NISTIR 6872

Evaluation of Fire Models for Nuclear Power Plant Applications: Cable Tray Fires

International Panel Report

Compiled by Monideep K. Dey, Guest Researcher

National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

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Phillip J. Bond, Under Secretary of Commerce for Technology
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Arden L. Bement, Jr., Director

Appendix C: Benchmark Analysis with MAGIC, Bernard GAUTIER, Helene ERNANDORENA, and Maurice KAERCHER, EdF, France

International Collaborative Project to Evaluate Fire Models for
Nuclear Power Plant Applications
Benchmark Exercise # 1
Cable Tray Fires of Redundant Safety Trains

Simulation of a single room problem using code MAGIC

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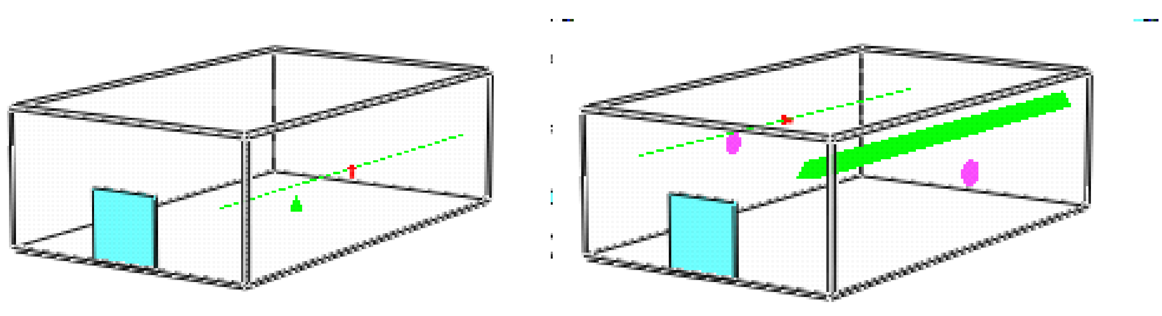
Introduction

The calculations presented here were done with MAGIC V 3.4.7. The code was used in its standard version. MAGIC uses a two-zone model including most of the classic features:

- Gaseous phase combustion, governed by pyrolysis rate, product properties and oxygen feeding (plume entrainment)
- Two homogeneous smoke and gas layer temperature and concentration stratification, mass and energy balances into gases
- Heat transfers by contact and radiation between flame, gases and smoke, walls and surrounding air, thermal conduction in multi-layer walls, obstacles to radiation
- Mass flow transfer: Fire-plumes, ceiling-jet, openings and vents
- Thermal behavior of targets and cables, secundary source ignition, unburnt gas flames across opening

A data base for combustibles and materials is also available. A description of the code features can be obtained in [1]. The validation file of the code [2] is based on full-scale experiment data. This file is used to improve the validated range of the code: volumes from 11 to 1300 m^3, fires from 100kW to 2.5 MW, mono-compartment and multi-compartment varied configurations, liquid fires, solid fires, pool fires, linear fires

Two case were proposed to the participants (figure 1 - [4]). Simulation were done with Version 3.4.7 of MAGIC with a LOL (Low Oxygen Limit) of 12%, then of 0%.



Part 1: fluxes on a target exposed to a trash bag fire (5 cases studied)

Part 2: redundant tray B exposed to a tray A cable fire (13 cases studied)

Figure 1 : the proposed cases

Input parameters

The data used for input was directly provided by the benchmark definition of scenario [4].

Some of the requested parameters were not taken into account :

- the wall emissivity (0.94 wanted) is fixed to 0.9 in MAGIC
- air humidity (Magic considers dry air)
- the door structure is not considered in MAGIC (adiabatic material)
- the specie yields are not considered in MAGIC. Only [O_2], [C_nH_m] and smoke properties are considered in MAGIC, their production is obtained from the source and plume behavior.
- chemical characteristics of cables were not taken into account: only thermo-physical characteristics are necessary in MAGIC.
- the tray width and depth were not necessary : we use a single cable to obtain a conservative approach of the cable temperature increase.

Some missing data which had to be set:

- smoke opacity for the trash-bag fire was fixed to 0.5 m^{-1}
- the missing stoechiometric ratio for the trash-bag fire was fixed to 1.184 gO2/g

Some other data was not fixed by the text and let to the user choice :

- wall effect on plume : this option impacts on the plume correlation, using a mirror effect when the plume in confined to a wall.
- the conduction meshing is not automated in version 3.4.7. The user is supposed to apply the Fourier Law in order to mesh correctly. This last point is one of the most current user effects observed on the code. The meshing is automated and optimized from version 3.4.8.

Least, the time step and the end of simulation time were not specified in [4].

