IChemE
www.ingentaselect.com/titles/02638762.htm

0263–8762/03/$23.50+0.00

Trans IChemE, Vol 81, Part A, January 2003

WHAT CAUSED TOWER MALFUNCTIONS IN THE LAST 50 YEARS?

H. Z. KISTER

Fluor, Aliso Viejo, CA, USA

Nine hundred case histories of malfunctioning towers reported over the last 50 years were surveyed and analyzed. Our analysis shows rapid growth in the number of malfunctions with no signs of decline. Plugging, especially of tray active areas, packing and distributors, tops the malfunctions list. Coking (refinery towers only), scale and corrosion, and precipitation were the most common causes. The tower base comes second, where liquid level rising above the reboiler inlet caused premature flood and even internals damage. Attention to level measurement and kettle reboiler pressure balance are key preventive measures. Next follow tower internals damage, abnormal operation incidents (startup, shutdown, commissioning), assembly mishaps, packing liquid distributors, intermediate draws, misleading measurements, reboilers, and explosions. Tray design and tower simulation, two topics that receive much attention in the literature, are not high up on the malfunction list. The survey teaches numerous lessons on each of the malfunctions which are invaluable for achieving trouble-free design and operation of distillation towers.

Keywords: troubleshooting; column failures; distillation; case histories; column malfunctions; distillation operation; debottlenecks; distillation troubleshooting.

BACKGROUND

The last half-century of research on distillation has tremendously improved our understanding and our designs. The introduction of high-speed computers revolutionized the design, control, and operation of towers. Invention and innovation in tower internals greatly enhanced tower capacity and efficiency. The application of gamma scans and pyrometers has given troubleshooters tools they would only dream of before. With all these advances in distillation technology, one would expect the failure rate in distillation towers to be on the decline. Our previous malfunction surveys (Kister, 1990, 1997) showed the converse: the tower failure rate is on the rise and accelerating.

Our 1997 survey (Kister, 1997) found that while 300 malfunction case histories were reported over the 40 years between 1950 and 1989, another 300 malfunction case histories were reported over the eight years between 1990 and 1997. The number of malfunctions reported per year rose 5-fold. While some of the increase may be attributed to more open sharing of experiences, one thing is certain: despite the huge progress in distillation, the number of tower malfunctions is not declining. It is on the rise and accelerating.

The objective of our 1997 survey was to project into the twenty-first century by comparing the 1990s malfunctions with those that prevailed in the four preceding decades. Our focus was to identify the trends, and to flag major regions of growing malfunctions. For instance, our survey flagged an alarming growth rate in poor installation mishaps. To these findings, we do not have much to add in the current survey.

In contrast to projecting into the twenty-first century, the current survey reflects back to the last five decades, seeking out the malfunctions that repeatedly and most commonly caused towers to fall short of achieving their objective. Lessons learnt from past malfunctions can save engineers and operators from falling into the same traps. They can also help troubleshooters identify root causes of operating problems. It is amazing how repetitious the case histories are. Table 1 provides an example. All the case histories listed involve premature floods resulting from liquid levels rising above the reboiler return inlet due to a faulty level indication. How many more times does this type of malfunction need to be reported before designers and operators learn the importance of ensuring adequate level indication (e.g. by adequate maintenance, checking, and redundant instrumentation)?

CURRENT SURVEY

In this work, 300 additional case studies that came to the author's attention in the last five years were added to the previously abstracted 600. The abstracts for the earlier case studies are in Kister (1990, 1997). The author wished to publish the abstracts of the 300 additional cases with this paper, but the maximum page limit precluded him from doing so. These cases will be published in a companion paper (Kister, 2003).

The complete data base now has 900 case histories. Of these, about half were reported in the last decade, the other half were reported in the four preceding decades. The

Table 1. Case histories where tower premature flood was caused by excess base level, which in turn was caused by faulty measurement or level control.

Case no.	Reference	Type of plant	Type of column	Brief description	Some morals
1520	Lieberman (1988)	Refinery	Deethanizer absorber using gasoline solvent	Loss of bottom level indication resulted in column flooding. Gasoline spilled over to the top knockout drum, thence to the fuel system, and ended spilling out of burners, causing several heater fires	Ensure adequate level indication
1168	Anonymous (2000)	Olefins	Demethanizer	Following introduction of liquid feed, it was not appreciated that the demethanizer level transmitter was disconnected. The apparent lack of level was attributed to having to control boilup on the manual reboiler bypass, because an isolation valve on the reboiler flow control set was broken. The tower flooded, filled the reflux drum, leading to excessive liquid drainage to flare. The level transmitter and alarm on the flare knockout drum were inadvertently isolated, so there was no indication that liquid was ascending the flare stack which failed by low-temperature embrittlement	Ensure all instrumentation is operational before introducing feed
1544	Charlton (1986)	Olefins	Stripper	The base level controller failed at startup, and liquid level in the column rose to fill half the column. This caused excessive heavies in the top product, possibly due to liquid carryover. The problem was diagnosed using gamma scans. Cutting feed rate provided short-term solution. Using a gamma-ray absorption level indicator provided a longer-term solution	
15,133	Xu and Martos (2001)		Deethanizer 26 trays	Column fully flooded due to liquid level exceeding reboiler return nozzle. There was no functional level gage in the bottom. Diagnosed by gamma scan, and cured by draining accumulated liquid while using a stationery gamma source/detector to monitor bottom level	Same as 1520
1560	France (1993)			Bottom liquid level rose above the seal pan in bottom of column, causing excessive pressure drop and poor stripping. Board-mounted instrument was improperly calibrated, and field level gage was neither blown nor even checked	Same as 1520
15,127	Sloley *et al.* (2001)	Petrochemicals		Out-of-calibration bottom level controller caused liquid level to exceed reboiler return inlet, causing premature flood, high dP and loss of product purity	Same as 1520
15,109	Lieberman (1991, 1997)	Refinery	C_3/C_4 splitter	A level control tap was plugged, giving a false signal, which induced level rise above the reboiler return nozzle and tower flooding	
15,110	Lieberman (1991, 1997)	Refinery	C_3/C_4 splitter	Tower flooded after level control float chamber was insulated. The insulation kept liquid hot, reducing its density, and generating low signal when the level rose above the reboiler return. Recalibration eliminated problem	Same as 1520
1586	Sattler (1990)	Refinery	Coker fractionator 4.3 m ID	A faulty level indicator caused the column to fill up with liquid. Two days later, asphalt and tar were found in the upper products and the pressure drop across the bottom four sieve trays rose from 0.4 to 0.6 bars, indicating plugging. Plugging confirmed by gamma scans	Same as 1520
1515	Lieberman (1991)	Refinery	Combination tower	Bottom liquid level rose above the vapor inlet nozzles because of a faulty level controller. The submergence backpressured the coke drum upstream. When the operator noticed this, he quickly lowered the bottom level. This caused foamover (a 'champagne bottle' effect) in the coke drum	Same as 1520. Avoid excessively rapid draining of column liquid
1588	Bowman (1993)	Refinery	Lube oil vacuum	Damage sustained due to level control problems led to off-spec products. Random packings were found in the bottom line. Gamma scans showed collapse of bottom three beds	

finding is well in line with a projection from our 1997 survey (Kister, 1997) that the number of malfunctions reported per year has been about five times higher in the last decade than in the four preceding decades. Also, the split between the sources of case histories is much the same as that reported earlier: i.e. 40% from refineries, 40% from chemicals, and the remaining 20% from olefins and gas plants (denoted O/G in the tables).

PLUGGING/COKING

With 121 case histories, Table 2 has plugging/coking as the undisputed leader of tower malfunctions. The number of plugging/coking incidents reported over the last decade is higher than that reported over the previous four decades, suggesting that these problems are neither easing off nor declining. Plugging/coking is here to stay, and most likely will continue to top the tower malfunction list. More plugging/coking cases have been reported in refineries than in chemical plants, probably due to the incidence of coking, which is a major problem in refineries but uncommon in chemical towers.

Table 3 breaks down the causes of plugging. With 26 case histories, almost all from refineries, coking is the leader. Coking incidents experienced rapid growth in the 1990s, with only four cases out of the 26 reported before 1991. This rapid growth reflects refiners shift towards 'deep cutting' of the crude residue, i.e. maximizing distillate recovery out of crudes by raising temperature, lowering pressure, and minimizing wash bed reflux in the refinery vacuum towers.

Table 4 shows that 17 out of the 26 coking ease histories were experienced in refinery vacuum towers. Of these 17, 11 were due to insufficient reflux to the wash bed. This wash bed removes the heavy ends ('asphaltenes') and organometallic compounds from the hot feed vapor by contacting the vapor with a volatile reflux stream. If insufficient, dry

Table 2. Causes of malfunctions.

No.	Cause	Cases	1992+	1991−	Ref.	Chem.	O/G
1	Plugging, coking	121	70	51	68	32	16
2	Tower base and reboiler return	103	51	52	51	22	11
3	Tower internals damage (excludes explosion, fire, implosion)	84	35	49	35	33	6
4	Abnormal operation incidents (startup, shutdown, commissioning)	84	25	59	35	31	12
5	Assembly mishaps	75	36	39	23	16	11
6	Packing liquid distributors	74	48	26	18	40	6
7	Intermediate draws (includes chimney trays)	68	45	23	50	10	3
8	Misleading measurements	64	31	33	31	9	13
9	Reboilers	62	28	34	28	13	15
10	Chemical explosions	53	17	36	11	34	9
11	Foaming	51	26	25	19	11	15
12	Simulations	47	35	12	13	28	6
13	Leaks	41	22	19	13	19	7
14	Composition control difficulties	33	16	17	11	17	5
15	Condensers that did not work	31	12	19	14	13	2
16	Control assembly	29	16	13	7	14	7
17	Pressure and condenser controls	29	14	15	18	3	2
18	Overpressure relief	24	10	14	10	7	2
19	Feed inlets to tray towers	18	11	7	11	3	3
20	Fires (no explosions)	18	8	10	11	3	4
21	Intermediate component accumulation	17	8	9	6	4	7
22	Chemicals release to atmosphere	17	5	12	6	10	1
23	Subcooling problems	16	11	5	8	5	1
24	Low liquid loads in tray towers	14	6	8	6	2	3
25	Reboiler and preheater controls	14	6	8	6	—	5
26	Two liquid phases	13	7	6	3	9	1
27	Heat integration issues	13	8	5	5	2	6
28	Poor packing efficiency (excludes maldistribution/support/hold-down)	12	8	4	4	3	2
29	Troublesome tray layouts	12	5	7	5	2	—
30	Tray weep	11	3	8	6	1	3
31	Packing supports and hold-downs	11	4	7	4	2	2

Table 3. Causes of plugging.

