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Modeling Energy Performances and Availability of Geothermal Structures

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ABSTRACT

The first part of the paper describes the main equipment used for cascaded geothermal uses (CGU), defining the input and output values and the possible perturbations in the system. In the second part, the "reliability" functions of the system and of its subsystems are defined. A mathematical model is then presented for the evaluation of safety and availability indices for CGU based on the elements and subsystems. The final parts contains references for the "objective" function of CGU systems and for the way of applying the "maximum economic efficiency" criteria, with the purpose of optimizing the diagram and the momentary operating structure of CGU.

1. THE OPPORTUNITY OF THE PROJECT

Energy is a vital component of the present civilization. The great efforts in energetic area follow, especially, four principal directions:

- the improvement of energy conversion efficiency;
- efficient technologies for decreasing the (CO_2, SO_2, NO_x) in fossil fuel combustion;
- the increasing of nuclear power plant safety;
- the development of renewable energy sources conversion and utilisation technologics (solar,geothermal, hydro, wind, biomass and waste).

In the area of renewable energies, recently, special attention is given to the preoccupation and achievments in geothermal area done under the umbrella of the International GeothermalAssociation (IGA).

The efforts in the geothermal area are mainly focused on: resource identification and assessment (Cataldi, 1994), extraction and reinjection technologics, the use of geothermal energy in heating processes, electricity generation, biomass production and medical treatment as well ascombined processes.

Such concerns are met in northwest Romania. Oradea's geothermal periemeter is exploited through 11 production bore holes with an average annual flow of about 80 l/s with temperature between 60°C and 105°C. For a more efficient heat use from geothermal water it is required the use of heating systems arranged in cascade so that the average temperature (ΔT) between the temperatures of the production and reinjection bore holes to be maximum.

Benefits (economic, environmental, energy) of using geothermal energy in the process of heating a space in the city of Oradea is now a certainty.

Aspects for using geothermal water of low and very low enthalpy for other purposes (biomass production, ice and snow melting, treatment, pisciculture) are researched from a technical-scientific point of view and will be subject to economic analysis.

Industrial applications that concern the use of geothermal energy involve – besides resolving technical issues – also appropriate economic analysis to cover their economic efficiency compared with classical technologies having the same destination. The practice of complex geothermal structures that facilitate – parallel or alternative – of geothermal energy obtained from a source (borehole, a group of boreholes) in useful processes of the type listed above, represents a way of making geothermal usage economically efficient. By practicing complex geothermal uses (CGU) can obtain, in certain conditions, economic benefits, because:

- such utilization generally allows the increase of thermal capacity which is recovered from the geothermal water, on the basis of incresing of average temperature between input and output points of the system (CGU);
- the complex utilisation allows the optimization, by applying the maximum efficiency criteria at CGU level, in respect with the momentary reliability status of the subsystems and components as well as the momentary demand of energy of various consumers (the consumption curves of electric, thermal and chemical energy).

The paper discusses methodological aspects of reliability analysis and the optimization of the execution and operation structure of CGU.

2. THE STRUCTURE OF COMPLEX GEOTHERMAL USES (CGU)

Complex geothermal use (CGU) is the equipment which gives the possibility of recovering geothermal energy in several ways [2,3,4,6]: domestic hot water preparation, heating public and private premises, warming technical spaces, culture of biomass, pisciculture, medical treatment and entertainment favoured in Romania.

The block diagram of CGU system is shown in figure 1. the authors consider that such a structure is justified by the specific needs of potential consumers, referring upon the economic and reliability analysis of CGU. The paper does not go into details with respect to the operating principles and to the intimate structure of CGU and of its subsystems, as these are known from the specialized literature.

According with the block diagram in figure 1, CGU comprises the following subsystems:

a) subsystem for domestic hot water production (SSDHWP) which through the solar panel and boiler takes solar and geothermal heat leasing it to domestic hot water. The subsystems intakes are geothermal water, working fluid of the solar subsystem. SSDHWP output is domestic hot water used by consumers at standard rates and temperatures. Because the solar subsystem circuit is using a working fluid, according to the type of the subsystem, other than water the attention should be increased in the equipping and operation of the SSDHWP. Into the subsystem are introduced two additional elements the safety valve (SV) and a control valve for secondary fluid retention (CVSFR).

