Guidelines for the safe design and operation of shell and tube heat exchangers to withstand the impact of tube failure

2nd edition

energy institute

GUIDELINES FOR THE SAFE DESIGN AND OPERATION OF SHELL AND TUBE HEAT EXCHANGERS TO WITHSTAND THE IMPACT OF TUBE FAILURE

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FOREWORD

This, the second edition of the *Guidelines for the safe design and operation of shell and tube heat exchangers to withstand the impact of tube failure* contains major additions to the first edition. Both first and second editions have been the result of joint industry projects (JIPs) managed by the Energy Institute (EI) and the former Institute of Petroleum (IP).

With shell and tube heat exchangers (STHEs) there is concern about the potential consequences of a tube failure allowing high pressure (HP) fluid on one side to enter the low pressure (LP) fluid on the other side. In the 1990s, with growing computer power and computer programming, some companies were using dynamic simulation to test the consequences of tube rupture to provide input to the design of the overpressure protection system. The IP formed a task group from which the first JIP was set up to commission full scale experiments of tube ruptures within a heat exchanger. The experiments investigated the pressures experienced by the heat exchanger, to which the accuracy of the simulations was compared.

One conclusion from the first JIP was that the relief device opening time was critical for the exchanger protection. At the time, only rupture discs had been reported to have fast opening times. As a consequence many heat exchangers were protected against sudden tube rupture using rupture discs. However, there have been a number of incidents in industry involving failure of these rupture discs on heat exchangers that would not have been as serious if other devices, especially reseating pressure relief valves (PRVs), had been used instead.

Consequently, the second JIP was set up to provide additional guidance and to perform additional experiments to investigate the opening times of pressure relief and pin valves of the typical sizes required to protect a heat exchanger. The second JIP included:

- Experiments with a larger shock tube and larger spring loaded safety valves than had been tested before, as well as tests with a pin valve.
- Simulation of the tests performed to gain extra detail and information from the measured results.
- A hazard and operability study (HAZOP) and hazard identification (HAZID) of typical STHE installations.
- Development of guidance on tube vibration failure modes and calculation of vibration potential.
- Simulations of heat exchanger tube rupture to compare the importance of different design parameters on the overpressures experienced.
- A survey of operators' experience with safety devices for overpressure protection of STHEs.
- A literature search to gather information on additional heat exchanger incidents and failure rate data.
- Using the results of the experiments and simulations to produce additional guidance on the selection of overpressure protection device types and operating setpoint specification.
- Using the HAZOP, HAZID and incidents to produce guidance on the design of pipework and instrumentation.

The output from the second JIP has led to these updated guidelines which, in particular, include:

- Flow charts for the process and decisions for:
  - overall design steps;
  - relief system design;
  - relief device selection;
  - decisions on instrumentation, and
  - reassessment of existing heat exchangers.
- Lists and outlines of past incidents involving failures with heat exchangers which can be considered to mitigate against repeat incidents.
- Further reliability statistics to aid quantitative risk assessments (QRAs).
- Relative impacts of changes to design parameters of a heat exchanger.
- Basis for analysing tube vibration.
- An equation to provide an initial estimate of the step increase in pressure following a tube rupture from which first approximation of the design pressure for the LP side can be chosen.
- Guidance on the issues to consider when designing the pipework connected to the heat exchanger.
- Discussion of the types of relief device available to protect the heat exchanger from overpressure and guidance for the selection of the relief device.
- Guidance on the location of the relief device relative to the heat exchanger and the flare header.
- Guidance for the specification of the set pressure of the relief device, taking into account manufacturing tolerance.
- Guidance on the software requirements and values to use when performing dynamic simulation of a tube rupture.
- Discussion on slug loads in the relief pipework as a result of opening of a relief device.
- Guidance on the selection of instrumentation for the heat exchanger to detect tube failure and to detect operation of the relief device.

Warning: It should be noted that if STHEs and associated relief systems are not designed correctly and a failure occurs then the result could be serious damage to the exchanger and/or its associated piping with potential consequential damage and/or injury.

The information contained in this publication is for guidance only, and while every reasonable care has been taken to ensure the accuracy of its contents, the EI, and its technical committees, cannot accept any responsibility for any actions taken, or not taken, on the basis of this information. The EI shall not be liable to any person for any loss or damage that may arise from the use of any of the information contained in any of its publications.

ACKNOWLEDGEMENTS

The main deliverable of the first JIP was *Guidelines for the design and safe operation of shell and tube heat exchangers to withstand the impact of tube failure* (1^{st} edition).

