Development of a Quantitative Risk Assessment Tool for Evaluating Risks at Natural Gas Compressor Stations and Above Ground Installations

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High-pressure natural gas compressor stations and Above Ground Installations (AGIs) present potential major hazards (fires and explosions) in the unlikely event of accidental releases of gas, due to a range of threats including accidental interference damage, corrosion, equipment failure. Under the Control of Major Accident Hazards Regulations (COMAH), National Grid is required to manage the risks associated with these assets effectively and to be able to demonstrate that risks are either broadly acceptable, or tolerable if ALARP (As Low As Reasonably Practicable).

This paper describes a project undertaken with Network Innovation Allowance (NIA) funding to develop a software package, known as ‘AGI Safe’ to assist National Grid by undertaking risk assessments; for example, assessing individual and societal risks, assessing fire-fighting provision, examining the impact of changes to the site layout, siting of temporary buildings used during site maintenance and evaluating potential risk reduction measures and their impact on reducing the likelihood of escalation events.

The AGI Safe package contains a number of different assessment options; the paper describes these and also indicates the practical situations when these assessments can be used as part of a decision-making exercise.

The paper describes in more detail a specific methodology to assess the risks of asset damage due to escalation from fires. Using a simple heat-up model, the temperature of metal equipment is calculated from the predicted time-varying incident thermal radiation. Information such as the steel thickness and grade is used to predict whether the equipment fails. This model is then applied to a large number of release scenarios, including leaks of various sizes, pipeline ruptures and vessel failures, allowing the frequency of a failure due to thermal radiation escalation to be assessed.

A worked example is presented examining the impact of changes to the isolation and blowdown of equipment on its predicted failure frequency. This type of assessment can be used to inform investment decisions, for example, evaluating the benefits gained by reducing the time to isolate the inventory or increasing the blowdown rate, which both provide an associated reduction in risk from a potential escalation event.

Introduction

High-pressure natural gas compressor stations and Above Ground Installations (AGIs) operated by National Grid present potential major hazards (fires and explosions) in the unlikely event of accidental releases of gas, due to a range of threats including accidental interference damage, corrosion and equipment failure. Under the Control of Major Accident Hazards Regulations (COMAH), National Grid is required to manage the risks associated with these assets effectively and to be able to demonstrate that risks are either broadly acceptable, or tolerable if ALARP (As Low As Reasonably Practicable).

As part of this commitment to understanding and minimising the risks of its operations, National Grid, in collaboration with DNV GL (and with the help of Network Innovation Allowance (NIA) funding), has developed a methodology based on a programme of theoretical and experimental work, to assess the risks from compressor stations and other AGIs associated with natural gas transmission pipelines; this methodology has been incorporated in the ‘AGI Safe’ software package (an earlier version of the package was known as ‘CompCab’ and has been described previously (Cleaver, 2012)).

Previous approaches used for the risk assessment of compressor stations and AGIs, using the more general DNV GL consequence modelling package ‘ORDER’(DNV GL, 2010), were found to be time-consuming. While AGI Safe contains the same consequence models as ORDER, the development of AGI Safe has been undertaken with the aim of improving the efficiency, consistency and auditability of consequence and risk assessments for such assets.

Due to the commonalities found across many compressor stations and AGIs, assessments for different assets can often use much of the same input data and assumptions, and the modelling results which are typically of interest for such assessments can be automatically generated in standard formats. As such, AGI Safe has been designed accordingly to minimise the level of user intervention required during the setup and reporting of assessments. As well as reducing the time and complexity associated with carrying out the assessments, utilising standardised modelling parameters can help to improve consistency between assessments across different sites, allowing the assessments to be directly compared and any remedial actions identified to be prioritised.

AGI Safe has been used by, and on behalf of, National Grid to help carry out tasks such as the following for compressor stations and AGIs:

- Plotting maximum hazard distances,
- Assessments of risks to people,
- Asset risk assessments,
- Fire risk assessments,
- Site layout assessments,
- Temporary building assessments,
- Occupied building assessments (based on Chemical Industries Association, 2010).

Key Package Features

Overview

The AGI Safe package has been designed to be used by people who are not familiar with the details of risk assessment techniques, but who are likely to have a good knowledge of the operation of a site. As such, only a minimal set of parameters are required to be specified by the user to define each item of process equipment, and other assessment inputs (such as failure scenarios and boundary conditions) have been pre-defined and are automatically generated by the package. This enables risk assessments to be set up more quickly and carried out more consistently.

Failure Scenario Definition

An important part of any risk assessment is the selection of failure scenarios to be modelled. This can require a good knowledge of risk and consequence modelling techniques, particularly for sites which carry out a lot of processing, or that handle liquids.

As part of the project, several National Grid compressor stations were examined, and 19 types of process units - or ‘site blocks’ - which were common across the sites were identified: fourteen generic equipment types, two generic types of ‘congested explosion region’ and seven types of ‘confined explosion region’, including five compressor cab designs (a complete list of site block types is given in Table 1).

A standard set of scenarios that would be modelled for each process block were identified; for example, pipeline ruptures and leaks with diameters of 100, 50, 20, 10 and 5mm are modelled for the ‘Inlet Pipeline Area’ block, and for a ‘Pig Trap Unit’ block the scenarios modelled are the catastrophic failure of the pig trap door, leaks from the pig trap door seal and leaks from the general equipment.

For many of the fourteen generic equipment types it is possible to specify whether the equipment is above ground, within an open or grated pit, or within a covered pit. Slightly different scenarios are modelled for each case; for example, horizontal and vertical free jets and impacted downward releases are modelled for above ground equipment, whereas for releases in open pits the majority of releases are assumed to impact the floor or walls of the pit, with the remaining releases assumed to form vertical and angled free jets.

The inputs required to run the consequence models for each scenario were examined and, where possible, generic values were selected, to minimise the amount of information entered by the user. For example, for the ‘Inlet Pipeline Area’ block mentioned earlier, the user is required to specify the operating pressure and the pipeline diameter, but the temperature of the gas takes a standard value of 8ºC and generic boundary conditions are assumed.

Failure Frequencies

Each of the site blocks also has a typical parts count associated with it, which is based on a review of several compressor stations; this is used to calculate the frequencies of the different leak sizes. The rupture frequency is calculated from the length of pipeline (which is a user input) and failure frequencies suggested by the UK HSE for Land Use Planning (HSE, 2010). The off-site risks can be sensitive to the frequency assumed for ruptures, and it is normally straightforward to estimate the length of above ground pipeline from a plot plan for the site.