Part I : result analysis

Base case:

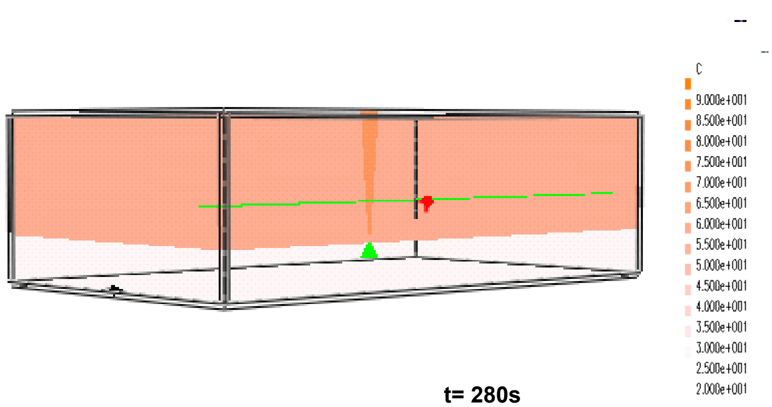


figure1: part 1 base Case : smoke filling of the room at t=280s

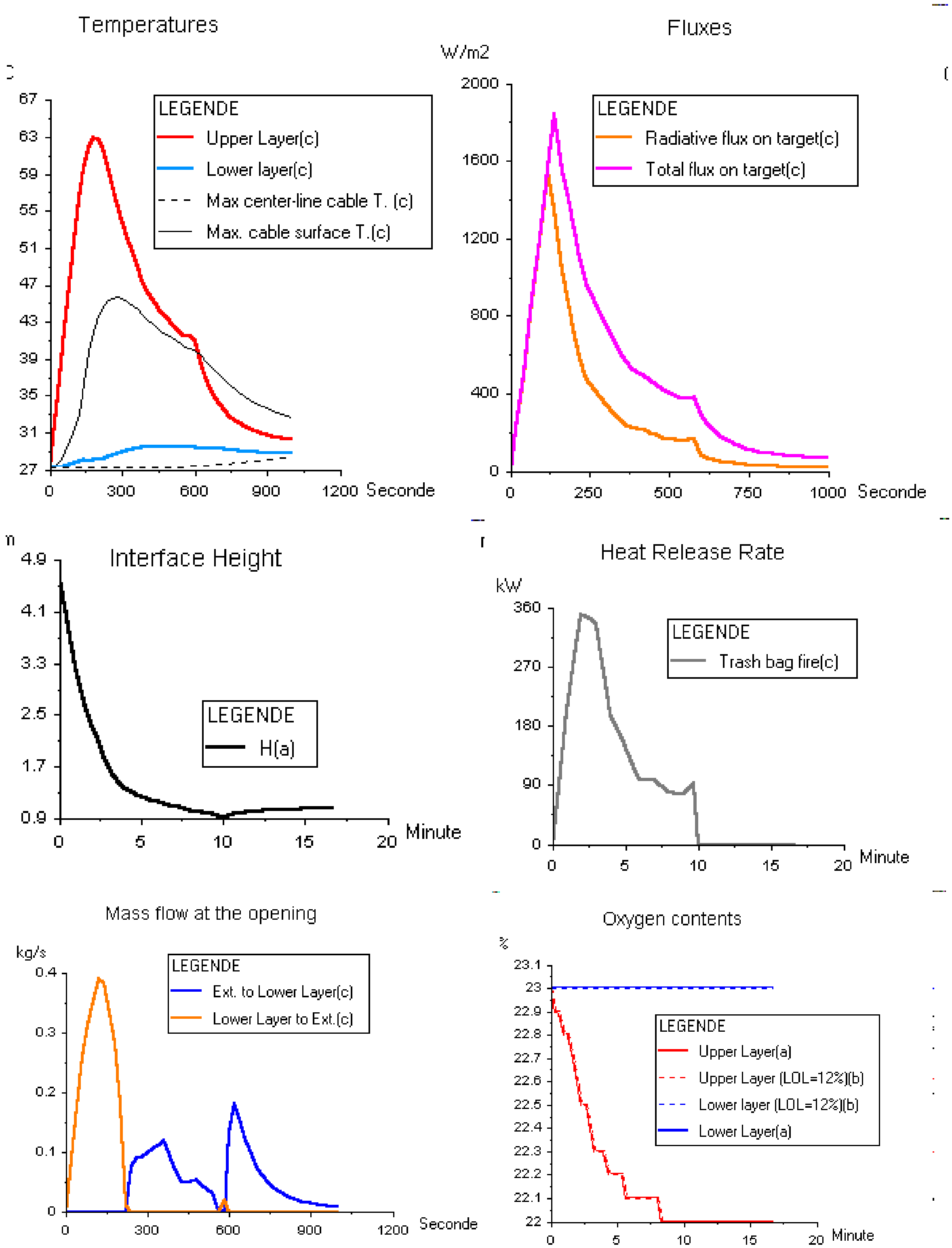


figure 2: part 1 base case

No damage of the target cable is observed in this case . the smoke filling is stabilized (~1m) but temperatures are low. There is not enough consumption of oxygen to show a difference between 0% and 12 % LOL.

