Cranfield Impact Centre,
Cranfield Innovative Manufacturing Ltd,
Building 56,
Cranfield University,
Beds MK43 0AL, UK.

A REPORT ON BEHALF OF
CRANFIELD IMPACT CENTRE

SAFETY FOR SPACECRAFT CRASHWORTHINESS AND CREW SURVIVABILITY

EXECUTIVE SUMMARY

Author: A.C. Walton
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Executive summary

This study was conducted for the European Space Research and Technology Centre (ESTEC) which is part of the European Space Agency (ESA), under a research project entitled 'Safety for Spacecraft Crashworthiness and Crew Survivability', (ESTEC Contract No 4000104865/11/NL/KML). The study consists of four parts;

- TN1 Literature Review
- TN2.1 Requirements Definition
- TN2.2 Verification Methods
- TN2.3 Identification of Knowledge Gaps

TN1 Literature Review

Document TN1 presents a literature review in the field of crashworthiness for space crew survivability. It also includes reviews of literature of other space-relevant crash safety domains including automotive, aviation and others.

The objective of this review is to describe the developments in the field and to identify assumptions, experimental weaknesses and knowledge gaps as well as to state the limitations and strengths of different frameworks. This report culminates by putting forward a critical evaluation of the findings in view of the definition of requirements to address crew survivability for nominal and off-nominal situations for all flight phases of a space mission to International Space Station.

Space capsule crew injury protection from landing forces originated from research originally conducted into fast jet ejection. There, the primary focus was on the protection of the pilot's spine from over-compression and led to the one-dimensional Dynamic Response Index (DRI) for assessing the spinal injury potential of measured acceleration pulses. This resulted in the expansion of the DRI measure into the three-dimensional Brinkley Index which has been used extensively by NASA for the prediction of astronaut whole-body injury potential from landings, launch pad aborts and other transient acceleration events.

With regard to injury protection, developments in the automotive field with Anthropomorphic Test Dummies has led the discipline of crash-injury research away from the whole-body injury index approach of Brinkley towards dummy-based injury criteria. Although the field of biomechanics and human injury tolerance is under continuous development, the current state-of-the-art allows automotive engineers to assess the crashworthiness of a vehicle based on dummy-based injury measures such as the Head Injury Criterion, Chest Severity Index and various others. These simplified mechanical injury indicators do not represent detailed human physiology and injury processes but are considered sufficiently validated to indicate tolerable limits of impact exposure for vehicle design-approval purposes. NASA has followed this dummy-based methodology of assessing injury risk in its on-going development of the Orion crew capsule. The literature review indicates that the application of current dummy-based injury criteria for space crew assessment is a useful and valid process, subject to recognition of the limitations of current injury criteria and also that space flight generates dynamic conditions for which dummy injury criteria were not initially devised. Space flight injury mitigation also extends to a number of areas that current injury criteria do not cover. These areas include astronaut injury from impact with hard points within the space suit itself, from connectors and other hard attachments to the space suit. Other considerations include the possibility of flailing arm and leg injuries where either blunt, or sharp, contacts may be made with the hands, arms and legs. Note that whilst the majority of studies are focused upon providing protection under nominal and off-nominal landing conditions, other short-duration events also have to be assessed in terms of human injury tolerance – this includes the acceleration-deceleration exposure from a launch pad abort.

With regard to spacecraft crashworthiness, the literature is dominated by studies conducted in development of the Orion capsule. The primary factor in determining the detailed characteristics of impact protection for a manned capsule is whether it will land on the ground or on water. It has been recognised for many years that nominal 'soft' water landings result in lower capsule decelerations and hence crew decelerations than 'harder' ground landings. However, the need for emergency landing sites in addition to a primary landing site may require a capsule to be capable of landing on both water and ground sites. The mixed landing site requirement means that the crew module has to provide additional protective measures to reduce the crew loads to tolerable limits – these may include retro rockets, airbag systems, energy absorbing heat shield, deployable landing legs and energy absorbing structures. A major part of the literature reviewed here is dedicated to the testing, analysis and comparison of various such systems. In addition to these devices which are deployed 'externally' to the structure of the crew module, various 'internal' load limiting devices have also been developed which again serve to minimise the landing loads on the crew. These include the use of crew floor pallets attached to the structure of the capsule by energy absorbing struts, energy absorbing seats, seat belts and other forms of restraint system. A clear mandate is on the crew module designer to ensure that all internal and external systems are fully integrated.