The failure rates that AGI Safe employs have been developed to be appropriate for National Grid assets and uses the most relevant data sources including the HSE OIR 12 data (HSE, 2016 (2)) As failure frequencies may be lower in the more benign onshore environment, the package includes the ability to use reduced component leak frequencies by application of a suitable reduction factor.

Package Description

Overview

AGI Safe can be used to carry out assessments for a variety of sites handling natural gas. In all cases, a site definition must first be created for the site in question (if one does not already exist), to specify the positions and parameters of compressor cabs and equipment items, areas of particular interest where the effects of release scenarios are to be measured (‘monitor points’) and a number of other inputs. The automatically-generated scenarios for the defined equipment can then be executed, and the modelling results interrogated.

The Sections below provide an overview of the site setup process including the input data required, the types of outputs which are generated, and examples of typical uses of the package.

Equipment Definition

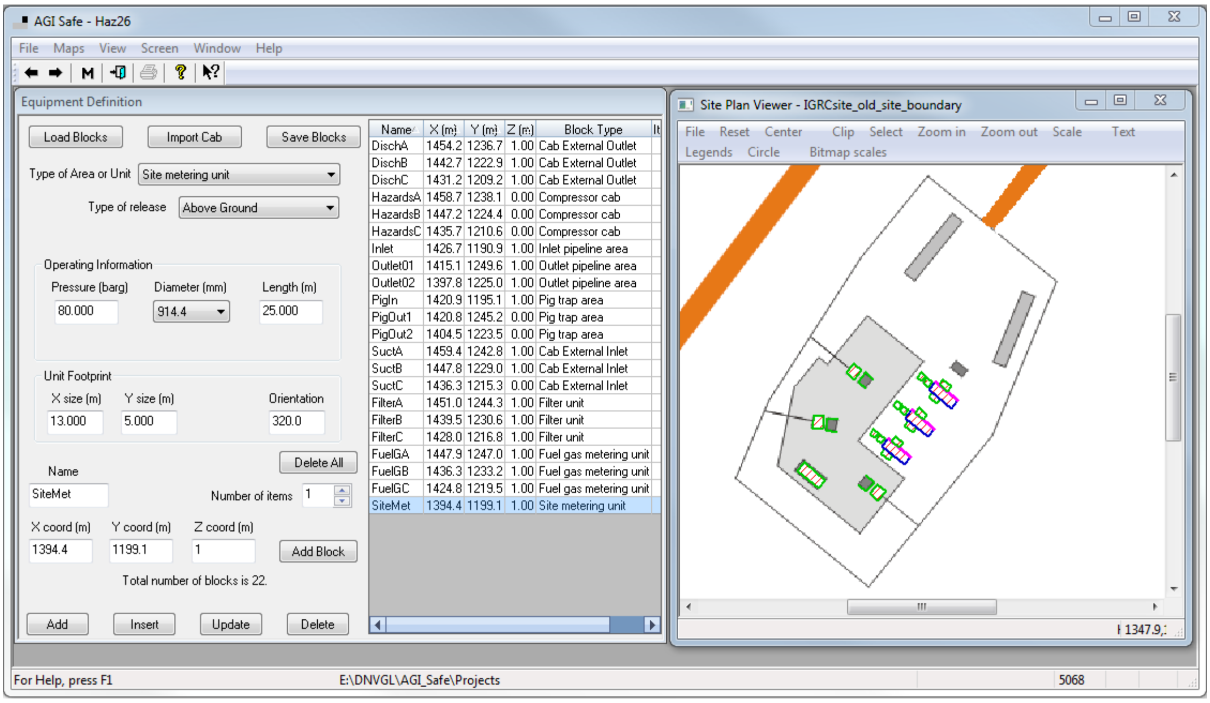
A site definition for a risk assessment is built up in AGI Safe by defining the site blocks present on the site, in terms of their block type (the complete list of site block types is given in Table 1), their physical footprint, their associated operating pressure, pipeline diameter and length parameters. For compressor cabs, due to the associated risks being sensitive to ventilation, isolation and gas detection parameters (unlike for other generic equipment blocks), these details must also be specified by the user.

Table 1: Site block types defined in AGI Safe

Category	Site Block Types
Equipment	Condensate Storage Area, External Compressor Cab Inlet, External Compressor Cab Outlet, Filter Unit, Fuel Gas Metering Unit, Inlet Pipeline Area, Interconnecting Pipeline, Outlet Pipeline Area, Pig Trap Area, Pre-Heating Unit, Pressure Reduction Unit Inlet, Pressure Reduction Unit Outlet, Scrubber Unit, Site Metering Unit
Congested Explosion Regions	Aftercooler, Piperack
Confined Explosion Regions	Compressor Cab (five types), Kiosk, Leak-Free Enclosure

Site blocks are positioned with the aid of a site map (the map is also used for defining areas of particular interest where the effects of the release scenarios are to be measured and for visualising results).

Figure 1 shows a screenshot of the ‘Equipment Definition’ screen in the AGI Safe package for an example site, together with its associated site map; the site blocks defined for the site are listed in the table and shown on the site map.



Type of Area or Unit: Site metering unit
Type of release: Above Ground
Operating Information
Pressure (barg): 80.000
Diameter (mm): 914.4
Length (m): 25.000
Unit Footprint
X size (m): 13.000
Y size (m): 5.000
Orientation: 320.0
Name: SiteMet
Number of items: 1
X coord (m): 1394.4
Y coord (m): 1199.1
Z coord (m): 1
Total number of blocks is 22.

