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PROPOSAL – JOINT INDUSTRY PROJECT (JIP)

FLACS-Fire

CFD Modelling & QRA Methodology

Client

Multi-sponsored project

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Document Info

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Title
FLACS-Fire: CFD Modelling and QRA Methodology

Extract
GexCon invites potential sponsors to participate in the development of the latest addition to the FLACS family of software products: *FLACS-Fire*. The area of application for the new software will be computational fluid dynamics (CFD) simulations of hydrocarbon fires in congested environments with varying degree of confinement. FLACS-Fire will be based on the existing CFD tool FLACS, but state-of-the-art models will be implemented for describing large-scale jet and pool fires in complex geometries, including escalating accident scenarios involving both fires and explosions. Of particular importance will be the development of methodologies for performing quantitative risk assessments (QRAs) related to fire hazards in the petroleum industry. The intention is to establish a four-year Joint Industry Project (JIP) where industry partners get the opportunity to take part in and influence the development process, and gain access to beta-releases as well as final commercial releases of FLACS-Fire. The project will create an arena for competence building amongst the participants.

Project Info

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Multi-sponsored project	
GexCon Project No.	GexCon Project Name
46250	FLACS-Fire – Modelling and QRA Methodology

Revision

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Introduction

Accidental fires represent a significant hazard to people, property and the environment. The potential consequences of hydrocarbon fires on offshore installations were clearly demonstrated by the Piper-Alpha disaster in 1988, and more recently by the Deepwater Horizon disaster in 2010. Experimental investigations of large-scale fire phenomena are inherently expensive, and extrapolation from experimental results is generally not suitable for site-specific safety studies.

Numerical simulations represent an attractive alternative to experiments and empirical correlations, provided the implemented models are able to capture the key physical phenomena sufficiently well. Realistic fire modelling should describe the complex interaction between turbulent flow, buoyancy, convection, entrainment of air, non-premixed combustion, soot formation, thermal radiation, fluid-structure interaction, dispersion of smoke and toxic combustion products, effect of mitigating measures, etc.

Fire models are often divided in two main categories: zone models and models based on computational fluid dynamics (CFD). Zone models divide the system in two parts, and analyse fire related parameters in hot and cold layers. This approach is limited to simple scenarios, and generally not suitable for the complex geometries found on typical offshore platforms or other facilities in the process industry. CFD models, on the other hand, divide the computational domain into smaller elements, or cells, and solve conservation equations for mass, momentum and energy for each cell. This approach has the potential to predict 3D transient fire scenarios, including heat loads, smoke/visibility and toxic exposure with reasonably good precision. The use of CFD for modelling fire and explosion phenomena is gaining increased popularity as modern computers become increasingly powerful.

The aim of JIP 'FLACS-Fire – Modelling & QRA Methodology' is twofold: FLACS-Fire will be developed into a robust state-of-the-art CFD tool for fire simulations, and methodology for a new *de facto* industry standard for quantitative risk assessment (QRA) related to fire hazards in the petroleum industry will be developed.

Why FLACS-Fire?

The main motivation for developing FLACS-Fire is the increased demand for fire studies, in particular probabilistic fire risk assessments, in the oil and gas industry. According to ISO19901:3 [1], offshore oil and gas installations shall evaluate the accidental risk from explosions and fires, and whenever a worst-case approach is not feasible, it should be demonstrated that the frequency for escalation or loss of main safety barrier is less than once every 10,000 years. Similar requirements are indicated in NORSOK Standard Z-013 (2010) [2], where Appendix E (currently blank) is supposed to describe procedures for how to perform probabilistic fire studies.

There are several software packages for CFD modelling of fire-related phenomena, both commercial and open source. FireFOAM, Fire Dynamics Simulator (FDS), Kameleon FireEx KFX and SmartFire are examples of special-purpose software, whereas ANSYS CFX/FLUENT, STAR-CCM+ from CD-Adapco and PHOENICS are general-purpose CFD software. Despite the fact that there exist other CFD tools for fire simulations, there are good reasons for developing fire capabilities in FLACS:

- FLACS is a commercial CFD tool that is widely used in the process industry, and well recognized by major oil companies and authorities.
- FLACS is user-friendly and efficient compared to most other CFD-tools.
- FLACS represents geometry on a structures a Cartesian grid by the so-called distributed porosity concept. Large objects and walls are resolved on the grid, whereas flow resistance, turbulence generation and flame folding due to smaller objects are represented by sub-grid models.
- FLACS has been extensively validated for explosion and dispersion studies in petrochemical facilities, and the same emphasize on validation will be employed for FLACS-Fire.
- Existing FLACS users will be able to use the same geometry models for dispersion, explosion and fire simulations.
- Existing FLACS users will get a significant discount on the fire simulator.
- For experienced FLACS users there will be limited need for additional training.

GexCon has worked on FLACS-Fire since 2005, and several key building blocks are already in place (Figure 1):

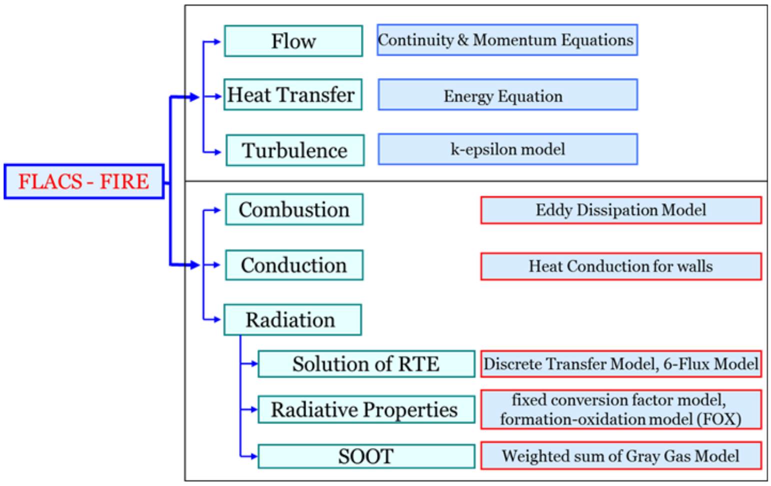

Figure 1: Key building blocks of FLACS-Fire already implemented

FLACS has primarily been developed for modelling dispersion and explosion phenomena, but models for simulating industrial jet and pool fires have been under development for some time. Although the initial validation work shows promising results for simple jet and pool fires, the model system must be further developed and validated before FLACS-Fire can be used with confidence for describing large-scale fire scenarios in industry.

