FR9103236

INSTITUT DE PROTECTION ET DE SURETE NUCLEAIRE

DEPARTEMENT D'EVALUATION DE SURETE

DES

RAPPORT DES/030

ANALYSIS OF NON SIMULTANEOUS COMMON MODE FAILURES. APPLICATION TO THE RELIABILITY ASSESSMENT OF THE DECAY HEAT REMOVAL OF THE RNR 1500 PROJECT

NATTA M.*, BLOCH M.*, HUBERT G.**, LAURET Ph.***

Colloque international sur l'utilisation
de l'évaluation probabiliste de la sûreté
aux fins de la sûreté d'exploitation - PSA'91
Vienne, 3-7 juin, 1991

cea

RAPPORT DES/030

ANALYSIS OF NON SIMULTANEOUS COMMON MODE FAILURES. APPLICATION TO THE RELIABILITY ASSESSMENT OF THE DECAY HEAT REMOVAL OF THE RNR 1500 PROJECT

NATTA M.*, BLOCH M.*, HUBERT G.**, LAURET Ph.***

Colloque international sur l'utilisation
de l'évaluation probabiliste de la sûreté
aux fins de la sûreté d'exploitation - PSA'91
Vienne, 3-7 juin, 1991

*CEA/IPSN/DES
**EDF/SEPTEN
***FRAMATOME/Division Novatome

Août 1991

AGENCE INTERNATIONALE DE L'ENERGIE ATOMIQUE
conjointement avec
l'AMERICAN NUCLEAR SOCIETY
la SOCIETE EUROPEENNE DE L'ENERGIE NUCLEAIRE
l'AGENCE DE L'OCDE POUR L'ENERGIE NUCLEAIRE

COLLOQUE INTERNATIONAL SUR L'UTILISATION DE L'EVALUATION PROBABILISTE DE LA SURETE AUX FINS DE LA SURETE D'EXPLOITATION, PSA '91

Vienne, Autriche. 3–7 juin 1991

IAEA-SM-321/49

ANALYSIS OF NON SIMULTANEOUS COMMON MODE FAILURES. APPLICATION TO THE RELIABILITY ASSESSMENT OF THE DECAY HEAT REMOVAL OF THE RNR 1500 PROJECT

M. NATTA*, M. BLOCH*, G. HUBERT** and Ph. LAURET***

* Département d'Evaluation de Sûreté, Institut de Protection et de Sûreté Nucléaire, CEA/Fontenay-aux-Roses, France
** Service Etudes et Projets Thermiques et Nucléaires, EdF, Lyon, France
*** Framatome, Division Novatome, Lyon, France

IAEA-SM-321/49

ANALYSIS OF NON SIMULTANEOUS COMMON MODE FAILURES. APPLICATION TO THE RELIABILITY ASESSMENT OF THE DECAY HEAT REMOVAL OF THE RNR 1500 PROJECT

The experience with the LMFBR PHENIX has shown many cases of failures on identical and redundant components, which were close in time but not simultaneous and due to the same causes such as a design error, an unappropriate material, corrosion, ...

Since the decay heat removal (DHR) must be assured for a long period after shutdown of the reactor, the overall reliability of the DHR system depends much on this type of successive failures by common mode causes, for which the usual "β factor" methods are not appropriate since they imply that the several failures are simultaneous. In this communication, two methods will be presented.

The first one was used to assess the reliability of the DHR system of the RNR 1500 project. In this method, one modelize the occurence of successive failures on n identical files by a sudden jump of the failure rate from the value λ attributed to the first failure to the value λ' attributed to the (n-1) still available files, this with a probability α which quantifies the probability of the first failure being due to a common mode.

This method leads to a quite natural quantification of the interest of diversity for highly redundant systems. For the RNR 1500 project where, in case of the loss of normal DHR path through the steam generators, the decay heat is removed by four separated sodium loops of 26 MW unit capacity in forced convection, the probabilistic assessment shows that it is necessary to diversify the sodium-sodium heat exchanger in order to fullfil the upper limit of 10^{-7}/year for the probability of failure of DHR leading to unacceptable consequences.

