HIPPS-Based No-Burst Design of Flowlines and Risers

Nikolaos Politis, Hugh Banon, and **Christopher Curran,** BP America Inc.

Summary
A methodology is proposed for design of subsea flowlines and risers coupled with a subsea high-integrity pressure protection system (HIPPS) for fields with high shut-in tubing pressure (SITP). The proposed approach uses a design pressure that is lower than the SITP while maintaining a high reliability against burst failure. This approach enables an inherently safer design and ensures that the system integrity is not compromised in the unlikely event that HIPPS valves fail to close upon demand. The proposed design methodology is supported by a combination of analytical and experimental results. Further, an example is provided for demonstration purposes.

Introduction
Background. As the oil and gas industry moves to high pressure reservoirs in deepwater with SITP in excess of 15 ksi, the design of fully rated flowlines and risers becomes extremely challenged because of increased wall thickness, difficulty of welding and inspection, and weight of the line pipe. For such fields, the use of HIPPS becomes an enabler (i.e., by allowing a reduced design pressure for the components downstream of HIPPS and hence reducing the wall thickness of flowlines and risers).

By definition, HIPPS is a high-integrity system with a low probability of failure on demand. The proposed design philosophy focuses on the unlikely event of the HIPPS valves failing to close upon demand and sets the following design objectives:

• In case of HIPPS failure and exposure of the system to SITP, flowlines and risers should have an adequate margin of safety against failure. This objective is set by introducing reliability-based acceptance criteria for flowlines and risers.

• Risers should be stronger than flowlines, thus keeping any potential failure away from the facility and avoiding harm to people.

• In case of HIPPS failure, there should be little or no damage to the flowlines and risers in order to minimize any follow-up replacement and repair.

In addition, in case of HIPPS valves successfully closing upon demand, a section of the flowline immediately downstream of the HIPPS may be subjected to pressures exceeding the design pressure and thus requiring to be fortified [as required by HIPPS design guidelines (Collberg 2010)]. It is proposed that this fortified section be designed with the same reliability objective as that adopted for risers.

In order to meet the aforementioned objectives, the flowlines and risers downstream of HIPPS must be checked against burst assuming that the system is subjected to the SITP. This design state is designated as the accidental limit state (ALS) if the frequency of this event is less than 1E–2 per year as defined in DNV-OS-F101 (2010). The design requirement for the ALS is a low probability of burst failure, and a second requirement is little or no damage to the pipe and equipment downstream of HIPPS.

API RP 1111 (2009) currently does not address the design of flowlines and risers in conjunction with HIPPS. Det Norsk Veritas (DnV) has recently issued guidelines regarding the design of flowlines and risers in conjunction with HIPPS (Collberg 2010). The design methodology outlined in the following sections follows the design formulae in API RP 1111, complies with existing regulatory requirements, and meets the recently issued DnV guidelines in terms of ALS acceptance criteria. The proposed requirements may also provide a bridge to future burst-critical designs when confidence in HIPPS integrity is gained.

For demonstration purposes, a Gulf of Mexico oil reservoir at a water depth of 6,000 ft with the SITP equal to 16.5 ksi is presented in this paper. Both flowlines and risers are API 5LX70 with 8.625-in. outer diameter. In the subsea architecture, subsea wells are tied into subsea manifolds and safety integrity level (SIL)-3 subsea HIPPS is placed in between the subsea well and the manifold. The operating pressure of the subsea system will be around 2.5 ksi at the mudline and the HIPPS is set to activate at 5.5ksi. The HIPPS valves will be designed such that they will close prior to the subsea pressure reaching 7.5 ksi. It is assumed that during shut-in, the riser will have a column of gas with a density of 0.36 specific gravity (SG).

Drivers for HIPPS. The following are the drivers for using HIPPS compared to a fully rated system:

• Lower design rating for all equipment downstream of the HIPPS, both subsea and topsides. This will allow the use of existing Gulf of Mexico 15k standard subsea equipment such as manifolds (i.e., valves), pipeline end terminations, and so on.

• Because of reduced wall thickness, conventional welding techniques and inspection for flowlines and risers can be applied, significantly reducing the manufacturing and welding risks. Current pipe manufacturing limitations result in a maximum pressure rating between 16 and 17 ksi for 8-in. steel catenary risers.

• The use of HIPPS will increase the available number of pipe lay and riser installation vessels owing to the reduced weight and welding requirements.

• HIPPS will enable pipe-in-pipe insulation, which would otherwise be too heavy to implement in a fully rated design.

• For the same nominal outside diameter, increased production rates become possible because of lower wall thickness and larger internal diameter.

Flowline and Riser Design Options. There are three possible options for design of subsea flowlines and risers. One would be the fully rated or conventional design (i.e., 16.5-ksi design pressure in this case) and two HIPPS-based solutions as follows:

Copyright © 2013 Society of Petroleum Engineers

TThis paper (SPE 163051) was accepted for presentation at the Offshore Technology Conference, Houston, 30 April–3 May 2012, and revised for publication. Original manuscript received 23 January 2012. Paper peer approved 27 June 2012.

TABLE 1—DESIGN, TEST, AND BURST PRESSURES FOR A RANGE OF MAXIMUM SOURCE PRESSURES					
MSP (psi)	7,500	10,000	12,500	15,000	16,500
Design pressure P_d (psi)	7,500	10,000	12,500	15,000	16,500
Test pressure P_t (psi)	9,375	12,500	15,625	18,750	20,625
API burst estimate P_b^{riser} (psi)	12,500	16,667	20,833	25,000	27,500
API burst estimate $P_b^{flowline}$ (psi)	10,417	13,889	17,361	20,833	22,917

• No-Burst: Flowlines and risers are designed to a pressure less than the full SITP. However, the ALS check of flowlines and risers should ensure that they do not burst in the unlikely event of HIPPS failure and exposure to the SITP. Hence, the overpressure may cause permanent deformation of the flowline and riser system requiring inspection, fitness-for-purpose assessment, or repair before it could be brought back into service.

• Burst-Critical: The flowline and riser design pressure is marginally above the HIPPS trip pressure. In the event of HIPPS failure, the flowline will yield and then subsequently burst.

In both HIPPS design cases, the system should be designed such that the riser is stronger than the flowline and therefore has a lower probability of failure. This paper focuses on the design methodology for the no-burst HIPPS solution.

The existing subsea applications of HIPPS are predominantly in gas and gas-condensate systems and are based on burst-critical designs. In most cases, adopting no-burst design would result in slightly heavier pipe downstream of HIPPS compared to burst-critical designs, but would significantly reduce the risk of loss of containment. It is shown that the HIPPS design can be as safe as a fully rated system if the no-burst design is implemented. The no-burst design is proposed as an interim solution until the industry has gained enough operational experience with HIPPS, especially when implemented in subsea oil production systems.

