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SEVEN expert system: a decision support tool for fire safety analysis in the nuclear area

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TECHNICAL SAFETY



MEMBRE DE

Why developing expert systems?

- The two-zone model SYLVIA is used for fire safety studies in nuclear facilities
- To take into account the different sources of uncertainty coming from initial and boundary conditions and from model parameters, SYLVIA is associated with SUNSET, one of the IRSN statistical tool used in support of risk analysis studies
- Such a use of SYLVIA requires a large number of runs and a significant statistical analysis, not always compatible with the requirements of safety assessments in terms of deadlines
- To overcome this difficulty, IRSN is currently developing expert systems based on SYLVIA databases. This approach allows deriving the most likely diagnosis or prognosis in a very short time, but also deriving a more complex form of reasoning combining prognostic and diagnostic inferences



The expert system

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 Computer program that has the ability to answer questions in a very short time, by reasoning from observations and generic knowledge



SUL

Expert system based on Bayesian Belief Network methodology



- An arrow models a causal relationship
- A single processor (processing unit) is associated with each arrow for the local transfer of the information
- The graph allows connecting all single processors



 The link between X and Y is encoded by means of a Conditional Probability Table CPT_{XY}

The computational machinery of the Bayesian single processor:



The two-zone model SYLVIA

- Software developed at IRSN for the study of ventilation, fire and airborne contamination transfers inside nuclear facilities
- Advantages of the SYLVIA software
 - Complete modeling of an industrial ventilation network
 - Coupling of the fire with the ventilation
 - Low CPU time consumption
 - Computer architecture suitable for big data



SYLVIA database

- SYLVIA database obtained from a Monte-Carlo simulation
- For each parameter of the study, a value is randomly drawn in its range of variation, creating a set of values of the parameters characterizing the SYLVIA calculation to be performed. By performing this simulation, we obtain the values of the responses associated with this parametric configuration
- The Monte-Carlo method consists in reiterating this procedure a large number of times

Conditional probability tables

- The link between responses and parameters is encoded by means of Conditional Probability Tables (CPTs)
- Two simplifications are made to limit the size of CPTs:
 - Discretization of the parameters and the responses of the study
 - Only the dependency links between a response and its influential parameters are taken into account due to the combinatorial explosion of the configurations

	R1	Class 1	Class 2	Class 3	Class 4
P_1 P_2 P_3	$P_{1}1P_{2}1P_{3}1$	0,96	0,04	0,00	0,00
	$P_{1}1P_{2}1P_{3}2$	1,00	0,00	0,00	0,00
	$P_{1}1P_{2}1P_{3}3$	1,00	0,00	0,00	0,00
	P ₁ 1P ₂ 2P ₃ 1	0,56	0,31	0,10	0,03
	•••				
R ₁	$P_{1}3P_{2}5P_{3}3$	1,00	0,00	0,00	0,00



The SEVEN expert system

 In the presence of radioactive materials, a fire can become a vector of resuspension and dissemination of these materials and thus, can generate uncontrolled radio exposure of workers or even a release of radioactive materials into the environment

$$S = \sum S_{i,j} = \sum At_{i,j} \times C_{0i,j} \times C_{1i,j} \times C_{2i,j} \times C_{3i,j}$$

S: total activity released into the environment (source term) (Bq) $S_{i,j}$: activity of radionuclide i in physicochemical form j released into the environment (Bq) $At_{i,j}$: total activity of radionuclide i under the form j present in rooms involved in the fire (Bq) $C_{0i,j}$: fraction of the activity of radionuclide i under the form j involved in the fire (-) $C_{1i,j}$: suspension fraction of radionuclide i under the form j (-) $C_{2i,j}$: fraction of aerosols of radionuclide i under the form j not deposited in the room (-) $C_{3i,j}$: fraction of aerosols of radionuclide i under the form j not deposited in the exhaust lines (-)

 The study of the behavior of the final level of aerosol filtration is a major step in the assessment of the fire source term by simulation tools



Perimeter of the knowledge base

 The perimeter of the knowledge base determines the scope of the expert system

Air inlet Fire damper damper Fire sector Fire sector Filters Fan Leaks from/towards other compartments

General framework of the study

- Soot deposition rate upstream of the filters is a parameter of the study
- Thermal losses in ducts are not taken into account, only the gas cooling due to a dilution in the exhaust line is considered
- The fire source is modeled by a design fire

Fan characteristic curve

 Parameterization of the fan characteristic curve from the observation of 39 ambient exhaust fan curves studied at IRSN



