# Quenching the wild wells of Kuwait

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The last of the hundreds of oil-well fires left in Kuwait by Iraq should be capped this week. Although progress has been remarkable, a mechanism is needed to cope with future large-scale disasters.

BEFORE the liberation of Kuwait by US forces and their coalition partners, the government of Iraq detailed about 1,000 military explosive experts and 30–40 engineers, together with the enforced assistance of people who worked in the oil fields, to sabotage and set fire to the 1,000 or so oil wells of Kuwait. Thirty to forty pounds of the military explosive C4 were used with sandbag tamping. Sabotage attempts were made on 732 wells and were successful in damaging and starting oil flows in 690 of them, about 640 of which were also set on fire. Data are scarce, but it seems that something near 2–3 million barrels per day were being lost initially, considerably less than the 6 million barrels per day estimated by Kuwaiti authorities, yet still representing a loss of as much as US$50 million per day.

The dollar loss was not the only consequence of this act of sabotage: the heavy flows damaged the underground reservoirs; plumes of smoke and combustion products from the flames created serious health and environmental problems, not only in Kuwait but at much larger distances; and lakes of oil developed, more than a metre thick and many square kilometres in extent, creating additional difficulties.

Iraqi land mines and unexploded coalition munitions in Kuwait were expected to add to the hazard and delay, as were administrative impediments. The scale of the disaster was unique: there had never before been more than five wells simultaneously out of control. Earlier experience had shown that an expert well-control company could typically kill and control a burning well in 2 weeks, although months might occasionally be needed. With an estimated 18 teams potentially available, it was believed that 700 wild wells would take several years to control. Numerous ideas were proposed by specialists to deal with the problems of bringing the oil fields under rapid control. But oil wells are far more complex than many realized and the vast majority of the ideas were poorly suited to the challenge. For example, the big problem is not in extinguishing the fires, but in stopping the flow of oil and gas with low risk to the well-control teams. Moreover, innovative techniques were thought to be required to deal with large numbers of mines in non-combat circumstances. There was initial concern, later shown to be groundless, that wells would be booby-trapped. Mine fields were later found to have been laid outside, but not within, the oil fields.

We, together with Howard Ris and the Union of Concerned Scientists, organised a symposium (later called Desert Quench) in Washington, DC, on 2–3 April this year, to bring together scientists and experts in wells and well control — including several people from the Kuwait Petroleum Company — to address these problems, discuss the usual solutions, and to search for means to expedite control of the wells and deal with challenges posed by the mines.

The problems are interesting, some remaining open despite the speed and efficiency of the capping-in effort so far. By early October, more than 550 wells had been brought under control, with remaining 140 expected to be capped by the end of this week. Nearly 30 crew were used.

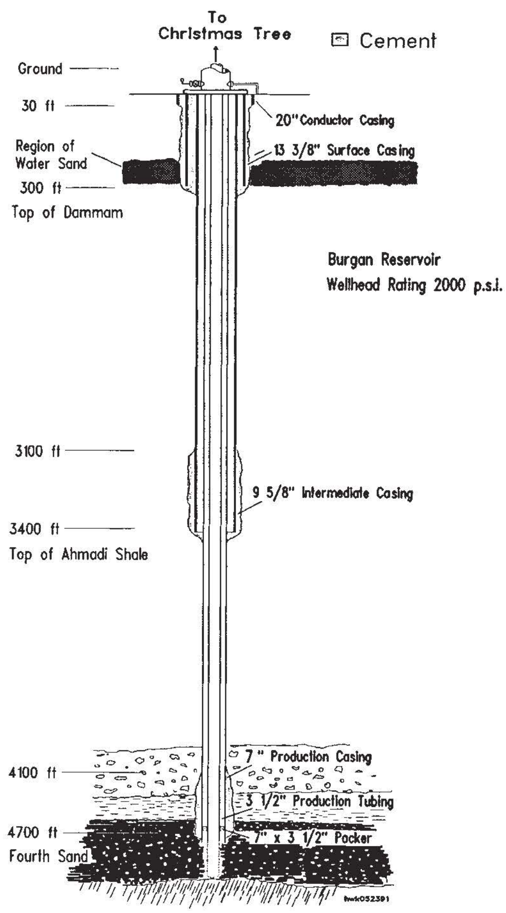


FIG. 1 A typical oil well in the greater Burgan field, south of Kuwait city, not to scale.