A separate assessment for the main sequence leading to DHR loss was performed using a different method in which the successive failures are interpreted as a premature end of life, the lifetimes being directly used as random variables. This Monte-Carlo type method, which can be applied to any type of lifetime distribution, leads to results consistent to those obtained with the first one.

ANALYSIS OF NON SIMULTANEOUS COMMON MODE FAILURES. APPLICATION TO THE RELIABILITY STUDY OF THE DECAY HEAT REMOVAL OF THE RNR 1500 PROJECT

1. INTRODUCTION - THE BACKGROUND

The main objective of this communication is to present particular methods which were used to calculate the probability of common mode failure of the emergency decay heat removal (DHR) system of the RNR 1500 project which is a system comprising four identical trains.

The two methods used are based on the fact that, in many examples, failures affecting identical components in an installation are not simultaneous, but occur at the same places over a period of several months. The operation of PHENIX reactor has produced several examples of this type in leaks that affected : mixing junctions in 1974, intermediate heat exchangers in 1976 and 1977, and then again in 1984, and steam generators in 1982 and 1983.

Two main conclusions can be drawn from the failures observed :

(1) the failures occur in close succession, but are not simultaneous ;

(2) they almost always have a common cause, which could be qualified as a conceptual error resulting in a faulty design and leading to high stresses, a poor material or welding technique, a corrosive environment, etc...

No account is taken of these two facts in the methods normally used to deal with common mode failures. In the so-called *"β factor"* method or the methods derived from that method :

(1) 2nd, 3rd or 4th order common mode failures are presumed to be simultaneous with the first failure, and this is obviously very pessimistic when these failures can be detected as soon as they occur, which in principle is the case with leaks ;

(2) on the other hand, the β factor values which express the probability of common mode failure are low, of the order of 10^{-1} to 10^{-2}, whereas most of the failures observed turn out to have had a common cause.

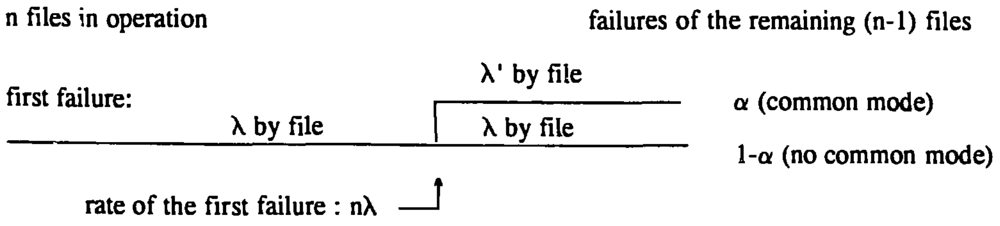
The methods described below enable the facts observed to be taken into account and the advantages gained through a high redundancy level and diversification to be treated in a straightforward manner.

2. MODELING THE NON-SIMULTANEOUS COMMON MODE FAILURES BY THE (λ, λ', α) METHOD

2.1. The (λ, λ', α) method

n identical trains are considered, each train initially having a failure rate λ. The method consists in modeling the fact that the first failure may, with a probability α, correspond to a common mode failure which is going to affect the other trains with a failure rate λ' which is greater than λ.

This model can be schematized as follows :



2.2. Data

The experience required with the various experimental sodium circuits in RAPSODIE and PHENIX indicated circuit leak rates of the order of 10^{-5} per hour and per circuit in respect of leaks requiring the circuit to be drained for purpose of repair.

Experience with PHENIX

The experience acquired with the leaks that affected the intermediate exchangers in PHENIX in 1976 and 1977 is particulary useful for quantifying the present problem. It is summarised in the Table I.

