SOUR GAS WELL-TEST FLARING REVIEW

Prepared for:

British Columbia Oil and Gas Commission and B.C. Ministry of Environment

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May 2007

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EXECUTIVE SUMMARY

A review was conducted for a selected number of pre-flaring and post-flaring well-test assessment reports associated with oil and gas exploration in British Columbia. The review assessed how well the reports conformed to the requirements set forth in the Oil and Gas Commission (OGC) Interim Guideline #OGC 00-01 and the draft B.C. air dispersion modelling guidelines, and how these relate to practices in B.C., other Canadian provinces and the United States. In addition, a literature review was conducted on flaring dynamics and flare dispersion modelling practices elsewhere.

A total of 29 production well-tests were considered in this review from the period 2000-2006. There was an overall consistency in the manner in which most of the analyses were conducted and reported, reflecting the fact that all but two of the analyses were conducted by a single consulting firm. The remaining two reports by another consulting firm were consistent with the overall guidance from the OGC, but differed in how the information was presented. Over the period examined, there appeared to be a trend in the evolution of the finer details of flaring management in B.C., such that the process appeared to be more protective of the environment during that latter half of the period 2000-2006 than during the earlier years. This was not simply due to changes in requirements by the Ministry of Environment or the OGC, but also due to an increased level of awareness by industry about the need to address environmental issues and increased effort on the part of industry in developing flare management plans. This is important because anecdotal information obtained during the review suggested that there has been an increased frequency of well-tests being conducted for gas deposits having higher H_2S concentrations and in more complex terrain settings, although the number of production well-test reports examined were insufficient to definitively confirm this trend.

With respect to the tools used to develop flaring management plans, the primary advantage to the use of dispersion models for well-test management is that they provide an objective means of estimating where and when vegetation damage might occur. The results of this modelling in the pre-flare stage are then used to screen out those meteorological conditions that are unsuitable for flaring with respect to the risk for vegetation injury. However, it must be recognized that none of the available air quality models currently being used to identify the potential risk for vegetation damage are ideally suited to the purpose. In particular, current dispersion modelling analyses for both pre-flaring and post-flaring evaluations cannot address the emissions that occur during the clean out phase of well-test operations, and there is some evidence to suggest that some vegetation damage that occurs near the well-test pads is due to these emissions, rather than during the mature phase of the well-test flaring. Some suggestions are made in the report that would potentially improve model performance (i.e., flare radiation loss and volumetric flow rate), but these would not address the fundamental inability of the models to adequately represent flare emissions during the clean out phase of operations.

Nevertheless, it is concluded that, despite their limitations, the use of dispersion models for the development of flare management plans is both necessary and beneficial. Reliance on relatively crude dispersion models for making key decisions on vegetation protection is seen as one of the primary issues that need to be addressed for future flaring work. In particular, there is a need for a formal recognition that the available dispersion models used to determine whether or not acute foliar damage criteria are being met or exceeded may represent an overly simplistic approach to well-test emissions management. Some studies have indicated that significant adverse effects on vegetation have been missed through the use of this process. Dr. A. Legge, from whose work the damage criteria were derived, has indicated that the way the criteria are being used to predict injury to vegetation has significant limitations. Although the Legge criteria provide an appropriate, if conservative, means to estimate foliar damage and establish protective measures for flaring, inherent uncertainties associated with predicting vegetation damage (or lack thereof) exist, and may require further investigation. These protective measures may include an assessment of effective dormancy, the presence of susceptible plant communities and the potential for cumulative effects if flare testing is to occur over a period of days.

The presence at the well-test site during flaring operations of a qualified field biologist with experience in assessing when vegetation damage may occur provides an added layer of protection against vegetation injury. However, during some well-test operations, differences of opinion about the relative risk for vegetation injury have arisen between on-site consultants and Ministry of Environment (MoE) staff located off-site who rely on dispersion modelling and monitoring data alone. There is a need to recognize that Ministry staff located in Prince George may not be available at the time when flare management decisions must be made about whether to shut in a well, or even in the best position to judge the circumstances that exist at the site. For high risk situations, interpretation of the differences between SO_2 concentrations predicted by the dispersion models and observed at static monitors may not be straightforward, and the use of qualified professionals with an understanding of environmental response to sulphur dioxide exposures can help to support on-site management decisions regarding the potential for damage to occur based on the interpretation of a susceptible community, and timing of dormancy..

There is also a need for better communications between on-site consultants and Ministry staff regarding changes to flare management plans. In addition, post-flare vegetation damage assessment should not hinge on modelling results alone, and could benefit from consideration of risk management by qualified professionals with a background in vegetation response to sulphur dioxide. At the present time there is no facility for judgement based on the potential for toxic response of susceptible plant communities.

For all of these reasons, the review has identified a need to clarify the roles and responsibilities of the various participants in the flaring management process. The report recommends the following management structure that could potentially address this issue:

a. The MoE is responsible for defining the goals for environmental protection during flaring and acts in an advisory capacity when requested to do so by the OGC, but is not responsible for the day-to-day decisions on implementing the well-test management plans;
b. Overall development and implementation of the management plan rests with the proponents and site managers, with assistance from their consultants and the approval of the OGC through the permit to flare;
c. If deemed necessary, site managers would be responsible for seeking the advice of an on-site meteorologist or suitably trained atmospheric scientist on when to flare or when to shut in a well;
d. The on-site meteorologist or atmospheric scientist could also seek the advice of a qualified, on-site biologist as to the likelihood of foliar damage, when preparing to advise the site managers as to the need to shut in a well;
e. The on-site meteorologist or atmospheric scientist could also seek advice from the MoE in preparing to advise the proponent's site manager, but the ultimate responsibility to act on the recommendation by the on-site meteorologist would rest entirely with the proponent's site manager.

Recommendations are also provided on suggested changes for:

- simplifying the review process for the regulators and minimizing the uncertainty associated with communicating the actual flaring conditions required for a post-flare investigation of foliar damage;
- standardization of current best management practices where production test dispersion analysis predicts injury to vegetation;
- specification of additional (i.e., non-meteorological) conditions under which the clean out flare is to proceed, specifically with respect to the use of lift gas to improve plume rise.

These recommendations are made bearing in mind that the Government of British Columbia has a stated goal to eliminate all flaring by 2012, and that it may be inutile to propose wholesale changes to the existing process for the next 5 years.

1.0 INTRODUCTION

SENES Consultants Limited (SENES), in association with Delphinium Holdings, was commissioned to conduct a review of selected pre-flaring and post-flaring well-test assessment reports associated with oil and gas exploration in British Columbia. The review involves assessing the requirements set forth in the Oil and Gas Commission (OGC) Interim Guideline #OGC 00-01 and the draft B.C. air dispersion modelling guidelines and how these relate to practices in B.C., other Canadian provinces and the United States.

The management of well-test flaring occurs directly through compliance and enforcement officers of the OGC, who ensure appropriate flaring conditions are set. The OGC relies on the B.C. Ministry of Environment (MoE) in an advisory capacity regarding potential environmental impacts. In practice, the MoE has equal authority to the OGC on well-test flaring conditions and the decision to shut in (close) a well. Currently, the OGC is conducting an exercise to produce revised flaring guidelines (for all flaring activities), which will include a strategy to minimize the total volumes of flare gas combusted in the province[1].

1.1 BACKGROUND

Flaring is a method for disposing of unusable flammable gas through combustion and is often used during routine oil and natural gas exploration processes. The Canadian Association of Petroleum Producers (CAPP) provides a practical definition for the term[2]:

> *Flaring - The controlled burning of natural gas that can't be processed for sale or use because of technical or economical reasons.*

As opposed to incineration, where an enclosure (furnace) is used to combust waste gas, most flaring systems ignite waste gas at stack top so that a visible flame is produced. Flaring associated with oil and gas exploration, or petrochemical refining, is entirely through use of open flame, since the flare gas can be quite corrosive, and there may be the need to dispose of a large volume of gas in a short amount of time. The terms flare or flaring in this report represent open-air combustion at the top of a stack.

Flare gas is a general term representing waste gas from oil/gas wells, refineries, chemical plants and landfills[3]. In many cases, flare gas poses a significant risk to animal or environmental health due to the presence of hazardous compounds (e.g., hydrogen sulphide). The degree of risk is related to the composition of the flare gas. However, flaring does not necessarily reduce the risk

[1] Personal communication with R. Slocomb, Resource Conservation, OGC. July 13, 2006.
[2] See http://www.capp.ca/default.asp?V_DOC_ID=768

to insignificant levels. The end-product gases, or combustion products produced by flaring, can also be detrimental when present in sufficiently high concentrations. Ultimately, flaring is considered to be a much more sound practice than simple venting of hazardous gases. The flaring process can be classified into three main groups: emergency flaring, process flaring and production flaring (Johnson *et al*, 2001).

Emergency flaring normally occurs in situations such as fire, rupture of valves, or compressor failures. In these cases, a large volume of gas with relatively high exit velocity is combusted in a short period of time. Process flaring is a continuous operation and usually involves a lower gas release rate. A common example of process flaring is that associated with petrochemical refining, as waste hydrocarbon products are removed from the process stream. Flare gas volumes at such facilities can range from a few cubic metres per hour during normal operating conditions to several thousand cubic metres per hour during major plant upsets[4]. The term solution gas flaring is also used to describe process flaring.

Production flaring is associated with processes in the upstream oil and gas industry. During the initial assessment of a gas well, a significant quantity of gas will be flared as an indication of the capacity of the well for production. This allows for characteristics such as reservoir pressure and flow rates to be determined. Well-test flaring is an example of production flaring. Well production tests can involve the combustion of large volumes of gases in a very short period of time.

A common assumption exists that process and production flaring efficiently converts hydrocarbon compounds in the gas stream into relatively innocuous gases such as CO_2, SO_2 and H_2O (Leahey et al, 2001). However, the combustion efficiency of a flare can vary with both gas composition and wind speed, leading to significant production of more complex chemical species, including volatile organic compounds (VOCs). The presence of liquids in flare gas further affects the combustion efficiency. SO_2 emissions due to flaring of sour gas during well-testing is of particular interest in B.C. and other provinces, since concentrations can be high enough to cause health effects in residential areas or foliar damage in forested areas. In almost all cases in B.C., production tests are undertaken far from any residential areas.

During 2004, approximately 110 billion cubic metres of gas were flared or vented worldwide (World Bank, 2004). There have been recent, successful initiatives to reduce the combustion of flare gas from both exploratory and operational oil and gas activity. In the U.S., some states forbid flaring unless it is shown that there is no market availability[5]. Alberta requires the use of

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[3] www.wikipedia.org
[4] See http://www.epa.gov/ttn/chief/ap42/ch13 section 13.5.
[5] The State of Ohio for example. See *Topical Summary of Ohio Oil and Gas Law*, http://www.ohiodnr.com/mineral/oil/index.html.

a 'decision tree process' to evaluate methods of eliminating or reducing flaring (EUB Guide 60). B.C. is currently considering a similar approach.

A preferred alternative to well-test flaring is in-line testing. *In-line testing* involves connecting the well under consideration to a nearby pipeline, thereby allowing testing to occur without the venting or combusting of flare gas. In-line testing may still involve flaring, although at greatly reduced volumes (EUB Guide 60, 2002). In-line testing is more feasible with developed infrastructure (i.e., a dense network of existing pipelines), as costs can be prohibitively high when existing conduit is at a significant distance from the well site. For this reason, in-line testing may not be reasonable to pursue in some areas of British Columbia.

Research conducted by the Geological Survey of Canada (GSC), the National Energy Board (NEB) and the Ministry of Energy and Mines (MEM) has determined that British Columbia has 739 billion to 1243 billion m^3 of potential natural gas reserves (OGC, 2004). Production tests occur largely in the northeastern part of B.C., because the majority of provincial gas extraction and exploration taking place in this region. According to the OGC, production tests accounted for 37% of the total flaring in the province for the year 2005.

Drilling activity has significantly increased in British Columbia over the past eight years. During 2003, a total of 1,376 well authorizations were issued, which is the highest annual level ever achieved. Almost 60% of these authorizations were received by five companies, with the top company alone receiving 32% of the total. Of these authorizations, 1041 wells were drilled, with 770 completed as gas wells (OGC, 2004). Also of significance, well depths drilled and the percentage of successful well completions were at an historic high. However, average production per gas well has been steadily declining, coinciding with the maturity of gas exploration in B.C. and the increasing development of relatively low permeability reservoirs (ibid).

1.2 WELL TEST (PRODUCTION) FLARING

Production test flaring is conducted to determine well characteristics such as reservoir pressure and potential flow rates. In doing so, determination of infrastructure requirements, economic considerations and potential operational difficulties (such as water intrusion) can be achieved. In general, a greater duration of flaring allows more data to be captured. A greater understanding of the reservoir and well characteristics reduces the risk to the licensee, particularly in economic terms. *Routine Flaring Volume Allowances* have been established in Alberta, which identify a reasonable volume of flaring gas associated with three main well types (CAPP, 2001). A Tier 1 allowance, applicable for exploration wells, is significantly higher than that associated with Tier 2 (usually termed development wells) and Tier 3 (a well that has already been tied in to infrastructure). However, when necessary, a greater amount of flaring than is indicated by the allowances may sometimes be granted. In contrast to Alberta, a licensee in B.C. is required to detail efforts to minimize flaring volumes by completing the *Application for Flaring Approval*.

During a production test procedure, there are typically two flaring intervals that should be distinguished; the clean-out flare and the production test itself. Acidizing the well hole is a common practice in some areas to prepare the well for subsequent production tests and eventual production. Acidizing is a method of improving porosity and permeability of a reservoir by injecting acid under pressure to dissolve rock[6]. The terms ‘clean-out’ or ‘clean-up’ flaring are used to represent the (usually short-term – up to several hours) flaring to clean the hole of drilling mud, sediment, water and residual acid that could not be collected following the high pressure injection. When in-line well testing is feasible, clean-out flaring may still occur. During clean-out flaring, actual emissions can be very different from emissions during a typical well-test flare. Different combustion by-products may be involved, and due to a lower combustion temperature and exit velocity, clean out flaring may exhibit different physical plume characteristics. The second flaring interval is the actual production test, which is of a longer duration than the clean-out interval.

The release of either SO_2 or hydrogen sulphide (H_2S) during flaring activity has the potential for causing impacts to both human and environmental health. H_2S is far more toxic to humans than is SO_2; however, H_2S is effectively destroyed in the combustion process. In practice, it is the release of SO_2 that has the most significant potential to cause either human health or environmental impacts during flaring activity. The SO_2 release rate from a well-test may be much higher than rates associated with common continuous sources (such as a power plant stack). The amount of SO_2 released from well-test flaring can be estimated from the expected volumetric flow rate of flare gas, and the concentration of H_2S within the gas. In B.C., permission to flare is based on these estimates and may include limitations on when flaring may be conducted to ensure favourable atmospheric conditions where either the plume is more readily dispersed, or the potential for foliar damage is at a relative minimum. Concentrations of unburned H_2S or other gas constituents from the stack may also be of concern. In Alberta, ambient criteria are applied to both SO_2 and H_2S concentrations due to flare emissions.

[6] Center For Energy. http://www.centreforenergy.com/

2.0 FLARING CHARACTERISTICS

Exhaust gases from flaring are emitted from the flame rather than the stack opening (top). This complicates either measuring or estimating the rates of pollutant release. There is general acknowledgement that emission characteristics from flares are not well-understood and have considerable sensitivity to environmental factors (in particular wind speed). Emission rates are additionally sensitive to flare stack design characteristics such as the flare tip diameter, which allows control of gas exit velocity. A challenge associated with characterizing well-test flaring is due to flaring research that primarily relates to process (solution gas) flaring, which is very different from sour gas production flaring. However, some commonalities between the two types of flaring activities do exist.

Both Canadian and U.S. regulatory agencies recognize the value of recent flaring studies that have been conducted in Alberta, from private, government and academic sources. A particularly relevant document for this review is *Sour Well Test Flaring Permit Application Process and Dispersion Modelling Nomographs* produced for the Canadian Association of Petroleum Producers (CAPP) and the Alberta Energy and Utilities Board (EUB) in 2001, referred to here as the CAPP report, or CAPP (2001). The CAPP report provides a detailed description of flaring, implications from Canadian and U.S. studies (including U.S. EPA guidelines) and recommended guidelines for flaring activities and dispersion modelling. A more recent publication regarding the findings of the *University of Alberta Flare Research Project* (Kostiuk *et al.* 2004) is also of relevance, particularly since it addresses the higher gas exit velocities associated with well-test flares (when compared to solution gas flares). Significant flaring research is continuing in Alberta, with financial support from Environment Canada, the Natural Sciences and Engineering Research Council (NSERC), CAPP, OGC and other bodies.