Exposure of Flowline and Riser System to SITP. Possible causes of the subsea system overpressure could be an accidental closure of the topsides boarding valve on the floating facility or hydrate formation in the flowlines and risers. In the example scenario considered in this paper, as the pressure rises, the HIPPS will be activated at around 5.5 ksi and should close by the time the pressure reaches 7.5 ksi. Hence the flowline and riser should be designed to a pressure in the range of 7.5–16.5 ksi; the selection of design pressure is described next. A typical design requires hazard and operability analysis and layers-of-protection analysis to determine the frequency of exposure to the SITP and the risk-reduction target for the HIPPS. However, it is assumed that the regulators will require a SIL-3 HIPPS system which has a probability of failure on demand in the range of 1E–3 to 1E–4. In this example, the demand on HIPPS is assumed to be once per year.

In case of a hydrate plug or accidental closure of the topsides boarding valve, the primary means of isolating the flowline and riser will be through the topsides control system by closing the subsea tree valves, and the secondary means will be through the HIPPS. However, conventional emergency shutdown/process shutdown may take several minutes, and in the meantime, the subsea production system could be exposed to pressures exceeding the design pressure. The time buildup of the pressure in the flowline and riser is fieldspecific and depends on many factors such as the permeability of reservoir rock, the size of the reservoir tank, and the crude characteristics. In some cases, it may either take several days for the pressure to build up to the SITP, or the pressure may never reach the SITP because of prior production from the field.

In the example field scenario, the safety instrumented HIPPS valves will activate at 5.5 ksi and will close in approximately 10 seconds. Flow-assurance calculations are performed to show that the time to reach 7.5 ksi is comfortably longer than 10 seconds for the flowline (i.e., outside of the fortified zone) and for the riser.

Flowline and Riser No-Burst Design Methodology for HIPPS-Based Subsea System

Current Design Codes and Regulations. The flowlines and risers in the Gulf of Mexico are designed according to 30 CFR 250.1002(a). Alternatively, the regulators allow the use of API RP 1111 on the condition the requirements of Notice to Lessees (NTL) 2009-G28 (MMS 2009) are met. In submitting such an alternative compliance request to the Bureau of Safety and Environmental Enforcement, two of the requirements are that (a) the pipeline design pressure is equal to or greater than the maximum source pressure (MSP) for all line pipe and riser pipe (this requirement is not applicable to HIPPS-based design because the system is not designed to the source pressure), and (b) the external hydrostatic pressure is not used to offset or reduce the minimum pipeline test pressure required by 30 Code of Federal Regulations (CFR) 250.1003(b)(1).

The second requirement is equivalent to designing for zero water depth. For the example design scenario, **Table 1** shows the pressure level relations for the API RP 1111 design when the NTL 2009-G28 is taken into account and the beneficial effect of hydrostatic water column is ignored. The pressures have been calculated according to the pressure level relations in Fig. 2 in API RP 1111. It is noted that, notwithstanding the beneficial effect of water column, the burst pressures listed in Table 1 are "code values" and are generally much lower than the actual burst pressure of API pipes (as will be shown later).

The DNV HIPPS guideline (Collberg 2010) was developed as part of a joint industry project (JIP). The intent of the guideline is to comply with recognized codes on HIPPS and pipeline design. DnV proposes reliability-based design criteria consistent with offshore standard DNV-OS-F101 (2010). The design equations in DnV have been calibrated to generate a design that meets the reliability-based criteria. While the proposed design methodology in this paper does not use the DnV design equations, it uses the reliability-based criteria proposed by DnV.

TABLE 2—ACCEPTABLE RELIABILITY LEVELS ACCORDING TO THE DNV HIPPS GUIDELINE

MSP (psi)	DnV Required Annual Prob. of Failure	SIL-3 HIPPS Annual Prob. of Failure Given Demand of One per Year	Conditional Prob. Of Burst Given HIPPS Fails	Conditional Prob. of Burst in Fortified Zone
Flowline	<1E–5	<1E–3	<1E–2	N/A
Riser	<1E–6	<1E–3	<1E–3	N/A
Fortified zone	<1E–6	N/A	N/A	<1E–6

TABLE 3—DESIGN, TEST, AND BURST PRESSURES FOR A RANGE OF MAXIMUM SOURCE PRESSURES

Event	HIPPS Successful?	Effect
Plug downstream of fortified zone	Y	– All system upstream of HIPPS exposed to 16.5 ksi – Fortified zone exposed to <10 ksi
	N	– All system exposed to 16.5 ksi up to plug
Plug in fortified zone	Y	– All system upstream of HIPPS exposed to 16.5 ksi – Fortified zone exposed to >10.0 ksi but less than 16.5 ksi
	N	– All system exposed to 16.5 ksi up to plug

Proposed Design Methodology. The wall-thickness calculations in the proposed design methodology are based on API RP 1111 and NTL 2009-G28, whereas the acceptable reliability levels are according to the DnV HIPPS guideline, as shown in **Table 2.**

The second column in Table 2 shows the target probabilities of failure allowed by the DnV guideline; these probabilities are target values for the system and not for an individual pipe. The third column in Table 2 shows the annual probability of failure for a SIL-3 HIPPS system. The fourth column shows the conditional probability of failure for the flowline and riser pipe given failure of HIPPS (i.e., this column multiplied by the third column should be lower than the criteria listed in the second column). The last column in Table 2 shows the annual probability of failure given successful closure of HIPPS valves. This criterion only applies to design of the fortified section of the flowline.

The design methodology comprises of calculating the wall thickness for a selected design pressure and checking whether the acceptance criteria are met. A step-by-step description is as follows:

1. Set the design pressure to the minimum HIPPS required pressure; for the example problem, that would be 7.5 ksi.
2. Calculate the wall thickness for the design pressure using API RP 1111 and NTL 2009-G28. In a typical design, a "corrosion allowance" is added to the calculated wall thickness. In the proposed methodology, the beneficial effect of this corrosion allowance is ignored.
3. For this design pressure and the resulting wall thickness, check whether the ALS acceptance criteria are met by checking the safety margin of flowline and riser against both yield and burst conditions. The estimation of required safety margins is described next.
4. If this is not the case, increase the design pressure and repeat Steps 2 and 3 until the criteria are met.

Fortified Zone. In order to account for the HIPPS response time in isolating the flow, a fortified length of flowline immediately downstream of HIPPS is often required. The length of the fortified zone can be determined by thermohydraulic simulations using transient solvers that take into account the PVT properties of the fluid content. The DNV HIPPS guideline requires that the fortified zone has the same safety class as the riser (see the reliability-based criteria in Table 2).