These data can be interpreted in different ways :

(1) If the total duration of presence under sodium up to the removal of exchanger A on 9 november 1977 without a leak is taken into consideration, one finds :
$\lambda = 1/(6 \times 24645\ h) = 6.8\ 10^{-6}/h$ and $\lambda' = 2/(162259\ h - 5 \times 24645\ h) = 5{,}1\ 10^{-5}/h$

(2) If only the time for which the exchangers are connected to the grid is taken into consideration, one finds :
$\lambda = 1/(6 \times 12224\ h) = 1.36\ 10^{-5}/h$ and $\lambda' = 2/(4 \times 59\ d + 3 \times 52\ d) = 2.12\ 10^{-4}/h$

With regard to the parameter α, the facts established in respect of the mixing junctions, the steam generators or the intermediate generators give grounds to believe that the value of that parameter is close to 1 ; if account is taken of the leaks that affected other circuits, a value within the range 0.5 to 0.8 seems to be more reasonable.

To sum up

The values established from the leaks observed in the sodium circuits and the intermediate exchangers in PHENIX correspond typically to the following values :

λ : $7\ 10^{-6}/h$ to $1.4\ 10^{-5}/h$
λ' : $5\ 10^{-5}/h$ to $2.2\ 10^{-4}/h$
α : 0.5 to 0.8

2.3. Practical formulae

The model proposed in Section 2.1 can be used in the calculations with Markov graphs ; these calculations also make it possible to take account of the repair options which modify the common mode failure rate by restoring a rate close to the initial rate. For simplified estimations, it is worthwhile having available a number of formulae deduced from the preceding model when the trains cannot be repaired during operation time. These formulae can be established by usual combinatory analysis and integration of exponentials ; at first order in λ and λ' they are reduced to rather straighforward formulae : for instance, during the duration t, the probability of failure of p files among the n files, all available at time 0 is $C_n^p \lambda \lambda'^{p-1} t^p$.

2.4. Effect of diversification

The model covers in a straighforward way the various possible diversifications of the circuits.

In the case of a system with four trains diversified two-by-two among lines A and lines B, each train having the same characteristics, the advantage gained by diversification can be estimated by calculating, for example, the probability of failure of the four trains during the time T, if all the trains are available at time zero.

With clear notations, at first order in λ and λ', and using the formulae mentioned in Section 2.3, for four non-diversified A trains :

$$P_{\overline{\text{4 files A}}} = \lambda_A\,[\alpha_A\,\lambda'_A{}^3 + (1-\alpha_A)\,\lambda^3{}_A]\,T^4$$

for two trains A diversified from two trains B :

$$P_{\overline{\text{2 files A + 2 files B}}} = \lambda_A[\alpha_A\,\lambda'_A + (1-\alpha_A)\,\lambda_A]\,\lambda_B[\alpha_B\lambda'_B + (1-\alpha_B)\lambda_B]T^4$$

Since there is no reason to attribute superior qualities at the design stage to either of the two systems, it may be supposed that :

$\lambda_A = \lambda_B = \lambda$, $\lambda'_A = \lambda'_B = \lambda'$ and $\alpha_A = \alpha_B = \alpha$

The advantage gained through diversification can hence be written as :

$$G_D{}^{-1} = \frac{\lambda^2\,[\alpha\lambda' + (1-\alpha)\,\lambda]^2}{\lambda\,[\alpha\lambda'^3 + (1-\alpha)\lambda^3]} = \frac{(1-\alpha + \alpha\lambda'/\lambda)^2}{1-\alpha + \alpha(\lambda'/\lambda)^3}$$

This advantage is of the order of $G_D \approx \lambda'/\alpha\lambda$ or typically a factor of 20 for $\alpha = 0{,}5$ and $\lambda' = 10\,\lambda$.

It will be possible to check that this formula is still valid when applied in first-order calculations in λ and λ' in complicated failure scenarios (this can, in particular, be verified with the calculation shown on the Figure 2 in this communication).

3. RELIABILITY OF THE D.H.R. SYSTEM OF THE RNR 1500 PROJECT

For the RNR 1500 project, at the design stage, the objective set for the decay heat removal is for its annual failure probability, resulting in unacceptable consequences, to be less than 10^{-7}/year.

3.1. The decay heat removal system

In that project, the decay heat can be removed (see Figure 1) either by the normal circuits (i.e. intermediate heat exchangers, secondary loops, steam generators and the feed water circuit) or by the emergency decay removal system which is split in four independant cooling circuits (RRA).

