TAKING CREDIT FOR LOSS CONTROL MEASURES IN THE PLANT WITH THE LIKELY LOSS FIRE AND EXPLOSION INDEX (LL-F&EI)

N. Jensen* **and S. B. Jørgensen**

CAPEC, Department of Chemical Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark.

Abstract: This communication proposes a new relationship for estimation of the damage factor (DF) used in the Dow Fire and Explosion Index (F&EI). The proposed new relation more clearly shows how the damage factor depends on other factors in the F&EI, such as material factor (MF) and Process Unit Hazards Factor, and leads to the definition of a new index which accounts for loss control measures implemented in the plant, and thus gives a measure of risk. Analysis shows that three types of relations exist between DF and Process Unit Hazards Factor depending on the size of the MF—low, medium or high. Further analysis shows, that the procedure in the current F&EI Guide may overestimate the DF for a very low MF and moderate to high Process Unit Hazards Factor.

The analysis leads to the definition of the Likely Loss Fire & Explosion Index, which provides an estimate of risk of losses from fires and explosions as well as degrees of risk similar to the estimate of hazards and degrees of hazard associated with the Fire & Explosion Index.

Keywords: risk assessment; Fire & Explosion Index.

Correspondence to:
Mr N. Jensen, CAPEC, Department of Chemical Engineering, Technical University of Denmark, Søltofts Plads 229 Kgs. Lyngby, DK-2800, Denmark.
E-mail: nj@kt.dtu.dk

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INTRODUCTION

The Dow Fire and Explosion Index was developed by the Dow Chemical Company in the 1960s as a tool for plant engineers to give relative value to the risk of individual process unit losses due to fires and explosions and to communicate these risk to management in terms easily understood, i.e., potential of financial losses due to lost production and damage to plant facilities. The index is still widely used, and has been upgraded seven times. This index estimates the hazards of a single process unit based on chemical properties and inventories, and then uses plant construction cost or replacement cost to estimate the potential risk in dollar terms. The aim of this communication is to develop an index, which is a measure of risk and takes into account risk reduction measures implemented or proposed for the plant unit, such as process control systems, material isolation systems and fire protection systems. Thus as the F&EI rates the hazards, the proposed index rates the risk.

DOW'S FIRE AND EXPLOSION INDEX PROCEDURE

Based on their in house experiences with fires and explosions during the late fifties and early sixties the Dow Chemical Company developed the Fire and Explosion Index (F&EI) as a tool to rate the hazards from fires or explosions at their world wide facilities on a uniform scale. Over the years the index has been adjusted based on both internal and external data as well as qualitative and quantitative analysis. The aim of this tool is to communicate the risk to management in such a way, that management may take appropriate actions to reduce the risk. The purpose is not to rate a given facility as safe or unsafe, but to give a relative ranking of hazards and risks within an organization. The current version of the guide is available from AIChE (1994), and is referred to as the F&EI Guide in the remainder of this communication.

The general procedure for using the F&EI Guide is shown in Figure 1, and involves the following steps:

(1) A material factor (MF) which is a measure of the reactivity and flammability hazards associated with a material as defined by the NFPA reactivity and flammability ratings, N_R and N_F. The flammability rating is further related to the materials flash point temperature and boiling point temperature.
(2) A general process hazards factor (F_1) which is a measure of reaction characteristics, i.e., exothermal or endothermal,