Since the real-time duration of typical fire scenarios is orders of magnitude longer than for explosions, computational speed becomes a key factor. The new software will benefit from recent improvements to FLACS, including the parallelized non-compressible solver that will be released in 2012.

Objectives:

The aim of the JIP is to develop FLACS-Fire to become an advanced tool for fire modelling in the process industry, and to establish QRA methodology for risk assessments related to fires.

The development of FLACS-Fire has following specific objectives:

1. To develop a robust, efficient and accurate simulator for jet and pool fires.
2. To upgrade the pre-processor CASD and post-processor Flowvis to support fire simulations.
3. To develop fire-specific models that can support efficient risk assessment, including models for radiative heat loads, soot production, smoke dispersion and visibility, and models for mitigation methods like sprinklers and passive fire protection.
4. To perform extensive validation of FLACS-Fire against experiments.

There are numerous research problems related to fire modelling, and this project will focus on specific issues of immediate relevance to turbulent non-premixed flames in complex geometries.

Intended use:

Although FLACS-Fire primarily will be developed to solve industrial fire problems in the oil and gas industry, the code will also be used as a tool for studying fundamental phenomena related to fire dynamics, such as:

- Jet and pool fires in petrochemical process plants, under varying atmospheric conditions.
- Confined or unconfined fires in congested geometries.
- Radiative and convective heat transfer to solid objects.
- Distribution of smoke and toxic products

The development of FLACS-Fire will represent a significant economic benefit to the oil and gas industry, as well as to the society. FLACS-Fire will make CFD simulations of fire scenarios more easily accessible to the petrochemical industry, and thereby increase competition and reduce prices for consultancy work. This is expected to result in a safer working environment with respect to the risks of accidental fires and explosions. Results from this project will also contribute to improving the understanding of the physical processes occurring in real applications involving combustion and fire.

Work Packages, description and prioritization

A prototype of FLACS-Fire is already operational, and a non-compressible solver will be added in 2012 to improve calculation speed. However, significant efforts remain to verify, validate and improve the implemented models. FLACS-Fire should also be able to simulate heat transfer to objects and structure, smoke production and visibility, the effect of mitigation measures such as passive fire protection and water deluge.

The work in the JIP will be divided into three work packages (WPs) and corresponding subtasks:

WP-A: Physical and chemical phenomena

- A.1 Combustion modelling – improvements to turbulence and combustion models
- A.2 Radiation modelling – improvements and optimization of adaptive ray-tracing, properties calculation, radiation-pool coupling, effect of soot, handling of sub-grid objects, etc.
- A.3 Soot and smoke modelling – improved modelling of incomplete non-premixed combustion, smoke production, visibility, toxic effects and dose, etc.
- A.4 Conductive heat transfer – methods for handling thermal active walls
- A.5 Mitigation – sprinkler systems, fiberglass and foams, passive fire protection, etc.

WP-B: Validation studies

- B.1 Jet fires – literature review and validation
- B.2 Pool fires – literature review and validation
- B.3 Other phenomena

WP-C: Methodology

- C.1 Literature review – QRA methodology for fire hazards
- C.2 Probabilistic QRA methodology for offshore studies
- C.3 Deterministic QRA methodology for onshore studies

Project management

A contract between GexCon and the individual JIP members defines the organization of the JIP. GexCon and the JIP members establish a Steering Committee during the kick-off meeting. The Steering Committee consists of one representative from each of the JIP members, the JIP Manager, and the WP Managers. The Steering Committee appoints a JIP Chair to oversee the organization and administration of the JIP. The Steering Committee also appoints a Secretary at the beginning of each board meeting. The Secretary is responsible for writing and distributing the minutes from the meetings. GexCon appoints a JIP Manager and one WP Manager for each of the three WPs. The WP Managers report to the JIP Manager.

Meetings

The intention is to organize biannual workshops and Steering Committee meetings. These meetings should become an attractive meeting place for safety experts from the JIP members and GexCon. The Steering Committee meetings will normally take place in connection with the workshops, and for practical reasons most of the Steering Committee meetings will most likely take place in connection with the biannual FLUG meetings (May/June and November/December), in order to reduce travel costs for JIP members that also are active in the FLUG meetings. The workshop on the first day will focus on results obtained since the previous meeting, whereas the Steering Committee meeting on the second day will focus on priorities for the next 6-12 month period.

Sponsorship costs

GexCon will propose work plans for the coming 6-12 month period at least two weeks prior to the Steering Committee meetings, in accordance with the available budget (based on agreed funding. Prior to and during the Steering Committee meetings the participants may alter the prioritization through discussions or formal voting.

Each external partner can choose to sign up for one or several 12 month periods, starting in either May or November each year of the project. When signing up for a given 12 month period, the partner has the right to participate in the Steering Committee meeting setting the prioritization of tasks for that period, as well as the Steering Committee meetings after 6 and 12 months.

The cost for each partner for participating is NOK 400 000 per 12 month period. In addition to the efforts paid by the partners, GexCon will contribute with in-kind work corresponding to at least one person-year per year.