Each of the four emergency circuits includes a sodium-sodium heat exchanger immersed in the hot primary sodium plenum, a sodium-air exchanger cooled by the natural convection of the air in a 40 m height stack, an electromagnetic pump which circulates the sodium in the loop, several auxiliary systems (argon, purification, drainage, raising, expansion). The electromagnetic pumps are run by two power lines fed by the external electrical sources ; each power line is secured by one diesel generator and supplies two loops ; if an electromagnetic pump is unavailable, the loop can remove heat by natural convection.

The unit thermal power of the loops is such that it enables the system to accomplish its task under all operating conditions taken into account in the design. For each category of operating conditions, that task takes the form of compliance with a maximum value for the average primary-sodium temperature which, at the preliminary design stage, was chosen to be, respectively, 520°C for second category incidents, 530°C for third category accidents and 630°C for hypothetical accidents of the fourth category. The cooling capacity of 26 MW of each loop under forced convection results from the compliance with the 520°C upset criterium in the incident where the loss of the feedwater is combined with the loss of off-site power supply and the failure of one of the two diesel generator, no account being taken for the cooling by the two unsupplied loops by natural convection.

3.2. Reliability assessment

For the reliability assessment, the following criteria are taken : first the average temperature of the reactor block must not exceed 630°C, which is the fourth category criterium (in this case, a single subsequent rise in temperature beyond 520°C is allowed). The decay heat removal system must in addition bring the temperature back to 300°C enabling the steam generators to be resupplied with water.

The initiating events taken into account are the principal operating conditions under which the decay heat removal system must accomplish removal of residual power :

- dryout of the four steam generators (SGD) ;
- loss of off-site power (MdT) ;
- normal reactor shutdowns at 180°C or 250°C for maintenance of the feedwater plant ;
- failure of one decay heat removal loop, the repair of which requires drainage of the loop, leading to immediate reactor shutdown on the basis of operating instructions ; the initiating event with the most serious consequences which has been taken into account is the sodium leak affecting a sodium-sodium exchanger.

In that presentation, one deals mainly with that last situation in which the sodium of the affected loop must be drained and the temperature of the primary sodium must be lowered down to 180°C to enable the handling of the sodium-sodium exchanger, a special operation which is assumed to last 15 days. As it is shown on figure 2 in schematic form, the time necessary to repair the sodium-sodium heat exchanger depends of the available systems : 10 h + 15 d = 370 h with the feedwater plant, or, 52, 126 or 326 days with respectively 3,2 or 1 emergency loops available.

The task of the set of systems "feedwater plant + 3 decay heat removal loops" is at least to ensure a total duration of 15 days at 180°C. The calculation of the probability of failure of this task is shown on figure 2 ; it takes into account the following pessimistic assumptions :

- the time required to repair the feedwater plant is taken to be 60 h = μ^{-1} ; it is assumed that, if the repair has not been completed after one month, the feedwater plant would be lost definitively, whereas it would be possible to resupply the steam generators with water, provided that the temperature of the primary sodium did not exceed 300°C ;
- it is assumed that the repair work on the decay heat removal loops can be performed only at 180°C ; if the repair temperature is increased to 250°C, the time required for the work is shortened significantly.

3.3. Results

The results corresponding to each of the above mentioned initiating events are presented in Table II and are discussed below.

Without common mode failures

The importance of the initiating event *"replacement of a sodium-sodium exchanger"* will be noted.

These results are based on pessimistic assumptions in the case of the calculations for temperature evolution (residual power taking account of a 20 % margin of error) and the determination of the critical times associated with each transition. They hence seem satisfactory in respect of the established objective (probability of loss of the decay heat removal function below 10^{-7}/year as order of magnitude).

With common mode failures of the second order

In an initial stage, consideration was given to common mode failures of the second order by using the *"β factor"* method (if the failure rate of a component is λ, the simultaneous common mode failure of two identical components is βλ). The common mode failures of the second order were hence taken into account in the case of :

- the diesels with $\beta = 0{,}02$;
- the forced convection of the decay heat removal loops (electromagnetic pumps, electrical control) with $\beta = 0.05$;
- the risks of sodium leaks, $\beta = 0.01$.

