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NEW GUIDANCE ON THE DESIGN OF OFFSHORE STRUCTURES TO RESIST THE EXPLOSION HAZARD

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ABSTRACT

In 1992 Interim Guidance Notes were issued in the UK to provide guidance for the design of offshore topsides for fires and explosions. This Guidance was one consequence of the Piper Alpha Tragedy in the North Sea. Since 1992 a great deal of further research and technology has been developed in order to improve understanding of the characteristics of fires and explosions and the response of the structures and equipment to these events.

In order to collate this new information in a readily useable format, the United Kingdom Offshore Operators Association (UKOOA) and the Health and Safety Executive (HSE) commissioned the MSL Consortium to update the existing Interim Guidance Notes and produce Part 1 of the new Guidance.

The MSL Consortium consisted of the organisations represented by the authors with contributions from WS Atkins (Houston) and Beth Morgan Safety Solutions. The project manager was Minaz Lalani of MSL.

The new Guidance is being developed in three parts. The first two parts deal with the philosophy for the avoidance and mitigation of explosions and fires respectively, which together establish the background for Part 3 which will provide detailed guidance on design practices for fire and explosion engineering.

This paper describes the first document. Specific issues which are discussed include installation risk screening, nominal explosion loads, inherently safer design, hazard management, and the derivation of Design Explosion loads. This paper also describes the recommended method for explosion response assessment given in the Guidance.

INTRODUCTION

In 1992, the Interim Guidance Notes (1) (IGNs) were published as the main deliverable for the £1M Phase 1 of the Joint Industry Project (JIP) on the response of offshore topside structures to fires and explosions.

Since 1992, approximately £40 million has been spent on research and testing resulting in significant technological developments, particularly in the areas of fire and explosion loading.

The application of this substantial additional information, in conjunction with the IGNs, has presented significant difficulties for duty holders, designers and regulators alike, primarily because the significance of the additional research and technology development has not been drawn together in a single usable document.

OBJECTIVES OF THE GUIDANCE

The primary objective of the Guidance is to offer advice on practices and methodologies which can lead to a reduction in risk to life, the environment and the integrity of offshore facilities exposed to the explosion hazard.

Preventative measures are the most effective means of minimising the probability of an event and its associated risk. The concepts of Inherently Safer Design or 'Inherent Safety' are central to the approach described both for modifications of existing structures and new designs.

The Guidance is intended to assist designers, duty holders and regulators during 'Greenfield' designs or 'brownfield' modifications and re-assessments, in order to optimise and prioritise effort and expenditure where it has most safety benefit.

Overview of the Guidance

Part 1 of the Guidance (2,3),'Guidance on Design and Operational Considerations for the Avoidance and Mitigation of Explosions', has recently been issued and is available from www.fireandblast.com. Part 1 has covered the following subject areas:-

Explosion Hazard Philosophy – this sets out the fundamental principles, goals and approaches including the risk classification of compartments and installations in order to focus design effort where it is most needed and to give an early indication of the severity of the hazard. The derivation of Nominal Explosion loads is discussed. These Nominal loads are for use at an early project phase or for low risk installations.

Explosion Hazard Management – describes how the philosophy is implemented and discusses the principles of inherently safer design; prevention, detection, control and mitigation; scenario definition; the management and choice of systems and risk acceptance criteria. One particular aspect is the classification of safety critical elements, again to focus effort where it is most required.

Determination of explosion loads – describes how explosion loads are derived; the advantages and limitations of the various methods and the determination of Design Explosion loads which can and should be designed against. Loads on equipment and piping are also discussed.

The worse credible case of a stoichiometric cloud engulfing the whole installation or filling an entire compartment will frequently give rise to loads which cannot be designed against. Design explosion loads are selected on the basis of their frequency of occurrence and should be accommodated by the safety critical elements (SCEs) of the installation which will include parts of the structure as well as equipment and pipework.

A Safety critical element is defined as any structure, plant, equipment, system (including computer software) or component part whose failure could cause or contribute substantially to a major accident, including any element which is intended to prevent or limit the effect of a major accident.

Response to explosions – discusses the general principles of explosion response calculation including the consideration of robustness, ductility, displacement and strength demands on the structure. Simplified methods are discussed and assessment methods based on the strength level blast (SLB) and ductility level blast (DLB) load cases are described. The SLB and DLB load cases are discussed under load cases for explosion response.