Table 3 shows the possible scenarios requiring HIPPS action and the resultant pressure in each section of the flowline for each scenario. As Table 3 shows, in case of a plug in the fortified zone and HIPPS valves successfully closing, it will be subject to a pressure greater than the 10-ksi design pressure. In such a scenario,

TABLE A-1—BP AND INDUSTRY (ISO/TR 10400 2007) BURST TEST DATA

Test Set	Source	Number of Tests	D/t	Mean of Ratio: FE Prediction of Burst Over Actual Burst	Mean of Ratio: Klever-Stewart Prediction of Burst Over Actual Burst	Mean of Ratio: Modified API CEBP Prediction of Burst Over Actual Burst
10.875-in. x 1.00-in., Grade C-110	BP	7	10.9	0.917	0.992	0.939
11.73-in. x 1.53-in., Grade C-110	BP	7	7.6	0.917	0.997	0.941
11.75-in. x 1.10-in., Grade C110	BP	3	10.7	0.874	0.952	0.889
8.625-in. x 1.35-in., Grade X90	BP	6	6.4	0.967	1.031	0.958
8.625-in. x 1.70-in., Grade X70	BP	3	5.1	0.958	1.068	0.994
10.75-in. x 1.60-in., Grade X90	BP	9	6.7	0.956	1.049	0.975
6.625-in. x 1.30-in., Grade X70	BP	3	5.1	0.953	1.066	0.986
ISO 10400 test no 68-73	Shell pipeline	6	7.4	0.893	0.907	0.965
ISO 10400 test no 74-75	Shell pipeline	2	11.8	0.908	0.909	0.997
ISO 10400 test no 76-79	Shell pipeline	4	11.8	0.901	0.897	1.009
ISO 10400 test no 92-93	Shell pipeline	2	9.9	0.917	0.944	0.958
ISO 10400 test no 94-95	Shell pipeline	2	8.6	0.894	0.913	0.951
ISO 10400 test no 96-97	Hydril n-wall	2	9.3	0.842	0.892	0.863
ISO 10400 test no 97-98	Hydril n-wal	2	9.3	0.864	0.904	0.873

TABLE A-2—STATISTICS OF ACTUAL BURST PRESSURE OVER PREDICTED BURST PRESSURE		
	Mean of Means	COV
FE	0.912	4.30%
Klever-Stewart	0.966	7.04%
Modified API CEBP	0.950	4.96%

the design criteria for the fortified zone should be an annual probability of burst failure <1E–6.

Minimum Required Safety Margins. The safety margin is defined herein as the ratio of the pressure-causing yield or burst divided by the exposure pressure. The safety margin calculations require yield and burst-pressure estimates for a given pipe thickness. These estimates can be obtained by empirical relations or by finite-element (FE) analysis. As part of the design verification, the accuracy of these estimates was studied extensively. In particular,

- Experimental burst data for thick wall pipe with D/t<12 were collected from BP and industry sources.
- Axisymmetric FE models for all the pipes in the experimental sample were built and FE analyses were used to predict burst pressures.
- A survey of analytical (or semi-empirical) predictions for ductile burst of pipes exposed to internal pressure was conducted to determine their applicability to pipe with low D/t. The selected analytical equations were used to predict the results from burst experiments and these results were also compared with FE results.

TABLE 4—MINIMUM REQUIRED SAFETY MARGINS		
Condition	Min. Flowline Safety Margin	Min. Riser Safety Margin
Yield (Lamé)	1.0	1.0
Burst (FE)	1.28	1.32

- For the sample of experiments, the Lamé equation for prediction of initial yield at the pipe internal diameter was compared to FE results.
- Finally, analytical and FE predictions were compared to the experimental data, and the statistical results are used to gauge their prediction performance.

Table A-1 of Appendix A summarizes the experimental results and the results from the FE predictions. Two more analytical models are also cited in Table A-1: (a) the burst prediction model developed by Klever-Stewart and (b) the capped end burst-pressure equation in API RP 1111 (2009) modified by replacing the yield strength with the average of the yield and the ultimate strength. In the rest of this paper, only the FE method is used as a tool to predict the pipe burst pressure.

Table A-2 summarizes the statistics of the actual burst pressure divided by the FE burst pressure (the same statistics are also shown for the analytical burst predictions). In order to meet the reliability-based acceptance criteria in Table 2, the statistics in Table A-2 are used to define the required burst design safety margins for the flowline and riser. Assuming a Gaussian distribution for the ratio of actual burst divided by FE predicted burst pressure and using the target probabilities in Table 2, the minimum safety margin against burst should be 1.26 for the riser and 1.21 for the flowline. In order