No.	Cause	Cases	1992+	1991−	Ref.	Chem.	O/G
1	Coking	26	22	4	25	1	—
2	Scale, corrosion products	22	11	11	14	4	4
3	Precipitation, salting out	17	13	4	9	8	—
4	Solids in feed	10	4	6	3	6	1
5	Polymer	9	5	3	—	4	4

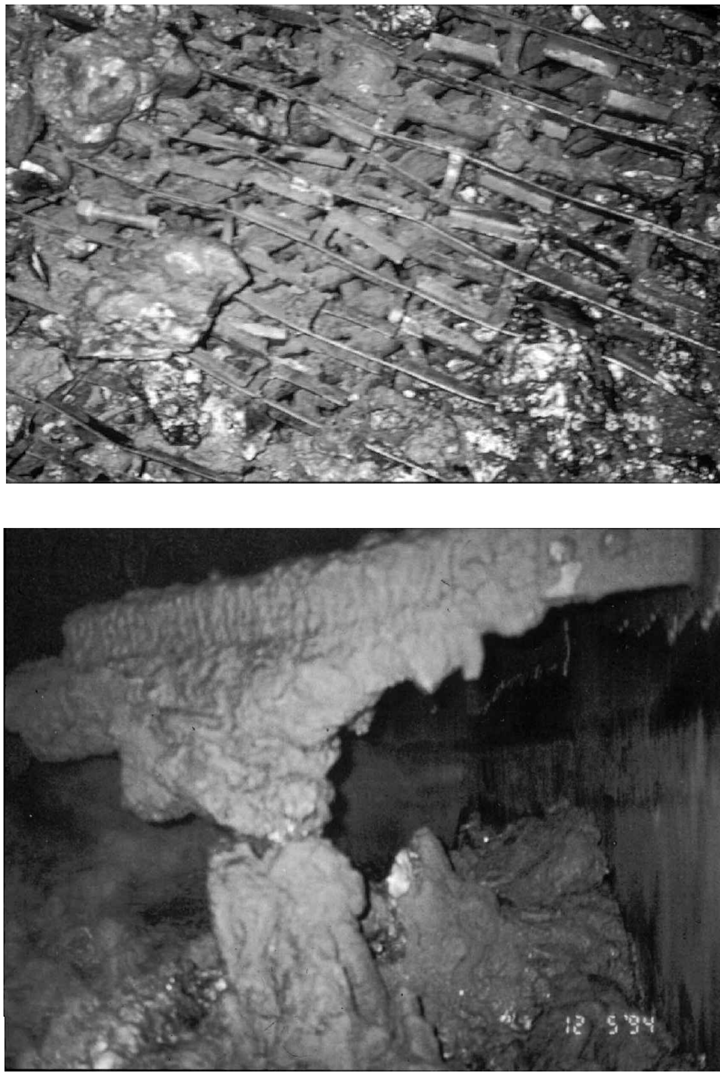

Figure 1. Grid packing is one of the most open and most fouling-resistant packing in the industry, yet it is no match for severe coking in a refinery vacuum tower. The coke is shown to fill the open spaces and to form stalagmites and stalagtites at the spray nozzle distributor.

spots form in the wash bed and coke up. The problem of insufficient reflux reflects a learning curve problem associated with deep-cutting the residue, a technology that emerged over the last decade.

Closely following coking, scale and corrosion products are the leading cause of plugging (Table 3), with 22 case histories. The case histories are split evenly between the last decade and the previous four, and appear to be more of a problem in refinery and olefins/gas towers than in chemical towers. Precipitation or salting out follows closely behind with 17 case histories. Precipitation appears to have become more of a problem recently, possibly due to a trend to use lower-quality feedstocks and to minimize plant effluent, and affects both chemical and refinery towers. The next two common causes of plugging, with nine to 10 case histories, are solids in the tower feed and polymerization. Solids in the feed and polymer formation are more of a problem in chemical than in refinery towers. In fact, no polymer formation case histories have been reported in refinery towers.

Table 5 details locations where plugging was reported. The case histories are evenly split between packed and tray towers. Both packings and distributors plug up. The large number of coking incidents in wash beds of refinery vacuum towers biases Table 5 toward bed plugging compared to distributor plugging. In other services, the case histories are evenly split between plugged packings and plugged distributors. In trays, cases of plugged active areas outnumber those of plugged downcomers by more than 3 to 1, suggesting that improving tray design for fouling service should focus on enhancing fouling resistance in the active areas.

Although most plugs take place in the tower, draw lines, instrument lines, and even feed lines, plug too. Line plugging appears to be less of a problem in chemical towers than in refinery and olefins/gas towers.

TOWER BASE AND REBOILER RETURN

Kitterman (1976) estimated that 50% of the problems in the tower originate in this region. With 103 case histories,

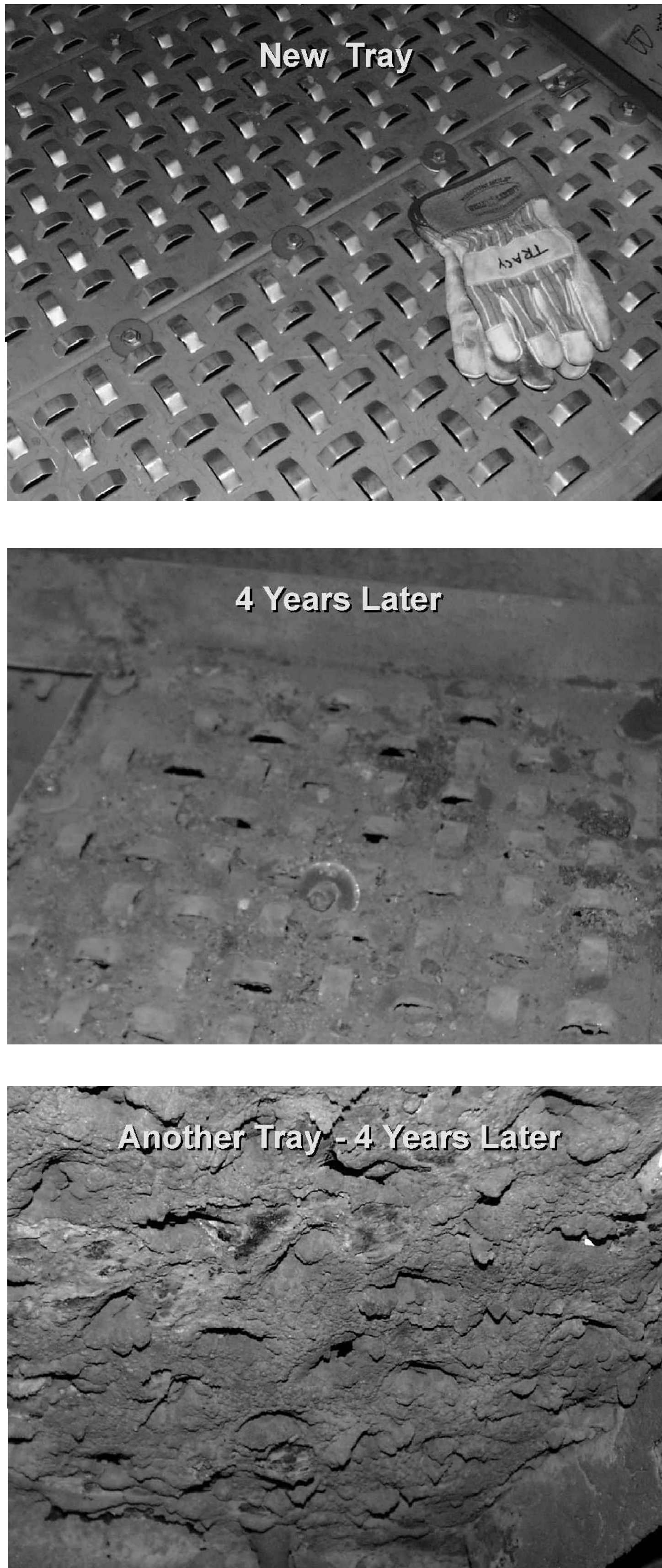

Figure 2. Even fouling-resistant trays are not immune to plugging under severe fouling conditions. These photos show active areas of one of the more fouling-resistant tray types in the industry plug up over a 4 year run. The plugging is believed to have been caused by severe salting out, a common cause of plugging.

Table 4. Causes of coking.

No.	Cause	Cases	1992+	1991−
1	Insufficient vacuum tower wash rate	11	11	—
2	Other causes, vacuum tower	6	4	2
3	FCC main fractionator slurry section	3	1	2
4	Other refinery fractionators	5	5	—

Table 5. Location of plugging and coking.

No.	Location	Cases	1992+	1991−	Ref.	Chem.	O/G
1	Packing	50	33	17	28	16	4
	Packed beds	32	23	9	21	8	2
	Liquid distributors	20	12	8	7	10	2
2	Trays	39	22	17	23	7	6
	Active areas	32	19	13	20	6	4
	Downcomers	9	5	4	4	3	2
3	Draw lines	16	8	8	8	4	4
4	Instrument lines	10	3	7	7	2	—
5	Feed lines	6	3	3	3	1	2

Table 2 verifies that indeed more problems initiate at the tower base than in any other tower region, although the actual percentage is lower than 50. The number of tower base incidents reported over the last decade is much the same as that reported in the previous four, suggesting little improvement over the years. The tower base will continue to be a major troublespot. Tower base problems trouble refineries more than chemical plants.

Table 6 gives a breakdown. Forty-nine case histories, half of those reported, were of liquid level rising above the reboiler return inlet or the bottom gas feed. Table 7 details the causes of these high levels. Faulty level measurement or control tops this list, but restriction in the outlet line (this includes loss of bottom pump, obstruction by debris, and undersized outlets) and excess reboiler pressure drop are also important. Almost all of the cases of excess reboiler pressure drop are for kettle reboilers, with liquid level in the tower base backing up beyond the reboiler return to overcome the pressure drop. With reboilers other than kettles, high pressure drop seldom causes excessive tower base levels.

In the vast majority of cases, high tower base levels caused tower flooding, instability, and poor separation. Less frequently (eight cases out of the 49), vapor slugging through the liquid also caused tray or packing uplift and damage.

The corrective measures to prevent excessive tower base level are those recommended by Ellingsen (1986): reliable level monitoring, often with redundant instrumentation, and good sump design. Based on the current survey, the author adds avoiding excessive kettle reboiler pressure drop to that list.

With far fewer case histories (13), vapor maldistribution is the second most common tower base malfunction (Table 6). Almost all these case histories were reported in packed towers, evenly split between refinery and chemical towers. Vapor maldistribution in the reboiler return region is an uncommon issue with tray towers.

Table 6. Troublesome tower base and reboiler return/bottom gas inlet.

No.	Cause	Cases	1992+	1991−	Ref.	Chem.	O/G
1	High base level	49	22	27	25	6	8
2	Vapor maldistribution	13	5	8	5	4	3
3	Impingement by reboiler return or incoming gas	10	9	1	2	6	—
4	Water induced pressure surges (e.g. due to wet stripping steam)	8	4	4	8	—	—
5	Leaking draw to once-through thermosiphon reboiler	7	3	4	6	—	—
6	Low base level	7	2	5	—	5	—
7	Gas entrainment in bottom liquid	6	3	3	3	1	—

Table 7. Causes of liquid rise above the reboiler return inlet.