Deliverables

The main deliverables from the JIP will be:

- Biannual updates of the main progress report from the JIP (restricted to JIP participants). This report contains a brief summary of all activities covered in the JIP, and partners will receive updates of this report as long as they are active sponsors of the project.
- For each sub-task there will be a more detailed annex to the main progress report with extensive information from the work. Each external partner will get access to the annexes that cover work performed during the periods when the partner was an active sponsor of the project.
- GexCon will keep the right to recompile content from annexes that describe implemented models and results from validation work, for the purpose of producing user documentation and validation reports for FLACS-Fire (which at some point will be made available to all FLACS users).
- External partners in the JIP will receive access to the most recent prototypes or commercial releases of FLACS-Fire, as well as support. [Commercial users that instead choose to purchase FLACS-Fire will not receive prototype versions]
- Twenty-five per cent of the invested funding can be deducted from the purchase price or upgrade price for FLACS-Fire, so that participants that join the project for all the four years will have paid for purchase of FLACS-Fire by the time the project is over.

GexCon may choose to release one or several commercial versions of FLACS-Fire during the project period. In addition, there will be prototype releases of FLACS-Fire during the project period, which will be available to partners in the JIP. For current FLACS users, the license level will follow their existing license level. JIP partners which are not FLACS users during the project period will receive the functionality of FLACS-Dispersion and FLACS-Fire at company internal license level.

GexCon will own all intellectual property rights (IPR) to the software product FLACS-Fire, including prototypes developed during the project.

The tentative pricing principles for FLACS-Fire are shown below (all prices indicated are relative to current full version of FLACS, lease or purchase):

FLACS (Dispersion, Explosion & Fire):	125%	[upgrade cost 25% from current Full FLACS]
FLACS (Dispersion & Fire):	75%	[upgrade cost 25% from FLACS-Dispersion]
FLACS-Fire	50%	[standard FLACS reduced pricing]

The basic FLACS-Fire version will not allow scenarios with delayed ignition (this will require FLACS-Dispersion & FLACS-Fire). To be able to perform explosion simulations in addition, the full FLACS version will be required.

1 Fire modelling and FLACS-Fire

Fire dynamics involves numerous complicated physical and chemical interactions. In addition to detailed chemical kinetics and reactions in the combustion process, it involves fluid dynamics, thermodynamics, radiation, multi-phase effects and much more. The art of CFD fire modelling is to be able to model the whole system accurately on the coarse numerical grid resolution and time stepping available. There is a need to sort out which mechanisms that are most important and needs an accurate modelling, and which mechanisms which are less critical. A lot of the physics will be of scales less than the numerical grid, and sub-grid modelling will be required.

The FLACS software has been developed for 30 years to become a leading CFD consequence tool for explosion and dispersion. In October 2011 FLACS was officially accepted by the US Department of Transportation as the first CFD consequence tool to be used for dispersion studies in connection to LNG facility siting according the NFPA-59A standard [3]. One important reason for the successes is the focus the development team has had on validation against experiments. FLACS is therefore an excellent starting point when developing a CFD fire consequence tool. In the following sections some current and planned fire related models in FLACS will be discussed.

1.1 Combustion modelling

Combustion and radiation are closely related and important features of fires. These are important to model accurately in order to predict flame development and heat loads with precision.

Combustion in a fire has been studied extensively in the literature, and several different combustion models are described for non-premixed flames, including Probability Density Function (PDF) model, Conditional Moment Method, Laminar Flamelet model, eddy-break-up (EBU) model, eddy dissipation concept (EDC) model, and the flame surface density (FSD) model. Due to its ability to handle turbulent reacting flows the eddy dissipation model has been implemented as default model in FLACS-Fire. For gas explosions of premixed flames a different combustion model (referred to as the Beta model) is used. For FLACS to be able to handle both premixed and non-premixed combustion, we have developed a hybrid version of the combustion model which will use the Beta-model for premixed regions and EDC model for regions with high significant concentration gradients (non-premixed).

The eddy dissipation concept (EDC) model [4]:
In turbulent flows, this mixing time is dominated by the eddy properties and, therefore, the rate is inverse proportional to a mixing time defined by the turbulent kinetic energy, *k*, and dissipation, *ε*.

Rate ~ ε/k

In many cases the reaction rates are fast compared to reactant mixing rates and can be considered as mixing controlled combustion.

1.2 Modelling radiative heat transfer

The governing equation for describing radiation intensity field in an absorbing, emitting and scattering medium is the Radiative Transfer Equation (RTE). The radiative transfer equation is given by

$$\mu \frac{dI(\tau,\mu,\phi)}{d\tau} = -I(\tau,\mu,\phi) + (1-\omega)\, I_B[T] + \frac{\omega}{4\pi} \int_{\mu'=-1}^{1} \int_{\phi'=0}^{2\pi} I(\tau\ ,\mu',\phi')\, \Phi(\mu',\phi';\mu,\phi)\, d\mu'\, d\phi' \qquad (1)$$

Where μ is the cosine of the polar angle θ, ϕ is the azimuthal angle, $I(\tau,\mu,\phi)$ is the intensity along direction μ, ϕ at optical depth τ measured perpendicular to the surface of the medium, I_B is the spectral black body intensity at temperature T, ω is the single scattering albedo and $\Phi(\mu',\phi',\mu,\phi)$ is the scattering phase function. The governing radiative transfer equation is of integro-differential nature which makes the analysis difficult and computationally expensive. Also radiation calculations are more difficult to incorporate into the models. In FLACS two types of radiation models have been developed; the six-flux model and the discrete transfer model.