In British Columbia, several studies funded by the OGC examined the effects of sour gas flaring on vegetation (Enns, 2004a, Ibid 2004b). This work reviewed several production tests and dispersion modelling both prior to, and after, the tests over a three year period. It showed that both pre- and post-production test modelling is useful, but does not always provide a realistic indication of the potential for injury to vegetation from sour gas production tests. The field results of the vegetation and passive monitoring responses indicated that occasionally mild injury to vegetation occurs as a result of a production test, but in general the effects are often not as predicted in the post-production modelling (which uses the actual meteorological conditions during the well test). In effect, modelling or simulating vegetation response is very challenging, due to uncertainties in both the computer models and the susceptibility of vegetation during the flaring period.

2.1 FLARING DYNAMICS

The products of flaring, or combustion gas, leave the flare tip with momentum and buoyant energy. *Crossover Temperature* is a dispersion term indicating the plume temperature at which plume rise due to buoyancy and momentum are equal. The CAPP report states that this temperature is approximately 100 ^{o}C for flares in general (meaning it applies to both lower gas volume continuous flares as well as well-test flares). Since typical well-test flaring exit temperatures are well over 100 ^{o}C (e.g., Beychok, 1995), plume rise is clearly dominated by the buoyant energy of the plume, due to the sensible heat of the gases.

Combustion efficiency is commonly used to represent the degree to which hazardous gas constituents are chemically converted to end-gases such as CO_2, SO_2 and H_2O. Flaring rarely achieves complete combustion, due to entrainment of air into the region of combusting gases (Leahey *et al*, 2001). Johnson *et al* (2001) describes two combustion efficiencies: carbon efficiency (hydrocarbons to CO_2) and sulphur efficiency (H_2S to SO_2). However, in many cases, one combustion efficiency value is used to represent both conversions. Combustion efficiency is influenced by stack and environmental factors, as well as by flare gas composition. Some studies note combustion efficiencies as low as 62% (e.g., Poudenx and Kostiuk, 1999). However, such low efficiencies may be due to relatively high wind speeds and/or flare gas composition of low internal (chemical) energy. Furthermore, the lower efficiencies relate to the low gas exit velocities associated with solution flaring. The EUB states that a combustion efficiency of 98% or greater is 'generally' achieved as long as a minimum energy content of the flare gas is adhered to (EUB, 2005). The EPA supports the same claim[7]. However, Leahey *et al* (2001) found that both theoretical and observational evidence support a lower efficiency of approximately 70% during wind speeds in the range 0 – 3.5 m/s. Again, the poor efficiencies likely have little significance to the high gas flow production flares.

Strosher (1996) completed an earlier investigation of solution gas flaring emissions in Alberta, consisting of laboratory, pilot scale and field scale studies. The laboratory and pilot studies indicated that pure gas streams (methane, propane, commercial natural gas) burn with a high degree of combustion efficiency, very close to 100%. Although many hydrocarbon products were produced during the flaring of input gases, the majority were effectively destroyed in the outer combustion zone of the flame. The addition of liquid hydrocarbons or condensates to the input gas streams inhibited the overall combustion efficiency and the destruction of the hydrocarbon products. Crosswinds were also found to lower combustion efficiency and increase the amount of hydrocarbon products (such as benzene, naphthalene and PAHs) in the emissions. The field studies involved flaring of sweet and sour gases at two oilfield battery sites in Alberta. The sweet gas tended to have 'considerable' liquid hydrocarbon content whereas the sour gas

[7] Air Pollution Control Technology Fact Sheet. EPA-452/F-03-019.

tended to be much drier. The results supported the general findings of the laboratory and pilot studies, with the sweet gas flaring achieving between 62 – 71% efficiency and the sour gas achieving 82 – 84% combustion efficiency. These efficiencies should not be considered typical to most solution gas flaring activities, but rather values that may accompany flaring with flare gas of significant liquid content, cross winds above 2 m/s, or a combination of both.

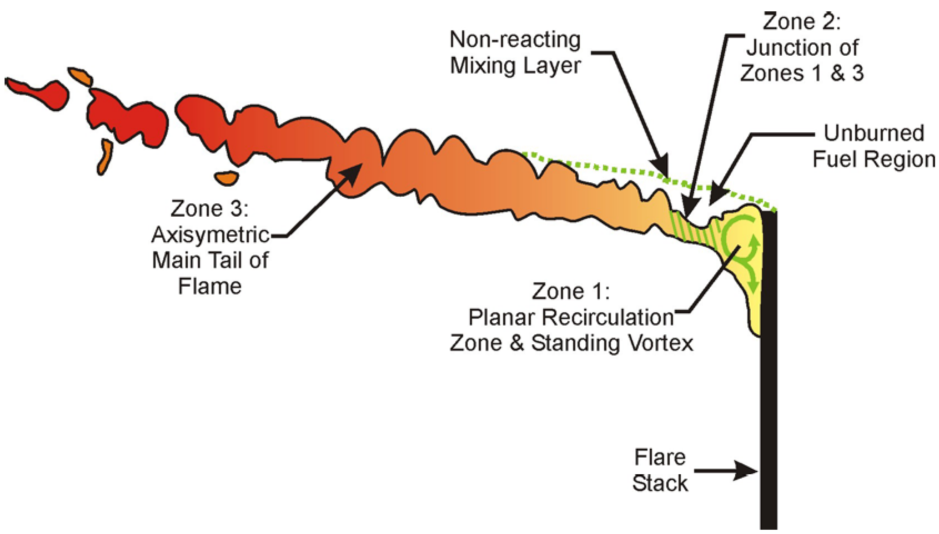
The EUB uses the term *destruction efficiency* to describe the destruction of hydrocarbon compounds produced as a result of complete and incomplete combustion (EUB Guide 60). Although it may be desirable to set limits or standards for acceptable combustion or destruction efficiencies, the EUB determined in 1999 that this approach was not currently practical, due to significant difficulties in assessing compliance. Instead, operators are required to follow good engineering practice in the design and operation of flaring systems. Although the EUB Guide 60 published in 1999 stated that flare combustion efficiency requirements would be determined no later than 2001, the 2003 update to Guide 60 (EUB 2003) shows that minimum combustion efficiency (or destruction efficiency) standards have not yet been established.

The University of Alberta (U of A) Flare Research Project Final Report (Kostiuk *et al*, 2004) addresses what has been described as 'historically conflicting results' from past flaring studies. The report rationalizes some of the differing conclusions from test site studies by use of a controlled environment in a wind tunnel. Although the test conditions within a wind tunnel would not fully represent the complexities of conditions experienced in the field, a controlled environment allows better analysis of the relationships between key factors that may affect combustion efficiency and related flare characteristics.

Figure 2.1 provides a representation of the flare stack flame in a laminar crosswind, with three separated zones of combustion. At higher cross winds, combustion efficiency is lowered, and downwash effects are noted in the low pressure zone just beyond the stack. An accumulation of unburned gases may result at sufficiently high wind speeds.

Of particular importance to this review of well-test flaring in B.C., the U of A analysis included wind tunnel testing results of high gas flow rates typical of operational well-test (production) flares. These tests were performed by the National Research Council in Ottawa. At gas exit velocities of 10 – 40 m/s and cross winds of speeds 3 – 4 m/s, combustion efficiencies were found to be 98.85% or higher. These results indicate that the potential for significant reduction of combustion efficiency during well-test flaring at commonly experienced wind speeds is rather low. However, this statement may not hold true for flare gases of low energy content.

Figure 2.1
Flame Representation for a Flare in a Crosswind*



*Reproduced from U of A Flare Research Project (Kostiuk *et al.* 2004)

Energy conversion mechanisms are important to consider for the prediction of flare gas plume travel and dispersion. The amount of sensible heat gained by the combustion products (the emitted plume) is significantly lower than the input chemical energy of the flare gas (i.e., the total combustion energy at the flare tip). The energy loss is primarily due to radiant heat transfer from the flame and the end-gases. The percentage of heat lost through this mechanism must be accounted for in determining the buoyant energy of the end-gases, and ultimately the plume rise potential. This loss is referred to as the *radiant heat loss*, which is dependent on flare gas composition, flame type/orientation, air-fuel mixing ratio, soot/smoke formation, quantity of fuel being burned, flame temperature and flame burner design (Schwartz and white, 1996). Leahey and Davies (1984) determined a representative radiant heat loss of 55%, while Guigard *et al* (2000) indicate that 25% may be more appropriate. The latter study, prepared for Alberta Environment, included a review of flaring studies conducted between 1961 and 1994. The review shows that the lower heat loss percentage (25%) is generally more applicable, but higher values are possible with gases of higher molecular weight (and potentially lower H_2S content). In example calculations, Beychok (1995) suggests use of the lower percentage and notes the same trend of higher heat loss with greater molecular weights. Davies *et al* (2000) indicate that use of 55% radiant heat loss is overly conservative. Proposed modelling guidelines for Ontario suggest that 25% '*has been recommended as a guideline by Alberta Environment as a default*'

(Lakes Environmental, 2003). Modelling guidelines prepared for Manitoba oil batteries assert the same guidance, although without citing any source (RWDI, 2002).

Radiant heat loss from the flare flame and plume can cause vegetation damage. The EUB requires flare stack heights to be designed such that the maximum radiant heat intensity does not exceed 4.73 kW/m^2 at ground level (EUB 1999). This requirement is in addition to meeting ambient air quality objectives for SO_2 and H_2S. There are no formal radiant heat guidelines or requirements in effect in British Columbia, and this appears to be the case for other Canadian provinces as well.

Leahy (1996) described the flammable composition of flare gas at two oil battery sites in Alberta to include butane, ethane, hydrogen sulphide, methane, pentane and propane. However, other constituents and differing relative fractions are possible, depending on location. The primary gas in both sweet and sour flare gas is methane. Higher percentages of compounds such as butane, ethane, pentane and propane tend to increase the total (combustion) potential energy, whereas higher percentages of hydrogen sulphide tend to decrease potential energy. The term *net heating value* (NHV) is the amount of energy released per unit volume of flare gas when combusted. Sweet gas tends to have higher NHV than sour gas. Leahey and Davies (1981) determined a threshold NHV of 10 MJ/m^3 to sustain the flame at stack top. According to the EUB, the minimum NHV guideline is 20 MJ/m^3 (EUB, 2005). This guideline likely relates to recommendations from the U of A Flare Research Project, which found that combustion inefficiencies were significant at NHVs below 15 MJ/m^3 (Kostiuk *et al*, 2004). CAPP (2001) states that typical flare gas NHVs for well tests are in the 25 – 35 MJ/m^3 range, meaning that in most cases a stable flame is achieved, and likely a high combustion efficiency.

All combustion products are released in a continuous plume that advects and dilutes in the atmosphere. An essential characteristic required to predict the plume movement is *plume rise*. Plume rise is dependent on the energy balances described above, and occurs gradually over time (or distance from the stack) to a maximum at some location downwind. In general, the greater the increase in internal energy of the combustion products, the greater is the plume rise. Plume rise is proportional to the *sensible heat release rate*, which is simply the NHV minus the radiant heat loss. In that sense, plume rise is highly sensitive to radiant heat loss.

A widely accepted method for calculating plume rise was initially proposed in 1969 by Briggs, and is now collectively referred to as the 'Briggs Equations' (Beychok, 1995). The equations allow for calculation of a *buoyancy flux parameter* to characterize plume rise. The determination of buoyancy flux is a common feature of many (if not all) air dispersion models. One representation of the Briggs buoyancy flux parameter is shown below:

$$F = gQ/(\pi c_{pa} T_a \rho_a)$$

where:

g = gravitational constant;
Q = sensible heat release rate;
c_{pa} = specific heat of ambient air;
T_a = ambient air temperature;
ρ_a = ambient air density.

Application of the buoyancy flux parameter allows for determination of plume rise at downwind distances from the stack. A hot plume continues to rise until entrainment of air reduces buoyancy to zero. Historically, Briggs '2/3 Law' has been applied in dispersion models to predict plume height. The 2/3 Law can be represented as:

$$\Delta h = 1.6F^{1/3}x^{2/3}u^{-1}$$

where:

Δh = plume rise
x = downwind distance
u = wind speed

The 2/3 Law is effective until a final plume rise has been reached[8]. A modification of the constant 1.6 is sometimes used for stable atmospheres.

2.2 COMPUTER DISPERSION MODELS AND FLARING

A regulatory dispersion model is a computer algorithm that predicts ambient air pollutant concentrations resulting from a source such as an industrial stack. The model requires the input of stack and emission characteristics, and an assessment of the atmospheric conditions (i.e., wind speed and direction, temperature, stability) in the vicinity of the source. Depending on the complexity of the model, output is expressed as maximum ground-level concentrations, potentially with further articulation of the temporal and geographical distribution of concentrations experienced over periods(s) of interest (e.g., a year or more). Early computer models, some of which are still used, represent emissions as a continuous plume that spreads (disperses) according to averaged atmospheric conditions. More recent computer models utilize a more sophisticated representation of the atmosphere, with realistic physical constraints (such as mass conservation) and statistical tendencies.

A 'screening' level model provides conservative estimates of maximum ground-level air concentrations and a 'refined' model provides more realistic estimates of air concentrations, at specified locations (and times) of interest. These terms are used for regulatory dispersion

[8] Industrial Source Complex, Version 3 (ISC3) Model, Volume 2 User's Guide.

models. A regulatory model is generally thought of as a tool that supports policy or regulatory decisions. In that sense, a regulatory body, such as the B.C. Ministry of the Environment, must define a set of existing regulatory models that are deemed to be appropriate for use in their jurisdiction. In addition, information on when and how these models are to be used must be communicated to the industrial and consulting communities that conduct related work. In British Columbia, this communication is in the form of *Guidelines for Air Quality Dispersion Modelling in British Columbia* (available from the Ministry website under 'publications').

Chemical transformation of emitted gases (beyond the transformations that occur as part of the combustion process) is typically not treated in regulatory dispersion models, although some refined versions are able to represent the more significant transformations in a simplified manner. As an example, some models represent the formation of sulphate (SO_4) from SO_2 by use of hourly conversion rates that may depend on concentrations of other gases in the atmosphere. In general, the chemical transformations that can lead to elevated concentrations of secondary gases (or particulates) require a period of time for the transformations to occur such that high concentrations of secondary transformation compounds are not necessarily experienced near the point(s) of release. Therefore, if secondary air contaminants are of concern, dispersion model simulations are typically accomplished within a regional context, incorporating all of the significant sources within an airshed. The dispersion models used are termed photochemical models and require additional effort and expertise to run. The use of photochemical models is not required for well-test flaring simulations because the primary air contaminants of concern (i.e., SO_2) is formed during the combustion process and maximum SO_2 impacts tend to occur relatively close to the point of release from the flare stack.

A regulatory dispersion model sanctioned for use in B.C. or other Canadian province may be classified as either a plume model or a puff model. The plume model assumes a steady state straight line trajectory of the pollutant release (the 'plume' itself) and utilizes the well-known Gaussian equation to govern plume spread in the horizontal and vertical. The Gaussian equation assumes a normal distribution of the plume in both the horizontal and vertical. Additional constraint can be applied within the model to reflect the plume when it comes into contact with either the ground (assumed to be at a zero height), or the top of the mixed layer. The rate of plume spreading in both the horizontal and the vertical depends on atmospheric conditions such as wind speed, temperature, cloud cover and solar insolation. Gaussian plume models parameterize the atmospheric affects by use of atmospheric stability classes. One of six stability classes is 'chosen' by the model based on hourly observations of wind speed, temperature and cloud cover. Within the model, the plume disperses at horizontal and vertical rates specific to the stability class.

A refined variant of the plume model is achieved when incorporating the effects of terrain into model dispersion calculations. Rather than an assumption of flat terrain, a gridded dataset of elevation is read into the model. The model then accounts for plume impingement at non-zero elevation, resulting in higher or lower concentrations than the simple plume model would predict. A dividing streamline approach is also used, where an object such as a hill causes the upper-layer of the plume to flow over the obstacle, whereas the lower layer is constrained to flow around (e.g., USEPA, 1989).

A modern variant of the Gaussian approach to dispersion is to simulate the plume as a series of discrete releases known as 'puffs'. In combination with this source representation, a better spatial representation of the atmosphere is required. Most importantly, instead of the assumption of a single wind vector for the modelling domain, a three-dimensional simulation of the atmosphere is produced. Terrain elevation and other surface information are also input. Each puff released follows the wind, potentially experiencing different dispersion characteristics in different locations of the modelling domain. The determination of pollutant concentration at a fixed location is achieved by summing the contribution from each nearby puff. Not surprisingly, a puff model requires considerably more computer processing than a plume model.

The steady state assumption assumed for the plume model holds reasonably well when the modelling domain does not extend to a large distance. The degree to which the plume models are considered representative, or appropriate to use, is somewhat subjective. In general, as long as the assumption of homogenous meteorology (in particular, consistent wind vectors throughout layers of the modelling domain) is reasonable, the plume models can be used. Plume models predict 'near-field' impacts, which have been described as within 10 km of the source(s) by at least one regulatory agency[9]. A further limitation of the plume models is their inability to represent stagnation conditions.

