Shell Catalysts & Technologies

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WHITE PAPER

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A low-cost hydrocracker revamp has delivered major value to Saudi Aramco Shell Refinery Co. (SASREF) by increasing diesel yield, cycle length and safety.

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Despite the important role that reactor internals play, many refineries continue to use conventional or bubble-cap distribution trays in their hydrocrackers. In doing so, they may be failing to capture the maximum value from their units. For example, the latest-generation reactor internals may enable the use of a higher-selectivity catalyst to produce higher volumes of valuable middle distillates; this could be worth $3.5 million per year for a 200-t/h unit (based on a $14/bbl naphtha–diesel spread). The benefits for some refiners, such as SASREF, a joint venture between Saudi Aramco and Royal Dutch Shell, have been even greater.

SASREF is one of the world's largest and most technologically advanced refineries. It has a complex configuration that includes a hydrocracker, a visbreaker, a thermal gas oil unit and an aromatics section. This enables it to generate a high-value product slate that includes diesel, kerosene, liquefied petroleum gas and naphtha, which it uses as a chemical feedstock and gasoline component.

The SASREF hydrocracker was initially designed to have a 6,000-t/d capacity. Before the revamp, this had increased to 7,500 t/d, which made it one of the largest such units in the world. When it was built in 1982, the hydrocracker was configured for maximum naphtha, but, by 2012, the momentum in global dieselisation meant that middle distillates, not naphtha, were now the highest-value product stream. So, keen to maintain its position as one of the world's most competitive refineries, SASREF took bold, decisive action.

The refiner's objectives were to retune the unit to maximise middle distillates and, to enhance its profitability further, increase the unit's capacity and cycle length. However, it was crucial that any changes were implemented efficiently and in one turnaround in order to maximise the project economics.

To achieve these objectives, SASREF worked closely with Shell Catalysts & Technologies. Teamwork was a key factor in the success of this project; there was high-quality interaction between the three parties that enabled the project to benefit from the refiner's highly valuable site-specific knowledge and the licensor and catalyst supplier's global operational and technical expertise.

The implementation phase was particularly successful. It is difficult to overstate the importance to SASREF of getting it right first time, safely and on schedule, but the refiner showed strong leadership during preparation and implementation was safely completed around eight days ahead of schedule (more details on project execution later in this paper).

THE REACTOR INTERNALS OPPORTUNITY

Over the years, some of the liquid distributors in SASREF's hydrocracker had been upgraded but not replaced by latest-generation reactor internals. This unit revamp, therefore, provided a major opportunity for improvement in this area.

The latest-generation reactor internals include:

- high-dispersion trays, which achieve near-perfect wetting of the catalyst right at the top of the bed, thus enabling an ultra-uniform utilisation of the catalyst and minimising radial temperature differences;
- anti-fouling trays designed to reduce pressure drop build-up;
- quench internals for uniform process and quench mixing at the interbeds;
- robust catalyst support grid panels;
- ultra-low bottom baskets; and
- reactor internal skirts to accommodate the elevations that may be required for minimisation of interbed spacing and maximisation of catalyst bed utilisation and volumes.

When installing the latest-generation reactor internals, there are often opportunities to capture additional value. For instance, depending on the axial temperature gradient, it could be possible to combine beds to increase catalyst uptake. And, when the quench internals, bottom baskets and filter trays are designed to occupy minimal reactor volume, they can enable more catalyst to be loaded into the reactor. This can be used to help extend the catalyst cycle life, lower the weighted average bed temperature, increase the throughput or process heavier, less-expensive feedstock, which results in a higher margin. In some cases, the unit yields can be redefined for better economics.

In addition, some latest-generation reactor internals are designed for fast removal and installation, which can help to increase days on stream and be worth significant revenue. There are also safety advantages, such as far less confined space working time because cutting and welding are not required, and large manways that enable fast entry and exit. In some cases, no physical entry is required to access the bed.

INCREASING CATALYST VOLUME BY COMBINING BEDS

When replacing conventional reactor internals with latest-generation hardware, refiners can typically benefit from an increase in the volume of catalyst that can be loaded into the reactor. If the same catalyst was used as in the previous cycle, this could help to extend the cycle length. Alternatively, a moderate-activity catalyst could be used that has higher middle distillates selectivity. SASREF selected the second option.