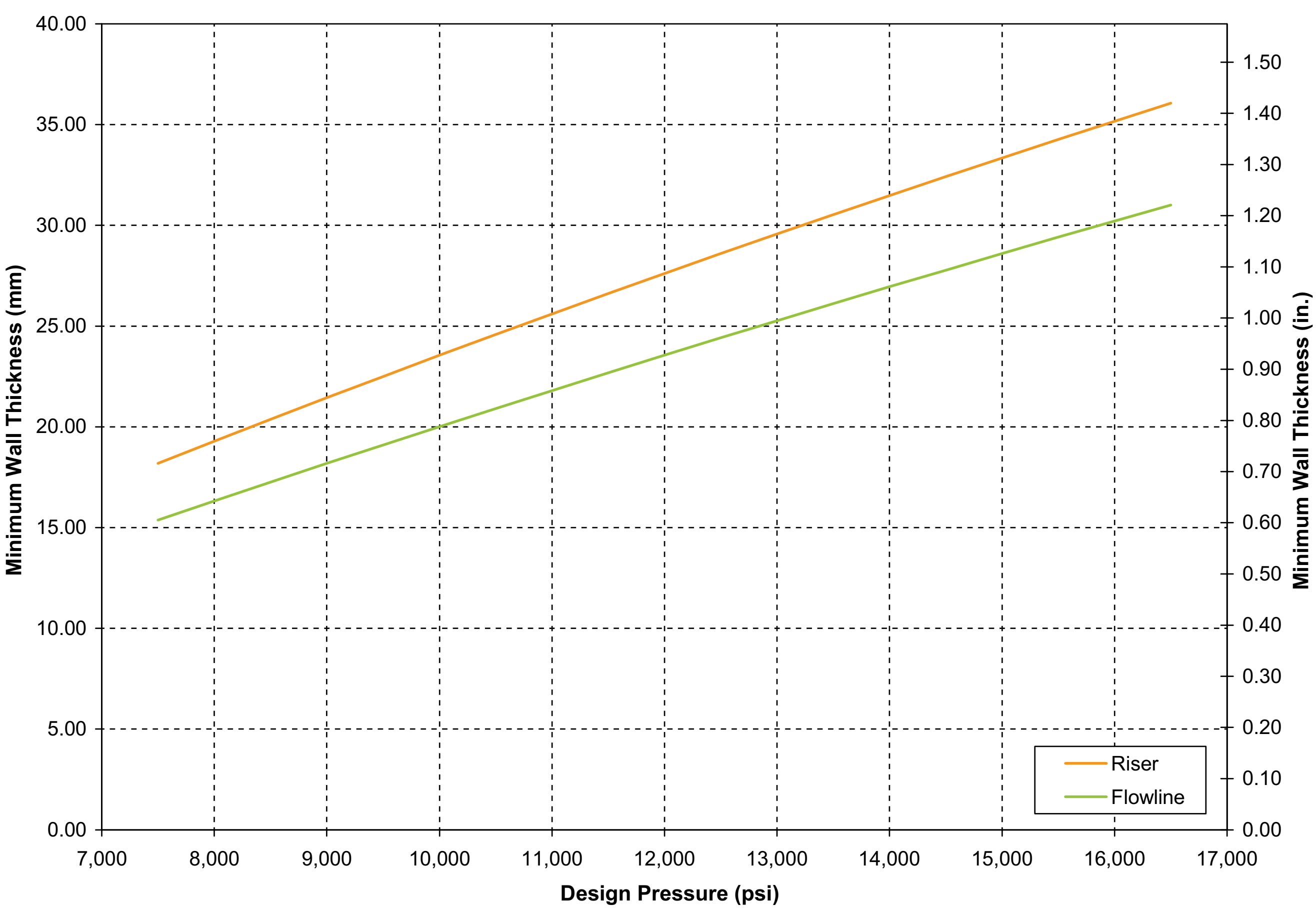

Fig. 1—Minimum wall thickness for Eq. 4 of API RP 1111 and NTL 2009-G28 requirements.

TABLE 5—BEST ESTIMATE PRESSURES ACTING ON RISER AND FLOWLINE; 6,000-FT WATER DEPTH AND 0.36-SG GAS IN RISER			
	Location		
Parameter	Flowline	Riser Bottom	Riser Top
SITP (psi)	16,500	16,500	16,500
P_w (psi)	2,667	2,667	0
P_{HC} (psi)	0	0	960
P (psi)	13,833	13,833	15,540

to account for the system effect, it is conservatively assumed that 100 joints of pipe are equally pressured by the SITP and contribute to the probability of failure. Next, a system reliability analysis was performed, showing that the probability of failure for the system would be one to two orders of magnitude higher than the probability of failure for an individual joint. Using these results, the safety margins for the riser and flowline were increased to 1.32 and 1.28, respectively, to account for the system effect while meeting the probability targets in Table 2. The system reliability aspect of the riser and flowline failure is further discussed later.

These minimum safety margins are based on the application of FE analysis to estimate the pipe-burst pressure. If analytical equations are used to estimate the burst pressure, minimum safety margins can be estimated in a similar manner.

A second ALS condition required for the pipe is little or no yielding in case of exposure to SITP. Using the Lamé equation to predict the pipe yielding (at the internal diameter), the minimum safety margin against yield is set equal to 1.0. **Table 4** summarizes the minimum safety margin requirements for the flowline and riser.

Minimum-Wall-Thickness Calculation for Riser and Flowline. **Fig. 1** shows the minimum wall thickness for the riser and flowline calculated for a range of design pressures ranging from 7.5 to 16.5 ksi. The wall thickness calculations use Eq. 4 in API RP 1111 while meeting NTL 2009-G28 requirements. The riser design pressure in Fig. 1 is independent of water depth because NTL 2009-G28 effectively dictates a zero water depth for the riser and flowline design. Assuming that a constant wall thickness will be used for the riser, design is controlled at the riser top because the highest differential pressure (i.e., the difference between internal pressure in the riser and external hydrostatic pressure) is at the hang-off location.

ALS Design Check. As described previously, in the proposed design methodology one needs to perform the ALS design check (i.e., exposure to the SITP) for a range of assumed design pressures (as shown in Fig. 1) to determine the acceptable design pressure (i.e., a design pressure whereby the pipe meets the minimum design safety margins listed in Table 4). In this design procedure, the ALS design check is a best-estimate evaluation, where one should use the best estimates of the pressures acting on the pipe, the yield stress of the pipe, and the predicted burst pressure of the pipe. In effect, the ALS design check accounts for explicit and implicit sources of conservatism in design.

For the example field in 6,000 ft of water, **Table 5** shows the best estimate pressures acting on the flowline and riser in case of exposure to SITP; P_w is the water pressure, P_{HC} is the pressure of hydrocarbon column inside the riser, and P is the net pressure acting on the pipe.

The pipe is assumed to be X70 steel with SMYS of 70.3 ksi and specified mean ultimate stress (SMUS) of 82.7 ksi. The best estimate yield stress is assumed to be 1.05 specified mean yield stress (SMYS) [i.e., the Lamé yield was calculated using a yield stress equal to 1.05 SMYS (this was shown to be representative for X65 or X70 pipe)]. The FE predictions of burst pressure use 1.05 SMYS as the best estimate yield stress, 1.05 SMUS as the best estimate ultimate stress, and the Ramberg-Osgood model for the stress-strain behavior (see Appendix A).

Fig. 2 shows the flowline safety margins against yield and burst for the range of assumed design pressures, from 7,500 to 16,500 psi using the aforementioned procedure. **Figs. 3 and 4** show similar results for the riser top and riser touchdown point, respectively. A comparison of these figures to the required minimum safety margins in Table 4 indicates that a 10-ksi design pressure meets the cri-