Outline guidance on detailed design is given, in particular for existing 'brownfield' developments. Reference is made to existing codes and terminology in current use.

The interaction between fire and explosion hazard management is also examined.

Reducing risks to ALARP must be demonstrated in all cases: both through the justification of the choice of design load and from a determination of the impairment frequency of the Safety Critical Elements subjected to these loads.

The first part of the Guidance consists of two documents, the 'Main Guidance' which summarises the main points of the 'Commentary'. These documents are based on ten 'Basis documents' produced by the MSL Consortium and prepared by the authors of this paper. Part 1 of the Guidance was assembled from the background documents in a similar way to that used for the generation of the IGNs.

The Guidance distils the experience gained during the period since the Interim Guidance Notes were prepared. This has allowed simplifications to be made and a more clearly defined approach to be adopted in some circumstances, without compromising safety.

The major topics identified above are discussed in this paper.

EXPLOSION HAZARD PHILOSOPHY

The underlying philosophy to any guidance related to fires and explosions is always to protect personnel both during and after the event as much as possible, to protect the environment and to minimise damage to the asset. The goals of the explosion hazard philosophy can be summarised as being:-

- To reduce risk from explosions to As Low As Reasonably Practicable (ALARP)
- To identify areas where explosions might occur;
- To, so far as is reasonably practicable, eliminate the potential for explosions to occur, or if not, to minimise the severity and consequences of the event and to minimize the exposure of personnel to the consequences of the event.

Installation/compartment risk screening

The higher the *risk* (frequency x consequence) in an installation or compartment the greater should be the rigor that is employed to understand and reduce that risk.

In order to focus effort where it is most needed, a risk screening method is described in the Guidance, which classifies installations and compartments according to their risk level. The measures for frequency and consequence severity are based on process complexity and the exposure potential for people on board. These measures are combined in a risk matrix to give low, medium and high risk categories. The risk level is an indication of the level of sophistication to be used in the explosion assessment process.

A simple approach which is frequently adopted for qualitative risk analysis uses a 3 x 3 matrix of potential consequence versus frequency or likelihood of an explosion event as indicated in the risk matrix given below.

		Consequence		
		Low	**Medium**	**High**
Frequency / Likelihood	**High**	Medium Risk	High Risk	High Risk
	Medium	Low Risk	Medium Risk	High Risk
	Low	Low Risk	Low Risk	Medium Risk

A number of explosion scenarios on various installations have now been assessed using the techniques described in the Guidance. However, it became evident that the sample data base required a wider spread of data and more detail to assist in the generation of credible nominal explosion loads. This has provided the information required for the definition of further work discussed at the end of this paper.

It was an intention of the Guidance to gather and prepare preliminary explosion data that could be used in the determination of 'nominal explosion loads' for use in the early quantification of explosion hazards for new offshore facilities. It is now hoped that these 'nominal explosion load' values will be available for inclusion in Part 3 of the Guidance. Nonetheless methods of deriving useable nominal explosion loads are discussed in the Commentary.

The intended use of nominal explosion loads is to minimise unexpected escalation of design overpressures at a late project phase when an optimum ALARP solution may not be possible and to aid in concept choice at an early project phase.

Nominal explosion loads must not be confused with default minimum values such as those given in DnV A101 (4).

High level performance standards

Performance standards for SCEs have been categorised as either high level (scenario based) or low level (element or system based). Typical high level performance standards are given below:

In an explosion event, at least one escape route must be available after the event for all survivors. For a manned platform, a Temporary Refuge (TR) or Safe Mustering Area must be available to protect those not in the immediate vicinity of an explosion These elements must survive the event and subsequent escalation events without loss of integrity.

For the ductility level blast (DLB), the primary structure should not collapse and evacuation should be possible from safe areas after the event. SCEs should have fulfilled their function before the explosion, or remain operational after the event if required for recovery from the event.