It is evident that we are not the most knowledgeable people about well control, but we write to provide some relevant information, and to indicate how people could contribute to the solution of such problems and similar ones that

## The classical approach

The classical and well-practiced control of a wild well involves delivering cubic metres of water per minute to the equipment involved close to the fire, to keep it at operating temperature at a distance at which it would normally melt, and to cool the corrugated-iron shields behind and below which firefighters work to remove debris by the use of caterpillar-tracked bulldozers, cranes and large water-cooled hooks. Getting the fire jetting straight up is almost always the first order of business. For instance, Red Adair in his successful quenching of the Devil's Cigarette Lighter in Algeria (a blazing plume of 10 million $m^3$ of gas per day), first drilled water wells to fill polyethylene-lined reservoirs 10-ft deep and the size of three football fields, about 30,000 $m^3$ of water. (We hope that readers will tolerate a mixture of English and metric units, English being conventional in the oil fields. Conversion is readily achieved as follows: 1 (42-gallon) barrel = 0.159 $m^3$; 1 inch = 2.54 cm; 1 foot = 30.48 cm; 1 pound per square inch (p.s.i.) = 0.0703 kg $cm^{-2}$ = 6,980 N $m^2$.) Before he snuffed out the fire, Adair cleared the site to table-top neatness and cooled the vicinity of the fire for days to ensure that there would be no re-ignition when the fire was put out. The flame is snuffed out in the classical method by exploding hundreds of kilograms of high explosive carefully shaped inside a thermally insulated oilfield drum supported by a crane at the base of the flame, and detonated from the safety of a trench or burrow at a distance of hundreds of metres.

Adair's biography, *An American Hero*, by P. Singerman (Little, Brown, 1990) is a highly readable account of the technology and of the remarkable people who have developed and practiced the demanding profession of control of wild wells, often with an unbeatable safety record. Not one of Adair's team has died in fighting wild wells. But the traditional approach typically takes much time in preparation, and much water; it had been practised at most against five simultaneously burning wells, compared with the hundreds in Kuwait.

## The sabotaged wells

The nature of the problems of gaining control of a sabotaged well can be understood by reference to Fig. 1. The well has a production casing of 7-inch diameter extending nearly to the total depth of the well, containing a 3.5-inch production tubing; each tube is of wall thickness adequate for the expected capped pressure. Oil may be produced from the annulus between these two pipes in additiona to the production tubing. Figure 1 shows the casing set for a typical well in the Burgan field of Kuwait, indicating the depth of the production zone and other characteristics. The wellhead pressure rating is 2,000 p.s.i., with a test pressure of 4,000 p.s.i.. Some wells have wellhead pressures of more than 6,000 p.s.i. The conductor casing of steel tubing 20–30 inches in diameter is drilled or driven about 30 feet into the ground before well drilling begins to stabilize the drill rig.

The well itself consists of four to seven concentric tubes, including the two described above, that terminate at different depths and may have different pressure ratings. Tubes other than the production tubing are called casings and may be up to 20 inches in diameter. The lower end of each casing is cemented to the formation for a hundred feet or more to prevent flow between otherwise hermetic geological strata. The annulus just inside the largest casing may also be cemented. Annuli may also be closed permanently or temporarily by the use of packers near their lower ends, installed along with the next smaller casing, lining or tubing.

The wells in Kuwait are topped by 'Christmas trees' of plumbing for delivering the oil into the gathering pipeline and for access for well maintenance and control (Fig. 2). The Christmas tree includes many features for control and safety. Blowout protectors, essential to safe drilling, are removed from completed wells, as are the derricks used for drilling and casing. The production tubing and the casings normally hang from flanges in the Christmas tree and, while cemented in at their lower ends, can be under great tension at the surface, the weight of steel — 60 tons or more — corresponding to about 4 p.s.i. stress per foot of depth. The Christmas tree starts above the floor of a small concrete cellar, typically 2 m in diameter, extending 2–3 m below ground, which reduced the required derrick height during the drilling and casing of the well. Some Kuwait wells are 'sour', yielding substantial $H_2S$, a gas lethal at concentrations of 200 parts per million, and one that leads to hydrogen embrittlement of high-strength steels. The petroleum from various wells in Kuwait has a great range of viscosity, and a gas content reportedly in the range 35–70 $m^3$ of gas at STP per $m^3$ of oil. This high gas content requires a gas–liquid separator under normal production conditions. Sand entrained in the flow at the well foot becomes more abrasive at the higher linear flow speed existing in the two-phase flow near the wellhead; under normal conditions sand-induced erosion of production tubing is monitored and the production tubing replaced when necessary.

