Final Report of the Investigation into the anomaly of the HyShot Rocket at Woomera, South Australia on 30 October 2001.

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Executive Summary

On 30 October 2001, the University of Queensland Department of Mechanical Engineering (UQ), launched an experimental supersonic-combustion ram jet (scramjet) payload via a two-stage solid-fuel rocket that was provided by Astrotech Space Operations Inc (Astrotech). The rocket was launched from the Woomera Prohibited Area in northern South Australia, that was operated by the Department of Defence (DoD). The planned flight was to validate data obtained in the hypersonic wind tunnel at the UQ facilities.

The launch occurred at 1301 Australian Central Summer Time and according to observers and video evidence, the first stage booster appeared to operate successfully, although UQ personnel noted an anomaly in the received telemetry data. After the initial coast stage, during which time the first stage separated, the second stage ignited and observers reported seeing the rocket and the resultant exhaust trails appearing to curl in a 'cork screw' fashion. That continued with the stability of the rocket appearing to deteriorate until it was out of sight.

The first stage (Terrier) was recovered from the intended impact area shortly after the flight, while remnants of the first stage fixed fins were recovered north east of the flight path and between the first stage impact area and the launch pad approximately 12 weeks after the launch. The separate location of the fins indicated that the fins separated from the vehicle during the first stage flight.

The second stage (Orion) with fixed fins and payload was recovered about 16 weeks after the launch from an area about 28 km east of the Stuart Highway and about 100 km north west from the launch site rather than the 373 km nominal aiming point. The highway had not been closed to traffic, nor was it required to be.

After the flight, the UQ team reported that while examining their telemetry data they noted an anomaly in the accelerometer and magnetometer data at approximately 2.8 seconds after first stage ignition. UQ also noted that the vehicle had not achieved the spin rate (4-6Hz) that was intended. However, the UQ team suggested that the low spin rate was more likely the result of some other event, perhaps the loss of one or more fins, rather than contributing to the accident. Additionally, a number of personnel who viewed the post-flight video reported seeing what appeared to be objects falling from the vehicle during the first stage burn. However, the Optical Coordinator from the launch team and Australian Transport Safety Bureau (ATSB) investigators considered that the video images lacked sufficient resolution to determine what occurred at those times.

ATSB specialist examination of the first stage indicated that the fixed fin support structure had broken up during the flight. Examination of the fracture surfaces indicated overload through the fixed fin spindle (journal) sockets. Larger Nike fins had been fitted by Astrotech rather than the smaller standard Terrier fins. This was to achieve the required stability and ensure a stable platform during the scramjet experiment. No pre-existing defects were found within the physical structure of the fin support. Some of the fin journal sockets showed evidence of excessive angular bending forces, suggesting possible movement or rotation of the fins during flight. A considerable proportion of the first stage fixed fin skin and internal honeycomb material had not been recovered at the time the investigation was carried out. Of the material that was recovered, most of the damage and deformation suggested both aerodynamic and ground impact forces.

The Nike fixed fin angle of incidence was adjusted using trailing edge adjustment lugs. Marks and damage around the fixed fin adjustment lug mounting points indicated in-flight movement and possible insecurity of the fin adjustment lugs. Crushing damage of the fin rib sections beneath the lug mounting set-screws was possibly pre-flight damage which may have contributed to in-flight movement. It was also noted that the Nike fins were not designed for securing in the location used and contained no reinforcement or other strengthening features in this area. The Nike fins were designed to be secured on the leading side of the fin base, whereas the original Terrier fins were designed to be secured on the trailing side of the fin base.

ATSB specialist examination of the payload found no evidence to suggest that the payload or associated components had contributed to the flight anomaly, however the level of impact damage limited the examination.

During launch preparation, sandbags were placed around the base of the launcher. The Astrotech "Operation and Inspection Log for the Assembly of the Terrier-Orion Suborbital Launch vehicle system" called for grout to be placed at the base of the launcher. However, grout was not available, thus sandbags were used to protect the base of the launcher. UQ suggested that it was possible that a sandbag or a rock in a sandbag could have damaged a fin during the initial launch phase. That would have required a sandbag or rock to have been deflected off the infrastructure and impact a fin. Video footage and still images viewed by the ATSB Specialists and Astrotech, indicated that a number of the sandbags were ejected and/or disrupted during the ignition and launch. However, it was not possible to determine if a rock had impacted a fin during the launch sequence.

The examination could not conclusively determine what caused or allowed the first stage Nike fixed fins to move during the flight. However, based on the available evidence, it is likely that the first stage Nike fins either sustained damage from aerodynamic overload due to their movement during the flight or the fin support structure was unable to support the increased aerodynamic load of the larger Nike fins. It is also possible that the sandbags or rocks ejected during the launch damaged the first stage fixed fins. As a result, at separation, the second stage would have been in an unstable flight attitude and possibly not able to recover stabilised flight.

Because the *Space Activities Act* and *Space Activities Regulations* did not provide for a launch licensing instrument with a fee structure appropriate to the resources of educational/scientific organisations, UQ was granted an exemption certificate by the then Minister following a recommendation from the Australian regulator, the Space Licensing and Safety Office (SLASO). As part of UQ's application for an exemption certificate, it was required to furnish a risk hazard analysis of the project based on statutory methodology and informal guidance provided by SLASO.

The investigation determined that although the risk analysis conducted by UQ allowed for failure of the first stage and non ignition of the second stage, insufficient allowance was made for the rocket vehicle malfunctioning and going off course. During the investigation, UQ indicated that as part of its hazard identification during the risk hazard analysis process, it had not specifically considered the possibility of the rocket impacting near the Stuart Highway. The second stage and payload impacted about 28 kilometres east of the highway.

Although SLASO had expressed reservations in an internal document, prior to the launch, regarding the risk hazard analysis submitted by UQ, it assessed the analysis as part of the application and recommended that UQ be granted the exemption certificate. SLASO was satisfied that a risk hazard analysis has been performed and that the launch would comply with the Launch Safety Standards of the Flight Safety Code[1], provided there were adequate exclusion arrangements for the WIR and the area around the nominal aiming point. As part of that assessment, SLASO also relied, in part, on the granting of a licence to Astrotech by the United States regulator, the Federal Aviation Administration (FAA), the submission of a risk hazard analysis to the FAA by Astrotech as part of their launch licence application and an analysis conducted by the FAA. Although SLASO requested a copy of that analysis from the US regulator, it was not provided. After the Launch, SLASO commented that there was no evidence that the launch violated the risk acceptance criterion spelled out in the launch safety standards of the Flight Safety Code.

1 The Flight Safety Code sets out the safety standards that must be achieved in respect of the risks posed to third parties by space launches and the methodology to be used to calculate the risk. (Also see footnote 9 on page 17)

SLASO is seeking to acquire specialist risk analysis software, with appropriate user training, to assist with assessing risk hazard analysis models submitted by applicants. SLASO also indicated that it plans to provide additional guidance for applicants wishing to apply for a licence, permit or exemption certificate. Additionally, Government approval has been granted to amend the *Space Activities Act* to provide for educational/research activities with an appropriate fee structure. That will allow the requirements to be clearly spelt out in regulations made in respect of that certificate.

UQ has indicated that it intends to reassess its risk hazard analysis.

Astrotech indicated that it plans to review its pre-launch assembly procedures of the rocket vehicle.

DoD has indicated that it plans to review its internal procedures for the approval of Woomera Prohibited Area activities and that the MoU with SLASO may also be reviewed.

In addition to these safety actions, the Investigator issues the following recommendations.

1) That Astrotech review the:
    a) suitability of the Nike fins for use on the Terrier vehicle;
    b) suitability of the fin support attachment structure when other than Terrier fins are used;
    c) suitability and effectiveness of the opposing set-screw arrangement for securing and setting the Nike fin incidence angle to the Terrier fin support structure; and
    d) suitability of the use of sandbags at the base of the launcher pedestal, in lieu of the specified grouting.
2) That SLASO require all Australian launch operators to submit a comprehensive risk hazard analysis for independent verification prior to the issuing of a licence, permit or exemption certificate.
3) That SLASO consider requiring launch operators to submit their risk hazard analysis to stakeholders and participants, for review and discussion.
4) That launch infrastructure providers make available sufficient resources to enable the provision of appropriate recording equipment with suitably trained personnel to provide additional recorded evidence to aid any occurrence investigation that may be necessary.
5) That overseas organisations involved in an Australian launch provide any risk hazard analysis and/or assessment to SLASO to better enable SLASO to properly assess a launch application.

Introduction

As a result of an anomaly with the HyShot rocket launched at Woomera, South Australia on 30 October 2001, the then Federal Minister for Industry, Science and Resources, the Honourable Senator Nick Minchin, appointed a senior investigator from the Australian Transport Safety Bureau, Mr Neville McMartin (the Investigator), to investigate the anaomaly in accordance with the requirements of the *Space Activities Act 1998* and the *Space Activities Regulations 2001.*

Sections 88(1) & (2) of the Act state:

> *(1) If an accident occurs, the Minister must appoint a person as the Investigator of the accident.*
>
> *(2) If an incident occurs, the Minister may appoint a person as the Investigator of the incident.*

Sections 89(1) & (2) of the Act state:

> *(1) An Investigator appointed under section 88 must investigate the circumstances surrounding the relevant accident or incident.*
>
> *(2) In particular, the Minister may determine the terms of reference of the investigation.*

The terms of reference for this space safety incident investigation were:

- establish the relevant facts and sequence of events associated with the incident, from the commencement of the launch sequence to the landing of the parts of the space object;
- identify and examine the factors, both direct and indirect, including technical, regulatory, human, organisational, systemic and procedural, which contributed to the incident;
- make appropriate recommendations for the prevention of accidents or other incidents occurring;
- provide an interim report by 30 November 2001, with the timing of a final report to be agreed after this has been assessed.[2]

The terms of reference, which categorised the occurrence as an incident, were determined prior to the commencement of the investigation and based on the available information. During the investigation, evidence showed that the first stage rocket was seriously damaged during its flight which meant that the second stage and payload failed to complete their planned flight prior to the completion of the mission.

Sections 85 of the Act states:

An ***accident*** *involving a space object occurs if:*

[2] The Minister, Hon Ian Macfarlane MP, agreed that a final report should be submitted by 29 March 2002.

(a) *a person dies or suffers serious injury as a result of the operation of the space object; or*

(b) *the space object is destroyed or seriously damaged or causes damage to property.*

Sections 86 of the Act states:

> *An incident is an occurrence associated with the operation of a space object that affects or could affect the safety of the operation of the space object or that involves circumstances indicating that an accident nearly occurred.*

Section 8 of the Act states:

space object *means a thing consisting of:*

(a) *a launch vehicle; and*

(b) *a payload (if any) that the launch vehicle is to carry into or back from outer space;*

or any part of such a thing, even if:

(c) *the part is to go only some of the way towards or back from outer space; or*

(d) *the part results from the separation of a payload or payloads from a launch vehicle after launch.*

Therefore, in accordance with Sections 8 & 85 of the Space Activities Act 1998, the occurrence was deemed to be an accident and the term accident was used from this point on.

The Investigator was provided with technical and general assistance by:

i. Space Licensing and Safety Office;
ii. University of Queensland;
iii. Department of Defence;
iv. Astrotech Space Operations Inc (USA);
v. Federal Aviation Administration (USA);
vi. Bureau of Meteorology;
vii. QinetiQ (UK);
viii. Aerosafe Risk Management;
ix. National Transportation Safety Board (USA); and
x. Australian Transport Safety Bureau.

Those organisations and individuals provided records, still and video images, reports and logs of the events leading up to the accident, as well as operating procedures and analysis of information pertaining to the accident. Their open participation and cooperation in the investigation process is acknowledged.

Investigation methodology

The purpose of this investigation was to determine the sequence of events which led to the accident and what factors contributed to the accident. Of particular importance was the need to understand what the accident revealed about the environment within which this particular launch operation was being conducted, and to identify deficiencies with the potential to affect public safety so that appropriate remedial action could be undertaken.

During the investigation, information was obtained and analysed from a number of sources, including:

i. visits to the launch site and other locations associated with the accident;
ii. recorded radar, video, photographic and telemetry information;
iii. documented operating procedures and practices;
iv. review of relevant files and correspondence;
v. interviews with personnel directly associated with the accident;
vi. e-mail and fax queries;
vii. interviews with personnel of organisations relevant to the accident;
viii. a review of the applicant's risk assessment methodology and application; and
ix. The Investigator had assistance from, and utilised the specialist technical facilities of, the Australian Transport Safety bureau in the conduct of this investigation.

1. Relevant organisations

Space launch activities are inherently expensive and require input and cooperation from a number of organisations. The HyShot project, which was initiated by the University of Queensland Department of Mechanical Engineering, required organisations to provide a launch vehicle, a launch range with infrastructure, meteorology data, telemetry hardware, financial assistance and a launch licence and permit.

The roles of a number of the organisations that were considered most relevant to this accident are described below.