Taking account of this type of failure yields an estimate of $3\mathrm{x}10^{-7}$ for the annual probability of failure of the function *"decay heat removal"*, which seems still compatible with the design objective if the repair procedures are sufficiently optimized.

In these estimates of the effect of common mode failures of the second order, the failures linked with sodium leaks provide a major contribution, since these failures require sodium drainage and repair work at 180°C on the intermediate exchangers when they are affected ty the leak.

With common mode failures above the second order

In the second stage, consideration was given to common mode failures above the second order.

In the case of the decay heat removal circuits, the installation and design arrangements (particularly the geographical separation of the loops supplied with power by different lines and the physical separation of loops supplied by the same power line) contribute to lower to a negligible value the risks of simultaneous failures of more than two identical components.

On the other hand, the risk of common mode failure which could affect in succession, but not simultaneously, identical components of each of the four decay heat removal loops must be taken into consideration, so that the estimate for the failure rate of the other identical components may be increased after an initial failure of one of these components occurs. The method described in section 2.1 was used to treat this kind of common failure, taking into account the incidents which affected the intermediate exchangers in PHENIX. In the calculations, the probability of losing the safety function depends on the possibility of repairing the initial failure before the last one occurs ; so the most important case, corresponding to the longest repair time, is here the failure of a sodium-sodium exchanger requiring replacement : for this case discussed previously, the calculation of the contribution of common mode failures of the 4th order is illustrated in Figure 2 ; obviously the conditionnal probability of losing the 3 remaining loops depends strongly on λ' and is 0,07 and 0,49 for respectively $\lambda' = 1{,}1\ 10^{-4}/\mathrm{h}$ or $2{,}12\ 10^{-4}/\mathrm{h}$.

The values in Table I were calculated with $\lambda = 10^{-5}/\mathrm{h}$, $\lambda' = 1.1\ 10^{-4}/\mathrm{h}$ and $\alpha = 0{,}5$. Taking account of common mode failures likely to affect the sodium-sodium exchangers in the decay heat removal system results in an overall estimate of $3\ 10^{-6}$/year for the probability of loss of the decay heat removal function, which, even when the margins arising from the pessimistic assumptions considered are integrated, does not seem to be compatible with the objective pursued.

Effect of diversification

As shown, in section 2.4, the method adopted for dealing with common mode failures of the 4th order makes it possible to treat the advantage gained through diversification in a straightforward manner. Provided that all trains function identically when the failures affecting each line are independent of those affecting the others, the advantage gained through diversification is approximately $1/G_D = \alpha\lambda/\lambda'$, which typically corresponds to a factor of 1/20 contributed by diversification.

Diversification of the sodium-sodium exchangers in the decay heat removal circuits makes it possible to reduce (see Table I) to about 3×10^{-7}/year the probability of failure of the decay heat removal function. This result is obviously very sensitive to the values adopted for the parameters λ and λ'. When λ' is taken to be equal to $2.12\ 10^{-4}$/h (instead of $1.1\ 10^{-4}$/h), the probability of failure of the function is of the order of 10^{-6}/year.

4. MODELING THE NON SIMULTANEOUS COMMON MODE FAILURES BY THE LIFETIME METHOD

4.1. General description

It was shown in section 3 and in Table II that the main sequence resulting of loss in the DHR function involves failure of replacement of a sodium-sodium heat exchanger. This operation requires cooling the sodium to 180°C and keeping that temperature for at least 15 days with redundant exchangers identical (if not diversified) to the failed one and which can be affected by the same aging problems (corrosion, wear, fatigue...) which lead to the premature end of life of the first system.

A constant failure rate λ applicable for the useful life of the system is no longer valid and section 2 describes one method for treating that type of problem. Another methodology uses directly the lifetime as the primary random variable with an assumed probability distribution. From that distribution, one can derive the probability laws for the time intervals τ_2, τ_3, ..., τ_N elapsing from the failure of the first system to the failure of the second, third and last systems, leading to the loss of the safety function realized with N redundant systems. Risk evaluation are then performed taking into account the possibility or reaching a safe state for the reactor before a critical time after detection ot the first failure. Further details can be found in [1] on this method which can be applied using Monte-Carlo technique to any kind of life time distribution.