No.	Cause	Cases	1992+	1991−	Ref.	Chem.	O/G
1	Faulty level measurement or control	18	8	10	9	1	4
2	Excess reboiler pressure drop	13	8	5	8	—	3
3	Restriction in bottom outlet	12	4	8	3	4	2
4	Operating problems	7	3	4	5	2	—
5	Foam	4	2	2	3	—	—

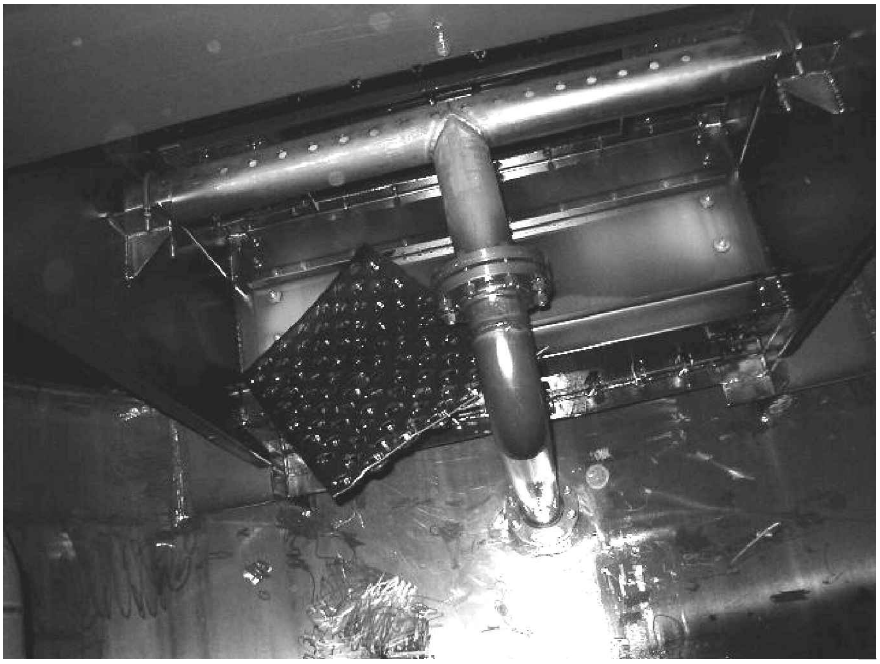

Figure 3. A displaced panel on the bottom tray in a refinery crude tower, the work of a water-induced pressure surge. Water-induced pressure surges can cause more severe damage; Amoco (1984a) has illustrations. The tower base is a common troublespot.

Impingement by the reboiler return or incoming gas is next with 10 case histories, almost all recent. Four of the 18 report severe local corrosion due to gas flinging liquid at the tower shell in alkaline absorbers fed with CO_2-rich gas, mostly in ammonia plants. This calls for special caution with the design of gas inlets into these towers. Troublesome experiences were also reported with inlet gas impingement on liquid level, instruments, the bottom tray, the seal pan overflow and the inlet from a second reboiler.

Four other troublespots follow with six to eight case histories. These are gas entrainment in the bottom liquid, low base levels, water-induced pressure surges, and leaking draws to once-through reboilers. Gas entrainment led to pump cavitation or contributed to base level rise above the vapor inlet. Low base levels appear to be particularly troublesome in chemical towers. In services distilling unstable compounds like peroxides, low base levels induced excessive temperatures or peroxide concentration, either of which led to explosions. A total loss of liquid level induced vapor flow out of the bottom which overpressurized storages.

All the reported water-induced pressure surges and leaking draws to once-through thermosiphon reboilers came from refinery towers. Most of the water-induced pressure surges initiating at the tower base were due to undrained stripping steam lines. With once-through thermosiphons, the bottom tray liquid is collected by a sump or draw pan, then flows through the reboiler into the tower base. The bottom product is reboiler effluent liquid collected at the tower base. Any liquid leaking or weeping from the sump or bottom tray shortcuts the reboiler into the tower base, which starves the reboiler of liquid. This leakage is the most common problem with the once-through thermosiphon reboilers, as evidenced by six case histories.

DAMAGE TO TOWER INTERNALS

With 84 case histories (Table 2), tower internals damage has been the third most common tower malfunction. Unlike plugging and coking, however, the number of damage case histories reported in the last decade is lower than in the past, suggesting that the industry is making progress in reducing these malfunctions. Tower internals damage is equally troublesome in refinery and chemical towers, but appears less of a problem in olefins/gas plant towers.

Table 8 details the main causes of internals damage. One cause towers above the others: water-induced pressure surges, accounting for 26 of the case histories reported, almost all from refinery towers. The good news is that these pressure surges are very much on the decline, with only eight cases reported in the last decade compared with 18 in the four preceding decades. Much of the progress here can be attributed to AMOCO, who experienced their share of pressure surges in the 1960s. AMOCO investigated these cases very thoroughly, and shared their experiences and lessons learned with the industry by publishing three booklets (AMOCO, 1984a–c).

Table 9 gives a split of these cases. The key to prevention is keeping the water out. The leading route of entry is undrained stripping steam lines, but other causes also listed in Table 9 are not far behind. Returning to Table 8, after water-induced pressure surges with 26 reported case histories, there is a large gap. With 10 case histories, insufficient mechanical resistance is the second leading cause of tower internals damage. All the reported cases are recent; in fact, in the last decade insufficient mechanical resistance has surpassed water-induced pressure surges as the top cause of tower internals damage. This finding

Table 8. Causes of tower internals damage (excludes fire, explosion, and implosion).

No.	Cause	Cases	1992+	1991−	Ref.	Chem.	O/G
1	Water-induced pressure surges	26	8	18	24	2	—
2	Insufficient mechanical resistance	10	10	—	4	5	1
3	High bottom liquid level	8	4	4	4	3	—
4	Downward flow in valve trays[a]	8	3	5	1	5	1
5	Uplift due to rapid upward flow[a]	7	3	4	1	5	1
6	Breakage of packing	6	2	4	—	5	1
7	Melting/softening of random packing	5	—	5	—	2	2
8	Poor assembly or fabrication	5	2	3	2	1	—
9	Flow-induced vibration	4	2	2	—	4	—
10	Valve pop-off	4	2	2	—	3	1
11	Downcomer compressed, bowed	4	3	1	3	—	—

[a]Excludes water-induced pressure surges or high bottom liquid level.

Table 9. Causes of water-induced pressure surges.

No.	Cause	Cases	1992+	1991−
1	Undrained stripping steam lines	6	4	2
2	Water in feed/slop	4	2	2
3	Water pockets in pump or spare pumps	4	1	3
4	Water accumulation in dead pockets	4	1	3
5	Accumulated water in transfer line to tower (including heater passes)	3	—	3
6	Condensed steam reaching hot section of tower	3	—	3
7	Hot oil entering a water-filled region	3	1	2

suggests that in services prone to damage, 'heavy-duty' internals design, as described in Shieveler's (1995) article, can offer much improvement.

At seven to eight case histories, there are three causes of tower internals damage: high liquid level in the tower base, downward flow through valve trays, and uplift due to rapid upward flow. The downward flow and rapid upward flow appear particularly troublesome in chemical towers. At four to six case histories, there are several causes: breakage of packings (mostly ceramics), melting/softening of packings (mostly plastic), poor assembly or fabrication, popping of valves out of valve trays (mainly legged valves), downcomers bowed or compressed, and flow-induced vibration.

Many of the damage incidents took place during abnormal operation, such as startup, shutdown, commissioning and outages. During these operations, special caution is required to prevent water entry into a hot oil tower, excessive base level, rapid pressurizing or depressurizing that can uplift trays, downward pressuring on valve trays, and overheating of plastic packings.

The relatively low incidence of cases of damage due to high liquid level at the tower base is surprising, in light of earlier reports that high base levels account for as many as half the tray damage cases in chemical towers (Ellingsen, 1986). The author's experience concurs with Ellingsen's that this cause of damage is underestimated by the survey. Damage due to high bottom level deserves to be a clear second in Table 8, well ahead of the others, and second only to water-induced pressure surges.

ABNORMAL OPERATION INCIDENTS (COMMISSIONING, STARTUP, SHUTDOWN)

The 84 incidents induced by commissioning, startup and shutdown place abnormal operation in equal third place in Table 2. These malfunctions are spread evenly throughout chemical, refinery and olefins/gas towers. Quite a few of these led to plugging/coking and internals damage. The good news is that the abnormal operation incidents reported in the last decade are less than half of those reported for the four preceding decades. The industry has made good progress in reducing these malfunctions. This progress was reported in our previous work (Kister, 1997), appears to continue, and can be attributed to greater emphasis on safety by most major corporations. Hazops and 'what-if' analyses, safety audits,

Table 10. Abnormal operation incidents (commissioning, startup, shutdown).

No.	Operation or Cause	Cases	1992+	1991−	Ref.	Chem.	O/G
1	Water removal	15	3	12	15	—	—
2	Blinding/unblinding	15	3	12	8	5	1
3	Backflow	15	6	9	5	6	2
4	Washing	12	2	10	4	6	—
5	Steaming and water operations	10	2	8	3	7	—
6	Overheating	7	—	7	—	4	2
7	Pressurizing and depressurizing	6	2	4	1	4	1
8	Overchilling	6	4	2	1	—	5
9	Purging	4	1	3	2	1	1
10	Cooling	4	—	4	1	2	1

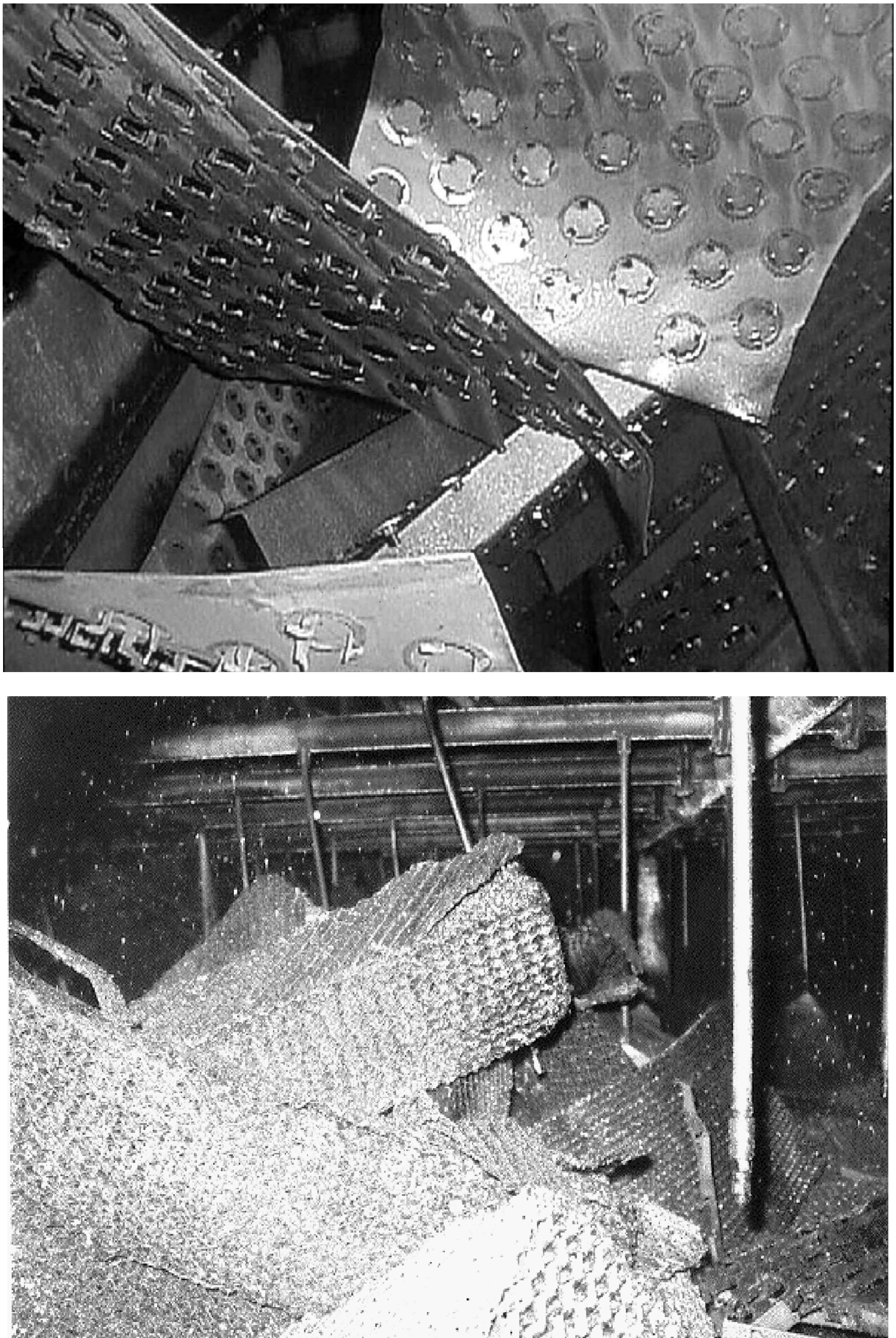

Figure 4. Liquid level rising above the reboiler return or vapor feed entry is one of the most common sources of malfunctions, including tray and packing damage, as shown. The author's experience is that these high liquid levels cause tray and packing damage even more frequently than the malfunctions survey suggests.