Name	X (m)	Y (m)	Z (m)	Block Type	It
DischA	1454.2	1236.7	1.00	Cab External Outlet	
DischB	1442.7	1222.9	1.00	Cab External Outlet	
DischC	1431.2	1209.2	1.00	Cab External Outlet	
HazardsA	1458.7	1238.1	0.00	Compressor cab	
HazardsB	1447.2	1224.4	0.00	Compressor cab	
HazardsC	1435.7	1210.6	0.00	Compressor cab	
Inlet	1426.7	1190.9	1.00	Inlet pipeline area	
Outlet01	1415.1	1249.6	1.00	Outlet pipeline area	
Outlet02	1397.8	1225.0	1.00	Outlet pipeline area	
PigIn	1420.9	1195.1	1.00	Pig trap area	
PigOut1	1420.8	1245.2	0.00	Pig trap area	
PigOut2	1404.5	1223.5	0.00	Pig trap area	
SuctA	1459.4	1242.8	1.00	Cab External Inlet	
SuctB	1447.8	1229.0	1.00	Cab External Inlet	
SuctC	1436.3	1215.3	0.00	Cab External Inlet	
FilterA	1451.0	1244.3	1.00	Filter unit	
FilterB	1439.5	1230.6	1.00	Filter unit	
FilterC	1428.0	1216.8	1.00	Filter unit	
FuelGA	1447.9	1247.0	1.00	Fuel gas metering unit	
FuelGB	1436.3	1233.2	1.00	Fuel gas metering unit	
FuelGC	1424.8	1219.5	1.00	Fuel gas metering unit	
SiteMet	1394.4	1199.1	1.00	Site metering unit	

Figure 1: Site block definition using AGI Safe

The package has been pre-populated with complete site definitions for twenty six National Grid sites, which can be modified and duplicated as required, but site definitions for further sites can also be created by the user.

Site definition data for all sites, including maps, is stored in a single database, rather than across multiple files for different sites, enabling easier auditability.

Monitor Point and Population Definition

AGI Safe also allows the user to define areas of particular interest (both on- and off-site) known as 'monitor points', where the effects of any failure scenario can be measured. Monitor points are usually used to define areas of human population, such as on-site control buildings, nearby houses, businesses and schools etc. In addition, AGI Safe automatically generates monitor points for all site blocks to enable escalation between equipment items to be assessed; further monitor points can also be used to identify other items of safety critical equipment which might be damaged in the event of an accidental release, such as ESD valves or firewater pumps.

AGI Safe is able to recognise that the population of a certain area or building will change over time. The user can input varying population data for each point for a period of time usually measured as a proportion of one week. The user is also able to input population information for road and rail networks with a high level of detail using traffic data or rail timetable information (if relevant to the site in question). AGI Safe can then be used to assess the probability of specific equipment failures on-site, and the potential effect each failure would have on the surrounding population producing an accurate picture of the societal risk posed by the site.

Modelling

AGI Safe performs gas outflow calculations for each scenario; many separate release 'realisations' are modelled to account for different possible combinations of release direction, release location, ignition time, wind speed and wind direction. For each realisation, consequence modelling is performed for one or more of the following hazard types: jet fires, flash fires, fireballs and explosions (the particular hazard types modelled are determined by AGI Safe based on the nature of the equipment item, the results of the outflow modelling and whether the release is ignited immediately or whether delayed ignition occurs), to calculate the physical effects of each hazard, in terms of thermal radiation or explosion overpressure experienced at different parts of the site.

The results of the consequence modelling are used as inputs to the risk modelling, where various measures of risk to individuals and populations on the site and in the area surrounding the site are calculated.

Results Reporting and Visualisation

The modelling generates standard risk assessment outputs, such as maximum hazard distances, location specific risks (LSRs), individual risks (IRs), societal risks (such as 'potential loss of life' (PLL) and F-N curves). Other output types also include hazard level exceedance frequencies (i.e. the frequency at which a particular thermal radiation or explosion overpressure level is predicted to be exceeded at a particular location) and firewater requirements.

All relevant consequence and risk modelling results are saved to a 'risk database' during scenario run execution; as such, it is not necessary for the user to specify which particular results types are to be recorded before commencement of run execution (this removes the risk of having to re-run scenarios to obtain a particular type of result which was not originally specified).

The risk database can be interrogated within the AGI Safe package to report and visualise a wide range of results. This can be done immediately after scenarios have been run, or in another AGI Safe session at a later time.

As well as presenting results values in tabulated format, results can be visualised in a range of graphical ways, including contour plots, exceedance curve plots, F-N curve plots and 'escalation matrices' (described later).

Example Usage

Examining the Impact of Site Layout Changes

The package can be used to assess the impact of potential site layout changes on the risk to on-site and off-site populations, e.g. when installing a new compression train in a new location and decommissioning the existing compression system. A risk assessment can be performed for the existing site layout to calculate the current (baseline) risk levels, followed by one or more sensitivity studies where the locations and parameters of certain equipment items are modified (or equipment items are added or removed altogether) in different ways. Multiple versions of a site can be stored in the database, as a record of options that have been assessed. Various measures of location specific and societal risk can be reported and plotted, and these can then be compared for the baseline and sensitivity cases to understand the impact of the site layout changes. Typically, this could involve comparing on-site and off-site LSR contours, PLL totals and F-N curves.

Assessing Siting of Temporary Buildings

It is often necessary to construct temporary buildings at compressor stations and AGIs during construction or maintenance campaigns. Functionality enabling National Grid to assess the suitability of potential locations for temporary buildings has been incorporated into AGI Safe, using a methodology developed to be consistent with HSE land use planning (LUP) guidance (HSE, 2016 (1)); this aims to align with the (more stringent) criteria for the siting of off-site buildings frequented by the general public. The methodology uses a set of criteria based on the 'dangerous dose' concept from the LUP guidance, which is more conservative than the criteria used to assess existing buildings (i.e. risk of death). The dangerous dose criteria represent the following effects:

- Severe distress to all,

- Substantial number require medical attention,
- Some require hospital treatment,
- Approximately 1% fatalities.

These effects have been translated into harm criteria for people inside, which are evaluated by AGI Safe during the consequence modelling. Harm criteria have also been chosen for people outside the building, since it is almost inevitable that people working inside the building will be exposed to outdoor risks to reach the building. The frequency of an individual exceeding these harm criteria, taking account of the time that they are in the building, is summed for all scenarios in the risk assessment. National Grid apply two dangerous dose criteria to define where a temporary building can be sited: locations with a frequency greater than an upper threshold can only be used in exceptional circumstances; locations with a frequency smaller than a lower threshold can be used without further assessment; locations between the two thresholds may be considered suitable following application of ALARP considerations. To assist with assessing the suitability of potential on-site temporary building locations, these exceedance frequencies can be visualised in AGI Safe in the form of a contour plot superimposed over a site map.

Fire Risk Assessments

Background

This Section describes the development of a methodology to assess the frequency of escalation due to thermal radiation in more detail.

Fire Risk Assessments (FRAs) of proposed and existing sites frequently include information about the likelihood of escalation occurring, that is, of a small release in one area of the site causing a larger release such as a pipeline rupture or catastrophic vessel failure on another part of the site.