The literature shows that Finite Element and other forms of analytical modelling have a large role to play in the concept crashworthiness development of a crew module. This includes structural models of the capsule, its occupants (through dummy models), the capsule's safety systems and the landing site (ground or water). Definition of the landing site soil material properties (or water landing site) is a key starting point in predicting the deceleration subjected on the capsule. Once all the primary and secondary landing sites are chosen, soil samples can be collected and material properties can be measured. Soil and water impact models can be generated and validated against full-scale drop tests of rigid body capsules. The ability of analysis codes to represent large displacement deformation of soil and water through FE and particle (mesh free) analysis methods continues to expand and the prediction of landing forces is under continuous development

The published material was dominated by NASA studies of Orion development and the large majority of the literature related to simplified, rigid ('boilerplate') concept models. Relatively few studies were found in the public domain of crash analyses of actual structure. Additionally, relatively little was written about the crash landing integrity of the structure of the capsule including hatch integrity and open-ability. It is assumed that other flight load design requirements account-for and dominate the hull structure landing loads as this was not discussed in the studies which considered impact forces.

Similarly, little information was found on space suit and helmet development with regard to injury protection. However, the need for these to be integrated within a complete systems design process was strongly advocated in the literature.

Additionally, little public domain information was found on winged body craft when compared to capsule spacecraft. However, winged body spacecraft design is subject to all human tolerance factors defined within the literature – the principal difference being the landings where loads on winged body occupants in nominal landings should be no greater than those making a conventional aircraft landing. For off-nominal 'crash landings', again winged body astronaut crash conditions should be broadly determined by those associated with conventional aircraft crash landings.

Over 300 literature sources were read for this review and of these, some 86 were considered relevant to be included in this document. The nature of a review of papers in the public domain means that it is not able to review unpublished or confidential research. Additionally, a review may not locate all material that is published. Therefore, any comment made about research that was found to be incomplete or missing from this review has to be judged on the basis of the above two caveats.

TN2.1 Requirements Definition

Document TN2.1 presents a technical requirements definition in the field of crashworthiness for space crew survivability. It is based on the results of a literature search and critical evaluation of published material completed reported in document TN1 of this project. This document relates to all forms of crewed spacecraft including capsule-type, winged-bodied and all other configurations.

TN2.1 commences with a definition of crashworthiness in the context of crewed spacecraft. The definition is wide-ranging to encompass impact events and also non-impact events such launch and re-entry which involve increased levels of acceleration. Increased levels of acceleration from both impact and non-impact events during a mission present a potential injury source to crew members and so all such events require assessment and application of preventative measures.

In terms of crew impact safety, each spacecraft design has its own unique dynamic characteristics at launch, landing and all intervening mission phases. From the perspective of injury prevention, these characteristics can be defined by the resulting acceleration-versus-time vectors. These are measured by accelerometers attached to the structure and also located within crash dummies at each crew position. Output from all of these is then related to the various types of injury tolerance measure. Therefore, a key step in providing crew impact protection is the quantification of all potentially injurious acceleration events throughout the mission. Each human body has its own tolerance limits to acceleration which, if exceeded, increase the probability that injury will occur.

As with all fields of impact biomechanics, there is no simple link between spacecraft acceleration and individual crew member injury risk. This is due to the complex, multi-variate nature of human injury tolerance (due to age, gender, body size, health and other factors). For this reason, impact requirements based on maximum permitted acceleration/force of the spacecraft structure (i.e. designs loads) alone cannot define a safe environment for each crew member under all mission phases.

Therefore, to ensure that human tolerance limits are not exceeded, use has to be made of a set of injury criteria. These are technical requirements with which the spacecraft design must comply at the mission-ready level of development. These requirements are used to specify the performance of the complete crew-related system (consisting of seats, restraints, helmets, air bags, retro-rockets and so on) with regard to accepted human limits. Injury criteria have been derived from laboratory tests and field accident investigation of human injuries under impact and high acceleration conditions.