SASREF's revised unit objectives warranted a close look into the possibilities to combine beds in this way. Extra catalyst volume would be required in order to apply more middle-distillate-selective, moderate-activity catalysts that still could process the future higher feed rate for the entire interval between planned catalyst change-outs. The latest, innovative middle-distillate-selective catalysts are a good fit because they limit the extent of secondary cracking to naphtha and lighter products.

To investigate the thermal behaviour of the existing system and the new options for the revamp, Shell Catalysts & Technologies conducted a thermal stability assessment for multiple bed combination scenarios. This took into account the proposed fresh feed intake, which SASREF wanted to increase from 7,500 to 8,000 t/d, the proposed catalyst system, the capacity of the existing interbed quench facilities and the hydrocracker's operating mode. It verified that the rate of occurrence of temperature excursions could be adequately minimised and that excursions, should they happen, would be adequately moderated by the available operational handles.

At SASREF, the two pretreatment reactors had four beds each and the cracking reactors had six beds each. Ultimately, the thermal stability assessment led to a recommendation to merge beds 3 and 4 in the pretreatment reactor and beds 1 and 2 in the cracking reactors (Figure 1).

As a result of merging the beds and the hardware's slimmer profile, the reactors' catalyst volume increased substantially. The catalyst load in the pretreatment reactors increased by 16%. In the cracking reactors, there was a 22% increase compared with the original loaded catalyst volume using conventional reactor hardware.

Reducing the number of beds has a positive impact on three main parameters:

- less hardware is required, which reduces capital expenditure;
- less turnaround time is required in every future catalyst exchange, as there are fewer manways to open and close; and
- easier and faster catalyst loading due to longer beds.