The criteria for escalation due to fire are often based on a particular thermal radiation level being exceeded for a specified time. A value of 37.5kW/m^2 is often quoted as the threshold above which thermal radiation can cause damage to process equipment (World Bank, 1985), and the frequency of this radiation level being exceeded for more than 10 minutes is sometimes required in FRAs. It is relatively simple to predict whether this criterion is exceeded for an individual realisation, and then by combining the predictions for all of the realisations in a risk assessment it is possible to estimate the frequency with which it is exceeded on targets of interest.

There are potentially some issues with these radiation duration criteria. Firstly, there can be problems for time varying radiation. For example, 300 kW/m^2 (typical of flame impingement) for 9 minutes followed by a negligible radiation would not exceed the criterion, but 40 kW/m^2 for 11 minutes would exceed it. However, the former is probably more likely to cause escalation than the latter. Secondly, they do not take account of the design of the equipment that might be damaged. For example, thicker walled vessels or pipelines operating at a lower pressure may be less likely to fail due to thermal radiation than thinner walled vessels or pipelines operating at a higher pressure.

The AGI Safe package calculates the possibly of transient thermal radiation being experienced at more than a thousand locations for each realisation. A typical assessment will contain more than a million realisations, so using criteria that are time consuming to calculate could result in excessively long run times.

Several models exist for evaluating more complex criteria, including the DNV GL model FIBRE (Schleyer, 1993) or the Vessfire model (Petrell, 2016). These models can take account of heat transfer to the contents of vessels or pipelines, de-pressurisation and many other factors, and they are typically used to carry out tens or hundreds of calculations for specific cases, but they would not be appropriate for the billions of cases considered by a risk assessment package. Therefore, a simpler model has been implemented that is capable of taking into account the transient nature of the head load and the design of the equipment but does not result in excessive calculation times.

Metal Heat-Up Model

To investigate the possible issues with radiation based criteria, a simple metal heat-up model was implemented in AGI Safe. The predicted temperature of the metal can then be used to assess whether escalation is likely to occur. The governing equation used in this model is

$$MC_{\mathrm{P}}\frac{dT}{dt} = Q_{in}(t) - Q_{out} \qquad (1)$$

Where

M = steel mass per unit area

T = steel temperature

t = time

$\mathrm{C_P}$ = specific heat of steel

$Q_{in}(t)$ = incident radiation, which may vary with time

Q_{out} = emitted radiation

Here the emitted radiation is given by:

$$Q_{out} = \varepsilon\sigma\left(T^4 - T_{Amb}^4\right) \tag{2}$$

Where

ε = Emissivity of steel

σ = Stefan-Boltzmann constant

T_{Amb} = ambient air temperature

This equation accounts for radiative heat transfer, but neglects convection and conduction.

The predictions of this model have been compared to the DNV GL model FIBRE (Schleyer, 1993). FIBRE is a more complicated model which takes account of both convective and radiative heat fluxes, and can account for other features such as heat transfer to the flowing contents of the pipeline.

A comparison of the predictions of FIBRE and the simplified model is shown below, for 17.5mm thick steel exposed to a constant thermal radiation of 37.5 kW/m^2. It is noted that for an ambient temperature of 10ºC the steady state solution of equation (3) for a constant thermal radiation of 37.5kW/m^2 is 655 ºC.

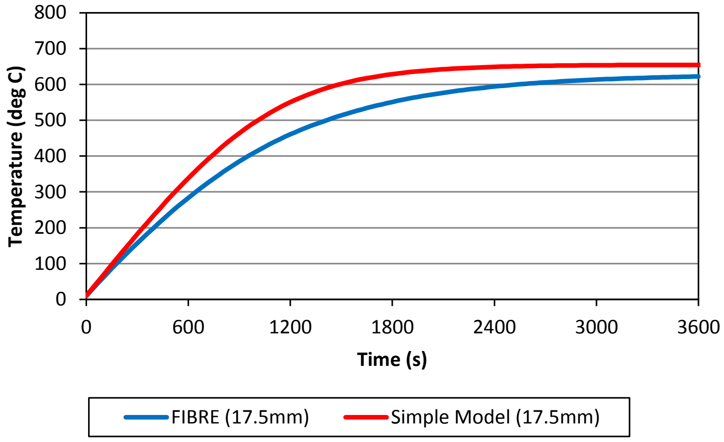


Figure 2: Steel temperature rise with a constant radiation in of 37.5kW/m^2

This suggests that the temperatures predictions of the simplified model are cautious. It takes around 30 minutes for the temperature to approach a steady state. This suggests that the incident thermal radiation between 10 and 30 minutes has the potential to influence whether a failure occurs, which would not be accounted for by a criteria based on the radiation after 10 minutes.

It has been suggested in offshore guidelines (Oil & Gas UK, 2007) that 400ºC is an appropriate temperature to use in a screening assessment of the effects of thermal radiation on structures. These guidelines suggest that at 400ºC the yield strength is 60% of the value at ambient temperatures. Since standards typically allow operation at a tensile stress of 60% of the yield strength, this is a convenient value to use. Other sources (OGP, 2010) suggest using metal temperatures around 600ºC as a failure criterion for onshore equipment. The 'Green Book' (TNO, 1992) gives the same temperatures and suggests that:

> "The failure temperature is dependent on the load, and for a conventionally dimensioned steel element, its value lies between 673 and 873K"

Based on this information, four generic failure criteria have been implemented in AGI Safe, the frequency of 10mm and 25mm thick steel exceeding 400 ºC and 600 ºC. The former temperature is intended as a cautious criterion, the latter as a more realistic criterion. Failure temperatures for specific metal equipment are discussed in the next Section. The frequencies of these generic criteria being exceeded are calculated in all AGI Safe risk assessments. A separate 'Equipment Response' assessment can also be carried out, which can include site specific criteria and this is described in the following Section.

Equipment Response Assessment

The equipment response assessment allows the user to specify additional details about any metal equipment which might be exposed to thermal radiation. The failure temperature of a pipeline can be calculated if its material grade, wall thickness, diameter and operating pressure are known. The burst pressure of a pipeline is given by (Schleyer, 1993)

$$P_{Burst} = \frac{\sigma_{Yield}}{\sqrt{3}}\left(1+\frac{\sigma_{UTS}}{\sigma_{Yield}}\right)\ln\left(\frac{D_{Outer}}{D_{Inner}}\right) \quad (3)$$

Where

P_{Burst} is the burst pressure

σ_{Yield} is the yield stress of the metal

σ_{UTS} is the ultimate tensile stress of the metal

D_{Outer} is the outer diameter of the pipeline

D_{Inner} is the inner diameter of the pipeline

σ_{Yield} and σ_{UTS} depend on the temperature of the metal, and in AGI Safe they are based on the material grade specified by the user.

