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Findings of an expert panel engaged to conduct a scoping study on survival design of floating production storage and offloading vessels against extreme metocean conditions

Prepared by **P A F A Consulting Engineers**
for the Health and Safety Executive 2005

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Findings of an expert panel engaged to conduct a scoping study on survival design of floating production storage and offloading vessels against extreme metocean conditions

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To address this question, the UK Health and Safety Executive (HSE) engaged PAFA Consulting Engineers to help identify a number of suitable experts and to facilitate discussions:

"to provide an informed view from a respected panel of relevant stakeholders of the future work that would need to be undertaken to determine the characteristics of extreme sea states / waves, the likely consequences for an FPSO subjected to such an environment and whether a satisfactory rationale for survival design currently exists or needs to be developed".

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EXECUTIVE SUMMARY

In recent years there have been several well-publicised occurrences of extreme waves and storm conditions that have caused severe damage to and loss of passenger ships and trading vessels. Consequently, the question arises: "Might current or planned FPSOs in UK waters be similarly vulnerable, with the attendant risks for loss of life or pollution?"

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The HSE indicated that the study should concentrate on design requirements for future vessels however, if any areas of concern should be identified, HSE will need to review the implications for existing vessels with respective duty holders.

Current regulations are framed in terms of vessels with "integrity which is reasonably practicable" subject to forces that are "reasonably foreseeable" for both intact vessels and vessels that might be subject to "reasonably foreseeable damage." Given the overarching requirement that risks should be as low as reasonably practical (ALARP), what currently represents good industry practice with respect to surviving extreme metocean conditions and what improvements might reasonably be required in the immediate future?

'Survivability design' is not clearly identified as a separate issue in current rules and therefore, unsurprisingly, there is no clear, rational basis for achieving this specific objective. Instead 'good survivability' arises through the interaction of a mixture of Rule-based requirements; first-principles global and component design calculations; risk mitigation measures applied on each project; and the application of sound engineering judgement to identify a number of appropriately-specified but distinct, extreme response criteria against which each vessel is assessed. But there is no subsequent assessment of each vessel configuration to ensure that it has the necessary robustness to withstand the wider range of conditions (both due to weather and operational loads) that will not have been considered explicitly during design. To a large extent, survivability is achieved by building on well-tested vessel configurations that have been found, historically, to perform well in the marine environment, albeit in slightly different roles and to match different design requirements.

Despite the above, FPSO configurations that have been developed for UK and Norwegian waters have a very good survival record. Over 160 vessel-years experience has been accumulated without loss. Several problems have been encountered and overcome since the introduction of FPSOs (aspects of severe green water loading, for example) and it may be that most vessels have not yet encountered true 'design sea states or responses.' Complacency about the status quo may be misplaced, but there is at least an indication that successful survivability design may not be too far removed from current practice.

The panel for this scoping study identified four areas of design uncertainty that may yet represent risks to survival of some conventional FPSO configurations. These are summarised as follows:

1. Lack of appreciation of the full range of extreme multi-variate responses caused by complex storm and wave development scenarios interacting with (one of) many FPSO configurations and various vessel operational parameters. Threat to the vessel may arise for an intact or damaged vessel or when some item of safety-critical equipment is less than fully operational.
2. Green water loading particularly for freeboard exceedance at the side and sea states that approach from large angles from the bow or cause significant roll response.
3. Wave impact (slam) loading including identification of appropriate pressures for structural responses for spread seas and their dependence on the relative heading of the vessel to approaching waves (or swell).
4. Consideration of less than the full range of vessel relative headings that might apply to each design limit state.

Five other areas of design uncertainty were also identified although these were not considered of immediate concern for FPSO survival – at least not for configurations that are deployed on the UKCS. The panel considered that one of these, assessment of mooring integrity, could be a threat to survival if the vessel were deployed close to some other obstruction but not otherwise.

On the basis of discussions held within the SAFE-FLOW JIP and advanced on several occasions during this scoping study, it would appear that a clear and satisfactory basis of survivability design for FPSOs should be developed from an examination of a range of extreme responses (and associated stresses in structural components) at a consistent 10^{-4} per annum level of occurrence. These ‘extreme response limit states’ should be treated in a similar manner to accidental limit state evaluations, that is, with reduced load factors, say, unity, and could allow a level of damage to occur to the vessel but this damage must not threaten system failure with associated risks of vessel loss, death or pollution. More explicitly, the objective of identifying a range of such limit states should be to identify any highly non-linear or threshold-type responses for which an ultimate limit state, ULS, approach might become unsafe when the ULS design parameters (traditionally set at 10^{-2} per annum probability of occurrence) are exceeded. For many cases the ULS condition applied with appropriate load and resistance factors will still govern design and no further action will be necessary. However, where some unusual trend in response causes the extreme condition to govern, the designer would be expected to review the associated risk and resolve the problem by managing it in the most effective manner. Where the risk can not be mitigated in some other way, the design parameters should be adjusted to reduce it directly.

1. INTRODUCTION AND OBJECTIVES

The study reported herein was commissioned by the United Kingdom Health and Safety Executive (HSE) to investigate the current status of FPSO design practice with respect to extreme metocean conditions. In recent years there have been several well-publicised occurrences of extreme waves and storm conditions that have caused damage to, and loss of passenger ships and trading vessels. Might current or planned FPSOs in UK waters be similarly vulnerable, with the attendant risks for loss of life or consequential pollution?

The objective of this study, as defined by the HSE, was:

> "to provide an informed view from a respected panel of relevant stakeholders of the future work that would need to be undertaken to determine the characteristics of extreme sea states / waves, the likely consequences for an FPSO subjected to such an environment and whether a satisfactory rationale for survival design currently exists or needs to be developed".

The HSE indicated that the study should concentrate on design requirements for future vessels rather than the design condition of existing vessels, though clearly, if any areas of concern should be identified, HSE may need to review the implications for existing vessels with their operators. Similarly, the panel were requested to focus on extreme weather hazards for FPSOs that are correctly maintained and operated. Otherwise a wider range of structural and marine hazards would need to be considered.

Currently, the process of survival design entails the verification that risks are acceptable for a set of performance standards. Many criteria are predefined but some may be identified as appropriate to specific design issues that arise on each project. Survival design will generally include various strength checks of the hull and moorings; specification of size and layout of water tight compartments to ensure hydrostatic stability in a range of intact and damaged states; component design against potential wave impact loads; and consideration of various accident scenarios. Other aspects important for long-term survival are the design of corrosion protection measures and the fatigue assessment of the many structural details, backed by well-considered through-life inspection and maintenance strategies.

In some (many) cases, design checks are carried out in adherence with Rules of the International Maritime Organisation (IMO) or a Classification Society but, in others, part of the assessment will be performed on the basis of a first principles analysis. Generally, any residual risk should be shown to be as low as reasonably practical (ALARP).

The rationale underlying the entire procedure is not always transparent. Seldom is any final assessment made of the 'resultant level of survivability' that incorporates the overlap of the numerous risk management decisions, design requirements and reliability assessments that have been imposed during the entire design process. Normally a vessel designed to survive an identified set of extreme scenarios or 'limit states' would be expected to have the necessary robustness to withstand a large range of 'less onerous' conditions that may not have been explicitly identified or represented in the design process.

To achieve the goals of the study, a panel of stakeholders was convened by PAFA Consulting Engineers on behalf of the HSE. Two meetings were planned, the size of the panel being increased between the first and second meetings to include additional recognised experts whose specific experience/expertise could be used to inform the panel in its more detailed deliberations. The members of the panel, the HSE staff who participated and the PAFA staff who helped plan the meetings and facilitate the discussion are listed in Appendix A.

2. MEETINGS AND DISCUSSION PROCESS

Two panel meetings were held under the chairmanship of Terry Rhodes of Shell. The first was a single day event held at the HSE's offices at Rose Court in London, while the second was convened over two days at the Lensbury Conference Centre, Teddington, Middlesex.

Peter Mills of the HSE briefed the panel on the objectives of the study and clarified the legal requirements imposed on FPSO duty holders. These are paraphrased in the following brief extracts:

Regulation 4. General Duty.

> The duty holder shall ensure that an installation at all times possesses such integrity as is reasonably practicable.

Regulation 5. Design of an installation.

> The duty holder shall ensure that the designs to which an installation is to be, or in the event is, constructed are such that, so far as is <u>reasonably practicable</u>
>
> (a) It can withstand such forces on it as are <u>reasonably foreseeable</u>,
>
> (e) In the event of reasonably foreseeable damage to the installation it will retain sufficient integrity to enable action to be taken to safeguard the health and safety of persons on or near it.

After Peter's introductory guide, HSE staff withdrew from the first meeting and Terry Rhodes introduced an 'open space session' as a means of involving everyone, opening up the discussion and identifying the full range of issues relevant to survivability design. The process considered the following questions:

- Does current practice adequately describe extreme metocean conditions for FPSO system design?
- Does current practice adequately define loading and response for extreme sea states?
- Does the industry define performance standards adequately?

A report based on the findings of this process is included here in Appendix B.

It generated a lively email-based discussion about some of the issues. In preparation for the second meeting, it was found convenient to collect these under five generic headings, namely:

1. General design issues
2. FPSO heading response and/or control
3. Steep waves and non-linear surface effects in design
4. Model testing route to survivability design
5. Feed back to design (from full-scale measurement, inspection and incident reports).

For the second meeting, each panel member was asked to prepare and give a presentation about their research, design and operational experience which covered, in considerable detail, most of the key issues underlying the above headings:

- James MacGregor and R V Ahilan tackled general design issues including how design requirements are specified and implemented, treatment of intact and damaged scenarios, potential for inconsistencies between first principle and Rule-based approaches and whether it might be possible, useful or beneficial to quantify 'survivability'.

- Michel Francois, in consultation with Peter Gorf and Chris Shaw, gave a detailed overview of some experience of predicting heading response of an FPSO. Although there is a tendency for weather conditions to become more unidirectional under extreme storm conditions, there are still phases in the passage of ***any*** storm when quite large angles (maybe of the order of 30 degrees or more) can develop between the vessel heading and approaching wind or waves. Later discussion also confirmed that several FPSO design conditions are governed by specific wave conditions and wave periods, not necessarily those that would normally be associated with extreme weather.

  The presentation went on to consider how extreme design conditions might be identified where several metocean parameters might influence extreme responses and associated load conditions.

  In the discussion it also became evident that situations arise, whether due to damage, operating errors or operating limitations for power generating equipment, in which an FPSO can present a beam-on orientation to some storm conditions. These situations may not be common but they continue to be reported from time to time and it is not entirely clear what metocean conditions should be used to design for these events.

- Christopher Swan, Julian Wolfram and Nigel Barltrop gave separate presentations about non-linear wave simulation and application to design; experience from measuring real wave conditions in the North Sea; and, identifying realistic design events and associated vessel responses. Fully non-linear simulation techniques can give excellent reproduction of the wave kinematics under extremely high or steep waves but may not be the best method for appreciating the important aspects of the underlying physics that cause these extreme events. The latter is an important issue since the statistics of extreme non-linear events are poorly understood. Experimental evidence was presented of how wave-structure interactions can cause a subsequent approaching wave front to steepen or break.

  It is important to appreciate that FPSO design is governed by a number of distinct limit states: hull-girder bending, bottom slam, green water, wave-hull impact loads, excessive roll response, to name a few, and all of these limit states are governed by different wave conditions some of which are neither strongly non-linear nor associated with what would normally be interpreted as extreme weather conditions.

- Sverre Haver provided an overview of Statoil's experience and approach to survivability design through model testing. Although model testing has some limitations, it does present a method for identifying and quantifying a range of non-linear wave interaction and response mechanisms that are difficult to predict by any other means. Sverre is keen to use longer test periods than are sometimes employed in routine testing to ensure that the statistics of extreme events can be properly identified.

  As Julian Wolfram pointed out in subsequent discussions, it is important to ensure that wave conditions established in a model basin are truly (statistically) representative of the sorts of conditions that are observed at a vessel's actual or intended location.