Three categories of injury criteria are documented in the space biomechanics literature;

a. for 'sustained' acceleration events (defined as of duration 0.5 seconds or longer) which are identified as being potentially injurious to crew, whole-body maximum acceleration-versus-time exposure curves are used.

b. for 'transient' acceleration events (defined as of less than 0.5 seconds duration) which are identified as being potentially injurious to crew, the whole-body Brinkley Injury Index is used.

c. for all acceleration events of any duration which are identified as being potentially injurious to crew, injury criteria based on Anthropomorphic ('crash') Test Dummies are used.

The 'sustained' and 'transient' injury criteria defined above have been used for crewed space flight safety-assessment for many years. The latter, dummy-based injury criteria have originated from the development of instrumented crash test dummies in the automotive and aeronautics sectors. Dummy-based injury criteria differ from 'whole-body' injury criteria in that individual dummy body-parts have their own injury criteria and are more representative of human injury mechanisms than simple whole-body analogues. Based on the findings of the literature review of this study, it is proposed that all three types of injury criteria should be applied for crewed spacecraft injury assessment.

Dummy-based injury criteria specifically for space crew injury assessment have not been developed. Application of dummy injury criteria to spacecraft is dependent on the use of existing injury criteria from the automotive and aviation sectors. In both sectors, injury criteria have been derived from extensive correlation-studies between dummy dynamic tests and corresponding cadaver, animal and human volunteer tests. From this, the measurement of internal dummy deformation variables for injury criteria calculations is largely independent of the cause of the impact in terms of the type of vehicle. However, the injury tolerance levels of space crew may be degraded by prolonged exposure to micro-gravity and the potential effect of this has yet to be accounted-for in current dummy-based injury criteria. This degradation-effect has been accounted-for in the 'sustained' and 'transient' (Brinkley) whole-body injury criteria outlined above.

Two other additional dummy-based injury criteria issues have been addressed in this document. Firstly, the likely mixed size, age and gender composition of a space crew requires that in addition to the 50th percentile male Hybrid III dummy, injury criteria should also be calculated for the 5th percentile (female) and 95th percentile (male dummy) for any proposed crewed spacecraft design. While injury tolerance limits are defined for the 50th percentile dummy in automotive and other crashworthiness legislative standards, relatively few standards specify equivalent tolerance limits for the 5^{th} and 95^{th} percentile variants. Therefore, in defining injury tolerance limits across all three sizes of Hybrid III dummy in this document, use has been made of recommended values from research where no mandatory value from automotive standards was identified.

Secondly, even for the 50th percentile Hybrid III dummy, the literature indicates that a range of alternative, injury criteria have been developed over the years and so the choice of criteria for spacecraft applications is not straightforward. The list of dummy-based criteria specified in this document for space application represents a comprehensive list of injury tolerance requirements based on the literature survey findings.

In addition to specifying injury criteria requirements, this document also includes requirements for the assessment of the primary and secondary landing sites. For a capsule spacecraft which makes landing via a parachute or parafoil, the landing site material (soil or water) will dictate the impact characteristics required from the rest of the spacecraft safety system. For off-nominal landing conditions including high lateral landing velocity components, high sea states and other acute landing conditions, the complete system is required to perform such that injury criteria limits for all crew positions are not exceeded under these conditions. For spacecraft which have more than one landing site (normal landing, pad abort, launch abort and contingency return), all such sites should be considered in the above assessment. For winged body spacecraft and hybrid types which make a runway landing using landing gear, compliance with the above human tolerance requirements applies. This includes those potential cases of off-nominal runway landings due to events such as landing gear failure, tyre burst, brake failure or similar.

In summary, this document presents a set of requirements using injury criteria and other measures as tools for assessing crewed spacecraft design to ensure that all crew safety-related systems do not exceed acceptable levels of human injury risk.

TN2.2 Verification Methods

Document TN2.2 follows technical requirements document TN2.1. In order to substantiate that the proposed requirements are appropriate, a series of Finite Element simulations have been conducted based on a set of capsule impact test scenarios.

With this objective in mind, the Finite Element modelling in this study consists of two parts. The first (and minor) part simulates a half-scale rigid boilerplate capsule undergoing a combined vertical and lateral landing vector. The aim of this simulation is to assess the overall ability of the FE methodology to simulate a rigid 'boilerplate' capsule landing on a deformable ground surface. Comparison is made with impact test results of a half-scale capsule landing from the published literature based on the NASA Orion design.