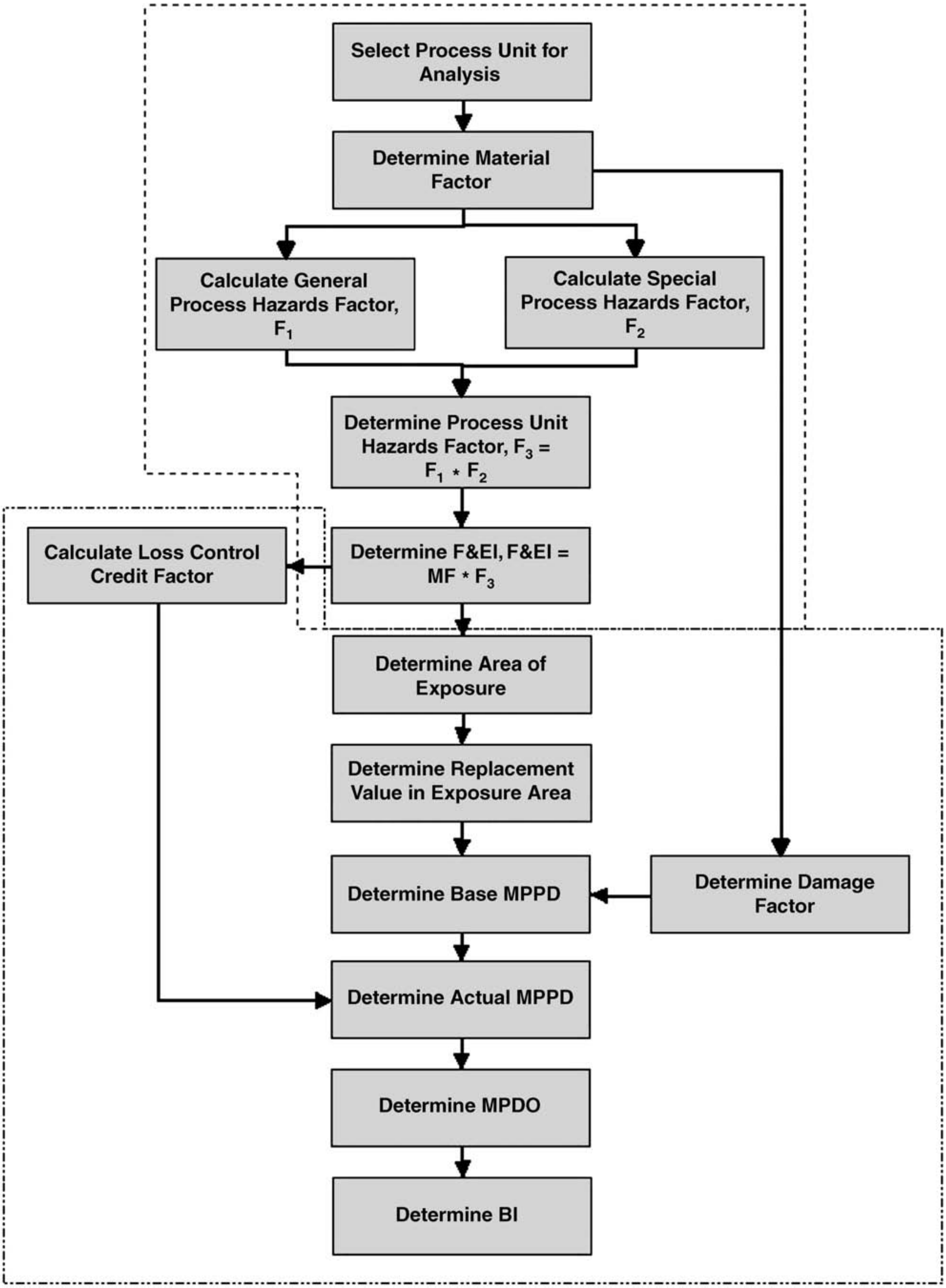

Figure 1. Procedure for calculating the Dow F&EI and other risk analysis information. The dashed line encloses the procedure for rating the hazards of a process unit, while the dash–dot line encloses the procedure for estimaing the management risk information. This paper proposes a risk index as an alternative to the management risk information estimations.

and of facility characteristics, i.e., access, drainage, outdoor or indoor units, and handling or transfer of chemicals.

(3) A special process hazards factor (F_2) which is a measure of material characteristics, i.e., toxicity, corrosion, dust, and of operation characteristics, i.e., extreme pressures and/or temperatures, temperatures in flammable range, amount of material and special equipment with high fire and explosion potential.

These steps—the hazard rating steps—are shown enclosed by a dashed line in Figure 1.

The F&EI is simply the product of these three factors, i.e.,

$$\text{F\&EI} = \text{MF} * F_1 * F_2 = \text{MF} * F_3 \quad (1)$$

Based on the value of the index, the hazard of a process unit is rated as light, moderate, intermediate, heavy or severe (AIChE, 1994).

MANAGEMENT INFORMATION CALCULATION

The F&EI is simply a number, which rates the hazards of a single process unit. It does not account for any measures taken to prevent or limit a loss due to a fire or an explosion or the value of the equipment within the fire or explosion area. However, the communication to management is in dollar terms, i.e., maximum probable property damage (MPPD), maximum probable days outtage (MPDO) and business interruption loss (BI). These steps—the risk estimation steps—are shown enclosed by a dash–dot line in the lower part of Figure 1.