- Govert Wagenaar gave an overview of Bluewater's experience relating to design, fabrication and incident reporting from their operational vessels. He emphasised the extensive nature of the calculations they performed to account for the range of vessel headings relative to incoming wave or other metocean conditions. He also gave information about some rare but difficult response conditions that had arisen when a sea contained a small swell component had caused much larger roll responses than had been anticipated in design. Sverre Haver also commented on an incident with a Statoil vessel when a sudden, unexplained change of vessel heading had led to a serious excitation of roll response before the vessel heading could be corrected. There was general discussion about databases of recorded incidents and whether these might be useful for avoiding problems in future designs. Some high-profile incidents have led to extensive reviews of operational and/or design practice. However, in general, it is difficult to determine sufficient information from standard incident reports unless they are subject to a rapid follow-up investigation

Brief summaries of recent conferences and the findings of joint industry research projects were also given to make the panel as a whole fully aware of the current state-of-the-art that might influence their judgement. These included the EU-supported Maxwave, Safe-flow, and Rebasdo JIPs and the Waveland JIP that was carried out in Norway. Table 1 contains a listing of some of the main JIPs that were discussed. HSE and PAFA staff participated and made full contributions to the technical discussions at this meeting.

Both panel meetings exposed a wide range of design uncertainties relating to current and future FPSOs and throughout the second meeting questions about whether or not any of these design uncertainties might have a strong bearing on FPSO survival were raised frequently. In a different type of study, it might have been appropriate to examine lists of specific performance standards or limit states in more detail, but within the context of the panel meeting it was necessary to concentrate on gaining an overall appreciation of the level of risk still associated with each of the physical mechanisms which might pose a threat to vessel survival and whether these risks were/are properly represented in the overall design process.

The meeting was drawn to a conclusion by identifying a list of specific issues and detailed points under the headings identified above. The list, a short-hand aide-memoire to the items discussed at the meeting, is presented in appendix C and, in brief, in Table 2. It formed the basis of a means for asking the panel to identify and discuss their considered opinions about whether any of these issues did represent an area of concern for survival of an FPSO. The panel were reminded to consider their responses for intact, damaged or operationally-impaired scenarios and to indicate priorities for future work in this area.

Table 1 Recent joint industry projects (JIPs)

Titles (of recent joint industry projects)	**Contractor(s) – involved in research, not simply sponsors**	**Duration**
1. Rebasdo	SHELL International Exploration and Production , Instituto Superior Técnico, Danish Hydraulic Institute - Water & Environment, Det Norske Veritas, Imperial College of Science Technology and Medicine, LISNAVE Estaleiros Navais S.A., Noble Denton Ltd, University of Oxford	1/1/01-30/6/04
2. Roll JIP	MARIN	Mid 2002 – on-going
3. Safeflow	Marin, PAFA, IST, Atkins, University of Glasgow and Strathclyde, Force, BV, IZAR, BP, University of Groningen	1/1/01 - Mid 04
4. Maxwave	GKSS Forschungszentrum GmbH, Det Norske Meteorologiske Institutt, Deutsches Zentrum für Luft- und Raumfahrt e.V., Meteorological Office, Instituto Superior Técnico, Météo France, OceanWaveS GmbH, Katholieke Universiteit Leuven, Technische Universität Berlin, Det Norske Veritas AS, Institute of Hydroengineering, Polish Academy of Sciences	Late 2000-Late 2003
5. Mooring Integrity JIP	Noble Denton Europe Ltd	May 2001 – March 2002
6. MARINTEK Slamming JIP (also known as Waveland phase 1) Wave Impact Loads on FPSO's and Floating Platforms	Marintek/SINTEF	Mid 2000 - Early 2002
7. FPSO Integrity	Marin	Mid 98 – 30/4/01
8. Greenlab	Marin	1996 -31/12/97

3. FINDINGS

3.1 EXPLANATION

The headings and issues identified during the second panel meeting as potentially of most relevance to the issue of FPSO survival design are presented in Table 2.

Table 2 List of issues identified at second meeting of scoping study panel

1. General Design Issues
    - 10^{-4} per annum is reasonably foreseeable
    - Multi-variate response-based criteria
    - Green water loading
    - Damage stability
    - Mooring integrity
    - Clarity and consistency of performance standards
2. FPSO Heading
    - Vessel and system configuration
    - Characterisation of 10,000 year event heading for design
    - Heading prediction
3. Steep Wave and Non-Linear Surface Effects
    - Slam damage
    - Use and dissemination of latest technology
4. Model tests
    - Specification of model test programme to capture extreme response events
5. Feedback to Design
    - Fatigue and fracture toughness
    - Quality of incident reporting
    - Performance standards of safety critical elements
    - Making better use of existing measurement data from operational FPSOs.

Full details including underlying, associated discussion points from the Lensbury meeting are contained in Appendix C. However, these lists are essentially aides-memoires to a complex sequence of presentations and discussions at the meetings so a few additional paragraphs of explanation are provided below when addressing each issue.

Appendix D contains the e-mail sent to panel members requesting their input to the identification of priority issues. Contributors were asked (at a minimum) to indicate the three issues which they perceived might pose the greatest threat to survival of an FPSO.

Panel members were also asked qualify their input according to whether they felt the issues:

- serious and in need of urgent consideration, or,
- less serious and amenable to less urgent treatment (within a joint industry research program, for example),

for any particular circumstances.

In considering the panel's responses, the issues emerged in three clear groups.

There was one group of four issues that were considered of highest importance to FPSO survivability design, namely:

– Multi-variate response-based criteria
– Green water loading
– Slam damage
– Characterisation of 10,000 year heading for each design event.

An overview of this group is presented in section 3.2 and each issue is considered in more detail in sections 3.3 – 3.6.

A second group of five issues emerged as being of less importance to survivability design though possibly still significant:

- Making better use of existing measurement data from operational FPSOs
- Mooring integrity
- Specification of model test programme to capture extreme response events
- Fatigue and fracture toughness
- Damage stability.

Clearly, these embrace a broader range of technical subjects. A few paragraphs about them are contained in section 3.7.

A third group of issues merited no more than a third priority assessment from any single panel member. These are recorded with a few words of explanation in section 3.8.

3.2 OVERVIEW OF IMPORTANT ISSUES

The panel found it relatively easy to agree that extreme design events with a 10^{-4} annual probability of response represented a "reasonable foreseeable" basis for survival design. Such design events might be expected to cause damage but not catastrophic loss or fatalities. This approach appeared to match the "as low as reasonably practical", ALARP, principal.

Such events are much less frequent than the 10^{-2} responses usually examined as part of an ultimate strength limit state (ULS) and they would normally be assessed in a similar manner to an accidental limit state (ALS), namely, with reduced (unity) load and resistance factors. ULS checks will govern in many cases and should continue to be used as the basis of design however, there are several load/response mechanisms where the responses or stresses associated with the 10^{-2} annual probability will be very small while those associated with even slightly lower probabilities of occurrence are very large. By examining events at 10^{-4} annual probability, the industry will protect each FPSO against any such thresholds characteristics of potential extreme responses that might threaten its survival. Where response is 'well-behaved' the examination of the 10^{-4} occurrence will make little difference because the ULS condition with appropriate partial factors will usually govern.

There was a degree of scepticism about the absolute reliability of any calculations made at this low level of occurrence. There was also some concern that the introduction of comprehensive methods based on such low levels of occurrence of specific metocean conditions would in fact imply considerably lower failure probabilities because of various conservative assumptions that underlie many engineering design calculations.

To a large extent, there is a common concern underlying all of the four most important issues identified above, namely, the ability to identify the full range of combined metocean conditions and vessel responses at the level associated with a 10^{-4} annual probability of occurrence. Two of the issues, green water and wave slam, are not 'single' issues at all but a combination of several similar scenarios that are highly dependent on the heading of the vessel when the design event might occur. Characterisation of the possible range of headings that might be associated with 10^{-4} design events is critical, not only for green water and wave slam design scenarios but also for mooring design, roll response and hydrostatic stability considerations.

There was not a common opinion about the level of concern surrounding the four high-importance issues. Some felt the issue of green water was still an area of concern, particularly if any breach of water-tight integrity might occur in the run-up to a severe storm event. However, there was recognition that normal internal compartment sizes and layout might make many FPSO configurations relatively robust in the face of green water damage: provided this issue has received appropriate consideration during design. There was also a recognition that the industry has already carried out a review of design and management of the risks of green water damage. If the effects of potential green water damage have already been assessed in full, then to some extent the problem has been recognised, considered and, one might hope, the associated risks have been substantially reduced. On the other hand, green water from the side, especially in association with roll response in crossing seas, is a very complex issue and despite recent advances (in the SAFE-FLOW JIP, for example) information on and experience of analysing these matters is far from complete.

At least three panel members identified the issue of wave slam as one that was possibly of concern. **If** slam pressures are sufficient to cause damage to the outer hull in head, quartering or beam seas, then there is an urgent need to consider all such situations. The risk of damage to the bow or bow-to-side transition area of a vessel in head or quartering seas will depend on metocean conditions at the specific site, vessel response and details of structural framing. Consequently this assessment is liable to be highly vessel-specific. On the other hand, it was suggested that the configuration of side shell structures were sufficiently common for most FPSOs that one single high quality assessment of the likely magnitude and effects of slam pressures on a typical side shell would be preferable to multiple assessments by many operators.

The design heading for many load conditions (green water, slam, capsize stability, mooring load assessment – for example) is affected by other basic design considerations such as the location of the turret and use of drag-chain or swivels, the use or otherwise of thrusters to provide heading control/assistance, reliability of the power supply system for the thrusters, cargo capacity given any draft restrictions and draft. In other words, relevant investigations of design issues that depend on relative heading to wind, waves, swell and current are liable to be highly specific to each FPSO configuration in the widest sense. Prediction of vessel heading is a complex calculation, subject to many uncertainties and difficult to validate under any realistic set of metocean conditions.

3.3 MULTI-VARIATE RESPONSE-BASED CRITERIA

For an FPSO, many design issues are affected by a large number of metocean and basic design parameters. Whereas for fixed structure a reasonably conservative approach might be to assume co-linearity of several metocean conditions, it is evident that this approach is seldom conservative when applied to an FPSO. Design events are usually based on some aspect of vessel response and the identification of a representative range of such events is not usually straight forward. Wave conditions that are onerous for fixed structures are not necessarily so for floaters. Recent discussions following a paper given at the FPSO Speciality conference in Houston (2004) even indicated that a well-documented ‘abnormal’ or ‘freak’ wave did not seem to pose any threat to midsection bending capacity, green water or bow slam of a ‘typical’ FPSO. However, much research would be needed before any similar statement could be generalised to the wider range of ‘abnormal’ waves

Consider too, for example, some well-known results that have been confirmed by the GREENLAB and SAFE-FLOW JIPs. Sea states most likely to lead to extreme green water inundation at the bow are associated with a specific spectral peak period which would not normally be associated with extreme weather. Further, due to the nature of some non-linear interactions and the inherent properties of occurrence statistics, the most severe design events are not expected to occur for the highest significant wave height (at the given period) but may be anticipated to occur in lower sea states! Considerations of green water at the side and bow slam lead to very different design sea states.

Several methods are becoming available as reasonable approaches to this type of analysis whether through the use of databases of hind cast metocean conditions or through inverse first order reliability methods (I-FORM). More work is required to develop these methods particularly for treatment of relative heading issues. Extrapolation of hindcast- based analyses to long return periods are still associated with considerable uncertainties – but these uncertainties are inherent in the design problem and are not reduced by ignoring them.

3.4 GREEN WATER LOADING

Deck inundation by green water and the subsequent loads it induces is seen as an important issue for FPSO survivability. Green water loads have not been found to pose a direct threat to integrity of the hull girder but damage to deck houses, deck mounted equipment and fastenings may make a vessel vulnerable to water ingress in subsequent events.

Prediction of freeboard exceedance at various locations around the deck is highly dependent on relative orientation of the hull to approaching waves. Prediction of quasi-static and dynamic components of vessel heading relative to incoming waves is difficult. For a more extensive discussion of this issue see section 3.6, below.

Freeboard exceedance at the bow has been studied extensively and, from available data, it is evident that head seas cause the most severe load effects, especially for deck housings, fixings and equipment located along the middle of the deck. For this reason, it is reasonably conservative to apply head sea data to design of bow equipment even for waves approaching from modest angles (say +/- 30 degrees).