4.2. Application to heat exchanger replacement

Two lifetime distributions have been used : uniform in a time interval Δ or normal with standard deviation σ. These parameters are evaluated from the PHENIX reactor failure observations (see Table I). For the uniform distribution, time intervals distributions can be expressed as polynomials and one finds $\Delta = 4 < \tau_2 > = 2 < \tau_3 >$ where $< \tau_i >$ is the mean value of τ_i fitted to observations. For normal distribution, one finds $\sigma = 1.16 < \tau_2 > = 0.59 < \tau_3 >$ from a straightforward Monte-Carlo type program.

The PHENIX data used as in section 2.2 ($\lambda' = 2.12\ 10^{-4}$/h) lead then to $\Delta = 0.65$ year and $\sigma = 0.18$ year.

It has been seen in section 3.2 that the time necessary to repair the sodium-sodium exchangers depends on the available systems. A rule to express failure for that operation is simply given by the logical condition : $(\tau_2 < T_1)$ AND $(\tau_3 < T_2)$ AND $(\tau_4 < T_3)$, where $T_1 = 52$ days, $T_2 = 126$ days, $T_3 = 326$ days (see Fig. 2).

This condition is easily introduced in a Monte-Carlo type program where 10000 sets of 4 lifetimes were drawn according to the distributions described above.

The probability of exchanger replacement failure is found to be 0.53 for uniform lifetime distribution, 0.54 for normal distribution. These values are consistent with the result obtained with the (λ λ' α) method which is 0.49, for $\lambda' = 2.12\ 10^{-4}$/h.

4.3. Effect of diversification

With that methodology, the interest of diversification comes from the observation that a premature aging occuring in a system will not occur in a diversified one or at least will presumably leads to an average lifetime which is significantly different. The Monte-Carlo method described above allows an easy quantification of the gain due to diversification.

Instead of drawing 4 times according to a single lifetime distribution, for instance normal with standard deviation σ, one draws 2 values with one distribution, then 2 more with a distribution (with the same σ for instance) displaced in time by an interval of time δ. Then the same failure algorithm is applied to get the result.
Table III summarizes the probability of failure for the replacement of a heat exchanger for different values of σ and δ.
For the purpose of comparison, the results of table III have been averaged assuming a distribution of δ uniform over a time interval of 11 years and $\sigma = 0.18$ year. The gain is then about 30 quite close to $\lambda'/\lambda = 21.2$, which is the value obtained for the gain by the method $(\lambda,\lambda',\alpha)$ when $\alpha = 1$.

5. IMPACT OF THE RELIABILITY STUDY ON THE DESIGN AND OPERATION OF THE DECAY HEAT REMOVAL SYSTEM

In view of the results presented above and the assumptions regarding the exchanger repair conditions, two-by-two diversification of the sodium-sodium exchangers would appear to be necessary. In the project, two types of exchanger were, in fact, developped, one with straight tubes and the other with U-tubes. Diversification of these exchangers hence appears to be feasible.

On the other hand, it does not seem necessary to diversify other components in the loops. Indeed, the average repair time for the other components is much shorter, and the risk of being unable to repair the first component before the last one fails would appear to be sufficiently low ; it can be shown that diversification is not indispensable provided that it is possible to carry out the repairs in less than five days, at least temporarily.

It is still necessary, however, to analyse in detail the risks of common mode failure caused by sodium solidification in the sodium-air exchangers which are not diversified, particulary with regard to the likelihood of operator error or of failure of anti-solidification devices.

The quantification of the advantage gained through these improvements to the procedures should allow to attain the reliability objective pursued.

6. CONCLUSIONS

The methods presented in this report allow a straightforward evaluation of the risk of common mode failure corresponding to non-simultaneous failures of identical or diversified trains with a high level of redundancy, when the tasks of the system must be fulfilled over a long period. Since sufficient statistics are now available on the operation of such circuits, these methods are well suited to a reliability study of the emergency decay heat removal system in fast reactors, for instance the european fast reactor project EFR whose DHR system includes six emergency loops.