The estimation of management information based on the F&EI involves several steps. First the area potentially affected by a fire and/or explosion is determined. In simple situations the area can be estimated directly from the index (in SI units):

$$\begin{aligned}\text{Area of exposure} &= \pi * (0.3048 * 0.84 * \text{F\&EI})^2 \\ &= 0.205939 * \text{F\&EI}^2 \quad (2)\end{aligned}$$

The value of the equipment inside this area is estimated from accounting records or other sources of economic data. Once the value of the equipment inside the exposure area has been determined it can always be expressed as value per unit of area, and then the MPPD may be estimated as follows:

$$\begin{aligned}\text{Base MPPD} &= 0.205939 * \text{F\&EI}^2 \\ &* \text{DF} * (\text{value per unit of area}) \quad (3)\end{aligned}$$

'Base' indicates that the above expression does not reflect any loss control measures, which may have been implemented on the unit. The parameter DF is the so-called damage factor, which accounts for the actual damage experience based on the MF and the Process Unit Hazards Factor, i.e.,

$$\text{DF} = f(\text{MF},\ F_1 * F_2) = f(\text{MF},\ F_3) \quad (4)$$

The actual loss control measures implemented on a unit is accounted for by multiplying the Base MPPD with a loss control credit factor (LCCF). The LCCF is a product of three loss control credit factors:

(1) A process control credit factor (C_1) which accounts for emergency power, cooling, explosion control, emergency shutdown systems, computer control, inerting, operating instructions/procedures, reactive chemicals review and other forms of process hazards analysis.

(2) A material isolation credit factor (C_2) which accounts for remote control valves, dump and/or blow down systems, drainage systems and interlocks.

(3) A fire protection credit factor (C_3) which accounts for leak detection, structural steel protection, fire water supply and availability, special systems, sprinkler systems, water curtains, foam systems, hand extinguishers and cable protection systems.

The loss control credit factor is the product of these three factors:

$$\text{LCCF} = C_1 * C_2 * C_3 \quad (5)$$

The actions behind this factor reduces the severity of a fire or explosion event, and therefore it reduces the maximum probable property damage, so the actual value is given by

$$\text{Actual MPPD} = \text{LCCF} * \text{base MPPD} \quad (6)$$

The MPDO is estimated directly from the Actual MPPD using a correlation in the F&EI Guide. Finally, the business interruption loss is estimated by multiplying the MPDO by the value of production for a day and a factor representing fixed costs and profits.

During preliminary design accounting information may not be readily available. However, there still is a need to estimate the business risk and compare the level of risk with existing or other company facilities. A modification of the management calculation procedure to calculate a risk index instead of losses in financial terms would accomplish this.

PREVIOUS WORK ON MODIFYING THE F&EI

Gupta *et al.* (2003) proposed a risk index called the 'Offset F&EI':

$$\text{Offset F\&EI} = \text{LCCF}^{0.5} * \text{F\&EI} \quad (7)$$

which has the same Actual MPPD as the original F&EI, and hence also the same values of the other management information items, i.e., MPDO and BI.

However, Gupta *et al.* (2003) in their interpretation ignore the difference between hazard, as rated by the F&EI value, and risk, as measured by the management information items, e.g., maximum probable process damage (MPPD).

This can lead to incorrect use and analysis, when using the 'Offset F&EI'. For example loss control measures, such as a process control computer or remote control valves or foam systems, can make a plant safer, but they may fail. Hence, their presence does not make the plant inherently safer or change its hazard level. These measures only change the risk level. It would for example, not be good engineering practice to reduce the layout spacing because of a process control computer in the control room. In the event of a fire and/or explosion the process control computer is not limiting the area impacted by that fire and/or explosion. Therefore credit cannot be taken for the process control computer or any other loss control measures when using the F&EI to calculate equipment spacing in plant layout, as in the equation for radius of exposure, F&EI Guide (AIChE, 1994):

$$R = 0.256 * F\&EI \qquad (8)$$

A plant layout, which minimizes the loss from fires and explosions will attempt to space equipment, so the exposure areas defined by the above radius does not overlap, and hence a fire or explosion in one process unit does not have a domino effect on a nearby unit. The interpretation of the radius of exposure or area of exposure calculated from the Offset F&EI using the same multiplication factor as in the F&EI Guide, i.e., 0.256 (in SI units), is unclear, as is the replacement value calculated from this area. Unfortunately Gupta *et al.* (2003) concludes, based on 'Offset F&EI', that 'the equipment can be spread out less to save from domino effect', and that 'it implies lesser land requirements' or 'shorter pipe lengths'.