University of Queensland

The University of Queensland Department of Mechanical Engineering (UQ), designed a supersonic-combustion ram jet (scramjet) payload. UQ and Astrotech Space Operations Inc. (Astrotech) signed a memorandum of understanding (MoU) on 16 March 1999. The MoU detailed a number of conditions that needed to be met by UQ. In return, Astrotech undertook to provide two solid fuel rocket vehicles, in addition to ancillary equipment and personnel to allow the program to proceed at Woomera. UQ liaised with the Department of Defence, the range operators, and applied for and was granted an exemption certificate from the Space Licensing and Safety Office for two launches at Woomera that included a payload from QinetiQ of the UK who had designed their own scramjet payload. UQ hoped to validate their experimental results that had been obtained from hypersonic wind tunnel tests located at the University of Queensland. Under the operations agreement with SLASO, UQ had ultimate responsibility for the execution of the HyShot project.

Astrotech Space Operations Inc.

Astrotech Space Operations Inc. of the United States was responsible for the provision of two solid-fuel rockets to launch the two UQ scramjet payloads and a launch crew to assemble and install the hardware on the launcher at the Woomera Prohibited Area (WPA). Additionally, Astrotech provided primary wind weighting services and was responsible for passing launch dates to the North American Aerospace Defense Command (NORAD) to ensure that collision with orbiting satellites or the International Space Station was not a possibility. The company applied for, and was granted, a launch licence from the US Federal Aviation Administration, Office of the Associate Administrator for Commercial Space Transportation.

Space Licensing and Safety Office

The Space Licensing and Safety Office (SLASO) was a sub division of the then Federal Department of Industry, Science and Resources (DISR). SLASO administered the *Space Activities Act* and had a regulatory role in overseeing civilian launch and space activities in Australia. SLASO received an application from UQ for an exemption certificate covering the HyShot project, that would otherwise have required a space licence and launch permit. They assessed UQ's application for an exemption certificate, including assessment of UQ's risk hazard analysis. Because there were no provisions within the *Space Activities Act* or

Space Activities Regulations to allow for a launch by educational/research organisations, SLASO recommended that the Minister grant UQ an exemption certificate to proceed with the project without a launch permit or space licence. Following the granting of the exemption certificate, SLASO entered into an Operations Agreement with UQ that made UQ ultimately responsible for the project with SLASO responsible for the appointment of a Launch Safety Officer, (LSO) for the two launches.

DISR and the Department of Defence (DoD) signed a Memorandum of Understanding (MoU) on 27 June 2001 which set out their various responsibilities and areas of cooperation in relation to the WPA.

The parties to the MoU agreed among other things, that SLASO would be responsible for:

- activities conducted within the WPA that required licensing or an exemption certificate to that licensing and ensuring that all such activities complied with the *Space Activities Act* and subsequent regulations;
- the review and acceptance of all supporting documentation relating to space launch activities in the WPA within the framework of the Act including safety templates, risk analysis, engineering data pack for the payload, hazardous and non-hazardous systems procedures and launcher installation and payload;
- the safety of all DISR activities related to the launch, including re-entry of all components of the launch vehicle and payload; and
- the appointment of a Launch Safety Officer (LSO). The MoU stated that any DoD safety personnel would co-operate with the LSO in the performance of these safety duties relating to a space launch.

Department of Defence

The Woomera Prohibited Area, of approximately 127,000 square kilometres, is located in northern South Australia and has been utilised as a rocket testing range for more than 40 years.

The WPA is bounded to the south by the Transcontinental Australian railway and traversed to the west of the launch site by the Central Australia railway lines and by the Stuart Highway. Additionally, part of the WPA is leased by pastoralists or owned by Aboriginal communities, with a number of mining companies also operating in the area.

Under the MoU between DoD and DISR, the parties agreed in general that the DoD would be responsible for scheduling and coordination of activities, access control to the WPA, maintenance of records, and liaison and consultation with affected local landholders and interested parties.

In particular, it was agreed that the DoD Area Administrator Woomera (AAW) was, among other things, responsible for:

- scheduling and coordination of all activities;

- the control of access to the WPA including the issuing of warning notices such as NOTAMS[3];
- liaison and consultation with local authorities, pastoralists and other interest holders; and
- general safety within the WPA and implementation of specific safety instructions that were not the responsibilities of users or SLASO.

These responsibilities were delegated from the DoD through the Defence Support Centre, Woomera (DSCW) and the Royal Australian Air Force Aircraft Research and Development Unit (ARDU).

DSCW coordinated all activity on the WPA, which included providing logistical, technical and infrastructure support to the HyShot program at the Woomera range. DCSW was also responsible for the operation of Woomera township and airfield.

ARDU operated the Woomera Instrumented Test and Evaluation Range which was where the HyShot launch was conducted and is contained within the WPA. All existing ground based instrumentation including communications, radar, launch circuitry and similar at the evaluation range was controlled by ARDU.

Prior to the launch, ARDU prepared a Range Operation Plan (ROP). The plan detailed, among other things, the project, vehicle specifications, instrumentation requirements and logistics, meteorological requirements, safety procedures, sequence countdown and stop and emergency actions. The plan was in part based on requirements of, or information provided by SLASO, UQ, Astrotech and DoD.

The plan was amended three times prior to the launch. That allowed for the inclusion and exclusion of items to the sequence countdown as additional information became available.

Personnel from a number of the participating groups who were interviewed after the launch, indicated that amendments to the ROP and the sequence countdown during the dress rehearsal were quite common. The rehearsal highlighted areas of concern, such as the correct sequencing of events and the allowance of sufficient time to complete a task.

ARDU also provided a Range Safety Officer (RSO) for the project. The RSO's responsibilities were in part based on requirements that SLASO required of UQ as part of their Operations Agreement, as well as defence responsibilities. That included public and range personnel safety for the duration of the project and the request for the issuing of a NOTAM to aircraft pilots. Responsibilities also included the notification of trial warnings to relevant homesteads 24 hours prior to launch and evacuation of personnel from homesteads within the second stage/payload impact dispersion area and ensuring that no trains were present on the sections of Central Australia or Transcontinental Australian railway lines that lay within the three – sigma impact dispersion area safety trace (see footnote next page).

[3] Notice to Airmen (advice to aircraft pilots of a change to any aeronautical facility, procedure or hazard)

QinetiQ

QinetiQ of the United Kingdom, formerly the Defence Evaluation and Research Agency (DERA) had built its own scramjet payload which was to be flown on the second flight if the first flight of the UQ payload was deemed to be successful. As UQ had applied for and been granted an exemption certificate from SLASO for the project which included the QinetiQ payload, QinetiQ did not apply for a space licence or exemption from the licence.

UQ noted in its application to SLASO that the QinetiQ payload was different, in that the device was constructed with different materials and didn't have the failure modes of the UQ payload. UQ noted that unlike its payload, the QinetiQ payload was considered to be unlikely to break-up during re-entry or at the load levels which were expected during ascent. UQ argued that the three-sigma impact dispersion area[4] determined for the UQ payload was larger than that for the QinetiQ payload. Based on this, UQ's view was that the analysis submitted for the UQ payload was expected to provide conservative estimates which could be used for the QinetiQ payload.

Federal Aviation Administration

As Astrotech was a United States company, they submitted an application for a licence, to allow them to conduct two Woomera launches. They also submitted a risk hazard analysis. The licence and analysis was submitted to the Office of the Associate Administrator for Commercial Space Transportation (AST), a sub division of the United States Federal Aviation Administration (FAA). The FAA granted Astrotech, the provider of the two-stage rockets, the launch licence to allow Astrotech to conduct two launches from the Woomera Prohibited Area.

Astrotech's application to the FAA included the possibility that the rocket may:

- explode at booster ignition;
- become unstable during flight;
- experience sufficient misalignments to cause the rocket and payload to impact outside the approved impact area; or
- experience sufficient wind changes to cause the rocket and payload to impact outside the approved impact area.

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[4] Three-Sigma dispersion area - Three-sigma dispersions define the expected uprange, downrange, and crossrange limits of normality for where the launch vehicle might impact. Impact dispersion of a launch vehicle is the statistical deviation of the actual impact point from the predicted nominal impact point. It is used to calculate the probability of impacting within a given distance of the nominal impact point. The dispersion distance is in terms of a standard deviation value (referred to as sigma). Theoretical dispersion is used when insufficient launches have occurred to adequately define flight dispersion with a high degree of confidence, and is determined by varying each of the parameters that affect impact range or azimuth. Each parameter is varied by its three sigma value, and then used to determine its individual effect on the vehicle's impact dispersion. The square root of the sum of the squares of the individual impact dispersions provides the total three sigma impact dispersion area of the vehicle. Assuming a normal distribution, this represents the area in which 99.7% of all impacts will occur. *http://ast.faa.gov/contest/attach_1.htm 29/11/01*

The predicted three-sigma dispersion of the HyShot second stage and payload equated to a circle with a radius of about 136 km centred on the nominal aiming point and about 373 km north west from the launch site.

Astrotech concluded that none of those risk factors presented a significant statistical threat to public safety. In the event that a booster exploded at ignition, damage would be confined to the launch area pad with no further threat to public safety. They stated that in the event that the vehicle became unstable, the vehicle would structurally fail, with all debris falling short of the predicted impact point due to loss of directed impulse and high drag profile energy losses.

Astrotech went on to say that in the event of excessive vehicle misalignments and/or unexpected wind changes, the vehicle and payload could impact outside the WPA. However, should the vehicle impact outside the WPA, Astrotech assessed that public safety would be threatened minimally due to the remoteness of the area of South Australia. Astrotech considered that there were no population centres, roadways or recreation areas located along the flight path or within the dispersion footprint for the vehicle with the exception of certain roadways which were to be closed by ARDU during launch operations.

Two FAA safety inspectors and a consultant to the FAA travelled to Woomera for the launch. The safety inspectors commented that the FAA usually attended launches. Their role was to ensure that Astrotech adhered to the FAA licence requirements during the launch. The licence became active at the time of first-stage ignition. After the launch the safety inspectors indicated that as Astrotech had adhered to the licence requirements prior to the launch, they saw no reason not to have allowed the launch to proceed. The safety inspectors also indicated that Astrotech would be submitting a written report to the FAA. The Investigator requested a copy of that report from the FAA, but was not provided with a copy of the Astrotech report.

2. History of the flight

Pursuant to UQ's MoU with Astrotech to launch their payload at Woomera in South Australia, the launch vehicle contained an experimental supersonic-combustion ram jet (scramjet) as part of the HyShot project. A two-stage solid-fuel rocket was provided by Astrotech to launch the scramjet payload on a ballistic trajectory to an altitude of about 314 kilometres within the WPA. During the unpowered ballistic return, UQ planned to introduce hydrogen into a combustion chamber of the scramjet, measure the resultant pressures and temperatures and relay those measurements via telemetry to ground stations. Two flights were planned, with three payloads available. Two were designed by UQ and the third was designed and provided by QinetiQ. The QinetiQ payload was to be used on the second flight, but only if the first flight utilising the UQ payload was deemed to be successful.

The first flight was planned for July 2001, but due to delays in payload readiness, delays in UQ submitting a final application from UQ to SLASO for an exemption certificate, the lack of an FAA-issued licence to Astrotech and a delay in finalising insurance and legal arrangements among the various parties, the launch date slipped to 30 October 2001. On the day prior to the planned launch, a full 'dress rehearsal' was held by the participants. All participants reported that the dress rehearsal was successful with only minor amendments being made to the countdown sequence, which was contained in the Range Operation Plan. Consequently, the go-ahead was given by the various groups[5] for a launch to be conducted on the following day, with the five hour countdown planned to commence at 0730 hours Australian Central Summer Time (CSuT).

The countdown commenced on time with only short delays occurring to allow for the recharging of batteries and extra time for fuelling of the payload. After each delay the countdown was resumed.

FIGURE 1.
Second stage burn. *Source: ARDU*

The launch occurred at 1301 CSuT. According to observers and video evidence, the first stage booster appeared to operate successfully, although some observers reported what appeared to be objects falling from the first stage vehicle. UQ personnel also reported an anomaly in the received telemetry data. After the initial coast stage during which the first stage separated, the second stage ignited and observers reported seeing the rocket and the resultant exhaust trails appearing to curl in a 'cork screw' fashion. That continued with the stability of the rocket appearing to deteriorate until it was out of sight.

The first stage booster was recovered from within its designated impact area.

[5] Astrotech, UQ, FAA, Launch Safety Officer and Range Safety Officer.

Remnants of the first stage fins were recovered north east of the flight path approximately 12 weeks after the launch. Based on radar and telemetry data ARDU, Astrotech and UQ personnel estimated that the second stage and payload impacted in an area approximately 100 km north west from the launch site rather than the 373 km nominal aiming point. An initial search for the second stage and payload, that was conducted by RAAF, UQ and DoD WPA personnel, was unsuccessful. However, the second stage and payload were recovered by UQ personnel about 16 weeks after the launch. The impact area was located about 28 km east of Highway 87, the Stuart highway.[6] The payload was designed to remain attached to the second stage during the flight, which it did.

After the loss of the rocket, and as part of the range operation plan, homesteads that lay within the planned trajectory path were contacted by the Range Safety Officer and asked if all personnel from the homesteads were accounted for. The homesteads were able to account for all personnel by the end of the launch day.

3. Sequence of significant events

TABLE 1.
Preparation.