This revised publication has been produced primarily as a result of work carried in the 'Bursting disks for shell and tube heat exchanger overpressure protection joint industry project (JIP)', referred to herein as the second JIP. The JIP used some £250 000 of funding provided by the following sponsors and participants, and work- and equipment-in-kind provided by other participants:

- Sponsors:
  - BG International Ltd
  - BP Exploration Operating Company Ltd
  - ConocoPhillips (UK) Ltd
  - Energy Institute
  - Nexen Petroleum UK Ltd
  - Total E&P UK Ltd
- Participants:
  - ABB Consulting
  - Genesis Oil and Gas Consultants Ltd
  - Petrofac Engineering Ltd
- Work- and equipment-in-kind participants:
  - Anderson Greenwood Crosby – Pentair
  - BS&B Safety Systems (UK) Ltd
  - GE Oil & Gas
  - Health and Safety Executive/Health and Safety Laboratory
  - Heat Transfer Research, Inc.
  - Hydraulic Analysis Ltd

The second JIP was directed by a Steering Committee, which comprised the following representatives from May 2012 through to publication of these Guidelines:

Glyn Addicott	Hydraulic Analysis Ltd
John Blitz	BS&B Safety Systems (UK) Ltd
Jean-Paul Boyer	Anderson Greenwood Crosby – Pentair
Michael Cloete	ConocoPhillips (UK) Ltd
Steve Coates	Petrofac Engineering Ltd
Tim Davies	BG International Ltd
Colin Deddis (Chair)	Independent
Philip Eost	BP Exploration Operating Company Ltd
David Evans	Heat Transfer Research, Inc.
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Dermot Grumley	Hydraulic Analysis Ltd
Sarah Harrison	ABB Consulting

Matt Hastings	Total E&P UK Ltd
Tariq Hussain	BG International Ltd
John Leonard	Total E&P UK Ltd
Tom Lestina	Heat Transfer Research, Inc.
Jim MacRae	Nexen Petroleum UK Ltd
Barrie Marsden	Petrofac Engineering Ltd
Dr Stephen Murray	Health and Safety Executive
Dr Mike Orley	Health and Safety Executive
Tom Rafferty	Nexen Petroleum UK Ltd
Dave Ransome	BG International Ltd
Karen Robertson	Total E&P UK Ltd
Dr Mark Scanlon (Secretary)	EI
Marcus Shepherd	Hydraulic Analysis Ltd
Colin Weil (Project Coordinator)	Consultant
Ian Wyatt	Atkins

The EI acknowledges their contribution to working collaboratively to ensure success of the JIP; in particular for ensuring the credibility of the deliverables by engaging in technical reviews of drafts. The listing refers to representatives' last affiliation whilst participating in the second JIP.
Other sponsor and participant representatives are acknowledged for engaging in the JIP, for example in the HAZID workshop of typical STHE installations.

Development of these revised guidelines, the main deliverable of the second JIP, was informed by interim deliverables from several work packages. On behalf of the Steering Committee, the EI commissioned the following technical service contractors to execute these work packages:

Work package	**Technical service contractor**	**Interim deliverable**
Relief device selection		
RD1 and RD2	The University of Sheffield (Dr Bruce Ewan)	Final report on RD1 and RD2 work packages University of Sheffield
RD3	The University of Sheffield (Dr Bruce Ewan) and Atkins (Ian Wyatt)	Report on RD3 work package University of Sheffield
Heat exchanger design		
HE1.3	Heat Transfer Research, Inc. (Tom Lestina)	Mitigating tube vibration in heat exchangers
HE2.1 and HE3	Hydraulic Analysis Ltd. (Glyn Addicott, Marcus Shepherd)	Model calibration against the University of Sheffield shock tube results
HE2.1 and HE3	Hydraulic Analysis Ltd. (Glyn Addicott, Marcus Shepherd)	Unrelieved STHE tube rupture simulation results
HE2.1 and HE3	Hydraulic Analysis Ltd. (Glyn Addicott, Marcus Shepherd)	Report: Past project simulation results

Work package	Technical Service Contractor	Interim deliverable
HE2.1 and HE3	Hydraulic Analysis Ltd. (Glyn Addicott, Marcus Shepherd)	STHE tube rupture simulation results with spring relief valves (RVs) installed
HE2.1 and HE3	Hydraulic Analysis Ltd. (Glyn Addicott, Marcus Shepherd)	STHE tube rupture simulation results with pin valve installed
Design guidelines		
DG2 and DG3	Genesis Oil and Gas Consultants Ltd. (James Adamson, Colin Deddis)	Guidance on relief device selection criteria for tube rupture and relief device set-point selection criteria
DG4 and DG8	Atkins (Gillian Dickson, Peter Henderson, Graham Maclean, Ian Wyatt)	Design criteria for overpressure protection of piping and flanges connected to heat exchangers
DG5	Health and Safety Laboratory (Matt Clay, Dr John Hare)	HAZID studies
DG5	Health and Safety Laboratory (Dr John Hare)	UK legislation and guidance
DG5.1	Atkins (Gillian Dickson, Peter Henderson, Graham Maclean, Ian Wyatt)	DG5 Disposal system design guidelines
Design guidelines		
DG5.2	Atkins (Gillian Dickson)	STHE/relief device interface design guidelines
DG6	Health and Safety Laboratory (Dr John Hare)	STHE failure rate data
DG6	Health and Safety Laboratory (Dr John Hare)	STHE summary of incidents (anonymised)
DG6	Atkins (Ian Wyatt)	Operator experience questionnaire
DG7	ABB Consulting (Sarah Harrison, Laza Krstin, Stanley Rowling)	Instrumentation requirements for detection of tube rupture and bursting disk rupture
TA1	Atkins (Ian Wyatt)	(This publication – the main deliverable)
PM1	Colin Weil (Consultant)	(This publication – the main deliverable)