Example results are shown below for a small and large diameter pipe, both of which have an MOP (maximum operating pressure) of 90 barg. Results are given for operating pressures of 40 barg and 70 barg.

Table 2: Failure temperatures of two pipelines

Material Grade	Nominal Diameter (mm)	Wall Thickness (mm)	Failure Temperature at 40 barg (°C)	Failure Temperature at 70 barg (°C)
X60	600	17.5	781	663
X65	1050	23.8	702	640

When the pipeline is operating closer to its MOP the failure temperature is only slightly above the 600°C identified as a typical onshore value, but when the operating pressure is significantly lower the failure temperature is higher. It is also worth noting that for a pipeline on an elevated piperack, escalation can be caused by the failure of supporting structures as well as by failure of the pipeline itself. A simple steel thickness and failure temperature criterion can be specified in an equipment response assessment to account for this situation. These criteria are in addition to the pipeline failure criteria.

Worked Example

A very simple, idealised example site has been constructed, which consists of six blocks: an inlet and outlet pipeline, the inlet and outlet of a pressure reduction station (PRS) and two lengths of above ground pipeline. The site is shown below. The figure also shows the location of a transect through the site which will be used later to demonstrate the variation of risks on the site.

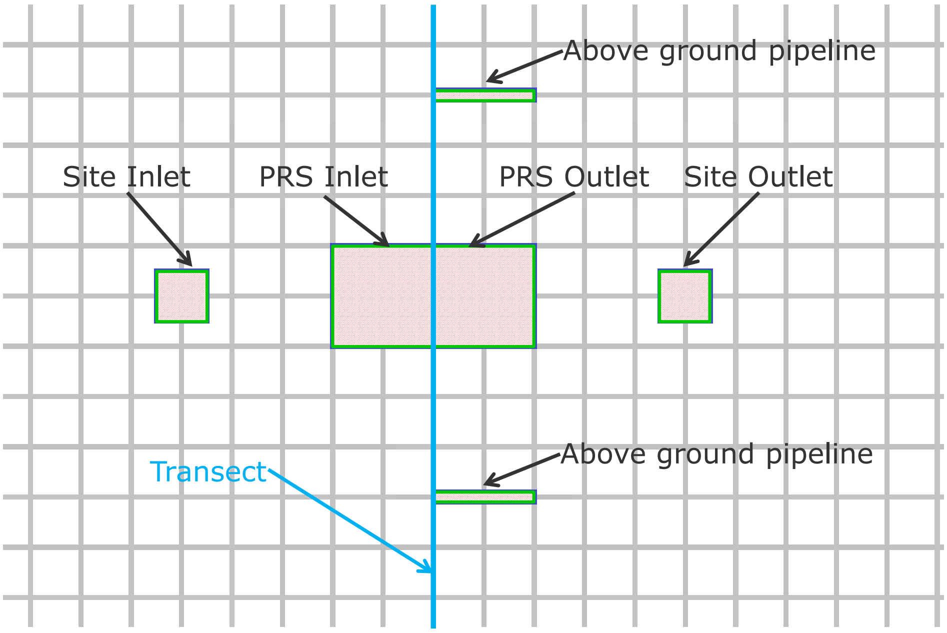


Figure 3: Example Site

The frequency of exceeding 37.5 kW/m^2 and the frequency of a 10mm thick piece of metal exceeding 600ºC, one of the generic criteria, have been calculated on the transect through the centre of the site, for steady continuous leaks on the PRS inlet and outlet only. Calculations have also been carried out for the frequency of the 600mm pipeline failing while operating at 70 barg. The results are shown in Figure 4.

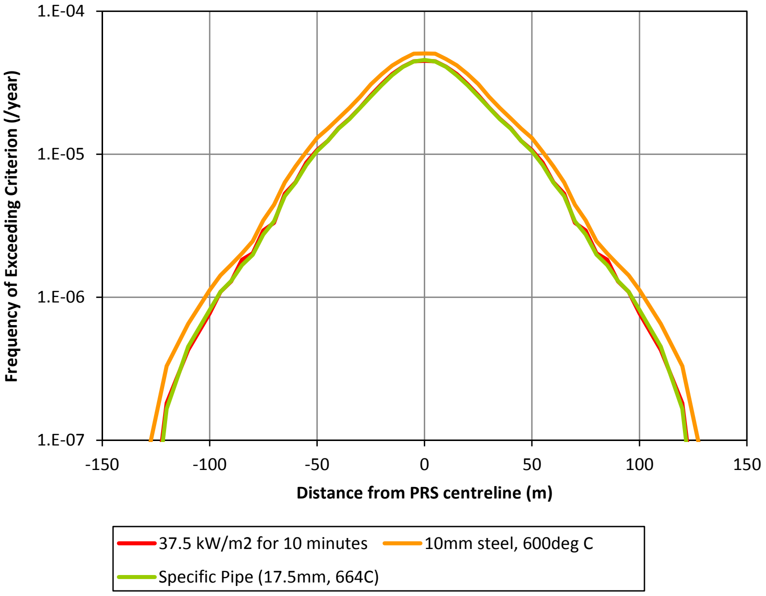


Figure 4: Predicted escalation frequencies on a transect running through the centre of the site, for 3 criteria

This suggests that for steady continuous releases the proposed generic criterion of a 10mm thick piece of steel exceeding 600ºC is slightly more cautious than the radiation based criterion of 37.5kW/m^2 for 10 minutes. Using the actual pipeline thickness, and the failure temperature for the specific material grade and operating pressure in the metal heat-up model gives frequencies that are almost identical to the radiation criterion. This is not always the case, as will be shown when transient effects are considered in the next Section.

Figure 5 shows contours of the frequency of exceeding the criterion for the specific pipeline, that is, a 17.5mm piece of steel exceeding 664ºC. The predictions are for steady continuous leaks on the PRS inlet and outlet only.