Six-flux model:
This model represents the radiation as six heat flows, one through each of the six sides of the cell. Since radiation is emitted in all directions and not just these six, the six-flux model cannot be used to predict accurately the radiation falling in any one place but gives an approximate prediction of the dispersal of heat throughout the geometry. The six-flux radiative transport equation model in FLACS is still used for radiative heat transfer, despite its known shortcomings in predicting the spread of radiation correctly. One should therefore be careful when examining the resulting heat fluxes. However, the six-flux model calculates the heat loss from flames with good precision.

Discrete Transfer Model:
In the Discrete Transfer Model (DTM) [5] rays are fired from surface elements into a finite number of solid angles that cover the radiating hemisphere about each element and the main assumption of the DTM is that the intensity through solid angle is approximated by a single ray. The number of rays and directions are chosen in advance. In the DTM method, RTE is solved for each ray from one solid boundary to another solid boundary in the geometry. Rays are fired from solid surface boundaries and traced through the volume. The calculation of radiation source term is based on the distance travelled in each control volume. At the boundaries radiative heat transfer boundary conditions are used to determine the intensity of rays fired from that surface area. As the correct initial intensities are unknown at the start of the calculation the procedure becomes iterative until correct radiative intensities are resolved. If ray intersection data is saved either in memory or as a file no ray tracing is required after the 1st iteration, available ray data can be readily used making the process efficient [6].

Radiative Properties calculation:
For the radiative transfer simulation several input parameters (to characterize the wall and the medium) are needed. The parameters defined are: gas temperature distribution of the medium, absorption coefficient distribution of medium, temperature and emissivity of walls, number of rays and firing directions, and control parameters like type of problem (temperature or source specified). The absorption coefficient is calculated from flow solver using transient temperature and mole fractions of CO_2, H_2O, and soot. For this the Mixed Gary Gas Model of Truelove [7] is used in the present study. In the present model, the products of combustion like CO_2 and water vapour, H_2O have been considered as the participating gases, which absorb and emit radiation depending on local mixture temperatures.

Data Transfer Procedure:
FLACS solves for continuity, momentum, and enthalpy equations. Solving the enthalpy equation requires a radiative source term. Solution of RTE through DTM ray tracing mechanism provides the source at every nodal point in the domain. In order to solve the radiative equation, we need the temperature and mole fractions of CO_2, H_2O and soot as input parameters. It is assumed that CO_2 and H_2O are the important emitting gases which contribute to the calculation of absorption coefficient. The radiation calculations thus provide the source term for enthalpy. This loop continues for every time step and thus source term is updated every time step. As these calculations are time consuming, there will in most cases not be necessary to update the radiation field in every time step of the simulation.

1.3 Modelling soot formation in flames

In industrial fires, the amount of soot is important for the radiation. Soot generation and development are difficult phenomena within the combustion science due to the lack of knowledge regarding the mechanisms for soot formation and growth. Independent on their complexity and degree of modelling and empiricism, models in the literature need some fitting to give good results [8]. A good review on soot modelling is given by Haynes and Wagner [9].

In FLACS-Fire the formation of soot has been modelled by the Magnussen soot model [10]. It assumes that soot is formed from a gaseous fuel in two stages, where the first stage represents formation of radical nuclei, and the second stage represents soot particle formation from these nuclei.

In FLACS, the soot level must be determined from known scalars, such as the mixture fraction, the fuel composition and the local equivalence ratio. Hence, models based on some intermediate species in the combustion process cannot be used. Furthermore, to limit memory requirements and computation time, soot progress will be described by one variable field only. The limitations stated above give two possibilities for modelling of soot:

1. A fixed soot conversion factor model (CFM), where a certain amount of carbon in fuel is converted to soot directly. The amount of carbon transformed to soot depends only on the fuel composition.
2. A formation-oxidation model (FOX), where there is a formation source term and an oxidation source term in the soot transport equation.

Both modelling approaches are implemented in FLACS-Fire.

1.4 Modelling conductive heat transfer

Solid walls should be included into the computation domain as the heat conduction into the wall accounted for a large portion of the total heat transfer, and this can influence the accuracy of the indoor gas temperature development.

The thermal behaviour of solid walls is necessary to include in fire modelling. Walls are heated by the fire and are heat sinks in the initial period of a fire. A confined fire can only be stationary when it is in thermal equilibrium with the walls. Furthermore, the wall temperature is an important output from fire simulations. Materials change properties with temperature and they extend their size when the temperature is rising. Expansion sets up stresses that may have dramatic consequences for the construction. Structural response is, however, beyond the scope of FLACS-Fire.

An example of a jet-flame simulation with the current version of FLACS-Fire is given in the figure below.

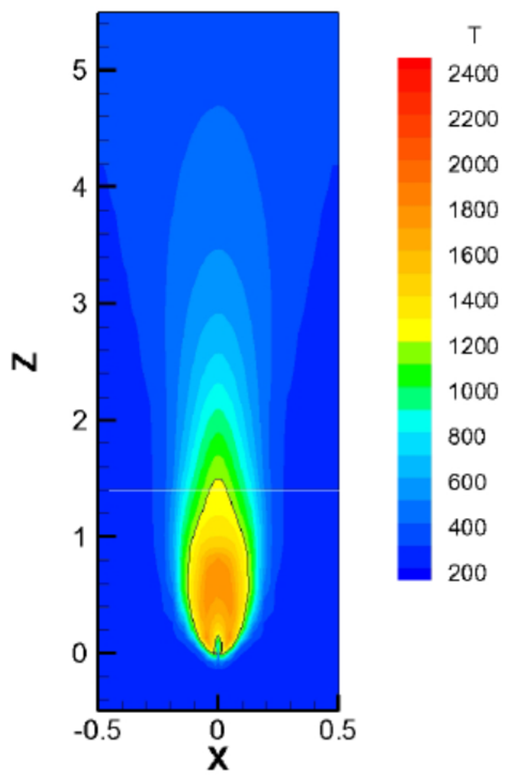

Figure: Temperature plots comparing 1200 K contour (black line) with experimental flame length (grey line) for propane-air jet flame from Røkke et al [11] using the current version of FLACS-Fire and the discrete transfer method (DTM) for radiation modelling

2 Physical and chemical phenomena (WP-A)

In this section work tasks to improve physical and chemical models, improved model output, as well as simulation efficiency, will be described. The indication of efforts required is very approximate and will be refined prior to prioritization meetings during the JIP.