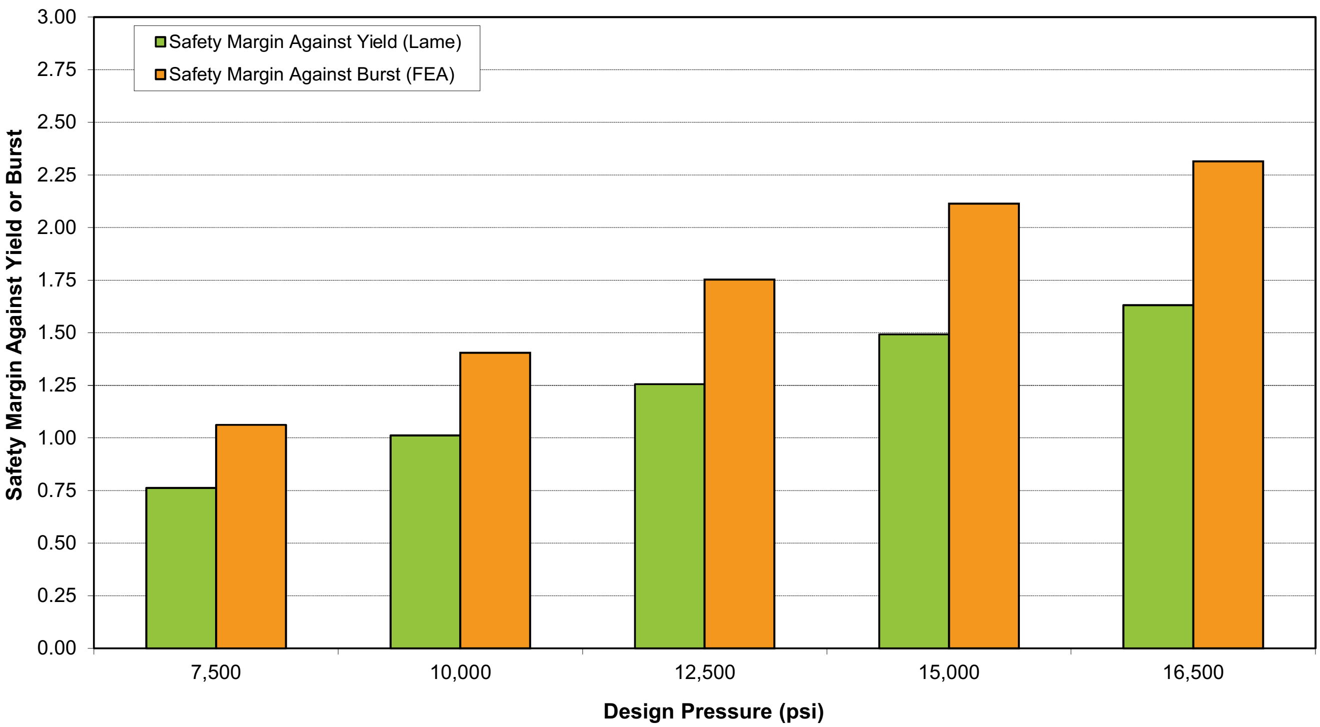

Fig. 2—Safety margins against yield and burst for the flowline.

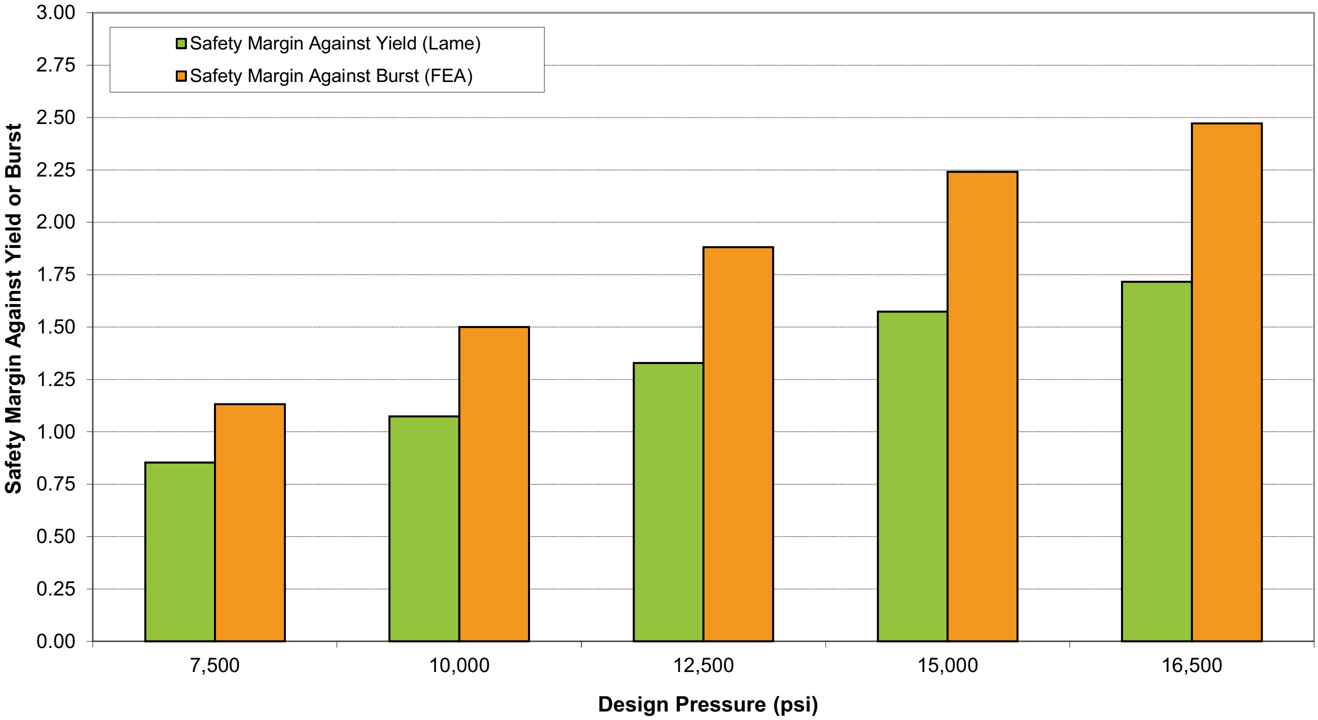

Fig. 3—Safety margins against yield and burst at the top of the riser.

teria in Table 4 and hence it can be selected as the design pressure. At this design pressure, the flowline nominal wall thickness is 20 mm and the riser nominal wall thickness is 23.6 mm (see Fig. 1). It is noted that 3–6 mm of corrosion allowance that is typically added to the nominal wall thickness is conservatively ignored in prediction of the burst pressure.

For the 10-ksi design, the predicted pressures causing yield (using the Lamé equation) and burst (using FE model) of the flowline and riser are calculated and shown in **Table 6.** The flowline is subject to a net pressure of 13,833 psi (see Table 5), which is slightly lower than the predicted Lamé yield pressure of 13,992 psi. The riser is subject to a net pressure of 15,540 psi (see Table 5), which is significantly lower than the yield pressure of 16,693 psi. The calculated safety margins against burst are 1.40 for the flowline (19,359/13,833) and 1.50 for the riser top (23,307/15,540). These values are higher than the acceptance criteria required shown

