AVAILABILITY PERFORMANCES OF GROUND-COUPLED HEAT PUMP SYSTEMS

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Abstract: - The paper presents aspects regarding the reliability and availability of ground-coupled heat pump systems (GCHP). Basic concepts of predictive reliability are introduced and the two modes of reliability analyses (quantitative and qualitative) are shown specifically for PCSS. In order to be able to model the availability of GCHP systems, global reliability indicators must be determined. Furthermore, failure manners and their effects on system reliability, as well as the graphical-analytical methods that could be applied to GCHP systems are analyzed. Finally, a case study for the experimental system installed in Thermodynamics Laboratory belonging to Energy Engineering Faculty is shown.

Key-Words: - Ground-coupled heat pump, availability, reliability, indicators

1. INTRODUCTION

The necessity of studying the predictive reliability of technical systems led to a diversified development of models and methods of probabilistic computation, dictated by the system nature and complexity. There are two types of predictive reliability analyses [1 ÷ 4]:

Qualitative analysis, that aims to offer information regarding the manner in which the failure of component elements is reflected into the system well-functioning operation. The following steps have to be covered when a qualitative reliability analysis is made:

- determine the failure manner and failure effects on the system (AMDE), allowing therefore to identify the failures and to assess their consequences on system operation;
- organize and graphically represent the information gathered from AMDE as a flow chart (equivalent reliability diagram, failure tree or events tree).

The objectives of a qualitative analysis are:

- weak points identification in the design phase, giving useful information to eliminate them;
- highlighting potential failures and identifying their importance or criticality;
- offering the necessary information for the quantitative reliability analysis.

Quantity analysis, aims to quantify – as numerical indicators – the reliability level of a system, in order to:

- compare from the reliability performances point of view two or more technical solutions;
- verify if the reliability indicators for the interface points with other systems, fit required limits;
- track down the weak links of the analyzed system;
- forecast guaranty indicators that are included in contracts between producers and costumers.

Methods for computing systems reliability may be grouped [2, 4] either by their nature (into analytical and grafo-analytical methods) or by the nature of repartition functions of the random variables (into exponential and non-exponential methods).

For the analyses of predictive reliability, the structure of GCHP systems will be detailed into subsystems, as shown in Fig.1, and having the following meaning:

- ground-coupled heat source subsystem (SSCS), includes the borehole heat exchanger (SCS) and the circulation pump;
- heat pump subsystem (SAPC), having an evaporator (V); a compressor (C); a condenser (Cd); and automation and control subsystem (SAC);
- consumer subsystem (SC), consisting of the heat distribution subsystem (SDC) and heating equipment subsystem (SUC);
- auxiliary heat source (SCR).

2. GLOBAL RELIABILITY INDICATORS FOR GCHP SYSTEMS

For ground-coupled heat pump systems, the concept of availability has a distinct meaning and needs specific particularization. Regarding the operational behavior of GCHP, they are characterized by the following quantities:

2.1 Time characteristic indicators

- T_{PF} – total programmed time of operation;
- T_F – total real (efectiv) time of operation;
- T_d – total time of failure (total power cut-down);
- T_R – total time of reserve (spare time);
- T_{MP} – total time of preventive maintenance.

Between these data the following relation may be written, for one calendar year (period of analysis):

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$$T_A = T_{PF} + T_R + T_{MP} = T_F + T_d + T_R + T_{MP} \quad (1)$$

2.2 Power characteristic indicators

- P_N – rated power;
- P_F – operational power;
- ΔP_d – forced partial reduction of power (because of failures, unavailabities etc.).

Between the above parameters the following relation may be written:

$$P_N = P_F + \Delta P_d \quad (2)$$

2.3 Safety characteristic indicators

- **R_T – time safety** (probability that GCHP system which is programmed to run, is really running):

$$R_T = \frac{T_F}{T_F + T_d} \quad (3)$$

- **R_P – power safety** (probability that GCHP being programmed to run, is really running and capable of covering the required power level):

$$R_P = \frac{P_F}{P_F + \Delta P_d} = \frac{P_N - \Delta P_d}{P_N} \quad (4)$$

This indicator characterizes the system capacity of providing a certain power level. In order to estimate the power safety a statistics regarding GCHP power is needed.