Gupta *et al.* (2003) also state 'the loss control measures are installed to reduce the hazard potential of a process'. Loss control measures are taken to reduce the risk, as indicated by MPPD, MPDO or BI. The hazard may only be reduced by applying the principles of inherently safer design. Neither is it correct to state, that the 'Offset F&EI' makes the system inherently safer. Only system changes, i.e., process design and process route changes will make the system inherently safer.

The proposed 'Offset F&EI' does however have the following benefit:

- Easier evaluation of cost versus benefit of different loss control measures especially during design and application for a permit from authorities.

However, the other advantages claimed by Gupta *et al.* (2003), such (a) reduction of the area of exposure and the hazard status of the process unit, (b) reduced insurance premiums due to use of a different index, (c) a more compact plant layout, (d) reduced cost of piping, (e) more manageable emergency plans, or (f) reduced on-site and off-site consequences, appear not to hold.

ANALYSIS OF DAMAGE FACTOR/MATERIAL FACTOR RELATIONS

The Process Unit Hazards Factor, F_3, is limited to values in the interval from 1 to 8 according to the F&EI Guide. In Figure 2 the Damage Factor is shown as a function of the MF, which can only assume the discrete values 1, 4, 10, 14, 16, 21, 24, 29 and 40. The Process Unit Hazards Factor is an almost continuously variable parameter, which can assume most values in the interval from 1.0 to 8.0. An instructive visualization is therefore to show the DF as a function of the Process Unit Hazards Factor, F_3, with the MF as a parameter, as is done in Figure 3.

Figure 3 reveals three clearly different shapes of the relationship between DF and Process Unit Hazards Factor. One almost linear relationship for small MF, i.e., 1, 4 or 10; an S-shaped relationship for intermediate MF, i.e., 14 or 16, and a damped exponential relationship for high MF, i.e., 21, 24, 29 or 40.

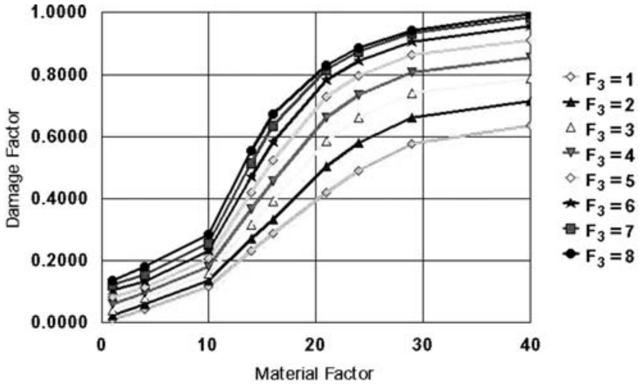

Figure 2. DF, as a function of the MF, with the Process Unit Hazards Factor, F_3, as parameter, as found in the F&EI Guide.

The parallel lines in Figure 3 indicate, that the DF is closely proportional to the material factor. This is confirmed by Figure 4, which shows a plot of the DF/MF versus F_3. For MF>1 all lines of DF/MF versus Process Unit Hazards Factor collapse to a single broad line. This analysis also indicates, that for MF = 1 and Process Unit Hazards Factor>2 the DF estimation according to the current F&EI Guide deviates from the general trend. This could mean, that the procedure in the current F&EI Guide overestimates the DF for a very low MF and a moderate to high Process Unit Hazards Factor.

Figure 5 shows an enlargement of a section of Figure 4. This enlargement also indicates three types of relationship between the ratio of Damage Factor to Material Factor (DF/MF), and Process Unit Hazards Factor. The relationship for MF = 1, 4 or 10 appears almost linear. For MF = 14 or 16 the relationship appears S-shaped, and for higher MF a damped exponential relationship is evident. This is confirmed by linear regression of the data, which give R^2 values above 0.997 for the lower MF values (1, 4 or 10), and less than 0.98 for the higher MF values (40, 29 or 24), when fitted to a linear function of F_3.

Regression analysis of DF versus Process Unit Hazards Factor for MF>1 gives the following equation:

$$DF = MF * (0.0143 + 0.00284 * F_3) \qquad (9)$$

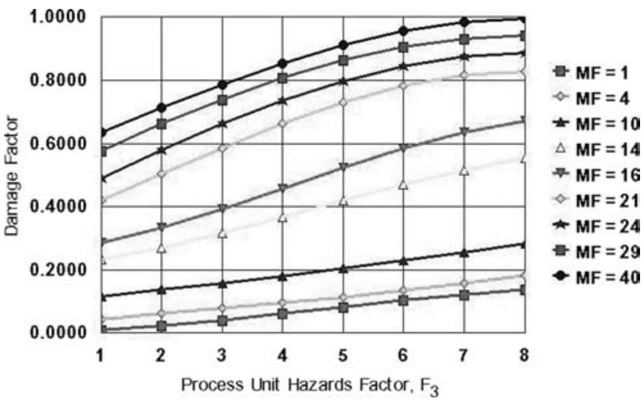

Figure 3. DF as function of the Process Unit Hazards Factor with the MF as parameter. The parallel lines indicate, that the DF appears to be proportional with the MF to a certain extend.