It is more difficult to be certain that appropriately conservative design conditions have been identified relating to freeboard exceedance along the side or at the stern of an FPSO. Green water occurrence from the side will take place in head seas but the level of freeboard exceedance along the side and the subsequent flow of water across or along the deck is strongly influenced by relative direction of the incoming wind-driven sea and the static heel or roll response of the vessel - and the roll response may be caused by another mechanism entirely such as a small swell component coming from a beam-on direction with a frequency close to the natural frequency of the vessel in roll.

Extreme roll and green water from the side will also be highly likely if there is some unusual yaw response or a breakdown in (active or passive) heading control. Note that in the case of active control this may occur as a result of loss of power to the thrusters. Such events may be characterised as damage events and therefore the associated probability of occurrence may be relatively low but they have occurred several times to UK and Norwegian vessels. It is far from clear what metocean conditions ought to be applied as design events in such cases to be consistently representative of a 10,000 year return period but ‘intelligent’ design conditions may be set by an appropriate study of the associated issues.

Currently, green water from the side may be analysed on the basis of a range of relatively severe wind seas approaching the vessel from some moderate angle to the head – typically 30 degrees – but it is by no means certain that this represents either a realistic extreme scenario for either an intact or damaged vessel.

Of course, having recognised that freeboard exceedance is likely, and taken some ‘appropriate’ measures to move sensitive equipment inwards and to higher elevations and to ‘marinise’ any essentially deck-mounted items to some historically-accepted level of robustness (i. e. thicknesses of steel or bolt sizes that conform to ship building practice), it can be argued that steps have been taken to improve the probability of vessel survival for most cases. However, 'marinised' ships still suffer green water damage in heavy seas and need to seek shelter. Generally this option is not available to an FPSO. There was still a sense of unease among some panel members that some seas (not necessarily extreme) may cause significant green water damage to deck housings or deck-mounted equipment which could put a vessel in jeopardy before the subsequent storm has subsided.

3.5 SLAM DAMAGE

Appropriate bow shapes and structural arrangements must be used when deploying a vessel in an area where it may encounter extreme slam pressures.

Data on bow slam pressures and tools to analyse such conditions are only now becoming available as a result of the SAFE-FLOW and WAVELAND JIPs. The slam pressures identified by these techniques are relatively high and it is unclear whether typical structural arrangements around the bows of all FPSOs are sufficiently robust to cope with them. Once again the issue of relative heading is very important. While the bow shape and bow structures of most ships are capable of resisting a slam event from a head wave without sustaining severe damage, it is less clear that this would be the case if the wave were approaching from a heading of 30 degrees, say.

Further, there is relatively little information or tools available for the identification of the levels of slam pressures that might be appropriate along the side of a vessel for seas from moderate to large heading angles.

High slam pressures are not only caused by vessel speed or 'extreme' sea conditions. Lower vessel speeds do reduce some slam pressures and the frequency of slam events and hence the small forward speeds associated with FPSO drift motion will not exacerbate this problem but the SAFE-FLOW and WAVELAND JIPs, backed by full scale measurements from the Schiehallion FPSO, do show that pressures capable of causing structural damage can be encountered, albeit infrequently, for a moored vessel. These high pressures appear to be related to wave propagation velocity and the steepness of wave fronts as they impinge against the hull.

3.6 CHARACTERISATION OF RANGE OF RELATIVE HEADINGS FOR 10,000 YEAR EXTREME EVENTS

There is a tendency to assume that severe seas will be more nearly unidirectional than less severe storms. This may be so, however, the panel heard of evidence based on two different sources of field data that there are certain phases in a storm development, when near- extreme wind conditions may be aligned at 30 degrees or more to the direction of the wind-sea that has been generated by it.

One event was also described during which a vessel underwent an abrupt change in heading following which rolling motion increased substantially before her head could be brought back to face the incoming sea.

If vessel heading is at a modest angle to a wind driven sea or if there is a small beam swell with waves close to the natural period in roll, the vessel can develop severe roll responses that may even cause difficulties for the vessel's power generators.

The full range of such events appropriate to the prescribed return period may be difficult to predict and hence the severity of some responses may go un-recognised.

Further, it has already been pointed out in section 3.3 that severe green water events in a given return period are not necessarily associated with the most extreme weather conditions, so one might expect that a wider range of other associated phenomena might also need to be taken into consideration when designing for such occurrences.

Part of the difficulty of predicting an FPSO heading lies in the need to identify appropriate joint distributions for a large number of metocean parameters or at least to decide on appropriate design values which are neither too extreme nor too insignificant. Further, there are significant uncertainties in the ability of design software to accurately predict responses for complex scenarios. Model tests may be able to give guidance on some effects but the difficulties in specifying appropriate test conditions still apply and model tests suffer other limitations (see Section 3.7).

As stated previously, vessel heading prediction will have important repercussions for assessment of green water and slam effects for quartering and beam seas.

Beam seas can occur for other reasons such as poor operating practice or break-down in heading control equipment. Several FPSOs have been caught beam-on to a rising storm so it is also important to take these issues into account in any full risk assessment of green water, slam or capsize issues and to make an appropriate assessment of the environmental conditions appropriate to design in these circumstances.

3.7 ISSUES OF INTERMEDIATE CONCERN

Making better use of existing measurement data from operational FPSOs

The first of these relates to the use of data that could be obtained from vessels in operation. A number of FPSOs already have performance monitoring systems in place to record a wide variety of information. Valuable data is also collected during routine inspection programmes. Industry could draw much benefit from this pool of information and operating experience. Feedback, perhaps even on a range of minor issues, offers the possibility of providing the means to anticipate and avoid or mitigate risks of more severe incidents. In addition, through a structured programme of reporting, long term measurement programmes could feed information back into the design process, for example in the calculation of extreme hull girder stresses. The recording of operational data need not be restricted to FPSOs operating in the North Sea although data from regions with similar climatic conditions would be of most relevance to the items pertinent to this study.

Mooring integrity

Mooring integrity was considered to present an area of concern owing to the difficulty in identifying and correctly analysing appropriate loads and associated conditions during the design process. Many aspects of design and operational performance of an FPSO have an impact on mooring loads and integrity of the mooring system. The correct identification of the extreme load combinations arising from these various aspects requires further work owing to potential consequences of mooring system failure. Clearly, mooring failure is very important to any vessel that is adjacent to other structures or production facilities. Work undertaken under the REBASDO JIP indicated that current methods of predicting mooring response are not adequate to describe the observations made on that project. More importance should be given to the analysis of moorings in spreading seas although such analyses would be difficult to specify and implement with current data and analysis software. Several panel members considered that mooring failure was of less concern for an isolated FPSO since most FPSOs have considerable reserves against complete vessel loss even in a free-floating state.

Specification of model test programme to capture extreme response events

Extended model testing programmes were considered to offer an important method of assessing survivability issues in a range of extreme metocean conditions. However, there was also some unease that present model testing techniques may offer limited capability to define design load conditions accurately. In particular, unless very long test durations are specified or specific preparations are made, waves used in tank testing programmes may not represent a reasonable sample of what would be expected in a real sea. Wave time-series to which a model is subjected must contain a statistically valid sample of extremely high and steep waves, both individually and in groups. Given the recognition in the discussion of the highest ranked events that it is important to include multi-directional test conditions (waves, wind and, occasionally, current) how is the adequacy of model test specification and practical realisation of these conditions in a test basin to be achieved? One panel member considers the time is overdue for a closer comparison between full scale wave measurements and those that might be used as 'appropriate to model testing for design' for some typical locations on the UKCS.

Fatigue and fracture toughness

The prospect of fatigue and fracture toughness being found wanting in extreme conditions was identified as important. According to information put forward by some panel members, it seems that many existing FPSOs on the UKCS may have adequate material and weld specifications in critical areas. However, greater benefit could be obtained from a process by which the latest thinking on fatigue evaluation, materials specification and fracture mechanics, combined with in-service inspection strategies, are brought together to produce a definitive best practice and drive a consistent approach. One suggestion was that, to compensate for uncertainties in loading, FPSOs should be designed to approach failure in a ductile way. This would require that steps be taken to ensure good fatigue detailing, use of high toughness materials for crack resistance and detailing that would ensure that the structure does not fail because of a local overload.

Damage stability

With regard to damage stability, the question was raised as to whether or not current stability criteria cover the possible effects of extreme waves. Although FPSOs have a large, well enclosed volume similar to tankers, their survivability might be affected by reduced initial stability owing to their heavy topsides equipment. Most panel members believed that wave-induced capsize was not a reasonably foreseeable event for an FPSO, intact or damaged, provided its weathervaning response (active or passive) was operating effectively. At present, such issues are addressed in accordance with MARPOL or IMO 'rule' requirements during design and these are generally considered to be fairly onerous. Panel members were less certain of stability if a vessel were to take up a large angle to an incoming sea and questioned whether it would be feasible to quantify the associated risk. They felt that the implications of the prescribed damage conditions for structural strength or the consequences of subsequent green water loading with seas at large angles of approach are seldom fully explored.

Table 3 provides an indication of the coverage of the JIPs previously identified in Table 1 with respect to the most important issues and several of those of intermediate concern.

Table 3 Scoping study issues dealt with in each JIP

	Extreme metocean conditions		***Extreme response***		***Associated extreme loads***				***Reliability***
Component	2D seas	Spread seas, SS, or multi-directional, MD, metocean input (waves, swell, wind, current)	Wave responses for FPSOs at fixed relative headings	Responses for freely weather-vaning FPSO	Green water loads for weather-vaning FPSOs - decks, deckhouses and deck equipment	Slam loading on bows of weather-vaning FPSOs	Green water and slam loadings for extreme yaw and/or roll responses	Moorings (includes slow drift response)	Applicat-ion to design methods
JIPs covering metocean conditions and general response prediction	1	SS – 1*, 3*, 4* MD – 1*, 4*		1				1	1
JIPs covering yaw or roll responses	2	SS - 2 MD – 2		2					
JIPS related to green water and slam	3, 6, 8	SS - MD -	3, 6, 8		3, 6, 8	3*, 6			3
JIPs dealing predominantly with fatigue loading and assessment		SS - MD -						1,5	1

* JIP involves metocean measurement and/or full-scale FPSO response measurements. Both aspects would be required to address most scoping study concerns. Most quoted JIPs relied on model testing to some extent.

It is unclear whether any JIPs explicitly consider the effects of veer in the representation of any weather parameters and associated FPSO responses. Nor is it clear the extent to which this issue is investigated in the design assessments for any particular project.

3.8 MINORITY ISSUES

Each of the following issues was identified by one panel member as being an area requiring some improvement in industry performance although none was rated as being of serious concern:

(1) Performance standards imposed within FPSO design and inspection are not only inconsistent but also inadequate.

(2) Some FPSO vessel and system configurations may be more vulnerable than others. The case was cited of vessels that rely on thruster assistance for heading control. This places great reliability requirements on power supplies and if a large rolling response were to cause a power outage, for example, this could pose a serious threat to such a vessel.

(3) Disseminating information about the latest technology seems to be problematic. Several high quality research projects have reported in recent years, but there does not appear to be a certain route for ensuring this information feeds into Rules and more general FPSO design work.

(4) It is difficult to spot serious incidents within existing data bases of incident reports. Further, despite the infrastructure of metocean measurements on each platform and surrounding oil and gas facilities, many required for statutory operational reasons, it can be difficult to determine what the weather conditions were at the time and whether they played any significant part in the cause of an incident.

4.0 CONCLUSIONS

The panel were not unduly alarmed about the status of survivability design for FPSOs, taking heart from the large number of FPSO operational years that have now been accumulated by vessels in UK and Norwegian waters without loss. Nevertheless, panel members were not inclined to be complacent with the status quo and recognised the possibility that few vessels will have been exposed to sea states that might truly represent realistic design conditions. Before the panel is totally satisfied with present methods of survivability design, some further work is required, particularly with the regard to the four top-rated issues. These are summarised as follows:

- The current basis of survival design should be determined by an appropriate set of performance standards in order that the risks associated with low-probability, extreme environmental conditions and vessel responses can be managed. This approach is only robust if the set of limit states (or empirical design checks) examined is sufficient to ensure that any probability of catastrophic failure due to vessel response to the weather has been reduced to less than 1 in 10,000 years across a wide range extreme response evaluations. More work is required to provide better methods of identifying the full range of such conditions that may apply during the evolution of realistic storms.

