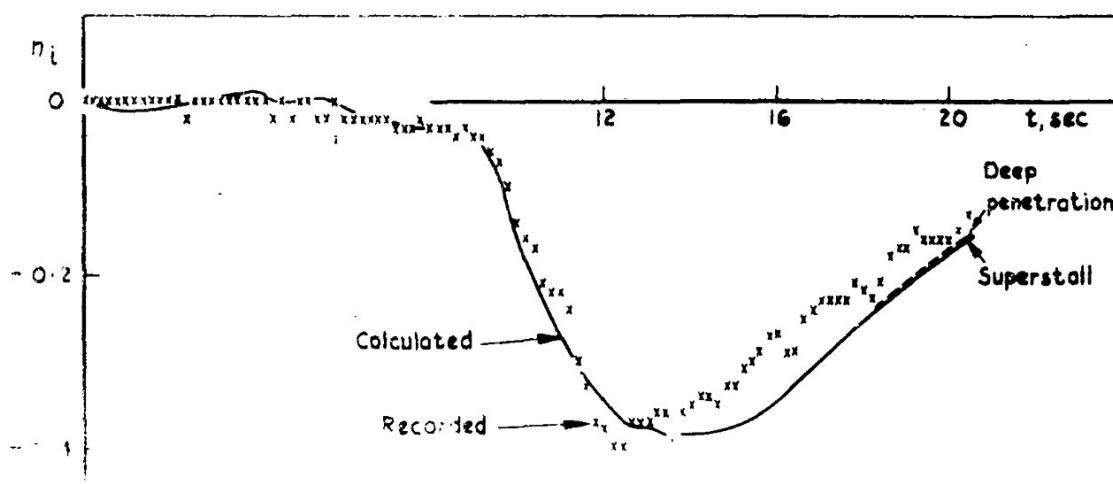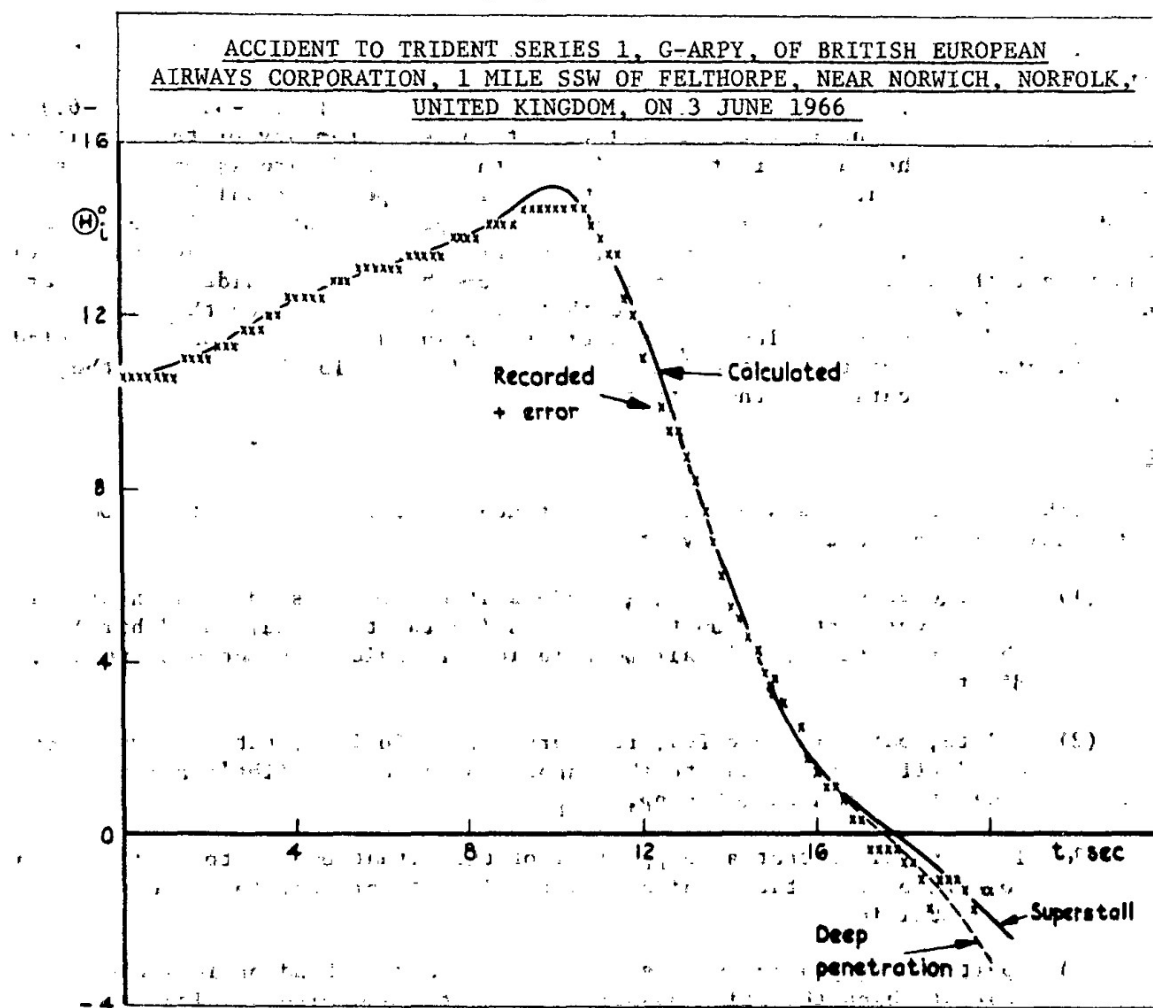
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Fig. 5-1 — Pitch attitude (angle of inclination), $(\theta)_i$, and