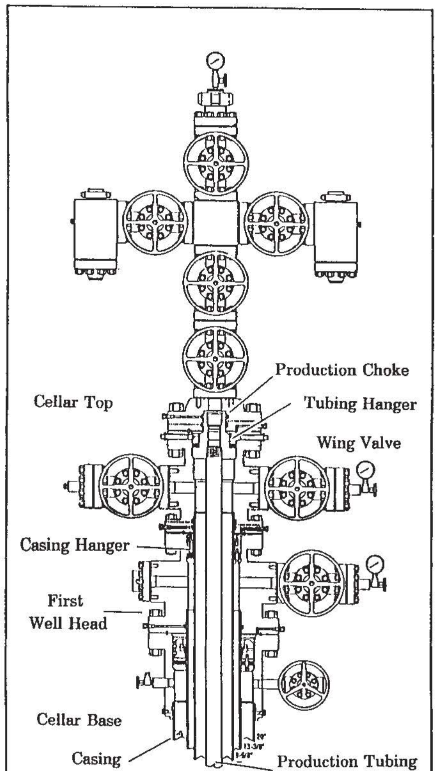


FIG. 2 Wellhead valving and piping, known as the Christmas tree, typical of many in Kuwait. The cellar top is at ground level, the base about 5 ft in the ground. The production tubing is 3½ inches in diameter and successive casings are 9⅝, 13¾ and 20 inches in diameter, respectively.

After the Iraqi sabotage, it was reported that two-thirds of the wellheads had been blown off and the rest badly damaged. Some of the uncontrolled and burning wells needed only to have their valves closed, but in most cases substantial work had to be done first. In some the valves and wellhead facilities were removed by explosives above ground level, whereas others had the casing and tubing severed in the well cellar. With pipehangers gone the production casing and the production tubing will drop into the well, damaging it, but not stopping the flow. Many wells are gushing free from unimpeded bores at typical rates of one or two thousand cubic metres per day. Others, whose jets impinge on wreckage or which are venting laterally, are flooding oil at similar rates, which then burns (incompletely) near the ground in great pool fires. The thermal power from a well flowing at this rate is about 300 megawatts. Conical mounds of hardened coke will have accreted around many of the wellheads. The well-known problem of clearing hundreds of tons of drilling rig from the well is absent on occasions like these, of course.

## Flow control

With destruction only of the gathering pipeline or of a valve on the Christmas tree above the lowest control valves, the well might be brought under control simply by closing one of these lower valves. But if there are no valves left on a production casing, and no flange, a massive fitting must be assembled to be fitted over the casing after preparation, cooling, and usually after snuffing the flame. This phase of the operation is fraught with danger, for example, from ignition by equipment spark, by lighting from dust or rain storms, or from static electricity.

With eroded pipe, a pit is usually dug to give access to the casing set at a depth at which sound casing can be found. Even if there is no erosion, the casing or casings may need to be exposed and then cut cleanly. The fitting (weighing at least a ton) must be pulled over the geyser in a controlled manner and pulled down over the casing, or clamped around the pipe. Grooved, tapered ramps, called slips, can be inserted between fitting and casing to prevent the large forcs that will be present after flow is stopped from pushing the fitting off the casing. For a typical casing of 7-inch diameter and a wellhead pressure of 5,000 p.s.i., this amounts to about 100 tons of force. An appropriate packing or seal is used to retain the fluid after the valve is eventually closed. The high-flow Kuwaiti wells pose particular problems to the traditional approach, as the typical well will spill 1,000 tons of oil a day on the activities at the wellhead between the time the flame is snuffed and the flow is stopped, and may flood the area with poisonous and explosive gas.

