Build-up of dirt deposits, or fouling, on the metal surfaces of petrochem plant heat exchangers is a major economic and environmental problem worldwide. Estimates have been made of fouling costs due primarily to wasted energy through excess fuel burn that are as high as 0.25% of the gross national product (GNP) of the industrialised countries. Many millions of tonnes of carbon emissions are the result of this inefficiency. Costs associated specifically with crude oil fouling in the pre-heat trains of oil refineries worldwide were estimated in 1995 to be of the order of $4.5bn. With oil prices at record highs, the payback from fouling reduction by increased throughput and less wasted fuel increases year on year.

Fouling of heat exchanger equipment results in increased cost of operation, costs vary depending on the process, location and manpower but major costs include:

- Loss of energy (due to heat transfer problems)
- Reduced flow
- Increased pressure
- Loss of throughput (reduced production)
- Increased investment (use of switchable exchangers)
- Replacement of equipment
- Cleaning and disposing of toxic wastes
- Increases safety hazards (fires)
- Use of costly chemical additives

Working with the major oil companies, IHS ESDU has been path finding new developments into reducing or even eliminating crude oil fouling in pre-heat train heat exchangers. A unique design methodology in the IHS ESDU heat exchanger design program EXPRESS™ allows refiners to identify fouling exchangers. The powerful graphical facilities of EXPRESS™ then drive the engineer to an optimum solution, perhaps using new hardware supplied by heat exchanger manufacturers, that can reduce or eliminate fouling and improve plant efficiency.
A proposed €4bn oil refinery at Sines in Portugal will come on stream early 2009. The 250,000 barrel per day refinery will produce 3000 barrels of diesel fuel per day and will be largest on the Iberian Peninsular. When fully on stream, the refinery will account for 3% of the Portuguese GDP. This new refinery alone is likely to produce 2.5 million tonnes of carbon emissions from fuel burn each year. At a carbon tax rate of €30/tonne this will cost €75 million p.a. in taxes alone. Data from refineries suggests that crude oil fouling accounts for between 3% and 10% of the total CO$_2$ footprint. Therefore, in this example a refinery of this size which had properly addressed the crude oil fouling problem could save €7.5 million p.a. in taxes alone with additional savings coming from increased efficiency and reduced fuel costs.

In 2002, French oil company Total revamped one of their refinery crude distillation units to improve efficiency. Soon after the plant restart, it was clear that the preheat train was experiencing heavy fouling leading to a significant throughput reduction as the furnace bottlenecked. Financial losses were estimated to be around $1.5M over three months after start-up.

Total decided to implement an in-house study of the problem following methods developed by IHS ESDU in their collaborative research work with Total and other major oil companies. The methods successfully highlighted the rogue exchangers and pointed to retrofit options that were subsequently adopted. Total presented the findings of their study at a major international conference in Santa Fe in 2003. Total's paper concluded that the predictions of rogue heat exchangers predicted by the methods were subsequently found to be very close to the true situation. They recommended that designers use the methods, built into the EXPRESS$^\text{TM}$ program, to identify rogue exchangers and identify retrofit scenarios.

IHS ESDU has recently issued the latest version of EXPRESS$^\text{TM}$, novel heat exchanger analysis software for heat exchanger fouling in the pre-heat train of a crude oil distillation unit. It was developed over a period of more than five years in close collaboration with the Oil Industry Fouling Working Party, a team of oil refiners, heat transfer equipment manufacturers and chemical suppliers. This program complements a state-of-the-art review, with practical guidance on the methods of mitigating fouling, developed by IHS ESDU.

The Oil Industry Fouling Working Party was formed to investigate the huge economic and environmental importance of fouling in crude distillation units and the potential benefits that can accrue from better understanding of mitigation strategies and represents some 70% of the global refining capacity. The close partnership between industry and the researchers was the key in developing unique anti-fouling design tools.

For more information visit www.ihsesdu.com.

General outline of crude oil fouling problems in pre-heat train exchangers

Crude oil from storage tanks is fed to the heat exchangers of the crude pre-heat train, initially at ambient temperature. The crude oil is then heated to around 250°C (480°F) at entry to the furnace. From the furnace, the crude is fed to a distillation column where valuable product streams, such as kerosene, gasoline and gases, are separated and collected.

Most fouling arises from asphaltenes deposition from the crude oil onto the metal surfaces of the pre-heat train heat exchangers. This fouling leads to a decline in furnace inlet temperature; by perhaps as much as 30°C (54°F), and a subsequent need to burn extra fuel in the
furnace to make up the temperature necessary for efficient distillation. Fouling also causes a significant decrease in the crude unit throughput, cutting production.

**Economic and environmental significance of fouling**

The huge costs associated with fouling in crude pre-heat exchangers mentioned above are categorised as follows:

1. **Energy costs and environmental impact.** This corresponds to the additional fuel required for the furnace due to the reduced heat recovery in the pre-heat train as exchangers foul. Energy losses due to increased pressure drop (pumping power) may also be significant. The use of more fuel leads to additional production of CO₂ with the associated environmental impact.