indicated normal acceleration, n_i.

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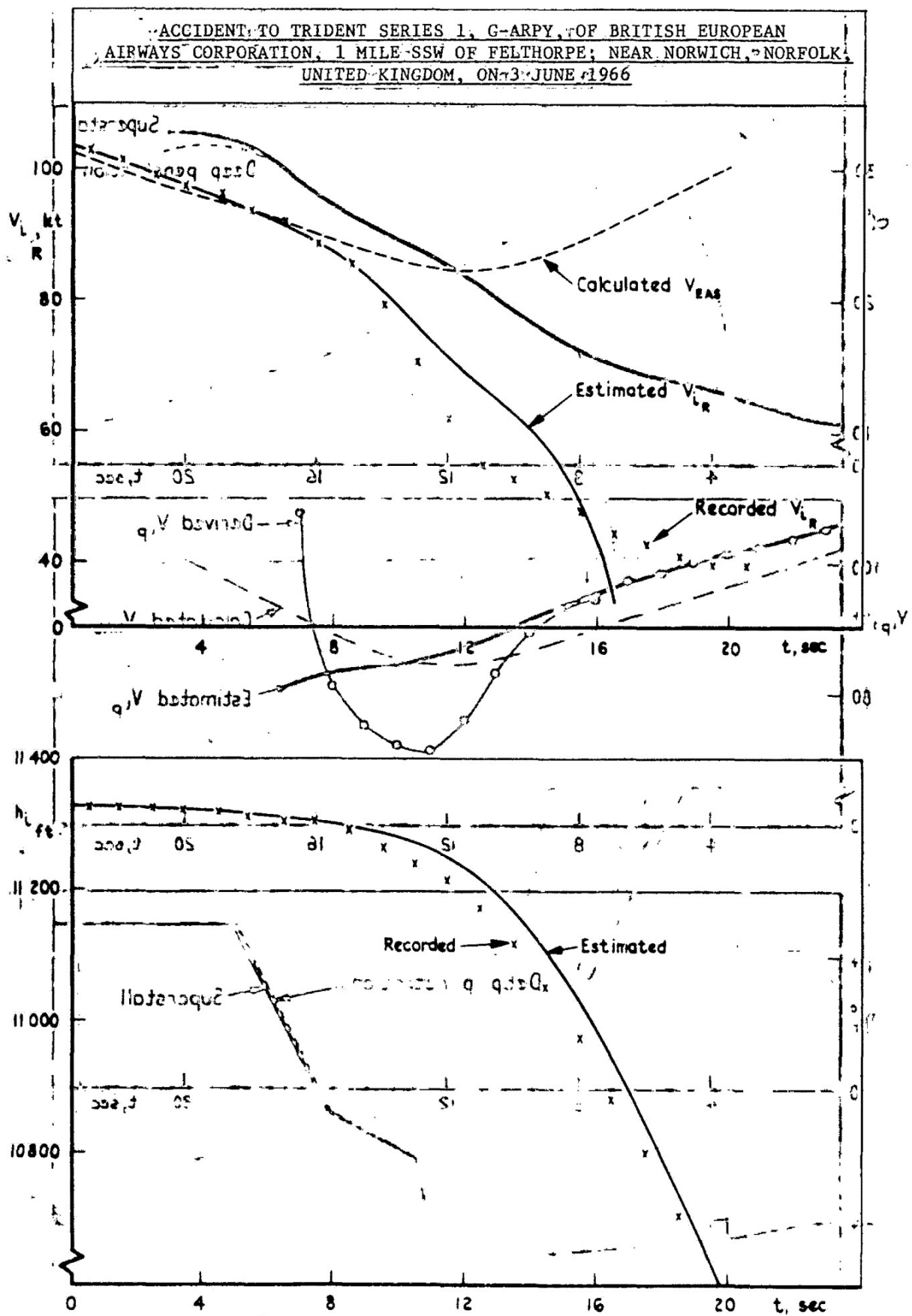
Fig. 9-2 - Recorded indicated velocity V_{i_R} and indicated
height, h_i