## Snuffing the flame

Classically, flames are snuffed by the use of high explosive. More recently, as described at the symposium and used simultaneously by a well-control company in Kuwait, liquid nitrogen has been used to quench the flame in a controllable fashion, with clear advantage over any technique that uses explosives that would imperil people and equipment near the wellhead. Nevertheless, liquid nitrogen has been used only on wells of relatively small flow.

Many have proposed the use of fuel–air explosives instead of high explosives, or the use of Halon gas or even ferrocene to terminate the flame-propagating chemical chain-reactions. Although some of these techniques may be feasible and valuable, it remains true that existing techniques of snuffing flames are cheaper.

Snuffing the fire has traditionally been a prerequisite to stopping the flow, and difficult operations frequently have to precede snuffing. It would be highly advantageous to be able to stop the flow without (or before) snuffing the flame to avoid dealing with the flood of oil and gas that would both hinder work and pose a hazard of explosion. Three approaches are immediately apparent and were discussed by participants of Desert Quench.

(1) Approaching the wellhead with a gathering culvert system, into which the geyser is suddenly diverted without snuffing the flame. This is being developed by several groups.

(2) Tunnelling below the surface to reach the casing set, drilling the production casing (and producing tubing, if necessary) by machines similar to those used at relatively low pressure in domestic distribution systems for hot-tapping an existing gas main, and inserting a stopper(s) adequate to stem or divert the flow. This is not viewed with favour by the drilling industry.

(3) Inserting and fixing a hollow probe or stinger in the bore, which is then valved off. Such a technique has been in use for some time in undamaged wells and was used successfully, early on, in small, damaged wells in Kuwait. It became the technique of choice for the bulk of the well-capping and, with numerous small improvements, has been responsible for the great success of the effort.

In this method, a stinger equipped with appropriate valving is inserted into the flow and restrained by heavy downward force. Powerful pumps are then used to inject drilling mud into the well at a high flow rate until the weight of the mud column halts the flow from the well. Stingers can also be used in wells with flow both through the production tubing as well as through the production casing: the production tubing hanger is cut off and the tubing drops a few feet down, allowing a stinger to be used in the casing.

## Other proposals

Several proposals were introduced and discussed at Desert Quench for speeding up both access to mined and booby-trapped wells and bringing the unconstrained flows of gas and oil under control. A few were unrealistic or unworkable; we discuss some of these briefly here to report the unexpected obstacles that surfaced.

**Mine clearing by robust harrows.** Conventional mine-clearing techniques are unsatisfactory for the circumstances in Kuwait, particularly because of the higher safety standards traditionally demanded for operations in peace time. The mines are virtually non-magnetic and could be equipped with anti-tamper fusing. Many land antitank mines consist of 10 kg of high explosive packaged in a disk-shaped plastic container, and are capable of driving a hole through the bottom of a heavy armoured tank, and of killing passengers in military or civil vehicles. Such mines can be swept by ploughing, requiring exceptionally well-protected sweep vehicles to prevent injury to their operators. The plough structures rapidly degrade from the detonations. An alternative is to search for the mines on foot by probing with sharp rods. Complex fusing options, which may involve more than one signature, such as pressure or magnetic influence, or which count or use inert periods, make confident clearing uncertain. There have been no satisfactory clearing techniques for mines submerged under a layer of oil.

One potentially valuable approach to mine clearing, proposed by W.H. Wattenburg and tested at Yuma proving grounds by Lawrence Livermore Laboratories, uses a sled of chains that incorporates harrow-like blades than can reach to a depth of a foot or so, clearing a 20-ft path. The device digs up mines which either detonate, degrading the sled only slowly, or are entangled in the chains for later destruction. It is drawn by a helicopter at a safe distance. For area-clearing in Kuwait, the sled could be dragged back and forth among several winches, to reduce the cost below the $3,000 per hour typical of helicopter operations.