- **R_W – energy safety** (probability that GCHP is providing the programmed energy):

$$R_W = \frac{W_F}{W_F + \Delta W_d} \quad (5)$$

where: W_F - produced energy (delivered);
ΔW_d – undelivered energy.

R_W indicator has got a more comprising and complex character comparing to previous two (R_T, R_P), reflecting both system behavior in time and level of produced power.

The relation between safety indicators is expressed as:

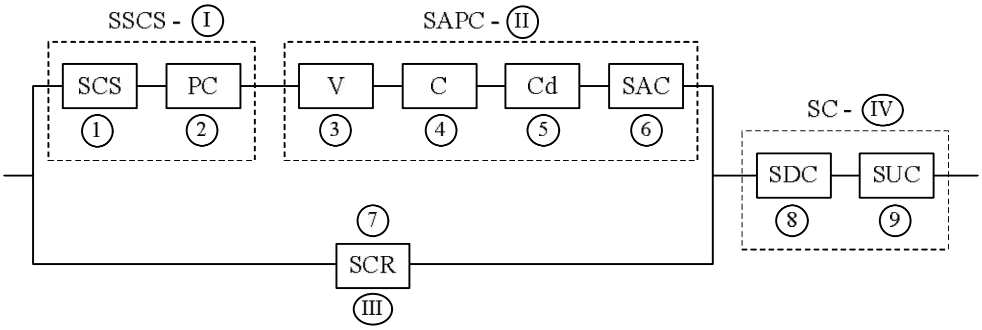

Fig. 1 – Schematic diagram of the analyzed GCHP system

$$R_W = R_P \cdot R_T = \frac{P_F \cdot T_F}{P_F \cdot T_F + \Delta P_d \cdot T_F + P_F \cdot T_d + \Delta P_d \cdot T_d} = \frac{W_F}{W_F + \Delta W_{d1} + \Delta W_{d2} + \Delta W_{d3}} = \frac{W_F}{W_F + \Delta W_d} \quad (6)$$

where: ΔW_{d1} – undelivered energy over operation time due to forced partial reductions of power;
$\Delta W_{d2}+\Delta W_{d3}$ – undelivered energy due to total reduction of power in T_d period.

The parameters involved in safety indicators computation are shown in Fig.2.

2.4 Availability characteristic indicators

The parameters used in the following expressions are highlighted in Fig. 3.

- **A_T – time availability** (capacity of GCHP system to fulfill the requirements):

$$A_T = \frac{T_F + T_R}{T_A} = \frac{T_A - T_d - T_{MP}}{T_A} \quad (7)$$

A_T indicator reflects only the GCHP capacity to fulfill in right time a requirement, regardless the required power level.

- **A_P – power availability** (capacity of GCHP to provide the consumer, on request, a certain power level):

$$A_P = \frac{P_F}{P_N} = \frac{P_N - \Delta P_d}{P_N} \quad (8)$$

Monitoring of power evolution over time is required in order to evaluate A_P indicator.

- **A_W – energy availability** (capacity of GCHP to satisfy energy requirement of the consumer over a time period and at a certain power level):

$$A_W = \frac{W_F + \Delta W_R}{W_N} \quad (9)$$

where: $W_N = P_N \cdot T_A$ – rated energy for uninterrupted operation (maxim solicitation) of GCHP;
ΔW_R – available energy (as reserve) for T_R. period.

There are different connections between the three indicators (A_T, A_P and A_W):

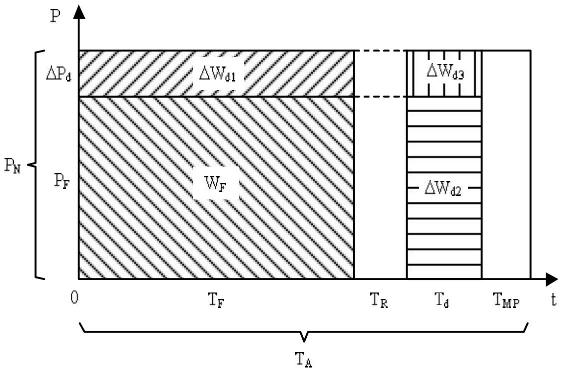

Fig. 2 – Time, power and energy characteristic indicators for defining the safety of GCHP systems

$$A_W = A_P \cdot A_T = \frac{P_F}{P_N} \cdot \frac{T_F + T_R}{T_A} = \frac{P_F \cdot T_F + P_F \cdot T_R}{P_N \cdot T_A} = \frac{W_F + \Delta W_R}{W_N} \quad (10)$$