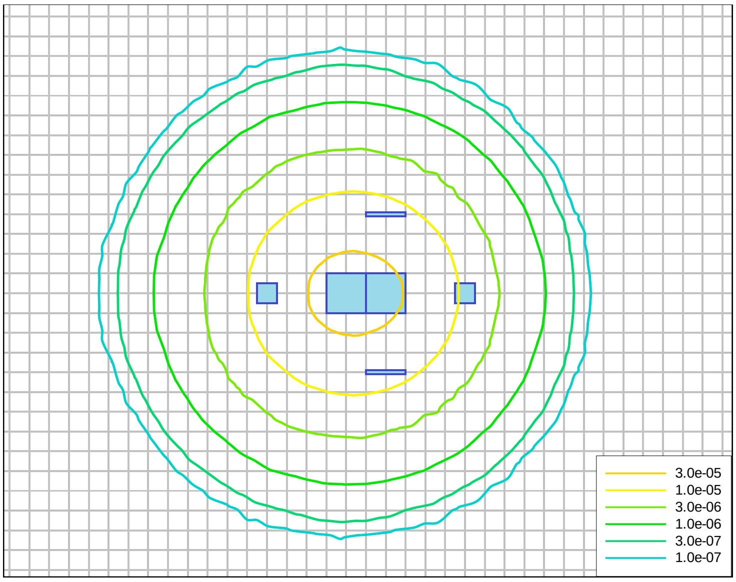


Figure 5: Contours of the failure frequency for a 600mm, X60 pipeline with a wall thickness of 17.5mm

The PRS inlet has a higher release frequency due to a larger parts count and higher ignition probabilities and larger hazard distances due to the higher operating pressure. As a result, the predicted risks are higher on the Western side of the site.

This shows that the above ground pipeline to the North of the PRS is most likely to undergo an escalation close to its Western end, with a frequency of 1.51 x 10^{-5} per year. In a Fire Risk Assessment which considers asset damage, the frequency of a failure at any point on the pipeline is of interest. The AGI Safe package automatically generates nine monitor points on the above ground pipeline, and by summing the frequencies of realisations where one or more monitor points exceed the escalation criterion, the overall frequency of a failure of the above ground section of pipeline can be assessed. Using this method, the overall frequency of a failure at any point on the pipeline is predicted to be 1.86 x 10^{-5} per year.

Isolation and Depressurisation

The calculations above are based on a steady, continuous release from the PRS equipment, and it is assumed that the pipeline continues to operate at 70 barg. In practise, if the fire is detected then action could be taken to isolate the PRS, which would limit the duration of the release, or to isolate and blowdown the pipeline, which would reduce the pressure in the pipeline and hence increase the temperature at which it would fail.

If transient radiation predictions have been made as part of a risk assessment, then equation (1) can be solved to predict the metal temperature for the transient incident radiation. Example calculations taking account of isolation and blowdown have been carried out for the above ground pipeline considered in the previous Section. Two incident thermal radiation fields have been modelled for a location approximately 30m downstream and 20m cross stream of a 50mm diameter horizontal natural gas jet fire. The first is for a steady, continuous release, which gives a constant radiation of 60kW/m^2. The second is for a steady release for 600 seconds, followed by isolation of a section with a volume of 50m^3 which gives a decaying release lasting for a further 550 seconds. The jet fire model is used to predict the radiation at seven times during the decay of the release, to provide the transient thermal radiation predictions used by the metal heat-up model. The time variation of the predicted temperature for the two cases is shown in Figure 6.

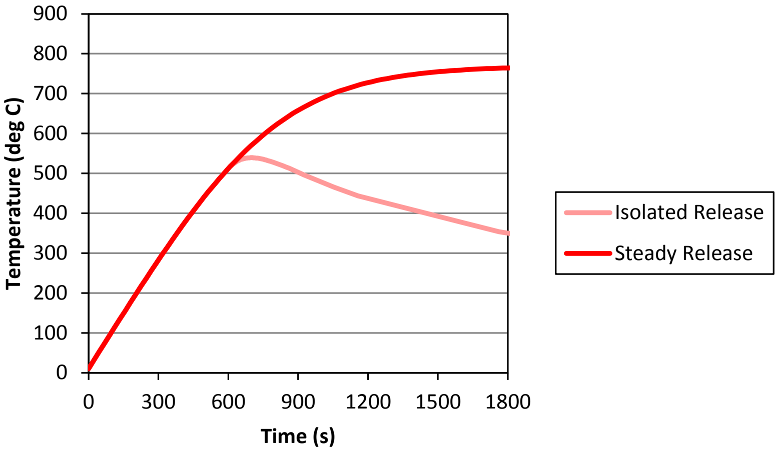


Figure 6: Predicted temperature of the pipeline for a steady state and a transient fire

The depressurisation of the above ground pipeline can be accounted for by estimating the decaying pressure within the pipeline, and hence the increase in the temperature at which it fails. The venting systems on National Grid's compressor stations usually have a fixed flow rate, to control the noise levels from the vent. Predictions with a transient outflow model show that venting at a fixed flow rate results in an approximately linear decrease in the pressure in the isolated section. This effect has been incorporated in the metal heat-up model. Calculations have been carried out for the case where the pipeline is isolated 600 seconds after the start of the fire, and then completely depressurised in the next 1000 seconds. This is consistent with the venting rates discussed in API 521 (API, 2014), where depressurisation to 6.9 barg within 900 seconds is suggested.

Figure 7 shows the variation of the operating pressure of the pipeline and the failure pressure of the pipeline with time. The failure pressure is calculated from the predicted temperatures shown in Figure 6.

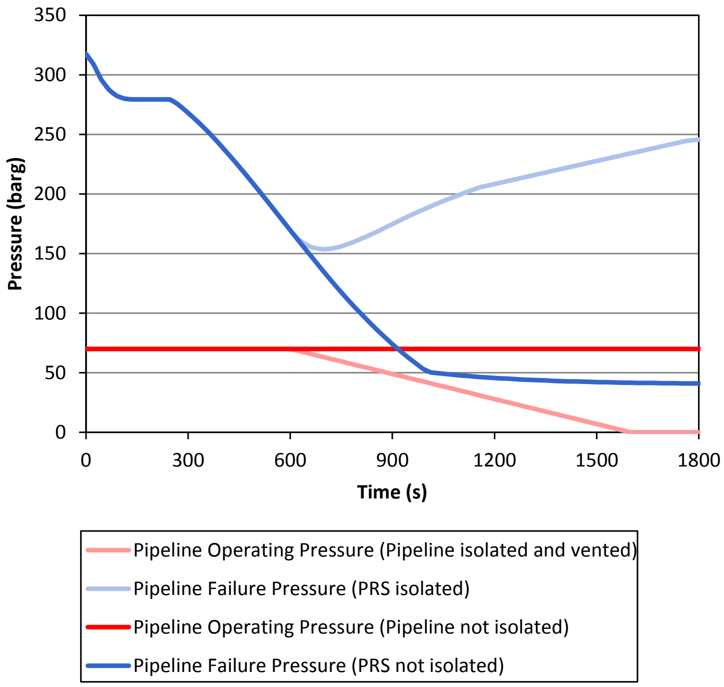


Figure 7: Predicted pipeline pressure and failure pressure with and without isolation