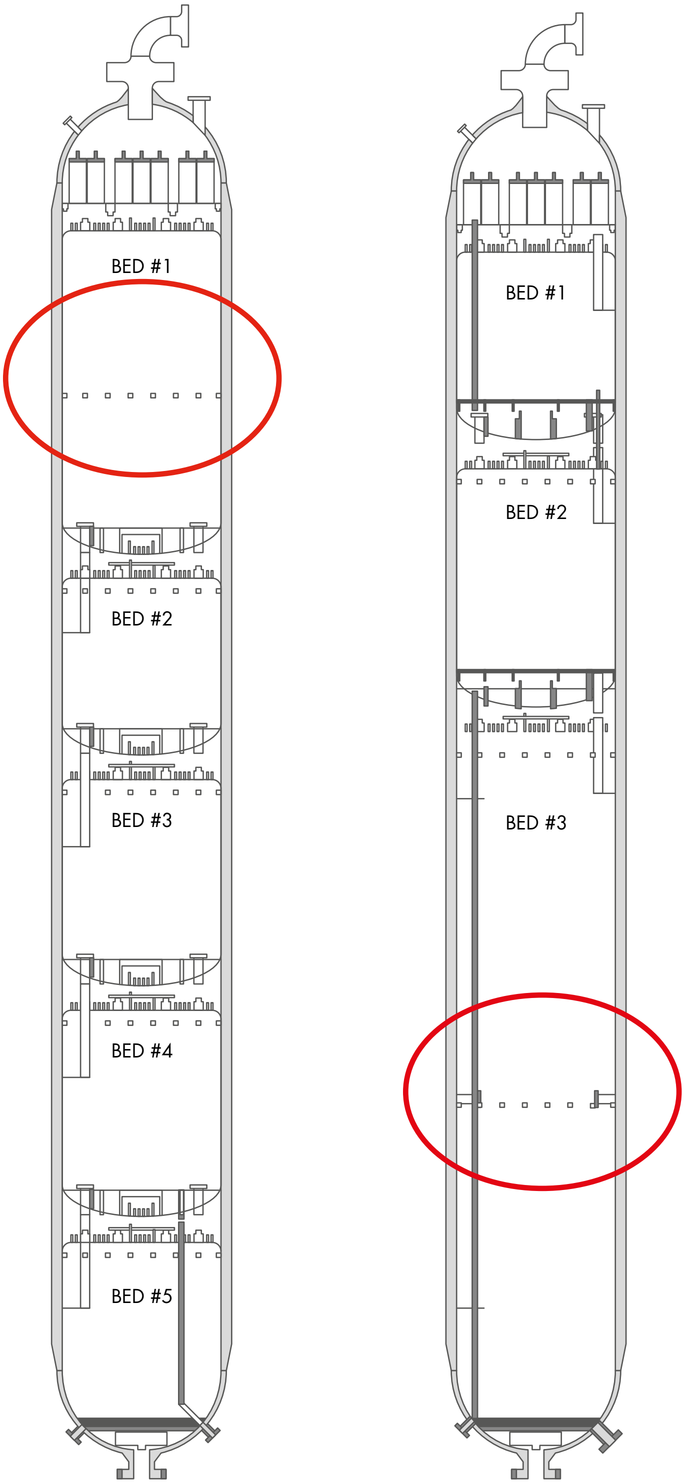

Figure 1: The Shell reactor internals portfolio offers the opportunity to combine beds because it provides enhanced vapour–liquid and thermal distribution throughout the bed and it takes up less space than conventional reactor hardware. This enables an increase in the volume of catalyst that can be loaded into the reactor and is complemented by improved catalyst utilisation. At SASREF, beds were combined in both the cracking reactor (left) and the pretreatment reactor (right).

IMPROVING CATALYST UTILISATION WITH HIGH DISPERSION TRAYS

In addition to increasing the catalyst volume, latest-generation reactor internals can utilise the catalyst load better. Whereas conventional designs typically use about 80% of the catalyst owing to poor feed distribution, latest-generation reactor internals enable close to 100% utilisation of the catalyst load by enhancing the uniformity of the gas–liquid distribution. They also help to ensure that the guaranteed catalyst cycle length is met by minimising radial temperature maldistribution and the associated risk of coke formation.

For example, SASREF's hydrocracker had been using conventional distribution trays. These are notorious for low uniformity of vapour–liquid distribution and undesirable radial temperature maldistribution. Using the latest-generation trays, the revamp team believed, could help to increase the middle distillates yield. This is because they feature customised nozzles that use the gas flow momentum to disperse the liquid as a mist. Unlike all existing distributor trays in the industry, the nozzles uniformly wet the entire catalyst surface and make very efficient use of the upper layers of the catalyst bed (Figure 2).

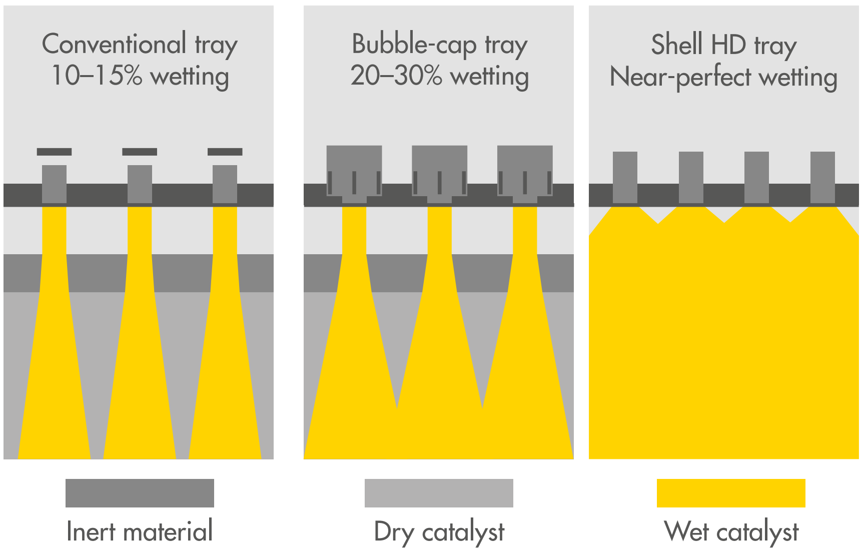

Figure 2: Some modern trays optimise catalyst utilisation by achieving enhanced vapour–liquid and thermal distribution. These trays can be extremely efficient; some enable nearly 100% of the catalyst inventory to be utilised and offer high feed rate flexibility.

Enabling more catalyst to be loaded into the hydrocracker's reactors and using almost 100% of the catalyst load gives SASREF the opportunity to increase yield and extend the catalyst cycle life.

The total catalyst utilisation improvement (catalyst loading plus wetting) was 21% for the pretreatment reactors and 52% for the cracking reactors.