An example of a screening-level plume model is the SCREEN3 model. As defined in the *Guidelines for Air Quality Dispersion Modelling in British Columbia*, SCREEN3 is a single-source Gaussian plume model that provides maximum ground-level concentration predictions for point, area, flare, and volume sources. It is, in fact, the only regulatory model that directly considers flaring emissions. However, as this model relies on a predetermined array of possible meteorological conditions rather than using meteorological data for a particular location, its usefulness for determining air pollutant concentrations for particular atmospheric conditions in a specific location is very limited.

Until recently, the Industrial Source Complex, Version 3 (ISC3) model was the standard regulatory model elide upon by regulatory agencies around the world. The model is a straight-line, steady-state Gaussian plume model that is capable of handling multiple sources, including

[9] New Zealand Ministry of Environment. See http://www.mfe.govt.nz/publications/air/atmospheric-dispersion-modelling-jun04/html/page5.html. Other agencies may use greater distances.

point, volume, area and line sources, and ISC3 uses measured hour-by-hour meteorological data that represents the conditions experienced by the source emissions (site-specific data) in contrast to the generic screening meteorological data matrix used for SCREEN3. ISC3 is considered by the MoE to be suitable for predicting hourly averaged air pollutant concentrations for all terrain heights, except on the lee slopes of hills. The ISC3 model was de-listed as a recommended regulatory model by the U.S. Environmental Protection Agency (EPA) in December 2006, but is still accepted by the MoE for use in British Columbia, particularly for well-test flaring application, because it is relatively easier to use than the more refined model AERMOD that has replaced ISC3 as the standard model in the United States and in other jurisdictions.

As defined in the B.C. dispersion modelling guidelines, the Rough Terrain Diffusion Model (RTDM3.2) is a straight-line, steady-state Gaussian plume model designed to estimate ground-level concentrations over a specified grid of receptors near one or more co-located point sources. It is to be applied to rural areas where the terrain is above the stack height. It provides concentrations at a grid of receptors in rural areas using a time series of hourly meteorological input data, and is considered by the MoE to be better suited than the ISC3 model for simulating plume dispersion in terrain above stack height. However, it has long been recognized that there exist potential problems with the use of the RTDM model in complex terrain settings[10]. In particular, it is known that, in complex terrain settings, representative wind flow (i.e., both speed and direction) at stack top height cannot be accurately defined from lower level measurements for use in the RTDM model.[11] As with the ISC3 model, RTDM was de-listed by the U.S. EPA from its suite of recommended regulatory models in December 2006, although it is still considered suitable for use in well-test flaring application in B.C. due to its relative ease of use.

For well-test flaring application in B.C., the MoE currently requires proponents to model SO_2 flaring emissions using either the SCREEN3 model (Level 1 Assessment), or a combination of the ISC3 model to predict concentrations at elevations below stack height and the RTDM model for all elevations above stack height (Level 2 Assessment).

AERMOD is an example of a refined plume model. As defined in the B.C. dispersion modeling guidelines, AERMOD is a straight-line, steady-state plume model that is an improvement over ISC3 and RTDM in that it incorporates recent boundary layer theory and advanced methods for handling terrain. AERMOD has some Gaussian plume characteristics, but also contains new or improved algorithms for: dispersion under stable and unstable conditions; plume rise and buoyancy; plume penetration into elevated inversions; treatment of elevated, near-surface, and surface level sources; computation of vertical profiles of wind, turbulence, and temperature;

[10] Memorandum from J. Tikvart, Chief, Source Receptor Analysis Branch, U.S. EPA to R. Werner, Chief, Impact Assessment Section, Region II, Re: Interpretation of On-Site Meteorological Data Requirements and the Use of RTDM for a PSD Source (November 7, 1989)

terrain effects on plume behaviour. Conceptually, AERMOD should be as well, or potentially better, suited to well-test flare modeling than the current practice of using a combination of ISC3 and RTDM.

CALPUFF is another example of a refined regulatory model. As defined in the B.C. dispersion modeling guidelines, CALPUFF is a Gaussian puff model that can account for time- and space varying meteorological conditions, different source configurations and contaminants, and chemical transformations. Specific algorithms in the CALPUFF model that are of particular relevance to well-test flaring applications include curved trajectories, plume penetration into a capping inversion, fumigation, terrain impingement, and atmospheric stagnation conditions. As with AERMOD, the CALPUFF model could be considered to be conceptually better suited for modeling emissions from well-test flaring in complex terrain. However, the CALPUFF model does require more effort on the part of modellers in terms of accurately defining meteorological inputs and interpretation of results than is required for the ISC3 and RTDM models.

Only one example of the use of the CALPUFF model for a post-flaring assessment was available for this review. In general, the MoE has been unwilling to accept the use of the CALPUFF model for such assessments, prescribing the use of the ISC3/RTDM models as the preferred method for both pre-flare and post-flare assessments. The MoE's rationale for this has been that the use of the more complex CALPUFF model would not necessarily provide improvement in the prediction of ambient SO_2 concentrations and associated protection against vegetation damage, but would increase the likelihood of modelling errors being made by some, less experienced modellers.

Regardless of the sophistication of a computer dispersion model, the model-predicted air pollutant concentration estimates and actual point-specific air concentration values (such as that which a sensor would measure, or a tree would be exposed to) are inherently different. Among other differences, the model estimate is representative of a substantial volume (i.e., grid cell) of space. At any specific location within this volume, a localized concentration could be markedly higher or lower (assuming the model estimate is 'correct') than what the volume average is. For this reason, comparing air concentration measurements from a sampler to model estimates is not straightforward.

2.2.1 Source Representation

Existing dispersion models such as ISC3, RTDM, AERMOD, and CALPUFF were not designed to represent flaring source characteristics. The modelling of emissions due to flaring has

[11] Memorandum from J. Tikvart, Chief, Source Receptor Analysis Branch, U.S. EPA to L. Nagler, Regional Meteorologist, Air Programs Branch, Region IV, Re: Alabama GEP SIP – Gaston Power Plant (May 29, 1987)

developed by way of considering the changes required to the modelling inputs to ensure that the flare plume is appropriately represented in the model simulation. In effect, the model is 'tricked' into simulating a pseudo-stack source that has different physical characteristics to the flare stack itself, yet leads to plume rise calculations consistent with the current understanding of flare plume behaviour. Thus, the resulting model predictions of ambient concentrations are thought to be appropriate representations of reality, at least in a regulatory sense.

Dispersion models typically require five parameters to characterize a combustion emission source: emission rate, temperature, exit velocity, stack diameter and stack height (CAPP, 2001). For traditional stack emissions (i.e., boiler stack, combustion turbine stack), these parameters can be measured and used directly in a dispersion simulation. For a flare however, the existence of an open flame at stack top means that the parameters must be calculated rather than measured. In that sense, the flare properties are commonly referred to as 'pseudo' parameters, and a number of assumptions are required to perform the necessary calculations.

Pseudo-stack parameters for flares represent *effective* values rather than physical measurements. Plume rise representation within a dispersion model is a crucial component for the simulation of plume transport and dispersion. The source representation for point sources within existing dispersion models assumes a traditional stack (i.e., with a physically defined stack height and diameter). If physical stack properties were used for a flare source, the dispersion model would incorrectly calculate actual plume rise, and hence achieve a poor representation of plume behaviour. The pseudo-stack parameters represent a 'back calculation' from a plume rise estimate, to ensure the model represents these features as accurately as possible. Flaring pseudo-stack parameters may include values for stack height, stack diameter, exit velocity and exit temperature.

The approach used to determine the pseudo-parameters is based on the Briggs equations for buoyancy flux. In essence, relating one form of the equation that relies on the sensible heat of the plume with another that relies on stack and plume properties allows for the determination of the stack/plume parameters. Inherent to the approach is the assumption of radiant heat loss. Currently, there is a significant difference between the approach used in B.C. from that used in Alberta, Manitoba and Ontario. Based on recent research conducted in Alberta, Alberta, Manitoba and Ontario assume 25% radiant heat loss in the determination of pseudo-stack parameters. The Ontario requirement does not appear stringent, but instead notes that Alberta Environment 'recommends' use of 25% and that specific data or measurements for the flare should be used, if possible (Lakes Environmental 2003).

The estimation approach cannot be used to solve for each of the pseudo-stack parameters, and assumptions must be used. A good discussion of the Briggs equations and determination of pseudo-stack parameters for flaring is provided by Beychok (1995), and this is followed within the SCREEN3 screening-level dispersion model (U.S. EPA, 1995). The assumptions used in SCREEN3 are as follows:

- 55% of the total heat released by the flare is 'lost' through radiation (radiant heat loss);
- an assumption for the flare exit temperature of 1000 ^{o}C (1273 ^{o}K);
- an assumption for the flare exit velocity of 20 m/s;
- the flare flame length is estimated from an empirical equation, dependent on total rate of heat release; and,
- the effective stack height is taken from the sum of the physical stack height and the vertical flame height (assumed to be bent 45^{o}).

In order for these assumptions to hold in SCREEN3, the 'Flare' source type must be used. With use of 'Point' source type, stack parameters must be entered. Therefore, for other models such as ISC3 or RTDM, pseudo-stack parameters must be estimated and used. It should be noted that Beychok uses a 25% radiant heat loss in sample calculations; although he notes that radiation losses may be 30 – 40% for gases of molecular weight 44 or higher.

The choice of 1273 ^{o}K for exit temperature and 20 m/s for exit velocity were determined by the U.S. EPA based on flaring studies of the past. Beychok notes that the actual exit temperature is not required for determination of plume rise by Briggs' method. In practice, plume rise is calculated based on the net heating value (NHV) of the flare gas constituents and the assumption of complete or near complete (i.e., 98%) combustion efficiency.

In terms of dispersion modelling, the assumption of 1273 ^{o}K over a different temperature such as 1000 ^{o}K or 1600 ^{o}K does not significantly affect model-predicted outcomes. British Columbia, Alberta, Manitoba and Ontario support the use of 1273 ^{o}K for stack exit temperature. CAPP (2001) states that this assumption actually leads to a 'minor mistake' in the determination of buoyancy flux within a model such as ISC. The buoyancy flux estimate (determined with the NHV of flare gas) stays constant, but the model applies slight changes due to hour-by-hour changes in ambient temperature. CAPP estimates that this error ranges in magnitude from +6 to -2%, for ambient temperatures of -40 ^{o}C to 30 ^{o}C. This error results from the assumed temperature differential in the model between the 1273 ^{o}K flare and the ambient atmosphere. With this in mind, it is appropriate to ensure that the assumed exit temperature is far greater than the ambient atmosphere. Therefore, the assumption of 1273 ^{o}K for well-test exit temperature is an appropriate choice to make for dispersion modelling. What should be of greater concern is whether other assumptions, such as 98% combustion efficiency, are properly satisfied.

British Columbia also supports use of 20 m/s for exit velocity, consistent with the SCREEN3 model with Flare source type. Both Ontario and Alberta require use of the *actual exit velocity to* *the flare* rather than the assumption of 20 m/s. Manitoba recommends the latter approach as well. This is a second difference between the practical approaches used by B.C. and Alberta/Manitoba/Ontario. A determination of actual exit velocity is made by consideration of the (maximum) gas flow rate, and the flare stack tip diameter (for example, see the EUB Directive060 well-test spreadsheet[12]).

Within a dispersion model, exit velocity affects plume momentum. Beychok describes plume momentum within a parameter defined by Briggs as *momentum flux parameter*, which is directly proportional to exit velocity. However, the concern with use of an assumed 20 m/s exit velocity by CAPP (2001) relates to determination of flare-tip downwash. The use of actual exit velocity for a lower gas volume flare potentially could lead to model prediction of flare-tip (stack-tip) downwash, if the actual velocity was lower than 20 m/s. With typical well-test flare exit velocities during the mature stage of production testing, significant stack tip downwash is very unlikely to occur. In fact ‘allowable’ meteorological conditions for flaring to occur in British Columbia (which are clearly described in a flare management plan) never include high wind speeds that can lead to stack tip downwash. Therefore, use of actual exit velocity for a dispersion model assessment is likely an appropriate criterion to set for flaring emissions in general, but not specifically for well-test (production) flaring. Again, other considerations such as combustion efficiency are more crucial to consider.

It should be noted that the ‘pseudo’ approach to model inputs can still be followed by use of actual exit velocity instead of 20 m/s. In Alberta, plume buoyancy flux, (assumed) exit temperature and actual exit velocity are used to calculate the pseudo-stack diameter with the following relation:

$$D = \sqrt{\frac{(F_b * T_{exit}) * 9.806}{(T_{exit} - T_{atmos}) * V_{exit}}}$$

Where: D = pseudo stack diameter

F_b = Briggs buoyancy flux parameter

T_{exit}, T_{atmos} = exit and atmospheric temperature

V_{exit} = stack gas exit velocity

In British Columbia, this same relationship is used, but with the assumed exit velocity of 20 m/s.

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12 http://www.eub.ca/portal/server.pt/gateway/PTARGS_0_0_270_233_0_43/http%3B/extContent/publishedcontent/publish/eub_home/industry_zone/rules__regulations__requirements/flaring/

3.0 PERMITTING

Flaring in Canada is controlled by provincial regulators by way of guidelines for assessing potential health and/or environmental impacts. A flaring permit in most cases identifies gas composition and the total volume of gas to be flared, which limits the aggregate air emissions. However, in some cases there is a considerable difference between permitted volumes and that which is ultimately flared. Actual flared volumes of gas in Alberta tend to be less than permitted levels, especially for larger volume permits. Many wells with flaring permits in place do not actually flare at all. In Alberta, the actual volume of gas flared was estimated in 2001 to be approximately one quarter of that permitted (CAPP 2001). This relationship may not exist in other provinces.

Flaring permits have start/end dates and also may contain limitations with respect to environmental conditions (wind speed and direction, atmospheric stability). Such conditions are set by the regulators, and may be based on the results of an initial environmental assessment involving dispersion modelling (referred to as ‘pre-flaring modelling’). The steps required to complete a dispersion modelling exercise varies by jurisdiction (province). However, there tend to be some similarities in the steps followed by each province, such as choice of acceptable dispersion model(s).

The steps required to obtain a flaring permit are clearly prescribed and documented in Alberta and British Columbia, the two provinces with a relatively high amount of related activity. The documentation includes specifics for air quality analysis and mitigation measures, including how to determine the level of analysis required. In Manitoba, a significant amount of guidance is also published. Other provinces do not offer as much in the way of documented procedure, and instead rely, and require, communication with the regulatory agency. Little U.S. state-specific guidance is available from jurisdictional media. Part of this is due to the over-arching responsibilities of the federal Environmental Protection Agency (EPA), which provides guidance on how flare assessment should be conducted, and what models (if required) should be used. However, much of the U.S. land over which flaring may occur is privately held and therefore may not be scrutinized to the same degree as that commonly associated with public lands (at least when sites are remote from populated areas). Also noteworthy, many producing regions in the U.S. have greater access to existing infrastructure, allowing in-line testing and minimal flaring activity.

All Canadian provinces require adherence to provincial and federal ambient air quality criteria. Differences between permit approval processes in the provinces relate to how a licensee is to demonstrate compliance with ambient criteria, and, potentially, what actions must be taken to mitigate the impact of the flaring emissions. In general, Alberta, B.C. and, to a lesser degree

Manitoba, have documented requirements specific to flaring, whereas other provinces rely on general directives applicable to many different industrial emission sources. Detailed investigation into the practices followed in the eastern Canadian provinces, where little flaring occurs, was beyond the scope of this work.

In British Columbia, an applicant must complete and submit the *Application for Flaring Approval* form to the OGC before permission to flare is granted. This process requires a licensee to adhere to the provincial *Waste Management Act*, which may involve conditions specified by the Ministry of Environment (MoE) Regional Waste Manager.

3.1 REGULATORY GUIDANCE

Dispersion modelling (pre-flaring) may or may not be required to support a licensee application to flare in Canada. In general, if modelling is required, documentation describing the modelling and predicted outcomes must be presented within the application process. This is similar in nature to the approval process for other types of industrial air emission sources.

Modelling of flaring events is just one emission scenario discussed within the B.C. Modelling Guidelines, similar to other Canadian and U.S. jurisdictions. A consistent approach is followed in B.C., Alberta and Ontario, where appropriate dispersion models are designated within regulatory modelling guidelines and representation of flaring emissions is briefly addressed. Other sources are used for further information or guidance, to be used in conjunction with the modelling guidelines. In Alberta, additional guidance is quite expansive, with both emergency flaring guidance (AENV 2003b) and a general flaring directive (EUB 2003). The Alberta Environment (AENV) and Energy and Utilities Board (EUB) documents are meant to be complementary. Manitoba does not have general modelling guidelines, but specific guidance for flaring is provided in the *Dispersion Model Guidelines for Oil Batteries in the Province of Manitoba* (available from the Manitoba Conservation website). In British Columbia, specific guidance is provided from the OGC in *Interim Guideline #OGC 00-01, Natural Gas Flaring During Well Testing* (available from the OGC website).