or:

$$A_W = 1 - \frac{\Delta W_{IOF}}{W_N} - \frac{\Delta W_{IMP}}{W_N} - \frac{\Delta W_{IRF}}{W_N} = 1 - I_{Wd} - I_{WMP} - I_{WRF} = 1 - I_W \quad (11)$$

or:

$$A_W = A_P \cdot A_T = \frac{P_N - \Delta P_d}{P_N} \cdot \frac{T_A - T_d - T_{MP}}{T_A} = \frac{P_N \cdot T_A - P_N \cdot T_d - P_N \cdot T_{MP} - \Delta P_d \cdot (T_F + T_R)}{P_N \cdot T_A} = \frac{W_N - \Delta W_{IOF} - \Delta W_{IMP} - \Delta W_{IRF}}{W_N} \quad (12)$$

where: ΔW_{IOF} – unavailable energy due to forced stops (in time period T_d);

ΔW_{IMP} – unavailable energy due to preventive maintenance (in T_{MP} period);

ΔW_{IRF} – unavailable energy due to forced reductions of power (in $T_F + T_R$ period);

I_{Wd} – energy unavailability due to forced stops (a probabilistic component of unavailability);

I_{WMP} – energy unavailability due to preventive maintenance (a deterministic component of unavailability);

I_{WRF} – energy unavailability due to forced power reductions (a probabilistic component of unavailability);

I_W - total energy unavailability.

Indicators referring to energy simultaneously reflect the system behavior in time and the power level, but for their assessment, a more complex statistics is needed.

3. GCHP reliability modeling using states and transitions graph

An essential issue for energy and reliability performance analyses of a GCHP system is defining the states and evaluating the probability of their existence. Fig. 4 shows the states graph of a GCHP system, highlighting also the realistic transitions between them. Theoretically, other transitions are possible, too, but practically they are not confirmed by GCHP operation.

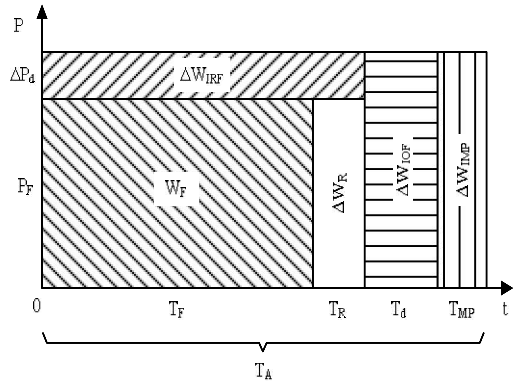

Fig. 3 – Time, power and energy characteristic indicators for defining GCHP availability

States marked in Fig. 4 have the following meaning:

- F (1) –normal operation, running;
- AS (2) – waiting;
- C (3) – critical (exposed), because normal limits are overlapped by one or multiple parameters (temperatures, pressures, supply voltage, drawn current etc.);
- D(4) – shut-down, representing an irreversible failure that causes the stop of the system and corrective maintenance work;
- MC (5) –corrective maintenance;
- MP (6) – preventive maintenance.

GCHP is in **operation state "F"** if simultaneously:

- ➢ all starting conditions are fulfilled and system has started;
- ➢ all elements belonging to SSCS, SAPC and SAC are running (Fig. 1);
- ➢ the thermal energy consumer accepts all the heat produced by GCHP.

Therefore, the probability of F(1) state is:

$$P_F = P_1 = P_{SSCS} \cdot P_{SAPC} \cdot P_{SAC} \cdot P_{SC} \quad (12)$$

where: P_{SSCS} – probability of well operation of SSCS:

$$P_{SSCS} = R_{SCS} \cdot R_{PC} \quad (13)$$

P_{SAPC} – SAPC availability:

$$P_{SAPC} = R_V \cdot R_C \cdot R_{Cd} \quad (14)$$

P_{SAC} – probability of well operation of SAC;

P_{SC} – probability of well operation of SC:

$$P_{SC} = R_{SDC} \cdot R_{SUC} \quad (15)$$

Transition from state "F" into **waiting state "AS"** is done when heat from the ground is missing or there is no need for heating the consumer. Therefore, the probability of state "AS" is:

$$P_{AS} = P_2 = (1 - P_{SSCS}) + (1 - P_{SC}) - (1 - P_{SSCS}) \cdot (1 - P_{SC}) = 1 - P_{SSCS} \cdot P_{SC} \quad (16)$$

Transition into "AS" state is done from one of F, MC or MP states in which GCHP system is when the unwanted event happens – unavailability of a link.