ETSOD

Responses of the study

 The behavior of the final level of aerosol filtration in a fire situation is conditioned by the thermal and mechanical stresses experienced by HEPA filters

3 responses

Response	Discretization
Maximum pressure difference through filters (Pa)	< 500 [500 ; 1000] [1000; 1500] [1500; 2000] > 2000
Maximum gas temperature through filters (°C)	[20; 50] [50; 100] [100; 150] [150; 200] > 200
Initial dilution rate of gas (-)	<5 [5; 50] [50; 500] [500; 1000] >1000

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Parameters of the study

In the second second

Parameter	Туре	Discrétisation
Compartment volume (m ³)	С	[50 ; 300] [300 ; 700] [700 ; 1000] [1000 ; 1500]
Compartment air renewal rate (vol.h ⁻¹)	С	[1;3][3;7][7;10]
Location of the inlet air vent (-)	D	{Low ; High}
Location of the exhaust air vent	D	{Low ; High}
Compartment leak rate (vol.h ⁻¹)	С	[0.1;0.4] [0.4;0.7] [0.7;1]
Fire dampers closing times Inlet/Exhaust (s ; s)	D	{150 ; +0} {150 ; +1800} {150 ; +3600} {1200 ; +0} {1200 ; +0} {1200 ; +0} {1200 ; +1800} {1200 ; +3600} { ∞ ; ∞ }
Fire dampers resistance in a closed position (m ⁻⁴)	D	{10⁴ ; 10⁶}
Soot deposition rate (%)	С	[0; 20] [20; 40] [40; 60]
Dilution volume flow rate of gas (m ³ .h ⁻¹)	С	[4.5 10 ³ ; 2 10 ⁴] [2 10 ⁴ ; 4 10 ⁴] [4 10 ⁴ ; 6 10 ⁴] [6 10 ⁴ ; 8 10 ⁴] [8 10 ⁴ ; 10 ⁵]
Slope of the fan curve at the functional point (-)	С	[-0.6 ; -0.2] [-0.2 ; -0.1] [-0.1 ; -0.01]
Regulation index (-)	С	{0;1}



Parameters of the study

• 7 parameters related to the fire

Parameter	Туре	Discretization
Mass of fuel (kg)	C	[100 ; 400] [400 ; 700] [700 ; 1000] [1000 ; 1500] >1500
Fire growth factor (kW.s ⁻²)	D	{3 10 ⁻³ ; 0.012 ; 0.047 ; 0.19}
Maximum HRR in open atmosphere (kW)	С	[200 ; 800] [800 ; 1500] [1500 ; 3000] [3000 ; 5000]
Heat of combustion (MJ.kg ⁻¹)	С	[15 ; 25] [25 ; 35] [35 ; 50]
Fire extinction on O_2 criterion (v/v %)	D	{ 8 ; 12}
Soot production rate (%)	С	[1;5][5;10][10;15][15;20]
Soot particle diameters (µm)	C	[0.005;0.02] [0.02;0.06] [0.06;0.1] [0.1;0.3] [0.3;1]

2 parameters related to the filters

Parameter	Туре	Discretization
Initial filtration velocity (cm.s ⁻¹)	С	[1.7 ; 1.9] [1.9 ; 2.1]
Initial pressure difference through filters (Pa)	D	[250 ; 500] [500 ; 1000]



Influential parameters

 Identification for each response of its most influential parameters done with a covariance analysis on a sampling of 100,000 runs

Parameter	∆P filters	T° filters	Gas dilution rate
Mass of fuel	0.00	0.00	0.00
Fire growth factor	0,02	0,14	0.00
Maximal HRR in open atmosphere	0.05	0,28	0.00
Fire extinction on O_2 criterion	-0,07	-0,02	0.00
Heat of combustion	-0,12	-0,01	0.00
Soot production rate	0,26	-0,01	0.00
Soot particle diameters	-0,44	0,00	0.00
Compartment air renewal rate	0,05	0,16	-0.31
Compartment volume	0,10	0,12	-0.46
Initial filtration velocity	0,01	0,00	0.00
Dilution volume flow rate of gas	-0,25	-0,43	0.31
Compartment leak rate	0,05	0,01	0.05
Location of the inlet air vent	0,00	0,00	0.00
Location of the exhaust air vent	0,12	0,28	0.00
Fire dampers closing times	0,26	0,14	0.00
Pressure regulation at exhaust	0,03	-0,03	0.00
Fire damper resistance	-0.17	-0,01	0.00
Soot deposition rate	-0,10	0,00	0.00
Slope of the fan curve at functional point	-0.01	0.01	0.00
Initial pressure difference through filters	0.38	0.00	0.00

