# ACHIEVING THE BALANCE BETWEEN SAFETY AND IMPACTS ON THE ENVIRONMENT

F.K. Crawley*,**, D. Ashton** and R. Morrell**
* Department of Chemical and Process Engineering, University of Strathclyde, Glasgow
** W S Atkins Oil & Gas, Clifton House, Clifton Place, Glasgow, G3 7LD, UK

This paper describes the development of the Concept Environmental Impact model for offshore oil and gas developments which complements the previously developed Concept Risk Assessment model[1,2]. The model shows that the main environmental impact occurs in the operational phase of the project, not the construction and abandonment phases. The two models have been run in parallel and show that for the offshore industry, improvements in environmental impact may carry a human risk and as yet there is no industry recognised way of weighing the benefits and debits in a meaningful model.

Keywords: offshore installations, environmental impact, concept ranking

## INTRODUCTION

Process safety begins with the selection of the inherently safer option during the concept development phase of the project. The provision of a safe working environment is then further assured during detailed design by the strategic addition of safety enhancing features. For an offshore oil and gas field there can be many development options which will require an assessment of risk levels. A Concept Risk Assessment methodology[1,2] was developed by WS Atkins, together with BP Amoco and Shell, for this purpose.

Increasingly, attention is being paid to the environmental impact of offshore oil and gas projects, requiring an analysis of the life cycle impact from construction, through operation, to final abandonment. This paper discusses the development of a Concept Environmental Impact methodology for offshore oil and gas development projects and highlights the potential for conflict between the principles of ALARP (*as low as is reasonably practicable)* and BPEO (*best practicable environmental option).*

When considering the optimum design for an offshore installation, there are a number of significant factors which must be taken into account, including cost, schedule, and technical feasibility. However, in recent years safety of personnel and more recently impact on the environment have gained increasing prominence.

Generally, to determine the development option which would have the least impact on the environment, the following aspects of each concept would have to be briefly assessed:

- Impact on the marine environment
- Air pollution – local and global
- Energy demands from cradle to grave (life cycle of the project)

Where a new development requires new or additional facilities to be built either on or close to land, the following factors can also be important:

- Impact on the land environment
- Cultural heritage i.e. historical/archeological importance
- Noise pollution
- Visual impacts

While there are now developed standards or criteria for safety[3,4], there are no absolute criteria for environmental impact. Further there are no clear criteria by which the optimum balance of Safety and Environmental impact can be assessed in a meaningful manner.

## CONCEPT ENVIRONMENTAL IMPACT MODEL DEVELOPMENT

During the initial development of the Concept Risk Assessment methodology[1,2], it was clear that the methodology had to be quick and easy to use. As so many concepts had to be screened, it had to be accurate so that the safest option would be chosen, but there would only be a limited amount of detail or definition with which to carry out the assessment. These conditions seemed to be incompatible until it was recognised that each piece of equipment (pump, compressor, vessel, wellhead, etc.) could be "characterised" as a "risk" to life or structural integrity. An analysis of the equipment items showed that the lack of a full fittings count was not a limiting condition as for any specific item of equipment the fittings and instrument counts were similar whatever the design house. It was also recognised that the total base risk obtained by summing the individual equipment risks could be moderated by discrete conditional probabilities which were a function of the design and layout. In other words the fine detail of the design was not essential for concept screening provided the characterisation could be carried out with confidence.

A similar approach was used to assess the environmental impact of oil and gas projects during the production phase by "characterising" equipment items as having an environmental impact determined by a basic set of parameters available early in the design.

The simple treatment of personnel risks during the construction and abandonment phases, using industry standard risk levels and a "man-hour" requirement for construction of each option is not acceptable for an environmental study, as there are significant environmental impacts from both these phases which must be incorporated in the overall model.

This paper therefore describes the methodology used for the development of an environmental impact methodology covering the following phases of a project's lifecycle:

- Construction
- Operation
- Abandonment

The input requirements for the methodology are, by design, very high level. These are limited to the following parameters, which will have been developed for costing purposes during the concept phase of an offshore oil and gas project:

- The process outline with all key process parameters - flows and pressures
- The drilling strategy, the number of wells, how they will be drilled and where the drill cuttings will be disposed of
- The weight of the production and accommodation module
- The weight and design of the support structure
- The means by which the oil and gas will be transported to shore
- Requirements for gas or water injection into the reservoir

Much of this data has to be collected for the concept risk assessment; therefore, there is very little additional data collection required for the Environmental Impact Assessment.