For this example, the pipeline is predicted to fail if neither the pipeline nor the release is isolated (at 920 s when the two 'not isolated' curves cross). However, if the release from the PRS is isolated or the pipeline is isolated and blown down, the pipeline will not fail. In this instance, isolating the source of the leak only gives a failure pressure which exceeds the operating pressure by more than 80 barg, whereas if only the pipeline is isolated and blown down, the failure pressure exceeds the operating pressure by less than 10 barg after 1000 seconds. Since the isolation is assumed to occur 10 minutes after the start of the release, the 10 minute thermal radiation would be the same for all of these cases, so a criterion based on the incident thermal radiation after 10 minutes would be unable to differentiate between them.

This example demonstrates that isolation and venting at 10 minutes can affect whether escalation occurs for an individual realisation. To investigate whether differences in individual realisations can have a significant effect on the overall failure frequency of the pipeline, the risk assessment model has been run to assess the potential for a leak on either side of the PRS to cause a failure on the above ground pipeline. Five cases have been modelled for the PRS, which is assumed to have an isolated volume of 50m^3, as follows:

- Steady continuous release,
- Isolation 10 minutes after the start of release,
- Isolation 10 minutes after the start of release, followed by blowdown,
- Isolation 90 seconds after the start of release,
- Isolation 90 seconds after the start of release, followed by blowdown.

Three cases have been modelled for the pipeline

- Continuous operation at 70 barg,
- Isolation 10 minutes after the start of release, followed by blowdown,
- Isolation 90 seconds after the start of release, followed by blowdown.

The blowdown is assumed to be at a constant rate which would completely depressurise the isolated equipment in 1000 seconds if there was no accidental release. As an illustration, the combined outflow from a 50mm diameter hole and this blowdown rate would completely depressurise the PRS in 260 seconds.

The predicted escalation failure frequency of the pipeline in these cases is shown in Figure 8.

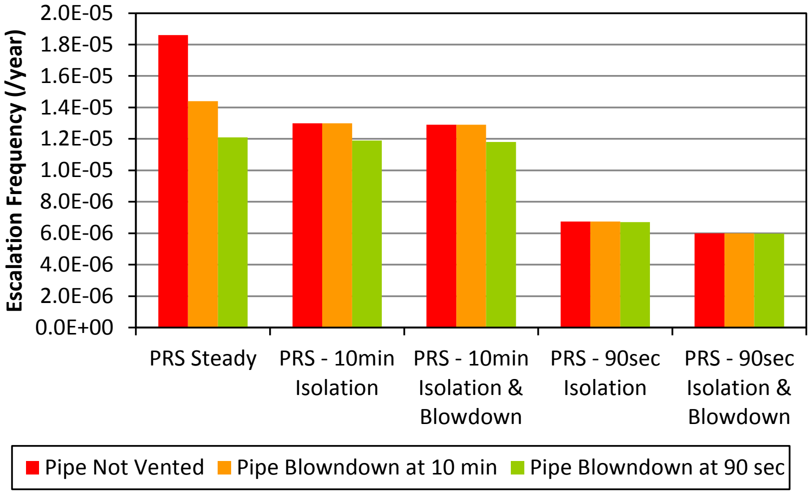


Figure 8: Predicted frequency of an escalation failure on the above ground pipeline due to a leak on the PRS for different isolation times and with blowdown

This shows that the isolation and venting of both the equipment where the release occurs and the equipment exposed to the incident radiation can affect the frequency that escalation is predicted to occur. For comparison, the frequency of exceeding two radiation based criteria, 37.5 kW/m^2 at any time or 37.5 kW/m^2 for more than 10 minutes is shown in Figure 9.

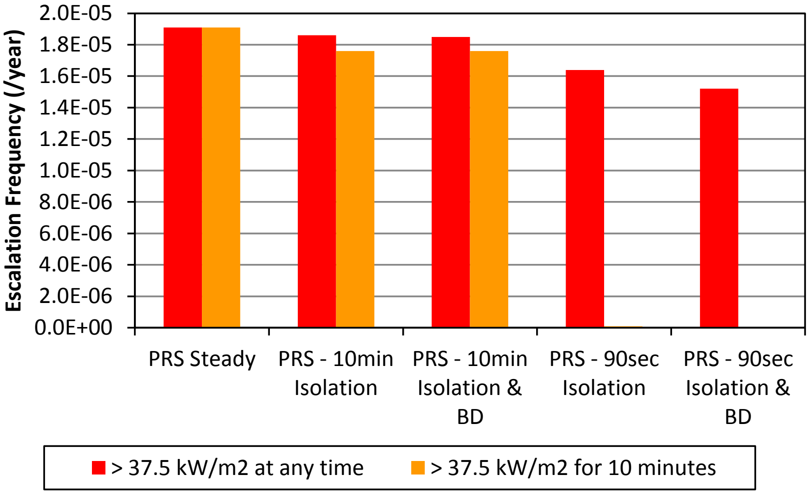


Figure 9: Predicted frequency of an escalation failure on the above ground pipeline due to a leak on the PRS for different isolations and depressurisations

For the case where the PRS is isolated after 90 seconds, the criteria based on the radiation after 10 minutes suggests that there would be no failures of the pipeline, whereas the metal heat-up model suggests that the failure frequency will be approximately one third of that predicted for a steady release.

The metal heat-up model can also be used to examine the effect of the pipeline wall thickness and operating pressure on the predicted failure frequency. Some example results are shown in Figure 10.