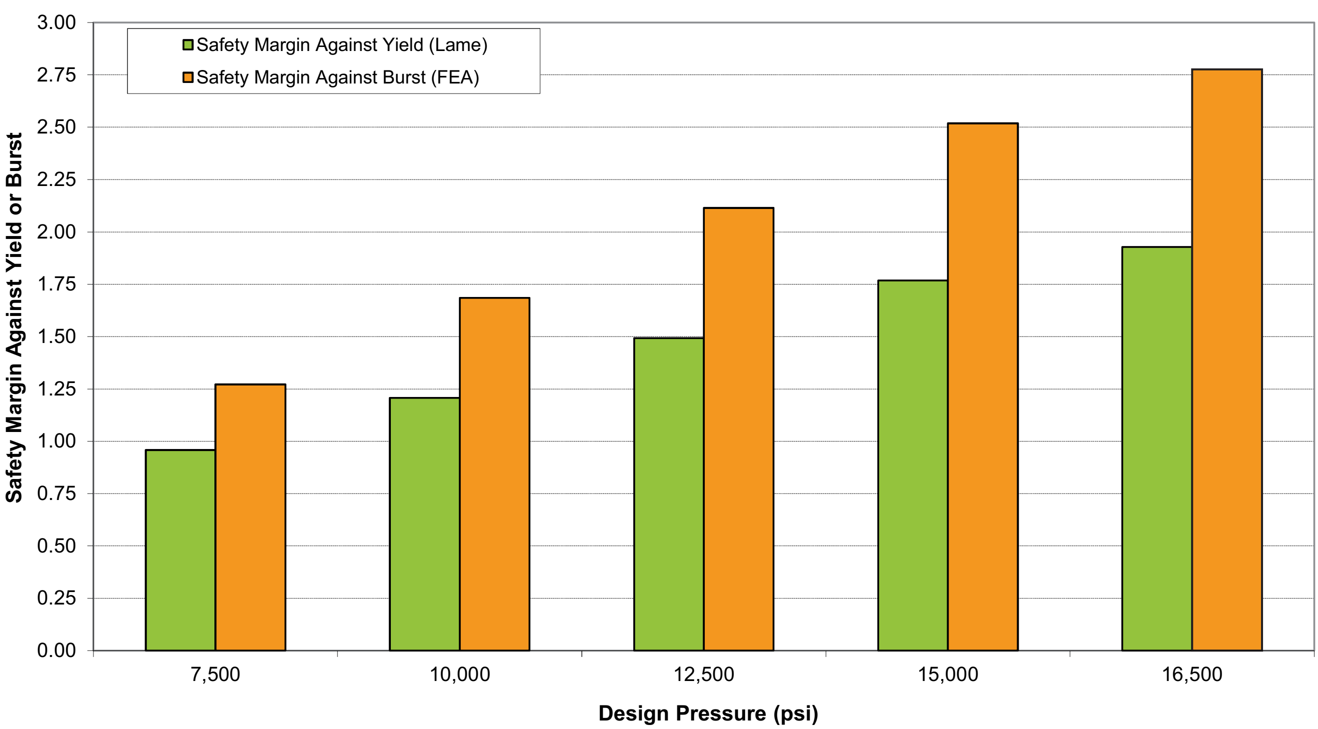

Fig. 4—Safety margins against yield and burst at the bottom of the riser.

TABLE 6—YIELD AND BURST PRESSURE ESTIMATES FOR 10-K FLOWLINE AND RISER		
Parameter	Flowline	Riser
Nominal wall thickness, *t* (mm)	20.0	23.6
Lamé yield pressure (psi)	13,992	16,693
FE burst-pressure estimate (psi)	19,359	23,307

in Table 4. The yield and burst safety margins for the 10-ksi design are summarized in **Fig. 5.**

Comparison of Different Designs. As noted previously, the three possible design scenarios for the example field are:

1. A burst-critical design using a design pressure of 7.5 ksi with subsea HIPPS.
2. A no-burst design with a design pressure of 10 ksi with subsea HIPPS.
3. A fully rated design with a design pressure of 16.5 ksi.

Table 7 compares the minimum wall thicknesses for the three design scenarios. In Table 7, the wall thicknesses of the two HIPPS-based designs include 6 mm of corrosion allowance. In the fully rated design, the calculated wall thickness is well over 1.0 in. (25.4 mm), which affects the pipe manufacturing quality in terms of the geometric HI/LO at the pipe ends. Hence another 3 mm is added to the calculated wall thicknesses of the fully rated design to account for machining of the pipe ends before welding.

Table 7 shows that, for the example subsea field, the no-burst design adds roughly 5 mm to the flowline and riser wall thickness. On the other hand, the fully rated design adds an additional 11–12 mm to the wall thickness required by the no-burst design. The fully rated design results in wall thicknesses that are at the edge or beyond current capabilities of steel mills. The significantly higher thickness of fully rated pipe increases the risks related to pipe manufacturing, welding, welding inspection, and pipe handling.

Reliability Calculations. The previous sections show that the flowline and riser designed to 10-ksi internal pressure meet the required minimum safety margins against burst; this should guarantee that they meet the reliability-based criteria in Table 2. However, it would be interesting to calculate the probabilities of burst failure for the flowline and riser and compare the results with the criteria in Table 2.

Table 8 shows the calculated conditional probabilities of failure for the flowline and riser joints (from FE predictions and using the statistics in Appendix A). These conditional probabilities are multiplied by the annual probability of HIPPS failure to calculate the annual probabilities of burst failure for a single joint of the flowline and riser. Because the system assumption for the flowline is that 100 joints are equally loaded, the annual probability of failure for a single joint is increased by two orders of magnitude to estimate the upper bound on the annual probability of failure for the flowline system. At the riser bottom, the system is assumed to be comprised of 10 joints, and the annual probability of failure for a single joint is increased by one order of magnitude. At the riser top, the highest loads are concentrated below the hang-off point and the system is comprised of a single joint; therefore, the probability of system failure is the same as the probability of a single joint failure. It is noted that in all cases, the annual probabilities of burst failure for the system are much lower than those required by the DnV criteria and adopted in this design (see Table 2). The reason being