## CONSTRUCTION AND ABANDONMENT PHASE

The environmental impact during construction and abandonment of an offshore installation requires life cycle analysis from raw materials to final recycle. Steel is by far the most common component used in platform construction and therefore dominates the overall environmental impact. By comparison, the contributions from copper, aluminium, insulation and plastics are very much second order. Although in recent years the use of concrete structures has been less favoured, their construction is also considered within the model.

The physical weight of steel is a function of the design. The environmental impacts of the construction phase are generated during all stages from mining of the ore through to the recycle of the material. These can be considered *direct* and *indirect* as shown below in tabular form.

Table 1. Emission Sources From Steel Production

| **Direct** | **Indirect** |
|---|---|
| Foundry emissions from the use of electricity, gas, oil, and from the steel making process itself. | Iron Ore Mining and associated emissions, direct and indirect eg diesel/electricity |
| | Coal Mining and associated emissions, direct and indirect eg diesel/electricity |
| | Emissions generated through electricity generation |
| | Emissions of road and sea transport of ore and coal from the mines to the foundry. |

Table 2. Emission Sources From Jacket/Topside Construction and Installation

| **Direct** | **Indirect** |
|---|---|
| Onshore emissions from the use of gas cutting and diesel. | Emissions from road and sea transport from foundry to fabrication yards and from fabrication yards to offshore location |
| Offshore emissions from the use of diesel generated electricity, gas cutting and marine support | Emissions generated through electricity generation onshore |

Table 3. Emission Sources From Decommissioning

| **Direct** | **Indirect** |
|---|---|
| Emissions through the use of marine support, vehicles, gas cutting and cleaning equipment | Emissions generated through electricity generation |

The impact assuming coal and iron ore are mined in Australia, the steel is produced in England, the structure is constructed in Scotland and towed out to its final location in the Northern North Sea is shown in Table 4.

Table 4. Tonnes of Pollutant per 1000 Tonnes of Steel made from Ore

| **Phase** | **$CO_2$** | **$SO_x$** | **$NO_x$** | **Particulates** |
|---|---|---|---|---|
| Mining | 45 | 0.70 | 0.18 | 0.03 |
| Road Transport – Minerals | 48 | 0.34 | 6.33 | 0.50 |
| Sea Transport – Minerals | 1667 | 0.92 | 24.18 | 1.28 |
| Steel Making | 1522 | 2.42 | 2.80 | 1.37 |
| Road Transport – Steel | 27 | 0.09 | 1.78 | 0.14 |
| Steel Structure Fabrication | 421 | 3.61 | 0.97 | 0.14 |
| Steel Structure Transport | 8 | 0.04 | 1.14 | 0.07 |
| **Totals** | **3737** | **8.12** | **37.38** | **3.53** |

Abandonment is not as complex as previously considered, as the government has adopted a "non-dumping" policy with the return of all steel for the disposal onshore[5,6]. The breakdown is as shown in Table 5.

Table 5. Tonnes of Pollutants per 1000 Tonnes of Steel Abandoned Offshore

| **Emission** | **Tonnes Generated** |
|---|---|
| $CO_2$ | 334 |
| $SO_x$ | 1.6 |
| $NO_x$ | 7.1 |
| Particulates | 0.4 |

The impact of a modern platform of combined topside and jacket weights of 30,000 tonnes is therefore as shown in Table 6.

Table 6. Tonnes of Pollutants for fabrication and abandonment of a 30,000 tonne installation.

| **Emission** | **Tonnes Generated** |
|---|---|
| $CO_2$ | 122,130 |
| $SO_x$ | 291 |
| $NO_x$ | 1,335 |
| Particulates | 118 |

These are compared with the results of the operational phase later.

## REMOTE FABRICATION

Within the model is also possible to assess the global impact of mining ore in, say, Australia, processing the ore in the Far East, fabricating the modules in the third world country and installing them in the UK. This will involve transportation and handling during the various stages of the process in areas where there may be different safety and/or environmental standards. There is a delicate balance of the responsibilities of the company to its shareholders and a return on the capital as well as minimising the environmental impact. It is possible that one phase of the process will be handled in a country that is not a signatory to the Kyoto Protocol. There is therefore a complex optimisation process required to produce a minimum impact. Table 7 shows the impact where coal and iron ore are mined in Australia, the steel is produced and the structure is fabricated in the Far East and the final product is sailed to the UK.