2.1 Combustion modelling (A.1)

Combustion model:
The combustion model is a key element in the fire modelling process. It provides the coupling between the turbulent flow and the chemical reactions. The assumptions underlying the interaction of the chemical reactions with the turbulent flow form the basis of a turbulent combustion model. There are two combustion models implemented in FLACS-Fire namely: mixed is burnt and Eddy Dissipation Concept (EDC). The 'mixed is burnt' works well for laminar flames and fine grid resolution. The Eddy Dissipation Concept (EDC), on the other hand, assumes a perfectly stirred reactor (i.e. very high turbulence intensity). None of these models are optimal for all conditions, and the following approach is proposed:

- Evaluate present models and search for credible alternatives
- Implementation and validation new alternative models

Estimated workload: 6 person-months

Turbulence model:
The turbulence in the fires controls the mixing. The FLACS software uses the k- ε turbulence model. It is essential to validate and quantify potential errors caused by the model. To improve the turbulence model following approach is proposed

- Evaluation of the present k-ε model.
- Implementation and validation of improvements

Estimated workload: 6 person-months

Two-phase jet model:
Releases of pressurized fuels often result in two-phase jets fires, characterized by evaporating and burning droplets. The aim of this activity is to model two-phase jets fires, including the effect of jets impinging on walls. In recent years there has been an extensive effort working with homogeneous equilibrium model (Euler-Euler) and Lagrangean two-phase models for non-reacting flow, and the idea of this task will be to merge these models with the fire model:

- Modelling of droplet-fire interaction, including convective and radiative heat transfer.

Estimated workload: 4-6 person-months

Pool model

The current version of FLACS-Fire can in principle model a pool fire as multiple diffusive jets, but also has a shallow-water pool model which automatically calculates the pool spread and evaporation rate. The purpose of the current activity is to ensure that pool fires can be modelled with good accuracy:

- Modelling burning spills by merging the pool and fire models in FLACS
- Modelling the heat transport from the flames to the pool, and the resulting enhanced evaporation
- Improved combustion modelling in general

Estimated workload: 6 person-months

Special Combustion Phenomena
The current version of FLACS-Fire can model jet fires, still due to choice of combustion model there is physics, e.g. the modelling of lift-off, which cannot be modelled in detail. This will in general be of low importance for a jet fire in a congested oil platform module, as one can expect that a flame will always stabilize in a congested area. To handle idealized tests and scenarios, on the other side, it would be good to be able to model lift-off. Other phenomena, which are of particular interest for domestic fires, are flashover and back-draft explosion. When used for accident investigations it may be of importance to predict these mechanisms well, however, there are not foreseen to be priorities in the initial

development of FLACS-Fire focusing on hydrocarbon fires. With time, to improve the scientific basis of FLACS-Fire, it will still be considered to improve in these fields:

- Modelling of lift-off
- Evaluate possibilities with regard to modelling of flashover
- Improvement of other aspects and weaknesses of jet fires identified by validation (Activity B)

Estimated workload: 6 person-months

2.2 Radiation model (A.2)

Parallelization

Fire calculations are time consuming, and this also applies to radiation calculations. During a previous JIP, “FLACS-2011 and beyond”, the standard FLACS version functionality has been parallelized. According to Amdahl’s law, most of the code must be parallelized before a significant speed-up can be achieved on a large number of CPUs. This means that the advantage of a parallelized FLACS not can be expected in calculation with radiation before also the radiation model has been parallelized.

- Parallelization of the Discrete Transfer ray-tracing model

Estimated work load: 6 person-months.

Adaptive Ray Tracing

Although the current Discrete Transfer Model is accurate, it requires a lot of memory and computational time, and only a small number of the calculated rays contribute significantly to the radiative heat impact far from the flames. A considerable speed-up can be achieved by introducing an optimizing scheme:

- Initial calculations with low number of rays
- Identify the most important contributing rays
- Increase accuracy by adding rays in contributing directions.

Estimated workload: 3 person-months

Improved radiative property calculations

The current test release of FLACS-Fire uses weighted sum of grey gas model to calculate properties. To improve the accuracy of properties calculations the following steps are proposed:

- Evaluate present properties calculation model and search for better alternatives.
- Implementation of new weighted sum of grey gas model.
- Validation of radiative properties models.

Estimated workload: 1 person-month

Radiation in fuel clouds

Most radiation models consider the effect of three-atomic gases (e.g. H_2O and CO_2), as well as soot. For some scenarios it is important to take into account the radiation absorbed and emitted by the fuel molecules, e.g. heat transport by radiation within a pool fire:

- Implement absorption and emissivity coefficient for the most common fuels in FLACS.

Estimated workload: 2 person-months

Sub-grid object influence on radiation

A major advantage of FLACS is the efficient handling of sub-grid objects in the modelling of flame acceleration in complex geometries. Because velocities generally are much lower in fires than in explosions, the turbulence generation effect becomes less important, but sub-grid objects must nevertheless be included for the modelling of radiation:

- Sub-grid objects hinder free sight.
- Sub-grid objects generally extract energy from a fire, but they also absorb heat and therefore emit radiation in all directions.