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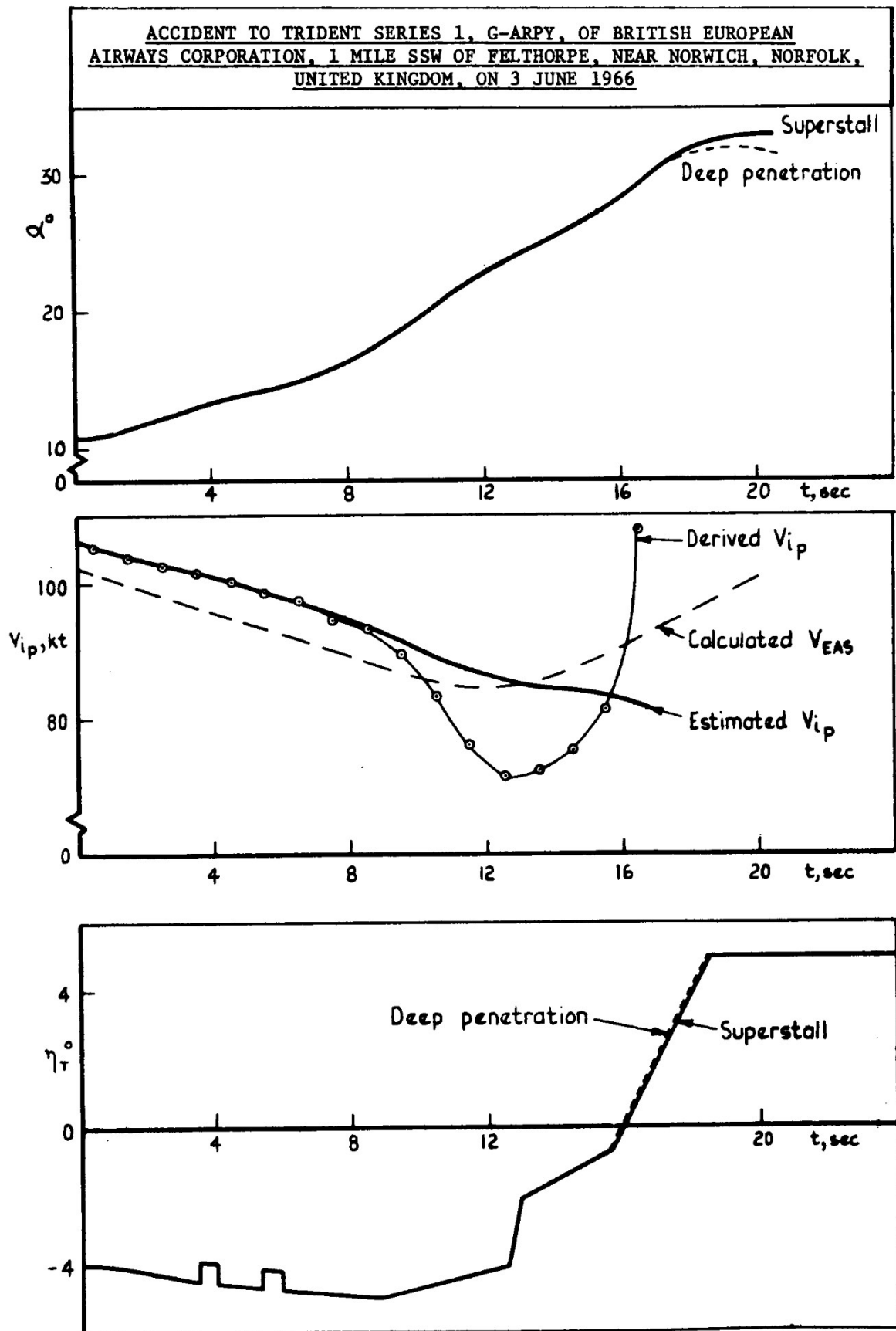
Fig. 9-3 - Angle of incidence, α , velocity indicated to
pilot, Vi_p and tailplane angle, η_T