Critical state "C" may occur on the operation period because some working parameters overlap normal limits, until control elements from SAC start working (inside the time delay period). Therefore, this state is very short. If working parameters come back to normal values, GCHP system goes from "C" state into "F" state. If they don't, there are two possibilities:

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- control elements belonging to SAC will work and GCHP system will go to MP state;

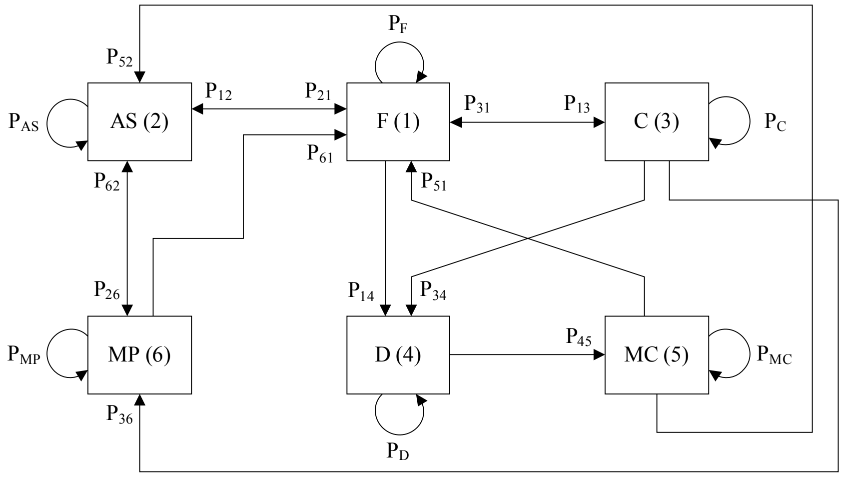

Fig. 4 – States graph of a GCHP system having state probability (P_i) and transition propability (P_{ij})as indicators

- overbusy elements will cross the supportability limits and will breakdown, the system will go to "D" state.

"C" state may be achieved when the following parameters deviate from required limits:

- inlet temperature into SCS: $T_{SCS\,i} \geq T_{SCS\,i\,min}$;
- outlet temperature from SCS: $T_{SCS\,e} \geq T_{SCS\,e\,min}$;
- outlet temperature from the condenser: $T_{Tur} \leq T_{Tur\,max}$;
- brine pressure in SCS: $p_{SCS} \in [p_{SCS\,min} , p_{SCS\,max}]$;
- freon pressure in heat pump circuit: $p_{freon} \in [p_{freon\,min} , p_{freon\,max}]$;
- water pressure in consumer circuit: $p_{Tur} \leq p_{Tur\,max}$;
- supply voltage: $U_{alim} \in [U_{min} , U_{max}]$;
- drawn current: $I_{total} \leq I_{max}$;

Accordingly, the existence probability of "C" state is:

$$\begin{aligned} P_C = P_3 &= \text{Prob}\,[T_{SCS\,i} \vee T_{SCS\,e} \vee T_{Tur} \vee p_{SCS} \vee p_{freon} \vee p_{Tur} \vee U_{alim} \vee I_{total}] = \\ &= \text{Prob}\,(T_{SCS\,i} \geq T_{SCS\,i\,min}) + \text{Prob}\,(T_{SCS\,e} \geq T_{SCS\,e\,min}) + \text{Prob}\,(T_{Tur} \leq T_{Tur\,max}) + \\ &+ \text{Prob}\,(p_{SCS} \in [p_{SCS\,min} , p_{SCS\,max}]) + \text{Prob}\,(p_{freon} \in [p_{freon\,min} , p_{freon\,max}]) + \\ &+ \text{Prob}\,(p_{Tur} \leq p_{Tur\,max}) + \text{Prob}\,(U_{alim} \in [U_{min} , U_{max}]) + \text{Prob}\,(I_{total} \leq I_{max}) \end{aligned} \quad (17)$$

Probability of multiple events was neglected in equation (17).