Estimated workload: 4-6 person-months

2.3 Soot/smoke and toxic effects modelling (A.3)

Improved soot model

The current test release of FLACS-Fire solves a transport equation for soot, including formation and combustion of soot. However, the implemented model neglects the most important step in the formation of the soot, viz. formation and growth of nucleates: **Note:** There are large uncertainties connected to the modelling of soot formation, and a complex model is not necessarily better than a simple model. Soot formation is important when modelling both radiation and visibility.

- Evaluate need for improved soot model based on validation
- Implementation of a two-step soot model

Estimated workload: 4 person-months

Smoke and visibility modelling

Visibility is one of the most important outputs from a fire simulation. Although it is the smoke and/or heat loads that pose the most direct treat to personnel, it is often the lack of sight that causes people to be trapped before inhaling toxic gases (CO); this activity includes:

- Modelling the visibility as function of soot and product concentrations.

Estimated workload: 2 person-months

Area source for smoke and hot products

If only the far-field effects of fires are of interest, significant speed-up can be achieved by defining areas that produces smoke and hot products. This simplification can reduce a fire simulation to a simple dispersion simulation on a coarse grid.

Estimated workload: 2-3 person-months

Modelling of toxic effects

For hydrocarbon fires CO may be the product of main concern with regard to toxicity, but also other toxic products may be of interest. This activity will ensure proper output of the most interesting toxic components, and estimates of dose.

Estimated workload: 2-3 person-months

2.4 Heat loads and conductive heat transfer (A.4)

Calculation of heat loads on walls and objects, including interfaces CASD and Flowvis

Walls and objects represent a significant heat sink in the fire calculations until they have been properly heated by the fire. At the same time, the degree of heating of such objects is of primary interest to estimate damage and escalation potential. In this activity models for heat calculation and conductive heat transfer into different objects will be developed in an approximate way. For the walls, decks and objects of primary interest (near field of fire) it will be possible to specify these objects with properties in CASD (surfaces and cylindrical vessels). It should also be possible to display the heat impact and change in temperature calculated by FLACS-Fire in the postprocessor Flowvis.

Estimated workload: 4-5 person-months

Export facility to structural code

A facility for exporting data from the CFD-tool to FEM-codes able to describe the response of structural components when exposed to high temperatures is proposed developed.

Estimated workload: 2-3 person-months

2.5 Mitigation (A.5)

Effect of sprinkler systems

The purpose of this activity is to describe the effect of sprinkling on fire scenarios. A research version of FLACS exist with a Lagrangean two-phase model for liquid particles, and this can be used as starting point for the development of sprinkler models in FLACS-Fire. Work tasks would include:

- Automatic initialization of droplets: the droplet distribution for some typical nozzles should be automatically calculated for a given fuel, pressure, and valve specifications (low user threshold)
- Adapt the Lagrangean multiphase model in FLACS to handle sprinkler systems with water
- Droplet-flame interactions: modelling local cooling, evaporation of droplets, and droplet-radiation interaction as well as impact on flammability

Estimated workload: 10-12 person-months

Effect of foam or fiberglass on pool fires

Mitigation methods for pool fires include e.g. foam and fiberglass. By injection of foam the pool will be protected from incoming radiation, and at the same time, evaporation is reduced as there is limited contact between the pool surface and the air. Fiberglass may have similar functionality, but may be permanently positioned on top of the liquid flammable pool (for instance in an LNG sump). Since these approaches are used in the industry, it will be of value to be able to predict the effects of these mitigation methods in FLACS-Fire.

Estimated workload: 6 person-months

Effect of passive fire protection (PFP)

Passive fire protection has been much used on oil platforms and elsewhere to protect pipes and vessels from being heated by fire loads. Challenges with maintenance and corrosion (below PFP) as well as higher general fire loads since insulated objects have less heat-sink effect, combined with a better understanding of the fire resistance of different systems have made many companies reconsider the massive use of PFP. Many companies also consider removing already installed PFP. In order to evaluate the safety effects when removing PFP it is important to properly describe the effect of PFP on fires in FLACS.

Estimated workload: 2-3 person-months

3 Validation studies (WP-B)

Introduction:

A detailed analysis quantifying the modelling and numerical uncertainties in FLACS-Fire simulations is important step in the proposed work. The main motivation for performing validation work is:

- To get an overview of the performance of various models and sub-models, and this way be able to prioritize efforts in the continued development of FLACS-Fire.
- To develop an understanding of validity and performance, to be able to develop guidelines
- To be able to demonstrate validity and performance to users, their customers and authorities

Optimally a validation exercise would include different steps [12]:

- Defining the model and scenarios for which the evaluation is to be conducted
- Verifying the appropriateness of the theoretical basis and assumptions used in the model
- Verifying the mathematical and numerical robustness of the model
- Quantifying the uncertainty and accuracy of the model results in predicting the course of events in similar fire scenarios

In real world there is not only uncertainty in the modelling, but also in the experiments to compare against, as well as in the understanding of phenomena like soot generation, and this will influence the ambition level with regard to precise conclusions in a validation exercise.

In the following the plans for the FLACS-Fire validation are described. A validation matrix will be established including a number of relevant, well documented experiments, to be able to evaluate various aspects of the physics of fires. The matrix will be built in a way, so that simulations can be repeated efficiently to evaluate the effect of model changes during development of FLACS-Fire.