Effect of ventilation (case 4 and 5)

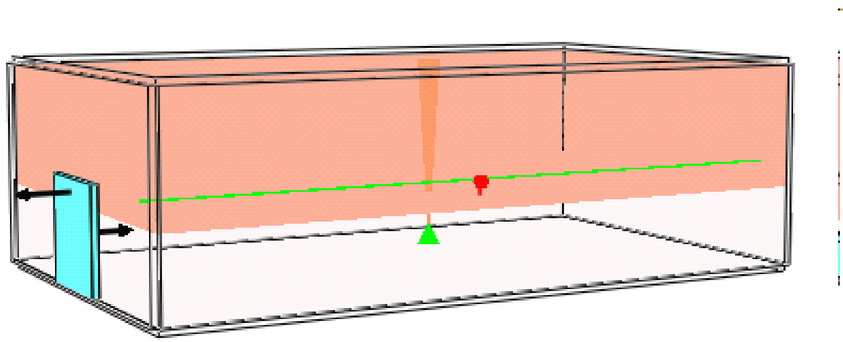


figure 3 : smoke filling in case 4 (door open) at t=800s

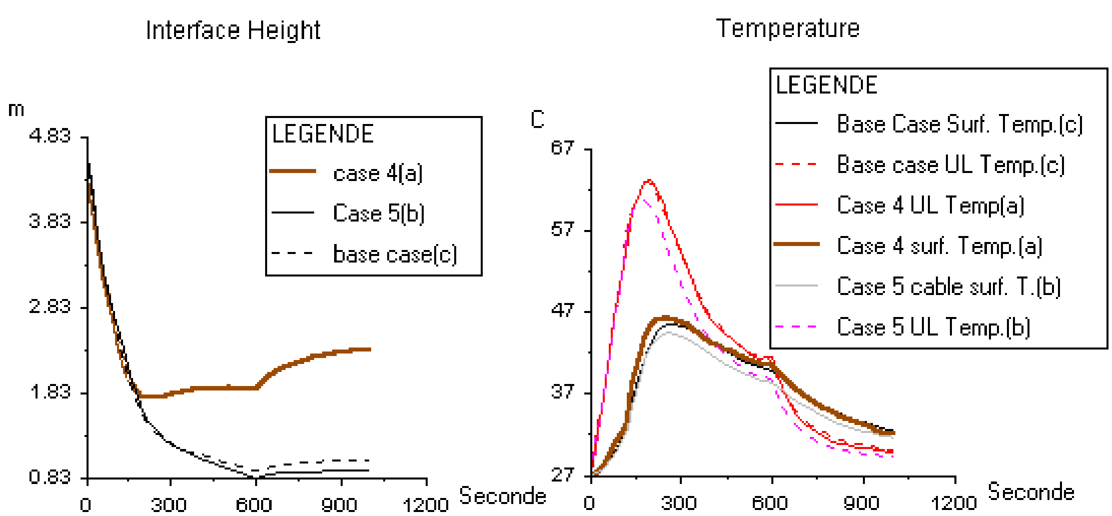


figure 4: ventilation case 4 (door open) and 5 (mechanical vent)

The mass flow balance smoke filling are changed in those two cases: nevertheless, this has no strong effect on the target, which remains in the Upper Layer.

Effect of distance (case 1, 2, 3)

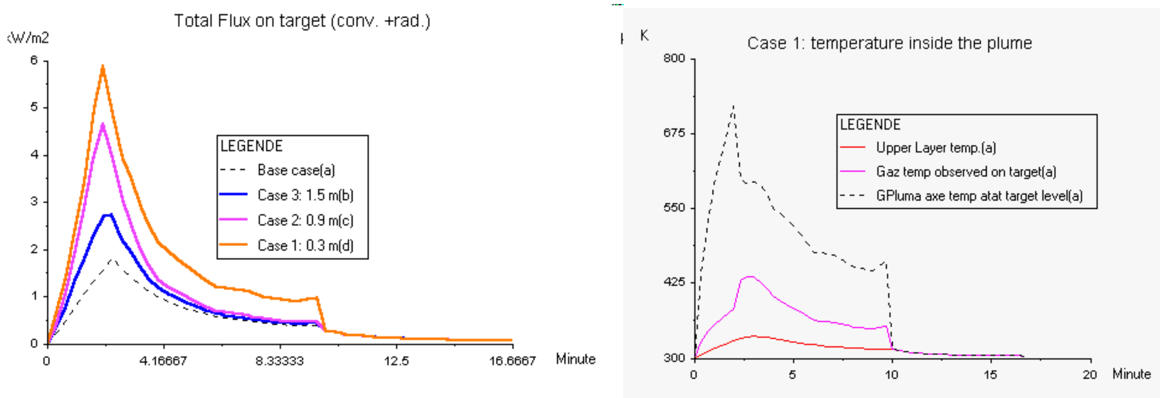


figure 5 : effect of distance

Distance has a strong effect on the radiative flux. The temperature on the target inside the plume is obtained[1] through the Heskestad correlation, taking into account the distance to the axis. As the temperature given by this correlation decreases quickly with the distance to the axis, it can be more conservative to consider the target on the axis (figure 5).