They can be extended to cover other types of safety problems or phenomena such as the variation of the failure rate with temperature. The $(\lambda, \lambda', \alpha)$ method can be integrated in the calculations by means of Markov graphs, account being taken of the repair of the systems which may restore the initial failure rate.

REFERENCE

[1] BLOCH, M., DUSSARTE, D., PIERREY, J.L., "Probabilistic risk assessment related to multiple ruptures of steam generator tubes, Nuclear Technology 84 3 (1989) 282.

TABLE I

EXPERIENCE WITH PHENIX INTERMEDIATE HEAT EXCHANGER LEAKS IN 1976-1977

Position	Intermediate heat exchanger	Date of the nth leak or of the removal from the reactor (R)		Duration of presence * under sodium since 10.01.73	Power operation (approx. 2/3NP) since the first leak
31	A	R	09.11.77	33 700 h	59 d
12	B	3	31.08.77	33 692 h	59 d + 52 d
11	C	R	13.09.77	34 900 h	59 d + 52 d
22	D	R	09.06.77	32 000 h	52 d
21	E	1	11.07.76	24 645 h **	modified and ** replaced by G
32	F	2	05.10.76	27 967 h	59 d

* On average, the period of connection to the grid corresponds to 51 % of the time under sodium

** At the time of the first leak, the exchangers had been operating for 12 224 h connected to the grid

TABLE II

RESULTS CORRESPONDING TO EACH OF THE INITIATING EVENTS

	Initiator	Loss of the feedwater of steam generator	Loss of external Osource	Shut down 180°C	Shut down 250°C	Replacement one IHX RRA	Total
	Annual probability /year	2	1h: 10^{-2} 8d: 10^{-3}	1	4	0.35	
Without common modes	Annual probability of failure	10^{-8}	7.3 10^{-9}	10^{-8}	1.1 10^{-8}	3.3 10^{-8}	7 10^{-8}
	Contribution (%)	14	10	14	16	46	100
With common modes of order 2	Annual probability of failure	5.4 10^{-8}	8.5 10^{-9}	6.9 10^{-8}	6.9 10^{-8}	10^{-7}	3 10^{-7}
Common modes of order 4	Annual probability of failure with: $\lambda = 10^{-5}$/h $\lambda' = 1{,}1.10^{-4}$/h and $\alpha = 0{,}5$	10^{-7}	10^{-8}	4.3 10^{-7}	1.1 10^{-7}	2 10^{-6}	2.7 10^{-6}
With diversification of the RRA *		6 10^{-8}	9 10^{-9}	8.5 10^{-8}	7 10^{-8}	1.1 10^{-7}	3.3 10^{-7}

* Diversification of the Na-Na heat exchangers the repair of which requires handling

TABLE III

PROBABILITY (in %) of failure for heat exchanger replacement
as a function of the standard deviation σ for the lifetime distribution
and the time separation δ for the mean lifetimes
of the diversified 2 by 2 systems

σ (year) δ	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
0	85.6	51.4	30.0	17.7	10.8	7.1	4.9	3.2	2.3	1.8
1σ	81.2	43.8	23.3	13.0	7.9	4.8	3.0	2.1	1.6	1.1
2σ	70.0	25.0	9.9	4.6	2.3	1.4	0.8	0.6	0.4	0.3
3σ	52.3	9.0	2.4	0.84	0.35	0.18	0.10	0.07	0.04	0.04
4σ	27.5	1.84	0.20	0.04	0.02	ϵ	ϵ	ϵ	ϵ	ϵ
5σ	8.8	0.14	ϵ	ϵ	ϵ	ϵ	ϵ	ϵ	ϵ	ϵ