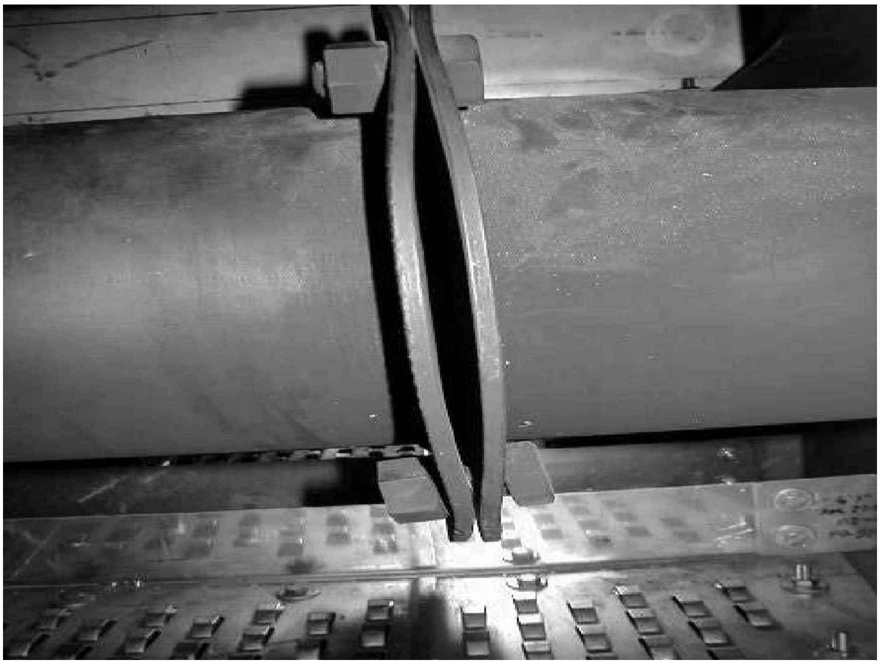

Figure 5. Damage often results from insufficient mechanical resistance. Flat-plate flanges on internal pipes, such as those leading to feed and reflux distributors, are weak and tend to spread apart. Gasketed raised face flanges of the appropriate pressure ratings should be used.

improved procedures, and extensive safety training have all contributed to this very welcome progress.

Table 10 shows that three malfunctions account for about half the case histories: blinding/unblinding, backflow and water removal from refinery fractionators. Water removal incidents are closely linked to water-induced pressure surges which tops the causes of tower internals damage. Of the 26 cases of water-induced pressure surges, about half were induced by startup, shutdown and abnormal operation; conversely, of the 15 incidents associated with water removal, 12 resulted in pressure surges. Refineries implement special procedures to remove water prior to startup of their hot oil fractionators, but if something goes wrong, a pressure surge often results.

There is some overlap between blinding/unblinding and backflow. In five case histories, poor blinding led to a backflow incident. Both blinding and backflow incidents led to chemical releases, explosions, fires and personnel injuries. High-pressure absorbers account for five of the backflow incidents. Here loss or shutdown of the lean solvent pump resulted in backflow of high-pressure gas into the lean solvent line, from where it found a path to atmosphere or storage. Four other incidents reported flow from storage or flare into the tower while maintenance was in progress. Three blinding incidents involved valves that were plugged or frozen.

Washing and steam/water operations are common commissioning operations, yet are quite troublesome. Each accounts for 10–12 case histories. Most malfunctions in washing led to fouling and corrosion, but in some cases, washing liberated toxic gas or transported chemicals into undesirable locations. Most malfunctions generated by steam/water operations either led to rapid depressurizing in the condensation zone, or to overheating. Rapid depressurizing in the condensation zone, in turn, either led to vacuum and implosion or to excessive flows and internals damage as vapor from above and below rushed towards the depressurized zone.

For all four operations (blinding/unblinding, backflow, washing, steam/water operations) the number of malfunctions reported over the last decade is well below the past number. Also, all four are quite evenly split between refinery and chemical towers. These four operations plus water removal account for about 70% of the reported abnormal operation incidents.

Overheating is next in Table 10 with seven case histories, none of which took place in the last decade. Some cases resulted from steaming, but there are also other causes, like failure of the cooling medium in a heat-integrated system during an outage. Following overheating, there are four operations with four to six malfunctions: pressurizing or depressurizing, overchilling, purging, and cooling. Pressurizing and depressurizing caused internals damage if too rapid or if performed backwards via valve trays. The main cooling malfunctions involve condensation which introduced air into the tower or formed a zone of rapid depressurization. The malfunctions of purging are varied.

The final item, overchilling, deserves special discussion. While all the abnormal operation malfunctions in Table 10 show a marked decline in the last decade, overchilling shows a rise. Five out of the six reported overchilling cases occurred in olefins or gas plant towers, the sixth being a refinery case. Recognizing that the total number of case histories reported in Table 10 by olefins and gas plants is 13, it can be appreciated that, for towers in this industry, overchilling is the major abnormal operation malfunction. Moreover, overchilling led to brittle failure, releasing gas clouds, which were responsible for major explosions, accompanied by loss of life, injuries and major destruction. The rise in overchilling case histories is the only setback, yet a major concern, to the progress achieved in reducing abnormal operation malfunctions.

ASSEMBLY MISHAPS

With 75 case histories, assembly mishaps are in fifth place in Table 2. Our previous survey (Kister, 1997) singled out assembly mishaps as the fastest growing malfunction, with the number of malfunctions reported between 1990 and 1997 more than double the number of malfunctions between 1950 and 1990. The good news is that this growth has leveled off. The number of assembly mishaps reported in the last decade is roughly the same as that reported in the four preceding decades. It appears that the industry has taken corrective action after noticing the alarming rise in assembly mishaps. Many major organizations have initiated systematic and thorough tower process inspection programs, and these are paying dividends.

Table 11 shows where installation mishaps most frequently occur. The largest number of reported cases is for packing liquid distributors. Most of these cases are recent. This suggests one area where inspections can be improved.

Sharing the top spot in Table 11 is incorrect packing assembly. This item is higher than it deserves to be. It has been inflated into the top spot by a relatively high number of incidents from fairly uncommon packing assemblies. Out of the 13 cases reported, two describe breakage of packings, which is troublesome with ceramics but rare with metal packings; two others describe disintegration of a poorly fastened grid bed; in another four the pre-revamp tray support rings were left in the tower (only one of these four is known to have caused a major loss in packing efficiency). All these are fairly uncommon specific applications, which should not reflect on the majority of packing assemblies. This split calls for special caution in specific situations like dumping ceramic packings, fastening the grid, and when deciding whether to leave the tray support rings in the towers.

With eight to nine incidents, improper tightening of nuts, bolts and clamps, and incorrect assembly of tray panels, are, as can be expected, near the top of the assembly mishaps, and deserve to be on the checklist of every tower inspector. Debris left in the column, and incorrect materials of construction, also belong on the same checklist.

The rest of the entries in Table 11 show malfunctions that tend to repeat themselves far more frequently than others. These spell out some of the items that the process inspector should focus on. Flow passage obstruction and internals misorientation in feed and draw areas are common. The possibility of leakage from 'leak-proof' and 'leak resistant' collector trays should be considered and water-tested at turnarounds. Finally, two very common flaws must never be overlooked in tray tower installations: downcomer clearances improperly set and tray manways left unbottled.

PACKING LIQUID DISTRIBUTORS

After the tower base, liquid distributors are the second most troublesome internal in distillation towers, with a total of 74 case histories (Table 2). The number of liquid distributor malfunctions reported in the last decade is almost double that in the preceding four decades, probably because of the wide use of packed towers in the industry over the last couple of decades.

More distributor malfunctions have been reported in chemical towers than in refinery and olefins/gas towers, probably due to the comparatively wider application of packings in chemicals. In chemical towers alone, liquid distributor malfunctions outnumber any of the previous malfunctions including plugging, tower base, internals damage and abnormal operation. Liquid distributors are the top malfunction in chemical towers.

Table 12 provides a breakdown of the distributor malfunctions. The two majors (17–20 cases) reported are plugging and overflow. While plugging is a common cause of overflows, only five of the 17 cases of overflows reported were due to plugging. Excessive liquid loads, insufficient orifice area, and hydraulic problems with the feed entry into a distributor caused the rest of the overflow cases.

The next two major malfunctions (13–14 cases) were poor irrigation quality and fabrication/installation mishaps. It is surprising that poor irrigation quality accounts for only 20% of the liquid distributor malfunctions. The literature on liquid distributors has focused on optimizing irrigation quality, yet other more troublesome items, like plugging and overflow prevention, received little attention. Further, the number of irrigation quality malfunctions reported is on the decline, suggesting the industry has learnt to produce good irrigation, at least in most cases. On the other hand, cases of distributor overflow, fabrication and installation mishaps, and feed entry problems, are sharply on the rise, so the industry should focus on improving these.

Feed entry malfunctions (11 cases) comes next, followed by poor hole pattern and distributor damage (eight cases). It is worth noting that distributor damage is the only item in Table 13 for which the number of refinery malfunctions exceeded the chemical malfunctions. Some items such as irrigation quality, feed entry, and hole pattern seldom appear on the refinery malfunction list.

Table 11. Assembly mishaps.

No.	Mishap	Cases	1992+	1991−	Ref.	Chem.	O/G
1	Assembly mishaps in packing liquid distributors	13	11	2	4	6	1
2	Incorrect packing assembly	13	6	6	2	5	2
3	Improperly tightened nuts, bolts, clamps	9	3	6	4	—	1
4	Incorrect assembly of tray panels	8	4	4	1	1	—
5	Flow passage obstruction and internals misorientation at tray towers feeds and draws	7	4	3	4	1	2
6	Leaking collector and low liquid load trays	7	4	3	3	2	—
7	Downcomer clearance and inlet weir malinstallation	5	—	5	3	—	—
8	Debris left in column	5	2	3	—	1	4
9	Tray manways, hatchways left unbolted	4	2	2	1	—	—
10	Materials of construction inferior to those specified	4	2	2	2	1	—

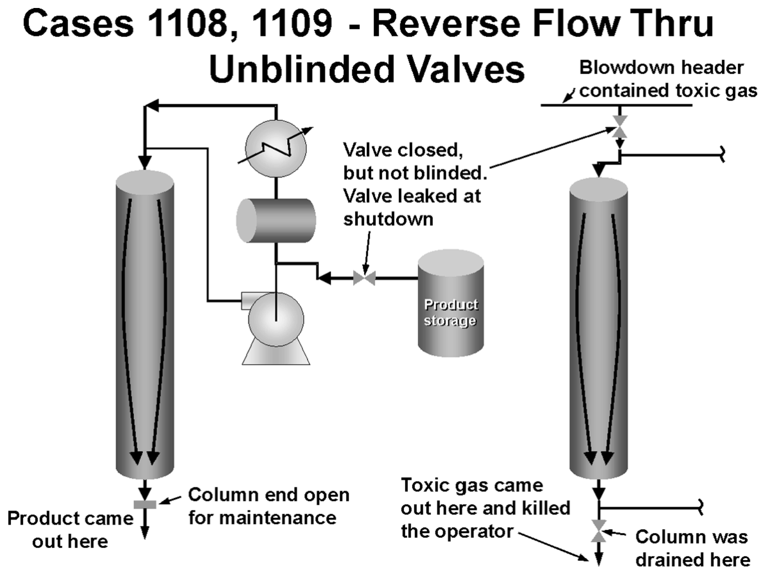

Figure 6. Two case studies in which reverse flow through shut but unblinded isolation valves led to chemicals leaking into the tower during a turnaround. In one case (left), the leaking valve allowed product from storage to back-flow into the depressured tower, coming out of the bottom end that was open for maintenance. In the second (right), toxic gas from the blowdown header back-flowed through the leaking valve into the depressured tower, coming out the tower bottom, where it killed an operator draining the tower. These cases emphasize the importance of following good blinding/unblinding practices. Based on Kletz (1988).