- Given current limitations in appreciation of the full range of non-linear responses of an FPSO to combined effects of many metocean parameters, there is a distinct probability that the ideal may not yet have been achieved for all situations. There seems to be one particular difficulty in making a proper evaluation of the statistics of heading and yaw response between an FPSO and several important contributing metocean phenomena that will have important influences on extreme load effects.

- The full range and magnitude of long-term green water load effects along the side and at the stern of an FPSO have not yet been determined. However the dangers of green water incidents are now well known and most companies have examined their vessels' exposure in this area and have taken measures to reduce risks accordingly. Since green water damage may occur before a storm has reached its peak it is important to re-assess whether a vessel that sustains any such damage or is already less than fully operational may be in danger of progressive collapse as a storm continues to build.

- The magnitudes and characteristics of slam loading pressures to which a moored vessel may be subject have only recently been identified. A more extensive review of FPSO survivability is required in this area. This study will need to make appropriate allowances for yaw response of the vessel and those occasions, perhaps infrequent, when a vessel may be affected by slam events due to seas approaching from the bow quarter or beam.

The panel did not go any further to identify how these issues might be addressed or the most appropriate format (research study, industry review, JIP etc) for doing so. The author of this report has made an attempt to identify an indicative set of studies that might lead to the development of consistent survivability design methods. This is presented in Appendix E.

Five separate areas were identified where further work would be expected to improve design and safety, although perhaps these are not considered to be as critical for the survival of existing or future vessels as the four top-rated issues.

- There is a need for improvement in the feed-back of operational experience and in-service measurements to enhance safety and give the best opportunities for spotting potential problems, reducing risks for other vessels and identifying future improvements in design.

- More work is required to identify the range of conditions that need to be examined to provide for the robust design of mooring systems. These are liable to involve better assessment methods for directional metocean effects (relative to the vessel) and also for extreme forces in spreading seas.
- Model testing offers many distinct advantages for exploring survivability issues, but more work is required to develop methods of reproducing in a model tank conditions that are truly representative of real extreme storm conditions that have been measured at sea. Initially this may involve critical comparisons between standard model tests of design conditions and those measured in the field.
- Benefits could be obtained by combining the latest thinking on fatigue evaluation, materials specification and fracture mechanics with in-service inspection strategies. Better fatigue detailing and selective use of high toughness materials may allow FPSO designs to approach failure in a ductile way.
- More attention needs to be paid to assessing strength of a damaged vessel to ensure that it is not vulnerable to progressive collapse.

Returning to the original question posed to the panel: Does a satisfactory rationale exist for survival design?

- Only partially, although lack of vessel loss in UK and Norwegian waters tends to suggest that the design community is not too far removed from one. Vessels designed to satisfy a 'normal' range of intact and damaged design scenarios do appear to have been sufficiently robust to withstand the **majority** of conditions not explicitly assessed.

- However, survivability design relies on the fact that when vessels are designed to withstand a finite number of extreme environment load cases, this set is sufficient to cover **all** occurrences within a very low level of occurrence or to an even lower probability of failure.

- Paradoxically, if the title of this report is taken literally and at face value, it is likely that FPSOs are sufficiently well designed to withstand extreme metocean conditions. Research done within the Maxwave, Safe-flow, Waveland and Rebasdo JIPs, has demonstrated repeatedly that the most onerous conditions for many aspects of FPSO design, do not correspond with those that would normally be considered the most extreme metocean conditions (storms or individual waves) within any given return period. Extreme design conditions are usually associated with some extreme **response** of the vessel to the environment and it is less clear whether all relevant extreme responses are anticipated by the normal range of design calculations.

- Both the metocean parameters that govern relative heading and yaw response of an FPSO, and the range of wind/wave/swell conditions that might lead to extreme responses or extreme (impact) loading in any part of the hull, topsides or equipment support structures are extremely complex. It is difficult to be certain that all such conditions are represented in design for all intact, damaged or operationally impaired conditions that might occur during the field life of a vessel.

- Severe impact loads occurring when a vessel is at a large relative incidence angle to an incoming wave might not only cause damage, but might further increase the yaw of the vessel and induce extreme rolling motions which could make it difficult for the vessel to regain a favourable heading for some protracted period.

- Likewise, a rapid veer of wind or current direction may also cause a vessel to take up an unfavourable heading.

- Neither of these scenarios is explicitly taken into consideration within design today. Combining this with the realisation that large motion responses or high impact loading can occur in sea states that are not too rare, may imply that the overall probability of occurrence of an associated design event may be too high to satisfy the overall target criterion for survival that was readily accepted by the panel.

- Overall, there would appear to be a range of responses and high loading conditions with relatively low frequencies of occurrence that are difficult to identify that may not be adequately covered by today's design methods. The dangers posed by (relatively common) green water incidents were only uncovered after several FPSOs had been deployed and damaging events had been experienced. It is still uncertain whether all combinations of heading, slam and roll response for intact/damaged/operationally impaired vessels have been experienced by the current fleet of FPSOs on the UKCS.

In many discussions held during this scoping study, panel members considered several extreme response scenarios with annual probabilities of occurrence of the order 10^{-4} accepting that when such extreme events occurred a structure might sustain damage but that there should be no collapse of system integrity (with the associated risks of loss of the vessel, loss of life or severe pollution). There was a general acceptance that such extreme responses and any resultant stresses in structural components should be evaluated in a similar manner to an accidental limit state (ALS), using reduced partial safety factors , say, unity, and allowing a degree of non-linear structural response such as plastic deformation.

It would appear that an extension of this approach could be developed as a clear and satisfactory method for FPSO survivability design. General examination of the range of possible FPSO extreme responses on the above basis should be implemented to identify any highly non-linear or threshold-type responses for which the traditional ultimate limit state (ULS) approach to design might be considered unsafe. Ultimate limit state design is implemented by applying partial load and resistance factors to specific design events at the level of 10^{-2} annual probability of occurrence. For many cases the ULS condition will continue to govern and no further action will be necessary. For those where some unusual trend in response causes the extreme condition to govern, the designer would be expected to review the associated risk and resolve the problem by managing it in the most effective manner. Where the risk can not be mitigated in some other way, design parameters would be adjusted to reduce it directly.

The SAFE-FLOW joint industry project has already indicated how this approach might be applied for some simple cases of green water and wave slam loading even allowing for substantial modelling uncertainties in the derivation of extreme response predictions. Doubtless improved models and better control of modelling uncertainties will be needed to apply these techniques to more complex extreme load scenarios but the process of examining these cases will improve appreciation of the range of unusual response mechanisms which appear to lie at the base of some of the panel's current concerns.

When this strategy is first adopted for a new configuration or indeed a new application of a traditional configuration, a wide range of responses may need to be examined to identify an appropriate set of 'extreme response limit states.' However, it might be expected that a greatly reduced set could be identified that would normally represent a sufficient coverage for most subsequent projects. Nevertheless, where a new usage or vessel relocation is proposed, it may be necessary re-expand the search until there is confidence that any new circumstances that might represent a threat have been identified.

APPENDIX A THE PANEL

The panel, HSE facilitators and PAFA staff who contributed to the scoping study are identified in the following table.

Panel Members	
Terry Rhodes (Chair)	Shell UK
RV Ahilan	Noble Denton Europe Ltd
Nigel Barltrop	Department of Naval Architecture and Marine Engineering, Universities of Glasgow and Strathclyde
Michel Francois	Bureau Veritas
Peter Gorf	BP
Sverre Haver	Statoil
James MacGregor	James MacGregor & Associates
Chris Shaw	Shell Netherlands
Don Smith	OGP
Chris Swan	Imperial College
Grovert Wagenaar	Bluewater Energy Services
Julian Wolfram	Heriot Watt University
PAFA Facilitators	
Sandy Fyfe	Principal Naval Architect
Edward Ballard	Naval Architect
Sonja Smedley	Office Manager
Paul Frieze	Managing Director
HSE Contacts	
Peter Mills	Principal Inspector
Robert White	Principal Inspector
Vanessa Forbes	Senior Inspector

APPENDIX B REPORT ON MEETING ONE OF HSE SCOPING STUDY ON EXTREME WAVES

PAFA Interpretation of Panel Discussions

The objective of this study, as defined by the HSE, is:

> "to provide an informed view from a respected panel of relevant stakeholders of the future work that would need to be undertaken to determine the characteristics of extreme sea states / waves, the likely consequences for an FPSO subjected to such an environment and whether a satisfactory rationale for survival design currently exists or needs to be developed".

Currently, the process of survival design consists, in its broadest terms, in the management of risk for a set of design events, many of which are predefined but some of which may be identified as appropriate to specific issues that arise on a project. It will generally include various strength checks of the hull and moorings; specification of size and layout of water tight compartments to ensure hydrostatic stability in a range of intact and damaged states; component design against potential wave impact loads; consideration of various accident scenarios; provision of corrosion protection and fatigue assessment of many structural details. In some (many) cases these checks are carried out in adherence with Rules of the International Maritime Organisation or a Classification Society, but in others part of the assessment will be performed on the basis of a first principles analysis. The rationale underlying the entire procedure is not easily established. Seldom is any final assessment made of the 'resultant level of survivability' that incorporates the overlap of the numerous risk management decisions, design requirements and reliability assessments that have been imposed in the process.

Much effort is devoted to identification of interactions that may pose a risk to the entire system, but little is expended to identify the overall benefits that may accrue from interactions among design requirements though these may be implicit in effective design configurations.

The ultimate focus of this project is on the recommendation of future work that may need to be carried out to determine the nature and effect of events arising from extreme seas and to formulate a basis for the incorporation of this information into a rational procedure for vessel survival. This report concentrates on the identification of these events. Through the evaluation of the probability of individual damage events arising from extreme seas, a more accurate assessment may be made of the possible combinations of events and their potential effect on the survival of the vessel in question.

In consideration of the deliberations of the expert panel, several issues may be identified which have a direct bearing on survival, at least potentially.

One of the primary issues identified is FPSO heading and the prediction of appropriate values of heading relative to waves and swell for design against green water, wave slam and extreme roll. It was reported that there is considerable uncertainty in the prediction of FPSO heading. This may be due to insufficient metocean data on the combined occurrence of wind, waves and swell. Some FPSOs have been exposed to rising storm conditions in a beam-on orientation and some, which rely on thrust to assist their heading control, have been unable to turn their head to the rising sea. Associated with this issue are those of rapid changes in direction of environment, steep wave impact on the side structure, green water damage to deck-mounted equipment.

The second issue that could have an effect on survival is design for steep wave and non-linear surface effects. There is an indication that steep/rogue waves do not lead to overload of midship bending when acting alone, although further work is required:

1) to confirm previous findings (for a range of wave conditions)
2) to determine the probability of such events
3) to investigate probabilities that these may occur together with some other adverse condition

If steep waves impinge on the bow then, provided the bow structure and foredeck equipment have been designed against "typical SAFEFLOW design loads and pressures", the risk of component failure is relatively low. For an intact vessel, design for watertight integrity provides a further survival safeguard and hence the probability of vessel loss due to this mechanism may be much lower than 10^{-4} per annum. For a vessel which has already sustained or sustains an 'allowable' extent of damage, the conclusion is less clear. Bearing in mind that slam damage may be more likely during storm build-up and the green water and wave slam damage have been experienced in storms no more severe than typical one-year return events it is possible that further damage could be sustained that might threaten the vessel's survival. More work is needed to confirm whether or not this is a realistic threat.

Shear force and bending moment assessments at the bow/hull transition are subject to considerable uncertainties because of the interplay between slam forces (horizontal and vertical) and air entrapment. More work is required in this area if FPSO design by first principles has been used or is to be allowed. Note that a vessel designed by ship's Rules, where full consideration has been given to the effects of forward speed and resistance to collision damage, may possess adequate strength in this location.

The design methodologies commonly used today are still unable to incorporate many important non-linear effects that are essential to the assessment of extreme loading. Model tests are regarded by the panel as being critical to the assessment of these non-linear effects, though they cannot be used directly as part of structural design owing to the difficulty in modelling elasto-plastic material properties at model scale. However, the use of model tests must also be accompanied by an awareness of their limitations. An example was cited of the model testing for determination of mooring forces. Because of the very long natural periods of mooring systems, model tests as currently implemented are often not long enough to enable accurate statistical information to be obtained from them.