Table 7. Tonnes of Pollutants for remote fabrication for 1000 tonnes of steel

| **Emission** | **Tonnes Generated** |
|---|---|
| $CO_2$ | 3,228 |
| $SO_x$ | 8.45 |
| $NO_x$ | 45.85 |
| Particulates | 4.13 |

The direct/indirect impact is similar but the hidden risks to the environment and life are less clear. The differences in processing the ore in the UK and in the Far East are due to minor differences in journey lengths and less waste (associated chemicals and waste) being sailed longer distances.

## CONCRETE STRUCTURES

When comparing the environmental impact of constructing a concrete as opposed to a steel jacket, there are a number of issues. Firstly the largest proportion of components, i.e. aggregate, sand and re-cycled steel for reinforcement will all be sourced locally, significantly reducing transport emissions. Against this is the chemical $CO_2$ produced during cement manufacture and the fact that a concrete jacket will be significantly more massive than the equivalent steel structure. These effects tend to balance resulting in an approximate parity in emissions during construction.

Concrete structures have tended to be used for oil storage prior to transport to shore in tankers. The abandonment of concrete structures is still in development as the installation settles into the sea bed such that it is not possible to float the structure without fluidising the soil underneath. The structure must first be made positively buoyant to permit release from the sea bed and if the release is not controlled the structure may become unstable and break up. The issue does not stop there, concrete has to be decontaminated to remove absorbed oils, usually by a combustion process and can only be reused as infill for roads as at present it cannot be recycled into new concrete. The model is flexible enough to deal with such issues but at present these can only be resolved in a fairly coarse manner.

## OPERATION PHASE

The main environmental issues identified during the operation phase of the project were:

- $CO_2$ Load
- VOC Losses
- Oil Losses
- $NO_x$/$SO_x$/Particulates production
- Water Soluble Chemical disposal
- Drilling Cuttings disposal

In the case of the last two, there are different strategies. Water soluble chemicals may be disposed into a pre-drilled well. This results in $CO_2$ production and disposal of drill cuttings from the pre-drilled well itself. In the case of drill cuttings, these can be cleaned and disposed offshore (or transported to shore and then cleaned) or they can be crushed and disposed of into a pre-drilled well. The pre-drilled well disposal hides the effluent by producing carbon dioxide - this will be discussed later.

## $CO_2$ LOAD

The $CO_2$ load is produced by either flaring gases, pilot burners or through generating electricity by gas turbine drivers or diesel engines. At the concept phase of a project there will be insufficient data with which to assess the total power load, however, an analysis of a number of installations shows that there is a factor of about 1.3 between the total power load and the power load of compression, water injection, produced water injection, drill cuttings injection and oil transportation. In other words, the power consumed by small power loads, heating and ventilation, lighting, lubricating oil, pumps, instrument air and the accommodation block is about 30% of the major power users and is a constant factor.

Knowing the basic data on the major power consumers in addition to the drilling program it is thus possible to assess the potential power load for production, services and drilling. Such data will be available at the concept phase from the basic general conditions and data.

## EQUIPMENT CHARACTERISATION

As with the concept risk model every effort was made to reduce the equipment to a series of characterised factors. The adiabatic head of a compressor can be reduced to two factors:

**Gas Characterisation Factor** which includes ratio of specific heats, molecular weight, compressibility and suction temperature.

**Pressure Ratio Factor** which includes suction and discharge pressures and the ratio of specific heats.

The overall power draw, making allowance for efficiency is:

Gas Factor x Pressure Ratio Factor x Throughput

In a similar manner it is possible to characterise the power draw of a pump knowing the differential pressure, throughput and efficiency.

Using these relationships it is possible to calculate the main driver power for the development, hence the total power load may be determined by factoring this value by 1.3.

Values can then be added for flare ignition pilots and leakage to flare if appropriate. In a similar manner to the compressor equation the power recovery from expansion turbines can also be assessed.

## CARBON DIOXIDE EQUIVALENT OF POWER

The conversion of the power into $CO_2$ load requires a knowledge of the fuel – the C:H ratio, calorific value and the efficiency of the prime mover. The properties of the fuels, whether diesel oil or self produced gas, are readily available and standard conversion efficiencies of the drivers are also known. It is thus possible to calculate a $CO_2$ load per Mega Watt of power generated by both fuel and prime mover. These are calculated as 20 tonnes $CO_2$ per day for a gas turbine using fuel gas and 18 tonnes $CO_2$ per day for diesel generation using diesel oil. Factors are also available where the non preferred fuel is used.