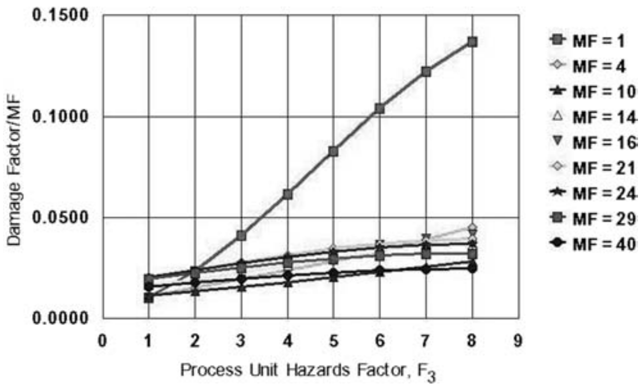

Figure 4. DF/MF, versus the Process Unit Hazards Factor. For MF > 1, all DF appears to fall on the same broad line.

with R^2 statistics of 0.64. This rather low R^2 value indicates, that this equation does not capture all the information in the original relationship shown in Figure 3. A common approach in risk assessment is to apply a conservative approach. In the case of DF, this means selecting largest DF/MF ratio for a given Process Unit Hazards Factor. This conservative approach corresponds to the following relationship

$$\mathrm{DF/MF} = 0.0174 + 0.00339 * F_3 \quad (10)$$

However, this approach may overestimate the DF/MF ratio by between 64% and 96% depending on the Process Unit Hazards Factor. This overestimation will be carried on to the MPPD, MPDO and BI information, which is not acceptable in evaluation of existing plants. However, during process design, where the goal is to compare the risk of alternative designs, the situation may be different, and it may have merit to use the conservative relationship given in equation (10).

The overestimation may be avoided by using the actual polynomial relations between DF/MF and F_3 given in Appendix A or the relations between DF and F_3 given in Appendix B for the different values of MF.

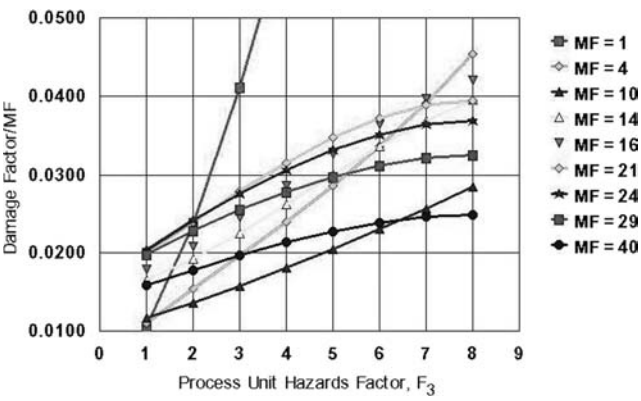

Figure 5. Enlargement of section of Figure 4 showing three types of relationship between DF/MF and Process Unit Hazards Factor. The relationship for MF = 1, 4 or 10 appears almost linear. For MF = 14 or 16 the relationship appears S-shaped, and for higher MF a damped exponential relationship is evident.

This analysis shows, that several possibilities exist for modifying the current relationships between DF, MF and Process Unit Hazards Factor in the current version of the F&EI Guide to obtain a more smooth graphical representation. The analysis further suggest, that a limiting DF/MF ratio can be defined for a given Process Unit Hazards Factor.