GUARDING AGAINST FOULING AND CATALYST MIGRATION

SASREF reported that, before the revamp, the unit had been affected by fouling, so the revamp team reviewed the filter tray configuration. Fouling in a hydrocracker can be costly. When contaminants build up on the surface of the catalyst, a layer of foulant particles can form, which leads to a sharp increase in the reactor's pressure drop that limits the unit throughput (feed pump and compressors bottleneck). Moreover, this can also cause residual build-up to loosen and flow through the reactor, thereby decreasing performance further.

The team found that the filter tray configuration and top bed filters were of first-generation, non-standard designs. Extensive welding repairs were required during shutdowns and, consequently, there was a risk of catalyst migration.

The solution was to replace the existing filter tray configuration with latest-generation filter elements. These have a reduced slit width to enable the even the smallest catalyst particles to be used as filter media. An additional benefit is that they have quick-to-open split keys to reduce shutdown time.

The wire mesh catalyst support grids panels were also old. They required significant maintenance and confined space residence time during turnarounds and the risk of catalyst migration was increasing. The solution was to replace the wire mesh panels with latest-generation catalyst support grids.

These feature a grid screen that utilises a wedge-wire construction to help prevent catalyst fall-through and that resists fouling. Wedge wire offers key advantages compared with wire mesh: most notably, that it is not prone to fouling. The V-shape of the wire means that it is self-cleaning. Moreover, there are no loose layers of wire mesh, no overlay is required for the wire-mesh pads and no knitting is required. Wedge wire also lasts up to five times longer than wire mesh.

THERMOMETRY UPGRADE TO RESOLVE TEMPERATURE INSTABILITIES

In 2011, SASREF and Shell had conducted a root-cause analysis into temperature instability issues that had been affecting the unit. This identified that the thermometry system was contributing to these problems because it was unreliable. To resolve this, the revamp team implemented a major upgrade: previously, each reactor had been fitted two old-fashioned vertical thermobars enabling six temperature measurements to be taken at just two radial and two axial locations in each catalyst bed.

The thermometry upgrade replaced the thermobars with multiple state-of-the-art flexible thermocouples. These thermocouples enable both radial and axial coverage that is in line with the latest design guidelines on tight, hydrocracking bed temperature control and extensive temperature monitoring. In addition, the plant's distributed control system and safety-instrumented system were upgraded to collect and process the information from these additional thermocouples. This has provided both site operations and technologists with more robust automatic temperature control and with tools to identify early indications of temperature instability or maldistribution so that remedial action can be taken in a timely manner.

By carefully selecting reliable thermocouples and appropriate voting systems, both the rate of trips caused by spurious high-high temperature measurements (leading to unit emergency shutdowns) and the reliability of reactor safeguarding against overheating have been brought in line with the latest standards.

REINSTALLING THE LIQUID RECYCLE

In addition to upgrading the reactor internals, key process changes were made to the hydrocracker. For example, a liquid recycle was installed. The unit was originally built with a liquid recycle, but it was removed when the unit switched to once-through mode. Reverting to this mode of operation provided an inexpensive opportunity to increase middle distillates yield. If, in the future, there was a product demand shift and SASREF wished to move back to gasoline mode, the liquid recycle could simply be interrupted again.

CUSTOMISING THE CATALYST SYSTEM

Technologists from SASREF and Shell Catalysts & Technology worked together closely to select the most appropriate hydrocracking and pretreatment catalysts to meet the refinery's individual process needs and to develop the most effective operating strategy for the unit.

This involved a detailed analysis that took into account the feedstock quality; the desired product slate; the design of the hydrocracker and its normal operating regime; the amount of hydrogen available; and the target cycle length.

A catalyst study was performed that evaluated three different catalyst systems proposed by Shell Catalysts & Technology alongside five different feed blends (Table 1).

These evaluations also took into account the liquid recycle option as a process parameter to boost middle distillate yield and to shift the yield more towards naphtha, when needed, by operating the hydrocracker in once-through mode only, thus switching off the liquid recycle.

The focus was to have maximum middle distillate yields within the targeted four-year cycle length, taking into account the maximum draw-off capacities for kerosene and diesel.