Date	Event
14 January 1998	UQ applied to DoD for approval to use the Woomera Prohibited Area
21 December 1998	Space Activities Act enacted
16 March 1999	MoU signed between UQ and Astrotech
21 January 2000	Unofficial UQ minutes of a meeting where Astrotech required from UQ that the scramjet exhaust ports were to be covered during ascent
20 February 2001	UQ submitted first draft application to SLASO for a space licence and launch permit exemption
27 June 2001	MoU signed between DoD and DISR
28 June 2001	Space Activities Regulations enacted
11 July 2001	UQ submitted second draft application to SLASO for a space licence and launch permit exemption
25 July 2001	Project agreement signed between Astrotech and UQ
07 September 2001	FAA issued a launch licence to Astrotech
26 September 2001	UQ submitted final application to SLASO for a space licence and launch permit exemption
04 October 2001	Launch Agreement signed between DoD and UQ
08 October 2001	On-site phase commenced at the WPA
10 October 2001	Minister, based on SLASO's recommendation, issued an exemption certificate to UQ allowing them to launch
15 October 2001	Operations Agreement signed between UQ and SLASO
29 October 2001	Full 'dress rehearsal' conducted on site
30 October 2001	First HyShot rocket launched at Woomera

[6] Stuart Highway; a national north-south highway that traverses the continent and connects Adelaide on the southern coast with Alice Springs in central Australia and Darwin on the north coast.

TABLE 2.
Launch phase, 30 October 2001

Time (hh:mm:ss.00)	Event
07:30:00.00	Countdown commenced, [ARDU]
13:01:00.00	HyShot rocket launched
13:01:01.31	Possible debris to the left of the 1st stage fin trailing edge observed by UQ
13:01:01.33	Possible debris to the right of the exhaust plume observed by UQ
13:01:02.50	Anomaly in the accelerometer and magnetometer data observed by UQ
13:01:03.67	Coning (corkscrewing) observed by UQ
13:01:06.37	First stage burn concluded. Two objects observed by UQ
13:01:06.47	First stage separated from the booster
13:01:06.49 to 13:01:07.55	Three to four objects visible at various times observed by UQ
13:01:11.31	Second stage ignition. Coning (corkscrewing) observed by eye witnesses
13:01:40.00	Planned second stage burn concluded, [range operation plan]
13:03:56.00	Adour radar 1 ceased tracking the second stage/payload, at about a range of 60 km and an altitude of 70 km [ARDU/UQ]
13:16:00.00	Countdown sequence completed, T+15 mins [range operation plan]

CSuT times based on time stamp from the video evidence unless noted in square brackets. Digital copies of the video evidence was examined frame by frame by UQ, DoD, the Investigator and ATSB Specialists.

4. Launch Vehicle details

According to the UQ exemption application, the Terrier – Orion 5A vehicle was a two-stage, solid-fuel rocket motor, sub-orbital launch vehicle. It was planned to boost the 113kg UQ payload to 314km.

The vehicle was based on a converted, surplus Terrier solid rocket motor as the first stage and a converted, surplus Improved HAWK M-112 solid rocket motor as the second stage.

The sustainer motor (second stage) was a Hawk M112 motor (designated Orion 5A for commercial launch applications) modified for use as a sounding rocket[7]. Astrotech reported that the motor had been flown in numerous sounding rocket applications in a single stage as well as Nike, Improved Honest John and Terrier boosted configurations.

FIGURE 2.
Recovered first stage alongside the adaptor and the assembled unused first stage.

The HyShot Terrier – Orion 5A vehicle did not contain flight termination hardware. That is, the vehicle's rocket engines could not be shut down once ignited, nor was there an explosive device fitted to allow for the remote destruction of the rocket had that been desired. Such hardware was not required for the launch by SLASO or FAA regulatory requirements, or by DoD as a condition of entry to the WPA. Additionally, Astrotech indicated that it would be difficult to implement a flight termination procedure for a solid fuel rocket.

[7] Sounding refers to any penetration of the natural environment for observation or measurement. A sounding rocket is a stabilised, but usually unguided rocket, carrying upper-atmosphere instruments. Jane's Aerospace Dictionary, Bill Gunston

5. Payload and Planned Flight Details

The HyShot launch was conducted from the National Aeronautics and Space Administration (NASA) launch pad within Launch Apron 2 in the Woomera Instrumented Range (WIR).

FIGURE 3.
UQ Payload without the nose-cone
Source: http://photos.cc.uq.edu.au/ HYSHOT/ 29/11/01

The rocket flight was to take the scramjet payload to an altitude of approximately 314km and a range of 373km on a nominal heading of 297.5ºT. During the flight outside the atmosphere, a number of attitude corrections were to be applied to reorient the payload along the flight trajectory.

The payload contained a laboratory scale test configuration of a scramjet engine. The scramjet experiment was to be conducted on the return section of the flight between an altitude of 37 and 23km at an approximate velocity of 2,350m/s (8,460km/h).The mission objectives included collecting temperature and pressure data during the operation of the UQ scramjet engine. The data collected from the experiment was to be used to validate measurements recorded in the UQ Hypersonic Shock Tube Test Facility using an identical scramjet engine.

6. Weather

The weather details prior to the launch were provided by the Bureau of Meteorology (BoM) on a fee for service basis. The BoM provided a general area forecast including temperature, cloud base and visibility. The BoM forecast for the day of the launch indicated fine weather with scattered high level cirrus cloud, a south westerly wind of 10-15 knots and a ground level temperature of 23ºC. The report issued by BoM to the Investigator indicated that conditions at the time of the launch were similar to those forecast.

On the morning of the launch, the BoM provided wind direction and speed data to the project's wind weighting team for the 31 levels ranging from ground level to 20,000 metres. In addition, wind direction and speed data for levels from 450m to 1,500m was passed to the wind weighting team 15 minutes prior to the launch.

7. Wind Weighting

It is crucial to know the direction and strength of winds in the area before attempting to launch a rocket, because the type of rockets used in research, such as the Terrier – Orion 5A vehicle are not guided. Once the rocket is in flight, deviations in its path due to wind at various levels cannot be corrected.

In addition to the anemometer measurements near the launch pads, balloons were used to estimate the effects of wind in the atmosphere above the launch site. Balloons were released periodically before a launch, and were tracked with theodolite and/or radar. The change in the balloon's horizontal position as it ascended was used to estimate the wind speed and direction. A process called 'wind weighting' was used to estimate the effect of wind at various levels on the rocket's trajectory and adjust the launch azimuth and elevation accordingly.

Primary wind weighting was undertaken by Astrotech, with backup for comparison and accuracy conducted by personnel from ARDU. As a crosscheck, the data was also sent in real time to the meteorology group at the White Sands Missile Range in the US. The data was entered into wind weighting software by the three teams which computed the azimuth and elevation launch settings.

8. Possible factors that may have contributed to the rocket instability

The following aspects were investigated and analysed by personnel from a number of organisations involved in the project, including ATSB specialist investigators, in an attempt to determine the possible factors that contributed to the instability of the rocket.

Terrier Fins

After the flight, the UQ team reported that while examining their telemetry data they noted an anomaly in the accelerometer and magnetometer data at approximately 2.8secs after ignition. UQ had also noted that the vehicle never achieved the spin rate (4-6Hz) that was intended. However, the UQ team suggested that the low spin rate was more likely the result of some other event, perhaps the loss of one or more fins or a collision between the first and second stage during separation, rather than contributing to the accident.

Two observers reported seeing something falling from the rocket at the conclusion or close to the conclusion of the first stage burn, with one observer describing it as a glint of metal. Additionally a number of personnel from UQ, DoD and the ATSB who viewed the post flight video observed what appeared to be objects falling from the vehicle during the first 10 seconds after first stage ignition. However, the Optical Coordinator from the launch team and ATSB specialists considered that the video images lacked sufficient resolution to determine what occurred at those times. The Optical Coordinator later commented that camera equipment with enhanced resolution capabilities may have provided improved images and thus assisted with the post launch analysis.

Each of the rocket motors were fitted with fixed fins to stabilise the rocket. Although the first stage was recovered soon after the flight, remnants of the fins from that stage were not recovered for about 12 weeks. The remnants and components were recovered in separate locations approximately midway between the launch site and the first stage impact area and indicated that the fins separated from the rocket motor prior to it impacting the ground. The debris dispersion pattern is consistent with an in-flight breakup during the first stage flight (refer to Attachment D: Terrier First Stage and Fin Debris Dispersion). Shortly after the launch, Astrotech expressed surprise at the loss of the fins from the first stage.

ATSB specialist examination (refer to Attachment E: ATSB Technical Report) of the first stage indicated that the fin support structure (carrying the non-standard Nike fins) had broken up during the flight, with all examinable fractures consistent with the effects of gross overload through the fin spindle (journal) sockets. The larger Nike fins were fitted rather than the smaller Terrier fins to generate adequate torque and thus ensure planned vehicle stability. UQ reported that they needed the stability to ensure a stable platform during the descent phase of the experiment. No pre-existing defects were found within the physical structure of the fin support. Some of the fin journal sockets showed evidence of excessive angular bending forces. Specialist examination indicated that bending loads from the Nike fins contributed to the failure of the fin support structure. UQ commented that their telemetry data indicated that a collision may have occurred between the first and second stages during separation. However, the investigation found no physical evidence from the recovered components to support this.

A considerable proportion of the first stage fin skin and internal honeycomb material had not been recovered at the time the investigation was carried out. Of the material that was recovered, most of the damage and deformation was consistent with aerodynamic and ground impact overload. It was also evident that forceful contact had occurred between fin components during the break-up event. Marks and damage around the fin securing lug mounting points indicated in-flight movement and possible insecurity of the fin-lug connections. Evidence was found on the base of the motor case of a forceful glancing impact with the forward base rib of a Nike fin. The angle and orientation of the impact marks indicated the distortion or physical failure of the fin before it struck the motor case.

The angle of incidence of each fin was secured by a small block with set screws that clamped the fin at the appropriate angle. Specialist examination indicated that crushing damage of the rib sections beneath the set-screws was possibly pre-flight damage, which may have led to in-flight movement. It was also noted that the Nike fins were not designed for securing in the location used and contained no reinforcement or other strengthening features in this area. The Nike fins were designed to be secured on the leading side of the fin base, whereas the Terrier fins were designed to be secured on the trailing side of the fin base.

ATSB specialist examination of the payload found no evidence to suggest the payload and associated components had contributed to the flight anomaly, however the level of impact damage limited the examination. ATSB specialists examination of the second stage noted uneven aerodynamic heating effects around the second stage fins and tail. However, this can be attributed to the observed corkscrewing of the vehicle flight path.

Orion Fin attachment bolt torque values

After the flight, personnel from Astrotech checked the fin attachment bolt torque values on the other second-stage rocket motor that had been partially assembled for the next launch. The values were found to be about 10 inch-pounds less than the required amount which, according to the Astrotech "Operation and inspection log for the assembly of the Terrier-Orion Suborbital Launch vehicle system", called for 180 inch-pounds. The document also stipulated the fitment of roll pins to lock the fin angle once it has been assembled and set. Roll pins were not fitted to the Orion fins for the HyShot launch.

Astrotech indicated that NASA did not consider the pinning of the configuration mandatory. Nor did the company feel that the lower torque values would have been sufficient to allow one or more fins to become misaligned during the launch. However, Astrotech indicated that they plan to drill and insert the roll pins to lock the fins prior to the next launch.

Sandbags

During launch preparation, sandbags were placed around the base of the launcher. The Astrotech "Operation and Inspection Log for the Assembly of the Terrier-Orion Suborbital

Launch vehicle system" called for grout to be placed at the base of the launcher. However, grout was not available, thus sandbags were used to protect the base of the launcher.

UQ suggested that it was possible that a sandbag or a rock in a sandbag could have damaged a fin during the initial launch phase.

FIGURE 4.
A number of sandbags adjacent to the launch rail pedestal and blast wall, after the launch. Source: ARDU

That would have required a sandbag or rock to have been deflected off the infrastructure and impact a fin.

Video footage and still images viewed by the ATSB Specialists and Astrotech, indicated that a number of the sandbags were ejected and/or disrupted during the ignition and launch. However, it was not possible to determine if a rock had impacted a fin during the launch sequence.

9. Safety management issues

The following aspects were investigated and analysed by the Investigator and a risk management specialist.

UQ Exemption Permit Application

The *Space Activities Act 1998*, Sections 18 and 26, required any person who was to undertake launch activities to obtain a space licence and launch permit. The *Space Activities Regulations 2001*, Part 2 and 3, provided detailed statutory requirements to applicants wishing to apply for a space licence and launch permit. The regulations included a requirement regarding the provision of a risk hazard analysis according to an approved methodology that was contained in the Flight Safety Code (Refer footnote 9 on page 17). If the applicant elected to use an alternative methodology, they were required to submit the analysis for independent verification.

The application for a space licence and launch permit attracted a fee. The fee and risk hazard analysis, according to SLASO, were quite onerous and were designed for large commercial organisations planning to conduct commercial launches of orbital payloads. There was no launch licensing instrument appropriate to the resources of an educational/scientific organisation in the Act or Regulations to allow for launches such as HyShot. An amendment to the Act to allow for such projects was being proposed by SLASO at the time of the launch.