Key to work packages

DG = Design guidelines

HE = Heat exchanger design

PM = Project Manager

RD = Relief device selection

TA = Technical author

That listing also includes the titles of the various interim deliverables arising from those work packages: these are only available to JIP sponsors, participants (and their affiliates, co-venturers and successor organisations) and technical service contractors.

In addition, JIP sponsors, participants (and their affiliates, co-venturers and successor organisations) and technical service contractors also have access to 'Report to The Institute of Petroleum on the *Development of design guidelines for protection against over-pressures in high pressure heat exchangers: phase one*', Trident Consultants Ltd. and Foster Wheeler Energy, Report J2572 known as *The Trident report* June 1993.

The following are acknowledged for providing permission to reproduce information:

- BS&B Safety Systems (UK) Ltd.
- HSL (from Internal report PS/99/01 and Report No. FS/98/17).

1 INTRODUCTION

1.1 BACKGROUND

The process industries frequently require to heat or cool HP gas. The most common method used has been in STHEs. The LP side of the exchanger, which contains a utility fluid such as sea water, is therefore at risk in the event of any leakage from the HP side of the exchanger. Such exchangers may have greatly differing operating pressures between the two fluids and the designer has to consider several variables when choosing the optimum exchanger type, selecting suitable materials, which fluid should be within the tubes and the design pressure and temperature for each side of the exchanger. It has become common practice for the LP side to be designed to withstand a pressure just above the operating or flow lock-in pressure of the utility fluid, but well below the HP side's operating pressure. There is a risk that tube failure could lead to failure of the LP pressure envelope and the release of large quantities of flammable gas. The LP side, therefore, should be protected against tube failure by fitting relief devices such as rupture discs, pin valves or safety relief valves (RVs). The adequacy of the methodology used to design the LP side to withstand the sudden release of HP gas through tube rupture was not proven before the work performed for the first edition of these guidelines. The consequences of such a failure can range from (at the worst) catastrophic rupture of the LP side with considerable financial loss and risk to personnel, to satisfactory release through the overpressure protection system.

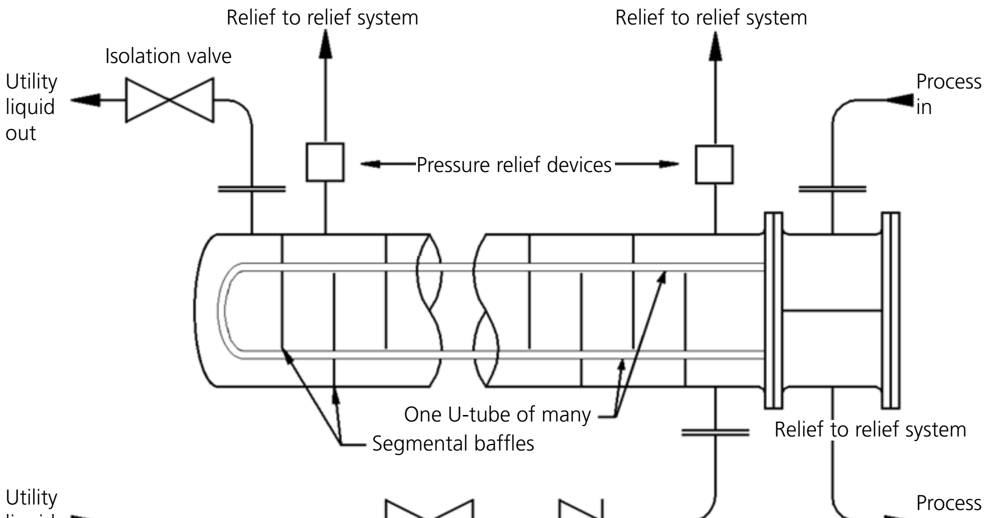

Figure 1: Typical HP/LP STHE (Tubular Exchanger Manufacturers Association (TEMA) type AEU)

The guidance in these guidelines is primarily for a heat exchanger where the HP gas is in the tubes and the LP heating/cooling medium is in the shell. A typical HP/LP STHE configuration is shown in Figure 1.