In addition to model tests, the use of on-going full scale measurement programs from operational FPSO vessels is also regarded by the panel as being of great importance for feedback to the design process. The standardisation of inspection and maintenance procedures was thought to be of benefit, eliminating the inconsistencies that exist in current approaches. This would allow comparison of observations from a number of vessels, improving the general understanding of the problem. These issues are perceived as highly relevant to design improvement, and may provide timely warnings of errors and unexpected consequences.

Results of Open Space Sessions

Discussion of the Results of Question 1

Question 1: *(As originally posed)*
Does current practice adequately describe extreme sea states for FPSO system design?

This question was challenged on the basis that the meaning of 'current practice' is unclear.

In some cases, 'current practice' constitutes the application of CS Rules to the original hull and some ill-defined group of additional calculations associated with the change of usage to FPSO application.

In other cases, calculations from first principles are employed to assess specific design limit states and demonstrate that the vessel can survive events that may occur at a nominal probability level of 10^{-4} per annum or less. Some of the panel expressed the view that these first principles calculations could now be specified in a consistent manner and were based on an application of second order wave theory in association with a range of storm conditions associated with identified contours on a long-term scatter diagram for the intended deployment area. Although this procedure has not yet been laid out in full, there was a feeling that it could be.

Although first principles calculations are applied to a range of limit states that have previously been identified as critical to the survival of some FPSO configurations, there will be many design details (hatch fixings, deck equipment protection details, ballast control systems and associated low pressure piping, to name but a few) to which some Rules-based design procedure will be applied because there is insufficient time to redevelop design from first principles in all cases. The Rules based approach is seen as time-efficient and incorporating historical lessons learned from previous incidents. However since its derivation is not fully spelt out, there is always a possibility that it may be applied in an inappropriate manner to some new vessel configurations or design details.

Although, the design methods described above could lead to inconsistencies, it was felt that all current methods must incorporate both first-principles based calculations and Rules-based historical experience.

The above discussion is reflected again in consideration of some of the more detailed points that follow. For the time being, the meaning of the words 'current practice' remain ill-defined.

It was also felt that the words 'sea state' should be replaced with 'metocean conditions.'

Question 1 *(As agreed in revision)*
Does current practice adequately describe extreme metocean conditions for FPSO system design?

Many of the issues identified by the panel in discussing all three questions relate to uncertainty in specific aspects of design of FPSOs rather than the more immediate question posed by the HSE scoping study, namely, can FPSOs survive extreme sea states and wave conditions. One can appreciate that there may be a greater probability of failure where there is uncertainty about what is covered by each aspect of the design assessment. However, FPSO design is an amalgam of intact, damage, accidental, progressive collapse and 'Rules-specified' design requirements and it is very likely that even though a particular loading mechanism may be poorly understood, it may be adequately represented either as a first line design requirement or by some other aspect of the overall design process. With this in mind, the following is an attempt to crystallize an opinion as to whether those issues arising from consideration of the discussion of question 1 may or may not represent a threat to the survival of an FPSO. The opinions expressed here need to be revisited by the expert panel and scrutinised by them to decide whether they can agree with the opinions expressed, whether they would wish to qualify them in some way or whether, as a result of further considering there remains a need for the panel to be better informed before it can pronounce its final judgement.

It is unclear whether or not current best practice makes adequate provision for the entire range of design conditions relating to extreme sea states and wave conditions.

For example, within the results of the original Greenlab JIP, there is a small subset of green water loading incidents that arise as a result of waves overtopping the bow and impinging directly against deck equipment. These are distinctly different from the majority of green water loading events which occur as a result of flow onto the deck following the occurrence of a freeboard exceedance. Within the Greenlab data, the loads generated in these overtopping events are absorbed within the overall statistics (spread) of the measured forces due to all load generating mechanisms (due to green water). Overtopping is much less frequent than freeboard exceedance, but, to the best of my knowledge, there has been no separate study to determine the predictions of long-term design load arising from this particular mechanism and demonstrate whether or not it represents a higher green water load than will occur as a result of the (statistically-biased) freeboard exceedance mechanism.

Similar comments apply to other aspects of FPSO design – e.g. bow slam loading or heading control with multi-component input from wind, current and waves. It is possible to identify potentially damaging scenarios but more difficult to properly assess their probability of occurrence.

Neither the metocean community nor those dealing with response and structural design appear to know sufficient to prescribe FPSO design conditions independently. There are several design issues for FPSOs that require the combined specification of waves, dynamic rigid-body and elasto/plastic structural response to identify meaningful simplifications that can be used as a basis for design. These require collaborative input from both communities!

Currently, there appear to be insufficient interfaces between designers and metocean people to enable appropriate, simplified design conditions to be developed and specified. More work is required in this area to confirm whether such conditions may represent a threat and to devise suitable design tests that can be applied to design of a wide range of FPSO configurations.

The identification of a range of appropriate design events at a 10^{-4} probability of occurrence requires both an appreciation of particular wave conditions and also several other aspects of vessel performance.

Where wave direction, wave spreading, swell, wind force, current, tide, and vessel loading condition all play a part in creating potential design scenarios (and associated limit states) simple considerations of probability of occurrence contours in a wave-height/ wave-period scatter diagram are insufficient. Close co-operation is required between engineer and metocean specialist to identify an appropriate combination of component probabilities that will represent a credible design condition. Where this is extremely difficult or not possible, it may be more appropriate to read a prescribed set of conditions from some CS Rules!

At least one well-founded design procedure does not take into consideration of 'freak waves'. On the one hand a freak wave might be defined according to some purely statistical property:

- that it is higher than twice the significant value

On the other, it might be identified by some recognisably different physical process.

The design procedure referred to takes full account of events occurring at greater than 10^{-4} annual probability and is based on use of a long-term scatter diagram and second order wave theory. It does not make specific allowance for freak waves on the basis that, if they do exist, their probability of occurrence is likely to be at a lower level. Whether this view is justified for all FPSO locations or whether there are some scenarios where this view can not be supported remains an open question.

The study needs an input to this aspect of the problem. Heriot-Watt university have made several publications of wave conditions that are observed in the Northern North Sea and have examined wave shapes and statistics that may be helpful in the identification of significantly different physical conditions (that might constitute freak waves). Imperial College, London, have also published studies of the wave propagation and superposition mechanisms that may underlie the occurrence of severe non-linearity. A combined statement from these two organisations about whether they believe they are researching similar events and some statement about probabilities of occurrence would probably be helpful in assessing whether more intense examination of the entire associated design issues would be merited. The organisations might also be asked to report whether the presence of a ship's hull in such wave conditions might be expected to exacerbate wave steepness effects or impulsive wave breaking phenomena against the hull.

To determine whether or not such a procedure is inherently safe, it is necessary to have a more extensive appreciation of what might constitute an appropriate range of 'freak wave' conditions that might adversely affect the design assessment of any particular design scenario/limit state, what might be their probability of occurrence and whether the hull of the vessel is at all likely to suffer catastrophic damage when it encounters any of these conditions.

In considering any FPSO design scenario (limit state), it is necessary to consider the appropriate specification of the full metocean conditions which could conceivably represent a threat to the vessel from the physical processes under consideration.

FPSO hulls are designed to a range of more-or-less independent intact and damage conditions. These independent considerations interact through the vessel configuration to produce a design which is more robust than would be achieved from any single condition acting alone. Thus, even if there is a small probability that a wave slam could puncture the outer hull, provided all the single compartment damage scenarios have been examined in full and the danger of progressive collapse has been reduced to an insignificant level, then the hull puncture is not expected to lead to a catastrophic failure scenario. Clearly, if recent research – such as that undertaken by the SAFEFLOW JIP – has established a better estimate of the maximum slam pressure that is higher than has previously been accounted in design, then it might be expected that a vessel designed to this more stringent requirement which also satisfies the other design requirements will be somewhat safer.

To demonstrate safety at a 10^{-4} annual probability of occurrence then it is possible that representation of extreme wave conditions at lower probabilities of occurrence may need to be identified. Scatter diagrams extending to lower probabilities of occurrence may be derived in some areas, but do these scatter diagrams, combined with a second order wave theory (say) identify all wave conditions that may be experienced at this low level of probability. There are at least two issues involved here:

1. What wave height, wave period, wave group or surface steepness are most severe for each design scenario
2. What are the probabilities of occurrence and damage potential associated with each entry in the scatter diagram

In addition, it might be asked whether the scatter diagram is at all appropriate to identification of conditions which may occur infrequently, caused by an otherwise independent physical mechanism – such as a contra-flowing current.

It was noted that the highest wave is seldom the cause of the problem. It is important to consider an appropriate set of metocean conditions for each design load or requirement.

If an evaluation of failure probabilities at a 10^{-4} level is to be made, then it is generally necessary to consider scatter diagram occurrences at lower probability levels. Frequently joint probability data is missing and there is a gap in our appreciation of steepness of individual waves or parts of the wave crest profile.

Given what we now know about potential ranges of bow slam pressures (SAFEFLOW and Schiehallion bow monitoring data), if we could check that typical plating, stiffeners and framing arrangements are adequate to resist this level of loading, then, when this type of design is combined with a full assessment of all single compartment damage scenarios and avoidance of progressive collapse, then the risks of catastrophic damage to an FPSO bow may be so low as to be negligible.

Given the current level of knowledge of green water incidents, these can be taken into account in the design procedure by application of the methods for analysis and model testing that are now available to the industry. Some difficulties remain with a full analysis of green water from the side and, in particular, if there is even a small probability that a vessel might have to sustain such sea states at a relative heading of between 45 and 135 degrees, then extensive model testing and design analysis will be required to demonstrate that the vessel can survive such conditions. These conditions would also give rise to the prospect that the vessel might have to sustain slam pressures on the side shell, which may already be weakened by the effects of internal corrosion and fatigue.

Discussion of the Results of Question 2

Question 2: *(As originally posed)*
Does current practice adequately define loading and response for extreme sea states?

Once again the phrase current practice was challenged in the same way as it was for Question 1. Otherwise the question was not changed by the panel. All three groups felt the general answer to the question is "No" but only provided specific comments in consideration of the more detailed points arising, not against the general question.

Question 2: *(As agreed in revision)*
Unchanged.

The following is an attempt to crystallize an opinion as to whether those issues arising from consideration of the discussion of Question 2 may or may not represent a threat to the survival of an FPSO. See the first paragraph of the discussion of question 1 for a discussion of the rationale of this mode of attack.

Are the sea states defined to an adequate degree of detail to check the "true" response of an FPSO? (Response can mean rigid body and structural dynamic elastic/plastic response).

It was felt that there was insufficient focus on 10^{-4} environmental events. The word 'events' was later changed to 'responses'. In the context of the issue of survivability, this question and its discussion merely indicates that we may not have adequate definition of events/responses at these low probabilities of occurrence. Some of these will represent extreme sea state/wave situations and so, if there is inadequate definition there may be a risk to survivability. This does not identify any particular scenario that may threaten survivability, but it raises the point that when considering each scenario, we must be cautious about assuming that we can specify it precisely.

Model testing is still critical due to the general lack of knowledge and adequate numerical tools. However, there are areas in which the results of model test are suspect, such as results that depend critically on damping levels. Likewise, it will generally be impossible to represent structural dynamics adequately in a model test. There is also the issue of model test specification and whether wave conditions set up in the laboratory properly represent these conditions, whether they under-represent them in relation to wind and current effects, or whether they over-represent them by producing waves that are extremely unlikely to occur in the natural environment. Once again this issue concerns a general uncertainty in design rather than a specific uncertainty about survivability.

Steep waves and non-linear surface effects on design are poorly understood, but how likely (less than 10^{-4} probability of occurrence ??) and/or important are they for routine design?

What is the totality of wave height/period/steepness/group effects that is conceivable at the 10^{-4} level and do any of these pose a threat to survivability? This is a restatement of the original question, not an answer!

Theoretical or numerical models are not adequate for handling the response of a diffracting structure in non-linear waves? This maybe so but it is secondary to the question of survivability. FPSOs have been, are being deployed without this knowledge and most seem to survive. On the other hand does it indicate that it is pointless to identify 'extreme' wave conditions because we could not determine with any certainty what their effects on an FPSO would be?