Section 46(1) of the *Space Activities Act* allowed for the granting of exemption certificates. The Minister could issue, to any person, an exemption certificate covering specified conduct that might have otherwise been prohibited under section 11, 13 or 15. To allow UQ to proceed with the launch and not place undue conditions on obtaining an approval, SLASO recommended that the Minister grant an exemption certificate to UQ under Section 46 of the Act. UQ was therefore exempted from the requirements of a space licence and launch permit for its proposed launches. The exemption certificate was signed by the Minister on 10 October 2001.

The Act did not allow for the exemption certificate to impose any conditions on UQ for the launch. However, prior to the launch, SLASO drafted an Operations Agreement with UQ which was signed on 15 October 2001. That allowed SLASO to provide UQ with detailed launch conditions and requirements. SLASO have indicated that the proposed amendment to the Act will allow for conditions to be attached to an exemption certificate.

Risk Hazard Analysis

The FAA required Astrotech to provide them with an acceptable risk hazard analysis as part of their licence application. In addition, the FAA undertook their own risk hazard analysis. SLASO understood that the FAA standards were slightly more stringent than SLASO's. Although SLASO requested a copy from the FAA of their risk hazard analysis, SLASO was not provided with the analysis.

As part of the exemption application, UQ was required to perform a risk hazard analysis of the launch. SLASO indicated that the analysis submitted by UQ in their final application covered successful launches and a possibility of non-ignition of the first stage or second stage, but did not adequately cover the first or second stage malfunctioning and going off course.

In a note relating to a draft submission by UQ to SLASO, dated 27 April 2001, to an internal SLASO file, the then Special Projects Manager of SLASO noted that:

> *'there does not appear to be a maximum individual risk (casualty) per launch calculation, or maximum individual risk(casualty) per year calculation. There is no analysis of any risks to high-value assets which are unoccupied by people: it is assumed there are none.'*

SLASO later commented to the Investigator that they felt that they were involved in a constant struggle to impose sufficient discipline on the project participants, but not place insurmountable hurdles to the success of the project. SLASO commented that they had also provided informal guidance during the application process to assist UQ with undertaking an acceptable risk hazard analysis.

In an assessment report dated 29 September 2001, relating to the UQ exemption certificate application, the then Acting Director of SLASO made a number of observations, among others, titled Risk Hazard Analysis and Flight Safety Code:

> *Based on the analysis presented, the SLASO is satisfied that a risk hazard analysis has been performed and that the launch will comply with the Launch Safety Standards of the Flight Safety Code, provided there are adequate exclusion arrangements for the WIR and the area around the nominal impact point .*
>
> *The SLASO understands that the FAA has undertaken its own risk hazard analysis of the HyShot launch, the results of which are not available to SLASO. The FAA standards are slightly more stringent than the SLASO standards.*

After the Launch, SLASO commented that there was no evidence that the launch violated the risk acceptance criterion spelled out in the launch safety standards of the Flight Safety Code.

The Range Operation plan (ROP), based on requirements from UQ, Astrotech and DoD, called for a check to be conducted to ensure that no trains were operating on those track sections within the three-sigma impact dispersion area prior to and during the launch and flight. The general public was evacuated from that area prior to and during the flight. The highway was not closed as it did not intersect the three-sigma impact dispersion area. The planned trajectory intersected the Central Australian Railway (Tarcoola-Alice Springs) and Stuart Highway.

As part of their risk hazard analysis, UQ was required to identify hazards such as structures and transport corridors. Additionally, as part of their analysis for determining the amount of insurance, UQ assessed the population density of the Stuart Highway within the 5.5-sigma impact dispersion area[8], which did not require evacuation, based on data from the South Australian Traffic Information Management Section. UQ also performed a similar analysis on the Railway Lines within the 5.5-sigma area. There were two railway lines within the 5.5-sigma area: the Trans Australian Railway and the Central Australia Railway. UQ calculated that the population density along the Stuart Highway was 263 people/km^2 while they calculated a population density of 422.9 people/km^2 for the Trans Australian Railway and 264 people/km^2 for the Central Australia Railway. Although UQ had assessed the population density of the transport corridors as part of its insurance methodology, it had not specifically considered the possibility of the rocket impacting near the Stuart Highway when it undertook hazard identification as part of the risk hazard analysis process. The second stage and payload impacted about 28 kilometres east of the highway.

Specialist risk management advice to the Investigator reported that the information provided in UQ's application indicated that the risk approach had been directed towards 'insurance methodology'[9]. That was reflected in the risk criteria where population considerations had been used. That approach had defined the context of the assessment and as a result had provided results in the area of casualty expectation, probability of impact, casualty areas, individual risk isopleth[10] and the total casualty expectation. In the specialist's opinion, the scope of the approach to risk should have been broadened to take a more holistic view of risk so that the process would add greater value and benefit to both the planning and conduct of the proposed launch.

The specialist report went on to state that the depth of analysis indicated in the documented part of UQ's application was not comprehensive. As a result of that, it was difficult to ascertain the process that was followed to reach the results and the associated considerations. The statement by UQ that 'the debris resulting from the possible failure modes in region 1 falls on an unpopulated area and hence a risk hazard analysis is not required' indicates the limited scope of the assessment against casualty expectations. UQ stated that it had followed the statutory methodology and guidance provided by SLASO. SLASO indicated that responsibility for the risk hazard analysis lies with the applicant and that UQ should have obtained additional guidance if required.

The SLASO document, The Flight Safety Code states:

> *Safety of the public, property and major national assets underpins the safety regime. The safety regime is based on a 'safety case' approach which places responsibility for the ongoing management of safety on the launch operator. A launch proponent will present a safety case to the regulator to demonstrate*

[8] The 5.5-sigma impact dispersion area, surrounding but excluding the 3-sigma impact dispersion area, described at footnote 4 on page 4, had a much lower probability of vehicle impact (0.27%) than the 3-sigma impact dispersion area.

[9] A document from SLASO titled 'Maximum Probable Loss Methodology' provided a methodology for estimating the amount of insurance required.

Statutory methodology and guidance material was available from SLASO to applicants. The Flight Safety Code contained a section titled 'Risk hazard Analysis Methodology' and was written to assist applicants with undertaking a risk hazard analysis.

[10] Line on a map passing through points with the same numerical values.

that the risks associated with the operation of the launch facility, the launch vehicle and the proposed flight paths are as low as reasonably practicable.

In summary, the specialist report commented that the UQ risk hazard analysis conducted was limited by the context of the submission of the licence application and the requirements imposed by insurance methodology. A broad approach to the identification, assessment and treatment of risk was not documented for this activity. A joint risk assessment was not conducted by the involved parties or stakeholder.

DoD has also indicated that it may request a review of the MoU between it and SLASO. Additionally, DoD has indicated that SLASO should sight all documentation in relation to risk assessment. This includes documentation produced by overseas organisations that are involved in a project at Woomera. Additionally, organisations required to undertake risk hazard analysis should submit their analysis for independent review prior to the project.

10. Analysis

Rocket Instability

After the launch and in the weeks following, UQ, Astrotech and DoD examined the available radar, telemetry and video data from the flight in an attempt to determine what contributed to the rocket's unstable flight. This included the data that indicated that an anomaly had occurred at 2.8 seconds of flight and that the vehicle had not attained the designed spin rate. In addition, the Investigator and ATSB Specialists examined the recovered components.

UQ considered the scenario of a sand bag or a rock contained within a sand bag, impacting one or more fins on the vehicle. However, the bag or rock would have had to have been deflected off the launch infrastructure. Although not all the sandbags are visible on the video recorded during the ignition and lift off stage due to smoke and dust, some bags can be observed being ejected and/or disrupted. However, it was not possible to determine if a sandbag or rock impacted a fin.

The fitment of the larger non-standard Nike fins may have played a part in the failure as they would have placed increased loads on the fin support structure. Examination of the first stage indicated that the fin support structure (carrying the larger Nike fins to generate adequate torque) had broken up during the flight. No pre-existing defects were found within the physical structure of the fin support. Some of the fin journal sockets showed evidence of excessive angular bending forces, suggesting possible out-of-plane movement or rotation of the fins during flight.

Of the fin material that was recovered, most of the damage and deformation was consistent with aerodynamic and ground impact overload. The observed crushing damage of the rib sections beneath the set-screws possibly allowed the fins to move in flight. A small amount of movement at supersonic speeds would be sufficient to cause the fins or the support structure to exceed their design aerodynamic load. The use of the Nike fins rather than the Terrier fins meant that the fin angle could not be locked using the set screws at the designed reinforced location.

After the launch, Astrotech checked the unused assembled second stage (Orion) fin attachment bolt torque values and found them to be about 10 inch-pounds less than the recommended 180 inch-pounds. This equates to about 5% less torque than recommended. The view of an ATSB engineering specialist was that under normal operational considerations it is unlikely that this would have been sufficient to allow the fins to move in flight.

No evidence was found, from the recovered components, to indicate that the Orion second stage, payload or associated components had contributed to the flight anomaly.

Based on the available evidence, it is likely that the first stage Nike fins either sustained damage from aerodynamic overload due to their movement during the supersonic flight and/or the fin support structure was unable to support the increased aerodynamic load of the larger Nike fins. It is also possible that the sandbags or rocks ejected during the launch damaged the first stage fixed fins. As a result, at separation, the second stage would have been in an unstable flight attitude and possibly not able to recover stabilised flight. However, it was not possible to determine what caused or allowed the fins to move during the flight.

Exemption Certificate and Risk Analysis

This was the first time that UQ had undertaken this type of project. UQ relied on the guidance material provided by SLASO. SLASO was itself undertaking the processing of an application for a launch under the new Act and Regulations for the first time. The Regulations had been enacted in June, only four months before the launch took place. Thus both organisations were in some part 'feeling their way'. Additionally, the application was made more complex because of the number of organisations involved, with some located overseas and in that a mechanism did not exist to licence an educational facility with limited resources such as UQ. SLASO realised that the only way forward was to utilise the exemption certificate mechanism contained within the Act. However, SLASO had to ensure that they could impose conditions and requirements on UQ after the granting of the exemption certificate as the exemption by its nature exempted the applicant from any requirements of a launch permit or space licence. This they did through the Operations Agreement with UQ that made UQ ultimately responsible for the project. The agreement also detailed conditions as well as extensive powers and responsibilities for the LSO.

UQ indicated that it wasn't always sure of what was required in the way of material for the application or risk analysis, but was aware of the guidance material and methodology available from SLASO. SLASO has since produced a draft document to assist applicants with their application. SLASO indicated that if UQ had applied for a Space licence and launch permit then it would have had to subject their risk hazard analysis to independent verification as called for in the Regulations. However, SLASO had indicated to the Investigator that with the granting of an exemption certificate they were not required to do this. SLASO commented that the onus was on UQ to provide a thorough risk hazard analysis and UQ was free to refer to additional material and an independent specialist to assist it with the analysis.

In its risk analysis, UQ concluded that the risk factors did not present a significant statistical threat to public safety. However the second stage and payload impacted an area about 28 km to the east of the Stuart Highway. The rocket's planned trajectory was to the north west. Sections of the two railways were closed because they intersected the three-sigma areas. The highway did not intersect the three-sigma area although the rocket's trajectory crossed both the north-south Stuart Highway and Central Australia Railway.

Although UQ had identified the highway and the rail corridors as part of its insurance assessment, utilising the SLASO insurance methodology, they did not identify the highway in the risk identification during the risk hazard analysis. UQ has indicated that they never specifically considered the possibility of the rocket impacting near the Stuart Highway.

In high risk and reliability industries, the conduct of a risk analysis provided the opportunity for risks of an associated activity to be communicated with stakeholders so that the acceptability of the risk could be determined. The level of detail of a risk assessment is usually determined by the:

- likelihood of the outcome occurring;
- importance of the activity and the significance of the outcome;
- potential consequence and severity of the potential outcome;
- complexity of the activity;
- level and type of information that is needed to communicate to stakeholders; and
- type of risks and hazards associated with the activity.

The risk assessment contained in UQ's application did not detail a great deal of information on the management, treatment or control of the risks. This is not to imply that risks were not treated or controlled through other means but the information was not well documented within the risk assessment in the application.

Had UQ submitted its analysis to independent verification and/or had UQ accessed or had access to additional material from Australia and/or overseas, then the possibility of something occurring other than what was allowed for may have been flagged. Additionally, although not required, had UQ shared or discussed their risk hazard analysis with the significant stakeholders, then that too may have resulted in additional hazards being identified. The SLASO Flight Safety Code states that the responsibility rests with the launch operator, in this case UQ, who must present a safety case to the regulator that the risks associated with the operation including the proposed flight paths are as low as reasonably practical. SLASO's comment that they struggled to impose sufficient discipline on the project participants, but not place insurmountable hurdles to the success of the project, indicated that UQ, although not necessarily taking the minimalist approach, probably viewed the risk hazard analysis process as an exercise to be completed in order to gain the exemption certificate. Had UQ recognised the need for it to assume ownership of the risk hazard analysis process then it would have been incorporated as part of the overall project. This then would have probably assisted UQ with the identification of additional risk hazards.

Based on the available evidence, the Investigator has determined that DoD and the LSO fulfilled their responsibilities for the launch.

11. Safety Actions

The following safety issues identified during the investigation have been or are being addressed by the participants.