As an example, a compressor with a flow of 3.6 tonnes per hour and pressure ratio of 3, the power draw is calculated as 150 kW, producing 3 tonnes/day $CO_2$ from a gas fired turbine.

## $CO_2$ SYNOPSIS

The $CO_2$ load for pump, compressor and other services can be reduced to a number of very simple equations using a set of predetermined factors. $CO_2$ from flaring and pilot burners and purges can also be assessed within the model using standard conversions.

During model application, it has been shown that typical life cycle loads during production are 5-20 times those during construction and abandonment, depending on the size and power requirements of the installation.

## VOC LOSSES

In terms of environmental impact, the $CO_2$ equivalent of Methane is about 21:1 with lower ratios for the higher molecular weight hydrocarbons. Losses occur from either involuntary leakage due to equipment failure, deliberate losses such as tank breathage and fugitive emissions through fittings.

Implicit in the Concept Risk Assessment methodology is a leak profile of frequency and outflow rate for involuntary leaks but there are also protective systems such as automatic isolation plus blow down/depressuring which limit the outflow duration. For a vessel at 100 bar the expected losses would be 115kg per year for a liquid vessel or 15kg per year for a gas vessel.

Tank breathage during transport and loading/off loading and tank movements can be assessed by techniques as described by API[7] and is built into the new model. Increasing use is made of Vapour Recovery at Marine Terminals such that a proportion of the vapours in the tanker are recovered and recycled, with the rest being either incinerated or used to power the process. This reduces the “greenhouse effect” to about 10% of the non-vapour recovery route but the environmental gain must be set against human risk of adding additional high pressure hydrocarbon equipment. Vapour recovery is not in general used with offshore loading.

Fugitive emissions are less readily predicted from historical data, being a function of:

- Design Standards
- Maintenance Standards
- Pressure Testing Standards
- Operating Pressure
- Molecular Weight

A practical analysis of the losses from flanges/valves carried out in the mid 1960s[8] showed that about 0.25% of the plant throughput was lost due to fugitive emissions and that these losses were a function of both leakage and diffusion, since an analysis of the leaked gases showed a higher mole fraction of low molecular weight gases than those of the process itself. Normal pressure testing standards (at start up) should achieve losses of less than 0.05% but this is very dependent on the loss to throughput ratio (hold up time). No truly reproducible and verifiable means of assessing fugitive emissions have been identified for the offshore oil and gas industry particularly with the pressures used (over 100 Bar), however, EPA[9] and Schaich[10] give a band of values which can be used in environmental models. The values quoted may be slightly higher than actual as the offshore engineering standards are very high and installed gas detection systems should give warnings of any significant emissions.

Typical fugitive emissions for a gas vessel are 1000kg per year or 500kg per year for a pump.

## $SO_X$, $NO_X$ AND PARTICULATES

$SO_x$, $NO_x$ and particulate production are a function of the fuel used and the type of prime mover. Of the three types of mechanism which produces $NO_x$; Fuel, Prompt and Thermal $NO_x$, the latter is entirely dependant on the combustion temperature. Below about 1300°C the Thermal $NO_x$ mechanism is negligible compared to other mechanisms, whilst at higher temperatures it becomes the most important. Particulate production, i.e. unburnt hydrocarbons, from diesel and gaseous fuels is dependent upon not only on temperature but mixing and the residence times within the combustion chamber. Generally higher efficiency leads to higher temperatures which in turn increases thermal $NO_x$ production but will decrease $CO_2$ production as the fuel to air will be close to stoichiometric ratio. Within the model the $NO_x$ and particulate production levels are based upon manufacturers data collected for the range of generators likely to be used on modern installations.

The value of $SO_x$ can be determined from the sulphur contained within the fuel.

## WATER SOLUBLE CHEMICALS

There are many water soluble chemicals used in the process, such as methanol for hydrate suppression, glycols for drying, anti-foaming agents, corrosion inhibitors and drilling fluids such as oils, barytes and other solids. All of these come under the UK Offshore Chemicals Notification Scheme from the DTI, where their impact on marine life is tabulated and the fluids are ranked by toxicity to marine life. There is an increasing trend to dispose of these by injecting them under ground.