Bow impact: - There is a perception that, as a result of recent research such as the SAFEFLOW JIP, the industry is more aware of the levels and characteristics of the pressures that are appropriate for design against bow slam. Today, it is unclear whether or not the bows of existing FPSOs can withstand these types of loading. It is also unclear whether all operators have considered in full, the event trees and consequences of a failure caused by extreme bow pressure within the type of storm conditions when such a failure could occur. If current designs are reviewed for these effects and future designs take them into consideration, then the remaining risk to survivability in the face of bow slam may be low enough that it does not merit further investigation at this stage. Such studies should also investigate the likely levels of bow slam that might be likely for a vessel that has sustained other physical damage. It is entirely possible that bow pressures in a one year storm are not so much less than those in the design life that they would also pose a threat to a vessel that has sustained damaged of some description.

Hull strength: - There is a suggestion, based on recent model test findings, that the midship bending moment that might be experienced due to an extreme high and steep wave is not any higher than would normally be considered as part of the normal 'Rules-based' design procedure. This is encouraging, but more work is required to confirm these findings and cast the results against a probability background so that appropriate assessments can be made about joint probabilities of a range of such events combined with other design conditions.

Green water: - See previous discussion. As a result of recent research within the Greenlab and SAFEFLOW JIPs there is a better overall appreciation of the potential levels of green-water loading that need to be accounted for in design. Provided current vessels have been re-assessed and new vessels are designed to resist these loads and a proper assessment has been implemented of the potential consequences of such events, then the remaining risks to survivability will be relatively small.

Capsize stability: - It is at least theoretically possible that particular wave conditions could pose a risk to capsize stability, especially when combined with vessel damage, poor heading control relevant to the incoming waves and interaction with mooring constraints.
This issue might repay an exploratory investigation to determine whether it may represent a credible threat to survivability.

Checks are required to determine whether current methods of progressive collapse assessment associated with stability and wave impact damage make use of the most recent tools that are becoming available and make provision for appropriate levels of corrosion and fatigue in an operating vessel.

FPSO heading: - recent assessments reveal that it is very difficult to predict the heading response of many turret-moored FPSOs particularly when more than one metocean parameter makes a significant contribution to the yawing moment. Many design conditions are based on assumptions that the FPSO will be within a specified range of relative headings to the incoming waves. If these calculations are inadequate to represent the true nature of heading response, then there will be a distinct risk that under some metocean conditions the vessel could sustain damage that might threaten its survival. One vessel rotates on its moorings as a result of the tidal cycle. If it experiences wave conditions that are insufficiently severe to completely suppress this tidal variation, then it may lie beam-on to the sea in moderately severe weather. One of the panel suggested that this was the sort of condition in which thrusters can be used to bring the vessel's head to face the waves and his experience was that thrusters were usually sufficiently effective to do this. This approach may not be successful in hours of darkness when it is difficult to ascertain the prevailing wave direction by observation.

Current design methods do not allow accurate prediction of low frequency responses in steep waves. It is unclear that this represents a particular problem for vessel survivability.

Rapid changes in direction of the metocean conditions: some environmental parameters may change direction rapidly and bring an FPSO into an adverse heading to the incoming waves for some time. Since the side shell is not generally sufficiently strong to withstand wave impact pressures, this brings a risk of damage. Being at a large angle to incoming waves also exacerbates roll behaviour and may make the vessel more vulnerable to green water incidents which may affect stability and loading. Generally, rapid change of direction of environmental forces is particularly difficult for operational issues (such as supply or shuttle loading) but generally these will not be attempted in severe weather.

Full scale monitoring and feedback: - this is a very important topic if industry is to learn from the operational experience and the 'near-misses' of others. There have been several anecdotal reports of FPSOs coming beam-on to rising waves. Where are the reports and assessments of these incidents that other vessel operators and designers can review for applicability to their situations.

Checks of shear force and bending moment throughout the length of the ship (not only at the midships section): - This was raised as a design check that was seldom performed. It was pointed out that ship Rules incorporate requirements that would normally ensure that if the midship strength capacity is sufficient, then so too will be the capacity at any other cross section. However, there may still be some doubt about whether a designer, working on the design of an FPSO hull from first principles, would build in adequate strength capacity at the bow to fully account for horizontal and vertical slam loading at the bow. The Safeflow JIP does address this issue but some uncertainties remain considering the effects of air entrapment. Air entrapment probably leads to a reduction in the highest pressures experienced at any point but it still enables substantial pressures to apply to a large area. Some caution would be advised in this area of design until this issue is more thoroughly researched and understood. Normally, a trading vessel will have a collision bulkhead in this area and may therefore be sufficiently strong to resist elevated slam pressures. A priori, there is no compelling reason for an FPSO to incorporate a full-strength collision bulkhead so it might be possible to bow slam pressures to cause damage in this area. Were substantial damage to occur in the area of the bow-to-main-body attachment area, it is perceived that this might have a direct effect on FPSO survival.

Discussion of the Results of Question 3

Question 3 (As originally posed)
Does the industry adequately define performance standards?

This question was not changed by the panel, but it did attracted the following comments:

> A 10^{-4} per annum failure probability is considered a reasonable system performance standard. However, there is a need for a clear definition of all contributions to this requirement – moorings, riser failure, etc.
>
> There is about 100 FPSO operating years experience in UK and Norwegian waters and it was felt important to have a clear statement about any messages that could be distilled from this experience.
>
> It was agreed in the discussion about the questions that this question needed to consider the resistance aspects of design together with operational effects such as inspection and maintenance.

Question 3 (final version) Unchanged

FPSO design and performance standards are set by a mixture of first principles design and design according to Rules. This can, potentially, lead to inconsistencies but the panel felt that this situation was more satisfactory than either route on its own. On the one hand it is important that all critical design issues are examined against the 10-4 /y failure requirement and this can only be done on the basis of first principles design, not on the basis of site specific data together with information currently contained in most Rules. On the other hand, there are many non-critical items that require specification as distinct from design and in this respect Rules offer a more efficient route. However, given the potential inconsistencies in this approach, the designer has always got to be alert to the possibility that he may be using old data in a way that was not intended and take action to avoid the dangers of so doing.

Some detailed points on this issue were as follows:

- Load and resistance (failure levels) may not be matched for components
- Superposition of loading components must be treated with care
- Internal tank loads – patterns, fluctuations and inspection requirements need to be examined carefully. But there was a statement to the effect that present methods are adequate in these respects.
- Do safety factors cover uncertainties – (may be do not cover issues that you do not know that you do not know. These need to be identified by creative thinking and vigilance in reviewing risks).
- What is an acceptable level of damage against which to assess normal design requirements? Can this be specified in terms of:
    - Fracture resistance
    - Leaks
    - Green water damage
    - Corrosion and fatigue effects on material properties.
- Need to check in case some aspects of design are affected by temperature
- Need to check mooring systems reliability and its potential effect on the FPSO.

Design standards: - It was felt that there was a need for more input of practical experience in the development of specific FPSO rules and that these should allow input of site-specific data. There may be a need to provide benchmark calculations of more first pricinples approaches.

Maintenance & inspection inconsistencies: - Need to better define timing, strategy, response to finding defects, need for follow-up calculations.

A failure probability of 10^{-4}/annum is OK but more specific advice is required about how this ought to vary with consequence. There is a need for more guidance on selection of different types of failure, clarification about how failure is defined, and recognition of the role of uncertainty in failure calculations.

There is a need to standardise reliability and risk analyses. However, the latter should not be so regimented that it precludes the finding of new, previously-unidentified failure modes.

All of the above issues deriving from question 3 only impinge on the issue of FPSO survivability in a very oblique manner!

Many of these issues are important for robustness in design which one might expect to lead to high operational survivability. However, the direct impact on survivability of an FPSO does not seem to have been addressed.

In fact, there has been little research into the ultimate survival performance of an FPSO. For example, it is doubtful whether anyone could quantify the overall effect of water tight integrity requirements on robustness of the design against bow impact damage. For an intact vessel, the water tight integrity provides considerable extra security for survival in the event of the failure of a component in the bow structure. For a vessel with pre-existing damage, it is probably still unclear whether green water and bow impact for 'appropriate storm' conditions pose a significant threat to the vessel, bearing in mind that bow slam and green water damage have occurred in metocean conditions no more severe than those in a typical 'one year storm.'

APPENDIX C HEADINGS, ISSUES AND POINTS

The following are a series of headings, issues and points used by the panel to discuss a wide range of FPSO design topics.

1. General Design Issues

1.1 10-4 PER ANNUM IS REASONABLY FORESEEABLE

1.1.1 Need to clarify that this relates to response, as opposed to environmental conditions for example.

1.2 MULTI-VARIATE RESPONSE BASED CRITERIA

1.2.1 How do we translate this into a usable approach for designers?

1.2.2 There are a range of methods available, this one being in its infancy.

1.2.3 In examining survivability, it is not necessary to use a large number of parameters

1.2.4 Improvements in the type of data that is supplied to designers, making it easier to use in methods like this.

1.2.5 Is there a need for guidelines on the kind of data that designers should be asking for from metocean specialists

1.3 GREEN WATER LOADING

1.3.1 Is this a significant issue in relation to survivability?

1.3.2 More work is required to address this problem in extreme sea states.

1.3.3 Is there a risk of sustaining further green water damage following an initial incident?

1.4 DAMAGE STABILITY

1.4.1 Are conventional damage stability criteria suitable for use in conjunction with extreme sea states, i.e. 10^{-4} sea state?

1.4.2 What is the present limit state employed in damage stability assessment? How does this compare to 10^{-4} sea state?

1.4.3 Should consideration be taken of likely actions in the event of flooding of compartments?

1.5 MOORING INTEGRITY

1.5.1 Is current practice sufficient to prevent mooring integrity affecting survivability?

1.5.2 Verification of the ability of current mooring integrity to meet demands of extreme conditions.

1.5.3 Greater uncertainty exists in mooring integrity than hull strength, for example.

1.5.4 Currently being examined as part of the Mooring Integrity JIP.

1.5.5 What effect does long term deterioration of mooring systems have on their reliability/integrity?

1.6 CLARITY AND CONSISTENCY OF PERFORMANCE STANDARDS

1.6.1 Inconsistencies appear to exist at present, both in standards and in the application of standards.

1.6.2 How is the knowledge developed in JIPs (e.g. SAFEFLOW) passed on to industry in a usable format?

1.6.3 Operators must specify the performance standards that they expect to be applied to a particular installation during the design process.

1.6.4 Where specific safety related information arises, the HSE should ensure duty holders take the appropriate action to address it.

2. FPSO Heading

2.1 VESSEL AND SYSTEM CONFIGURATION

2.1.1 Passive or active heading control

2.1.2 Drag chain or otherwise

2.1.3 Reliability of heading control systems

2.1.4 Hull configuration

2.1.5 Have topsides been designed to withstand beam-on conditions?

2.2 CHARACTERISATION OF 10000 YEAR EVENT HEADING FOR DESIGN

2.2.1 10,000 year event involves head sea case

2.2.2 Sea states used in model testing should not only be unidirectional.

2.2.3 Testing should be carried out at angles to the waves.

2.2.4 Metocean community should be asked to provide an envelope of credible conditions for model testing process.

2.3 HEADING PREDICTION?

2.3.1 What range of headings should be considered during the mooring design process?

3. Steep Wave and Non-Linear Surface Effects

3.1 SLAM DAMAGE

3.1.1 Identification of wave mechanics of 10000 year event.

3.2 USE AND DISSEMINATION OF LATEST TECHNOLOGY

3.2.1 No current techniques answer all questions. Need to identify best practice which comes as close as possible to modelling realistic situations.

3.2.2 Shortcomings exist in determination of global loading. E. g., hull girder loads due to slamming.

4. Model Tests

4.1 SPECIFICATION OF MODEL TEST PROGRAMME TO CAPTURE EXTREME RESPONSE EVENTS

4.1.1 Benefit in setting out specific events, with the aim of causing particular extreme load actions.

4.1.2 How does one define the specific event associated with a particular level of probability?

4.1.3 Improvements could be obtained through the introduction of randomness to the amplitude and phase of the wave components used in the tank testing process.

4.1.4 Dangerous sea states should be repeated a sufficient number of times in order to produce data suitable for use in the design process.

4.1.5 Directionality and spreading should be used more often, given that facilities exist which can account for them.

4.1.6 Different conditions should be used in tests for particular responses

5. Feedback to Design

5.1 FATIGUE AND FRACTURE TOUGHNESS

5.1.1 Some vessels may not have good fracture toughness owing to the grades of steel used. Does this affect their ability to withstand wave slam loading?