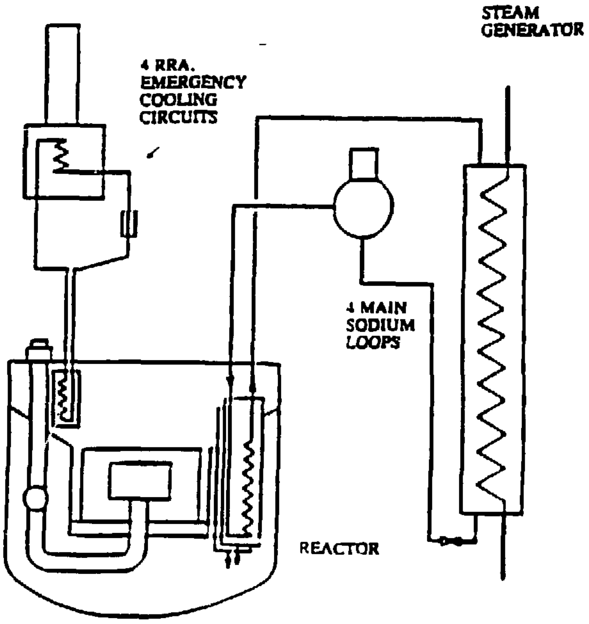
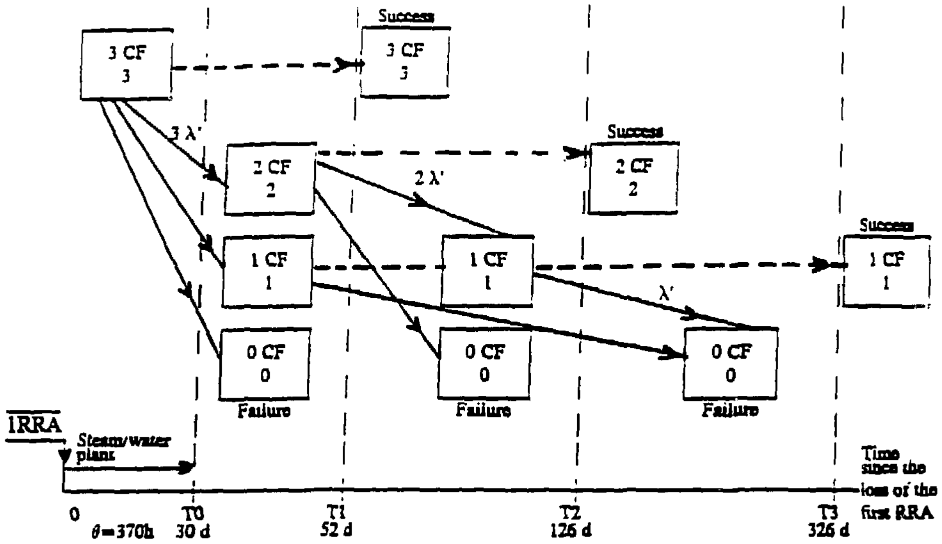


FIGURE 1: RNR 1500 - DECAY HEAT REMOVAL SYSTEMS



$$P_{\overline{3RRA}} = P_{3\to0}(0,T_1) + P_{3\to1}(0,T_1).P_{1\to0}(T_1,T_3) + P_{3\to2}(0,T_1).P_{2\to0}(T_1,T_2) + P_{3\to2}(0,T_1).P_{2\to1}(T_1,T_2).P_{1\to0}(T_2,T_3)$$

$\boxed{\begin{matrix}\text{nCF}\\ \text{n}\end{matrix}}$ state n characterized by n loops RRA in forced convection

$P_{i\to j}(T,T')$ = Probability of the transition of the state i towards the state j during the time interval T

$= C_j p^{i-j}(\lambda',T,T')$ with $p(\lambda',T,T') = e^{-\lambda'T}(1-e^{-\lambda'(T'-T)})$

$P_{\overline{EPR}} = f_{\overline{1RRA}} . P_{\overline{1PE}} . P_{\overline{3RRA}} . f_{\overline{1RRA}} = 4\lambda$ with $\lambda = \lambda_{\overline{1RRA}}$

$P_{\overline{1PE}} = \frac{\lambda}{\lambda+\mu}\left[1-e^{-(\lambda+\mu)\theta}\right]e^{-\mu(T_0-\theta)}$, with $\lambda = \lambda_{\overline{1PE}}$

FIGURE 2: CALCULATION OF THE PROBABILITY OF FAILURE OF THE EVACUATION OF THE DECAY HEAT CORRESPONDING TO THE LEAK ON 1 RRA