Tabulations within the model allow rapid comparison of the chemicals required for the development options being considered.

## CASE STUDY

An indication of the variety of design concepts that can be considered are shown in Figure 1. As space does not permit a full detailed example to be presented here, only the life cycle $CO_2$ production predicted by the model for these three options is presented as Figure 2. Full listings of $NO_x$, $SO_x$, particulates, routine releases and potential accidental losses are also available broken down by operational phase.

Figure 1. Diagram of Options Considered Within Case Study

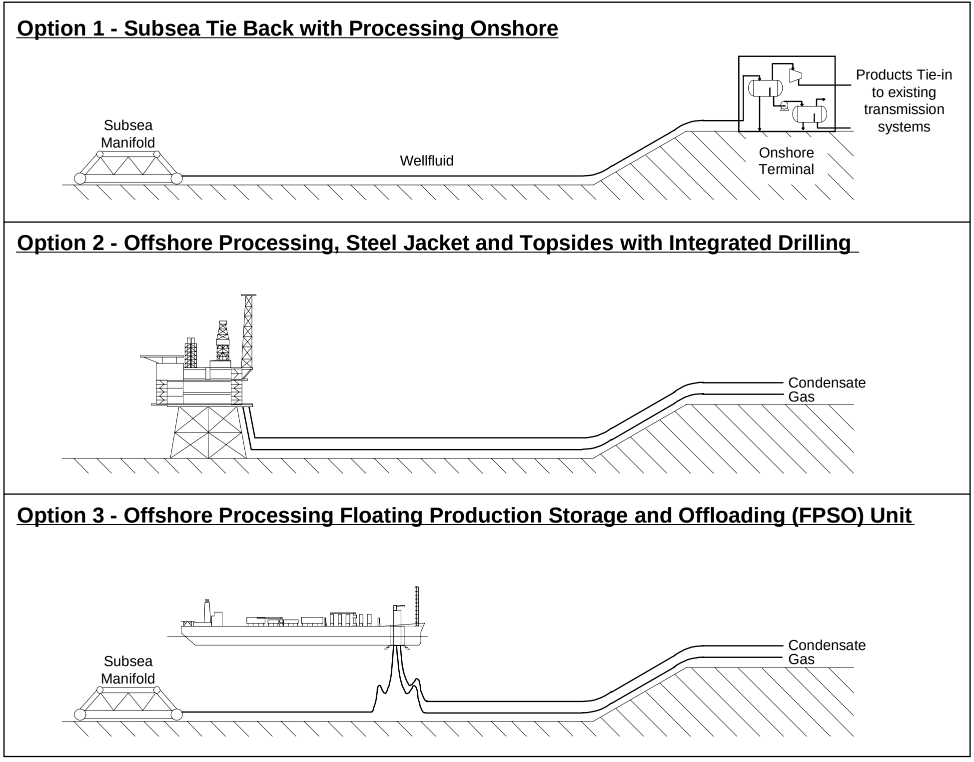
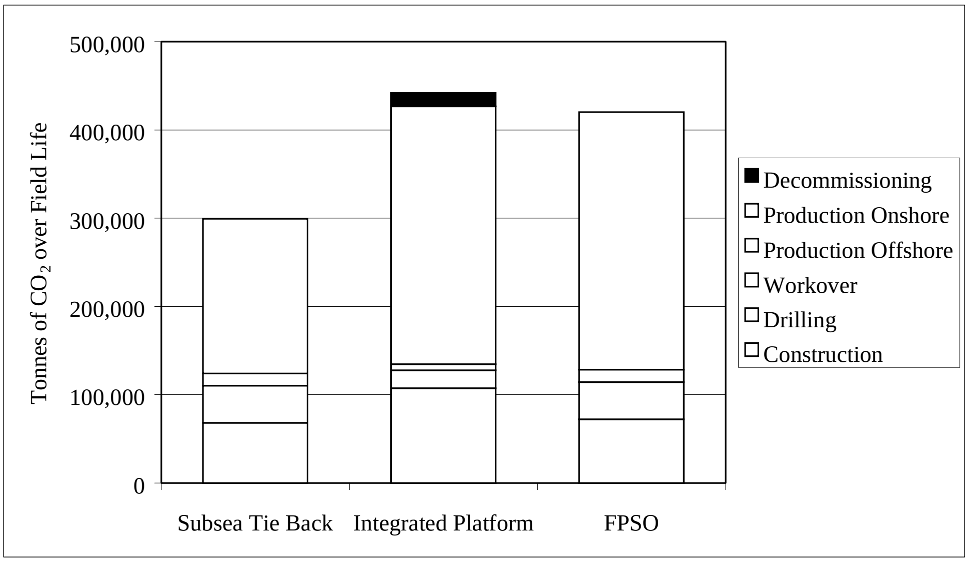