Damage state "D" is, obviously, the most undesirable because it involves the highest risks, leading to economic and social consequences (absence of heat to the consumers).

Transition into "D" state can be done in two ways:

- from state "F" when catastrophic faults suddenly occur to GCHP elements;
- as a result of parametric failures of GCHP elements, cumulated with the working refuse of SAC (from state "C").

Based on the above mentioned, Fig. 4 and equation (17), the probability of "D" state may be written:

$$\begin{aligned} P_D = P_4 &= F_{SDC} + F_{SUC} + (F_{SCS} + F_{PC} + F_V + F_C \\ &+ F_{Cd} + F_{SAC}) \cdot F_{SCR} + P_C \cdot F_{SAC} \end{aligned} \quad (18)$$

Corrective maintenance state "MC" is the consequence of the fact that "D" state exists. After identifying the broke element, determining what caused the failure and setting repairing actions, equipment/subsystems being in damage state will go to "MC" state. Existing probability of this state is, practically, equal to the probability of damage state:

$$P_{MC} = P_5 = P_D \quad (19)$$

After MC works are finished, GCHP system goes to:

- state "F" – if both starting conditions and produced heat delivering conditions are fulfilled;
- state "AS" – if one of the links with a neighbor system is not available.

Transition into **preventive maintenance state "MP"** may be done by two ways:

- as a result of a preset program, based on operation time. This is called programmed preventive maintenance (MPP) and the transition into it is done from waiting state (AS), namely in that period of time when external conditions of GCHP operation are not satisfied;
- as a result of equipment degradation, that is detected by SAC and recorded as critical ("C" state). In this case, the equipment are subject to a preventive maintenance to object (MPO).

After finishing the MP work (either MPP or MPO), GCHP system goes to one of the states "F" or "AS" , according to the two links with exterior.

Probability of MP state is calculated using:

$$P_{MP} = P_6 = P_{MPP} + P_{MPO} = 1 - \sum_{j=1}^{5} P_j \qquad (20)$$

Equations (12)÷(20) are used for computing the states probabilities for GCHP system with the architecture given in Fig. 1.

4. MARKOV CHAINS METHOD USED FOR MODELING GCHP RELIABILITY

A system with the architecture presented in Fig. 1 is considered in order to exemplify the application of Markov chains with continuous parameter [4,5] to the study of GCHP reliability.
States graph of the analyzed system is shown in Fig. 5. Based on graph, the transitions matrix was written (equation 21).