Plastic deformation of the structure is acceptable provided collapse does not occur and barriers remain in-place and are able to adequately resist any subsequent fires. The ability of the structure to satisfy these requirements will depend on its ability to respond in a ductile manner and the ability of the barrier connection details to respond without rupture

The frequency with which accidental events, from all causes, will result in loss of TR integrity within the required endurance time will not exceed 10^{-3} per year from all causes (5). The required endurance time is the estimated time for people to travel from their work stations to the TR, to muster and assess the situation and then if necessary to proceed to the primary and secondary means of evacuation, allowing for the possibility of helping injured colleagues.

EXPLOSION HAZARD MANAGEMENT

Hazard Management provides the engineer with the means of managing the various factors which contribute towards;

- the probability of explosion occurring;
- the overpressure experienced once the explosion has occurred;
- the control and mitigation of consequences of the explosion.

Chapter 2 of the Guidance Commentary deals with two main topics.

- The project management system and how getting that right forms the basis of managing the explosion hazard.
- The management of the explosion hazard itself and how an installation may be designed to reduce risk from explosions to as low as reasonably practicable (ALARP).

Inherently safer design

Risk which cannot be eliminated by the application of inherent safety methods may be referred to as residual risk. Inherent safety methods should be applied to the management of the risk by consideration of the general principles indicated below:

ELIMINATION is better than
MITIGATION is better than
CONTROL is better than
EMERGENCY RESPONSE.

As regards systems to reduce risk
PASSIVE systems are more reliable than
ACTIVE systems are more reliable than
OPERATIONAL systems are more dependable than
EXTERNAL systems

This indicates:-

- The use of passive rather than active control and mitigation systems
- No reliance on personnel to prevent, control or mitigate hazards

Element specific performance standards

In addition to the high level performance standards, it is necessary to define measurable performance standards for specific key items or systems relating to the systems' functionality, availability and survivability. These are referred to in the Guidance as element specific performance standards which are used in the evaluation stage of an explosion assessment. These are sometimes referred to as low level or element specific performance standards.

Criticality categories for SCEs (6,7)

It is helpful to consider a hierarchical approach to the identification of SCEs. It is suggested that the number of SCEs (systems, equipment or functions) requiring detailed assessment are classified into three levels of criticality with respect to the explosion hazard..

Criticality 1 Items whose failure would lead to direct impairment of the TR or evacuation escape and rescue (EER) systems including the associated supporting structure.

Performance standard – These items must not fail during the DLB or SLB. Ductile response of the support structure is allowed during the DLB.

Criticality 2 Items whose failure could lead to major hydrocarbon release and escalation affecting more than one module or compartment. (Indirect impact on the TR is possible through subsequent fire).

Performance standard – These items must have no functional significance in an explosion event and these items and their supports must respond elastically under the strength level blast (SLB).

In this context the term 'functional significance' should be taken to imply that such elements are not directly involved in control or mitigation during the explosion event and are not required after the event to limit its severity.

Criticality 3 Items whose failure in an explosion may result in module wide escalation, with potential for inventories outside the module contributing to a fire due to blowdown and or pipework damage.

Performance standard – These items have no functional significance in an explosion event and must not become or generate projectiles.

Following this approach, those elements which have the highest criticality rating towards ensuring the achievement of the overall hazard management objectives, should be identified and should receive the most attention.

DERIVATION OF EXPLOSION LOADS

Available tools for explosion assessment

Consequence assessment

There are a number explosion assessment tools available for the assessment of the severity of the explosion hazard, these are listed below in order of increasing sophistication:-

1. Installation risk screening – here the general level of vulnerability to explosion events is estimated using a risk matrix, as described in a previous section. This is not scenario specific – it will only give a general view of the severity and likelihood of explosion events.

2. Comparison with recent design situations – the use of past experience and nominal explosion loads if they can be justified. There are difficulties with the justification of the use of 'similar cases' resulting from the sensitivity of the explosion phenomenon to initial and environmental conditions. Advances in the science of explosion load determination may invalidate previous analyses.

3. Simple or empirical models – these are correlations with experimental data and relate to specific scenarios and geometries. Extrapolation to different situations will depend on the extent of the data on which the methods are based.

4. Phenomenological models – these model the underlying physical processes in a simplified manner and enable some extrapolation to situations not available from experiments. Generally they will give some measure of the general level of loading within the explosion zone, detailed information on local overpressure and dynamic pressure behaviour will not always be generated.