5.1.2 Concern regarding possibility of crack growth from longitudinal members to shell. How does material grade affect this?

5.1.3 How does the use of a mix of steels affect fatigue and fracture performance?

5.2 QUALITY OF INCIDENT REPORTING

5.2.1 Is the current reporting system adequate?

5.2.2 Do we learn anything relevant to survival conditions from information on incidents in less serious conditions.

5.2.3 Are installations monitored adequately to provide useful data

5.3 PERFORMANCE STANDARDS OF SAFETY CRITICAL ELEMENTS

5.3.1 Monitoring of mooring lines

5.4 CAN WE MAKE BETTER USE OF EXISTING DATA THAT IS BEING OBTAINED?

5.4.1 How long does it take to get this information back into project design?

APPENDIX D E-MAIL REQUESTING PANEL OPINIONS

From: Sandy Fyfe
Sent: 19 November 2004 13:35
To: 'Terry Rhodes'; 'Chris Shaw'; 'Chris Swan'; 'Don Smith'; 'Govert Wagenaar'; 'James Macgregor'; 'Julian Wolfram'; 'Michel Francois'; 'Nigel Barltrop'; 'Peter Gorf'; 'Raj Ahilan'; 'Sverre Haver'
Cc: Edward Ballard; Sonja Smedley; Paul Frieze
Subject: Panel votes following second meeting of scoping study

Gents,
Many thanks for your presentations, participation and input to the deliberations of the scoping panel over the last two days.

Ed has mounted the list of issues identified during the final session on the web site. I would now urge you to provide a vote for the three items that you consider carry the biggest threat to the survival of any FPSO on the UK continental shelf based on your own experience and the discussions you have had over the duration of the scoping study.

I should prefer if, as a minimum, you could rank your choices 1, 2 or 3 according to your perception of the threat whether or not you provide any additional information. Ed has edited the presentation of the list of issues into three levels, e. g. 1, 1.1 and 1.1.1. I should prefer if you could indicate your vote based on the intermediate (1.1) level although you may wish to qualify your vote with reference to one or more of the more detailed issues (or some other detailed point) as you feel appropriate.

You may also wish to qualify your vote in some way by providing notes about particular circumstances or types of vessel that you would feel are most at risk. It would be helpful if you could indicate whether you feel any of the issues you identify are:

- serious and in need of urgent consideration, or
- less serious and amenable to less urgent treatment (e. g. by a joint industry or some other research investigation)

for any specific circumstances.

However, to allow us to make a reasonable assessment of your opinions and reflect these in the final report on the scoping study we need your replies by Friday 26th November and I would ask you to adhere strictly to this deadline when providing your ranked vote even if you feel a need to provide more extensive documentation of your considerations in the following week.

Best regards
Sandy
Alexander J Fyfe
P A F A Consulting Engineers,
Hofer House,
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TW12 1BN, UK

APPENDIX E

SOME IDEAS FOR FUTURE RESEARCH TO ADDRESS THE IMPORTANT ISSUES IDENTIFIED BY THE PANEL

The following is an initial attempt by the author of this report to indicate a range of studies that may begin to address some of the main issues identified by the panel and, at the same time, to build the capability to address the broader objective of developing a rational basis for survivability design.

1 Studies for prediction/identification of FPSO mean headings, relative headings and veer caused by realistic time-development of main metocean drivers.

a. Validation of hindcast models of magnitudes and directions of metocean parameters that make appreciable contributions to mean FPSO heading prediction over a range of averaging periods (between 20 minutes and 180 minutes, say). These models must distinguish, as a minimum, mean wind speed and direction, significant wind-driven wave heights and directions, swell magnitude and direction.

b. Investigation of appropriate models for surface current (tide, wind driven or other) as they might affect predictions of mean FPSO heading.

c. The validity of these models, singly and in combination, should be checked for several different locations around the UKCS where suitable metocean instrumentation is available and, if possible, where FPSOs are deployed, such as, the Western Approaches, the Northern North Sea, the North Central North Sea, the Central North Sea and the Outer Moray Firth, say.

d. Specification of models for predicting mean heading for several different configurations of FPSO. It should be expected that different models may be required for swivel and drag chain turret configurations, for different turret locations and for vessels for which appreciable thruster assistance is used to maintain vessel heading.

e. Validation of combined predictions of mean FPSO headings and variations in relative headings between the vessel and each major environmental input parameter. It may be necessary to constrain validation to ranges of wave conditions that are known to make strong contributions to green water effects at the bow, green water effects at beam, quartering and stern locations; steep waves that are liable to cause substantial hull impact loads, significant roll responses and high global mid-ship loads. It is not important to validate these models under the multitude of low sea states that do not cause significant FPSO responses.

2 Development of statistical models that would enable appropriate, simplified design conditions for combined effects of relative heading and green water to be specified. The range of relative headings identified in the first task should be explored whether these arise as a result of veer, swell, current or otherwise.

Identify a range of appropriate model tests which, using standard Greenlab model test conditions, would enable green water design conditions to be identified for bow, quartering, beam and stern locations. This work would need to combine the results of the previous studies with appropriate models of vessel response in short term sea states to identify long-term design conditions that take into consideration the likely range of vessel headings relative to incoming waves. The study would, to some extent, be limited by the range of current green water test conditions that have been used within Greenlab and Safe-flow JIPs although it should also enable identification of an ‘adequate’ range of tests for examination of extreme response limit states. The objective should be to identify whether current data are sufficient to enable extreme green water response limit states to be treated in an appropriate manner or whether existing test programmes and methodology need to be expanded in some way. The effects of uncertainties in model test specification and measurement should be combined within a reliability framework similar to that developed within Safe-flow, but considerably expanded to enable green water from quartering, beam and stern locations to be investigated more systematically.

This study should seek also seek to identify whether roll response might have any significant affect on the results. To date, the range of data on the effect of (independent) roll response components (due to wave or swell forcing matching a natural roll frequency, for example) on green water predictions is very limited.

3 Development of statistical models that would enable appropriate, simplified design conditions for combined effects of heading and wave slam to be specified.

This study would be similar to that envisaged for green water, but the main objective would be to determine the range of vessel headings that need to be investigated and the appropriate level of slam pressure appropriate to each location around the bow and at the bow-to-side transition.

4 Development of statistical models that would enable appropriate long-term distributions of roll response and appropriate design limit states to be developed.

More work is required to develop the specification of an appropriate study in this area, but the objective should be to identify whether current design methods are adequate or whether they need to be enhanced in some way to allow for strong interactions between roll response, heading/yaw response, green water and slam loading for those low probability events characterised by large heading angles between incoming waves and the vessel.

5 A similar range of studies is required to identify what level of design intervention is required to represent the above issues for a vessel which has sustained damage or for which the (active or passive) heading control mechanisms are less than fully functional.

6 Validation studies that model basin wind and wave conditions are statistically representative of realistic metocean conditions that occur at sea

In view of the fact that several of the issues identified above rely on the successful simulation of infrequently occurring events in model basin tests, it would seem to be appropriate that an attempt is made to confirm that model basin wave simulation techniques are representative of the range of metocean conditions that are measured in the field. In this respect it would be important to develop an appropriate set of statistical measure to compare full scale and model-scale simulation conditions.

Such studies should also address the issue of identifying appropriate test durations that may be necessary to obtain valid measurements of extreme responses for typical FPSO response models.

7 Structural assessment studies are necessary, even with currently available data, to determine whether typical FPSO structural arrangements at the bow and at the bow-to-side transition are adequate to withstand the levels of slam pressure loading determined within the Safe-flow JIP.

In due course these studies might be extended to a more thorough investigation of the levels of slam pressure loading consistent with the findings of some of the above tasks.

APPENDIX F

COMMENTS FROM WIDER INDUSTRY

Comments received from:

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25 April 2005

Attn: Sandy Fyfe

PAFA (by e-mail)

Dear Sandy:

Re: PAFA Report C143-235-R Rev 6:
Findings Expert Panel – FPSO Survival Design of FPSOs against Extreme Metocean Conditions

I have reviewed the above referenced report which you sent me last Wednesday and offer the following comments. The comments are based on a presumption, that if the HSE are asking the question, then the response should reflect the demography of FPSOs operating in the UK sector. Although the phraseology in the report often implies changes in future design, the bulk of the UK fleet affected are likely to have been designed and in place before the panel met.

The comments are also based on a second presumption that the 10^{-4} values really refer to combined accidental response probabilities that might arise from, for example:

a) An intact FPSO experiencing the worst 10^{-4} response event from any directional combination of wind, wind-sea, swell and current (i.e. metocean conditions 'accidentally' higher the 10^{-2} ULS response threshold, which for an FPSO may well not involve the 10^{-4} extreme sea state in terms of height).

b) An FPSO experiencing a combination of "moderate to low" probability accidental damage, in combination with the worst directional combination of wind, wind-sea, swell and current at a higher probability of occurrence than 10^{-4}. (i.e. It would not be reasonable to impose a 1 in 10,000 year metocean response event as a survival condition for any FPSO that has suffered an accident e.g. vessel collision?)

I for one would have been very interested in the panel's opinion of what they saw as a reasonable upper-bound extreme survival metocean event in combination with another accidental event. This doesn't appear to have been addressed, even though the report and executive summary makes reference to intact or damaged vessel and is arguably within the breadth of the HSE's original brief.

I think the report is a good piece of work and meets the HSE objective of identifying remaining areas of major uncertainty regarding the survivability of FPSOs in extreme metocean conditions…as might be expected from the quality of the expert panel. I believe the panel's highest importance grouping correctly identifies the remaining areas most likely to produce a step change in load effect at a 10^{-4} p.a. probability of response. I am however somewhat surprised by the dismissal of some fairly fundamental resistance effects as not being worthy of "serious concern" within the "minority issues" part of the report.

1. **Re Section 3.8, item 1 “Performance Standards imposed within FPSO design and inspection are not only inconsistent but also inadequate”.** This issue is rated as being of minority interest to the panel and hence is reported as “not being of serious concern”.

The most recent FPSO market research I have seen, suggests that the UK sector has 22 floating production systems already extant (though only 60% of these are FPSOs and there are at least two FSU’s in addition to the count of 22). The same research suggests that there might only be 2 to 3 new UK FPS projects in the next 5 years (of which 1 to 2 may involve the redeployment of existing units to a different UK field). In short, maintenance standards and the persistent application of potentially inadequate standards could have wide relevance to the UK fleet in the coming period, even if the panel regards it to be a minor issue for survivability in extreme metocean response events.

Shipping P&I Insurance club reports and indeed public reports of shipping casualties all seem to point to the standard and variability of hull maintenance being a significant contributor to world fleet casualties including complete losses (under what is intended to be a fairly consistent set of IMO and Class standards). There seems to be a noticeable difference between: owners with a strategy characterised by high maintenance to ensure high utilization at good shipping contract value; and owners who pursue a low operating cost base and competitiveness in lower value shipping contracts. Interestingly the latter group often acquires the former group’s tonnage at the critical break point where either reliability is expected to decrease, or maintenance cost is expected to increase to keep the vessel operating at the former group’s standards. The contribution of this variability in vessel maintenance to vessel insurance claims (including loss in survival events) appears to increase from vessel age 10 years onwards…with reasonable underlying logic.

85% of the UK FPSO fleet currently have between 5 and 10 years service since last deployment. The underlying average hull age is somewhat higher at 11 to 12 years with the oldest being circa 22 years. The single Panel member that raised or supported this issue, might well have flagged an issue pro-actively, that will become much more important than the others currently give him credit for. There are offshore parallels to the two shipping business and maintenance models. Often field economics go through a phase where production decreases very rapidly as the field comes off plateau, followed by a long tail of ever dwindling production rates. In this phase, an aging asset faces ever tighter needs for operational cost control. There is some evidence from UK fixed platforms (and the semi-submersible FPS fleet) of a trend for the initial operator to divest the asset - or at least duty holder responsibilities - to companies operating a lower cost business model to maximise value in late field life. It is a bold step by the Panel to assert that inconsistent or inadequate maintenance performance standards will not be of serious concern, at the probability levels being considered.