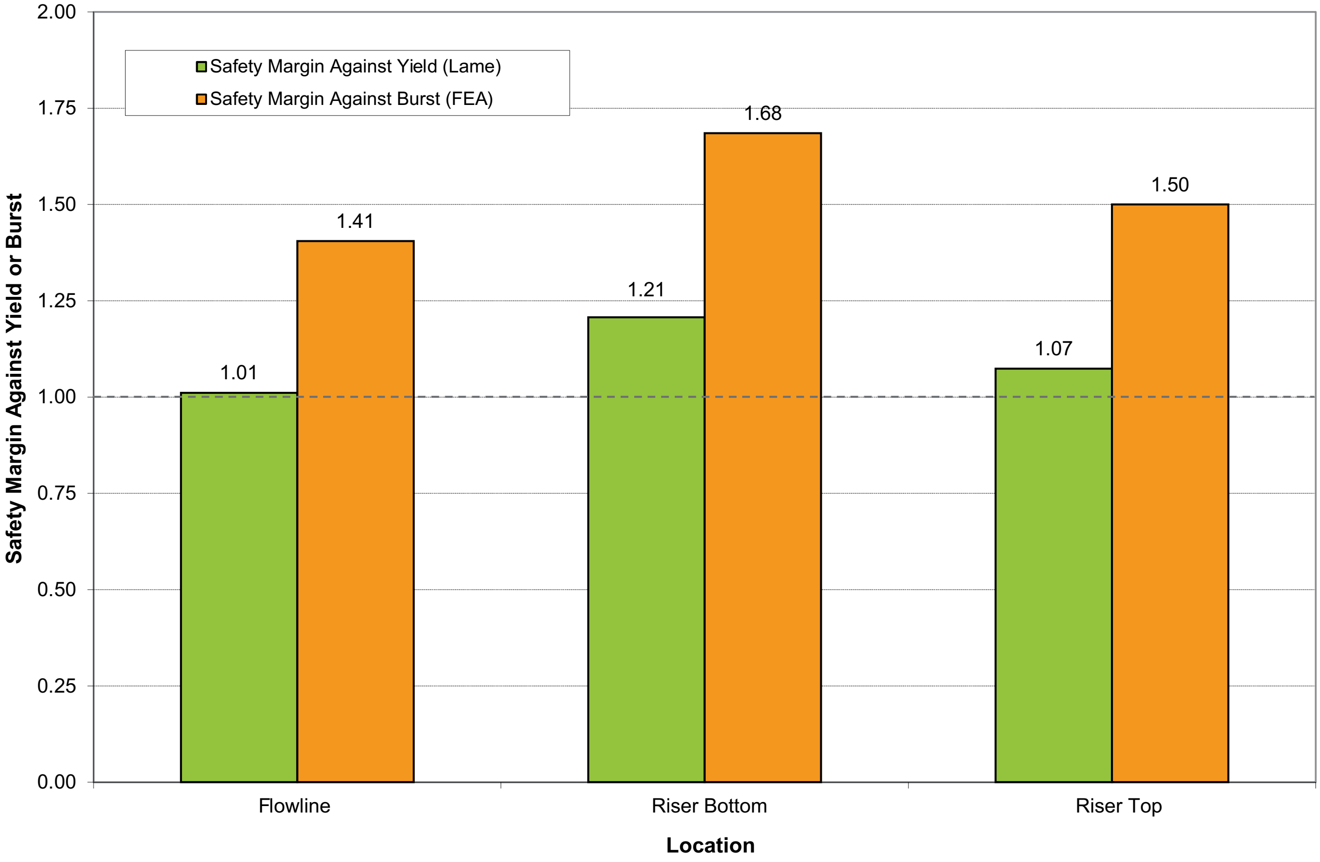

Fig. 5—Safety margins against yield and burst for the 10-ksi design pressure.

TABLE 7—WALL-THICKNESS COMPARISON; VALUES INCLUDE MANUFACTURING TOLERANCES AND CORROSION ALLOWANCE

Nominal Wall Thickness	Design Approach		
	Burst-Critical (7.5 ksi)	No-Burst (10.0 ksi)	Fully Rated (16.5 ksi)
t_{riser} (mm)	24.2*	29.6*	45.1**
$t_{flowline}$ (mm)	21.4*	26.0*	40.0**

* Includes 6-mm corrosion allowance.
** Includes 6-mm corrosion allowance and 3-mm HI/LO allowance.

the low coefficient of variation (COV) of the FE predictive model (i.e., a small increase in the design safety margin against burst) can significantly lower the probability of burst failure for the flowline and riser.

As for the fortified zone, because the demand is equal to once per year, the conditional probability of burst failure for this section of the flowline has to be <1E–6 (see Table 2). As a starting position, it can be assumed that the fortified zone will have the same wall thickness as the rest of the flowline and will be comprised of 10 joints.

As shown in Table 8, such a design approach meets the proposed reliability-based criteria because the annual probability of system failure for the fortified zone is <1E–6. The implication of this result is that a fortified zone will not be needed. On the other hand, one may choose to increase the reliability of the fortified zone by increasing the wall thickness of joints in this zone to that of the riser (i.e., 29.6 mm instead of 26 mm as shown in Table 7). This approach increases the safety of the fortified zone while maintaining the relative safety levels of the flowline and the riser.

Conclusions

API RP 1111 does not currently address the design of flowlines and risers in conjunction with HIPPS. DnV has recently issued reliability-based guidelines regarding the design of flowlines and risers in conjunction with HIPPS. The proposed design methodology follows the design equations in API RP 1111 and NTL 2009-G28 while it adopts the DnV guidelines in terms of reliability-based acceptance criteria for the ALS. A combination of analytical methods, FE analysis, and testing is used to develop the proposed design procedure.

The proposed design methodology is applied to a field with SITP of 16.5 ksi. It is shown that using 10-ksi design pressure leads to a pipe thickness that meets the ALS check:

- Given exposure to the SITP, the annual probabilities of burst for the flowline and riser meet the reliability-based design criteria.
- The riser margin of safety against burst will be greater than that of the flowline.
- The flowline stresses will be slightly below the pipe yield stress while the riser will be well below yield.

Acknowledgments

The authors wish to acknowledge Det Norske Veritas for their valuable contributions in reviewing the proposed design methodology.

References

API RP 1111, Design, Construction, Operation, and Maintenance of Offshore Hydrocarbon Pipelines (Limit State Design), fourth edition. 2009. Washington, DC: API.

Collberg, L. 2010. Guideline on Design of Pipeline Systems with Over Pressure Protection System. Report No. 2010-9414, 12TB6X5-10, Det Norske Veritas (DNV), Oslo, Norway.

DNV-OS-F101, Submarine Pipeline Systems. 2010. Høvik, Norway: Det Norsk Veritas (DNV).

ISO/TR 10400:2007, Petroleum and Natural Gas Industries—Equations and calculations for the properties of casing, tubing, drill pipe and line pipe used as casing or tubing. 2007. Geneva, Switzerland: ISO.

MMS. 2009. Alternate Compliance and Departure Requests in Pipeline Applications. Notice to Lessees (NTL) No. 2009-G28, US DOI/BOEM, Minerals Management Service, Gulf of Mexico OCS Region, New Orleans (13 October 2009), http://www.boem.gov/Regulations/Notices-To-Lessees/2009/09-G28.aspx.

Appendix A—Burst-Test-Data Statistics

Table A-1 lists the experimental burst tests used in this paper and the source of each test (i.e., whether the tests were performed by BP or by the industry). Three burst predictors are used:

1. FE analysis
2. The Klever-Stewart equation (ISO/TR 10400 2007)

$$P = \frac{2\text{SMUS}}{\frac{\text{OD}}{t}-1}\left(\left(\frac{1}{2}\right)^{(1+n)}+\left(\frac{1}{1.732}\right)^{(1+n)}\right),$$

where

$$n = 0.169 - \frac{0.000882SMYS}{1000}.$$

3. The CEBP prediction from API RP 1111 [1] modified by replacing the yield strength with the average of the yield and the ultimate strength and also using the nominal wall thickness.

$$\text{CEBP} = \frac{2}{\sqrt{3}}\ln\left(\frac{\text{OD}}{\text{ID}}\right)\left(\frac{\text{SMYS+SMUS}}{2}\right).$$

It is noted that failure was not observed at $t_{\min}$ for any of the BP burst tests. Therefore, the D/t ratio in Table A-1 corresponds to nominal thickness values.