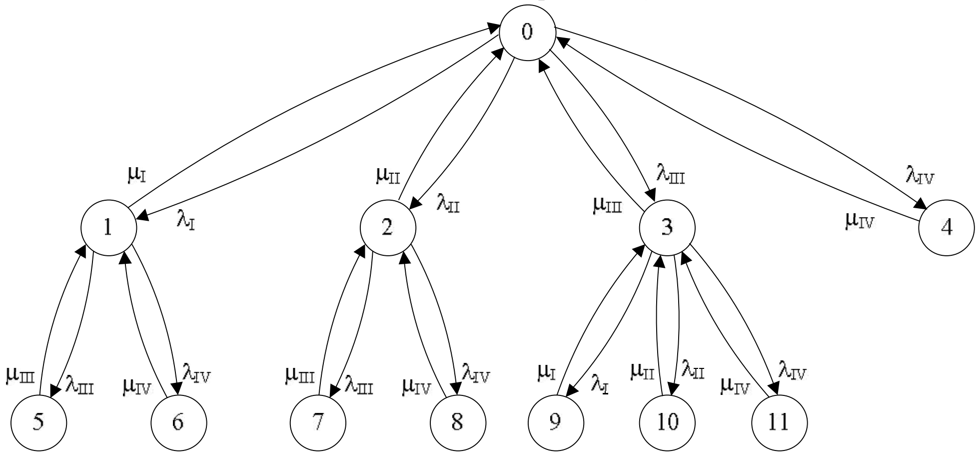

Fig. 5 – States graph for GCHP system

$$[a_{ij}]=\begin{bmatrix}
-\sum_{i=I}^{IV}\lambda_i & \mu_I & \mu_{II} & \mu_{III} & \mu_{IV} & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
\lambda_I & -(\lambda_{III}+\lambda_{IV}+\mu_I) & 0 & 0 & 0 & \mu_{III} & \mu_{IV} & 0 & 0 & 0 & 0 & 0\\
\lambda_{II} & 0 & -(\lambda_{III}+\lambda_{IV}+\mu_{II}) & 0 & 0 & 0 & 0 & \mu_{III} & \mu_{IV} & 0 & 0 & 0\\
\lambda_{III} & 0 & 0 & -(\lambda_I+\lambda_{II}+\lambda_{III}+\mu_{III}) & 0 & 0 & 0 & 0 & 0 & \mu_I & \mu_{II} & \mu_{IV}\\
\lambda_{IV} & 0 & 0 & 0 & -\mu_{IV} & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & \lambda_{III} & 0 & 0 & 0 & -\mu_{III} & 0 & 0 & 0 & 0 & 0 & 0\\
0 & \lambda_{IV} & 0 & 0 & 0 & 0 & -\mu_{IV} & 0 & 0 & 0 & 0 & 0\\
0 & 0 & \lambda_{III} & 0 & 0 & 0 & 0 & -\mu_{III} & 0 & 0 & 0 & 0\\
0 & 0 & \lambda_{IV} & 0 & 0 & 0 & 0 & 0 & -\mu_{IV} & 0 & 0 & 0\\
0 & 0 & 0 & \lambda_I & 0 & 0 & 0 & 0 & 0 & -\mu_I & 0 & 0\\
0 & 0 & 0 & \lambda_{II} & 0 & 0 & 0 & 0 & 0 & 0 & -\mu_{II} & 0\\
0 & 0 & 0 & \lambda_{III} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\mu_{IV}
\end{bmatrix} \qquad (21)$$

By solving the set of equations using well-known methods [2, 4] the state probabilities and reliability indicators of GCHP system are determined.

A calculation example of predictive reliability indicators is presented in the following. The considered values of failure intensity and repair intensity are indicated in Table 1.

Table 1. Values of intensity of failure and repair of the component elements of GCHP system

Element	λ [x10^{-4} h^{-1}]	μ [x10^{-4} h^{-1}]
SCS	0.04	40
PC	0.25	500
V	0.1	500
C	0.3	400
Cd	0.08	500
SAC	0.2	300
SCR	0.1	600
SDC	0.4	200
SUC	0.2	300

After performing the calculations of states probability, the following results came up (Table 2).

Table 2. Values of state probabilities for GCHP system

State	Probability of state occupancy
0	0.993922566
1	0.00149091
2	0.001765865
3	0.000165654
4	0.00265046
5	$1.879\cdot10^{-7}$
6	$2.138\cdot10^{-6}$
7	$1.797\cdot10^{-7}$
8	$1.743\cdot10^{-6}$
9	$6.055\cdot10^{-8}$
10	$1.146\cdot10^{-7}$
11	$1.205\cdot10^{-7}$

Numerical values of reliability indicators for GCHP system are shown in Table 3.

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Table 3. Reliability indicators for GCHP system

Reliability indicator		Value
Probability of success	P_S	0.997344995
Probability of refuse	P_R	0.002655005
Mean probable duration of system success in analyzed period (1 year)	M[α(T)] [h/year]	8736.74
Mean probable duration of system refuse in analyzed period (1 year)	M[β(T)] [h/year]	23.26
Mean probable number of failures in the analyzed period (1 year)	M[ν(T)] [failure/year]	0.5989
Mean time between failures	MTBF [h]	14588.14
Mean time to maintenance	MTM [h]	38.84
Equivalent intensitaty of failure for entire system	λ_S [h^{-1}]	$0.685\cdot10^{-4}$
Equivalent intensity of repair for entire system	μ_S [h^{-1}]	$257.47\cdot10^{-4}$

5. CONCLUSIONS

Reliability performances of a GCHP system may be assessed based on global indicators that have specific expressions and the following meaning:

- safety of time, power and energy;
- availability of time, power and energy.

Energy unavailability of a GCHP may have different causes: failure, preventive maintenance, power reductions (forced or deliberate), waiting state etc.

A reliability analysis for GCHP systems consists of all states identification, explanation of their significance and the transition behavior between them. GCHP can develop six states: normal operation, critical, waiting, damage, corrective maintenance and preventive maintenance.

Method of Markov chains with continuous time can be successfully used for predictive reliability analysis of GCHP systems, allowing calculation of the most utilized reliability indicators.

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