Safety Actions conducted by Organisations

SLASO has indicated that:

1. it is seeking to acquire specialist risk management software with appropriate user training to assist with the assessment and verification of risk hazard analysis as submitted by applicants;
2. it has gained Government approval to amend the *Space Activities Act* that will allow the issuing of licenses and permits solely for educational or research projects;
3. it plans to provide additional guidance for applicants wishing to apply for a licence, permit or exemption certificate; and
4. it is considering giving greater prominence to the Flight Safety Code which contains the Risk Hazard Analysis Methodology, and to the need for comprehensive hazard identification.

UQ has indicated that:

1. it plans to reassess the risk hazard analysis prior to the next launch.

Astrotech has indicated that it plans to:

1. pin the second stage fins prior to the next launch; and
2. review its pre-launch assembly procedures of the Terrier – Orion 5A vehicle.

DoD has indicated that:

1. it plans to review its internal procedures for the approval of Woomera Prohibited Area activities; and
2. the MoU with SLASO may also be reviewed.

Recommendations

In addition to these safety actions, the Investigator issues the following recommendations.

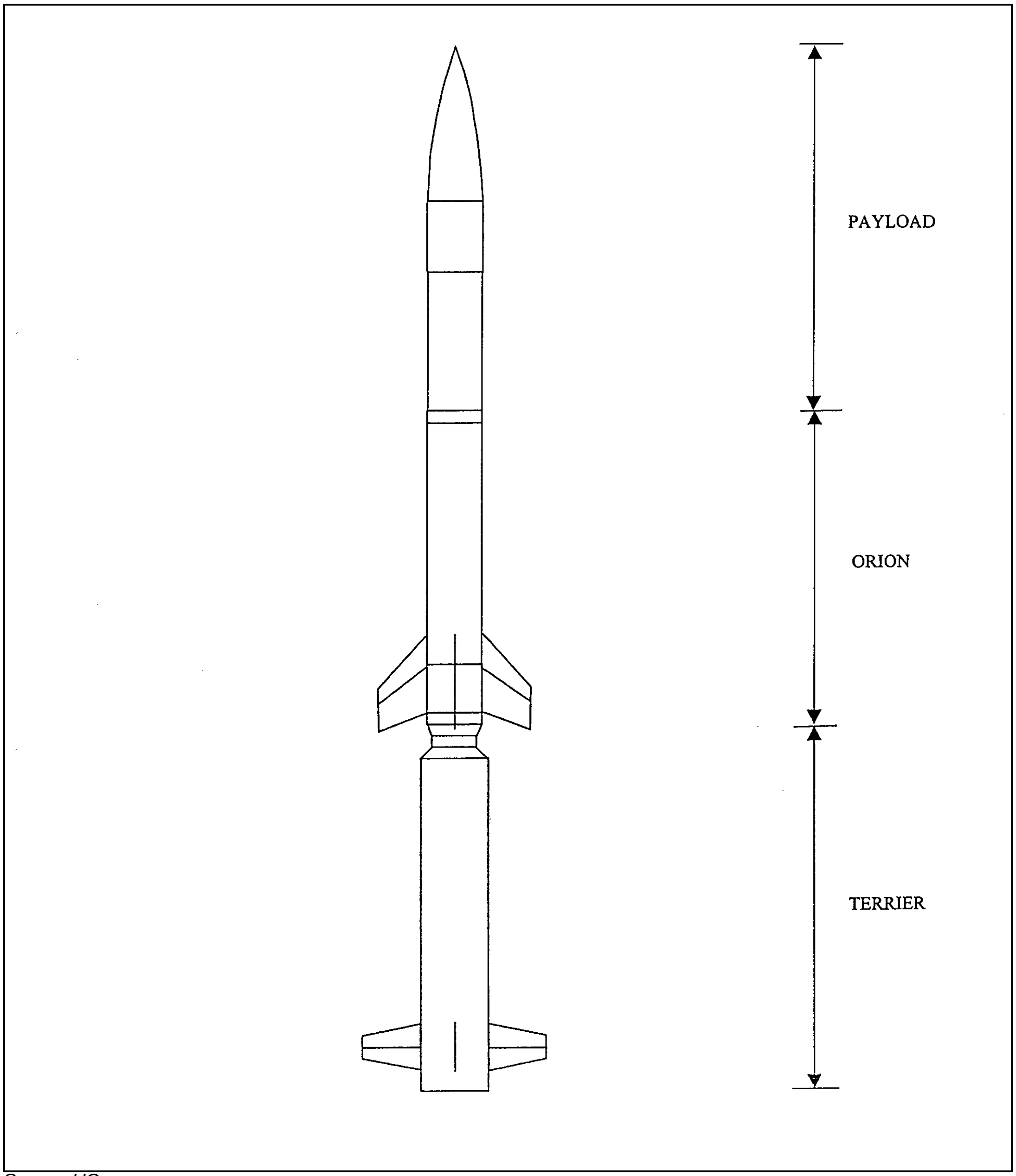
1) That Astrotech review the:
    a) suitability of the Nike fins for use on the Terrier vehicle;
    b) suitability of the fin support attachment structure when other than Terrier fins are used;
    c) suitability and effectiveness of the opposing set-screw arrangement for securing and setting the Nike fin incidence angle to the Terrier fin support structure; and
    d) suitability of the use of sandbags at the base of the launcher pedestal, in lieu of the specified grouting.
2) That SLASO require all Australian launch operators to submit a comprehensive risk hazard analysis for independent verification prior to the issuing of a licence, permit or exemption certificate.
3) That SLASO consider requiring launch operators to submit their risk hazard analysis to stakeholders and participants, for review and discussion.
4) That launch infrastructure providers make available sufficient resources to enable the provision of appropriate recording equipment with suitably trained personnel to provide additional recorded evidence to aid any occurrence investigation that may be necessary.
5) That overseas organisations involved in an Australian launch provide any risk hazard analysis and/or assessment to SLASO to better enable SLASO to properly assess a launch application.

12. Attachments

Attachment A: Terms and Abbreviations

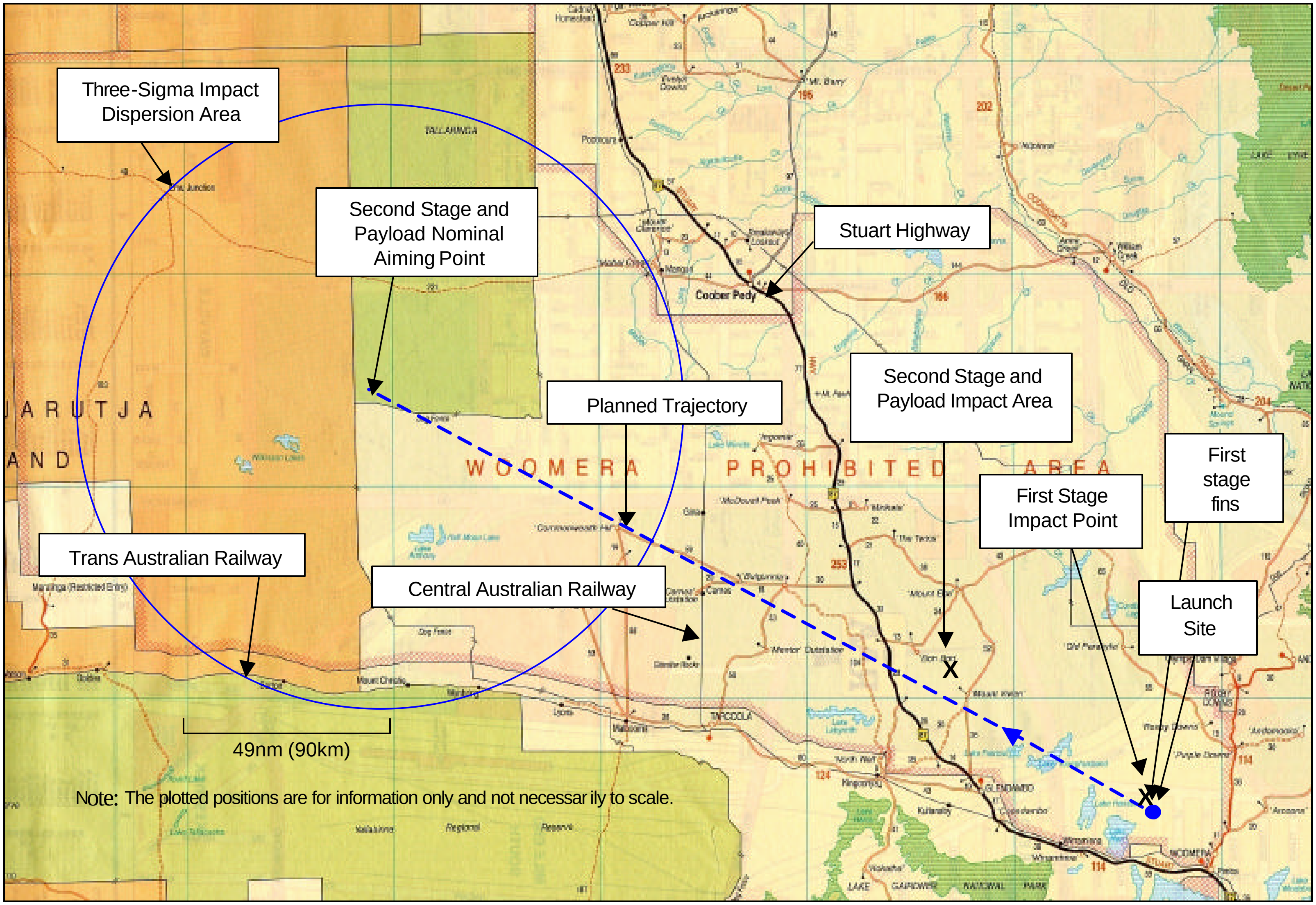
AAW	Area Administrator Woomera
AMSL	Above Mean Sea Level
ARDU	Aircraft Research and Development Unit
ASO	Astrotech Space Operations Inc. (USA)
AST	Associate Administrator for Commercial Space Transportation (USA)
ATSB	Australian Transport Safety Bureau
BoM	Bureau of Meteorology
CSuT	Australian Central Summer Time (UTC + 10.5 hours)
DISR	Department of Industry Science and Resources
DoD	Department of Defence
DSCW	Defence Support Centre Woomera
FAA	Federal Aviation Administration (USA)
HS	Homestead
km	Kilometres
km/h	Kilometres per Hour
LSO	Launch Safety Officer
m/s	Metres per Second
MoU	Memorandum of Understanding
NASA	National Aeronautics and Space Administration (USA)
NOTAM	Notice to Airmen (advice of a change to any aeronautical facility, procedure or hazard)
OS	Out Station
RAAF	Royal Australian Air Force
ROP	Range Operation Plan
RSO	Range Safety Officer
SLASO	Space Licensing and Safety Office
UQ	University of Queensland (in this case the Department of Mechanical Engineering)
US	United States
WIR	Woomera Instrumented Range
WPA	Woomera Prohibited Area

Attachment B: Terrier-Orion 5A

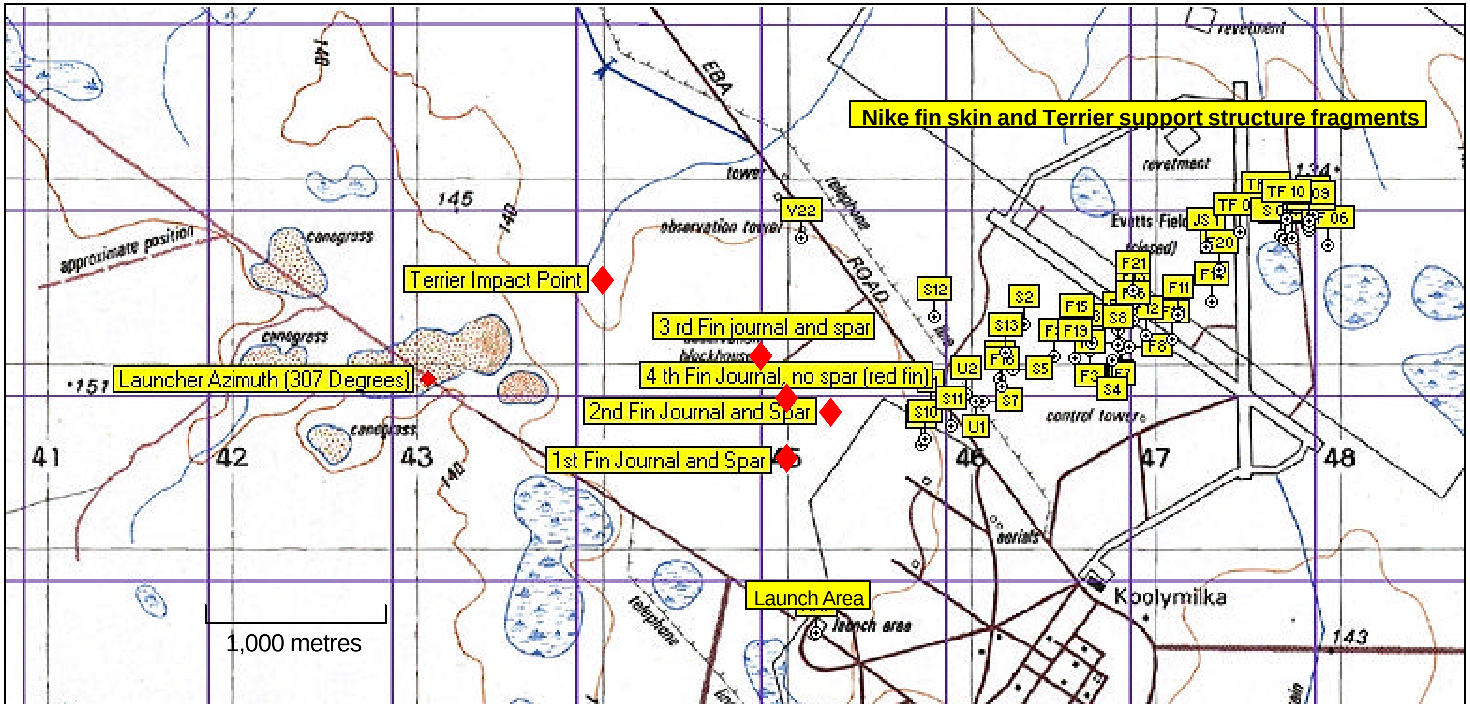


Source: UQ

Attachment C: Launch Site and Impact areas



Attachment D: Terrier First Stage and Fin Debris Dispersion



Source: DSCW

Attachment E: ATSB Technical Report

TECHNICAL ANALYSIS REPORT No: 08/02

REFERENCE No: BE/200200007

Examination of launch vehicle debris from the HyShot 'Scramjet' Flight Program

1. FACTUAL INFORMATION

1.1 Introduction

1.1.1 Flight anomaly

On 30 October 2001, the University of Queensland Department of Mechanical Engineering, in conjunction with Astrotech Space Operations Inc, launched the first of two planned flights of an experimental supersonic combustion ramjet engine (scramjet). The scramjet was carried as a payload aboard a two-stage solid-fuel rocket assembly.