A Conservative MPPD Estimate

Based on the above analysis and equation (3) a conservative estimate—upper bound—on the Base MPPD may be expressed by

$$\begin{aligned}\text{Base MPPD} &= 0.205939 * \text{F\&EI}^2 * \text{MF}\\ &\quad * (0.0174 + 0.00339 * F_3)\\ &\quad * (\text{value/unit area}) \qquad (11)\end{aligned}$$

or

$$\begin{aligned}\text{Base MPPD} &= 0.205939 * \text{F\&EI}^2\\ &\quad * (0.0174 * \text{MF} + 0.00339 * \text{F\&EI})\\ &\quad * (\text{value/unit area}) \qquad (12)\end{aligned}$$

Finally, if account is taken of loss control measures already implemented in the plant or unit through a loss control credit factor (LCCF), then an upper bound on the Actual MPPD could be

$$\begin{aligned}\text{Actual MPPD} &= \text{LCCF} * 0.205939\text{F\&EI}^2\\ &\quad * (0.0174 * \text{MF} + 0.00339 * \text{F\&EI})\\ &\quad * (\text{value/unit area})\end{aligned}$$

LIKELY LOSS FIRE AND EXPLOSION INDEX

While in many cases economic data such as construction cost and equipment value per unit of area may be available, this is not the case during initial phases of process design. During initial process design an index is desired, which accounts for the hazards due to the chemicals used and the inventories needed, as well as the risk reduction inherent in loss control measures, such as e.g., a computer process control system. This section proposes such an index.

The maximum probable property damage is seen from the foregoing analysis to be of the following form

$$\text{Actual MPPD} = g(\text{LCCF, MF, } F_3, \text{value/unit of area}) \quad (13)$$

since the F&EI is function of MF and F_3. From this functional relationship it is evident, that one can define an index, which takes into account the loss control measures implemented in the plant or unit under investigation. One possibility for such a likely loss fire and explosion index or LL-F&EI is the following

$$\text{LL-F\&EI} = 0.205939 * \text{LCCF} * \text{DF} * (\text{F\&EI})^2 \quad (14)$$

where the coefficient derives from the exposure area calculation in the F&EI Guide (AIChE, 1994). However, since the likely losses after implementation of loss control measures, will be lower than without these measures, it is desired to create a LL-F&EI with the property, that its value is less than or equal to the F&EI. Therefore the following definition is more suitable:

$$\text{LL-F\&EI} = 0.453805 * \text{SQRT}(\text{LCCF} * \text{DF}) * \text{F\&EI} \tag{15}$$

The index defined here is based on the same information as the F&EI, i.e., the material in the plant, MF, and the plant hazards level, F_3, as well as the loss control measures. This information is generally available during process design, and hence the LL-F&EI may be applied during design to arrive at a design which limits risk to an acceptable level. Furthermore, if the damage factor is calculated using the equations in appendix A, then the MPPD, MPDO and BI information may be obtained using the relations in the F&EI Guide. The procedure for estimation of the LL-F&EI is shown in Figure 6.

Also based on already accumulated information in companies like The Dow Chemical Company risk severity categories may be defined similar to the hazard severity categories associated with the F&EI. Actually for the worst case of unit loss control credit factor and unit damage factor the categories in Table 1 could be used.

Table 1. Suggested LL-F&EI degrees of risk categories.

LL-F&EI range	Degree of risk
1–27	Light
28–43	Moderate
44–57	Intermediate
58–71	Heavy
72–up	Severe

For details on the calculation of MPDO and BI from the Actual MPPD the reader is referred to the F&EI Guide (1994).

USING THE LL-F&EI

Table 2 shows the use of the proposed risk index on an industrial size aniline reactor, which was placed indoors with poor access and drainage, and to the heat integrated distillation pilot plant (HiDPP) at the Department of Chemical Engineering at the Technical University of Denmark, which is also placed indoors with poor access. In neither case are meaningful economic data available. Both the reactor and the distillation column involve materials with a moderate material factor. Both are indoor units with poor drainage and inadequate ventilation. However, the reactor represents an intermediate to heavy hazard due to