1.2 SCOPE OF GUIDELINES

Although these guidelines are based on experiments and other studies where the HP fluid is in the tubes, they are also suitable to form a basic approach for the alternate geometry where the HP fluid is contained within the shell.

Typically, in the designs relevant to these guidelines, the LP side fluid (usually a utility), operates at low pressures <15 barg, whilst the gas in the tubes may be at pressures ranging from several times the utility pressure to orders of magnitude higher.

There are four main scenarios that could generate pressure above the normal operating pressures within the utility side of the exchanger. These are thermal expansion, external fire, tube failure or flow lock-in. However, the designer should identify all credible causes of overpressure. These guidelines have been written to clarify the process industry's approach to designing for the tube failure scenario (which for HP services will usually be the most onerous). They provide good practice for the engineers faced with decisions on the safe design and operation of heat exchangers.

The experiments and studies upon which the guidelines are based were limited to applications of HP single phase gas discharging into LP single phase liquids. Hence, they may not be fully applicable to situations where multiple phases are present on either the tube or shell side prior to a tube failure, or where phase changes occur during a tube failure event e.g. flashing of the LP liquid phase.

The scope of the guidelines includes:

- heat exchanger including tubes and baffles;
- inlet heating/cooling medium pipe;
- exit heating/cooling medium pipe;
- relief devices;
- interface between the exchanger and relief devices;
- relief device tail pipes and impact on downstream disposal, and
- instrumentation for tube failure events and relief system operation.

1.3 APPLICATION

These guidelines are intended for process, mechanical and instrumentation engineers to use when designing systems incorporating STHEs, when reviewing systems designed prior to publication of these guidelines, or when the process conditions are to be changed that could invalidate assumptions made in the system design.

This publication is based primarily on the UK and European legislative framework, but also international publications (codes of practice, design standards, specifications, guidance, etc.) and good practice. However, its guidance is universally applicable provided it is read, interpreted and applied in conjunction with relevant national and local statutory legislation and publications. Where the requirements differ, the more stringent should be adopted.

This publication adopts the notation of a comma for decimal mark (e.g. 4,2 mm) and a space as separator for thousands (e.g. 2 000). Also, it largely aligns to relief device terminology defined in API Std. 520 Part 1, except where there is uncertainty in what type of relief device is under consideration (e.g. in old reports).

These guidelines provide additional guidance and information for the safe design and operation of STHEs, supplementing the design methodologies provided in various design publications (e.g. standards (Stds), codes, etc.) such as:

- API Std 521: *Pressure-relieving and depressuring systems*
- API Std 660: *Shell-and-tube heat exchangers*
- ASME Section VIII Division 1 and 2: *ASME boiler and pressure vessel code*
- EN 13445: *Unfired pressure vessels*
- PD 5500: *Specification for unfired pressure vessels*
- TEMA: *Standards of the Tubular Exchanger Manufacturers' Association*

Where the heat exchanger is being designed to one or more of these standards, these guidelines are applicable internationally. If operating outside of the UK the legislation applicable will differ from that listed in 1.4, in which case local legislation should be applied.

Section 2 describes issues with the design of STHEs for tube failure events. Past failures are described and incident statistics are presented. This all forms a background as to why the risk of tube failure should be considered and some of the issues to be considered in improving the safe design and operation of these heat exchangers.

Section 3 provides guidelines for the design of the heat exchanger and associated LP inlet and exit pipework. Section 4 provides guidelines on the pressure relief system design to protect the exchanger in the event of a tube rupture. Dynamic simulation of tube rupture in heat exchangers is covered in section 5 and section 6 describes the options for instrumentation of the heat exchanger for detecting a tube failure event and detection of relief device operation. Section 7 includes guidance for the management of the heat exchanger once it is in operation.

The suggested design process, shown in Figure 2, is to first select the required heat exchanger type, then design the heat exchanger followed by the relief system. The design should then be checked for the consequences of tube rupture, maybe using dynamic simulation. If excessive pressures are predicted then the heat exchanger design should be reconsidered. If the design cannot be changed then it may be possible to change the design pressure of the LP side. Failing that, the relief system design should be modified. Once a suitable design is finalised the instrumentation can be added.

For existing heat exchangers, especially those designed before the first edition of these guidelines, the process in Figure 3 is suggested. On a periodic basis, the process hazards associated with the heat exchanger should be reviewed (see section 7). If the design publications have changed since the previous review then an investigation into the effects of tube rupture should be considered. If the analysis determines excessive pressures in the LP side as a result of tube rupture then the changes to LP side design pressure should be investigated. If that is not possible the modifications to the relief system should be investigated. If that is not possible then replacement of the heat exchanger should be considered.