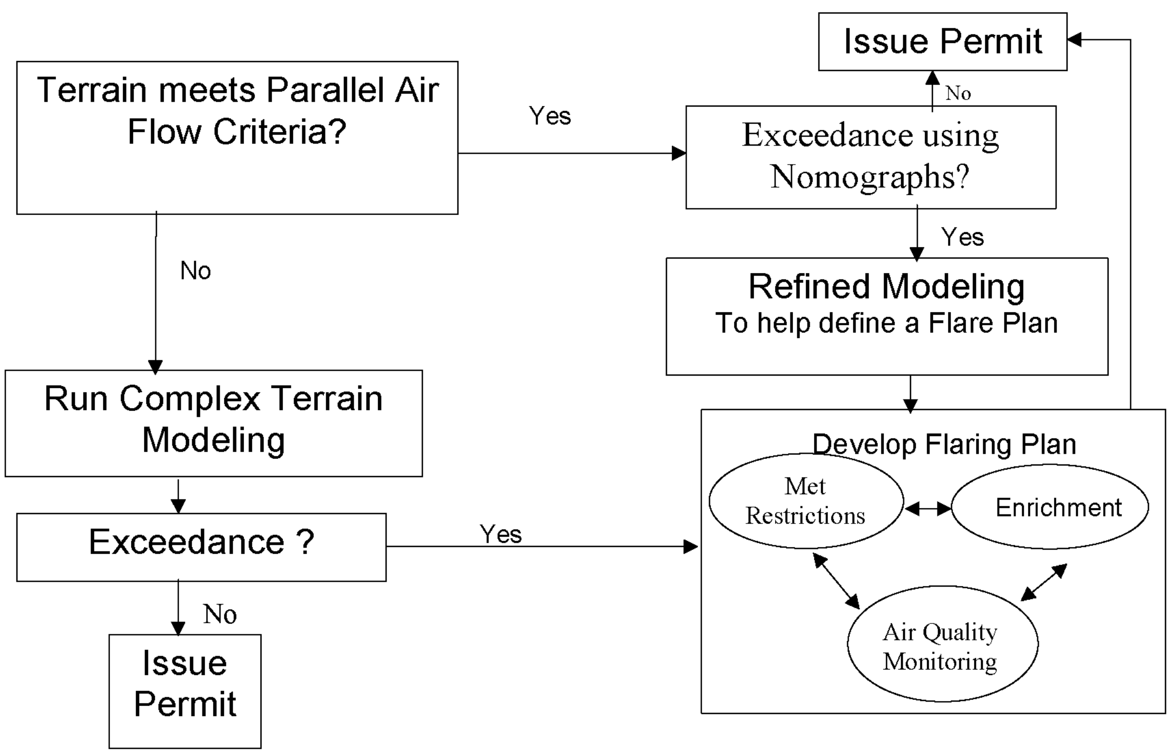
In Alberta, the EUB flaring directive has the same role as the OGC Guideline. Similar to the case in B.C., the requirement of dispersion modelling is based on the composition of flare gas (H_2S content). If either the flare gas contains 10 mol/kmol of H_2S or greater, or the total expected amount of sulphur released is one tonne or greater, an air quality assessment must be conducted[13]. Furthermore, even if these requirements are met, the licensee is encouraged to consider dispersion modelling as part of environmental due diligence. Rather than specifying individual SO_2 criteria, the EUB directive states that all Alberta Ambient Air Quality Guidelines

[13] EUB directive060-draft 2003.

(objectives) must be considered. In practical terms, this means that the provincial H_2S objectives have significance. If the results of dispersion modelling indicate that 1/3 of the provincial 1-hour SO_2 objective of 450 µg/m^3 may be exceeded, a combined assessment must be conducted, including the effects of other nearby continuous SO_2 emission sources. 'Nearby' includes the area surrounding the flare stack that may experience ambient SO_2 concentrations equal to or higher than 1/3 of the provincial 1-hour objective, due to emissions from the stack alone.

The EUB directive does not identify specific dispersion models and criteria for selection as is done in B.C., but instead directs the licensee to criteria in the provincial modelling guideline. As a result, choice of dispersion model is not prescribed (at the screening or refined level), but the user must be able to justify the selection. For refined modelling, details 'should be verified' with AENV before submission. Figure 3.2 shows the flare permitting process for Alberta (from CAPP, 2001).

Figure 3.1
Temporary Flare Permitting Process in Alberta*



* SENES understands that this process is still followed in Alberta

The AENV modelling guidelines states that terrain 'must be considered' if there is any complex terrain within the modelling domain, or if terrain elevation rises more than 5%. The consideration involves a test of whether or not the parallel air flow assumption (necessary for the assumed dynamics in a flat terrain model) is valid. As a result, the steps required to conduct an appropriate dispersion modelling analysis of a flaring event in Alberta may be more complicated than the approach required in British Columbia. However, AENV provides a spreadsheet to perform the necessary calculations to determine: a) if dispersion modelling of any kind is required, b) whether terrain inputs are required for the dispersion modelling (if needed), and c) the flaring pseudo-parameters that should be used with an appropriate dispersion model (if needed). The spreadsheet was developed through the EUB and the CAPP Well Test Flaring Sub-committee and is provided free of charge[14].

The AENV *directive060_EUBWellTest* spreadsheet requires both stack and flare gas inputs and uses the Alberta modelling guidelines criteria to determine the maximum allowable terrain height within the modelling domain. If the terrain criteria are not exceeded, the user can rely on further tests performed automatically within the spreadsheet. In particular, nomographs are consulted to verify that there are no expected exceedences of ambient SO_2 and H_2S criteria. If the outcomes of these additional tests are positive, no dispersion modelling is required. Should dispersion modelling be necessary, the appropriate input parameters are available. In many cases, the spreadsheet simplifies the management of flaring activity in the province by avoiding the necessity of having a regulator check over proponent assumptions and calculations.

As is the case in B.C., a permit may still be granted in Alberta if exceedences of the provincial criteria are predicted from the air assessment. As identified in Figure 3.2, mitigative measures are to be considered within a flare plan, such as the addition of fuel gas to the flare gas stream (to increase combustibility and plume rise), liquid stripping, flaring only under ideal atmospheric conditions and, potentially, real-time ambient monitoring.

Other Canadian provinces use less prescriptive approaches and rely on communication between a regulator and the licensee rather than an established decision making process. Consistent with B.C. and Alberta, adherence to provincial air quality criteria is required. Manitoba also provides a spreadsheet to perform source calculations for dispersion modelling, but does not detail further modelling parameters such as the need for terrain inputs (RWDI, 2002). Saskatchewan is currently piloting a multi-stakeholder approach for managing air emission sources, including flaring. However, this process mainly focuses on stationary, continuous sources and may have little application potential for well-test flaring.

[14] See http://www3.gov.ab.ca/env/air/index.html.

3.2 PERMITTING IN BRITISH COLUMBIA

The significant difference between the sour gas flaring approval process in B.C. and that effective in Alberta is the assessment of risk associated with foliar exposure to elevated concentrations of SO_2 at differing times of the year (Legge 1995). The OGC Guideline permits flaring to proceed with knowledge of risk in the form of the dispersion modelling simulations, and in some cases with pre-test assessments of the condition of vegetation. During the post-production test modelling, the maximum concentrations and durations are compared with estimated acute SO_2 injury threshold concentrations (ug/m^3) as a function of time based on equations derived by Legge (1995). These equations were derived from the literature for a stationary, continuously flaring gas plant, to provide guidance on how best to avoid injury thresholds when periodic high volume flaring may exceed the levels produced during operational flaring. Table 3.1 shows the calculated SO_2 hourly concentration (µg/m^3) required for the onset of foliar damage for each group of consecutive hours, as listed in the *Guidelines for Air Quality Dispersion Modelling in British Columbia*.

Table 3.1
Criteria for the Onset of Acute Visible Foliar Injury

No. of consecutive hours with concentration above given level	**Apr-Jun (daytime)** (µg/m^3)	**Jun-Sep (daytime)** (µg/m^3)	**Apr-Sep (nighttime)** (µg/m^3)	**Oct-Mar (all hours)** (µg/m^3)
1	1306	1741	4724	7086
2	832	1110	3025	4538
3	639	852	2331	3496
4	530	707	1937	2906
5	459	612	1678	2517
6	408	543	1493	2239
7	369	491	1352	2028
8	338	451	1241	1861
9	313	417	1150	1725
10	292	390	1075	1612
11	275	366	1011	1516
12	260	346	956	1434

The concentrations shown in Table 3.1 are derived from the same data presented in Legge (1995). They show that considerable differences in tolerated exposures occur in winter hours vs.

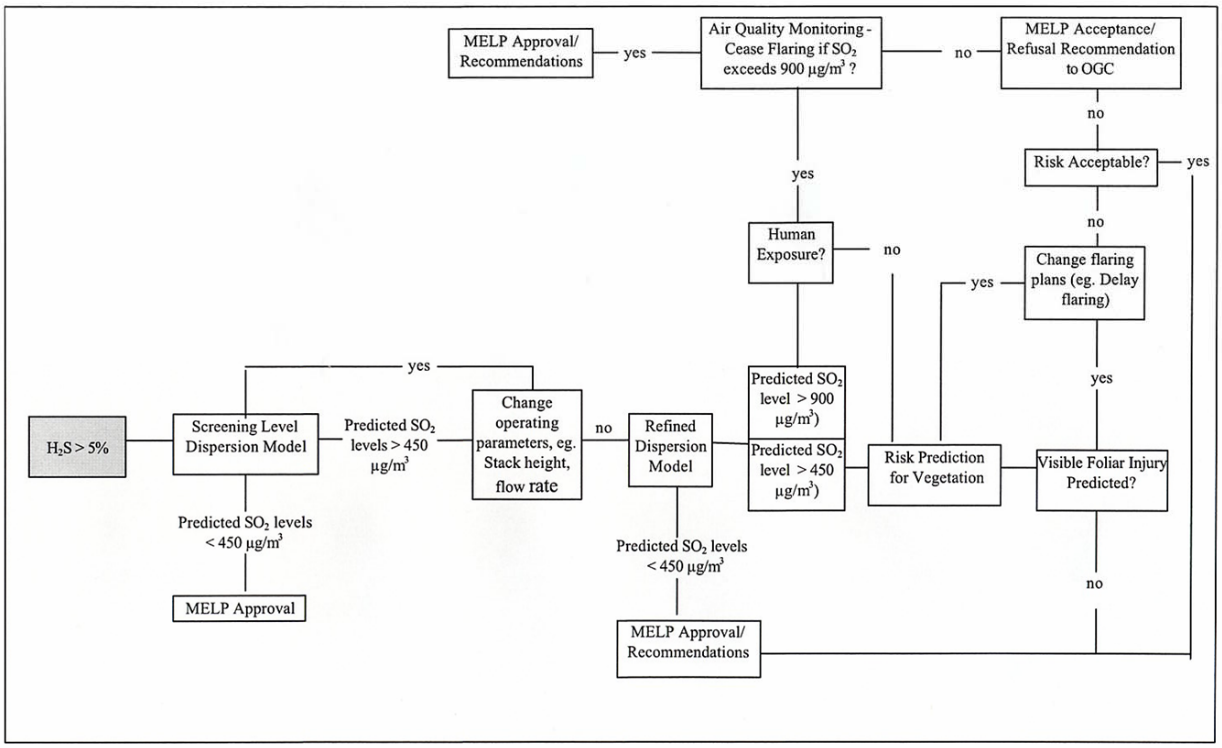
summer exposures and are an indication of when the safest periods are for flaring in northeastern B.C. However, a great deal of variation in tolerance to exposures hinges on environmental conditions up to and during the production test.

The OGC Guideline requires a pre-application emission dispersion study and a human health and vegetation effects assessment for all well-test flaring events with flare gas of 5% H_2S or higher. The vegetation effects assessment relates to a general assumption of vegetation and not variations that may exist near the test site. The vegetation assessment is effectively a modeled prediction based on thresholds derived in *"An Environmentally Significant Flare Event from a Sour Gas Processing Plant"* (Legge 1995) and not a field-based vegetation assessment. If the flare stack is less than 12m, the requirement holds for flare gas of 1% H_2S or higher. In these cases, the involvement of the B.C. Ministry of Environment (Regional Waste Manager) is required under the *Waste Management Act*.

The OGC Guideline specifies that the SCREEN3 model *must* be used to complete the screening model evaluation, which is the first step in the pre-application study. If exceedences of the B.C. Level A hourly SO_2 objective of 450 µg/m³ are predicted, refined modelling is required. For refined modelling, either ISCST3 or RTDM is to be used, unless the B.C. Ministry of Environment approves use of a different model. A decision tree showing the steps required to conduct an air assessment and obtain approval for sour gas flaring in B.C. is shown in Figure 3.2.

Figure 3.2 shows that, if screening level modelling indicates that the B.C. Level A 1-hour SO_2 concentration (450 µg/m³) will be exceeded, and modification of operational parameters cannot reduce maximum concentrations below the Level A limit, refined modelling is required. The choice of refined dispersion model depends on the local terrain. In B.C., a combined modelling approach is often required where the ISCST3 model is used to predict air concentrations at elevations below stack height, and the RTDM model is used to predict concentrations at elevations above stack height. This reflects the typical situation in northern B.C. where a well-test site is situated in complex terrain. The modelling domain should have a minimum radius of 10 km from the flare.

Figure 3.2
B.C. Sour Well Test Review Process*



*From the OGC Interim Guideline #OGC 00-01

The review process contains a risk component in the event that the provincial guidelines may be exceeded. A vegetation assessment is stressed if the Level A 1-hour concentration is predicted to be exceeded. The assessment must predict the potential for 'visible foliar injury' following a prescribed approach determined from previous research (Legge, 1995). If model predictions show that the Level B guideline of 900 µg/m³ may be exceeded at any residential locations, continuous monitoring of SO_2 is required at these locations for the duration of the flaring. In effect, flaring may be allowed even though exceedences of the provincial SO_2 guidelines are predicted, as long as mitigation and remediation strategies are in place. In these situations, strict approval conditions are specified to the well site operator, including allowance to flare only under appropriate atmospheric conditions. In terms of foliar response, flaring is often limited to winter time, since the potential for foliar damage is significantly reduced during winter dormancy (Legge 1995). However, even in wintertime conditions, exceedence of the provincial SO_2 guidelines may not be acceptable (Enns 2006).

The OGC Interim Guideline sets out a clear directive for operators testing wells containing hydrogen sulphide (as described above). The Guideline stipulates that if damage to vegetation occurs, it should be documented and remediated. Determination of damage relies primarily on 'post-flaring' dispersion modelling, which utilizes actual release rates and meteorological conditions during the flaring event. In addition, the assessment requires application of the Legge equations. The Guideline states that if the operator decides to proceed with a production test that has the potential to cause vegetation damage, the operator will be responsible for any resulting environmental damage, and will be required to immediately remediate any significant damage that may occur. Remediation may include removal of trees. If visual monitoring detects visible foliar damage, then samples must be obtained and analyzed to determine if the damage was caused by the well test. An assessment of the extent, degree and significance of the damage must be prepared, as well as a remediation plan. The language in the Guideline places the onus on the operator to define, describe and remediate any damage that occurs and to distinguish whether the injury was in fact caused by the production test as opposed to other sources of injury. As the post-flare modelling does not actually confirm that vegetation damage has or has not occurred, operators may perform assessments as part of the records taking required to meet due diligence. However, there is no obligation to verify the outcome of the post-flare modelling if it concludes no effects have occurred.

It should be noted that the post-flare modelling does not include an assessment of the potential for dormancy in vegetation, the pre-existing pathological condition of the vegetation at the time of the flare, the species composition and subsequent variable susceptibility of the receiving community. These factors are important when predicting the potential for injury, diagnosing the correct cause of injury and judging the severity of sulphur dioxide toxicity over other causes. The following sections provides a more detailed discussion of the limitations inherent in applying the criteria for acute visible foliar injury listed in Table 3.1.

3.3 LIMITATIONS OF EXISTING FOLIAR INJURY CRITERIA

"Visible foliar injury" polygons in the dispersion analysis are determined using the concentration versus duration equations developed in (Legge 1995). This document was produced in response to a request from then West Coast Energy Inc. for the development of quantitative definitions for concentrations and durations of sulphur dioxide that have been shown in the literature to be associated with acute foliar injury under ambient field conditions. The document was not intended to be used as a guide for single episodic flares, but rather for continuously flaring facilities (i.e., Pine River Gas Plant) where some limits can be set predicting the environmental consequences of a single short-term episode.