Redistribution, handling flashing feeds, out-of-levelness, and insufficient mixing (four to five cases) constitute the remaining entries in Table 12. It is worth noting that distributor out-of-levelness, which is frequently suspected when a tower malperforms, is one of the minor entries in Table 12. Finally, insufficient mixing is a size-related issue, seldom troublesome in smaller towers (<5 m ID), but rises in significance with larger diameter.

Table 12 provides support for recommendations by Olsson (1999) for minimizing distributor malfunctions. Olsson advocates critically examining the fouling potential and absence of vaporization in streams entering the distributor, testing distributors by running water through them at the design rates, either in the shop or *in-situ*, and, finally, ensuring adequate process inspection. Table 12 suggests that Olsson's measures would have prevented more than 80–90% of the reported malfunctions.

INTERMEDIATE DRAWS

With 68 case histories (Table 2), intermediate draws are the third most troublesome internal in the tower, following the tower base/reboiler return and packing liquid distributors. In the last decade, the number of intermediate draw malfunctions rose to almost double the malfunctions in the preceding four decades. It appears that either the design of intermediate draws is becoming a forgotten art, or the pushing of towers to maximum capacities is unveiling flaws and bottlenecks previously hidden in oversized towers. In any case, there is much room for improvement. Good and bad practices for intermediate draw design are described elsewhere (Kister, 1990). Intermediate draw malfunctions are by far most troublesome in refinery towers because of the large number of intermediate draws in each refinery main fractionator.

Table 13 shows that 35 of the 68 cases occurred in chimney trays, 31 in downcomer trapouts (including drawboxes). The other two involve vapor side draws. About half the reported cases involved either leakage at the draw or restriction to the exiting liquid. Leakage was a greater problem in total draw chimney trays, which need to be leak-proof, while restriction to the exiting liquid was more of a problem with downcomer trapouts that are short of residence time to degas the liquid. Trapped gas bubbles often choke outlet lines or aggravate a restriction problem.

Table 12. Why liquid distributors don't work.

No.	Cause	Cases	1992+	1991−	Ref.	Chem.	O/G
1	Plugging	20	12	8	7	10	2
2	Distributor overflow	17	15	2	2	5	4
3	Poor irrigation quality	14	4	10	1	12	—
4	Fabrication/installation mishaps	13	11	2	4	6	1
5	Feed entry problems	11	8	3	—	8	1
6	Poor hole pattern	8	6	2	1	6	—
7	Damage	8	7	1	5	2	—
8	Inferior redistribution	5	3	2	1	1	1
9	Flashing feeds	4	3	1	1	1	1
10	Out-of-levelness	4	3	1	—	4	—
11	Insufficient mixing	4	3	1	2	1	1

Table 13. Intermediate draw malfunctions.

No.	Cause	Cases	Chimney trays	Downcomer trapouts	1992+	1991−	Ref.	Chem.	O/G
1	Leakage at the draw	17	10	7	10	7	14	2	—
2	Restriction or vapor choke of draw line	15	4	11	7	8	13	2	—
3	Plugging, coking	7	4	3	6	1	4	1	1
4	Level measurement	6	4	2	3	2	4	—	—
5	Vapor impingement	4	4	—	4	—	2	—	1
	Miscellaneous		9	8					
			35	31					

Other malfunctions in Table 13 are plugging/coking and level measurement, each with six to seven case histories. It is incredible that people are attempting to measure liquid level on partial draw trays, but these are real cases. Finally, there are four cases reported in which vapor from chimneys impinged on the seal pan overflow or on the tray liquid.

MISLEADING MEASUREMENTS

With 64 case histories (Table 2), misleading measurements range from those leading to minor headaches when validating a simulation, to major contributors to explosions and accidents. The problem is ongoing, with the number of case histories reported in the last decade much the same as the number reported in the past. In proportion, Table 2 shows an abnormally low number of misleading measurements in chemical towers compared with those in refinery and olefins/gas towers. This does not match our experience. We have seen chemical towers in which we could not trust a single meter.

Incorrect measurements featured in 17 reported case histories (Table 14). In five cases, incorrect levels and control valve position indicators led to discharge of flammable liquid to the flare or fuel gas. Two of these discharges led to accidents with injuries or loss of life, two more to a fire, the fifth remained a near-miss. In four cases, incorrect level indications caused pump cavitation, some with damage. Non-optimum operation resulted from the remaining incorrect measurements. This finding emphasizes the importance of independent validation of level measurements, especially

Figure 7. Incorrect assembly of tray panels is one of the most common assembly mishaps. Here panels of fixed valve trays were installed upside down. Also note the rocks in the downcomer; fouling was also a major issue in this tower. This diagram highlights the importance of inspecting tray and packing installation.

Case 956 - The Overlong Feed Pipe

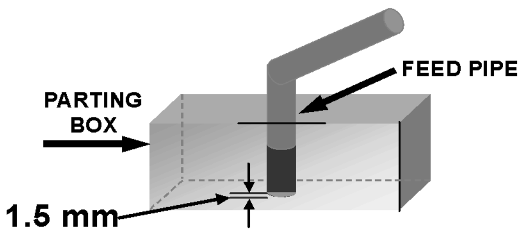

Figure 8. Poor fabrication and installation of packed tower distributors is one of the most common assembly mishaps and also one of the most common packing distributor malfunctions. Feeding packing distributors has also been a common source of problems. Here the feed pipe into a parting box clears the floor of the box by 1.5 mm, leaving a tiny crack for liquid exit. This diagram highlights the importance of tower inspection following construction or modifications. Based on Olsson (1999).

where there is a risk of flammable liquid discharge or pump cavitation. A 'what if' or hazop analysis should address what will happen if a level measurement fails.

Misleading level indication due to froth or lighter liquid comes next, with 12 case histories. It is surprising to find this issue so high up in Table 14. This is a major issue with some services, such as amine absorbers (three of the 12 cases), where either foam or hydrocarbon condensation in the tower base lowers the density of the tower base fluid below normal. In two other cases, an interface level measurement failed, probably due to emulsification or poor phase settling. Two other cases were attempts doomed to failure to measure liquid level on partial draw trays. The rest of the cases except one took place in foaming systems. So while in the specific situations mentioned, misleading level indication due to froth or foam is a major issue, in other services this is seldom troublesome.

Plugged instrument taps or lines and incorrect location of instruments follow, each with nine case histories. The consequences of plugged taps and incorrectly located instruments were similar to incorrect measurements (above). Four case histories resulted in explosions, four others in near misses, and the other 10 in non-optimum operation. Incorrect calibration and incorrect installation are other items in Table 14.

The encouraging news is that, out of the 64 case histories, only nine (about 15%) were due to the absence of a meter when one was needed. In most cases, the meters were there. However, to minimize misleading measurements they need to be continuously validated and properly installed, checked and inspected.

REBOILER MALFUNCTIONS

With 62 case histories (Table 2), reboilers are the most troublesome auxiliary equipment in a distillation system. The number of cases reported in the last decade is much the same as that reported for the four preceding decades. Fewer reboiler malfunctions were reported for chemical towers compared with refineries and gas plants. This is because two of the more troublesome reboiler types, the once-through thermosiphon and the kettle reboiler, are uncommon in chemical plants.

Table 15 breaks down these cases. Circulating thermosiphons, by far the most common type of reboiler, account for only about one-fifth of the troublesome case histories. This indicates quite a trouble-free performance that has characterized this reboiler type. The malfunctions reported are varied. They include excessive circulation causing loss of heat transfer or tower flooding; insufficient ΔT and resulting pinches; surging due to presence of a small quantity of low-boilers in the tower base, and others.

Even though kettle reboilers are far less common than thermosiphons, the number of kettle reboiler malfunctions in Table 15 exceeds that of circulating thermosiphons. Excess pressure drop in kettle reboiler circuits is the dominant malfunction (12 out of the 15 case histories), causing liquid to back up in the tower base beyond the reboiler return elevation. This high liquid level leads to premature flood and capacity loss. Kettle reboilers whose pressure drops are OK are seldom troublesome.

A very similar situation applies to once-through thermosiphons, the next item in Table 15. Nine case studies for this very uncommon reboiler type signify a very troublesome reboiler. Yet, like the kettle, six of the nine cases describe one dominant malfunction: leakage at the liquid draw that feeds the reboiler. This was discussed earlier in reference to the tower base malfunctions.

Forced circulation and internal reboilers have places in Table 15, each with four or five case histories. For internal reboilers, which are infrequently used, four cases is quite high, so they can be regarded quite troublesome. Also in Table 15 are side reboilers of various types, with five cases. Finally, 10 cases concern the condensing side of reboilers heated by latent heat, where accumulation of inerts (six cases) or problems with condensate draining (four cases) are occasionally troublesome. No heating-side malfunctions were reported for the heating side of sensible-heated reboilers.

CHEMICAL EXPLOSIONS

Chemical explosions occupy the tenth spot in Table 2, with 53 case histories. The words 'chemical explosion' are

Table 14. Misleading measurements.

No.	Cause	Cases	1992+	1991−	Ref.	Chem.	O/G
1	Incorrect measurement	17	9	8	10	1	3
2	Level instrument fooled by froth or lighter liquid	12	3	9	6	2	2
3	Plugged instrument tap or line	9	3	6	7	2	—
4	Incorrect location	9	6	3	4	3	—
5	Missing instrument	9	6	3	3	—	5
6	Incorrect calibration	5	4	1	2	1	1
7	Incorrect installation	4	1	3	—	—	2

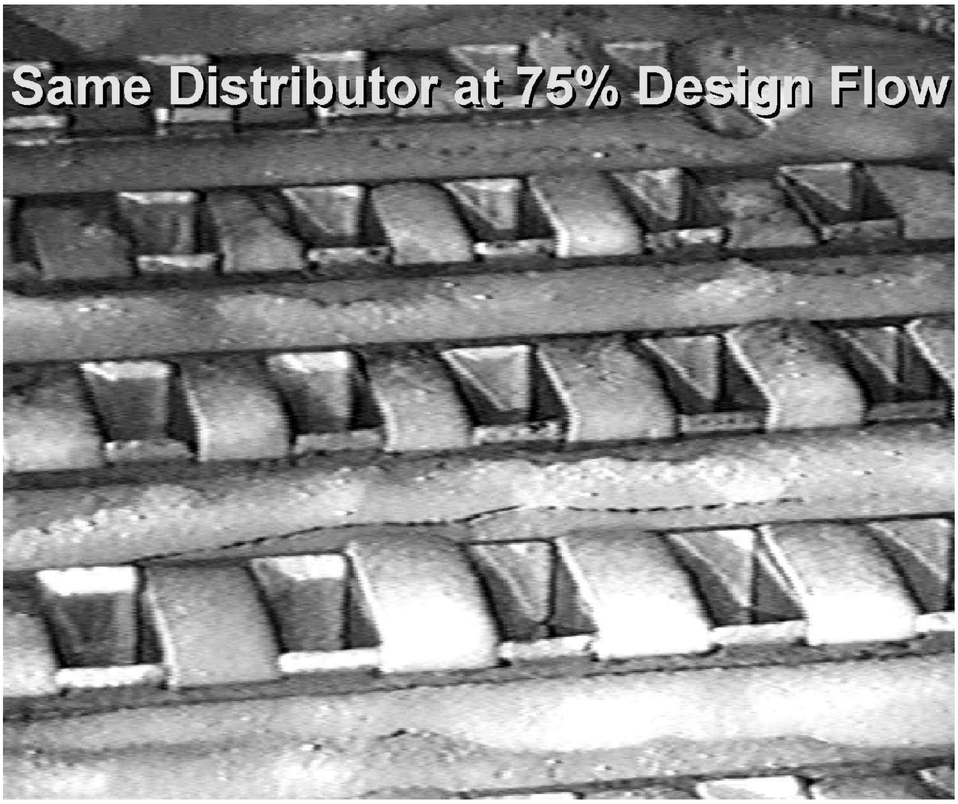

Figure 9. Next to plugging, overflow is the most common packing distributor malfunction. Here a packing distributor is water-tested *in-situ* during the turnaround (after cleaning). At 75% of the design liquid flow, the water is seen to reach the top of the vapor chimneys. This diagram highlights the importance of water-testing distributors.