Part II : result analysis

Base case

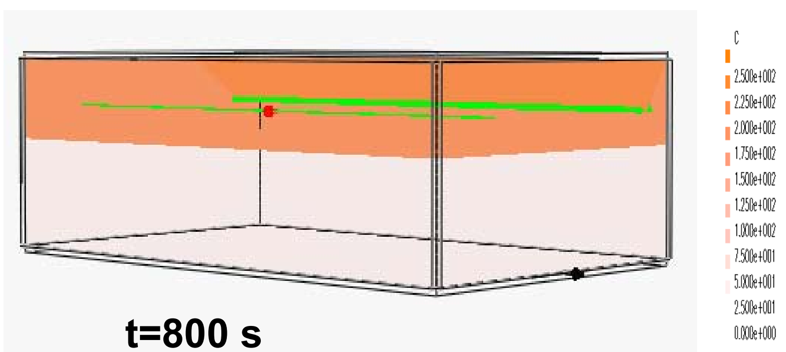


figure 6: smoke filling in part II base case at t=800s

In the base case of part II, no damage of the redundant cable in tray B was obtained. In fact this is due to the lack of oxygen: even if the source is more important, the heat release becomes quickly weak. Note than in this case, the standard MAGIC thermal model of cable was used.

[1] Unlike what was said during the slide presentation...

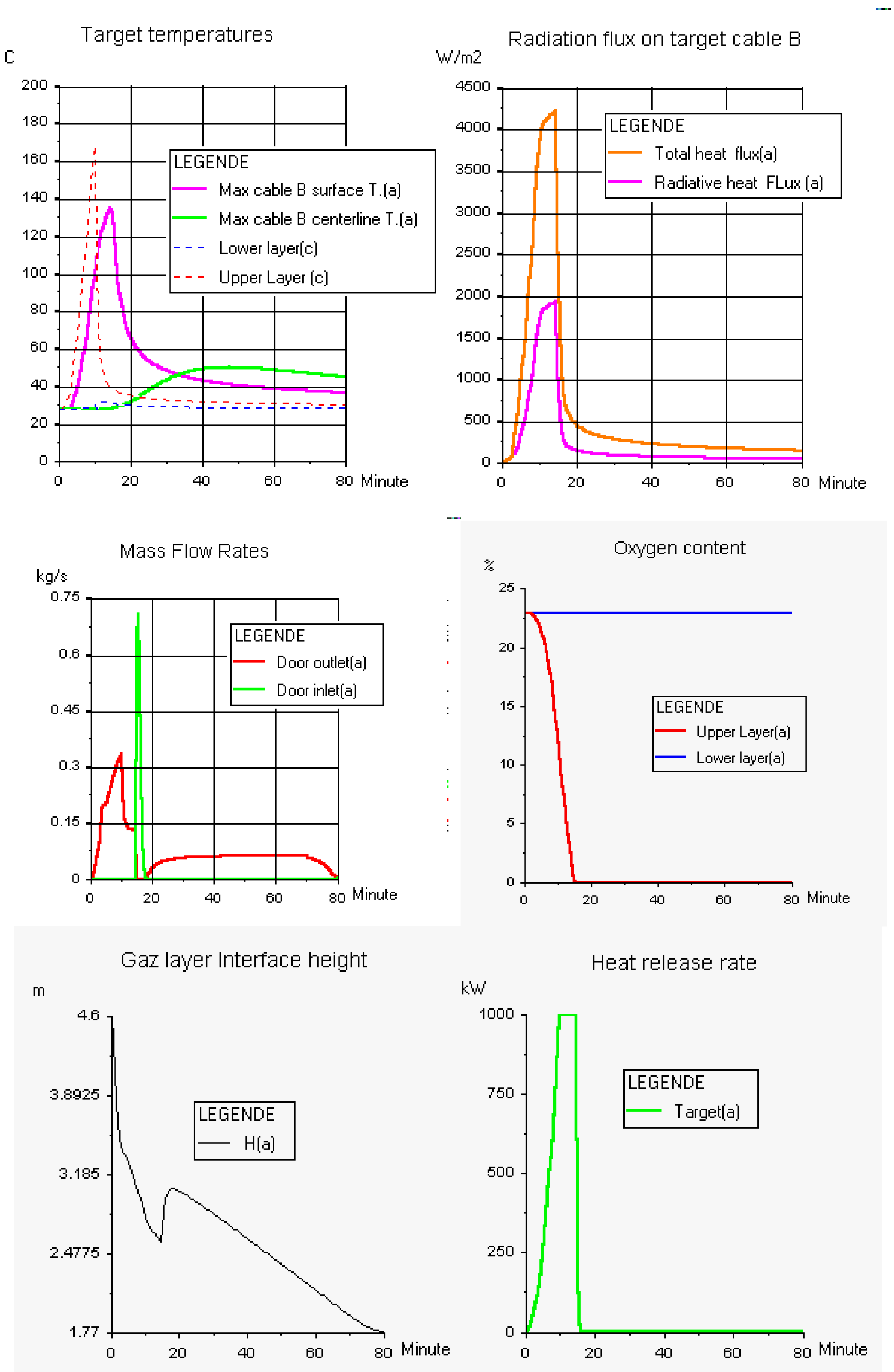


Figure 7: Part II Base case (LOL=0%)

Effect of the LOL

Unlike in part I, the results obtained in part II with a LOL of 12% or a LOL of 0% are quite different. Here, we have an oxygen limited fire, has shown in figure 8. The heat release can be performed further in case LOL=0%, with significant influence on the target temperature peak.