Cracking catalyst	Z-733/Z-FX10	All Z-FX10	Z-FX10/Z-623
Cycle length (months)			
Valid feed case			
101	78	71	50
102	127	105	93
108 C	80	77	55
105	71	68	48
106	59	57	38
Combined kerosene and diesel yield (t/d)			
Valid feed case			
101	4,145	4,305	4,446
102	3,336	3,487	3,587
108 C	3,778	3,945	4,057
105	3,847	4,025	4,142
106	4,138	4,320	4,446

Table 1: SASREF and Shell Catalysts & Technologies worked together to customise the catalyst system according to SASREF's specific objectives.

Key:
Below target
Valid
Invalid

Shell Catalysts & Technologies also advised SASREF to reuse part of the regenerated catalyst that was available on-site in order to reduce fill costs.

Following the catalyst selection study, SASREF opted to fill the pretreatment reactors with:

- **ASCENT® DN-3551** hydrocracking feed pretreatment catalyst; and
- partly regenerated and fresh **Zeolyst Z-503**, a cracking catalyst that has high middle distillates selectivity.

The cracking reactors were filled with:

- regenerated **Zeolyst Z-733**, a cracking catalyst designed to produce middle distillate range products with improved properties such as density, smoke point and cetane number; and
- **Zeolyst Z-FX10**, a flexible catalyst that can be used for high yields of middle distillates or naphtha.

AN EFFICIENTLY EXECUTED PROJECT

The hydrocracker is, of course, the heart of the refinery and drives its profitability. The unit's normal turnaround window was extended from 18 to 38 days (excluding start-up and shutdown days) to enable the reactor internals and catalysts to be installed. SASREF was determined to ensure that the unit would come back on stream according to this project timeline. This was economically imperative; it had to be right first time, as there would be no second chance.

However, SASREF, which led the preparation and execution phases, closely supported by Shell Catalysts & Technologies, faced major challenges. For example, it had never executed a project of this type and there were complicating factors such as the need to cut out beds and the presence of asbestos in the reactors.

In addition, there were the challenges that are common to all refineries: installation has to be completed during a single turnaround window, during which time there are many contractors on-site tackling numerous activities in a highly congested area.

SASREF believes that the way in which it mitigated challenges such as these was crucial to the success of this project. Key elements of its approach include:

- **high-level sponsorship**. Senior management widely communicated that this was the refinery's highest-priority project of the year, and everyone aligned to this common goal.
- **adopting successful practices from other sites**. Because SASREF's experience with projects of this type was limited, it actively sought out best practices and key lessons from other refineries. It visited other sites and learned from their projects.
- **high-quality people**. SASREF formed a multidisciplinary team to work on the project from its most highly qualified and experienced people, and acknowledges that Shell Catalysts & Technologies did the same. SASREF also involved fresh, young Saudi graduates so that they could benefit from knowledge transfer.
- **selecting a highly experienced contractor**. Shell Catalysts & Technologies proposed construction contractors that had experience of similar projects, but SASREF was keen to evaluate their track records and technical capabilities. It also paid special attention to the contractors' leadership teams because it felt this would drive the success of the project.
- **building reactor mock-ups**. During the turnaround window, the reactor internals had to be assembled inside the four reactors, but by building reactor mock-ups beforehand the contractors had the opportunity to practice their assembly offline. The contractors repeated this assembly until they were confident that they could install the new hardware safely and efficiently during the turnaround window.
- **developing a detailed execution plan**. This plan addressed all the activities to be carried out in all the reactors during the turnaround window and helped to ensure alignment with other activities planned in the same area.

- **holding a scope optimisation workshop**. Through this activity Shell Catalysts & Technologies, SASREF and the execution contractor challenged the scope and proposed duration. This also helped to ensure that nothing had been missed.
- **conducting a readiness assessment review**. A different Shell team took a fresh look to confirm that the project was ready to be implemented.
- **establishing very clear interfaces with the other activities and contractors that were working in the same area**.
- **performing risk assessments for every critical activity**.

Because of this preparation, the team actually gained on its schedule during the shutdown and was able to hand over the unit for start-up some eight days early. Crucially, it did so with an excellent safety record.