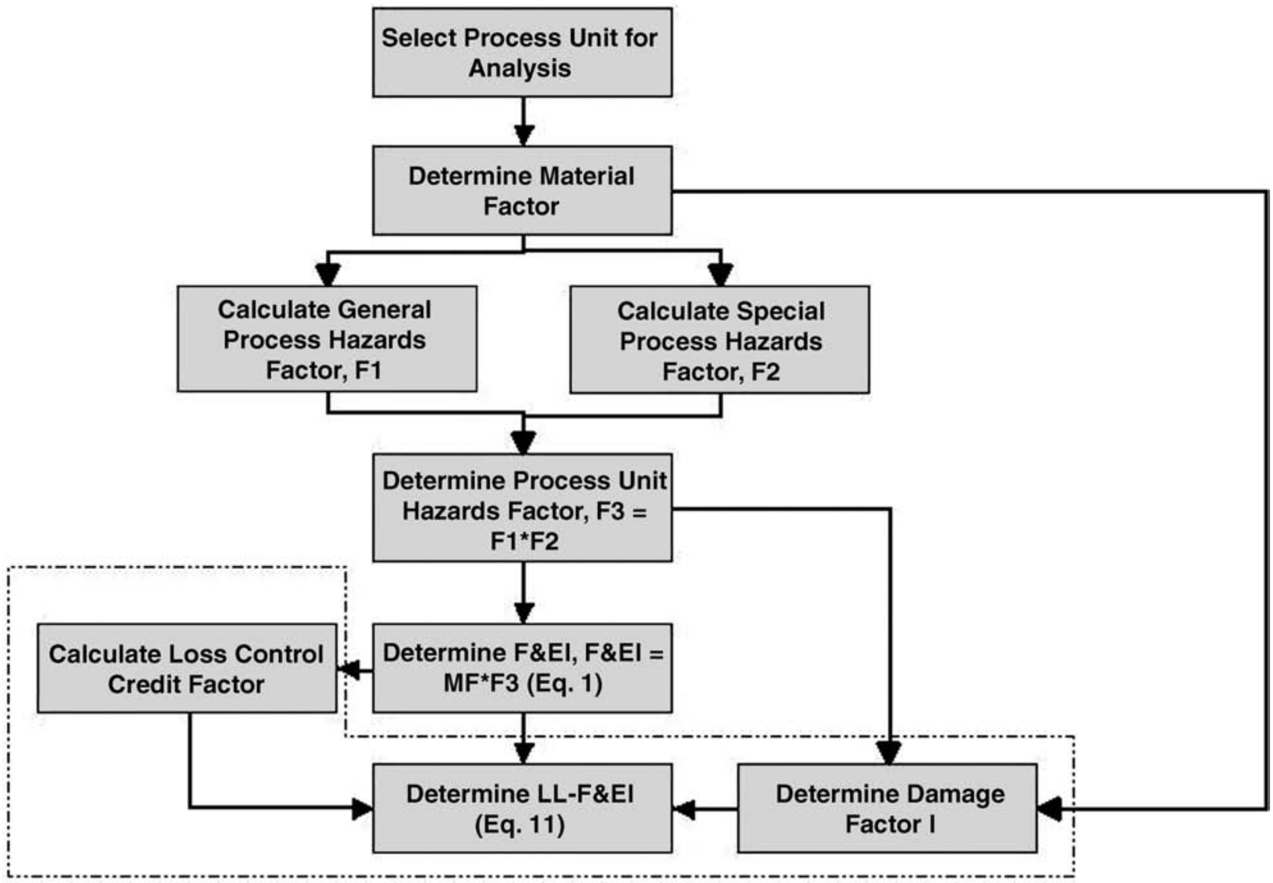

Figure 6. Procedure for estimating of the LL-F&EI. Only the elements within the dash–dot line has changed compared with the procedure shown in the F&EI Guide.

Table 2. Application of LL-F&EI to reactor and distillation column.

	Reactor	Distillation
Material factor	16	16
General process hazards factor	3.25	2
Special process hazards factor	3.5	1.2
Process unit hazards factor	8	2.4
Fire & Explosion Index	128	39
Damage factor	0.68	0.35
Loss control credit factor	0.96	0.96
Maximum probable property damage	?	?
Maximum probable days outage	?	?
LL-F&EI	47	10
Risk level indicated by LL-F&EI	Intermediate	Light

the exothermic nature of the reaction and the amount of material involved, while the distillation column represents a light hazard.

The reactor after a number of years of operation experienced a runaway condition due to overfilling and a malfunctioning relief system. The distillation column has been operated without major problems by students over a 20 year period. The values of the LL-F&EI appear to reflect the operating history by indicating, that the reactor is an intermediate risk, and that the distillation column represent a light risk. In the university environment, where the distillation column is located, risk measures such as MPPD, MPDO and BI make little sence, but whether a particular activity represent a light, intermediate or severe risk is relevant information. The same could apply to industrial pilot plants.

CONCLUSION

The F&EI Guide is a very carefully written engineering document. Careful analysis of the relationship between Process Unit Hazards Factor and MF on the one side and DF on the other side reveal, that the current procedure given in the F&EI Guide could possibly overestimate the DF for low MFs and high Process Unit Hazards Factors. A plot, which more clearly shows the relationship between the involved quantities has been presented and polynomials regressed to represent the relationships.