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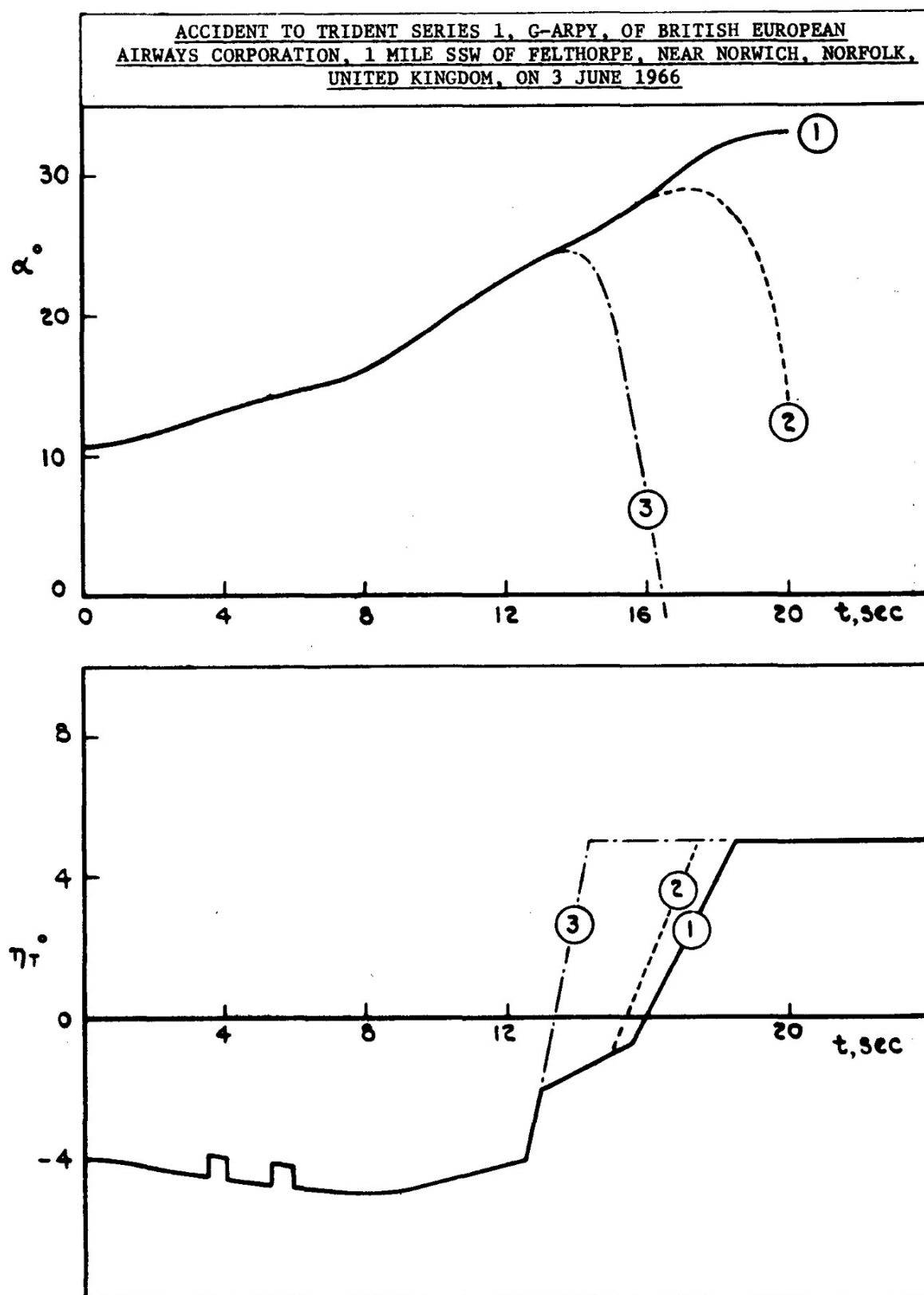UNITED KINGDOM, ON 3 JUNE 1966

Fig. 9-4 - Effect of different recovery action shown on
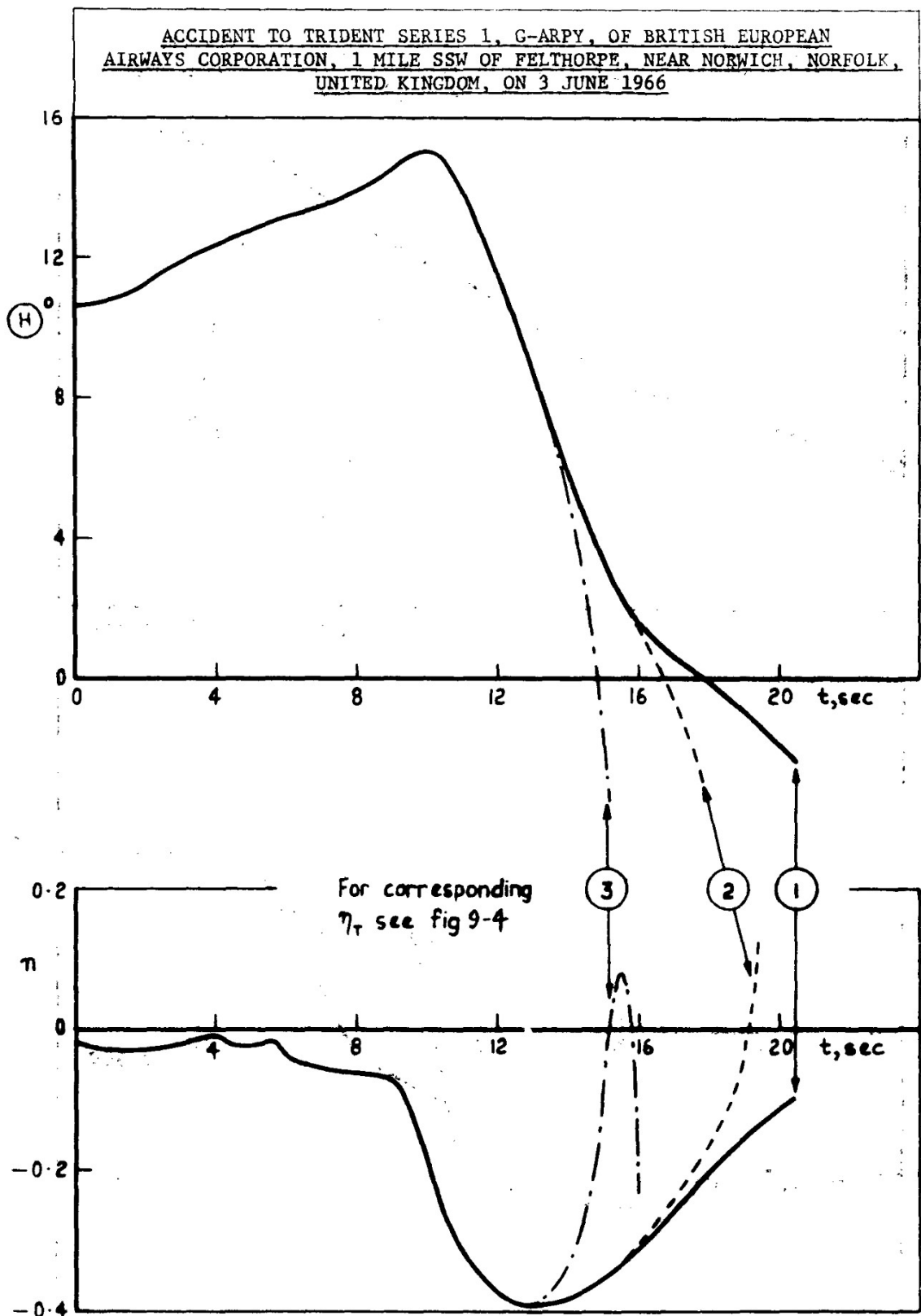the angle of attack, α

Fig. 9-5 – Effect of different recovery action on pitch
attitude (angle of inclination), (H) and on
normal acceleration factor, n

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