Video images showed what appeared to be objects falling from the first-stage vehicle during the early stages of the flight,. During the subsequent second-stage burn the vehicle's stability appeared to deteriorate, with the rocket and exhaust trails curling in a 'corkscrew' fashion. The motion continued until the vehicle was beyond visible range.

1.1.2 Scope of examination

The purpose of this examination was to identify and define any engineering deficiencies that may have contributed to the flight anomaly experienced by the HyShot launch vehicle. This was to be achieved primarily through the study of the physical evidence presented by the recovered components.

1.1.3 Debris recovery

The first stage booster section of the launch vehicle was recovered from within it's designated impact area. Fragments of the booster fins, which were not found with the main body of the booster, were subsequently recovered from a location to the north east of the planned flight path, around twelve weeks after the launch. An initial search of probable impact points for the payload and vehicle second stage was unsuccessful, however a subsequent search by University of Queensland personnel located the vehicle wreckage in late February 2002.

Several small ground searches in the area to the north west of the launch site recovered additional fragments of the booster fins and the fin support structure. All items were gathered at a central location to facilitate the study and analysis.

1.2 Vehicle construction

The HyShot scramjet launch vehicle comprised two solid-fuel rocket motors configured for unguided, sub-orbital flight (figure 1). The 'booster' first-stage was based on a converted 'Terrier' Mk70 rocket motor, fitted with non-standard 'Nike' fins. The Nike fins were appreciably larger in surface area than the original Terrier fins (figures 3 and 4). Supplied drawings for the Nike fins illustrated a chamfered end on the inner trailing edge – a feature that was not present on the installed items. On this installation, the fin trailing edge protruded into the exhaust efflux (figure 6). Also of interest was note 13 on drawing sheet 1, which stated "This fin is for use on a 3 fin Nike vehicle only. See drawing ___ for modifications required for Taurus fins".

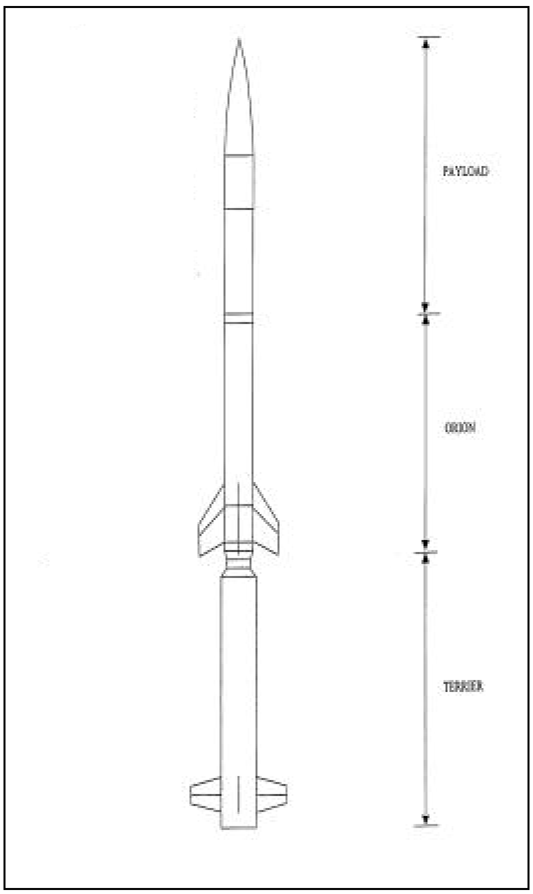


Fig. 1 (above). HyShot launch vehicle general assembly.

Fig. 2 (right top). 'Nike' fin as installed on the Terrier booster.

Figs. 3 & 4 (right middle & bottom). Size comparison between the Nike fins as installed on the HyShot vehicle, and the original fins as intended for the Terrier booster.

Because of differences between the design of the Nike fins and the Terrier fin support structure, each of the fins was fitted with an adaptor on the spindle post to suit the journal socket diameter. Additionally, four fin locating studs fitted with cup-point set-screws were used to secure and set the fin incidence angle (figure 5). These studs affixed to the aft section of the fin base rib by clamping down on the U-section from both sides (figure 6). The original Nike design provided a reinforced region on the forward rib section for that purpose, however the area on the fin, was not used because of design incompatibilities between the Nike and Terrier components.

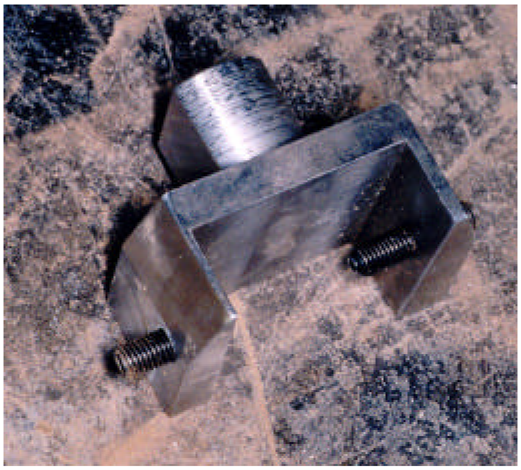


Fig. 5. Fin securing lug, as manufactured for the Terrier vehicle to suit the Nike fins.

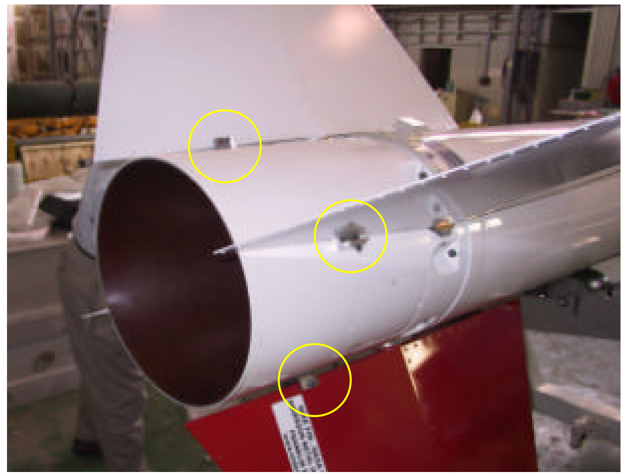


Fig. 6. Fin securing lugs (circled) installed with Nike fins on a Terrier vehicle. Note the trailing edge of the fins extending past the exhaust nozzle.

The 'sustainer' second-stage motor was based on a 'Hawk M112' motor, commercially designated as an 'Orion 5A'. The Orion vehicle carried the scramjet payload and was coupled to the Terrier booster by a tapered adaptor, which also contained the ignition assembly for the booster. Two locating dowels and two offset keys ensured the radial alignment of the vehicles and a shallow taper on the coupling seat allowed for smooth decoupling in flight after burnout of the booster motor. The fins used for the Orion vehicle were of sandwiched honeycomb construction, with a solid framework and a composite leading edge shroud (figure 7). It was understood that the fins used were the design-intended items for the Orion vehicle.

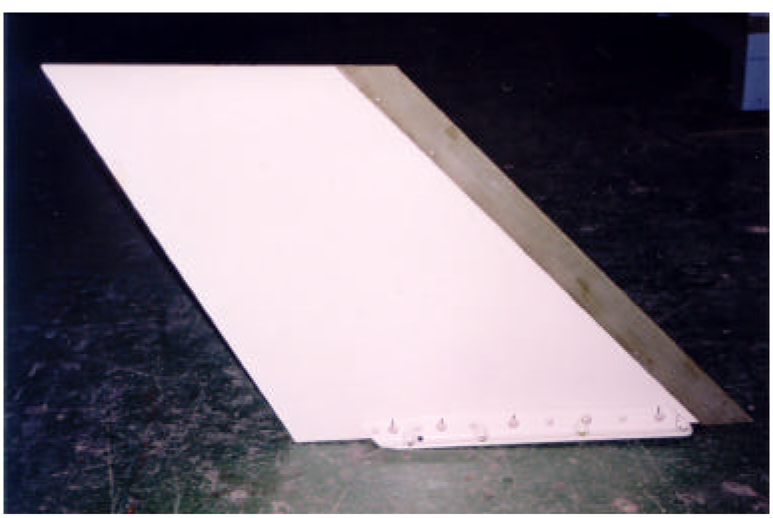


Fig. 7. Original Orion vehicle fin with composite leading edge shroud.

1.3 Payload and Orion motor body

As a result of the extreme forces associated with the high velocity ground impact, the scramjet payload was extensively fragmented (figure 8). Reports from the recovery personnel indicated that a small grass fire had started following the impact and evidence of this was found amongst the payload debris. There was no evidence to suggest that this fire had originated during the flight. Fragments of the vehicle nosecone were recovered with the payload – indicating that nosecone ejection did not occur in-flight (figure 9). Both scramjet exhaust port covers ('muffs') were also found with the nosecone debris (figure 10). The level of fragmentation and damage to the payload and support structures prevented any meaningful examination of the scramjet mounting security or other features of relevance.

Fig. 8 (top L). Debris and remnants of the HyShot scramjet payload and Orion motor casing.

Fig. 9 (top R). Remnants of the vehicle nosecone structure.

Fig. 10 (left). Scramjet exhaust port covers (muffs) recovered with the payload debris.

1.4 Orion tail can and fins

The Orion tail can unit was a cylindrical casting, affixed to the base of the motor casing and carrying the four vehicle fins. As recovered, the can had fractured longitudinally in four locations, producing three large sections and several smaller pieces (figures 11 – 14). The nature of the longitudinal fractures was consistent with the tail can impacting the ground in a sideways fashion and breaking open under bending loads from the attached fins. Of the four original vehicle fins, only three were found at the impact site. The remaining fin was not recovered despite a thorough search of the area. Of the recovered fins, two had fractured along the base of the mounting flange and the third remained attached to the tail can wall. A basic re-construction of the tail can and fin assembly was used to visualise the damage distribution.

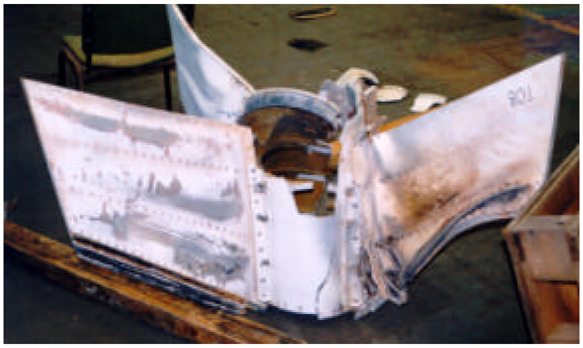
Figures 11 & 12. Sides of the Orion tail can and recovered fins.

Fig. 13. Multiple longitudinal fractures within the tail can – typical of sideways impact.

Fig. 14. Re-assembled sections of the tail can, showing the orientation and positions of the recovered fins.

When viewed from all sides (figures 15 – 17), it was readily apparent that several of the Orion fin surfaces had sustained significant aerodynamic heating, and that the level of heating varied markedly around the vehicle. On the 'cool' side, the fin and tail can surfaces showed minimal thermal effects, with the paint remaining glossy and surface printing clearly visible (figure 17). Contrastingly, the opposite 'hot' side of the vehicle (figures 15 & 16) presented areas on the fin surfaces and tail can where the paint had completely burnt away and the underlying sheet metal had sustained cracking and burn-through (figures 18 – 21). The thermal damage to the fins was most prominent in bands running parallel to the leading edges and situated between the span-wise rows of rivets.