Other improvements may be possible, and the suggested 'Offset F&EI' (Gupta, 2003) definitely is one way to allow designers to evaluate the impact loss control measures before the plant is build or costed. However, it has been shown, that the analysis of the 'Offset F&EI' by Gupta *et al.* is incorrect and leads to incorrect conclusions due to the difference between hazard and risk. An alternative called the Likely Loss Fire & Explosion Index or LL-F&EI has been proposed in this work. For the LL-F&EI, degrees of risk have been defined similar to the degrees of hazard associated with the F&EI.

REFERENCES

American Institute of Chemical Engineers (AIChE), 1994, *Dow's Fire & Explosion Index Hazard Classification Guide* (F&EI Guide), 7th edition (The American Institute of Chemical Engineers, New York, USA).

Gupta, J.P., Khemani, G. and Mannan, M.S., 2003, Calculation of Fire and Explosion Index (F&EI) value for the Dow Guide taking credit for loss control measures, *Journal of Loss Prevention in the Process Industries*, 16; 235–241.

Lutus, P., 2003, *Polynomial/Trig Regression Data Fit*, URL: http://vps.arachnoid.com/polysolve/index.html (viewed 2005-05-24).

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APPENDIX A

Results of calculation of polynomials to fit the data in Figure 3. Even though a second degree polynomial fits the data with an R^2 greater than 0.998 a third degree poloynomial fit has been used in analogy with the polynomials in the F&EI Guide. The Tabel A1 contains the coefficients of the polynomial relating the ratio damage factor/material factor to the process unit hazards factor

$$\mathrm{DF/MF} = a_0 + a_1 * \mathrm{F}_3 + a_2 * \mathrm{F}_3^2 + a_3\mathrm{F}_3^3$$

calculated using the tool provided by Lutus (2003).

APPENDIX B

Results of calculation of polynomials to fit the data in Figure 2. Even though a second degree polynomial fits the data with an R greater than 0.998 a third degree poloynomial fit has been used in analogy with the polynomials in the F&EI Guide. The Tabel A2 contains the coefficients of the polynomial relating the damage factor to the process unit hazards factor

$$\mathrm{DF} = a_0 + a_1\mathrm{F}_3 + a_2\mathrm{F}_3^2 + a_3\mathrm{F}_3^3$$

calculated using the tool provided by Lutus (2003).

Table A1

MF	R^2	S-error	a_0	a_1	a_2	a_3
1	1.00000	2.47644E-5	0.390000E-2	0.295234E-2	0.403149E-2	−0.289899E-3
4	1.00000	1.71993E-5	0.633571E-2	0.486829E-2	−0.226732E-3	0.287879E-4
10	1.00000	2.03682E-5	0.989286E-2	0.172742E-2	0.875541E-4	−0.176768E-5
14	1.00000	1.54303E-5	0.147143E-1	0.130996E-2	0.525000E-3	−0.388889E-4
16	1.00000	2.31065E-5	0.159714E-1	0.130996E-2	0.679221E-3	−0.545455E-4
21	1.00000	2.97900E-5	0.162000E-1	0.367161E-2	0.175866E-3	−0.338384E-4
24	1.00000	2.63181E-5	0.164143E-1	0.407107E-2	−0.636364E-4	−0.156566E-4
29	0.99999	2.73268E-5	0.167793E-1	0.317031E-2	−0.558442E-4	−0.118687E-4
40	0.99997	2.54824E-5	0.138786E-1	0.199820E-2	0.151515E-4	−0.116161E-4

Table B1

MF	R^2	S-error	a_0	a_1	a_2	a_3
1	0.99999	2.47644E-5	0.390000E-2	0.295234E-2	0.403149E-2	−0.289899E-3
4	0.99999	2.74585E-5	0.258071E-1	0.191012E-1	−0.816666E-3	0.1083333E-3
10	0.99999	2.65908E-5	0.986000E-1	0.175904E-1	0.810606E-3	−0.131313E-3
14	0.99999	3.51250E-5	0.205857	0.189795E-1	0.761742E-2	−0.569192E-3
16	0.99999	2.62494E-5	0.256814	0.198081E-1	0.110723E-1	−0.881061E-3
21	0.99999	2.76548E-5	0.340264	0.765700E-1	0.390260E-2	−0.729293E-3
24	0.99999	2.59731E-5	0.395821	0.964008E-1	−0.134167E-2	−0.380556E-3
29	0.99999	1.87064E-5	0.484843	0.942001E-1	−0.213561E-3	−0.311869E-3
40	0.99999	9.10893E-6	0.554093	0.808253E-1	0.319481E-3	−0.439141E-3