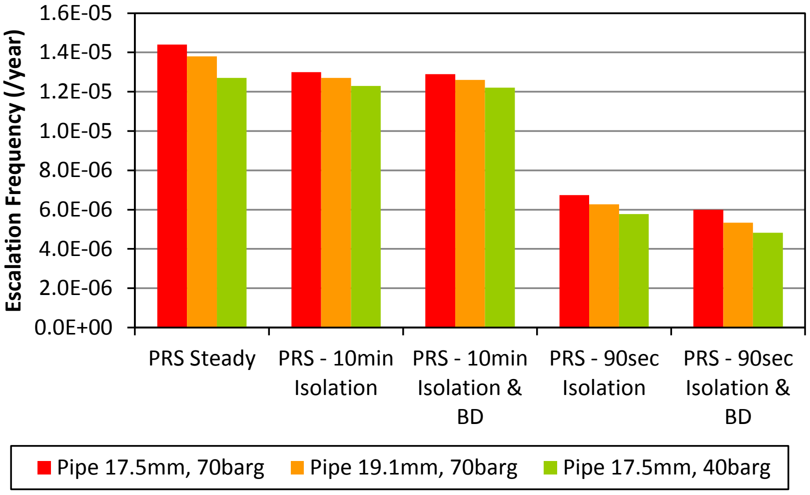
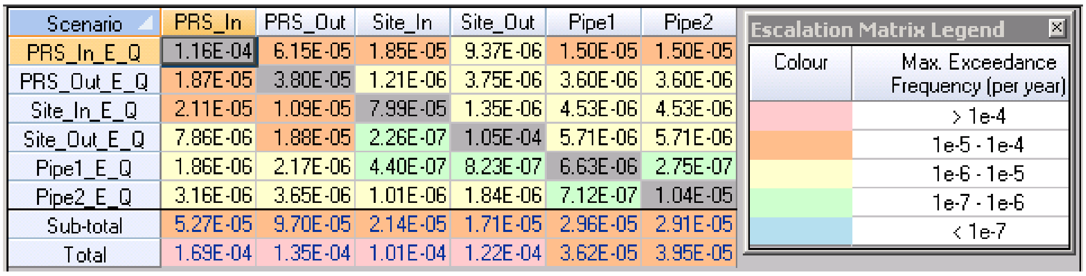


Figure 10: Predicted frequency of an escalation failure on the above ground pipeline due to a leak on the PRS for different pressures and wall thicknesses. All predictions assume that the pipeline is isolated after 10 minutes, and depressurised in 1000 seconds.

The predicted failure frequencies are lower for the thicker walled pipeline, and for a pipeline operating at a lower pressure. This enables different risk reduction options, such as installing thicker walled pipe, faster isolation and faster de-pressurisation to be compared.

Escalation Matrix

The example above considered the effect of a release from the PRS on one of the site pipelines. In an FRA, the interaction between all pairs of equipment blocks needs to be considered. The package has been designed to present the results in the form of a colour coded matrix, as shown in Figure 11.



Scenario	PRS_In	PRS_Out	Site_In	Site_Out	Pipe1	Pipe2
PRS_In_E_Q	1.16E-04	6.15E-05	1.85E-05	9.37E-06	1.50E-05	1.50E-05
PRS_Out_E_Q	1.87E-05	3.80E-05	1.21E-06	3.75E-06	3.60E-06	3.60E-06
Site_In_E_Q	2.11E-05	1.09E-05	7.99E-05	1.35E-06	4.53E-06	4.53E-06
Site_Out_E_Q	7.86E-06	1.88E-05	2.26E-07	1.05E-04	5.71E-06	5.71E-06
Pipe1_E_Q	1.86E-06	2.17E-06	4.40E-07	8.23E-07	6.63E-06	2.75E-07
Pipe2_E_Q	3.16E-06	3.65E-06	1.01E-06	1.84E-06	7.12E-07	1.04E-05
Sub-total	5.27E-05	9.70E-05	2.14E-05	1.71E-05	2.96E-05	2.91E-05
Total	1.69E-04	1.35E-04	1.01E-04	1.22E-04	3.62E-05	3.95E-05

Escalation Matrix Legend

Colour	Max. Exceedance Frequency (per year)
🟥	> 1e-4
🟧	1e-5 - 1e-4
🟨	1e-6 - 1e-5
🟩	1e-7 - 1e-6
🟦	< 1e-7

Figure 11: Escalation matrix, showing interaction between each pair of equipment

The 'own goals', where a leak on an equipment block exceeds the criterion to cause escalation on itself, are indicated in grey on this matrix, and totals are shown which include and exclude the 'own goals'. It might be appropriate to include these when assessing the risks to people, but for the purposes of asset protection, or estimating the frequency of a site being unable to operate, further damage to equipment that is already releasing gas is of less interest.

Conclusions

The AGI Safe package has been produced to assess the risks from National Grid's compressor stations and AGIs. Descriptions of many sites can be stored in a single database, and the package is supplied with descriptions of over 20 sites. AGI Safe assesses a set of pre-defined scenarios for each type of equipment block. This significantly reduces the effort required to carry out an assessment, and ensures consistency when comparing the risks from different sites, or for different design options for a new site.

A simplified metal heat-up model for calculating the temperature of metal equipment has been developed and implemented in AGI Safe. This can be combined with information about equipment parameters such as material grade and operating pressure to predict whether equipment will fail due to incident thermal radiation. Isolation and blowdown can also be accounted for. The model is sufficiently simple that it can be run billions of times within a risk assessment.

For realistic pipeline parameters and steady continuous releases, the methodology predicts similar failure frequencies to the commonly used criterion of exceeding 37.5 kW/m^2, either as a maximum or for 10 minutes. However, the new methodology is able to account for the design, operation, isolation and blowdown of the equipment that is subjected to thermal radiation. The model can also account for a transient incident thermal radiation, which will depend on the isolation and blowdown of the equipment where the release occurs. These features can be useful when comparing risk reduction options or in a risk ranking exercise, and the methodology provides a useful intermediate step between the use of a radiation based criterion within a risk assessment, and carrying out a smaller number of very detailed calculations.

The sites which are included in the AGI Safe package handle dry natural gas only. The heat-up model might require further development before being applied to sites handling liquids, to avoid misleading results when comparing equipment containing gas and liquid. A more sophisticated heat-up model which accounts for the differences between radiative and convective heat transfer would give less cautious predictions for events where flame impingement occurs. On manned sites with automatic isolation and blowdown systems linked to fire or gas detection, the isolation times are likely to be short, and events causing flame impingement are likely to dominate the escalation frequencies; as such, the current heat-up model might be overly cautious for these sites. However, for the unmanned sites included in the AGI Safe package this is less of an issue.

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