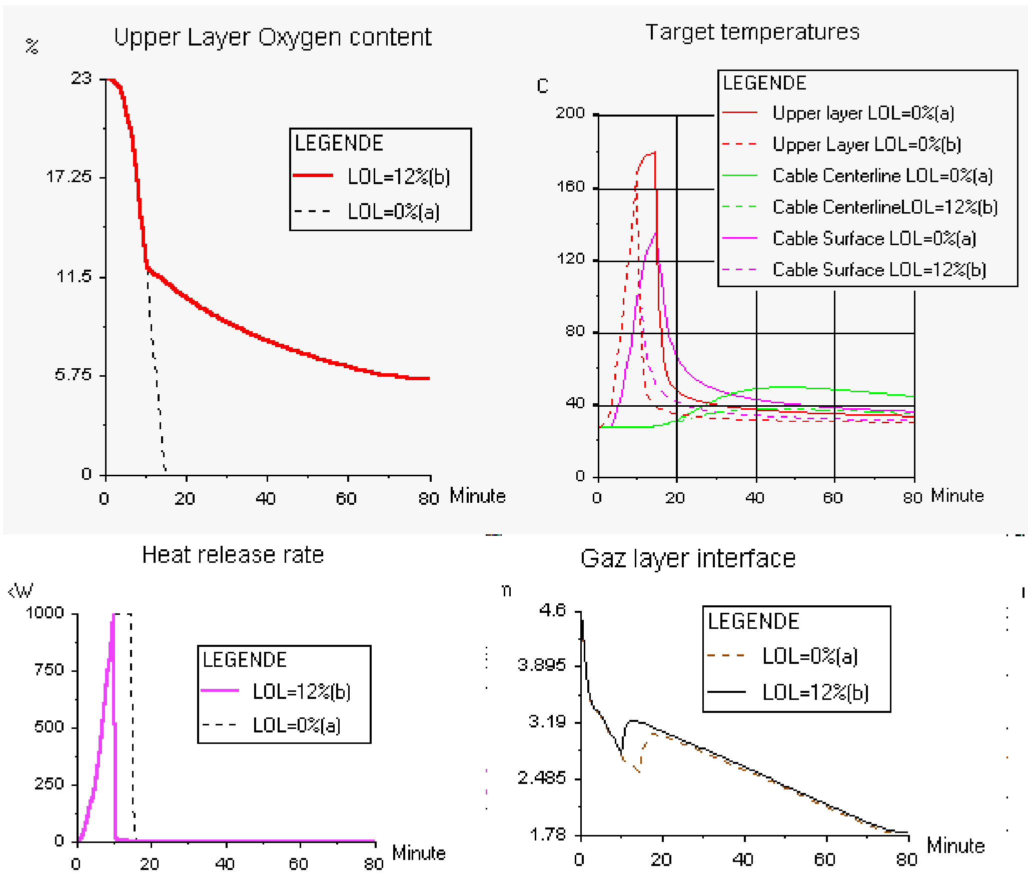


figure 8: effect of the LOL

Mass loss rate increase (case 3-8)

Due to the existing lack of oxygen, the increase of mass loss rate has no significant effect on the fire, which is controlled by the ventilation rate. This is even more true with LOL=12%.

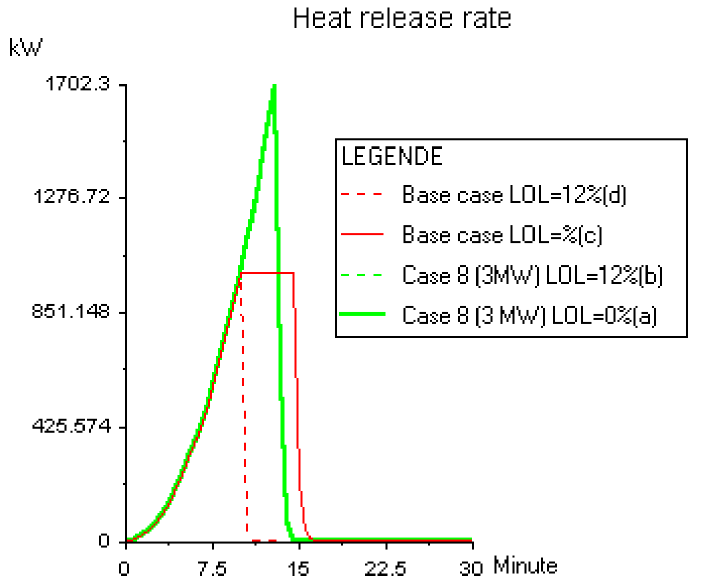


figure 9: mass loss increase

Ventilation effects (cases 9-10)

Due to oxygen rate depletion below the ceiling, the fire conditions are not noticeably changed.