**Mine clearing with compressed air.** Compressed air with sufficient pressure and flow could be used to clear away earth and mines rapidly with a relatively high degree of safety. To illustrate his concept at Desert Quench, S.A. Colgate described a unit with a compressor in the 10,000-hp range; air from a 4-inch nozzle at a pressure in the range 200–400 psi will have a flow of about 5,000 $ft^3$ per min and will develop a reaction force of more than a ton, sufficient to remove desert soil with great speed down to a depth of from 1–4 ft, as desired. Mounted at the end of a movable boom 30–50 ft long on a tracked vehicle with a protected cab, it might move at 100 ft per min. It would either detonate mines or transport them out of the way along with other debris. Used in conjunction with sled mine sweeping, and with multiple passes over the ground, areas could be cleared to a reasonable level of confidence. It could be used to construct access roads, staging and work areas, and ditches and ponds for either water or oil. The device might dig a pit around a wellhead 60 ft in diameter and 20 ft deep in less than an hour. Not only could such an approach clear mines and booby traps in an area inaccessible because of radiant heat from the fire, it would also remove ground in the wellhead area heated by months of exposure to the flame.

Sand added to the air stream would provide an effective abrasic cut-off tool which would rapidly deal with oil well pipes and valving, reinforced concrete and other materials, facilitating debris removal and nondestructive preparation of the well head. Air-blast excavation and high flow air-abrasive cutting would benefit from increased theoretical and practical study, including the scaling laws applicable to currently available information.

**Explosive pipe closure.** Ring or cylindrical shell explosives can be used to pinch shut a pipe or multiple annular pipes. The explosive charge or charges must be selected, placed and detonated with more care than, for example, in pipe cut-off. The technique appears unsuitable for oil-well control because of the difficulty of ensuring no further damage. The production tubing and production casing may have suffered wall thinning from stream erosion that is difficult to assess; some of the wells are decades old and the metal of the pipes may have become embrittled from exposure to $H_2S$. Hence the task of selecting a charge that will confidently close the pipes without severing them becomes difficult, especially as the pipes are suspended under tension. Squeezing pipes shut inside a cemented casing set poses additional difficulty. In some cases, the task may be complicated by the transient pressures expected from the hydraulic ram effect induced by the near-instantaneous halt of the mixed oil-gas fluid in a couple of kilometres of well tubing and, even more important, shock-induced overpressure of the fluid in the pipe or annuli near the explosion that can induce rupture. With the very gassy oil in Kuwait these transient overpressures would be mitigated.

**Penetrating bomb.** Use of an air-delivered, earth-penetrating bomb to seal off an injured well 50–100 ft below the surface suffers all the problems and more of explosive pipe closure, owing to the lack of precision with which the bombs can be delivered at depth, and to the inherent one-sided nature of the explosion. Severing a well below the surface converts a difficult situation into a disastrous one, in which the excess pressure in the sub-surface soil exceeds by far the available lithostatic pressure, and leads to the formation of a crater.

**Shallow relief well.** In cases where the stinger approach is for some reason unworkable, consideration might be given to using a very shallow intercept by a large-diameter, low-pressure, steeply angled well. Connection could be made in conventional manner by explosives at the foot of the relief well, blocking the original well so long as no impediment was posed to the flow of oil out the relief well and into the gathering system. Replaceable lining, resistant to abrasion, would probably be necessary for the relief well. In due time, re-entry could be made through the original well head with several options, including pulling the production tubing from depth and restoring the well.

**Tunnelling to the well.** Efficient tunnelling techniques could provide a very shallow intercept by a cased, large-diameter tunnel from a point 30–40 m or so from a damaged well to the cemented casing set of the well 30–50 ft below the surface of the ground. The tunnel shaft would be cased and a room mined, shored and cased to provide working space around the casing. To avoid potential explosion hazards from encountering gas or petroleum fumes, or from minor leaks in the apparatus, the tunnel might be kept inerted with $CO_2$, exhaust gas or nitrogen, with air supplied to masks or hoods for any workers. For the many low-pressure wells, one might bare the outermost casing and attach a saddle to allow drilling under pressure, removal of successive cores, insertion of stoppers and the like — all within the environment of a massive set of pressurized valves and tubes. This technique is essentially foreign to the well-control teams, who emphasize open and quick escape routes, but it might be practised by those experienced in tunnelling, with much help from those experienced in well control.