Table 15. Reboiler malfunctions.

No.	Cause	Cases	1992+	1991−	Ref.	Chem.	O/G
1	Kettle reboilers	15	9	6	8	1	5
	Excess ΔP in kettle circuit	12	8	4	8	1	2
2	Circulating thermosiphons	13	2	11	4	5	4
3	Once-through thermosiphons	9	3	6	6	1	1
	Leaking draw pan to once-through	6	2	4	5	1	—
4	Non-condensables on condensing side	6	2	4	2	4	—
5	Forced circulation reboilers	5	1	4	1	3	—
6	Side reboilers	5	4	1	2	—	2
7	Condensate removal problems	4	2	2	1	—	2
8	Internal reboilers	4	4	—	4	—	—

used here to distinguish them from explosions due to rapid vaporization, e.g. when a pocket of water enters a hot oil tower. Table 16 gives a breakdown. Just over half of the explosions in our survey were initiated by exothermic decomposition reactions. Of the 27 decomposition-initiated explosions, seven were reported in ethylene oxide towers, six in peroxide towers, five in nitro compound towers, and three in sulfoxide towers. The remaining six came from a variety of towers. Decomposition-initiated explosions are associated with specific services. In these services, excessive temperatures (either a hot spot or a high tower base temperature) or excessive concentration of an unstable component initiated the decomposition. In some cases, the excessive temperature resulted from a rise in pressure due to rapid generation of non-condensables by a decomposition reaction. In others, precipitation or low base levels led to the concentration of an unstable component at the hot temperature. Catalysis by metal or catalyst fines and by air leaks have also contributed to some decomposition explosions.

The good news about decomposition explosions is that the number of case histories reported appears to be on the way down, with 19 explosions reported before 1991, and less than half of this number reported in the last decade.

Line fractures is the next leading cause of chemical explosions, with 13 case histories (Table 16). All cases, except one, were of lines carrying light hydrocarbons ranging from C_1 to C_4, and their fracture led to the formation of vapor clouds that ignited and exploded. Unlike decomposition reaction explosions, which appear to be on the decline, the number of line fracture explosions had been much the same over the last decade compared with that before 1991. Half the reported cases came from either gas or olefins towers, indicating that line fracture is a major issue in those towers. The other half came from refinery towers.

Less common yet important causes of explosions in towers are commissioning operations and hydrocarbon releases, each with five to six case histories. Almost all these case histories were reported before 1991. In all the reported commissioning cases, an operation such as purging, flushing or deinventorying, led to the formation of an explosive mixture. Three of the five cases under hydrocarbon/chemical release involved releasing C_4 hydrocarbons trapped in a plugged or frozen valve. Finally, violent chemical reactions led to three explosions, all prior to 1991.

This section of the survey emphasizes the requirement for extremely cautious design, operation and maintenance in towers handling compounds prone to exothermic runaway decomposition or violent reactions, and in light hydrocarbons (especially C_1–C_4) towers. Lessons drawn from previous accidents and near-misses must be incorporated into existing and new facilities. Although other services reported fewer explosions, the possibility of their occurrence should always be considered, and the appropriate preventive measures incorporated.

FOAMING

Foaming is eleventh in Table 2, with 51 case histories. Unlike most of the other malfunctions, foaming is a service-specific phenomenon. Table 17 lists the services in which foaming was reported. About 35% of the cases reported were in ethanolamine absorbers and regenerators that absorb acid gases such as H_2S and CO_2 from predominantly hydrocarbon gases. Another 10% were also in acid gas absorption service, but using alternative solvents such as

Table 16. Causes of chemical explosions in tower.

No.	Cause	Cases	1992+	1991−	Ref.	Chem.	O/G
1	Decomposition						
	Ethylene oxide towers	7	3	4	—	7	—
	Peroxides	6	—	6	—	6	—
	Nitro compounds	5	1	4	—	5	—
	Sulfoxides	3	3	—	—	3	—
	Others	6	1	5	—	6	—
	Total	27	8	19		27	
2	Line fracture	13	7	6	6	1	6
3	Commissioning operations	6	1	5	2	3	1
4	Hydrocarbon/chemical release	5	2	3	2	2	1
5	Violent reactions	3	—	3	1	2	—

Case 883 - High Hydraulic Gradient Causing Overflow into Chimneys

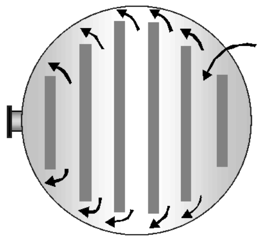

Figure 10. Excessive hydraulic gradients have been the cause of overflows both in liquid distributors and on intermediate draw trays. Here an excessive hydraulic gradient led to liquid overflow down the vapor chimneys of a total draw tray. Based on Kister *et al.* (2001).

hot potassium carbonate (hot-pot), caustic and sulfinol. Another 10% were in absorbers that use a hydrocarbon solvent to absorb gasoline and LPG from hydrocarbon gases. Since these services are most common in refineries and gas plants, more foaming cases originate from these industries than from chemicals (Table 2). There does not appear to be much change between the number of cases reported over the last decade and those reported in the previous four.

In addition to Table 17, one case history of foaming was reported in each of the following services: *chemical*—aldehyde column, soapy water/polyalcohol oligomer, solvent residue batch still, ammonia stripper, DMF absorber (mono-olefins separation from diolefins), cold water H_2S contactor (heavy water GS process); *refinery*—crude stripping, visbreaker fractionator, coker fractionator, hydrocracker depropanizer; *gas*—sulfinol absorber, glycol contactor; and *olefins*—high-pressure condensate stripper.

Table 18 surveys factors that induced or promoted foaming. In about 30% of the reported cases, solids catalyzed foaming. Solids could have catalyzed foaming in many of the others, but this was not specifically reported in the other cases. In eight cases, the foaming was caused or catalyzed by an additive such as a corrosion inhibitor. Hydrocarbon condensation into aqueous solutions, certain feedstocks, small downcomers and low temperatures were reported to promote foaming. The additives and hydrocarbon condensation appear to be most troublesome in olefins/gas towers.

SIMULATIONS

Simulations is next in the twelfth place in Table 2 with 47 case histories, most of which were reported in the last decade. Table 2 shows that among the last decade's malfunctions (the 1992+ column), simulations were in the equal sixth spot. Simulations have been more troublesome in chemical than in refinery towers, probably due to the difficulty in simulating chemical non-idealities. The subject was discussed in detail elsewhere (Kister, 2002).

Table 19 shows that the three major issues that affect simulation validity are using good VLE predictions, obtaining a good match between the simulation and plant data, and using graphical techniques to troubleshoot the simulation. Case histories involving these issues account for about two thirds of the cases reported in the literature. Add to this ensuring correct chemistry and correct tray efficiency and these items account for 85% of the cases reported in the literature.

An in-depth review of the VLE case (Kister, 2002) reveals three major troublespots. Most cases involved close-boiling components, either a pair of chemicals (e.g. hydrocarbons) of similar vapor pressures, or a non-ideal pair close to an azeotrope. Correctly estimating non-idealities has been another VLE troublespot. A third troublespot is characterization of heavy components in crude oil distillation. This is a major troublespot in simulating refinery vacuum towers. Very few case histories have been reported with other systems. It appears that VLE prediction for reasonably high volatility systems (e.g. ethane–propane, or methanol–ethanol) is not frequently troublesome.

Table 17. Services where foaming was reported.

No.	Cause	Cases	1992+	1991−	Ref.	Chem.	O/G
1	Amine absorbers and regenerators	18	12	6	6	—	8
2	Hydrocarbon absorbers	5	2	3	3	—	1
3	Solvent deasphalting	3	3	—	3	—	—
4	Extractive distillation	2	—	2	—	2	—
5	Crude preflash towers	2	—	2	2	—	—
6	Caustic absorbers (acid gas absorption)	2	2	—	—	—	2
7	Hot pot (potassium carbonate) absorbers	2	1	1	—	—	2

Table 18. Foams catalyzed or promoted by . . . .

No.	Cause	Cases	1992+	1991−	Ref.	Chem.	O/G
1	Solids	15	9	6	5	4	6
2	Additives	8	3	5	1	1	5
3	Hydrocarbon condensation (into aqueous solution)	5	3	2	1	—	4
4	Some, but not all feedstocks	4	—	4	3	1	—
5	Small downcomers	3	—	3	1	1	1
6	Low temperatures	2	—	2	1	1	—

Table 19. Issues affecting simulation validity.

No.	Cause	Cases	1992+	1991−	Ref.	Chem.	O/G
1	Poor VLE predictions	13	9	4	3	8	2
2	Simulation not matching plant data	13	13	—	6	4	3
3	No graphical checks	10	9	1	2	6	2
4	Incorrect chemistry or process sequence	5	3	2	—	5	—
5	Incorrect efficiency prediction	5	1	4	1	4	—

The major problem in simulation validation appears to be obtaining a reliable, consistent set of plant data. Getting correct numbers out of flowmeters and laboratory analyses appears to be a major headache requiring extensive checks and rechecks. Compiling mass, component and energy balances is essential to catch a misleading flowmeter or composition. One specific area of frequent mismatches between simulation and plant data is where there are two liquid phases. Here comparison of measured to simulated temperature profiles is invaluable for finding the second liquid phase. Another specific area of frequent mismatches is refinery vacuum towers. Here the difficult measurement is the liquid entrainment from the flash zone into the wash bed, which is often established by a component balance on metals or asphaltenes.

The key graphical techniques for troubleshooting simulations are the McCabe–Thiele and Hengstebeck diagrams, multicomponent distillation composition profiles, and in azeotropic systems, residue curve maps. These techniques permit visualization and insight into what the simulation is doing. These diagrams are not drawn from scratch; they are plots of the composition profiles obtained by the simulation using the format of one of these procedures. The book by Stichlmair and Fair (1998) is loaded with excellent examples of graphical techniques shedding light on tower operation.

In chemical towers, reactions such as decomposition, polymerization and hydrolysis are often unaccounted for by a simulation. Also, the chemistry of a process is not always well understood. One of the best tools for getting a good simulation in these situations is to run the chemicals through a mini plant, as recommended by Ruffert (2001).