The composite leading edge shroud was found intact on the two fins facing the cooler side of the Orion tail section and showed further evidence of the differential heating between the surfaces of the fins. Both shrouds examined showed marked differences in the appearance of the ablated material from side to side. The cooler faces of the shrouds tended to show a smoother, less disrupted surface, whereas the warmer faces had sustained a greater level of charring and delamination (figure 22).



Figs. 15, 16 & 17 (below left). Reconstruction of the Orion tail can and fins as recovered, showing the aerodynamic heating effects and the variation in these effects around the vehicle.

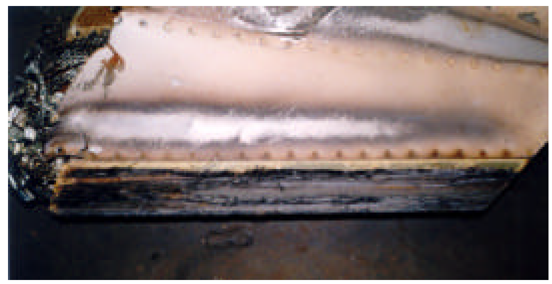


Fig. 18. Bands of heating behind the leading edge of an Orion fin.

Fig. 19. Closer view of the heated area, showing the development of transverse cracking.

Fig. 20. Area of skin burn-through, with associated thermal damage to the internal honeycomb structure.

Fig. 21. Closer view of the burn-through area shown in figure 16.

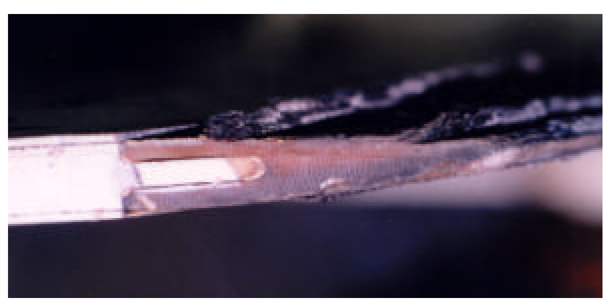
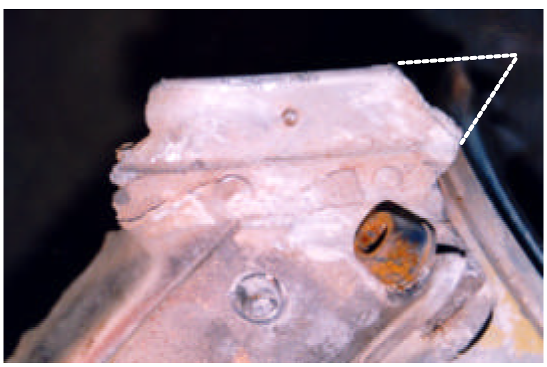


Fig. 22. Edge of the phenolic leading edge shroud, showing differences in the surface appearance from side to side.

Despite the loss of the leading edge shroud from the third remaining fin, the underlying strip had not sustained any notable thermal damage, even though the material back from the leading edge showed the effects of severe heating (figure 23). The immediate tip of the leading edge strip was well preserved, despite appreciable melting and metal-loss from the skin and structure behind (figure 24). In comparison, the tip of the leading edge strip from the adjacent (missing) fin showed extensive melting and ablation of the tip and the structure immediately behind the tip (figure 25). Separation and partial exfoliation of the wrought section was evident, with the edges deflecting away from the 'hot' side of the vehicle (figure 26). Deposits on the tail can surface immediately behind the melted edges clearly depicted the molten, oxidised material streaming backward (figure 27).

Fig. 23. Fin leading edge strip. Showing no thermal damage, despite the obvious damage to the skin behind.

Fig. 24. Tip of the leading edge strip shown in figure 23. No evidence of thermal damage, although the skin behind is partially melted and eroded.



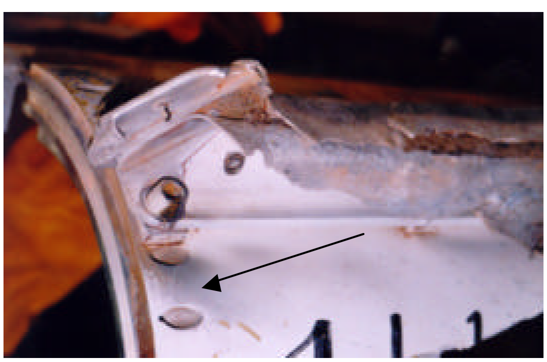
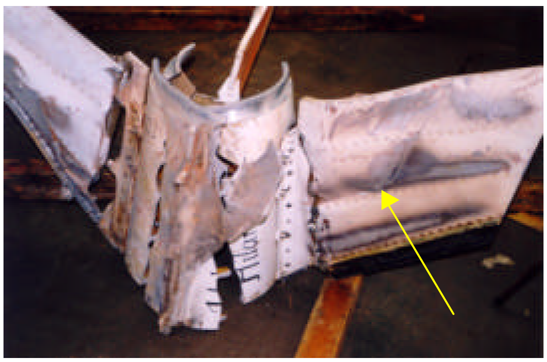


Fig. 25 (above left). Melting and metal loss from the leading edge tip on the missing fin. The skin and surfaces immediately behind also show metal loss.

Fig. 26 (above right). View from the opposite side, showing the exfoliation effects and backward distortion of the tip material.

Fig. 27 (left). Flow patterns on the tail can surfaces from the molten, oxidised material streaming backwards.

One of the Orion fin surfaces appeared to show witness marks to the impact with another component. The affected fin (facing the location of the missing fin) bore an angular impact mark that could be clearly attributed to forceful contact with the outer leading edge corner of the missing fin (figures 28 & 29). Contact marks at the corner showed an impression of the leading edge strip, which suggested the loss of the protective shroud (figure 30). Also evident were several impressions from rivet heads along the fin tip. The fin surfaces in the impact area showed a uniform band of aerodynamic heating, with the characteristic discoloured, flaking paint. Close examination showed that this heating had occurred before the impact, as much of the flaking paint had been removed and the exposed edges remained bright and unaffected. Had the impact occurred before the heating, thermal damage to the exposed metal edges and a less uniform heating pattern would have been expected.



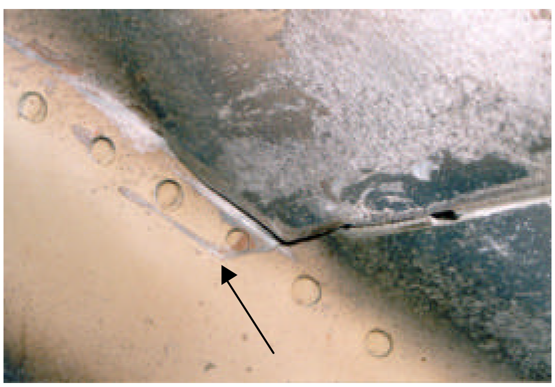


Fig. 28 (top left). Re-assembled tail can and fins, showing the orientation between the missing fin and the impact mark on an adjacent fin (arrowed).

Fig. 29 (top right). Closer view of the impact mark on the fin surface – note the clearly defined edges.

Fig. 30 (left). Corner of the impact mark, showing the impressions left by the edge rivets and the exposed leading edge strip (arrowed).

The fractures and tearing within the structure and skin at the attachment point of the missing Orion fin showed evidence of failure under bending towards the adjacent (impacted) fin. Remnants of torn skin remained attached on the surface facing the adjacent fin, whereas the skin on the opposite side had predominantly failed along the base of the mounting flange (figure 31). Further evidence of severe aerodynamic heating was found on the skin and structure surrounding the fin, with the skin fracture surfaces showing the effects of the irregular, thermally induced cracking that characterised some of the other heated areas (figure 32).

Figs. 31 (left) & 32 (above). Failure of the surface skin from the missing fin. Note the differences between the heavily heated side (above) and the opposite side (left).

1.5 Terrier-Orion adaptor

The coupling and transfer of thrust loads from the Terrier booster to the Orion sustainer and payload vehicle was achieved using a tapered adaptor (figure 33). Abrasion damage to the adaptor was limited to one side, indicating an angular ground impact (figure 34). Structurally, the adaptor unit appeared sound and showed no evidence of failure or prior damage that may have contributed to the flight anomaly. The parts of the connector that coupled with the base of the Orion vehicle showed several bands and scuff marks within the plated surface. The most prominent of these marks was found adjacent to one of the coupling keyways, although the key itself was missing (figure 35). All of the scuffing that produced the marks showed an axial orientation and as such, was likely related to the initial assembly of the HyShot vehicle, or the in-flight separation of the vehicles after the first-stage burn. The largest of the bands of scuffing showed an angular orientation to the axis of the adaptor – suggesting a degree of axial misalignment existed between the Terrier and Orion vehicles as they separated.

The adaptor surfaces (both inside, [figure 36] and out) showed no evidence of combustion products that may have indicated either a leakage from around the ignition assembly, or proximity to the Orion vehicle when the second-stage burn commenced.

Fig. 33 (left). Terrier – Orion adaptor showing the abrasion damage over the external surfaces produced during ground impact.

Fig. 34 (right). Opposite side of adaptor – damage free.

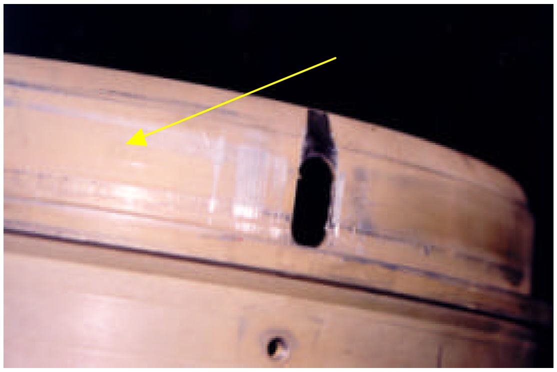


Fig. 35. Orion coupling area – note the missing key and the bands of axial scuffing. The angular band (arrowed) is indicative of misaligned vehicle separation.

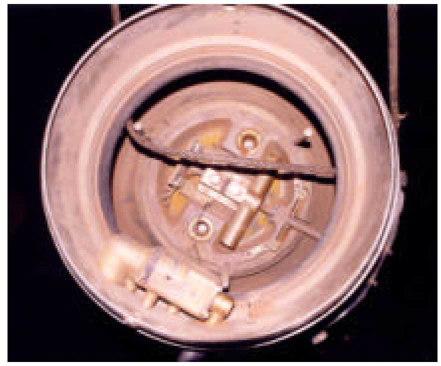
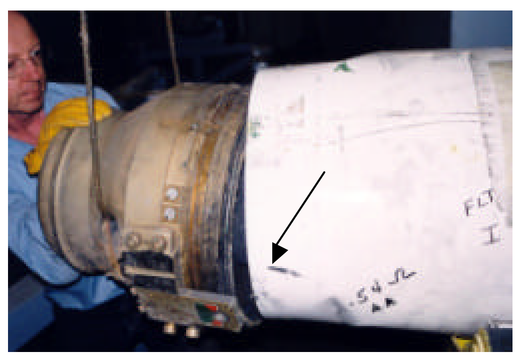


Fig. 36. Internals of the adapter unit, showing the ignition mechanism. All surfaces were free from combustion products.

1.6 Terrier motor body

The Terrier booster motor body (figure 37) comprised a rolled, cylindrical vessel, to which the adaptor assembly was coupled at the top and the discharge nozzle and fin support structure affixed to the base. The separation of the adaptor from the motor body occurred from the angular ground impact, with all associated fractures of the motor body shell being consistent with that event. A small emission of combustion products was evident from a bleed hole in the upper motor casing (figures 38 & 39).



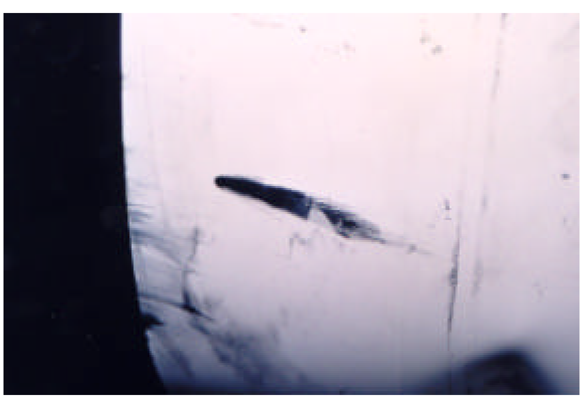


Fig. 37 (top left). Terrier booster body casing.

Fig. 38 (top right). Adapter unit, showing interconnection with the Terrier casing. The small bleed of combustion products (fig 39) is arrowed.

Fig. 39 (left). Small bleed of combustion products from a vent hole designed to allow the escape of o-ring bypass gasses.

The base of the Terrier motor body displayed two angled abrasion marks that were witness to a glancing impact with one of the Nike fins (figure 40). The orientation and edge definition of the marks indicated an angled, downward movement of the fin when it struck the motor body. The undamaged area between the two marks also matched with the recessed area beneath the forward end of the fin rib (at the Nike fin incidence setting point, figure 41).

Fig. 40. Nike fin impact mark with the side of the Terrier motor casing. The direction of the impact is shown.