There are some fundamental ecological differences between a continuous flaring environment with the infrequent excursions that can be timed and managed to some extent, and a series of high concentration exposures over several days in a previously unexposed environment. The duration of exposure over days and weeks and the characteristics of the receiving environment are factors that are not fully considered in current well-test modelling practice, and these factors can make a difference in predicting (and preventing) severity of injury. The exposure/duration values in the Legge (1995) vegetation effects equations are based on four categories:

- April 1st to June 30th during daylight hours;
- July 1st to September 30th, during daylight hours;
- April 1st to September 30th during night-time hours;
- October 1st to March 31st for both daylight and night-time hours

Legge (1995) has distinguished the above categories based on potential for dormancy due to the lesser effects of sulphur dioxide on plants when stomatal closure and lowered metabolic rates in vascular plants occur. For example, Legge noted that Katz and McCallum (1939) found no acute foliar injury in Douglas-fir when exposed intermittently to 52,360 ug/m3 of sulphur dioxide, and other high exposures were undertaken in winter with no visible acute injury symptoms being expressed. McLean et al (1986) also showed reduced uptake of sulphur dioxide in Douglas fir at temperatures around -8 ^{0}C. The temperatures leading up to and including an exposure are important however. The dates of the above categories are fairly rigorously maintained, even though Legge (1995) presents them as a preliminary classification, and cautions that altitude and location are important considerations. In fact, winter dormancy in the north-eastern part of B.C. may not follow a similar pattern as those areas where the sulphur dioxide exposures were derived, in Summerland and Trail near the U.S. border (Katz 1939; Katz ,1949; Katz and Shore 1955) nor are they similar to Sudbury (Dreisinger and McGovern, 1970). Winters in the Monkman gas field can be mild up until January, usually have heavy snowfall and very late spring time break-up in late April to early May. Furthermore, winter conditions can persist past April 1st at high elevation. Dr. Legge cautioned that flexibility and the ecological interpretation of dormancy conditions of the receiving environment should be used when applying the climatic classification conditions he described.

The dispersion analysis and post-flare modelling in B.C. tends to consider exposures as isolated hourly events, and does not take into consideration that cumulative effects are an important consideration when predicting whether injury will occur or has occurred. Legge (1995) is careful to point out that the longer the exposure time, the lower the concentration of sulphur dioxide required to cause acute foliar injury. In general, production tests have tended to take less time than ten years ago when it was not unusual for a test to be intermittently run over a period of several days. Injury observed around well sites was more common in the earlier years (Enns 2004). However, Legge (1995) is very clear that cumulative exposure times result in lower tolerance for high concentrations over time. Legge suggests that it would be useful to use a more precautionary approach if tests must persist over long periods[15].

As mentioned above, Legge (1995) was written for a continuously flaring source and not a single flaring source in an isolated area. The main concerns with applying this paper to sour gas well production test flaring are as follows:

- Most single stationary sources with an occasional need to flare are monitored rigorously using real time monitors and are observed by environmental staff on site.

- Forests around single stationary sources have been pre-exposed and may have developed a degree of resistance to sulphur dioxide sources (Iqbal et al. 1996)[16], thus allowing for the application of a level "C" objective in winter where higher concentrations may be acceptable. This level "C" may have limited applicability to a previously unexposed forest consisting of sensitive species, especially during vulnerable periods of their growth (Legge, 1995).

- Stationary sources often have larger footprints than sour gas well test flare pads, and forest edges are physically not as close to the flare stack or the plume edge as they can be at the average test site[17].

- Most importantly, the cumulate effects of several high concentration exposures over a short period (production test) is very different from an occasional controlled high concentration exposure near a continuously operating flare. Peak concentrations do not play as important a role as the overall long-term concentration duration profile (Legge et al. 1996).

Legge (1995) uses literature from the 1930's to the 1950's for his equations, as this period represents one of the most complete set of data for sulphur dioxide exposures in the literature. There is very little recent dose – response reporting in the current literature, and there have been very few occasions, other than in the cited work in Legge (1995), where exposures were monitored *in situ* (McLeod, 1995).

Legge (1995) points out that relative humidity was noted as a precursor to higher incidences of injury with similar exposures, and this is perhaps not completely accounted for in the curves that

[15] Based on personal communication between Legge and Enns.
[16] There is also considerable evidence that chronic exposures to sulphur dioxide can interfere with plant resistance to disease.
[17] Note that injury from stationary sources typically starts at the edge of the source, and not as a disjunct polygon, as the modelling implies.

are being used because of the areas they were developed in. The *in situ* exposures from the work by Katz and others took place in much drier and warmer climates than seen in Northeastern B.C. This means that if plants are metabolically active during the early winter months, and the air is moist, it may take less sulphur dioxide to cause injury than would be indicated by the curves and dates. It is possible that leaving the decision of potential for injury to models alone may not be sufficiently cautious. Certainly effects have occurred when they were not predicted. Conditions such as exposed, south facing slopes adjacent to well sites, juvenile stands very close to a well production test and in the direct path of the plume and other vulnerable situations may call for interpretation of sites, as well as modelling.

4.0 WELL TEST FLARING IN B.C.

Within the OGC Application for Flaring Approval, the proponent must identify the volume of gas to be flared, the H_2S content of the flare gas, maximum expected SO_2 emission rates and estimated duration of discharge, among other information. For sour gas wells (H_2S content of 5% or higher), the application must be supported by computer modelling of maximum impacts and frequency of concentrations above ambient criteria. An emergency zone and emergency response plan must also be established. Development of a flaring management plan is addressed in a pre-flaring analysis report. Modification of the management plan recommended in the pre-flaring report may occur before establishing the actual management plan in the flaring permit.

When a pre-flaring analysis indicates that foliar damage may occur during a well test, a post-analysis must be conducted (assuming the well test occurred). The post-flaring modelling assessment indicates whether or not damage to vegetation was actually likely to have occurred. If the post-flare modelling indicates damage to vegetation, other factors are considered to assess how well the model predictions represent the on-site observations of plume behaviour. This latter statement reflects commentary that is present in some of the post-flaring reports. The OGC Interim Guideline 00-01 states that a visual monitoring plan ***must*** be initiated if the post-flaring assessment indicates potential for foliar damage. A logical interpretation of the Guideline is that a visual monitoring plan is required if the post-flaring simulation indicates damage (i.e., whether or not any following commentary in the report suggests a contrary conclusion).

The Guideline stipulates that environmental assessments must be conducted by personnel with appropriate training and knowledge, and if conducting assessments for the first time, the MoE must be contacted. The post-flare test assessment must include sampling of the damaged vegetation which is done by visual inspection and comparison to known examples of sulphur dioxide injury. Acute injury from sulphur dioxide is highly characteristic (Legge et al. 1998), but other conditions may resemble sulphur dioxide injury; for example, drought, salt injury, *Rhabdocline* infections in Douglas-fir, etc. Chemical analyses of the damaged vegetation are also done to determine whether sulphur dioxide from the production test was the cause of injury. Because several environmental causes can result in similar injury, it is necessary to use a number of different diagnostic tools to arrive at a conclusion of injury from an acute exposure to sulphur dioxide (Enns, 2004). The extent, degree and significance of the damage must be documented, along with a plan to remediate the damage. The pre-flare and post-flare test reports are submitted to industry, and these are further provided to the OGC.

The MoE selected a number of post-flaring reports produced over the last six years and a larger number of pre-flaring reports for SENES to review. SENES additionally obtained three recent post-flaring reports to further investigate trends identified in the original reports. The reports considered for this review are listed in Table 4.1.

Table 4.1
Well Test Modelling Analyses Reviewed

Well Test ID No.	Report Date		Production Test Date		H_2S Content
	Month	Year	Month	Year	%
C-46-H/93-P-4	Apr	2001			17
c-23-H/93-P-4	Sep	2001			17
					8
c-23-H (D-33-H)/93-P-4	Jan	2002	Dec	2001	15.76
B-79-J/93-P-4	Jan	2002			8
B-79-J/93-P-4	May	2002	Apr	2002	5
c-86-E/93-P-3	Nov	2002			26.3
c-86-E/93-P-3	Feb	2003	Jan	2003	26.15
a-2-E/93-P-3	Feb	2003			14
d-50-C/93-P-5	Apr	2003			6
d-50-C/93-P-5	Oct	2003	Sep	2003	3.1
b-3-G/93-P-3	Apr	2003			28
b-3-G/93-P-3 (Pardonnet/Baldonnel)	Sep	2003	Aug	2003	11-20.5
b-3-G/93-P-3 (Belloy/Taylor)	Sep	2003	Jul	2003	15-30.7
b-77-J/93-I-14	May	2003			13
b-77-J/93-I-14	Oct	2003	Aug	2003	25
b-2-E/93-P-5	Oct	2003			7
b-2-E/93-P-5	Jan	2004	Nov	2003	9.1
b-60-E/93-P-5	Nov	2003			6
d-2-I/93-I-14	Nov	2003			6
b-80-C/93-P-12	Apr	2004			21.9
a-37-J/93-P-4	Jul	2004			6
c-3-a/93-P-5	Jul	2004			19
c-3-a/93-P-5	Feb	2005	Jan	2005	15.5-25.25
c-A12-G/94-B-16	Jul	2004			7.5
a-16-F/93-P-3	Oct	2004			31
a-16-F/93-P-3	Feb	2005	Nov	2004	24-29.1
b-2-G/94-B-16	Dec	2004			7
c-40-d/93-P-3	Mar	2005			17
c-40-d/93-P-3	Jun	2005	May	2005	11
c-52-K/93-O-8	Mar	2005			6
c-52-A/93-P-3	Apr	2005			14.79
a-45-L/93-I-9	Apr	2005			25-35
a-45-L/93-I-9	Oct	2005	May-Jun	2005	17.5-25
d-34-A/94-B-16	May	2005			8
d-34-A/94-B-16	May	2005			9.5
a-66-E/93-P-3	Jun	2005			6
8-22-86-24 W6M	Mar	2005			20
b-80-B/93-P-3	Nov	2005			31
b-80-B/93-P-3	Jan	2006	Nov	2005	27-27.8
b-A77-J/93-I-14	Jan	2006			19
a-85-I/93-I-14	Jan	2006			19
a-43-E/93-P-3	Apr	2006			31
a-43-E/93-P-03	Jul	2006	Jun	2006	28-30.86

These reports were used to conduct a general analysis of sour gas well-test flaring experiences in B.C. and the Sour Well Test Review Process outlined in Figure 3.2. By concentrating on the well-test flares that required a post-flaring report, the analysis relates to those cases that underwent the full Review Process and had a higher degree of environmental risk. A number of questions were developed during the review, which were then posed to MoE, the OGC, and Levelton Consultants Limited. The latter were consulted because all but one of the reports reviewed was produced by this consulting firm. The questions were related to issues that are not communicated in the pre-flare and post-flaring reports, and experiences with the Review Process in general.

Section 4.1 provides a general overview of the pre-flare and post-flare modelling analyses. A more detailed discussion of the modelling results is presented in Section 4.2.

4.1 GENERAL OVERVIEW OF MODELLING RESULTS

A total of 29 well-tests were considered in this review, 14 of which had both pre-flare and post-flare reports. The production tests were reasonably well-distributed seasonally, with a total of six production tests conducted in the cold season (November through March) when vegetation would be dormant, and eight production tests in the period April through September when vegetation might be either starting to grow (i.e., in April-May) or well into the growing season. For one of the tests (b-77-J/93-I-14), pre-flare estimates of H_2S concentration underestimated actual concentrations during the production test by close to 100%. In three cases (i.e., d-50-C/93-P-5, c-40-d/93-P-3 and A-45-L/93-I-9), H_2S concentrations during the production tests were significantly lower than was assumed during the pre-flare test modelling analysis.

Table 4.2 summarizes the range of parameter values used in the modelling analyses, as well as both the range of maximum predicted SO_2 concentrations and distances to predicted maximum concentrations. The following are some observations related to pre-flare and post-flare modelling analyses:

- All of the pre-flare and post-flare analyses completed by Levelton Consultants Ltd. used the ISC/RTDM modelling approach. The one pre-flare analysis (8-22-86-24 W6M) completed by RWDI Air Inc. relied on a single modelling input scenario using a variant of flat terrain, simple terrain, complex terrain – valley approach, and complex terrain – simple approach using the SCREEN3 model to estimate downwind SO_2 concentrations. Only one post-flare analysis (A-45-L/93-I-9) was conducted using the CALPUFF model by RWDI Air Inc. (Plume-RT).

- Although some analyses were completed using only one or two scenarios in 2001-2002, after November 2002 most pre-flare analyses were completed using 3-4 modelling scenarios (assuming different gas flow rates), while one analysis (H_2S concentration 28%) required up to 5 modelling scenarios.

- There was only one obvious error in reported model input parameters (for pre-flare test A-45-L/93-I-9) in which the heat release rate (cal/s) for scenarios 3 and 4 were listed as being one order of magnitude lower than they should have been for the given flow rate and gas composition. However, it is not clear whether this was simply a typographical mistake in the pre-flare report, or whether the lower values were actually used in the modelling analysis. Based on the reported modelling results, it seems more likely to have been the former than the latter.

- SO_2 emission rates varied by up to 2 orders of magnitude between maximum and minimum emission scenarios.

- Maximum predicted 1-hour average SO_2 concentrations exceeded 2000 µg/m^3 for all stability classes, indicating that foliar damage would have been likely for any daytime flaring without the development and use of a flare management plan.

- Minimum predicted SO_2 concentrations exceeded 2000 µg/m^3 under Pasquill-Gifford (P-G) stability class 6 in all modelling scenarios, and approached or exceeded the 2000 µg/m^3 for all P-G class 5 modelling scenarios.

- The Level A criterion of 450 µg/m^3 was exceeded in all modelling scenarios for P-G classes 1, 5 and 6.

- The minimum distance to the maximum point-of-impingement (POI) for pre-flare modelling analyses was never less than 300 m.

- The minimum distance to Level A or Level B exceedences was never less than about 200 m from the flare site for pre-flare modelling, and never less than 850 m for actual production flare (post-flare) modelling analyses. The latter is most significant because vegetation damage has often been reported at locations in close proximity to the flare site platform rather than at distances of 850 m or more from the site. The modelling results indicate that any such vegetation damage close to the well site is not being, and perhaps can never be, captured by the production test modelling analyses.

- In the case of one pre-flare well test (a-43-E/93-P-3), the SO_2 concentration was predicted to potentially exceed 125,000 µg/m$_3$ (1-hour average) for a distance of nearly 600 m from the well, although SO_2 concentrations during the actual production test were not predicted to exceed 6500 μg/m^3, violating restrictions in the management plan for both wind direction and exceedence of the foliar damage exposure limit of 2000 μg/m^3. Nevertheless, no damage to vegetation was reported for this production flare test.

Table 4.2
Range of Model Parameter Values and Results

	Pre-flare Test		**Production Test**	
	Model Input Parameters			
	Minimum	Maximum	Minimum	Maximum
No. of modelling scenarios	1	5	1	1
Flow rates (mmscfd)	1.77	70		
Flow rates (e^3/m^3/d)	20	1,162	27.6	786.8
H_2S concentration (%)	5	35	3.1	30.7
Heat release rate (cal/s)	1.04E+06	1.00E+08	0.2	5.16E+07
Effective stack height (m)	18.50	91.33	34.04	89.16
Effective stack diameter (m)	1.09	6.63	0.8	5.03
SO_2 emission rate (g/s)	50.1	9,320	33	7376.5
	Model Results			
Maximum predicted 1-h average SO_2 (μg/m^3)	Minimum	Maximum	Minimum	Maximum
Pasquill-Gifford stability class - 1	478	6,055	357	43,849
Pasquill-Gifford stability class - 2	302	6,831		
Pasquill-Gifford stability class - 3	351	8,762		
Pasquill-Gifford stability class - 4	377	33,108		
Pasquill-Gifford stability class - 5	1,853	97,281		
Pasquill-Gifford stability class - 6	2,167	128,418		
Distance to Maximum POI (m)	300	10,069	0	9,055
Distance to Level A Exceedences (m)	224	14,111	854	854
Distance to Level B Exceedences (m)	224	13,911	854	854
Distance to SO_2 >2000 μg/m^3	412	13,859	854	854
Distance to SO_2 >4000 μg/m^3	424	14,000	922	922
Distance to SO_2 >10000 μg/m^3	854	14,487		
Distance to SO_2 >25000 μg/m^3	632	14,802		
Distance to SO_2 >50000 μg/m^3	632	15,000		
Distance to SO_2 >75000 μg/m^3	671	985		
Distance to SO_2 >100000 μg/m^3	500	671		
Distance to SO_2 >125000 μg/m^3	583	583		

With respect to vegetation damage, it has been reported (Enns 2004) that observed foliar injury seldom corresponds to the areas of injury predicted by the dispersion models. Whereas the post-flare dispersion modelling analyses have consistently predicted exceedence of the Level A, Level B and concentrations above 2000 μg/m^3 at distances of 850 m or more (see Table 4.2 above), observations of injury to vegetation are generally confined to a small number of trees on the edge of the well-test pad, always downwind of prevailing winds during the test, and lessening in severity within a few metres of the edge of the pad. In a few isolated cases in very steep terrain, injury has been noted to occur up to 100 m on steep facing slopes, possibly due to plume impingement. In all cases, the direction to sites of vegetation damage, if present, is consistent with the direction indicated by post-flare modelling, but occurs much closer to the pad than is predicted by the model.