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Minimum size of the database

- The number of simulations must be sufficient to contain simulations for each configuration of the influential parameters associated with the responses
- The CPT associated with the response "△P filters" includes 201,600 configurations. A SYLVIA database of 10 million calculations ensures that each parametric configuration is observed in the database (7 days of CPU time distributed on 144 cores)

	∆P filters	T° Filters	Dilution rate
Size of CPTs	201,600	13,440	180



Example of an inference combining prognostic and diagnostic modes

What are the configurations that could lead to the loss of the final level of aerosol filtration due to filter clogging during an in-cell solvent fire in a reprocessing facility?

Results of the expert system

Fire growth factor			Maximum HRR				
			in open atmosphere (kW)				
slow		0%	200-800	~	25%		
medium		0%	800-1500	V I	25%		
fast	~	100%	1500-3000	~	25%		
ultrafast		0%	3000-5000	~	25%		

Heat of combustion (MJ kg ⁻¹)						
15-25		0%				
25-35	~	100%				
35-50		0%				

Fire dampers closing times						
Inlet (s)/Ex	haust (s)				
150 / +0		0%				
150 / +1800	~	100%				
150 / +3600		0%				
1200 / +0		0%				
1200 / +1800		0%				
1200 / +3600		0%				
00 / 00		0%				

Fire dampers aeraulic resistance (m ⁻⁴)						
10 ⁴		81%				
10 ⁶	~	19%				

Soot particle diameters Soot pro		Soot production rate (%)		Soot deposition rate (%)		Initial pressure difference through filters (Pa)					
0.005-0.02		0%	1-5		0%	0-20	V	100%	250-500	~	20%
0.02-0.06		0%	5-10		0%	20-40		0%	500-1000	V	80%
0.06-0.1		0%	10-15	V	100%	40-60		0%			
0.1-0.3	~	100%	15-20		0%						
0.3-1		0%									

Compartment volume (m ³)			Compartment renewal rate (vol h ⁻¹)			Compartment leak rate (vol h ⁻¹)			Dilution volume flow rate (m ³ h ⁻¹)			Exhaust vent location		
50-300	V	19%	1-3	~	33%	0.1 - 0.4	~	33%	4.5 10 ³ - 2 10 ⁴	~	72%	Low	V	34%
300-700	~	28%	3-7	v	33%	0.4 - 0.7	~	33%	2 10 ⁴ - 4 10 ⁴	V	22%	High	V	66%
700-1000	~	27%	7-10	v	33%	0.7 - 1	~	33%	4 10 ⁴ - 6 10 ⁴	V	4%			
1000-1500	V	27%							6 10 ⁴ - 8 10 ⁴	~	2%			
									8 10 ⁴ - 10 ⁵	V	1%			



Maximum press through fi	sure diffe Iters (Pa	erence)	Maximum gas through fil	tempera ters (°C)	ature)	Initial dilution rate (-)			
500		0%	20-50	~	72%	5	~	18%	
500-1000		0%	50-100	~	24%	5-50	~	65%	
1000-1500		0%	100-150	~	3%	50-500	~	17%	
1500-2000		0%	150-200	~	1%	500-1000	~	0%	
>2000	~	100%	>200	~	0%	>1000	V	0%	

 Case of a fire damper closing time at the inlet air vent at 2 minutes and 30 seconds and a fire damper closing delay at the exhaust air vent of 30 minutes



Fire source term



- Step 1: single ES developed in the frame of IRSN 2030 project
- Step 2: introduction of intermediate responses to aggregate the effect of some parameters (to do as part of a PhD thesis)
- Step 3: development of "satellite" ES for fire and ventilation
- Step 4: introduction of radionuclides to calculate the fire source term



Conclusion

- This new software can be considered as a complementary tool of the SYLVIA software
- Expert systems are specially designed to be used as a decision support tool for expertise in nuclear safety area
- The next step will consist in developing "satellite" expert systems that will be plugged to the SEVEN expert system. This step will allow the calculation of the soot deposition and thermal exchanges
- Expert systems represent a new generation of calculation tools in the field of probabilistic fire simulation. They contribute to build tools based on numerical technologies to better target issues in the frame of an expertise

"The enhanced expertise"