Figure 2. Life Cycle $CO_2$ Production



For each option the production phase is the most significant contributor to $CO_2$ emissions, due to the length of this phase. The long subsea tieback has a lower contribution during this phase as there is no offshore accommodation that requires servicing. The integrated platform has the highest contribution during construction due to the amount of steel and energy required for fabrication. In this example the FPSO is assumed to be a conversion from a tanker rather than a new build, hence the construction emissions are those associated with fabrication and installation of a new topsides only. It is seen that the integrated drilling facilities lead to some benefit during the drilling and workover phases, as there is no requirement for servicing the accommodation on a third party drilling rig or any mobilisation requirements. The final issue raised here is that of decommissioning. While the onshore facility can be readily decommissioned and the FPSO can be re-used, the integrated platform must be returned to shore for dismantling and recycling, which is an energy intensive activity.

The power of the model is thus to identify the major issues at the very earliest stages of facility development. Sensible design solutions can then be identified to allow fine tuning of the design at the concept stage. This process then allows a solid demonstration that the BPEO principles have been applied.

## DECISIONS AND THE DILEMMA

The global impact of a unit mass of pollutant cannot be assessed with any significant degree of confidence. While it is possible that a reduction in $CO_2$ load will incur an increased risk to those associated with its production, the impact of the $CO_2$ reduction on $6 \times 10^9$ persons is less clear. It is possible to assess the small increment of risk to a small group but not the infinitesimally small benefit to the large group; such is the difficulty with Risk Assessment.

There is a known link between $SO_x/NO_x$ emissions and asthma and bronchitis. The pollutants are also major contributors towards acid rain, which has a serious effect on forest land, aquatic life and on some natural stone building materials.

VOC and $NO_x$ are known precursors to ozone which in turn can increase susceptibility to respiratory infections and long term exposure can lead to scarring of lungs tissue and lowered lung efficiency. Likewise there is also a link between particulates and lung impairment, which can be exacerbated by the toxic chemicals carried by the particulates.

The effects are known but there is as yet no way of assessing the "global cost" either in life or environmental impact (which may affect life) of many of the pollutants above. As a result, the equation for balancing risks has some unknowns. (As the end point of most of the products of the offshore oil and gas industry is fuels, it is fair to note that the end users of the hydrocarbons generate more pollution than the producers).

## PERCEIVED VALUES

### LIFE

Many companies have determined a sum of money that they consider should be "spent" to save a "statistical life". National governments adopt values that vary between Transport, Health, etc. The value of a statistical life (VOSL) (1998) for an improvement has been quoted in the UK as £902,500[11]. Courts of law are now setting a value of life of about one million pounds in the UK and higher in the USA. Insurance and values or sums required for inflation proofed trust funds for dependants would be nearer £700,000.

Clearly there is no fixed value of life in terms of risk assessment for industry but many large organisations involved in upstream oil and gas operations are known in the past to have used £5 million per statistical fatality averted.

### POLLUTION

Increasingly, companies are developing their own inhouse short term and long term goals, with many companies displaying the annual loads in their annual reports. There is clear evidence of a downward trend which must be beneficial in the long term.

### OIL SPILLS

The remedial costs of an oil spill and the environmental damage are a function of the properties of the oil, the mass released, it’s location and the weather at the time of release. Light oils, such as those in the UK Continental Shelf tend to disperse or emulsify with wave action and are decomposed biologically. Heavy oils tend to clump, weather off lighter components and sink where they decompose more slowly. Spills close to the shore, obviously, have more potential impact particularly if they are close to habitation, sea farms or bird colonies.

The International Oil Pollution Compensation Funds publish annual reports on the claims on the fund. The 1998 data[12] shows that small losses cost disproportionately more per tonne released due to mobilisation and demobilisation costs and naturally the vast majority of claims originate from releases close to shore. Taken all in all there is a wide range of claims per tonne of oil spilled, the lighter oils are about £2,000 per tonne spilled (allowing for inflation) and for heavier oils are around ten times this. It should be noted that the USA is not a member of the fund and if punitive damages are imposed the cost could rise to £100,000 per tonne spilled[13].