In established processes, such as separation of benzene from toluene or ethanol from water, estimating efficiency is quite trouble-free in conventional trays and packings. Problems are experienced in a first-of-a-kind process or when a new mass transfer device is introduced and is on the steep segment of its learning curve.

LEAKS

Leaks are in the thirteenth place in Table 2 with 41 case histories. Table 2 shows that leaks are equally troublesome in chemical, refinery and gas/olefins towers, and have been equally troublesome in the four decades preceding 1991 as in the last decade.

Table 20 lists the most troublesome leaks. Heat exchanger leaks top the list with 16 case histories. Of the 16, nine were reboiler tube leaks including two cases from fired reboilers. Six were leaks in preheaters and pumparound exchangers, most in refineries, and only one was a condenser tube leak. Most of the exchanger tube leaks led to product contamination. In two, the leak also led to instability. In one case, it led to rapid vaporization pressure surge, and in one to overchilling and an explosion. In at least one of the two fired reboiler cases, the tube leak led to a fire.

Closely following the heat exchanger leaks are leaks of chemicals to atmosphere or air into the tower. Of the 13 atmospheric leaks, four led to explosions, one to a fire, while six discharges of flammable materials remained near-misses. With six case histories, two other types of leaks follow: chemicals leaking in/out of the tower from/to other equipment, and seal/oil leaks from pumps and compressors. Of the six chemical leaks reported, one led to an explosion with unstable chemicals, one to a fatal accident, and two to major damage. It appears that leaks into or out of the tower, whether to/from atmosphere or to/from other equipment, are some of the prime safety hazards in towers. Consequences of the compressor/pump seal leaks were less severe, although one caught fire, and another led to a pressure surge, damaging tower internals.

CONDENSERS

Condensers are in fifteenth place in Table 2 with 31 case histories, evenly split between chemical, refinery and olefins/gas towers. Of these 19 were reported before 1991, and 12 in the last decade, indicating a slight decline in condenser malfunctions. Table 21 gives the breakdown. Two major headaches with condensers, namely condenser fouling and corrosion, have been excluded from our survey, being primarily functions of the system, impurities and metallurgy. Fouling and corrosion have only been included in our survey if induced or enhanced by a process, equipment or operational reason.

Table 20. Leaks.

No.	Cause	Cases	1992+	1991−	Ref.	Chem.	O/G
1	Heat exchangers	16	11	5	6	6	4
	Reboiler tube	9	7	2	2	4	3
	Preheater, pumparound exchanger	6	4	2	4	1	1
	Condenser	1	—	1	—	1	—
2	Column chemicals to atmosphere or air into tower	13	9	4	4	6	1
3	Chemical leaking into or out of tower from other equipment	6	1	5	2	4	—
4	Pumps, compressors	6	1	5	1	3	2

A famous statement made by Smith (1974) that to troubleshoot a condenser one needs to ask three key questions: 'Is it clean? Is it vented? Is it drained?' Table 21 verifies that, indeed, once fouling is excluded, inadequate venting (12 cases) and inadequate condensate removal (six cases) constitute 18 out of the 31 reported condenser case histories. Other issues do not get close, but may be important in specific situations. These include flooding in or entrainment from partial condensers, especially knock-back condensers, an unexpected heat curve resulting from Rayleigh condensation or presence of a second liquid phase, and maldistribution between parallel condensers.

CONTROLS

Three control malfunctions, each with similar numbers of case histories, 29–33, are in the fourteenth, sixteenth and seventeenth spots in Table 2: composition control issues, control assembly difficulties and condenser and pressure control problems. Table 2 shows that these malfunctions have been equally troublesome in the four decades preceding 1991 as in the last decade. The composition and assembly malfunctions dominate in chemicals and olefins/gas towers, where splits are usually much tighter than between petroleum products in refinery towers. Pressure and condenser control malfunctions dominate in refinery towers. One reason for this is refiners' extensive use of hot vapor bypasses, which can be particularly troublesome (below).

Tables 22–24 give a breakdown. There are three major composition control issues. Topping the list (Table 22), with 17 cases, is finding a suitable temperature control tray. This is followed by achieving successful analyzer controls (12 cases) and obtaining adequate pressure compensation for temperature controls (nine cases). The search for a suitable control tray appears to be less of an issue in the last decade than it had been previously, probably due to the publication of an excellent method by Tolliver and McCune (1980). On the other hand, successful analyzer controls are commonly associated with advanced controls, and have grown in significance in the last decade.

Turning to control system assembly difficulties, over half of the reported malfunctions resulted from violation of three basic synthesis principles (Table 23). The first is violation of the material balance control principle. The second is violation of what has become know in some circles as 'Richardson's rule', which states (Richardson, R.E., Union Carbide, Private Communication) 'Never control a level on a small stream.' The third is attempting to simultaneously control two compositions in a two-product column without decoupling the interference between them.

Turning to condenser and pressure control problems (Table 24), a third of the cases were problems with hot vapor bypasses, practically all in refineries. There is little doubt that this is potentially the most troublesome pressure control method. Most of the problems are due to poor configuration of hot vapor bypass piping, which evolves from poor understanding of its principles. When configured correctly, the author's experience is that hot vapor bypasses are seldom troublesome. Other major items in Table 24 are problems with coolant throttling, including fouling and instability when throttling cooling water flow, and problems with vapor flow throttling, most of which result from low points that accumulate condensate in vapor lines.

OVERPRESSURE RELIEF ISSUES

With 24 reported case histories, overpressure relief issues take the eighteenth place in Table 2. The incidents are evenly split between chemical, refinery and olefins/gas

Table 21. Causes of condenser malfunctions.

No.	Cause	Cases	1992+	1991−	Ref.	Chem.	O/G
1	Inadequate venting	12	5	7	9	3	—
2	Inadequate condensate removal	6	2	4	1	3	1
3	Flooding/entrainment in partial condenser	3	—	3	—	1	1
4	Exchanger hardware issues	3	1	2	1	2	—
5	Maldistribution between parallel condensers	3	2	1	2	1	—
6	Unexpected heat curve	2	—	2	—	2	—

Table 22. Composition control issues.

No.	Cause	Cases	1992+	1991−	Ref.	Chem.	O/G
1	Finding a suitable temperature control tray	17	7	10	5	11	1
2	Achieving successful analyzer control	12	7	5	5	4	3
3	Pressure compensation for temperature controls	9	4	5	2	6	1

Table 23. Control system assembly difficulties.

No.	Cause	Cases	1992+	1991−	Ref.	Chem.	O/G
1	No material balance control	7	5	2	1	5	1
2	Level or difference control on small stream	6	5	1	5	1	—
3	Controlling two compositions simultaneously	5	3	2	—	1	4

Table 24. Condenser and pressure control problems.

No.	Cause	Cases	1992+	1991−	Ref.	Chem.	O/G
1	Hot vapor bypass	10	4	6	9	—	—
2	Coolant throttling	5	1	4	2	2	—
3	Vapor flow throttling	5	3	2	2	1	1
4	Throttling condenser inlet/outlet						
	Valve in condensate line	2	1	1	1	—	—
	Flooded drum	2	1	1	1	—	1
	Valve in vapor inlet	2	1	1	1	—	—

plant towers. There has been a slight decline in incidents reported in the last decade compared to the preceding four.

Table 25 gives a breakdown. Topping the issues is correctly setting the relief requirements (seven cases). In some cases, small modifications to controls, steam supply or vacuum breaking gas entry permitted large reduction in relief requirements. In others, towers blew up because their relief capabilities were short of the relief loads. A surprisingly large number of refinery cases (six) reported overpressure in the tower or in downstream equipment due to the unexpected presence of lights or a second liquid phase. Four cases were reported in which hazardous materials were discharged to atmosphere from a relief valve, including hydrocarbon liquids and gases that caught fire. Finally, in three reported cases relief valves were incorrectly set.

THE 10–20 CASE HISTORIES GROUP

Thirteen malfunctions follow, each with 10–20 case histories.

Faulty feed arrangement in tray towers contributed 18 case histories, more from the last decade than the four decades before. Six of these describe maldistribution of feed into multipass trays, mostly in large refinery towers. Four of the cases described feed entries that induced vapor or flashing into downcomers. Chemical towers usually employ one or two pass trays, which are less prone to maldistribution, and therefore report fewer cases of feed malfunctions (Table 2).

Fires that did not lead to explosions were reported in 18 case histories. Six of these were structured packing fires while a tower was open for maintenance during turnaround. In all these fires, pyrophoric or combustible deposits in the packings played a role. These fires damaged the packings, but in a couple they also damaged the tower shell. Of the six packing fires reported, five took place in refinery towers. Most of these cases were described in an excellent paper by Bouck (1999), which also reviews the chemistry behind these fires and many of the solutions practiced by the industry. Of the remaining fire case histories, three were caused by line fracture, another three by unexpected backflow, two by opening the tower before complete cooling or removal of combustibles, and two others by atmospheric relief that was ignited.

Intermediate component accumulation was troublesome in 17 case histories, evenly split between the last decade and the four preceding decades. A disproportionally large number of cases came from olefins and gas plant towers, where hydrates and freeze-ups (three cases) resulted from such accumulation. Water accumulation in de-ethanizers of refineries and gas processing plants contributed five cases. In eight of the case histories, the accumulation led to periodic flooding in the tower. Other problems induced by the accumulation were corrosion (two cases), inability to draw a product stream (three cases), product losses (two cases), and product contamination (two cases).

Chemical releases to the atmosphere from distillation and absorption towers was described in 17 cases. Of these, three were caused by inadvertent venting or draining to the atmosphere, five were caused by unexpected backflow, another three resulted from runaway reactions, cooling water loss or vessel boilover and another three were caused by sudden clearing of trapped chemicals. The numbers of atmospheric releases in the last decade is well below that for the four preceding decades, probably due to the tighter requirements on safety and the environment in recent years.

Subcooling was troublesome in 16 case histories, more in the last decade than in the four preceding decades. In seven cases, subcooling enhanced internal condensation and reflux, which hydraulically overloaded trays, packing or liquid distributors. In seven cases, subcooling caused excessive quenching at the inlet zone, diverting light components into the section below with consequent product losses, excessive reboil requirement or component accumulation.

Low liquid loads handling difficulties in tray towers were described in 14 case histories. Practically all of these described one out of two problems: either leakage of liquid from the tray deck, causing the trays to dry out, or vapor breaking into downcomers, causing difficulties (even making it impossible) in establishing a downcomer seal. In many cases, inability to seal the downcomer made it impossible for liquid to descend, and led to flooded trays above the unsealed downcomer.

Reboiler and preheater controls were troublesome in 14 case histories. The cases were equally split between refineries and olefins/gas towers. Out of the 14, six involved preheaters, and two involved fired heaters. Temperature

Table 25. Overpressure and relief issues.

No.	Cause	Cases	1992+	1991−	Ref.	Chem.	O/G
1	Relief requirement issues	7	3	4	—	2	1
2	Overpressure due to unexpected component entry	6	1	5	5	—	—
3	Hazardous atmospheric discharges	4	2	2	1	3	—
4	Poor setting of relief pressure	3	3	—	—	2	1

control problems with preheaters were common, in most cases due to disturbances in the heating medium or due to vaporization in the feed lines. All the reboiler case histories reported involved a latent-heat heating medium. Hydraulic problems were common when the control valve was in the steam/vapor line to the reboiler, while loss of reboiler condensate seal was common when the control valve was in the condensate lines out of the reboiler.