LESS SHUTDOWN TIME AND ENHANCED STAFF SAFETY

SASREF's future hydrocracker shutdowns will also be shorter. This is because the latest-generation reactor internals can be serviced much quicker: they are designed to eliminate the need for cutting and welding, and to make catalyst loading and unloading easier and faster, and there are now fewer interbed manway panels to open and close. In fact, the new hardware has cut the time required for shutdowns at SASREF by some four days, which is worth about $2.56 million per turnaround.[1]

Moreover, there are safety advantages because the reactor internals reduce the time required for confined space entry to at least a quarter of the time generally taken when compared with older hardware. This is because they are quicker to open, clean, inspect and close, and the confined space entry requirements have been greatly reduced, especially because some of the beds have been combined.

In addition, the reactor internals have the largest possible manways to enable people to move very quickly through the trays and quenches, which is particularly important in the case of a serious incident. For example, the larger manways facilitate faster recovery of an unconscious person from the reactor. Furthermore, they have been designed to eliminate the need for hot work in the reactors because they can be installed without welding and opened and closed using just a hammer.

VALUE TO SASREF

Calculations show that the new reactor internals and catalyst system will provide a 4% increase in middle distillates, which will increase SASREF's bottom line by $10.5 million a year.[2]

In addition, adjusting the hydrocracker's mode of operation by implementing the liquid recycle adds flexibility as it can enable the product slate to swing from naphtha to middle distillates without any investment. Moreover, turnarounds will be shorter and there are safety advantages.

In addition, the catalyst system that Shell Catalysts & Technologies designed and SASREF validated has a reduced catalyst refill cost of a further $7 million for this cycle because it uses partly regenerated catalyst.

[1]Assumes $80/t margin.

[2]Assumes $14/bbl diesel–naphtha price differential, 7,500 t/d intake, 350 operating days a year and 4% shift from naphtha to diesel.

KEY TAKEAWAYS

SASREF's revamp, which consisted of upgrading the reactor internals in all four reactors, modifying the bed configuration in each reactor, installing new thermometry, innovative catalyst selection, revising the quench system and increasing safety, required little capital expenditure but enhanced its profitability by over $10 million a year.

This was a major project whose success hinged on bold decisions taken by its owner, SASREF, and the mutual focus and close collaborative relationship with the other key stakeholders and Shell Catalysts & Technologies.

Value can often be lost during the implementation phase of such a project, so it is vital that the project team is well prepared. SASREF was able to avoid unforeseen issues by, for example, selecting a highly experienced contractor, setting up an extensive working document and building mock-ups of the reactors to enable the contractors to practice installing the internals off the project's critical path.

Latest-generation reactor internals were also key because they:

- take up less space than conventional hardware, thereby enabling high reactor volume utilisation for catalyst loading while increasing catalyst run length;
- provide enhanced vapour–liquid and thermal distribution under a wide range of operating conditions to provide safe and optimised operation using nearly 100% of the loaded catalyst; and
- have a boltless, weldless and ergonomic design that facilitates fast installation, easy maintenance and a shorter future turnaround.

ENDORSEMENT FROM THE SASREF LEADERSHIP TEAM

"It was a matter of great pleasure for SASREF to work with Shell Catalysts & Technologies on this initiative. The project is helping us to derive the intended value, which is quite timely considering the current economic conditions and tightening refinery margins," Ali Al-Hazmi, President, SASREF.

"This project was a great example of how the right people working together on the right technology deliver value to a business. The value it has delivered since implementation is very promising and we expect the value generation to continue," Roelof Heezen, Vice President, SASREF.

ABOUT US

Shell Catalysts & Technologies supports Shell and non-Shell businesses by working with them to co-create integrated, customised solutions comprising licensed technologies, refining and petrochemical catalysts, and technical services. It was formed by combining Shell Global Solutions, a technology licensor with a track record of delivering pioneering process schemes and innovative configurations; Criterion Catalysts & Technologies, the world's largest hydroprocessing catalyst supplier; and CRI Catalyst Company, a pioneer in the petrochemical catalyst sector. It operates across the energy value chain, from upstream, gas processing and liquefied natural gas through to downstream refining and petrochemicals.

The fact that Shell Catalysts & Technologies supports Shell's global downstream network means that it has already addressed many of the challenges that its third-party customers face; the catalysts and technologies that it licenses have been developed in response to the same challenges.

For further information, please visit our website at **www.shell.com/ct**.

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