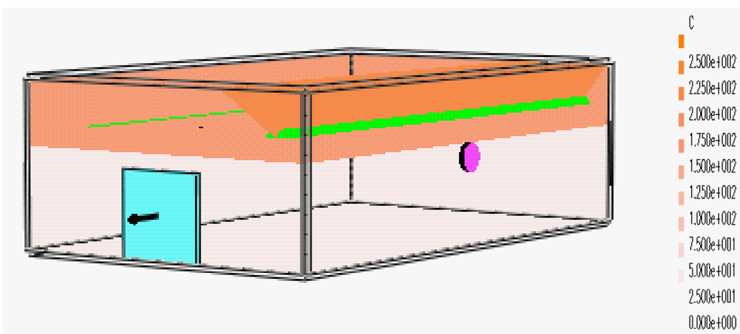


figure 10 : smoke filling at t=600s in case 9

Effect of the cable structure and elevation (cases 13 and 11)

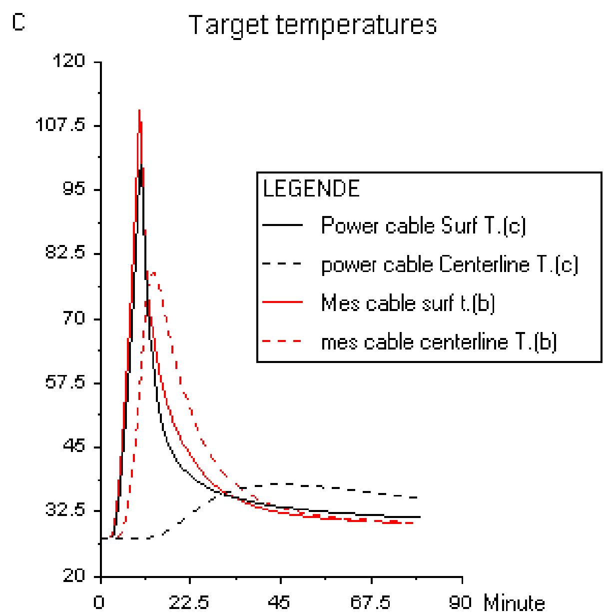


figure 11: effect of cable structure and elevation

The structure of the cable has a strong effect on its resistance: the power cable has more inertia and resists longer (figure 11).

In case 11, the influence of the target elevation is not significant: cable B remains outside of the ceiling-jet region. In fact this point should be discussed further, for the ceiling-jet model is not calculated for R/H > 3, this value being the limit of the validation field (COOPER model [1]). In any case, the target model is not connected to the ceiling-jet model in Version 3.4.7 of MAGIC. In the present case, the cable should be considered lost in a real life risk study.

Result summary

Part I :

Part I	O2 Conc. @ 600s (%)	Max Plume Flow (kg/s)	Max Pressure (Pa)	Max outflow (kg/s)	Layer Ht @ 240s (m)	Max UL Temp. (K)	Max flux on Target (W/m2)	Max. Target CL Temp. (K)
Base Case	R : ZC 22%	NA	R : 961 Pa	R-from LL: 0,389kg/s	R : 1,37m	R : 336 K	Rad :1550,6 W/m2 Total : 1839 W/m2	R : 301,3 K
Case 1							Rad : 11648,8 W/m2 Total : 12855 W/m2	R : 302,9 K
Case 2							Rad : 4654 W/m2 Total : 4665 W/m2	R : 302,3 K
Case 3							R : 2688 W/m2 Total : 2732 W/m2	R : 301,6K
Case 4			R- for neg.peak : -0,1Pa	R - form UL 0.855kg/s	R : 1,77m	R : 336 K	R : 1545 W/m2 Total : 1845 W/m2	R : 301,4 K
Case 5	R :ZC 22,5%		R : 714 Pa		R : 1,43m	R : 333,6 K	R : 1571 W/m2 Total : 2042 W/m2	R : 301,3 K

Part II:

Part II	O2 Conc. (%)		Max Pressure (Pa)		Time @ (s)	Max UL Temp. (K)	Max flux on Target (W/m2)	Max. Target CL Temp. (K)
Base Case	R-@500s : 17%		R-for pos.peak : 721Pa		Layer Ht=3,4m : 206s	R1 : 452,5 K R2 : 440 K	R1 :rad 1920W/m2 Total : 4207 W/m2 R2 : rad 1677W/m2 Total : 3785 W/m2	R1 : 322,6 K R2 : 310,7 K
Case 1							R1 : 1920W/m2 Total : 4208 W/m2 R2 : 1677W/m2 Total : 3785 W/m2	R1 : 322,5 K R2 : 310,7 K
Case 2							R1 : 1920W/m2 Total : 4208 W/m2 R2 : 1678W/m2 Total : 3784 W/m2	R1 : 322,5 K R2 : 310,7 K
Case 5							R1 : 3165 W/m2 Total : 6205 W/m2 R2 : 1678W/m2 Total : 3785 W/m2	R1 : 322,2K R2 : 310,7K
Case 10	R -@ 3800s R1:0% R2:5,77%				Layer Ht=2,4m no value	R1 : 453,5 K R2 : 440,8 K	R1 : 1938,2W/m2 Total : 4238 W/m2 R2 : 1681W/m2 Total : 3792 W/m2	R1 : 322,2 K R2 : 310,7 K
Case 11							R1 : 1920W/m2 Total : 4207 W/m2 R2 : 1677W/m2 Total : 3784 W/m2	R1 : 322,6 K R2 : 310,8 K
Case 12							R1 : 1000,8W/m2 Total : 1119.8 W/m2 R2 : 832,5W/m2 Total : 877 W/m2	R1 : 306 K R2 : 302,6 K
Case 13								R1 : 398,1 K R2 : 351,7 K

Plume flow is not a standard output of MAGIC. All results are in acceptable domain.