It has been reported (Enns 2004) that, in many cases where damage from a production test has been reported, foliar injury cannot be exclusively attributed to SO_2 emissions due to flaring alone. Injury is often a product of a mix of causes, including plant pathogens, drought, environmental exposure (e.g., Chinook winds), and deposition from unknown substances, possibly from the clean out flare. In at least one case (c-86-E/93-P-3), damage due to the production flaring was mixed with pre-existing injury from exposure to SO_2 emissions from a pre-existing continuous source of emissions.

On a number of occasions when injury was noted in post-flare assessments, subsequent visits to the site over a number of years has indicated recovery of the affected trees (Enns, 2004). In some cases, recommendations for remediation of individual injured trees were made during the post-flare assessments, but such recommendation have not always been implemented (K. Enns 2007, personal communication).

4.2 DETAILED DISCUSSION OF MODELLING RESULTS

4.2.1 Pre-Flaring Assessments

Within the Review Process defined for B.C. in Figure 3.2, pre-flaring analyses are conducted in a consistent manner using expected gas composition and flow rates to model maximum expected 1-hour air pollutant concentrations of SO_2 and associated foliar response during the well-test. The preparatory stage of activity – the clean out flare – is not uniquely addressed, even though the gas composition and flow rates during the clean out phase are very different from those that exist during the production test flaring phase. Due to the fact that well test sites are almost always located in areas far removed from people, foliar response was the primary issue of concern for the reports reviewed, and this is the typical situation in Northern B.C. The pre-flaring reports detail the allowed meteorological conditions that would prevent vegetation damage. The allowed or forbidden conditions are detailed in a list-type format, separated by emission scenarios (volume of flare gas released per unit of time). Recommendations towards avoiding adverse meteorological conditions, if accepted by the OGC and MoE, become part of the flaring management plan, and the resulting flaring permit (if granted).

The pre-flaring dispersion modelling analyses (reports) are not meant to be representative of the actual conditions during the short-term flare, but rather conservative estimates of maximum potential impacts under different meteorological regimes. The dispersion modelling uses meteorological station data removed from the actual site; in some cases the data clearly are not representative of winds and/or temperatures at the well test site. Although the use of a full year of meteorological data in the predictive modelling does not necessarily capture the worst-case ambient conditions that may result during the short-term production flaring, in many cases this is all of the meteorological data that are available for an analysis. However, it is considered highly unlikely that the maximum concentrations presented in the pre-flaring reports would actually occur during the future flaring event; and this appears to be well understood by all affected parties[18]. The maximum modelled pollutant concentrations are used to complete a season-dependent analysis of potential foliar response. In effect, potential damage to vegetation (trees) is much greater during growing periods than in the winter, and this reality is reflected by the application of Legge's season-dependent equations previously described in Table 3.1.

The pre-flaring reports reviewed by SENES were almost exclusively produced by Levelton Consultants Ltd., although one pre-flaring report produced by RWDI Inc. (for 8-22-86-24 W6M) was also obtained. The Levelton reports were very similar to each other in framework, with several descriptive sections copied verbatim, or near verbatim from past reports. This is reflective of the fact that the same modelling approach (choice of dispersion models, model configuration) is used from assessment to assessment, with only the model input data varying from one report to another. The calculated flaring parameters differ from report to report, but are generally communicated in a consistent fashion. Over the past six years, significant differences noted in the pre-flaring reports include:

- *Choice of meteorological data to support dispersion modelling*. In earlier years, the nearest surface meteorological station was obtained and where determined necessary, wind directions were rotated to better reflect the localized topography. During the last several years, a consistent, conservative approach has been used that utilizes a combined meteorological dataset of 1) the nearest station data to the site, and 2) this same dataset with the wind directions rotated by 180^{o}. In effect, the modelling is now performed with two years of meteorological data.

- *Presentation of adverse meteorological regimes that lead to foliar injury*. Some reports present atmospheric conditions to be avoided during flaring, while others report regimes suitable for flaring. Recent reports now include a diagram showing allowed meteorology for flaring to occur (both Levelton and RWDI reports). The delineation of suitable atmospheric conditions for flaring in the single RWDI report provided a simpler, and

[18] Based on discussions with MoE, OGC and Levelton.

more easily understandable management plan than some of the management plans listed in the Levelton reports, although this may simply be a reflection of more difficult flaring situations evaluated in the Levelton reports.

All pre-flaring analyses with predictions of exceedence level SO_2 concentrations contain a series of graphs showing maximum concentrations and frequencies of exceedence. In addition, a summary is produced describing the results of applying Legge's foliar response equations (Legge, 1995) and geographical areas of potential foliar injury. However, direct identification of the appropriate equation and sample calculations are not provided in any of the reports. Also missing is a description of the vegetation characteristics of the receiving environment.

4.2.2 Post-flaring Assessments

Post-flaring assessments include a revision of the pre-flaring dispersion modelling representative meteorological data and flaring parameters measured during the flaring procedure. If damage to foliage is predicted at this stage, a follow up visual monitoring plan may be required. As with the pre flaring analyses, only the well-test flare is addressed, and not the clean out flare preceding it.

4.2.2.1 Post-flare Modelling and Reporting

In cases where a well-test pre-flaring analysis indicates that foliar damage may occur, a post-flare modelling analysis must be conducted. The post-flare analysis uses the same dispersion modelling methodology used in the pre-flaring assessment, except that meteorological data collected on-site during the production test flaring activity is used in the model instead of the entire year of data used for the pre-flaring analysis, as well as the actual flow rates and gas composition from the production test. In that sense, the post-flaring assessment provides a representation of actual SO_2 emissions and expected downwind pollutant concentrations resulting from the flaring, and the potential foliar response. Not surprisingly, the post-flare modelling outcomes indicate lower maximum SO_2 concentrations – this is largely due to the avoidance of adverse flaring conditions described in the pre-flaring assessment (and flare permit).

The post-flaring modelling assessment indicates whether or not foliar damage occurred. In the cases where the modelling predicts damage, additional observations of plume behaviour may be added, potentially originating from an on-site meteorologist. These observations relate to visual assessments of plume dispersion and/or travel. A final estimate of the potential for foliar damage is then produced and discussed in the report conclusion. However, if the post-flare modelling analysis indicates that no foliar damage was likely to have occurred, the model's predictions are accepted at face value as being accurate, and no follow-up vegetation damage assessment is completed.

4.2.2.2 Visual Monitoring Plan

Post-flaring vegetation damage assessments have been conducted on behalf of industry as part of due diligence in response to the identification of responsibility for damage to vegetation in the OGC Guideline. Where potential for damage to vegetation has been identified in the pre-flaring report, two-stage vegetation assessments have been conducted. A typical monitoring program for a well test consists of the following components (Enns, 2004):

- A field evaluation of vegetation condition before and after well test is conducted. The evaluations are accomplished as close as possible prior to the production test and within 3 – 6 weeks following the test in summer, or up to 3 months following the test in winter (as a delay occurs in expression of injury in winter). The assessment includes records of symptoms attributable to sulphur dioxide (Legge et al. 1995), and other symptoms of pathogenesis similar to sulphur dioxide toxicity, including exposure to drought, root damage, plant pathogens, brine deposition, acid deposition, radiant heat, etc. Prior to the test, records are taken in areas judged to be susceptible to injury based on past experience, and in areas predicted to be impacted. Permanent plots are established prior to the test, and replicates of lichen and conifer tissue samples are collected. Photographs of the permanent plots are taken, along with photos of the surrounding stand, and the areas predicted in the dispersion modeling to be effected.
- Passive monitors for sulphur dioxide (time-averaged over the period of exposure) are installed in areas predicted to receive emissions, including in areas predicted by the dispersion model. Recently, continuous-recording SO_2 monitors are being used as they are more accurate and do not require averaging over the non-exposed period.
- Other sources of sulphur dioxide are identified and pre-existing injury is noted. .;
- Following the test, the site is re-assessed, tissues re-collected from the same marked populations, and photographs are compared and re-taken.
- Following total sulphur and sulphate analysis, comparisons are made between pre-flare and post-flare well test sulphur status in conifers, lichens and some vascular plants. This may include other chemical analysis for substances such as chlorides, and organic compounds.
- Comparisons are made between sample analyses from tissues having known sulphur dioxide injury from the literature, and post-test injury from similar areas in the province.
- An assessment is compiled of vegetation health before vs. after the production test, including all potential adverse factors (changes in groundwater, soil compaction, root damage, pre-existing insect and disease damage, etc). The extent, severity and

significance of vegetation damage are summarized and recommendations for remediation or reclamation are made.

The field evaluation includes individual tree foliage and lichen population sampling, as well as characteristic symptoms of exposure to indicator species (after Legge et al. 1998), if the period of exposure is during the growing season.

4.2.2.3 Post-flaring Reports

A total of 14 post-flaring reports were identified and used to assess how the Sour Well Test Review Process was followed in B.C. during 2000 – 2006. The accompanying pre-flaring reports could not be accessed in all cases. However, use of the post-flaring reports to assess the Review Process is appropriate, since these reports document the actual restrictions present in the permit to flare and whether or not adjustments were made to these restrictions before flaring commenced. The assessment presented here is not comprehensive, but instead allows an objective impression to be formed regarding operational realities and trends during the last several years.

The post-flaring reports show that, in some cases, adjustments are made to the flaring management plan described in the pre-flaring report, typically well in advance of the flaring activity (for example, when it is clear that flaring will occur in a different season than identified in the permit). In one case, changes were made on site just shortly before flaring was to commence. This adjustment was made due to the realization that there was very little sensitive vegetation that could be impacted along a potential plume track direction (one that was identified as a problem in the pre flaring report). In addition, some vegetation was completely covered by snow. For these cases, the changes were made in consultation with the OGC and MoE, and were then identified in the post flaring report.

During well-test flaring, the operations crew has the management plan and is aware of the wind regimes under which flaring can occur. A well-test site is required to have a meteorological station on-site to measure temperature, wind speed and wind direction in order to follow the restrictions described in the management plan. In addition, determination of atmospheric stability may require assessment of other parameters (i.e., cloud cover). SENES understands that during recent well-test flares, adherence to the meteorological regimes described in the flare management plan was managed by a qualified meteorologist.[19] SENES does not know if this was the case for previous years.

[19] Based on comments from D. Fudge, MoE.

There has been greater difficulty establishing feasible management plans to follow during a planned flaring period during the past few years, due to the fact that recent drilling activity has occurred in areas having gas with higher H_2S contents. If a management plan is highly restrictive, the likelihood of halting (shutting in) a flare before necessary data capture is complete is higher. Any changes to a previously established management plan (for any reason) must be made in consultation with the OGC and MoE. Reasons for adjusting the meteorological restrictions documented in the flaring permit for actual flaring may include[20]:

- significantly different H_2S content in the flare gas than initially estimated;
- decision to add propane to the gas flow to decrease H_2S content and improve dispersion;
- flaring is to occur during a different season than initially determined and therefore a higher or lower threshold for foliar injury is expected; and,
- local vegetation different than assumed – fewer trees, rock formations, etc.

Table 4.3 provides a selected summary of flaring activities in northern B.C. that underwent the full sequence of requirements as specified in Figure 3.2, from pre-flaring assessment, to permit approval, to flaring itself, and finally the post-flaring assessment. These examples are for cases of sour gas wells for which there were predictions of potentially significant foliar damage in the pre-flaring reports. In all cases, the actual meteorological restrictions followed for the flaring were taken from the post-flaring reports, as in several cases there were differences noted between the recommended restrictions in the pre-flaring reports and those described in the post-flaring reports – reflecting the review process and pre- or post-permit modifications that may have been made. It is common for changes to be made to the recommended management plan described in the pre-flaring report, but not to changes described in the flaring permit.

Table 4.3 provides a limited historical view of criteria used in flare management plans and associated operations at well test sites. Criteria were chosen to identify trends (if existing) in operational practices.

[20] These types of adjustments may not be made without the consultation of the OGC.

Table 4.3
Summary of Selected Sour Well Test Flaring Events, 2000 - 2006

Date of report (post report date in brackets)	Well Test ID	**Permit Conditions** *Restrictions on meteorology?*				**Post Modelling Report** *Restrictions Violated?*				*Implications?*		
		Stability	Direc-tion	Wind speed	Persistence	Stability	Direc-tion	Wind Speed	Persistence	SO2 exceed-ence?	Foliar Damage Predicted?	Revised Damage Prediction
(May-00)	C-42-K	not provided				not possible to assess				yes	yes	"unlikely"
9/11/2001 (1/22/2002)	C-23-H/93	yes	yes	no	no	yes	yes	n/a	n/a	yes	yes	"unlikely"
(May-02)	B-79-J/93-P-4	yes	yes	no	no	no	no	n/a	n/a	no	no	
Feb-03	C-86-E-93-P-3	yes	yes	yes	yes	no	no	no	no	yes	no	no damage
(Sept-03)[1] July Flare*	B-3-G/93-P-3	yes	yes	no	yes	yes	yes	n/a	no	yes	no	
August Flare*		yes	yes	no	yes	yes	yes	n/a	yes	yes	no	
(Oct-03)	B-77-J/94-I-14	yes	yes	no	yes	no	no	n/a	no	no	no	
(Oct-03)	D-50-C/93-P-5	yes	yes	no	no	no	no	n/a	n/a	no	no	
(Jan-04)[2]	B-2-E/93-P-5	yes	yes	no	no	yes	yes	n/a	n/a	no	no	
Oct-04 (Feb-05)	A-16-F/92-P-3	yes	yes	no	yes	no	no	n/a	no	yes	no	
Mar-05 (Jun-05)	C-40-D/93-P-3	yes	yes	no	no	no	no	n/a	n/a	no	no	
Jul-05 (Feb-06)	C-3-A/93-P-5	yes	yes	no	no	no	no	n/a	n/a	yes	no	
Nov-05 (Jan-06)*	B-80-B/93-P-3	yes	yes	no	yes	yes	no	n/a	no	yes	no	
Apr-06 (Jul-06)*	A-43-E/93-P-3	yes	yes	no	yes	no	yes	n/a	yes	yes	yes	no damage

Notes: [1] Two separate well test flaring events occurred for the one well site (July and August 2003).
* Indicates well test was halted due to unfavourable meteorological conditions.
[2] Short duration flare of 10 hours. Decision to shut in may have been made at the end of the flaring period, which was when the permit restrictions were violated (last two hours).

Table 4.3 describes the meteorological restrictions developed through the Review Process and whether or not the restrictions were violated during the flaring event. As shown, permit restrictions on meteorology can involve limitations to allowable stability classes (‘stability’), wind direction (‘direction’), wind speed (‘wind speed’) or persistence (‘persistence’). Persistence relates to the allowance for a particular wind direction only if it does not hold steady (within +/- 5^{o}) for a specified period of time. This limitation has relevance to vegetation damage, which is more likely to occur if an elevated concentration is experienced for a prolonged period. The permit restrictions are communicated using a combination of one or more of the four meteorological parameters. In some cases a restriction is simple and involves just one parameter – for example *flaring may not occur during stability class 6* (strong stability – limited vertical mixing). In most cases the restrictions involve stability class and wind direction (since stability class has implication of wind speed). The first columns showing ***restrictions?*** and ***restrictions violated?*** summarize the restrictions asserted by the OGC in the flaring permit (as described in the post flaring reports), and whether one or more of the asserted restrictions were violated. SENES determined compliance/violation by assessing the hourly meteorological records that are presented in a post-flaring report. Violation of the permit restrictions can indicate non-compliance with the flaring permit, but only if the well is not subsequently shut in.

The use of an asterisk denotes the well-test flares that were halted (‘shut in’) due to unfavourable meteorological conditions. Unfortunately, clear identification of whether or not a decision to shut in the well was made is not always provided in the reports. In particular, if a well-test is halted and not re-started until several hours (or a day) later, there may be no indication in the post-flaring report that a decision to stop was made. In at least one case, SENES understands that a well-test was halted before schedule and the decision was made to ‘make do’ with the information collected to that point. This appears to be the case described in the January 2004 post report (B-2-E/93-P-5).