5. Computational fluid dynamics (CFD) models – these models have a more detailed representation of the underlying physics of the explosion process than phenomenological models, solving the equations of mass conservation, momentum and sub models for turbulence generation and turbulent combustion. These models have the highest potential for modelling new situations including the dispersion of the gas cloud. The main limitation of their use is the relatively long execution time and the degree of detail required for the simulations.

The first three approaches may be useful at an early stage when geometry details are not available. They will not, however, yield detailed overpressure or dynamic pressure information for use in component design or the assessment of SCE response.

Frequency assessment

The frequency of a particular explosion scenario is an equally important aspect for the determination of risk defined as the product of probability and consequence or severity. This frequency of explosion loads of a particular intensity will depend on:-

1. The release frequency for a particular release site which should be available from published sources based on past experience (8,9,10) . The release direction, released material and rate of release will also affect the severity of the event.

2. The availability of detection, control and mitigation measures such as blow down, deluge and inventory isolation measures.

3. The dispersion characteristics determined by the detailed geometry, ventilation conditions including wind speed and direction. Environmental conditions and frequencies should be available for the location.

4. The probability of ignition determined by the ignition source location, timing and duration and its position relative to the flammable regions of the gas cloud.

5. The probability of failure of physical barriers such as blast walls and other pieces of safety critical equipment will depend on the response of these items to overpressure or dynamic pressure loads.

Load cases for explosion response

Two levels of explosion loading are recommended for medium and high risk installations by analogy with earthquake assessment. These are the ductility level blast (DLB) and the strength level blast (SLB). Low risk installations may be assessed using only the DLB (or in some cases only the SLB if it can be justified), as the overpressures are likely to be low.

The risk levels and frequencies may not be the same as for earthquake analysis. This reflects the fact that an explosion is perceived as a preventable event.

The ductility level blast is the overpressure used to represent the extreme design event. This is a high consequence event important for the establishment of survivability. SCEs of criticality 1 will also be assessed for their resistance to this level of load.

The strength level blast represents a more frequent design event where it is required that the structure does not deform plastically and that the SCEs of criticality 1 and 2 remain operational. This load case is suggested for the following reasons:-

- An SLB event may give rise to an unexpected DLB by escalation..
- The prediction of equipment and piping response in the elastic regime is much better understood than the conditions which give rise to rupture. The SLB enables these checks to be made at a lower load level often resulting in good performance at the higher level (strength in depth) and robustness.
- The SLB enables the classification of SCEs and a focussing of effort on the assessment of those most critical with respect to the explosion hazard.
- The SLB offers a degree of asset protection.
- The SLB is a low consequence event important for the establishment of operability.

The SLB may consist of a number of scenarios of equivalent severity. These scenarios will contain within them the variability of the load within the explosion region and should include details of the dynamic pressure loads on equipment which will be at a different level from the representative overpressure.

Determination of explosion Design loads

Overpressure acts directly on loaded surfaces. This may be developed for each scenario using the predictive tools described earlier.

The accepted level above which the overall risk is considered intolerable relates to an individual risk of greater than 10^{-3} per year or a TR impairment frequency of greater than 10^{-3} per year from all causes. The overall individual risk from all hazards must be less than this value. If risks are in the intolerable region then risk reduction measures must be implemented, irrespective of cost. Hence the risk from other hazards may indirectly affect the acceptability of risk from explosions and these may need to be considered in setting the target risk levels for the explosion hazard.

A single event frequency of exceedance between 10^{-4} and 10^{-5} per year is considered a reasonable frequency for the ductility level design event or DLB, by analogy with the treatment of environmental and ship impact loads which are often considered at the 10^{-5} level. In order to determine the DLB, an exceedance curve must be constructed which represents the frequency of exceedance of a given space averaged peak overpressure. This curve will enable the DLB overpressure case to be identified. If the event impinges directly on the TR, escape routes or means of escape, then the target level should be the 10^{-5} level. If the event impinges on one or more barriers before impinging on these SCEs then it may be argued that the 10^{-4} level is more appropriate.

It should be emphasized that duty holders must set their own targets based on the risk to personnel on the installation, and considered within the ALARP framework. This framework requires duty holders to always seek to reduce risks, and only to argue against implementation of a measure if it is not reasonably practicable.