Discussions

About uncertainties...

Like the physical models choices are fixed in MAGIC, the calculation uncertainty can be related to the limits and the accuracy observed in the field of validation of the model, and to the user input uncertainties. It is difficult to define a exhaustive rule for the validation field. In the validation file, the experimental configurations present compartments from 10 to 1300m3, fire source from 100 kW to 2,5 MW. The results obtained are globally satisfactory, with different accuracy in each test.

The most significant input parameter are the source power, the thermophysical parameters (k, h, C, ρ) and source characteristics (stoechiometry , radiative part, etc..).

...and user effect

The "User Effect" is limited as much as possible through the graphical (3D) control and the tests performed by the interface (definition range of values, coherency of the building). The stronger user effect has been observed on conduction meshing : significant errors can be committed on gas temperature in the dynamic steps when the meshing is not fine enough. That the reason why this input will be automated in the next version of the code.

The second user parameter identified was the wall effect on the plume . In this case no significant effect (less than 1 °C) can be observed on temperatures.

The interpretation of result data is a strong source of user effects: for instance in MAGIC the cable behavior is not accurately evaluated inside the plume or ceiling-jet. In EDF practice, we consider than a cable is lost when in a plume of Ceiling-Jet. This is an example of the good knowledge of the code feature needed.
Another example is the cable dysfunction criterion. It can vary from one author to another and is very important in safety assessment. This is an example of the good methodology needed.

Models used in MAGIC and significant for the tests

A short summary of the models used in Magic would be:

- the plume and flame experimental entrainment correlation from MAC CAFFREY[a]
- an integrated radial conduction model for cables
- a 1D conduction model into walls, ceiling and floor
- a semi-transparent radiation model for gas, and a radiosity system for walls,
- HESKESTADT correlation for flame height[b] and thermal targets.
- a medium specific area model for opacity of cable smokes[c] (BARAKAT-VANTELON)
- a Ceiling-Jet[d] (L.Y. COOPER)
- "Bernoulli" flow at vertical vent (CURTAT-BODART)

The physical models resulting from the integration of physic laws have no other domain limits than those of the material properties. For (a) (b) (c) and (d) , specific domain limits have been defined in the original experimental works.

Validation of MAGIC

The type of configuration (power, room-size) proposed in the benchmark is well represented in the Validation File of MAGIC [2]. This validation concerns mainly field temperatures and fluxes. The cable center temperature model has been validated at laboratory scale in a "Tewarson" calorimeter device through an EDF experimental program [3].

The validation process of MAGIC gives an idea of the calculation uncertainties. In general, conservative errors are less regarded than "unconservative" ones, for design purpose. For instance, calculated temperature are rarely less than 10°C lower than measurement, but 50°C higher than measurement can be observed.
The flux calculation is less accurate due to many experimental effects. A 50% lower than measurement can be observed. Mass flows are often not available (significant measurement uncertainties).

Effect of the source height

Source height is an important parameter that could have been considered in the benchmark, especially when a door is open (cable trays can be found in lower location). A supplementary calculation has been done in that way (figure 12).

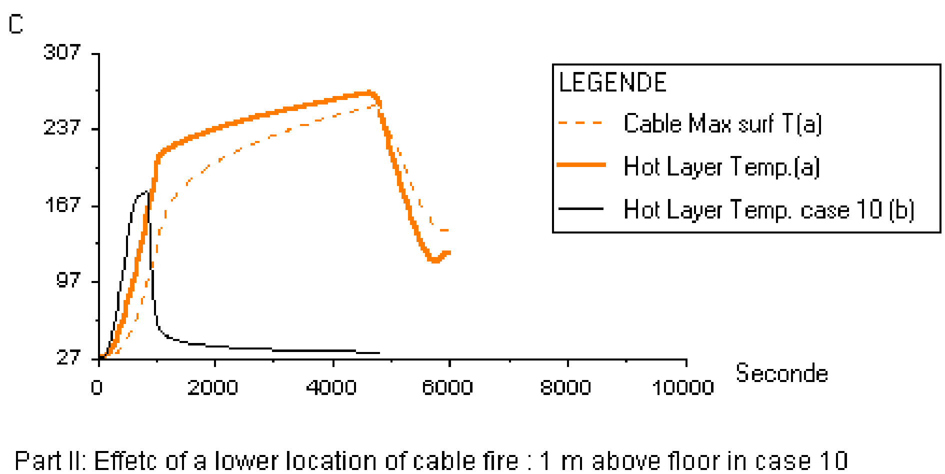


figure 12: effect of a lower fire source location

The comparison with case 10 shows that the consequences of the fire are quite different: due to the oxygen feeding by the open door, the fire can go on. In this case, cable B would have been probably lost.