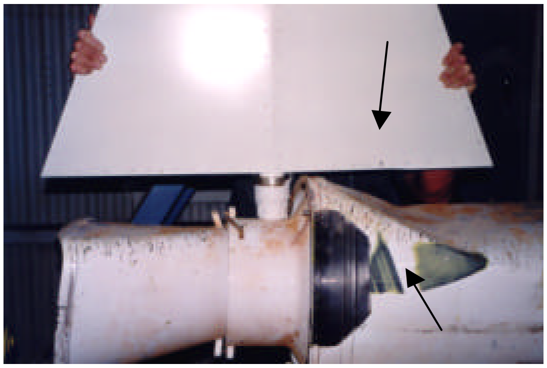


Fig. 41. New Nike fin held in place over the Terrier casing to illustrate the relation between the recess in the fin base rib and the abrasion mark.

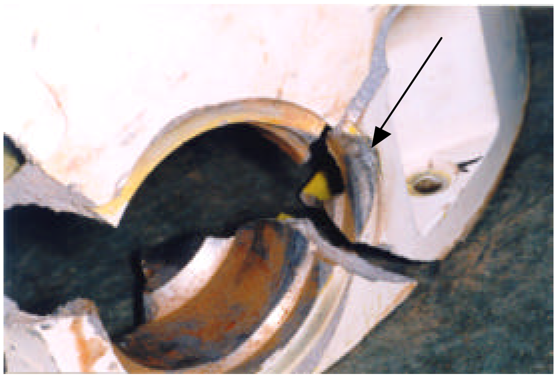
1.7 Terrier fin support structure (tail can)

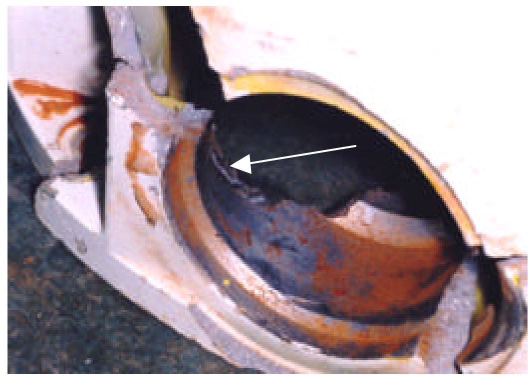
The Terrier booster vehicle fins were carried by a cast tail can structure affixed to the base of the motor body. The central spar of each fin engaged into a socket within the tail can and was secured by a single circlip around the outer socket diameter. Following the flight, fragments of the Terrier tail can were recovered over a path oriented with the approximate track of the vehicle before ground impact. The only structure remaining with the motor body was some of the mounting points where the tail can bolted to the motor base (figure 42). Re-assembly of the recovered fragments from the tail can illustrated the degree of disruption (figure 43), with all four fin sockets broken apart. All fracture surfaces presented a typically brittle appearance that were consistent with the component failing under gross overload conditions.

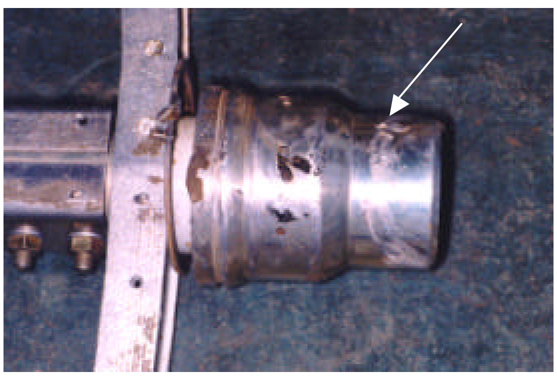
Fig. 42 (left). Terrier motor base with the remnants of the fin support structure in place.

Fig. 43 (right). Partially reconstructed fin support structure, showing the level of break-up.

Inspection of the failed fin sockets showed evidence of breakage under angular bending loads from the fin spindles. Diagonally opposing areas of distortion and indentation within the sockets (figures 44 & 45) matched with semicircular score marks on the fin spindles (figure 46) and provided good evidence that bending loads from the Nike fins contributed to the failure of the tail can structure. The examination did not find any evidence of material or manufacturing defects within the recovered tail can sections.







Figs. 44 & 45 (above). Journal socket within the Terrier fin support structure, showing evidence of break-up under sideways bending of the fin spindle.

Fig. 46 (left). Fin spindle, with score marks corresponding to the socket damage shown above.

1.8 Nike fins

Figures 47 to 50 present the remnants of the Terrier's Nike fins as they were recovered from the flight path. All had sustained very significant levels of break-up and fragmentation, with a good proportion of the fin skin and internal honeycomb material not being recovered. In a general sense, most of the mechanical damage to the fin structure was consistent with the effects of aerodynamic loads. The backward or sideways distortion of the central spars and the folding and twisting of the skin fragments was all attributed to aerodynamic effects.

The largest section of Terrier fin skin recovered showed an unusual level of abrasion over the outer painted surfaces. The forward-facing plane of the fin (forward of the central spar) showed almost complete removal of the surface and primer paint layers (figure 51). Rearward of the spar, the abrasion was appreciably less, however still evident. Sections of skin from similar areas of the other fins did not show the same level of abrasion and paint removal.

The same section of fin that showed the abrasion also showed witness marks from a glancing impact with the edge of another fin (figure 52). Regularly spaced impressions from rivet heads were identified across the surface, with the spacing of these marks matching the spacing of the row of domed head rivets along the fin leading and trailing edges. Parallel drag marks extended behind each of the rivet impressions, indicating the relative movement of the two surfaces following the impact.

Figs. 47, 48 (top left & right), Figs 49, 50 (above left & right). Recovered remnants of the skin and structure from the Terrier (Nike) fins. A large amount of the fin skin was not located.

Fig. 51. Nike fin skin section, showing abrasion and removal of the paint from the leading face surface.

Fig. 52. Nike fin skin section showing a clear impact mark from the leading or trailing edge of another Nike fin. Note the row of rivet indentations.

As mentioned in section 1.2, the adaptation of the Nike fins for use on the Terrier booster vehicle required the use of a securing / incidence setting lug on the trailing side of the fin base – opposite to the area designed into the Nike fins for this purpose. Evidence exists on several of the trailing rib sections of the cup-point set-screws seating irregularly against the surface of the fin (figure 53). Appreciable indentation and in one case, partial crushing of the fin rib had occurred (figure 54). While it was not possible to determine at what stage of the flight the damage occurred, the indications did highlight potential deficiencies with this method of securing the fins.

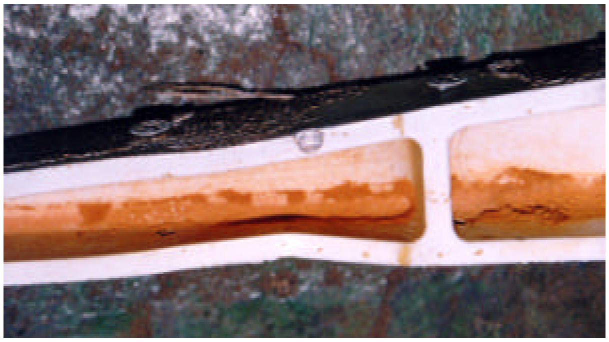


Fig. 53 (left). Clamping point for the fin securing lug – note the disruption produced by in-flight movement.

Fig. 54 (above). Crushing of the fin rib beneath the clamping point.

1.9 Launch rail structure and umbilical lead

The HyShot vehicle was launched along a boom-mounted rail structure that was positioned at an appropriate azimuth and elevation before the launch (figure 55). The rail, boom and supporting pedestal were inspected on-site for any evidence of damage or failure that could have been contributory to the anomalous flight. The inspection noted that the base of the launcher pedestal was raised some twenty millimetres above the top of an underlying grout pad, with no evidence of re-grouting activities having taken place (figure 56). It was understood that hessian sandbags (figure 57) were used around the base of the pedestal in lieu of the grouting, to protect the control wiring passing down through the base of the pedestal.

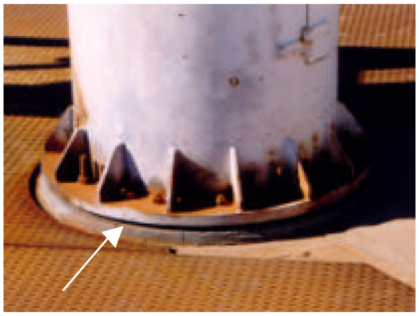


Fig. 55 (left). General view of the launch rail structure.

Fig. 56 (above). Base of the launch rail pedestal, showing the absence of grouting.

An inspection of the full length of the launch rail (figure 58) found no damage or anomalies that may have affected the early flight of the vehicle. All internal surfaces were smooth and free from distortion.

The umbilical connection between the launch vehicle and the control circuitry was inspected in-situ on the launcher (figure 59). While the various electrical connectors were present, it was found that the two gas-line connectors had been removed and were not able to be inspected. All components examined showed no evidence of striking the launch vehicle or having otherwise interfered with the launch.

Fig. 57 (above). Sand bags typical of those used around the base of the launcher pedestal, in lieu of the grouting.

Fig. 58. (top right). Launcher rail – good condition.

Fig. 59 (right). Umbilical connections (less the gas connectors) – all undamaged.

2. ANALYSIS

2.1 Payload and Orion Motor

All significant components from this section of the vehicle were accounted for at the impact site and as such, had remained with the vehicle during the entire flight. No evidence was found to suggest that the payload or associated components had contributed to the flight anomaly, however the level of impact damage limited the examination.

2.2 Orion tail can and fins

The break-up of the Orion tail can structure was consistent with the final ground impact of the vehicle. The examination found no indications of in-flight tail can structural damage occurring before the impact. The uneven level of aerodynamic heating effects around the fins and tail can was attributed to the observed corkscrewing of the vehicle flight path. A bias in the airflow across the vehicle resulting from such motion would be expected to produce the heating effects as noted. Remnants of the skin at the base of the missing fin also showed the influence of severe aerodynamic heating, with the fractures bearing evidence to extensive thermally induced cracking. Impact marks on an adjacent fin indicated the missing fin had failed in sideways bending, with a counter-clockwise motion about the vehicle axis. Partial melting of the immediate tip of the leading edge strip from the missing fin indicated the loss of the protective phenolic shroud while the vehicle was in-flight. The impact witness mark on the adjacent fin also showed evidence that the shroud was absent when the fin loss occurred.

2.3 Orion – Terrier adaptor

Although having sustained appreciable abrasion damage from the final ground impact of the Terrier booster, the adaptor unit did not show any specific evidence of having struck or otherwise contacted any other part of the HyShot vehicle. Sliding marks on the coupling surfaces bore testament to a degree of axial misalignment during the in-flight separation of the vehicles, however there was no evidence to suggest that the misalignment existed before the separation event. A thorough inspection of the adaptor found no pre-existing structural or other damage that may have contributed to the misaligned separation or the flight anomaly in general. Separation of the adaptor and the associated damage to the Terrier motor body was a result of ground impact forces.

2.4 Terrier motor body

On inspection, the Terrier motor body showed no evidence of structural failure, distortion or other physical damage associated with the flight. Evidence was found on the base of the motor case of a forceful glancing impact with the forward base rib of a Nike fin. The angle and orientation of the impact marks indicated the distortion or physical failure of the fin before it struck the motor case.

2.5 Terrier fin support structure

The Terrier fin support structure (carrying the larger Nike fins) had evidently broken up during the flight, with all examinable fractures consistent with the effects of gross overload through the fin spindle (journal) sockets. No defects or deficiencies were found within the physical structure of the fin support. Some of the fin journal sockets showed evidence of excessive angular bending forces, suggesting possible out-of-plane movement or rotation of the fins during flight.

2.6 Terrier (Nike) fins

A considerable proportion of the Terrier fin skin and internal honeycomb material had not been recovered at the time the investigation was carried out. Of the material that was recovered, most of the damage and deformation was consistent with aerodynamic and ground impact overloads. It was also evident that forceful contact had occurred between fin components during the break-up event. Marks and damage around the fin securing lug mounting points indicated in-flight movement and possible insecurity of the fin-lug connections. Crushing damage of the rib sections beneath the set-screws was possibly pre-flight damage, which may have led to in-flight movement. It should be noted that the Nike fins were not designed for securing in the location used and contained no reinforcement or other strengthening features in this area.

The abrasion and paint removal from the forward faces of a section of Terrier fin skin was unusual in that other similar surfaces did not show such an effect. Abrasion from impinging sand or other finely divided product during the launch was a potential contributory factor, however other substantive evidence of this theory was not found.

2.7 Launch structure and umbilical

The absence of suitable grouting at the base of the launch structure pedestal (requiring the use of sandbags to protect the internal wiring) was the only anomalous feature identified during the inspection. The use of friable, loose sandbags in lieu of the grouting was considered inappropriate, given the forces generated during the vehicle launch.

3. Safety Deficiencies

While the physical examination of the recovered HyShot vehicle debris failed to conclusively identify the reasons for the flight anomaly, a number of potential safety deficiencies were identified. It is recommended that these deficiencies be addressed prior to future launches of similarly configured vehicles.

- Suitability of the Nike fins for use on the Terrier vehicle .
- Suitability and effectiveness of the opposing set-screw arrangement for securing and setting the Nike fin incidence angle to the Terrier fin support structure.
- Suitability of the use of sandbags at the base of the launcher pedestal, in lieu of the specified grouting.