A realistic value for the costs of lighter oil spills is taken as £6,000 per tonne reflecting a mixture of historic costs, public aversion and environmental damage.

## CALIBRATION

In order to assess the accuracy of the predictive methodology, calibration has been performed against the detailed Environmental Impact Assessment for a modern installation, submitted to the DTI as part of the consent application for the development.

The installation chosen for this exercise is an integrated drilling and production platform located in the North Sea. Production from both local and remote subsea wells is processed prior to export via tie-ins into existing pipeline systems. Provision is made for re-injection of cuttings into the reservoir, in preference to onshore disposal or clean-up and overboard dumping. The results of this exercise are shown in the Table 8.

Table 8. Comparison of Results (Tonnes per Annum)

| **Emission** | **Predicted Values from Model** | **Values from Environmental Impact Assessment** |
|---|---|---|
| $CO_2$ | 185,734 | 184,625 |
| $CO_2$ Flare | 12,828 | - |
| $SO_x$ | 2.9 | 10.99 |
| VOC | 471 | 473 |
| Oil Loses | 1.985 | 2.0 |

This shows that the predicted and measured values in most cases agree to within a few percent. The variation in $SO_x$ emissions resulted from platform shutdowns where power generation switches to diesel rather than fuel gas. This was not accounted for in the model, although this has now been addressed. Constant flaring of pilot gas and fugitive emissions past relief/blowdown valves are accounted for in the model, but were not measured in the detailed analysis.

In this particular case the predictive model has been shown to very accurately predict the impact levels upon the environment, but with the benefit of only taking around 5% of the time required to perform the detailed analysis.

## DO SAFETY AND THE ENVIRONMENT PULL IN THE SAME DIRECTION?

Project decisions are not taken lightly and only after detailed analysis of the available (but incomplete) data. This results in an element of professional judgement which suggests that there are some perceived criteria which might be met. The risk and the environmental impact assessment models allow some of the decisions to be tested and to determine if there are some perceived values, which can be used in a risk/environment model. The values derived will only reflect the blend of perceived and given values.

As a generalisation, additional equipment used to reduce environmental impact will, by definition, be likely to increase the risk to humans, albeit that the extent of the risk increase may be extremely small. The following case studies represent some of the conflicts that can occur.

Before any analysis can be carried out it is necessary to put some fixed values on:

| | |
|---|---|
| Life | £5M per fatality |
| Oil Spilled | £6,000 per tonne |

CASE STUDY 1

The first oil fields (and some of the newer ones West of the Hebrides) use tanker transport for oil instead of pipeline transport to a terminal. This is largely because the capital cost of a dedicated pipeline could make the development uneconomic. The case study revolves round the analysis of money not spent to adopt the safer/lower environmental impact option.

The notional assessment will be based on 100,000 tonnes of oil per 14 days (about 50,000 bopd) over a notional 100 miles. All values are presented on a per annum basis.

Table 9. Case Study 1 – Pipeline / Tanker Comparison

| | **Pipeline** | **Tanker** |
|---|---|---|
| **Capital Expenditure** | £20 Million | £10 Million |
| **Oil Loses** | 0.75Te | 130Te |
| **$CO_2$ Production** | 5750Te Pumping | 575Te Pumping<br>36Te Auxiliaries<br>14,000Te Tanker Steaming<br>1,300Te Inerting |
| **VOC Loses** | 0 | 365Te |
| **Life Loses** | $6.6x10^{-5}$ | 0.0177 |

The life element for the pipeline option is associated with hazards related to the Main Oil Pumps. For the tanker option, the life element is is made up from contributions from structural failure, tank explosion, slips, trips, falls and oil pumping. The equation balancing the impacts reduces to:

$$\text{£}10\text{M} = 365 \text{ Tonne VOC} + 130 \text{ Tonne Oil} + 10{,}291 \text{ Tonne } CO_2 + 0.0177 \text{ life}$$

Values can be applied to oil and life, and a $CO_2$ equivalence of VOCs can be used to determine the inferred value of $CO_2$. This infers that $CO_2$ is valued at £780 Tonne produced or that a single life is equivalent to 800,000 Tonne $CO_2$.

CASE STUDY 2

Gases leak to flare through relief valves and blow down valves. The gas can be burnt or it can be recovered by a compressor and re-injected into the process. The gas can only have a value if it is exported into the gas pipe line and it can only be considered to give a lower environmental impact if it is injected into a reservoir.