The second (and major) part of the FE study used a full-scale rigid boilerplate model derived from the half-scale model based on the Orion design. Four FE Hybrid III dummies were located within the capsule – these consisted of two 50^{th} percentile male, one 5^{th} percentile female and one 95^{th} percentile male occupants. The reclined body and limb postures of the dummies were based on photographs of typical crew members in capsule spacecraft. A rigid seat was fitted to each dummy and a tight-fitting 5-point harness system was also fitted. An energy-absorbing foam mechanism was devised to connect each seat to the floor with the intent to provide impact energy dissipation in the spinal direction and normal to the plane of each dummy's torso. Six parametric simulations were conducted using a combination of vertical and lateral landing velocities and impact ('hang') angles onto a 'hard' ground surface. The parametric simulations were then repeated using a 'soft' ground surface. The principal aim of this effort was to evaluate each landing case using dummy-based injury criteria proposed in the technical requirements document – where possible, these were calculated for each of the four dummies in each parametric case along with the Brinkley Injury Criterion as measured at the centre of gravity of the spacecraft. The parametric cases were chosen from a published study of capsule landing simulations. This published study was closely related in terms of engineering content and methodology to the published half-scale study referenced previously and so was partly chosen as a reference work for this reason. In addition, the landing velocities and impact angles were from the more severe 'off-nominal' end of the typical landing spectrum – from an FE modeling point of view, this represented a severe test of the robustness of the modeling methodology and would detect weaknesses in the modelling approach more readily than nominal and less severe landing cases. Unfortunately, the published study did not include models of dummies within its scope and so no cross-correlation with injury predictions of the current study was possible. However, this approach did enable some limitations of predicting injury from the current dummy models to be identified.

The purpose of considering hard and soft ground was that soil material properties can vary significantly and capsules may be required to land at various contingency landings sites. The inclusion of this parameter within the study served to demonstrate the need for consideration of this factor in full-scale verification testing.

With regard to the application of design verification methods for crewed spacecraft, it is proposed that impact testing would form the method of verification, where possible. This is because in all crashworthiness areas, impact testing is still regarded as the most reliable means of verifying the crash performance of a vehicle. A series of supporting requirements forming the verification method were defined

TN2.3 Identification of Knowledge Gaps

Based on the literature reviewed in this study, a number of key knowledge gaps relating to manned spacecraft crashworthiness and crew survivability are identified. These are mainly related to general gaps in understanding of human tolerance to injury with specific issues relating to space crew tolerance.

At the present time, whilst injury criteria are defined for the 50th percentile crash dummy, corresponding values for the 5th and 95th percentile size dummies are not fully defined.

Prolonged micro-gravity deconditioning effect on the physiology of crew members is acknowledged by the Brinkley Injury Index in that it requires the use of lower tolerance values for crews returning to earth landing. For dummy-based injury criteria, the literature indicates that no similar compensatory measures to include crew-deconditioning effects have so far been introduced.

The physical differences between dummies (as re-usable mechanical surrogates) and the human body define the limitations of these devices in predicting human injury. It is likely that dummy development will extend to more human-like dynamic behaviour through advances in materials.

Finite Element models of the complete human body for crash analysis have existed for a number of years and these may form the basis on which analysis of human injury mechanisms is progressed.

FE and other numerical analyses form a major part of the development process of all aerospace structures. It is important that these tools are able to simulate the behaviour of current and future spacecraft materials under all likely loading conditions – the transition from aluminium alloy to composite materials under impact presents a challenge for FE analysis in terms of representation of material behaviour. As more composite variations are developed for specialist applications, reliable material algorithms to simulate their behaviour will be required.

Finally, for crew modules which return to earth via parachute, the literature study showed that the nature of the terrain on which a capsule lands (in combination with the capsule mass, velocity vector and capsule orientation) will dictate the deceleration experienced by the capsule. Therefore, once primary, pad abort, secondary and other contingency landing sites are identified, it is necessary to define the material properties of all the chosen sites – these could include water as well as ground landing sites. This data will be used in FE models of the capsule during the development stage. The accelerations derived from these analyses will dictate the level of crashworthiness features included within the complete capsule. Therefore, knowledge of the properties of all landing sites has to be defined at an early stage in the development process.