Table 4.3 also details the communicated results of the post-flare modelling SO_2 predictions and foliar response analysis (through application of Legge’s equations), along with a final conclusion or ‘revised damage prediction’ which incorporates observations during the well-test. Indication of SO_2 exceedence is relative to both the Level A and Level B objectives, although in most cases the exceedence was above both. An exceedence of either of the ambient objectives is not an indication that the flaring management plan failed to be adequately protective, since the well-test sites were well away from inhabited areas and protection of vegetation was the primary focus (i.e., through application of Legge’s response equations).

The post-flare modelling report review suggests that there have been changes during the last six years, regarding flare management plan development, and the degree of adherence to the meteorological restrictions within a management plan. Some of these changes are clearly reflected in Table 4.3. For the sour gas well-tests that occurred in 2000 and 2001, the permit restrictions were violated, flaring was not halted and ultimately foliar damage was indicated from the post-flare modelling in two instances. In both of these cases, the proponent's consultant (Levelton) judged that the model-derived prediction of foliar damage was not realistic. This judgment relates to differences in how the computer model represented the flare plume (in particular, direction of travel) and either direct wind observations or weather analyses (such as fields produced from a numerical weather model). The two computer models (ISC3 and RTDM) used for dispersion predictions assume homogeneous wind direction, meaning that the potential for differing wind direction at higher elevations is not represented. As previously discussed, there is no requirement from the OGC Interim Guideline that a revised assessment be conducted on the post-flare modelling to establish how reasonable the model predictions were. In effect, the revised assessments are opinions that are stressed without involvement or requirement from the OGC or MoE[21]. Although such opinions tend to be helpful in a dispersion modelling assessment, they do not abrogate responsibility to adhere to the terms of the flaring management plan (i.e., to conduct a follow-up visual assessment of potential foliar damage).

The review of flaring practices, for the dates and reports indicated in Table 4.3 suggests that since 2002, flare management plans have been developed and followed in a manner that was more protective of the environment. This suggestion is based on the observation that there has been no continuation of flaring following violation of the allowed meteorological conditions specified in the flaring permit. In contrast, two well tests prior to 2002 continued flaring while in violation of the permit conditions. It can be seen that either with or without a decision to stop flaring, there were no post-flaring predictions of foliar damage in the post-flaring reports written on and since May 2002. The exception is the last well-test flare (A-43-E/93-P-3), which is discussed in more detail further on in this report. Regardless of the post-flare determinations of (no) foliar damage, small amounts of foliar injury have been observed at well-test sites, and this is discussed in the following section.

By 2003, persistence (of wind direction) began to be used as part of the meteorological restrictions[22]. This is reflective of Legge's 1995 analysis of potential foliar damage due to SO_2 concentrations, and the likelihood of damage increasing with longer term (i.e., greater than 1, or even several, hours) exposure. The post-flaring report of September 2003 (actually two reports, since two separate flaring events were conducted) shows that the meteorological restrictions in the management plan were followed as intended. In each case where unfavourable meteorological conditions arose, the flaring was halted. The well-tests described in the report (B-3-G/93-P-3) appear to have been particularly problematic, and likely very frustrating for the licensee. The first well-test occurred in July and had to be shut in twice, due to development of adverse meteorological conditions and the restrictions in the permit. A second well-test occurred

[21] Based on comments from D. Fudge, MoE through commentary on the draft version of this document.
[22] This is based on the post-flaring reports SENES viewed. It is possible that persistence was used prior to this date and discussed in flare reports; SENES was not able to access.

in August and again had to be shut in twice. A weather forecast was used as justification to begin flaring in both cases, according to the post-flaring report. For the first well-test, and potentially the second as well, the forecasts were likely in error. The post-flaring assessment indicated no damage to vegetation.

The post-flaring report of June 2005 (C-40-D/93-P-3) is also worthwhile to note. This is a case where changes were made to the initial meteorological restrictions indicated from the pre-flaring assessment (prepared in March 2005). Although it is not clear from the documentation in the post-flaring report, it appears that these initial restrictions were also stressed in the flaring permit. The changes made 'upon inspection of the site' were made in consultation with the OGC.[23] A judgment was made that foliar damage was less likely to occur than initially estimated in the pre-flaring report, due to the fact that some of the higher slopes had little vegetation. The newly altered meteorological restrictions were then followed during the flaring. The post-flare modelling showed that even the lower Level A SO_2 objective (450 µg/m³) was not exceeded during the production test, and therefore no foliar damage was predicted. However, anecdotal information provided to SENES by the MoE indicates that the MoE's own modelling runs for the production test indicated much higher concentrations than was reported in the post-flare report.

The final well test in Table 4.3 (A-43-E/93-P-3) involved a very high H_2S content (approximately 30%) and high gas volumetric flow rate, leading to the highest estimated SO_2 release rate of any well-test reviewed. Only one of the additional well-tests, reviewed but not included in Table 4.3 (A-45-L/93-I-9), had the potential for a higher SO_2 release rate (the pre-flaring report for A-45-L/93-I-9 had an initially estimated H_2S content of 35%, although actual concentrations during the flare test never exceeded 25%). Due to the relatively high risk associated with flaring at A-43-E/93-P-3, the management plan developed as part of the Review Process included ambient SO_2 monitoring to coincide with the flare and real time plume modelling to estimate the SO_2 impacts as they occur. Based on the predictions of the real time dispersion modelling, MoE called for the well to be shut in before the scheduled end of the well test.

Since most of the post-flare analyses have been conducted using the older, simpler models ISC3 and RTDM, it is worth considering the results of the one example of the use of the CALPUFF (RWDI Plume-RT version) model in the assessment of SO_2 emissions from the A-45-L/93-I-9 flare test. The model was run in real-time during the flare test, and then used to re-analyze the emissions in the post-flare modelling report to determine whether any improvements could be made to achieve better conformity with observed concentrations at monitoring sites. The qualitative comparison of predicted to observed SO_2 concentrations by RWDI suggested that the

[23] The MoE were not made aware of these changes according to comments made on the draft version of this report (D. Fudge, MoE).

magnitude of the predicted concentrations "*generally tracked monitored values*", but that the maximum predicted values were shifted in both time and space from those observed at the monitoring sites. Both modelled and monitored values reported during the well test flaring exceeded foliar damage criteria during several periods, suggesting that damage to vegetation was possible during the flaring events. However, because the predicted maximum SO_2 concentrations did not occur at the same time or in the same locations as was indicated by the monitors, the use of the real-time refined modelling analysis did not appear to provide any additional benefits with respect to the prevention of vegetation damage during flaring events. The report made a number of recommendations to improve the use of the Plume-RT model. These focused on changes to the modelling system (e.g., better information on flare flow rates, higher grid resolution, assumptions about radiative heat loss, and combustion efficiency, etc.) and improvements in the siting and use of ground-based meteorological data in the model.

4.2.2.4 Visual Monitoring and Foliar Assessments

Both pre-flare and post-flare assessments have been conducted on behalf of industry, for well production tests with varying levels of hydrogen sulphide, and where the pre-test dispersion analysis predicted the potential for foliar injury to occur. Many of these are summarized in Enns (2004a, 2004b). The pre-flare and post-flare production test monitoring includes the use of passive monitors in areas predicted to receive high concentrations, and areas where high concentrations usually occur, vegetation is sampled and photographed prior to and after the test. Total sulphur, sulphate sulphur and calculated sulphur inorganic ratios are compared between the pre-flare test and post-flare test sampled vegetation. The passive monitors are analysed and the results are compared with continuous monitor data (if the latter is available). Symptoms of injury (as shown in Legge et al. 1998) are recorded, and other sources of pathogenesis are documented for each production test.

For 12 of the 14 well-tests reviewed and described in Table 4.3, a vegetation assessment was initiated and conducted at the request of industry. These assessments were initiated before flaring commenced, due to identification of risk from the pre-flaring assessment produced months in advance of the well-test. Table 4.4 provides a summary of the visual monitoring assessments that were conducted for the 12 well-tests.

Table 4.4
Summary of Select Sour Well Test Flaring Vegetation Assessments in B.C., 2000 – 2006

Date (post report date in brackets)	Well Site	Post Modelling Report *Restrictions Violated?* Stability	Direc-tion	Wind Speed	Persist ence	Post Assessment SO_2 exceed-ence?	Foliar Damage Predicted?	Revised Damage Prediction	Visual Monitoring and Assessment Passive SO_2 monitoring	Total S or Si:S ratio	Post flare injury diagnosis
(May-00)		not possible to assess				yes	yes	"unlikely"	Eight biomonitoring plots with 8 passive monitors placed in areas predicted to receive injury. Two in the direction of prevailing winds in very exposed locations but not in modelled areas received slightly higher concentrations than the remainder. All were still below 0.007 ug/m3 indicating the model overpredicted concentrations.	Highest ratio was 0.45 in area predicted to receive maximum	Most of the sulphur dioxide injury was confined to trees on the edge of the pad in the direction of prevailing wind. Sulphur concentrations in tissues declined with distance from the edge of the pad into stand. Very slight banding injury on a few exposed trees in areas predicted by the post-flaring modelling to receive injury
9/11/2001 (1/22/2002)	c-23-H/93-P-4	yes	yes	n/a	n/a	yes	yes	"unlikely"	Five biomonitoring plots with passive monitors, the one on the edge of the pad in the direction of prevailing wind received the highest sulphur dioxide concentrations, all below 1.4 ppm.	Sulphur levels and ratios increased slightly, especially in the area next to the pad in the direction of prevailing winds during the test.	Drought and winter injury was nore common prior to the test than after. A very small amount of injury was present on the edge of the pad in the direction of prevailing winds, it appeared to be a combination of drought, injury to roots and possibly a mild exposure sulphur dioxide.
(May-02)	B-79-J/93-P-4	no	no	n/a	n/a	no	no		Twelve biomonitoring plots installed, but the passive sulphur dioxide monitor date was not used, due to the length of time left exposed in the field.	Pre-test sulphur status greater than post-test due to presence of old glycol dehydrator near by (since shut in) indicating a decline in overall sulphur status at this test site.	Very slight injury to trees both before and after production test, most directly attributable to drought and winter injury.
Feb-03	c-86-E/93-P-3	no	no	yes	yes	yes	no	no	Nine biomonitoring plots, each with passive sulphur dioxide monitors.	Previous exposure to sulphur dioxide from a continuously flaring source was evident, both in the foliar chemistry and in the symptomology.	New foliar injury at various distances from the well but within the first 50 meters in the direction of prevailing winds was evident following this production test, and attributable to sulphur dioxide. It was difficult to distinguish some injury from the pre-existing injury caused by long term exposure to sulphur dioxide from the continuously flaring source nearby (e.g. all sulphur concentrations and ratios were high, lichens no longer occur).
Sep-03 July flare*	B-3-G/93-P-3	yes	yes	n/a	no	yes	no		Ten biomonitoring plots, each with passive monitors.	See below	See below
August flare*		yes	yes	n/a	yes	yes	no			Lichen sulphur concentrations increased in plots in the direction of prevailing winds, no significant change in sulphur inorganic to organic ratios.	Minor and contained injury caused by sulphur dioxide to needles of conifers in the direction of prevailing winds adjacent to the well pad.

Table 4.4
Summary of Sour Well Test Flaring Visual Assessments in B.C., 2000 – 2006 (continued)

Date (post report date in brackets)	Well Site	Post Modelling Report *Restrictions Violated?*				Post Assessment			Visual Monitoring and Assessment		
		Stability	Direc-tion	Wind Speed	Persistence	SO_2 exceed-ence?	Foliar Damage Predicted?	Revised Damage Prediction	**Passive SO_2 monitoring**	**Total S or Si:S ratio**	**Post flare injury diagnosis**
(Oct-03)	B-77-J/94-I-14	no	no	n/a	no	no	no		Four biomonitoring plots with passive sulphur dioxide monitors and eleven observational plots (viewed and photographed)	No significant change in foliar or lichen chemistry.	No visible injury to vegetation either at the pad edge or in the areas predicted to be impinged upon by the model.
(Oct-03)	D-50-C/93-P-5	no	no	n/a	n/a	no	no		Five biomonitoring plots with passive monitors.	Foliar and lichen tissue sulphur increased in the same area the monitorng indicated exposure to sulphur dioxide occurred.	Severe to moderate injury on trees along the edge of the pad, influenced by the production test, but also by the pad construction. This injury was attributable to a mix of drought, blasting injury and exposure to sulphur dioxide, possibly during the cleanout flare.
(Jan-04)	B-2-E/93-P-5	yes	yes	n/a	n/a	no	no		Six biomonitoring plots with passive monitors.	Foliar sulphur increased in one of the plots where monitoring indicated an exposure to sulphur dioxide.	Mild symptoms of acid deposition on shrubs adjacent to well pad.
Oct-04 (Feb-05)	A-16-F/92-P-3	no	no	n/a	no	yes	no		Three biomonitoring plots with passive monitors and ten observational points.	No significant trends in foliar or lichen chemistry. (Very large pad).	No evidence of injury that could be attributed to sulphur dioxide.
Jul-05 (Feb-06)	C-3-A/93-P-5	no	no	n/a	n/a	yes	no		Five biomonitoring stations.	No significant changes to foliar or lichen chemistry. Sulphur dioxide exposure evident in one monitor on the edge of the pad in the direction of prevailing wind.	Slight injury resembling acid deposition in one pad-edge plot.

Table 4.4

Summary of Sour Well Test Flaring Visual Assessments in B.C., 2000 – 2006 (continued)

		Post Modelling Report ***Restrictions Violated?***				**Post Assessment**			**Visual Monitoring and Assessment**		
Date (post report date in brackets)	**Well Site**	Stability	Direc-tion	Wind Speed	Persist ence	SO_2 exceed-ence?	Foliar Damage Predicted?	Revised Damage Prediction	**Passive SO_2 monitoring**	**Total S or Si:S ratio**	**Post flare injury diagnosis**
Nov-05* (Jan-06)	B-80-B/93-P-3	yes	no	n/a	no	yes	no		Three biomonitoring plots with passive monitors and eighteen observational points with photographs.	Increase in foliar and sulphur chemistry in on pad side plot in the direction of prevailing winds.	Relatively severe but contained injury to a small number of trees in the direction of prevailing winds near the edge of the well pad, confirmed as acute sulphur dioxide injury combined with some radiant heat injury.
Apr-06 (Jul-06)	A-43-E/93-P-3	no	yes	n/a	yes	yes	yes	no	Four passive monitors installed, one at pad edge in direction of prevailing winds registered higher sulphur dioxide concentrations than all others.	Total post flare S was higher than preflare in the area observed to receive the clean out plume. Lichen tissue S was higher in the area noted to be exposed to the production test plume, than in surrounding high elevation areas.	Injury was noted adjacent to the pad in the exact same area where the cleanout plume was noted to remain for some time during the entire cleanout. Injury was typical mild sulphur dioxide injury, and coincided with changes in sulphur concentrations but was restricted to a few typical indicator plants. No injury was noted in the areas predicted to receive high concentrations by the modelling and in the monitoring, despite both model and monitors registering concentrations that are associated with injury to sensitive plants. These plants would likely have shown some injury response if the modelled and monitored concentrations were present.

As indicated in Table 4.4, the post-flare well-test modeling reports often documented that exceedences of the Level A and B objectives occurred, yet no damage to vegetation was expected. However, in follow-up environmental assessments, on occasion injury was found in areas where the post-test modelling predicted no injury (and, in some cases, no exceedence of the Level A and B objectives). In all of these cases, if injury occurred it was distinguishable from the pre-flare test condition. For a number of well-tests, a variety of indications of injury from sulphur dioxide exposure have been present in vegetation, almost exclusively in small, well defined areas adjacent to the well-test on the side of the pad receiving prevailing winds. Indicators of damage include the following:

- elevated sulphur dioxide concentrations recorded in the passive monitors placed prior to the test;
- typical red banded and yellow-tipped foliage in lodgepole pine, Douglas-fir or subalpine fir on exposed crowns near the well edge or in the area of prevailing winds, usually not more than 100 meters from the test site;
- foliar injury to sides of crowns facing the well, often primer red in color and not present prior to the test;
- elevated total sulphur and higher sulphur inorganic to organic S ratios in both lichens and foliage in comparison to pre-test levels;
- singed appearance in formerly healthy lichens;
- spotting, interveinal chlorosis in alder and other vascular plant indicators (if the test was in the growing season).