3.1 Jet fires – overview and planned validation work (B.1)

The topic of jet fires has been studied in great detail by numerous authors, both experimentally and numerically. It has been attempted to find relevant case studies for both vertical and horizontal jets. While there are a lot of experimental studies on jet flames, the majority of these are concerned with laboratory-scale flames. Larger field-scale flames will be simulated when published experimental data have been made available. Røkke et al. [11] investigated unconfined turbulent non-premixed and partially premixed propane flames in quiescent air. The studied flames were for a range of different nozzle diameters and velocities, and up to 2.5 m long. Models for flame length, lift-off and NOx-emissions were presented and discussed. Larger vertical propane jet fires were studied by Palacios et al. [13] where the length and lift-off of both sonic and subsonic flames up to 10 m long were measured using cameras that registered visible light, in addition to an infrared camera. Using the same experimental set-up, axial temperature profile and radiant heat were measured and published by Gomez-Mares et al. [14, 15]. Measurements of large scale hydrogen jet fires were performed by Schefer et al. [16] to characterise the dimensional and radiative properties. Flame length and lift-off were estimated using visible, infrared and ultraviolet imaging. Radiation heat flux was measured at various axial positions along the jet.

The radiation flux from a variety of turbulent jet diffusion flames was measured by Sivathanu & Gore [17]. The measured data were plotted in normalised coordinates and a method for estimating total radiation output based on single point radiation heat flux measurements was reported. Extensive measurements of the shape and size of hydrocarbon diffusion flames in cross-flow were reported by Kalghatgi [18]. Wind tunnel experiments were conducted with jet to cross-flow velocity ratios ranging from 0.02 to 0.22, with a variety of different hydrocarbon fuels. The visible flame was described by a frustum of a cone defined by three lengths and two angles, and the values for these were measured and reported. Other experimental studies on vertical jet flames can be found in Becker & Liang [19] and Bagster & Schubach [20], and for high pressure sonic jets in Cleaver et al. [21] and Schefer et al. [22]. Further studies on jet flames in cross-flow with respect to size and radiation were conducted by

Fairweather et al. [23, 24], respectively. Studies on horizontal jets are much less common, but there are still some pertinent studies. Smith et al. [25] investigated the trajectory and other characteristics of horizontal jet flames from both circular and elliptic burners. The jet was in a quiescent environment and had exit velocities ranging from 9 to 57 m/s. Another survey on horizontal free diffusion flames was published by Gosman et al. [26], but this article focuses more on the modelling of flames. Impinging jet flames have been studied by many different authors. Experimental data on vertical natural gas fires and weak plumes impinging on a horizontal ceiling were reported by You [27], for fires with heat-release rates of 1.67 and 8.51 kW. Both heat-fluxes and profiles of mean temperature, pressure and species concentrations were measured for the impinging fire. Horizontal sonic jet flames impinging on a box-like test target (an I-beam) were measured by Wighus & Drangsholt [28] for a 14 MW propane jet. Heat flux at the surface, as well as temperatures and velocities were reported for various jet locations. Other articles also addressing impinging fires were published by You & Faeth [29] and Dong et al. [30], and reviews on the subject were written by Baukal & Gebhart [31] and Baukal & Gebhart [32]. General reviews on the topic of fire and fire modelling are given by Tieszen [33] and McGrattan [34].

As a part of the validation of FLACS-Fire, different jet flame scenarios will be studied. We will also include two-phase jets in this comparison. These simulations will be compared with experimental studies to verify the results obtained using FLACS-Fire. Proposed work of this package includes

- Identify and model relevant jet-fire scenarios, including two-phase releases
- Include the most valuable cases in validation matrix
- Report validation status
- Simulation setups will be shared with supporting companies

Estimated workload: 12 person-months. Work should be split into smaller activities

3.2 Pool fires – overview and planned validation (B.2)

Intensive research has been carried out over decades on pool fires [35-38], though only a small proportion of the work has looked specifically at large-scale pool fires [39].

The pool fire phenomenon consists of many different processes:

- The liquid fuel pool development and vaporization rate depending on fire and geometry
- Shape and concentration of vapour cloud above the pool
- Flame development, temperature and shape, including interaction with objects in the flame
- Plume of products of fire
- Radiation from flame to pool and surroundings
- Mitigation options like foam or fiberglass

Recent research on large pool fires [41, 42] has identified the increased production of soot in large-scale fires as a key factor controlling the behaviour of these fires. Unlike in smaller fires, where flames are relatively clean-burning and soot emerges only at the flame tip, as we move towards increasingly large source diameters soot is produced in large quantities lower in the fire plume [40].

As a part of the validation of FLACS-Fire, different pool flame scenarios will be studied. These simulations will be compared with experimental studies to verify the results obtained using FLACS-Fire. Proposed work of this package includes

- Identify and model relevant pool-fire scenarios
- Include the most valuable cases in validation matrix
- Report validation status
- Simulation setups will be shared with supporting companies

Estimated workload: 12 person-months. Work should be split into smaller activities

3.3 Other phenomena and validation cases (B.3)

In this activity it will be evaluated how FLACS-Fire can handle other aspects related to fires, e.g. BLEVE's, flashovers, back-draft explosions and more. This activity is currently not a high priority, and will be described more in detail at a later stage.

4 Methodology (WP-C)

According to the ISO 19901:3 (2010) standard there is a requirement to estimate the probability for accidental escalation from fire and explosion scenarios for topside structures, if worst-case loads are non-tolerable. For explosion loads such studies have been performed for more than a decade, either according to guidelines in NORSOK Z-013 Annex G (2001; revised to Annex F 2010) or other company internal or country specific guidelines. For probabilistic fire studies, few guidelines exist, and there may be a need to develop guidelines for such studies and how these best can be combined with an explosion study. This will be the content of WP-C.

4.1 Literature study – QRA methodology for fire hazards (C.1)

A literature study is planned to systematically search for and collect information on tolerance criteria, standard or company requirements for fire studies.

Estimated work load: 1 person-month

4.2 Probabilistic QRA methodology for offshore installations (C.2)

The ambitions with this activity are to propose a framework for a probabilistic fire risk assessment for process areas on an offshore platform or installation. The framework will be proposed so that it can be combined/integrated with approaches for probabilistic explosion studies (e.g. Norsok Z-013 Annex F (2010)).