**Flow diverters.** It is possible in principle to place a flow diverter over a well (extinguished or not) and conduct the oil–gas mixture into a long culvert-like pipe fitted with one or more sumps that would provide for separation of the gas from the oil, with the gas flared under control. This scheme temporarily halts the production of soot and other pollutants, and recovering the oil. Care would have to be taken to ensure that an explosion could not develop in the tube and that erosion of the diverter was controlled. The oil could be delivered to plastic-lined holding ponds, dirt tanks, constructed in the desert and using heat-sealed plastic sheets to prevent evaporation and seepage into the sand.

The flow emerging from an uncontrolled well is highly abrasive, in view of the entrained sand and the high velocity to which the gas content carries the fluid on expansion to near-atmospheric pressure. Means are required to retain the integrity of the elbow exposed to this environment; measures such as diamond-coating or massive self-feeding rubber blocks might be useful.

**Stove pipes and liquid nitrogen.** Cylindrical tubes (3–8 m long) have been used to elevate the flame from a burning well much in the manner of a Bunsen burner. They do not require the cooling screen needed with the burner to prevent flashback; the relative absence of oxygen in the fuel and its high velocity result in the flame base remaining at the top of the tube. A tube hinged along one side, parallel with the tube axis, could prevent its interrupting the fuel stream during insertion but for the lengths so far used this has not been necessary. Liquid nitrogen was used in the first of the damaged Kuwaiti wells, a small one, to have its fire put out. A tube stove pipe was used and the fire extinguished and reignited several times to fine tune the process. Liquid nitrogen can be advantageous where water is in short supply.

**Pollution from burning oil.** Wells should burn more cleanly if there is better mixing with air (see R. Seitz, *Nature* **350**, 183; 1991), and North Sea drilling operations have long practised the addition of sea water to the oil after the start of free flow of oil to the production platform and into the atmosphere, where the oil is burned to avoid pollution of the sea. The water clearly reduces the atmospheric pollution from the burning oil, and similar approaches could help in Kuwait.

Ducts or driven air can swirl a rising, flaring column of burning fuel. In small flames this produces a narrowing of the column, will raise the level at which burning of the fuel first starts, and appears to promote improved air–fuel mixing and therefore combustion efficiency. If successfully applied to a well fire, such flame control could decrease the radiant heat at the wellhead without the need to extinguish the fire. This would decrease or eliminate the production of pollutants.

Further research into the potential of vortex alteration of large flames would be valuable. On the other hand, if less effort is involved in stopping the flow from a typical well than in providing air or water entrainment, pollution could be reduced sooner by well control than by modification of the burn.

**Gaining control.** Shields against the radiant heat of the flame have for decades been made like medieval shields, from corrugated steel, with handles. Spray from water monitors has been used to cool the shields and the firefighters, as well as the hot ground. It would be useful to have a light, thin, robust, multi-layer shield that would not be damaged by contact with water or oil. Reflective shields do not long remain reflective in the rain of combustion debris around a burning well. It would also be desirable to have a shield mat that could be placed on the ground to keep shoes from melting or burning.

For wild wells that feed a pool fire instead of a plume fire, control might most readily be achieved in two steps (without first snuffing the flame). First, a surface culvert could be built to approach near the wellhead, with oil diverted into it from the pool by means of a centrifugal pump placed remotely in the well cellar or in an expedient sump. A large lid could then be placed remotely over the wellhead area, excluding air and serving as a crude gas–liquid separator, with the gas taken through a large elevated culvert to be flared (burned) at a reasonable distance.

## Conclusions

We have attempted to provide an analysis of the problems and constraints relating to controlling the types of wild wells encountered in Kuwait. We hope that new ways of dealing with such catastrophes will emerge from our discussion. But it is difficult to prepare for a disaster that is likely to happen to somebody else, in a community in which interests are divided and even opposed. In the case of Kuwait, there have certainly been missed opportunities. For instance, if a share in the future production of several wells had been given to one company (and that replicated tenfold), with the proviso that the methods used to control their wells would be available to be practised by others, progress might have been made more rapidly and with higher confidence. As $50 million a day was being lost in Kuwait, considerable money could have been saved by a fast response to the problem. Not only have important resources been destroyed by the action of Iraq, they have been unnecessarily squandered by an inability to permit technical measures to be implemented to control the wild wells of Kuwait. □

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