The assessments indicated that injury to vegetation from the well-test was mixed with drought injury from exposure of the pad edge tree crowns and root systems during the pad construction (e.g. c-23-H/93-P-4, d-50-C/93-P-3 in Table 4.4). Injury from well-tests is often mixed with winter (or Chinook) injury, especially at high elevation (e.g., a-43-E/93-P-3 and other well sites not shown in Table 4.4; Enns 2004b). In some cases, radiant heat energy may have been responsible for singeing crowns of trees facing the flare or close to the flare, as in the case of b-80-B/93-P-3 (Table 4.4). In many cases, droplet-type symptoms of injury were present on exposed leaf and grown vegetation surfaces (e.g. b-2-E/93-P-5, c-3-A/93-P-5 in Table 4.4). At one site, not included in Table 4.4, salt concentrations in lichens were noted to decline with distance from the edge of the pad to the interior of the stand over a distance of 180 meters. This injury is assumed to be from the clean out flare. Sulphur dioxide injury from the clean out flare has also been directly observed (e.g., a-43-E/93-P-3 from Table 4.4). In the latter case, observed injury relates to before flare / after flare sample plots in areas which were observed to experience interaction with the plume over a noted period of time.

In almost all occasions, injury from production tests is mixed with symptoms of other pathogens, drought, exposure and deposition from unknown substances, possibly from the clean out flare.

In at least one case (c-86-E/93-P3 in Table 4.4 above), previous exposure to a nearby, continuous source of sulphur dioxide resulted in a higher level of post-flare test damage evident in the stand around the production tests (than what would be expected given the modelled sulphur dioxide concentration and duration of exposure). It was difficult to distinguish the injury caused by the production test from the pre-existing injury from the continuous source, except in marked, photographed trees.

Injury is usually confined to a small number of trees on the edge of the well-test pad, always in the direction of prevailing wind during the test, and lessening in severity within a few meters of the edge of the well-test pad. In a few isolated instances in very steep terrain, injury has been noted to occur up to 100 meters away from the pad edge on steep slopes, possibly due to increased exposure to the plume from the flare. These sites were the exception, however, to the usual condition where injury is noted near the well site. The largest incident of injury to vegetation from a production test occurred at d-13-G/93-I-9 in the summer of 2000 (Legge and Jaques 2001). The production test injured a 23.9 hectare area of lower montane forest. The injury was due in part to sulphur dioxide and potentially other substances. The injury extended from the edge of the well pad into the forest in the direction of prevailing winds. A large proportion of the trees affected by the injury during this production test had recovered after 3 years (Enns 2004a).

As in the case of d-13-G and other production test sites, the direction of the injury, if injury occurs, is the same as noted in the post-flare model, but is situated much closer to the pad than indicated in the model. In a number of instances when injury was noted in the post-flare test assessment, subsequent visits over a number of years to the same sites indicate that trees recovered and their crowns tended to fill in over time and obscure the original location of injury on the trees (summarized in Enns 2004a, 2004b). Recommendations for remediation of individually injured trees are usually made in the post-flare test assessment report.

5.0 DISCUSSION AND RECOMMENDATIONS

5.1 DISCUSSION

To the extent possible, well-test flaring management issues identified through the review of flaring literature and the pre-flare and post-flaring reports were explored through personal and phone interviews with OGC, MoE and consultants involved in the Sour Well Test Review process. In addition to these formal interviews, informal questions were asked of others that have been, or currently are, involved in gas flaring in B.C. Finally, questions were posed to regulators in other Canadian provinces.

There are two noteworthy trends that have been identified as part of this work. The first is that the finer details of flaring management in B.C. have evolved during the past several years and that the process appears to be more protective of the environment than during earlier years of well-test flaring. This is not simply due to changes in requirements from MoE or the OGC, but also due to industry taking a greater interest in management plan development and a greater awareness of environmental issues in the field. The second trend is that gas deposits with higher H_2S concentrations are being targeted and explored, often in areas of complex terrain, which increases the risk to the environment simply due to higher SO_2 emission rates during well testing.

An additional recent trend must also be considered, relating to additional tools to be used as part of the flaring management plan. In particular, the use of real-time dispersion modelling as flaring is undertaken (and the ability for a regulator to access the modelling predictions). Two other tools include on-site direction from a designated biologist with experience in SO_2 foliar injury (to prevent or mitigate foliar damage) and use of real-time SO_2 monitoring data in susceptible areas. The designation of an on-site biologist was specified in the permit for a43-E/93-P-3 and may not have been used to date for any other well test. SO_2 monitors have been used in past well-test flares; however, the post-flaring report for A-43-E/93 used SO_2 monitoring results as partial justification for the assertion that no foliar damage occurred as a result of flaring, indicating a potential difference in how the results of monitoring may currently be interpreted. Each of these three tools as described is relatively new to the flaring management system in B.C., and how they may be used in future well-test applications is still being discussed by all parties involved in the Review Process.

There are two primary issues that need to be addressed as improvements in the flare management plans for B.C.:

1) the reliance on relatively crude models for a number of key decisions, namely:
   (a) the determination of whether vegetation damage might occur and the location of any such damage;

(b) the determination of conditions for the flare management plan (i.e., the appropriate meteorological conditions when flaring can occur);
(c) the determination of whether a post-flaring assessment is required;
(d) the determination of whether a vegetation damage assessment is required;

2) the roles and responsibilities of individuals and agencies participating in flaring management:
   (a) what is the decision–making process and who is responsible for making key decisions at various stages in the process?
   (b) What changes to the process might be required to clarify roles and responsibilities?

Each of these issues is discussed in more detail below.

5.1.1 Dispersion Modelling and Vegetation Damage Assessment

The primary advantage of using dispersion models for well-test flaring management is that they provide an objective means of estimating where and when vegetation damage might occur. The results of the modelling assessments can then be used to screen out those meteorological conditions that are unsuitable for flaring in order to allow well testing to proceed without causing such damage. However, as noted above, all of the available models are limited in their ability to accurately predict downwind SO_2 concentrations. Consequently, the results of the modelling analyses may at times identify meteorological conditions as suitable for flaring to proceed that might in actual fact not be acceptable for flaring. Alternatively, and this is likely the more typical situation, the models may be too conservative in overestimating SO_2 concentrations, and thus unnecessarily restricting the periods when flaring is permitted.

SENES appreciates the situation that there is no perfect model or modelling configuration that can be used to represent flares; however, there are steps that can be taken to ensure that the modelling procedures are consistent with current understanding of flaring dynamics. There are technical improvements that can be made to the dispersion modelling methodology currently used. Some of these improvements are based on the literature review conducted as part of this work, and not necessarily on errors or weaknesses that have been identified in the modelling outcomes.

However, there is a particular need for formal recognition that the computer models are limited to simulating flaring conditions following the start up procedures. In effect, the flare can be simulated reasonably well only after start up conditions have passed (i.e., after the completion of the clean out flaring phase), and this would be the case for any dispersion model chosen. In particular, emissions during the clean out flare are not addressed in the pre-flare or post-flaring assessments, and the potential effect of these emissions can not be adequately simulated within any of the available models. During the clean out phase, less than ideal combustion conditions exist and a variety of additional chemical compounds are released in addition to SO_2. It is common for the clean out flare to continue for 6 – 8 hours or longer. Therefore, the clean out flare emissions have the potential to cause damage to vegetation, which is not reflected in the pre-flare modelling analyses. Due to reduced buoyancy, the plume from the clean out flare has been observed to descend into vegetated areas very near the well site. Vegetation damage has been found near the well-test pad on several occasions and at times the damage has been associated with high SO_2 levels. The computer models do not predict damage near the well pad, since the assumption of high combustion efficiency, vertical velocity and exhaust temperature are always applied – and these relate to flaring once the clean out period has passed. The dispersion models are performing as well as can be expected, and the predictions determined – that damage may occur at distances of 850m and beyond – appropriately match observations during the mature stage of the well-test.

A clearly apparent issue of uncertainty associated with well-test flaring in B.C. is the prediction and measurement of foliar damage that may be due to some stage of the well-test procedure. An important step was taken by the industry in the 1990s to develop an approach to estimate foliar damage due to SO_2 concentrations (Legge, 1995). Dr. Legge has indicated that, in his opinion, the information presented in his 1995 study has been misapplied. The use of Legge (1995) to predict injury thresholds is based on sound science and should not be discontinued. However, there are some limitations to the use of the predictive curves for injury thresholds for longer exposures, the timing of dormancy and the potential for injury to sensitive plant communities. Legge's document was written for a facility undergoing continuous flaring, in order to provide guidance for how to avoid injury in instances where exceedences of usual levels may occur. The response of vegetation to this scenario is somewhat different from the response to single, short-duration, high volume flares in previously unexposed vegetation (i.e. well flare tests). In some cases predisposition to injury may exist due to lengthy continuous exposure to a source such as a gas plant nearby. Such predisposition could influence the injury thresholds for vegetation next to a production test (Enns, 2004).

From a theoretical perspective, use of the Legge equations are an appropriate, if conservative, means to estimate foliar damage and establish protective measures for flaring. Inherent difficulties associated with predicting damage (or lack thereof) are:

1) how well the computer models are able to predict exposure to actual SO_2 concentrations in the surrounding vegetation;
2) consideration of the duration of the exposures over the entire period of flaring and subsequent cumulative effects; and,
3) an accepted method to validate damage, or lack of damage, during site visits after flaring has occurred.

Criticism regarding the application of Legge's equations in the post-flaring reports may be related to the difference between modelled and actual SO_2 concentrations (i.e., point number 1 described above) rather than a misapplication of the equations themselves. This issue requires further investigation.

5.1.2 Roles and Responsibilities

There is a need to clarify the roles and responsibilities of all individuals and agencies involved in the implementation of well-test management plans. As currently constituted, the roles of various participants in the process are as follows:

- well-test proponents retain air quality and biological consultants to develop a management plan based on dispersion modelling analyses;
- the management plan is reviewed by MoE staff prior to being approved by the OGC;
- consultants with experience in air quality dispersion modelling and in vegetation damage assessment assist the proponents in implementing the management plan during the well-test flaring, with oversight provided by the MoE staff from Prince George;
- consultants with experience in air quality dispersion modelling and in distinguishing sulphur dioxide injury from other pathologies conduct a post-flaring assessment (and possible a pre-flare assessment) to ensure that no vegetation injury has occurred.

Insofar as events during the flaring program unfold as envisioned in the well-test management plan, the process works reasonably well. However, difficulties in the process have arisen in the past when events on-site during the well-test have not conformed to the predetermined management plan. Specifically, there have been cases when consulting staff present on-site at the time of the well-test have identified issues with vegetation protection that were either not envisioned at the time that the management plan was developed, or because the well-test is to be conducted at a time of year that was not anticipated when the management plan was proposed. In such cases, consulting staff on-site have suggested or implemented changes to the well-test management plans after consultation with the OGC. Among the post-flare assessment reports reviewed in this study, there were cases where changes made to the management plans were not identified in the post-flare reports, and which MoE staff has stated they were not informed about. Conversely, consulting staff have stated that they always differ to the judgement of the MoE staff when decisions have to be made about whether or not to shut in a well due to elevated SO_2 concentrations predicted by the models during the well-test. Difficulties have also arisen during flaring events when MoE staff could not be contacted to obtain an opinion on whether or not to shut in a well. It is suggested that these types of difficulties stem from the lack of clear definitions of the roles and responsibilities that various parties are intended to have in the overall process.

Part of the problem with the definition of roles and responsibilities in the flaring process stems from the fact that although the MoE staff see themselves as acting in an advisory capacity to the OGC, all other participants see the role of the MoE as having the *de facto* final decision-making authority on when to continue flaring and when to shut in a well. When a decision has to be made, the MoE staff has only the real-time dispersion modelling results and static SO_2 monitor data provided to them on which to base their decision. Reliance on modelling and monitoring data by MoE staff may result in a different perception of the risk for vegetation injury by the MoE staff compared with the on-site air quality and biological consultants who can see the terrain and, at times, plume behaviour which may not be well-represented by the models. In such situations, the question arises as to whether the MoE's perception of the risk to vegetation damage should prevail, or whether the on-site consultants ought to have a discretionary power to use their professional judgement in making decisions about potential vegetation impacts?

5.2 RECOMMENDATIONS

A number of recommendations are presented with the intent to focus discussion on key issues that were identified as part of the review work completed by SENES and Delphinium Holdings. Some of the recommendations relate to a current lack of understanding regarding the potential effects of flaring, and are not meant to provoke immediate change to the Sour Well Test Review Process. Rather, some recommendations are directed towards further research and collection or reporting of data that will better support the future evolution of the Review Process. Other recommendations, particularly with respect to roles and responsibilities of participants in the process, are directed at providing greater clarity in the process rather than making fundamental changes to the process.

In considering these recommendations, it is important to bear in mind that the stated goal of the Government of British Columbia is to eliminate all flaring by 2012. Therefore, it may be inutile to propose wholesale changes to the existing process in the short-term if the entire issue of flaring is slated for termination within another five years. Furthermore, for the short-term (i.e., until 2012), the goal of the flare management plans should be to prevent large-scale vegetation damage, rather than to protect against small-scale damage effects that are comparable in magnitude to the scale of damage caused by building the well-test drilling platforms in the first place. If the damage is small and localised, such that the vegetation is likely to recover in a few years, it may not be worth the effort to develop elaborate new procedures for the development and implementation of well-test management plans, or for vegetation damage assessment.

5.2.1 Dispersion Modelling Configuration

As a result of the literature review on flaring dynamics, the following recommendations are made towards improving the existing methodology used for dispersion model configuration:

2) Use of 25% initial radiation loss for the plume, unless justification is given for a different percentage (for example, flare gas of a high molecular weight).
3) Use of vertical velocity estimate deriving from gas volumetric flow rate and stack dimensions.

5.2.2 Changes to Pre-flare and Post-flare Assessments

The suggested changes here relate to simplifying the review process for the regulators and to minimizing the uncertainty associated with communicating the actual flaring conditions required for a post-flare investigation of foliar damage.

4) Adoption of a spreadsheet tool to develop the calculated parameters used in dispersion modelling. An example to use as guidance in the development of a B.C. tool is the AENV *directive060_EUBWellTest* spreadsheet. The completed spreadsheet should be included as part of the pre-flaring report.
5) Adoption of a revised standard format for the post-flaring reports. The reports should serve as a stand alone reference that can be consulted should vegetation damage be noted near a particular well-test site following flaring. In addition to the current criteria, the standard format should potentially include:
   a. A copy of the permit to flare;
   b. Hourly (or more frequent) visual observations of the flare, including shape and direction of travel for the entire flaring period, including the start up and clean out phases (this may or may not be achievable during evening hours);
   c. Hourly gas flow measurements to accompany the meteorological data reported[24].
   d. Discussion and sample calculation of vegetation response using Legge's approach.

5.2.3 Environmental Assurance

The suggested changes relate to standardization of current best management practices where production tests dispersion analysis predicts injury to vegetation. In these instances, a pre-flare and post-flare assessment (as described above) should be done, particularly if the test is to be conducted between April and September. This would allow for the identification of special circumstances such as the early or midwinter breakage of dormancy, susceptible vegetation, etc.

[24] Data confidentiality may be a concern here.

5.2.4 Future Studies to Improve the Understanding of Potential Impacts of Flaring

6) Conduct investigations to better understand the role of clean out flare emissions (and, potentially, radiant heat) in vegetation damage that may occur near the well-test pad.
7) Alternatively, in lieu of more research on the effect clean out flaring emissions and radiant heat on vegetation, define a Best Management Practices code for clean out flares to minimize the effects of this phase of the well-test flaring process.

5.2.5 Sour Well Test Management Plan

8) Specify additional (non-meteorological) conditions under which the clean out flare is to proceed. In particular, the conditions should relate to use of 'lift gas' such as propane to ensure combustion supports adequate dispersion of the plume. Currently, the permits specify that lift gas must be available on the well-test site, but not that it must be used to attain any criteria regarding the flare gas or the plume itself. Criteria considered could include visual observations of the plume.

5.2.6 Clarification of Roles and Responsibilities in the Flaring Management Plan

9) The recommended management structure is as follows:
    a. The MoE is responsible for defining the goals for environmental protection during flaring and acts in an advisory capacity when requested to do so by the OGC, but is not responsible for the day-to-day decisions on implementing the well-test management plans;
    b. Overall development and implementation of the management plan rests with the proponents and site managers, with assistance from their consultants and the approval of the OGC through the permit to flare;
    c. If deemed necessary, site managers would be responsible for seeking the advice of an on-site meteorologist or suitably trained atmospheric scientist on when to flare or when to shut in a well;
    d. The on-site meteorologist or atmospheric scientist could also seek the advice of a qualified, on-site biologist as to the likelihood of foliar damage, when preparing to advise the site managers as to the need to shut in a well;
    e. The on-site meteorologist or atmospheric scientist could also seek advice from the MoE in preparing to advise the proponent's site manager, but the ultimate responsibility to act on the recommendation by the on-site meteorologist would rest entirely with the proponent's site manager.

In order for the MoE and/or proponents to have confidence in the advice they would be receiving from the on-site meteorologists and biologists, the OCG may need to establish either a training course or suitable screening procedures to ensure that the individuals participating in on-site flaring activity are truly trained and qualified to do this type of work.

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