Estimated work load: 6 person-months (Activity should be split into smaller packages)

4.3 Deterministic QRA methodologies for onshore facilities (C.3)

In many situations there is a need for a simpler approach than probabilistic QRA, for instance for onshore studies or screening studies. This activity will propose a framework for such studies based on realistic worst-case considerations.

Estimated work load: 6 person-months (Activity should be split into smaller packages)

5 Work schedule

Table 1 shows an overview of the different planned activities of the JIP 'FLACS-Fire – Modelling & QRA Methodology'. The actual effort level and distribution will be decided later on the kick-off and biannual planning meetings among the sponsors.

The main efforts first half of 2013 will include, incompressible solver and parallel version of FLACS-Fire (Except radiation part), define new output parameters, initial validation against large scale jet fire experiments, and work to ensure that the new DTM radiation model is working properly. Some work preparing QRA methodology development is also planned.

***Table 1** Work schedule for JIP 'FLACS-Fire – Modelling & Methodology'.*

Activity \ Year (term)	**2013**		**2014**		**2015**		**2016**	
	T1-1	**T1-2**	**T2-1**	**T2-2**	**T3-1**	**T3-2**	**T4-1**	**T4-2**
A.1 Combustion modelling								
A.2 Radiation model								
A.3 Soot/smoke and toxic effects								
A.4 Heat loads and conductive heat transfer								
A.5 Mitigation								
B.1 Jet fires								
B.2 Pool fires								
B.3 Other phenomena								
C.1 Literature study – QRA methodology for fire hazards								
C.2 Probabilistic QRA methodology offshore								
C.3 Deterministic QRA methodology onshore								

6 Deliverables

The main deliverables from the JIP 'FLACS-Fire – Modelling and Methodology' to the sponsoring partners will be:

- Twice a year updates of the main progress report from the JIP (restricted to JIP participants). This report contains a brief summary of all activities covered in the JIP, and partners will receive updates of this report as long as they are active sponsors of the project.
- For each sub-task there will be a more detailed annex to the main progress report with extensive information from the work. Sponsoring partners will only get access to the annexes for work-tasks that have been initiated during their sponsorship period.
- GexCon will keep the right to recompile WP-B annexes and produce validation reports for FLACS-Fire (which can be made available to all FLACS users).
- Partners will receive FLACS-Fire simulation setups for tests included in main validation matrix of FLACS-Fire.
- Partners will receive access to most recent commercial release or prototype release of FLACS-Fire, including support. [Commercial users that instead choose to purchase FLACS-Fire will not receive prototype versions].
- 25% of invested funding can be deducted towards purchase price or upgrade price of FLACS-Fire.

7 Quality assurance

The project will be performed in accordance with the procedures given in the quality assurance system of GexCon AS. All input and output data and calculations will be checked by means of the following main activities:

- Control of own work.
- Quality check by experienced personnel.
- Approval/independent control of the project and of the quality assurance.

8 Payment schedule

Table 2 shows a tentative payment schedule for prospective participants in JIP ‘FLACS-Fire – Modelling & Methodology’.

Since the prospective sponsors of the JIP may have very different budget processes we realize it may be challenging to define one common start-up date and rigid content of the JIP. Instead we are proposing a flexible structure as follows:

Each sponsor of FLACS-Fire will commit for a minimum of 1 year at a time (NOK 400 000). For this the sponsor gets the following:

a) Free access to company internal license level test versions of FLACS-Fire (+Dispersion) during the sponsorship period.
b) 20% of the sponsorship funding can be deducted against future purchase of FLACS-Fire (and other FLACS-SW payments if excess deductions).
c) Participation in meetings during the support period, including planning meeting at start-up and results meeting at end of support period.
d) The main results report during their sponsorship period, as well as detailed result appendices for the activities prioritized during their sponsorship period.
e) Simulation setups for tests in main validation matrix during support period
f) The right to prioritize 3 man-months R&D work in the voting process when prioritizing work for the next budget period.

***Table 2** Tentative payment schedule for participants in JIP ‘FLACS-Fire – Modelling & Methodology’.*

Invoice date	Amount per participant (NOK)*
December 2012	100 000
June 2013	200 000
December 2013	200 000
June 2014	200 000
December 2014	200 000
June 2015	200 000
December 2015	200 000
June 2016	200 000
December 2016	100 000

*A participant must sign up for a minimum of 12 months (=400 kNOK) at a time, but can enter at any time

Invoices will be issued to sponsors that have committed to participation in writing, the invoices for each 12 month period will be issued according to the payment schedule in Table 2. The payment is expected within 30 days of receipt of an invoice.

9 Project team

The project team will consist of the following key personnel:

Name	Position
Bjørn Lilleberg	Project manager (core fire team)
Deiveegan Muthusamy	Project member (core fire team)
New research engineer (PhD)	Project member (core fire team)
Idar Storvik	Project member (numerical solver)
Lars Pesch	Project member (numerical solver)
Tommy Lea	Project member (graphical user interfaces)
Thomas Landvik	Project member (graphical user interfaces)
Ole Jacob Taraldset	Project member (graphical user interfaces)
Vagesh D. Narasimhamurthy	Project member (turbulence modelling)
Trygve Skjold	Project member (Verification and QA)

Disclaimer

Please note our disclaimer, which will be included within the test report(s) from GexCon:

“GexCon shall not be liable for damages, which the assignor, or assignor’s clients, vendors, consultants or other third party, suffers when applying or using the results of GexCon’s work, unless there is misconduct or gross negligence on the part of GexCon or on the part of the persons used by GexCon to carry out the work.”

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We look forward to your positive response and remain,

Yours Sincerely
For GexCon AS

Prankul Middha

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