A notional one tonne per hour will be used for the assessment. The overall pressure ratio will be taken as 125 barg (for pipeline injection). All values are presented on a per annum basis.

Table 10. Case Study 2 – Gas Flaring / Recovery Comparison

| | **Flaring** | **Recovery** |
|---|---|---|
| **Capital Expenditure** | 0 | £1 Million |
| **$CO_2$ Production** | 25,000Te Flaring | 2,200Te Compression |
| **Life Loses** | 0 | $3.5x10^{-4}$ |

The life element is associated with hazards from the additional high pressure gas plant and the additional maintenance required. Balancing these contributions gives the following equation:

$$£1M \text{ spent} = 22800 \text{ tonnes of } CO_2 \text{ saved} + 3.5 \times 10^{-4} \text{ life}$$

Thus in this case, $CO_2$ has an inferred value of £42 per tonne or a single life has an inferred value of 64 million tonnes of $CO_2$.

CASE STUDY 3

The issue of water disposal normally requires careful consideration for each new development. Produced water (plus associated chemicals) can either be re-injected back into the reservoir with minimal cleaning, or the water can be cleaned to around 30ppm of oil and discharged to sea. Table 11 presents the issues to be considered for this example, in which a flow of 15,000 Tonne of water per day (100,000 bwpd) is assumed, with an injection pressure of 2000 psi. All values are presented on a per annum basis.

Table 11. Case Study 3 – Produced Water Disposal Options

| | **Clean Up and Dumping** | **Re-injection** |
|---|---|---|
| **Capital Expenditure** | £0.5 Million | £0.5 Million |
| **$CO_2$ Production** | 750Te Clean Up | 500Te Clean Up<br>500Te Drilling (over 10 years)<br>24,000Te Re-injection |
| **Oil Losses** | 160Te Overboard | 0 |
| **Life Loses** | Neg | Neg |

Injecting oily water prevents 160 tonnes of oil being released into the sea with a cost of 24,250 tonnes of $CO_2$ being generated in the running of the injection pumps. 1 tonne of oil is thus equivalent to 150 tonnes $CO_2$.

## CONCLUSION

A model has been developed to assess the Environmental Impact of fabricating, operating, and abandoning an offshore oil or gas installation. This can be used in conjunction with the Concept Risk Assessment model to give an early ranking of a large number of concepts in terms of environmental impact and safety and allow an informed decision of which design option should be developed.

However, an examination of historic environmental enhancements shows that there is an inconsistency in the perceived values in terms of life and financial impacts of the pollutants. Until a consistent set of values can be ascribed to pollutants (or guidance notes on decision making are produced), there will always be a subjectivity of the design which offers both BPEO and ALARP.

## REFERENCES

1 Crawley, F K, Grant M M, Green, M D, 1995, A Methodology for Concept Risk Assessment of Offshore Developments, *IChemE* Series No 139.

2 Crawley F K, Grant M M, 1997, Concept Risk Assessment of Offshore Hydrocarbon Production Installations, Trans *IChemE* Vol 75, Part B pp 157-163.

3 The Tolerability of Risk Assessment from Nuclear Power Stations, 1988 (Revised 1992) HMSO, London. ISBN: 011.886368.1

4 Risk Criteria for Land Use Planning in the Vicinity of Major Industrial Hazards, 1989, HMSO, London ISBN 011.8854917

5 Oslo and Paris (OSPAR) Convention for the Protection of the Marine Environement in the North East Atlantic , OSPAR Decision 98/3

6 Consultative Document: Guidance Notes on Decommissioning Under the Petroleum Act 1998, DTI, London

7 Atmospheric Hydrocarbon Emission from Marine Vessel Transfer Operations, AP12514A, 1987, American Petroleum Institute, Washington DC, USA

8 Confidential Study, 1961

9 1995 Protocol for Equipment Leak Emission Estimates. Report EPA 453/R-95-017

10 Schaich J R, 1991 Estimate Fugitive Emissions from Process Equipment, Chemical Engineering Progress, Vol 89 No8 AICHE

11 Reducing Risk Protecting People – Discussion Document, 1999, HSE, HSE Books, Suffolk

12 International Oil Pollution Compensation Funds, 1998, London, UK.

13 Environmental Protection Bulletin, 1999, No.60, page 22, IChemE, Rugby, UK.