2. **Production loss during shutdowns due to fouling.** If the pre-heat train throughput is furnace-limited, a typical 10% loss of production due to taking a heat exchanger out of service in a 100,000 US barrel/day plant would cost $20,000 US per day (assuming $2 per US barrel of marginal lost production). After shutdown, there is an additional cost due to out-of-specification production after production is restarted.

3. **Capital expenditure.** This includes excess surface area, costs for stronger foundations, provisions for extra space, increased transport and installation costs, costs of anti-fouling equipment, costs of installation of on-line cleaning devices and treatment plants, increased cost of disposal of the (larger) replaced bundles and, finally, the (larger) heat exchangers.

4. **Maintenance costs.** This includes staff and other costs for removing fouling deposits and the cost of chemicals or other operating costs of anti-fouling devices. There are also economic and environmental penalties associated with disposal of cleaning chemicals after cleaning.

The cost of fouling in the crude distillation unit is the dominant fouling cost in a refinery, hence the focus of the ESDU study into that area.

**Factors influencing fouling**

Fouling in refineries and petrochemical plants is a function of many variables. Factors affecting fouling in crude oil pre-heat exchangers include process conditions (temperature, pressure, flowrate), exchanger and piping configuration, crude oil composition, and inorganic contaminants. Effective control of these variables may minimise fouling in crude oil units.

Recent experimental studies have shown the existence of ‘fouling thresholds’ for chemical reaction (asphaltene) fouling in particular crudes and crude blends. These thresholds are both temperature and velocity dependent. Given the existence of fouling thresholds it was possible to develop EXPRESS™ for heat exchanger design.

**Fouling mitigation and control**

The objectives of schemes for controlling hydrocarbon fouling are broadly preventing solids from forming, adhering to themselves and to the heat transfer surfaces, and removing solids from the surfaces.

The ESDU Working Party developed a list of possible actions for fouling mitigation and control. These recommendations are presented in the User Guide, and include consideration of various design and operational variables. For example, heat exchange equipment should be designed and controlled to keep surface temperature to a minimum and the fluid velocities as high and, on the shellside, as uniform as practicable.

**Prediction of fouling and heat exchanger modelling**

Chemical reaction fouling is essentially dynamic in nature but the design of heat transfer equipment is generally based on the summation of time-independent resistances to heat transfer (such as the TEMA values). Although the TEMA tables were originally only considered to be rough guidelines for heat exchanger design, they are unfortunately often treated as accurate values. This may cause considerable errors, not least because the transient character of the fouling process is neglected. Conditions in initially over-designed heat exchangers often promote deposition, thus making fouling a self-fulfilling prophecy.

A wide variety of mechanistic models and correlations for fouling have been proposed and are discussed in the User Guide. The application of these methods in design software illustrates that, with reliable data for crude fouling threshold behaviour, it is possible to either design plain-tubed exchangers with little or no fouling or identify cases where mitigation devices might be essential. In parallel with the development of the User Guide, ESDU developed two computer programs for approximate heat exchanger design and analysis. These programs include for the first time the opportunity to identify designs that
operate below the fouling threshold and to investigate performance in relation to the threshold as the exchanger operates off the design condition.

The program EXPRESS™ allows the generation of parameter plots associated with a given duty for plain-tubed shell-and-tube exchangers. Feasible designs are illustrated graphically, where constraints on overall thermal duty, tubeside pressure drop, shellside pressure drop and maximum and minimum tubeside velocities are met. A further constraint can be introduced on such plots to represent the fouling threshold. An example parameter plot is shown in Figure 1. EXPRESS™ allows the designer to identify exchanger geometries in which fouling is likely to be minimised and then provides operability information on the performance of that geometry, including fouling propensity, under various operating conditions.

For the conditions shown in Figure 1, the fouling threshold is indicated and designs satisfying the thermal and pressure drop constraints lie above the fouling threshold value. Therefore there is no viable non-fouling heat exchanger with this particular baffle cut and number of tubeside passes. It is however possible to develop a non-fouling design by manipulation of the design parameters. Two simple design modifications shown in Figure 2 bring the optimum design point below the fouling threshold. Firstly, for the existing two-pass configuration, increasing the baffle cut from 25% to 42.5% relaxes the shellside pressure drop constraint and gives a design with a reasonable margin to account for the uncertainty in the exact position of the fouling threshold line. Secondly, by increasing the number of tubeside passes to four with a baffle cut of 27.5% an acceptable design is also identified.

The advantage of using the EXPRESS™ program for investigating design is that the designer obtains a visual guide on the effect of making particular changes similarly it is possible to investigate the effects of changes of operating conditions and modification on fouling thresholds.

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**Figure 1.** Parameter plot from EXPRESS program showing constraints for heat transfer, flow velocity, pressure drops and crude fouling

**Figure 2.** Possible design modifications to design out fouling