The FE analysis predictions were performed using the ABAQUS FE software. In particular, axisymmetric models (ABAQUS CAX4R element type) of the capped-end burst sample with nominal wall thickness were built. The material law used in the FE model was the Ramberg-Osgood (ABAQUS deformation plasticity) with parameters determined by the actual yield and ultimate

TABLE 8—FAILURE PROBABILITIES

Parameter	Flowline	Riser Bottom	Riser Top	Fortified Zone
Calculated safety margin, M_c, against burst (FE)	1.40	1.68	1.50	1.40
Conditional probability of burst for exposure to SITP	7E-08	nil	3E–11	7E–8
Range of probabilities for SIL 3		1E–3 to 1E–4		N/A
Annual probability of burst for a single joint	7E–11 to 7E–12	nil	3E–14 to 3E–15	7E–8
Number of joints in the system	100	10	1	10
Upper bound on annual probability of burst for the system	7E–9 to 7E–10	nil	3E–14 to 3E–15	7E–7

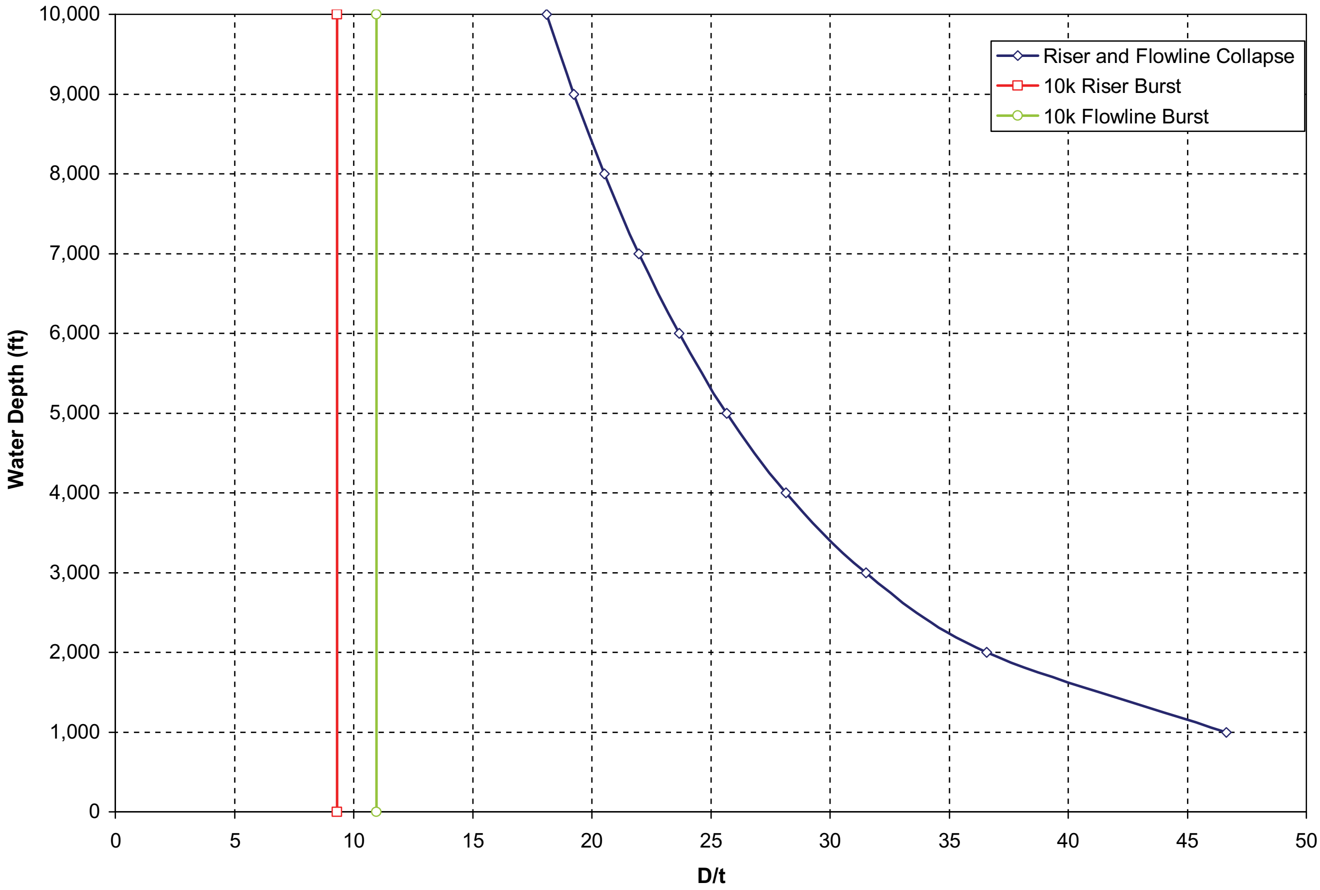

Fig. B-1—Flowline and riser-design interaction diagram for API 5L X70 line pipe. The collapse design is based on Eq. 9 of API RP 1111; the burst design is based on Eq. 4 of API RP 1111 and NTL 2009-G28.

stresses. The FE burst pressure was taken at the point of the analysis loss of convergence.

Table A-2 shows the statistics of the actual overpredicted burst pressure ratios for the BP and the industry burst test samples. It is noted that each sample is composed of 2-9 tests of a given pipe and typically there is a small variation among the experimental results in a given sample. The COVs listed in Table A-2 take into account both the variability in actual burst pressures within a sample as well as the variability among all the samples.

Appendix B—Collapse Pressure Check

A flowline and riser design interaction diagram for API 5L X70 line pipe was developed. In particular, **Fig. B-1** shows the flowline and riser-design interaction diagram where the burst design is based on Eq. 4 in API RP 1111, taking into account the conservative requirements of NTL No. 2009-G28 (MMS 2009). For the burst design of the riser a design pressure of 10ksi is assumed. The collapse design is based on Eq. 9 in API RP 1111.

The design-interaction diagram shows that for the proposed design, both flowline and riser designs are controlled by the burst (10-ksi internal design pressure) rather than by collapse.

Nikolaos P. Politis is a Deepwater Developments Engineer with BP America. His research interests in deepwater facilities include subsea flowlines, risers, and floating structures. He holds a BS degree from the University of Thessaly, and MS and PhD degrees from Rice University.

Hugh H. Banon is an Engineering Manager with BP America. His research interests in deepwater facilities include subsea flowlines, risers, and floating structures. He holds a BS degree from the University of Illinois, and MS and PhD degrees from the Massachusetts Institute of Technology.

Christopher Curran is a Team Leader with the Deepwater Facilities Flagship for BP. He is also the focal point within BP for development of HIPPS systems and is Chairman of the API 17V Subsea Safety Committee, as well as Chairman of the Society for Underwater Technology's Houston Branch. He has over 30 years of experience with subsea systems, concentrating primarily on subsea production control systems. Curran holds a degree in physics from Bristol University.