A second liquid phase, either present where undesirable, or absent where desired, was troublesome in 13 case histories. Most of these came from chemical towers. In five cases, a fault in the overhead decanter or its piping caused refluxing of the undesirable phase; in another case, a similar fault caused the undesirable phase to go into the product. In two more cases, a component entering or building up in the system stopped overhead decanter action. In four other cases, the problem was inability to decant a second liquid phase that formed inside the tower.

Heat integration generates complexity and operability issues, which led to 13 case histories. There were also control problems, especially with preheaters, but these are grouped under a different heading in this section. Most of these cases came from refineries and olefins/gas towers, where a high degree of heat integration is practiced. Most of the cases involve the simpler forms of heat integration: multifeed arrangements (four cases), preheaters (three cases), inter-reboilers (two cases), and recycle loops (two cases). In some of these cases, the fix was as simple as bypassing a stream around the preheater or bypassing a smaller feed stream around the tower.

Poor packing efficiency for reasons other than poor liquid or vapor distribution was reported in 12 cases, mostly recent, evenly split between chemical, refinery and olefins/gas towers. Of the 12, four were because the packed beds were too long. In wash sections of two refinery vacuum towers, this led to drying up and coking; in the other two cases, the long bed gave poor packing efficiency. In four cases, a unique system characteristic, such as high pressure in structured packings, high hydrogen concentration, high viscosity or surface tension, caused the loss of efficiency. The other cases involved corrosion, chipping, and oil layers on packing in aqueous service.

Tray layouts were troublesome in 12 case histories. In three, downcomer inlet areas were short due to design, assembly or obstruction by a truss; in two a restriction occurred at an inlet weir. Other cases described insufficient hole area, incorrect number of passes, undersized manways, poorly designed bottom seal pan, and undefined non-standard design features.

Tray weep was troublesome in 11 reported case histories. Surprisingly, nine of the 11 took place in valve trays, which are inherently more weep-resistant than sieve trays. Most of the problems were cured by blanking or replacing with leak-resistant valve units. The number of weeping case studies in the last decade is well below the number in the previous four decades.

Random packing supports or hold-downs were troublesome in 11 case histories. These were split evenly between refinery, chemicals and olefins/gas plant towers, and between the last decade and the four preceding decades. In seven of these, insufficient open area on the support or hold-down caused a capacity restriction. In three, packing migrated through the supports. In two, I beams supporting the bed or stiffening the hold-down interfered with vapor or liquid distribution.

THE LESSONS LEARNT: AN EPILOGUE

Plugging/coking has been, and will continue to be the undisputed leader of tower malfunctions. Coking, scale and corrosion products, and salting out have been the major sources of plugging in refineries, with most coking incidents induced by insufficient wash rates in refinery vacuum towers. In chemical towers, precipitation, solids in feed, polymer, and scale and corrosion products, have been the major sources. The case histories are evenly split between tray and packed towers, with packing distributors and tray active areas the most likely parts to plug (the exception being refinery vacuum towers).

The tower base and reboiler return region is the most troublesome tower internal. About half the malfunctions were base level exceeding the reboiler return/vapor feed inlet, causing tower flooding, and less frequently, also tray or packing uplift. Faulty base level measurement, restriction in the bottom outlet and excessive kettle pressure drop are the prime causes of the high liquid levels. Of the other malfunctions in this region, vapor maldistribution to a packed bed above and impingement by the entering gas are the most prominent.

The leading cause of tower internals damage (excluding fires, explosions and implosions) is water-induced pressure surges in refinery towers. The key to prevention is keeping the water out. Water sources are numerous, the most common being undrained stripping steam lines. The number of water-induced pressure surges has been well down in the last decade. Other common causes of internals damage have been insufficient mechanical resistance, high base liquid level, downward flow through valve trays, and rapid upward flow. Many other causes are not far behind.

Malfunctions induced by commissioning, startup, shutdown and abnormal operation are less in the last decade compared to the four preceding decades. Water removal, blinding/unblinding, and backflow are the leading troublespots and account for more than half the case histories. Mishaps while dehydrating refinery fractionators during startups led to many of the pressure surge incidents above. Blinding/unblinding mishaps and backflow caused chemical releases, explosions, fires and personnel injuries during abnormal operation. In the olefins and gas towers, overchilling has been a major issue.

Assembly mishaps, identified as the fastest growing malfunction in our previous survey, appear to have leveled off in growth. Mishaps involving liquid distributors lead the list. Incorrect assembly of tray panels, improperly tightened nuts and bolts, obstruction and misorientation at tray feeds and draws, and leaking collector trays have also been troublesome. Some packing assemblies such as dumping of ceramic packings and fastening of grid beds have been troublesome.

After the tower base, packing liquid distributors have been the most troublesome tower internal. In chemical towers alone, liquid distributor malfunctions outnumber any of the previous malfunctions. About half the reported distributor problems involved plugging and overflow. Poor irrigation quality, which is the focus of the literature on the subject, only accounts for about 20% of the distributor malfunctions. The other major liquid distributor troublespots were fabrication and assembly and feed entry. Liquid distributor malfunctions have been on the way up in the last decade.

Intermediate draws are the third most troublesome tower internal, especially in refinery towers. Intermediate draw malfunctions have been on the way up in the last decade, and are equally split between chimney tray draws and downcomer trapouts (including draw boxes). Leakage at the draw (especially in chimney trays) and restriction or vapor choke of the draw line (especially in downcomer trapouts) were the dominant malfunctions.

Misleading measurements, ranging from those leading to minor problems to those contributing to explosions and accidents, have been troublesome. Incorrect measurements have been most troublesome, with plugged instrument taps, incorrect location, and missing instruments following. In some services, fooling a level measurement by froth, foam or a lighter liquid has been troublesome.

Reboiler malfunctions are common with two less common reboiler types: kettle reboilers, where excess pressure drop in the reboiler circuit is the dominant malfunction, and once through reboilers, where leakage at the liquid draw feeding the reboiler is the dominant malfunction. Circulating thermosiphon reboilers, the most common reboiler type, have been relatively trouble-free.

Chemical explosions and foaming have been major problems in specific services. Most of the explosions were caused either by a decomposition runaway reaction or by rupture of a line carrying hydrocarbons in the C1–C4 range. High temperature or concentration of unstable components usually triggered the decomposition.

Over half of the foaming incidents were reported in amine or other acid-gas absorbers and regenerators or in hydrocarbon absorbers. In over half the incidents, foaming was promoted by solids, additives, or hydrocarbon condensation into an aqueous solution.

Simulations have most frequently gone wrong due to incorrect VLE predictions, poor match of the simulation results to plant data, and lack of graphical checks. Incomplete understanding of the chemistry and poor tray efficiency predictions in new services have also been troublesome.

Leaks in tower heat exchangers and atmospheric leaks have been common, leading to explosions, fires and contamination.

Condensers did not work mainly due to inadequate venting or inadequate condensate removal.

Finding the best control tray, analyzer control problems and adequate pressure compensation to temperature controls have been the greatest difficulty experienced with composition control.

The main problems experienced with control system assembly have been violation of three basic principles: material balance control, not controlling levels on small streams, and not controlling two compositions simultaneously.

The most troublesome condenser and pressure control method has been the hot vapor bypass.

Correctly setting the relief requirements, and overpressure due to unexpected presence of lights, have been the major overpressure relief issues.

REFERENCES

AMOCO, 1984a, *Hazard of Water*, 6th edn (AMOCO, Chicago, IL, USA).

AMOCO, 1984b, *Hazard of Steam*, 2nd edn (AMOCO, Chicago, IL, USA).

AMOCO, 1984c, *Safe Ups and Downs*, 3rd edn (AMOCO, Chicago, IL, USA).

Anonymous, 2000, A major incident during startup, *Loss Prev Bull*, 156: 3.

Bouck, D.S., 1999, Vacuum tower packing fires, in *API Operating Practices Symposium*, 27 April (with Addendum/Revisions, 21 February 2000).

Bowman, J.D., 1993, Troubleshoot packed towers with radioisotopes, *Chem Eng Progr*, September: 34.

Charlton, J.S. (ed.), 1986, *Radioisotope Techniques for Problem Solving in Industrial Process Plants* (Gulf Publishing, Houston, TX, USA).

Ellingsen, W.R., 1986, Diagnosing and preventing tray damage in distillation columns, *DYCORD 86, IFAC Proceedings of International Symposium on Dynamics and Control of Chemical Reactors and Distillation Columns*, Bournemouth, UK, 8–10 December.

France, J.J., 1993, Troubleshooting distillation columns, Paper presented at the *AIChE Spring Meeting*, Houston, TX, March.

Kister, H.Z., 1990, *Distillation Operation* (McGraw-Hill, New York, USA).

Kister, H.J., 1997, Are column malfunctions becoming extinct or will they persist in the 21st century? *Trans IChemE, Part A, Chem Eng Res Des*, 75: 563.

Kister, H.Z., 2002, Can we believe the simulation results? *Chem Eng Progr* October: 52.

Kister, H.Z., 2003, Recent trends in distillation tower malfunctions. Paper accepted for presentation at the *Distillation Topical Conference, Spring National AIChE Meeting*, New Orleans, LA, March–April.

Kitterman, L., 1976, Tower internals and accessories, Paper presented at *Congresso Brasileiro de Petroquimica*, Rio de Janeiro, 8–12 November.

Kletz, T.A., 1988, *What Went Wrong?* 2nd edn (Gulf Publishing, Houston, TX, USA).

Lieberman, N.P., 1988, *Process Design for Reliable Operation*, 2nd edn (Gulf Publishing, Houston, TX, USA).

Lieberman, N.P., 1991, *Troubleshooting Process Operations*, 3rd edn (PennWell Books, Tulsa, OK, USA).

Lieberman, N.P. and Lieberman, E.T., 1997, *A Working Guide to Process Equipment* (McGraw-Hill, New York, USA).

Olsson, F.R., 1999, Detect distributor defects before they cripple columns, *Chem Eng Prog*, October: 57.

Ruffert, D.I., 2001, The significance of experiments for the design of new distillation column sequences, in *Distillation 2001: Frontiers in a New Millennium, Proceedings of Topical Conference, AIChE Spring National Meeting*, Houston, TX, 22–26 April, p. 133.

Sattler, F.J., 1990, Nondestructive testing methods can aid plant operation, *Chem Eng*, October: 177.

Shieveler, G.H., 1995, Use heavy-duty trays for severe services, *Chem Eng Progr*, August: 72.

Sloley, A.W., Zygula, T.M. and Kolmetz, K., 2001, Troubleshooting practice in the refinery, Paper presented at the *AIChE Spring National Meeting*, Houston, TX, April.

Smith, R.A., 1974, Question: is it clean? *Chem Eng Progr*, 70(7): 78.

Stichlmair, J.G. and Fair, J.R., 1998, *Distillation Principles and Practice* (Wiley, New York, USA).

Tolliver, T.L. and McCune, L.C., 1980, Finding the optimum temperature control trays for distillation columns, *InTech* 27(9): 75.

Xu, S.X. and Martos, L., 2001, Flooding phenomenon in distillation columns and its diagnosis, part I, trayed columns, in *Distillation 2001: Frontiers in a New Millennium, Proceedings of Topical Conference, AIChE Spring National Meeting*, Houston, TX, 22–26 April, p. 123.

ADDRESS

Correspondence concerning this paper should be addressed to Mr H. Z. Kister, Fluor, Aliso Viejo, CA, USA.
E-mail: henry.kister@ fluor.com

This paper was a plenary lecture at the International Conference on Distillation and Absorption held in Baden-Baden, Germany, 30 September–2 October 2002. The manuscript was received 8 July 2002 and accepted for publication after revision 18 November 2002.