Conclusion

The conclusion with follow the suggested guide line [5].

Capability and strength of code MAGIC

From the physical modeling point of view, capability and strength of code MAGIC could be summed up in:

- the global energetic balance done and the good prediction of the level of temperature within the room
- the targets and cable flux and thermal behavior models
- the mass flow prediction by taking into account pressure,
- the calculation of oxygen balance and consumption
- the good level of the radiation model and the wall conduction model
- the good level of information and control provided by the interface (see further).

Weaknesses and limitation:

The behavior of cables is not modeled into plume and flame (cables are considered lost in EDF approach in those cases). This point could be enhanced. The thermal target give a "correlated" response in those cases (Heskestadt model).

The zone model can't represent some 3D aspects like aeraulic "by-pass". A conservative approach is used considering that all the oxygen given to the plume can be used. Some real scale fire tests have shown that confined fires could be maintained with a measured O_2 concentration lower than 10%. In those cases, aeraulic by pass and distant flame were observed. For this reason, EDF does not use the Low Oxygen Limit in safety studies.

The most important criticism one can make about the MAGIC fire model is that mass loss and thermal behavior of source are not coupled. It is the same for most of the existing codes, apart some very specific cases. The problem is that this coupling is really a difficult problem, especially for solid fire. This can be balanced by using characteristic mass loss profile for one given combustible in one given situation. This type of profile is at the center of the methodological discussions for safety assessment.

Need of a more advanced model?

Maybe the most significant progress has to be made on the mass loss rate of the cable. On this aspect a lot of studies have been done [3]. It seems that a complete fire spread model coupling heat release and mass loss could only be proposed in CFD codes, due to the level of local information needed. For common purpose, one will have to use standard profiles and correlation. An important discussion on this data should be held in the nuclear assessment field to agree of the more adapted ones.
Another important point is the target behavior which could be enhanced in the "dynamic" zones (plume, ceiling-jet). Adapted real scale tests would be of interest, especially for thermal behavior of cables.

Could a simpler model be sufficient in those cases?

In some cases a simpler model can be adapted, but cable thermal response, oxygen consumption balance and ventilation effects had to be taken into account in the cases studied here. That means a minimum of balanced model is necessary: zone models are the minimum level of modeling needed here.

Additional type of model needed:

Cable behavior inside the plume or Ceiling-jet would be of interest. Of course, more information would necessary here.

User interface of MAGIC

The user interface is probably one of the most outstanding strengths of code MAGIC. Many automated controls are performed on value definition range, building coherency, and the graphical 3D view provide a powerful visual control to the user. The use of such an integrated interface limits notably the risk of input mistake.

Nevertheless, the user must be aware of some aspects of zone modeling not to forget:

- the conservative approach of phenomena (ex: combustion efficiency)
- the rough representation of air stratification temperature
- some 3D aeraulic and flame effects are not considered (ex: horizontal distance ventilation/source) but over-predicted (always conservative).

Outlook

The most relevant parameter in the deterministic fire modeling is certainly combustible mass rate. There is a great need here for conventional curve profiles or formulas, and experimental process for cable behavior identification.We should define a consensus mass loss profile data file
On that point, from EDF experience we should at least consider:

- not confined cable tray with low ignition (slow spread)
- not confined cable tray with strong ignition (up to ~x00kW: fast spread)
- confined cable trays (in smoke) : "flashover" (global instantaneous ignition)

Cable or component dysfunction is another important parameter

- the cable temperature criterion has to be enhance. Internal temperature of cable seems to be a reliable variable to correlate [7].
- on that point, experimental test benches could be normalized

Multi-room configuration is also an essential issue. For instance, in EDF NPP configuration, component in the first room are always protected if concerned by safety issues : what is important and has to be modeled is what happen to component in secondary rooms. For this reason, it would be of interest to propose more multi-room configurations in the future benchmarks...

To conclude, we should remind the "good way" to process is to go from the more conservative to the more complex: in safety assessment, one should use simple (conservative) formulas or models when sufficient and go into details with zone or CFD codes when necessary. If the methodology is organized in that way, it will be easier to promote the use of numerical model in the fire risk assessment.

REFERENCES

[1] B. GAUTIER, O. PAGES "MAGIC software version 3.4.1: mathematical model" EDF HT-31/99/007/A.
[2] B. GAUTIER, Ch. LE-MAITRE "Validation file of Software Magic Version 3.4.1". HT-31/99/002/A Feb.99.
[3] E. THIBERT *"Modélisation de la combustion des gaines de câbles électriques"* Thesis from University of Poitier-FRANCE Nov. 1999.
[4] M. Dey "International Collaborative Project to Evaluate Fire Models for Nuclear Power Plant Applications, Benchmark Exercise # 1: Cable Tray Fires of Redundant Safety Trains: definition of scenarios" NRC September 11th 2000.
[5] M. Dey "suggested guideline/questions for presentation of Results of Benchmark Exercise".NRC 2000