The space averaged peak overpressure for the compartment is used for determination of the design explosion load cases as it is more representative of the severity of the event. A local overpressure peak may be used to generate exceedance curves for the determination of load cases for the local design of a blast wall for instance. Impulse exceedance curves may also be generated which take into account the duration of the load and its peak value; these give a better measure of the expected response of the target which will be dynamic in nature.

The SLB may then be identified from a space averaged peak overpressure exceedance curve, as that overpressure corresponding to a frequency one order of magnitude more frequent or with a magnitude of one third of the DLB overpressure whichever is the greater.

The requirement for the SLB to be **at least** 1/3 of the DLB is to guard against cases where the DLB is relatively low and the SLB derived using the frequency argument is so low that it can no longer be considered a useful or relevant design case.

If it is desired that the SLB will also size or dimension the primary and secondary structure to resist the ductility level blast (DLB) using the elastic limit as a performance standard, then the 1/3 factor may require justification. The determination of the 'dimensioning explosion load' is discussed in some recent References for example reference 11.

The Guidance suggests the use of modified code checks for the sizing of primary members, using an elastic analysis and the DLB. This represents the geometry and post yield response characteristics better than the definition of an equivalent 'dimensioning' load level intended for application in a linear elastic analysis.

Loads on equipment items

The explosion loads on equipment items and pipework (6,7,12) are referred to as dynamic pressure loads.

- Drag loads (similar to the Morison drag loads experienced in fluid flow) proportional to the square of the gas velocity, its density and the area presented to the flow by the obstacle.
- Inertia loads proportional to the gas acceleration and the volume of the obstacle.
- Pressure difference loads.
- Loads generated by differential movement of the supports.

Dynamic pressure loads may be determined directly from CFD explosion simulations or calculated indirectly from gas velocities and pressure time histories.

Drag loads dominate for obstacles with dimensions less than 0.3m or on cylindrical obstacles less than 0.3m in diameter and, in particular, in regions of high gas velocity near vents. Pressure difference loads become important for obstacles with dimensions greater than 0.3m where they must be added to the drag loads.

Care must be taken in interpreting the results of CFD simulations as the cell size/obstacle size ratio may make it difficult to obtain accurate pressure and flow information at points near the obstacle.

Equipment items in the interior of a compartment away from the vents will generally experience loads composed mostly of inertia loads due to gas accelerations. It is likely that these loads will, however, be lower than the drag and pressure difference loads experienced by items in the vent paths.

Exceedance curves for local dynamic pressures may be developed from simulations and used in the same way as for overpressures in deriving design dynamic overpressures for the DLB and SLB load cases. It is recommended that the DLB dynamic pressures are applied to SCEs of criticality 1 and that the SLB overpressures are applied to SCEs of criticality 1 and 2 with the requirement for elastic response of the supports and that the SCEs remain functional.

A number of explosion loading experts have suggested that a suitable load level for the representation of dynamic pressure loads is 1/3 of the smoothed peak overpressure local to the equipment item. The duration of the load should be chosen to match the impulse of the overpressure trace. This load must also be applied in the reverse direction. In open areas, such as the decks of FPSOs, these loads should also be applied in the vertical plane.

In general, equipment items should be located to minimise obstruction of vents and be in-line with the predominant flow direction. Where practicable, piping runs should be located behind structural elements if near vent areas. Supports and equipment items should be made as resistant to explosion loads as is reasonably practicable. Often the differential movement of supports will be the determining consideration.

RESPONSE TO EXPLOSIONS

The aims of blast resistant design of topside structures and plant expressed in terms of high level performance standards and expressed in terms of the criticality levels above, place a considerable demand on the structural response of items such as blast walls, decking and the primary structure. Designing structures for such extreme events requires the consideration of many issues commonly faced in the design of structures to resist earthquake loads where attention to detail, ductility and providing continuity are important considerations.

In order to achieve an efficient design such that it meets the desired aims, the concept of structural robustness must be emphasised. The term robustness used in a structural engineering sense ensures that the structure can withstand loads that go beyond the intended design load by being able to absorb some of the energy of the blast, normally by deflecting and allowing plastic deformation in regions detailed for high energy absorption.

This will normally mean that the structure is able to redistribute load to other less stressed regions requiring redundancy of the structural arrangement.