2. Re Section 3.8, item 2 “Some FPSO vessel and system configurations may be more vulnerable than others – raised in relation to vessels that rely on thruster assistance for heading control”. This issue is again rated as being of minority interest to the panel and hence is reported as “not being of serious concern”.

Approximately 46% of current UK FPSOs use active heading control and this might actually exceed 50% if one included all units that either use thruster assistance in extreme conditions because they have them, or become tempted to incorporate the thrusters as a partial mitigation of the 10^{-4} responses arising from the proposed ongoing research into multivariate FPSO responses. The issue may have had minority interest on the panel but should have wide relevance to the FPSO community.

The UK active heading FPSOs have their turrets, to a greater or lesser degree, much further aft than purely passive weathervaning units. An unmoored hull of this type will tend to lie closer to “beam on” than “head to” the incoming wind and sea states when its propulsion system is disabled, as demonstrated by OCIMF amongst others. Hence a passive (or unpowered active heading control) FPSO relies on the distance the turret is forward of amidships to produce a turning moment to reduce its heading to the environment – even in near co-linear conditions. Four out of four of the panel’s most important issues appear to relate to (or at least are exacerbated by) the FPSO taking hitherto unexpectedly high headings to incoming waves or swell. The heading of an active heading control FPSO has a bifurcated solution for any combination of metocean parameters. It has one set of headings (that might even be close to the optimum achievable) provided the system is a) functional b) can cope with the metocean conditions and c) is used intelligently in the more confused combinations of non-co-linear metocean events. It has a second set of headings if the active heading control system is a) not functioning, b) can’t cope with the metocean conditions or c) isn’t used intelligently or compromised by human error. The second set of headings is likely to be radically more divergent from incoming wave forcing and certainly will produce very different responses to the original active heading design cases. The further aft the turret, the greater the difference between the second and first sets of headings is likely to become.

The panel seems to indicate that many of the potentially unpleasant “design surprises” arising from the introduction of a 10^{-4} accidental metocean response case are likely to come from new high angle of heading cases. The heading step function between “active heading control working” and “active heading control failed” is an important extra variable that needs to be addressed in the multivariate considerations – and this is recognized elsewhere in the report (executive summary, section 3.2, section 3.5 etc). If the potential step function is an important variate; then the factors that might trigger the step and the variability across the fleet can’t logically be dismissed as “not being” of serious concern - especially if they might effect such a high proportion of the UK FPSO fleet is unlikely to have been originally designed for the10^{-4} scenarios.

Yours sincerely,

Michael Taggart

From: López-Cortijo García, Joaquín (PR) [jlcortijo@navantia.es]
Sent: 25 April 2005 16:41
To: Sandy Fyfe
Subject: RE: Final Report on UK HSE's Scoping Study re FPSO survival in extreme weather

Dear Sandy,

I have gone through the Document and find it fairly well focused and comprehensive (it couldn't be otherwise looking at the people in the panel)

I just have two comments:

1) Heading control.- As this is proved to be one of the most critical issues in FPSO survivability, and the experience from operating FPSOs is that active heading control (with adequate redundancy or in self-weather-vaning vessels) helps significantly to improve the operational performance of the vessel (minimise rolling, reduce fish-tailing during offloading, select optimum heading, ...), it seems reasonable to address the use of thrusters in any guidelines related to FPSOs combined with a suitable set of design and operational recommendations based on feedback from Operators

2) Freeboard.- This is another critical issue in FPSO survivability. Besides the use of "state of the art" methodology to assess green water and wave impact phenomena, the HSE could propose a sort of "FPSO Load Line", which would serve as reference (minimum) freeboard to ensure acceptable freeboard exceedance for a given vessel and for a specific geographical area. As generally an FPSO is a "fit for purpose" design, it is relatively easy to design the vessel with a freeboard higher than that normally required, with no impact in cost due to weight increase, ...This leads to "dryer-deck" FPSOs which in turn are safer and provides some additional margin against very low probability events

It is difficult to provide valid comments as the report covers in full all the relevant aspects about FPSO survivability

I appreciate that you have submitted the report. I like these matters

Thanks and best regards

Joaquin López-Cortijo Garcia
Manager of Concept Engineering

NAVANTIA San Fernando/Puerto Real

From: Sam Paulding [spaulding@numast.org]
Sent: 26 April 2005 15:10
To: Sandy Fyfe
Subject: FINAL REPORT ON UK HSE'S SCOPING STUDY RE FPSO SURVIVAL IN EXTREME WEATHER

Dear Mr Fyfe

Thank you for your e-mail dated 12 April 2005 with the attached documentation concerning the UK HSE's Scoping Study re FPSO Survival in Extreme Weather.

I found the documentation interesting and informative. Given the limited time frame for response, my comments and observations are confined to the principle issues raised in the Scoping Study.

The issue of abnormal waves and their reported increased frequency is of concern to NUMAST. The construction of vessels and installations should be designed not only to withstand adverse weather conditions, but also what may be considered abnormal conditions. It remains disappointing that the industry and the nautical press continue to refer to "freak waves" when such incidents occur. The medical profession has long since dispensed with such terminology with respect to medical conditions and refers to "the frequency of a condition". The use of the term "freak wave" implies that it is something so unusual that it is not possible nor desirable to take measures to combat such conditions.

As a consequence of effective monitoring of the seas and oceans by satellite, it is apparent that frequency of abnormal waves is greater than previously expected. Furthermore, as incidents have revealed, they are not confined to the deep ocean and are found to occur in seas adjacent to continental land masses.

NUMAST has concerns at the structural integrity of such vessels, given the competitive nature and incestuous relationship between owner, builder and class. This has resulted in reduced scantlings and reduction of life expectancy in a range of ship types. There is no evidence to suggest it is any different with respect to an FPSO. This is particularly so where an FPSO is converted from an ageing tanker.

While acknowledging the areas of operation for FPSO's and recognising that over 160 vessel-years experience has been accumulated without loss in UK and Norwegian waters, there is no room for complacency. This is particularly so given the potential for greater exposure to abnormal conditions as new areas are developed.

Given the extended life of an FPSO, the report is correct in identifying the design of corrosion protection measures and the fatigue assessment of structural details, backed by well considered through-life inspection and maintenance strategies. However, these will be of little value if the FPSO is inadequate in structural integrity at the outset.

Looking at the list of issues identified in the findings; it is "green water loading" that has the potential to cause catastrophic failure. It is recognised that currently rules of construction are inadequate in taking account of the dynamic forces experienced by "green water loading" on a number of vessel types where less than and abnormal wave types are encountered. Whilst the findings identified in the report should not be neglected, it is this issue that is particularly important.

I note with reference to the minority issues (1) "Performance Standards imposed within FPSO design and inspection are not only inconsistent but also inadequate". NUMAST notes that the panel, before being totally satisfied with the present methods of survivability design, believes some further work is required, particularly with regard to the top four-rated issues. In order to verify this position, it would be entirely appropriate for additional model testing to be used to explore survivability issues. In essence, an FPSO must be fit for purpose and be able to withstand not only adverse weather conditions but abnormal conditions. Whilst damage will not be prevented it is important to avoid catastrophic failure. Whilst recognising the difference between an FPSO and a vessel designed for forward speed, it is important that design methodologists take account of extreme loading in abnormal conditions. For this, as the report suggests, model tests are critical.

If you require any clarification with respect to the above or wish to discuss this matter further, please do not hesitate to contact me.

Yours sincerely

Allan Graveson
Senior National Secretary

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Reply received from S P Kjeldsen, Trondheim Maritime Academy, Norway, 28th April 2005

FINAL REPORT ON FPSO SURVIVAL IN EXTREME WEATHER.

We wish to draw your attention to two new subjects:

1. A design data bank is developed in order to predict wave forces caused by extreme waves on FPSO-ships.

   Data are obtained from wave impact measurements at sea.

   Model tank experiments with an FPSO ship is part of a study that was performed.

   Our data bank is described in the publication presented at the RINA conference in January 2005 ("Measurements of Freak Waves in Norway and Related Ship Accidents" by S P Kjeldsen, RINA International Conference on Design and Operation for Abnormal Conditions III, 26 – 27- January 2005, London, UK, pp31 – 38).

2 Our company, POLARTECH, has, in co-operation with Trondheim Maritime Academy, developed a course for control room personnel working on FPSO ships.

   The course is called "Intact Stability and Damage Stability on FPSO Ships" and is performed for Statoil personnel. It is a simulator training course using a 3-dimensional FPSO-ship model in the computer with all free surfaces in tanks modelled correctly.

   This course covers also government regulations on stability in various countries.

   We will be glad to give you further information on these 2 subjects if you contact us by e-mail.

With best regards

Peter Kjeldsen
Maritime Coordinator.

POLARTECH.
E-mail; Peter.kjeldsen@c2i.net

Comments on FPSO Survivability Scoping Study report, PAFA report C-143-235-R Rev 6 March 2005.

It appears that the report concentrates on green water and bow impact but I would suggest that other failure modes may be more important for survivability.

Green water and bow impact can cause local damage but this is unlikely to result in loss of an FPSO.

1. Loss of survivability scenarios

Two scenarios which may cause complete loss of an FPSO are as follows:
1. FPSO suffers complete loss of integrity of a cargo tank due to overpressure. The global hull integrity is compromised and the hull girder fails.
2. FPSO suffers gross mooring failure, turns beam on to waves and wave loading causes progressive structural damage leading to loss of the vessel.

2. Likelihood of these scenarios

A major loss of FPSO cargo tank integrity due to overpressure has already occurred in UKCS so the likelihood of this scenario cannot be considered negligible.

Single mooring line failures occur intermittently. Complete loss of mooring integrity is not unknown in UKCS. There have been enough other near misses to suggest that the likelihood of complete mooring failure is significant.

A drifting, FPSO will naturally turn beam-on to waves due to the Munk moment hydrodynamic effect. The recent Prestige catastrophe illustrates the fact that tankers are not capable of withstanding wave loads in this condition.

3. Design practice

By inspection, the above scenarios are reasonably foreseeable. In my experience, there is no requirement, nor is it usual design practice to consider the above load cases in FPSO design.

Arthur Stoddart, Director
Atkins Consultants Ltd

Re: Final Report on UK HSE's Scoping Study re FPSO survival in extreme weather

Comments by Carl Trygve Stansberg, MARINTEK, Trondheim, Norway.
Date: 2005-04-29.

The report gives a good description of the current status, and proposes some interesting issues for further work.

Based on our own experience within analysis and model testing on green water and bow slam problems on FPSO's during the recent 5 – 10 years, I have the following remarks.

In addition to what has been described, concluded and suggested for further work, I think that one should address more the governing physical mechanisms, since there are still significant uncertainties and inaccuracies in common analysis methods for the hydrodynamics. Much progress has been made in the physical understanding of non-linear hydrodynamics during the recent years, but there is still good potential for implementing this into industry practice. This also involves the statistical variability and uncertainty, which can be more consistently treated when the physics is better modelled.

One should also address the benefits and challenges in implementing the state-of-the-art knowledge on non-linear random waves into engineering design practice. Thus model tests have shown that much of the green water and bow slam loads observed in steep random waves can, to a large extent, be consistently predicted by use of second-order wave modelling, i.e. increased elevations and kinematics, which is readily available for engineering use today. Reference is made to results from the WaveLand JIP referenced within the report.

Finally, for the future use of floating production units in UK waters, should one also address other vessel types such as platforms etc?

From: Kevin Drake [K_DRAKE@meng.ucl.ac.uk]
Sent: 03 May 2005 12:31
To: Sandy Fyfe
Subject: RE: Final Report on UK HSE's Scoping Study re FPSO survival in extreme weather

Dear Sandy,

Please find my comment on the report below:

“This is a very good report that examines important aspects of design uncertainty for FPSO vessels.

From my own viewpoint, it provides very useful guidance to those engaged in university-based research. It appears to endorse further research into the prediction of nonlinear hydrodynamic loading effects, with particular emphasis being given to wave slam loading.

At UCL, we are involved in an EPSRC-funded project with Oxford University to investigate the nonlinear interaction between steep transient waves and flared bodies using a coupled finite element and boundary element method. This work was motivated partly by an interest in investigating the effects of varying geometry above the waterline, such as in the case of an FPSO vessel with a rounded bow and flare. We hope that in the longer term this research will contribute to the understanding of some of the matters raised in the report.”

With best wishes

Kevin

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