Key to the issue of robustness is the detailing of connections between the various components, which are likely to experience significantly different loading conditions from the service condition for which they have been designed. The response may involve large rotations, reversal of rotations, high shear forces and, if membrane action develops, large tensile forces.

Possible failure modes should also be identified in order to prevent brittle failure modes from occurring such as global buckling modes involving a large portion of the structure.

Design and assessment strategy

The structural assessment process which is recommended in the Guidance is a two stage process and is analogous to the requirements in ISO 19901-2, “specific requirements for offshore structures – part 2: seismic design procedures and criteria”. This recommends assessment of a strength level and a ductility level earthquake. This has been successfully applied to earthquake resistant design of steel frame structures for many years.

At the SLB load level selected elements are required to remain elastic such that codes of practice based on static design which have been used for the design of the primary structure can be used. It is permissible at this stage to relax certain safety factors such as the use of typical coupon strength values as opposed to the design strengths for the steel strength and some enhancement at the yield stress due to strain rate effects. It is also important to note that this has limitations, namely

- Buckling checks in static codes may be invalidated
- Enhanced reactions at connections may occur
- Membrane forces may not be accounted for in code checks

Of particular significance are the increased reactions at the connections as the elastic range has effectively been extended by the use of an enhanced yield strength.

At the DLB load level, permanent deformations due to yielding are acceptable and sometimes desirable as a means of dissipating energy and achieving an economic design. However the resulting damage should be such that progressive collapse and loss of platform does not occur.

Clearly in some areas deflection limits will need to be specified to avoid compromising the supports of vital equipment or pipework. The resulting damage mode should be controlled in such a way that the damage areas are detailed for high energy absorption. These areas are likely to be the blastwalls and the decks. The primary structure and safety critical elements required for survivability may be required to remain predominantly elastic in the overall failure mode. This applies particularly to the primary structure as it is likely to be very stiff and subjected to large service loading. Again the connections details which are almost certainly to be the weak link in the system need to be designed for high rotations and to provide continuity.

The overall philosophy behind the two stage process is that initial design can be carried out at the SLB level but robustness must be incorporated at an early stage such that the structure survives the assessment at the DLB.

CONCLUSIONS

1. This paper gives an overview of Part 1 of the new Guidance on fires and explosions.

2. Explosion risk screening methods and the use of nominal explosion loads are discussed.

3. This paper describes the preferred approach to the derivation of explosion loads given in the Guidance, including loads on equipment and piping items.

4. Two levels of load are recommended for explosion assessment, the ductility level blast (DLB) and the Strength level blast (SLB). The SLB is defined in terms of the frequency of exceedance relative to the DLB. A minimum value of DLB/3 is suggested for the case where the SLB determined on entirely frequency arguments would be so small as to be an inappropriate load case.

5. **If** it is desired that the SLB represents an equivalent load level to the DLB through more stringent requirements on the response, then further justification of the value of the ratio between the SLB and DLB load levels will need to be made. Recommendations on this issue will be included in Part 3 of the Guidance.
6. Barriers and their connections should be checked against the full DLB level of loading.

7. Criticality categories are given for safety critical elements in order to focus attention and effort on those elements which have the highest criticality in the achievement of the hazard management objectives.

8. The concept of robustness is discussed in the context of explosion response.

The views of the authors do not necessarily reflect the position of their employers or the sponsors of the Guidance. Anyone making use of this document assumes all liability arising from such use.

FURTHER WORK

Following the completion of the Part 1 Guidance, and as a result of the increased understanding of remaining issues, a joint industry project entitled, ‘Generation of nominal explosion loads’ is currently being developed by MSL Engineering and other organizations. As a first step, it is proposed that a suitable data set should be developed which:-

- Gives an indication of the general level of severity of the explosion loads over the affected area. One suggested definition of such a measure is the average of the highest 20% of simulated (or measured and smoothed) overpressure peaks.
- Gives an indication of the variability of the overpressure peaks throughout a compartment or installation. Ranges and confidence limits should be included.
- Gives an indication of the form of the overpressure traces (duration and impulse)
- Details loads on safety critical elements including equipment and piping (pressure difference and dynamic pressure loads).
- Is based on scenarios which represent the DLB for the ductility level event occurring at the appropriate frequency of exceedance level.

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