b) The subsystem for heating and snow melting (SSHSM) is for heating living spaces, heating technical spaces, heating the pool, ice and snow melting and drying of alleys. Transfer of heat from geothermal fluid to the secondary fluid is made in heat exchangers (HE_1, HE_2, HE_3, and HE_4). The four secondary circuits operate in closed circuit system and are equipped with recirculation pumps (RP) and expansion vessels (EV), which takes the volume fluctuations due to fluid density change with temperature.

c) The subsystem of own services (SSOS) consists of: power circuits subsystem (PCSS), which supplies electricity (EL) for main consumers of CGU, the necessary pumps for extraction and reinjection of geothermal fluid; monitoring and control subsystem (MCSS) has the role of measuring, signaling control, supervision and adjustment (including automatic adjustment on the basis of a pre-established software). Connection between SSOS and the two process subsystems is ensured by the transmission of information flows in order to have suitable management of the system.

d) The subsystems for geothermal fluid production (SSGFP) and reinjection (SSGFR) consist of the two bore holes (production, reinjection), the necessary pumps for production and reinjection of geothermal fluid equipped with related equipment (motor, control valves, secondary circuit for command and control etc.).

To maximise the momentary operation regime of CGU, taking into account the restrictions imposed by links (inputs, outputs, internal) as well as the solicitations given by the energy carriers, it is necessary to:

- include in its structure the primary regulation elements (variable rotation pumps, adjustable valves);
- collect infomation about the dues involved in the process (flow rates, pressures, temperatures, voltage, currents, speeds, etc.) thorough proper transducers;
- transmit and process the infomation on a computer inside MCSS, on the basis of a pre-established software, related with the mathematic model of the process and taking into account the physical structure of the system;
- upgrade the operators to the technical level of CGU, in order to be able to operate in all CGU subsystems.

Where: BHGFP is borehole for geothermal fluid production; GFLE is geothermal fluid of low enthalpy; DCW is drinking cold water; DHW is domestic hot water; DS is domestic sewage; HWB is hot water boiler; HE is heat exchanger; RP is recirculating pump; P is pump; TV is thermostat valve; CV is control valve; EV is expansion vessel; TS is technical space; BHGFR is bore hole for geothermal fluid reinjection; SSOS is subsystem of own services; PCSS is power circuits subsystem; MCSS is monitoring and control subsystem; EIF is energetic information flow; SSGFP is subsystem for geothermal fluid production; SSGFR is subsystem for geothermal fluid reinjection; SSDHWP is subsystem for domestic hot water production; SSHSM is subsystem for heating and snow melting; SP is solar panel; SV is safety valve; CVSFR is control valve for secondary fluid retention; SWF is secondary working fluid; SHC is secondary heating circuit.

3. ABOUT THE CGU RELIABILITY

The CGU has various elements (electric, hydro-mechanic, thermo-mechanic, electronic, computation). Concerning the reliability, CGU, its subsystem as well as the majority of the elements are included in the category of the restoring systems (Felea 1996).

Concerning the qualitative aspect, the CGU reliability represents its capacity to acomplish the designed task, at a giventime and in a certain period.

As far as quantity, the CGU reliability assessed through the probability for the system to acomplish in a correct way, and at the preestablished level of performance its functions, at a given time and over a certain period:

$$R_S = P_{rob}\left(t > T \big/ UE_{ij} \geq UE_{cij}\right) \quad (1)$$

where:

t = time variable;

T = design operation period,

UE_{ij} = useful effect of subsystem"i"(i = (BHGFP, SSGFR, SSDHWP, SSSH)), produced at a given time (t_j) or over a period of time (At),

UE_{cij} = the requested useful effect.

The job of CGU being satisfied when all its subsystems, potentially solictited at a given time (t_j) are able to accomplish the specific tasks,we can evidently write:

$$R_S = R_{BHGFP} \cdot R_{SSGFR} \cdot R_{SSDHWP} \cdot R_{SSSH} \quad (2)$$

The reliability functions of the subsystems (R_{BHGFP}, R_{SSGFR}, R_{SSDHWP}, R_{SSSH}) are defined similarly with the reliability function of the system (R_S), implying, evidently, the good operation of the OSSS parts.

Thus defined, the reliability function of CGU involves the following functions: security, availability, intrinsic and associate safety.

a) The security problem arises only in relation with SSDHWP avoiding the danger of secondary fluid losses trough leaks, explosions due to overcoming the permisible pressures, by loss of control over elments of adjustment. Elements that may directly influence the security of the SSDHWP are: CV_{12}, CV_{13}, RP_5, EV_5, SP, HWB.

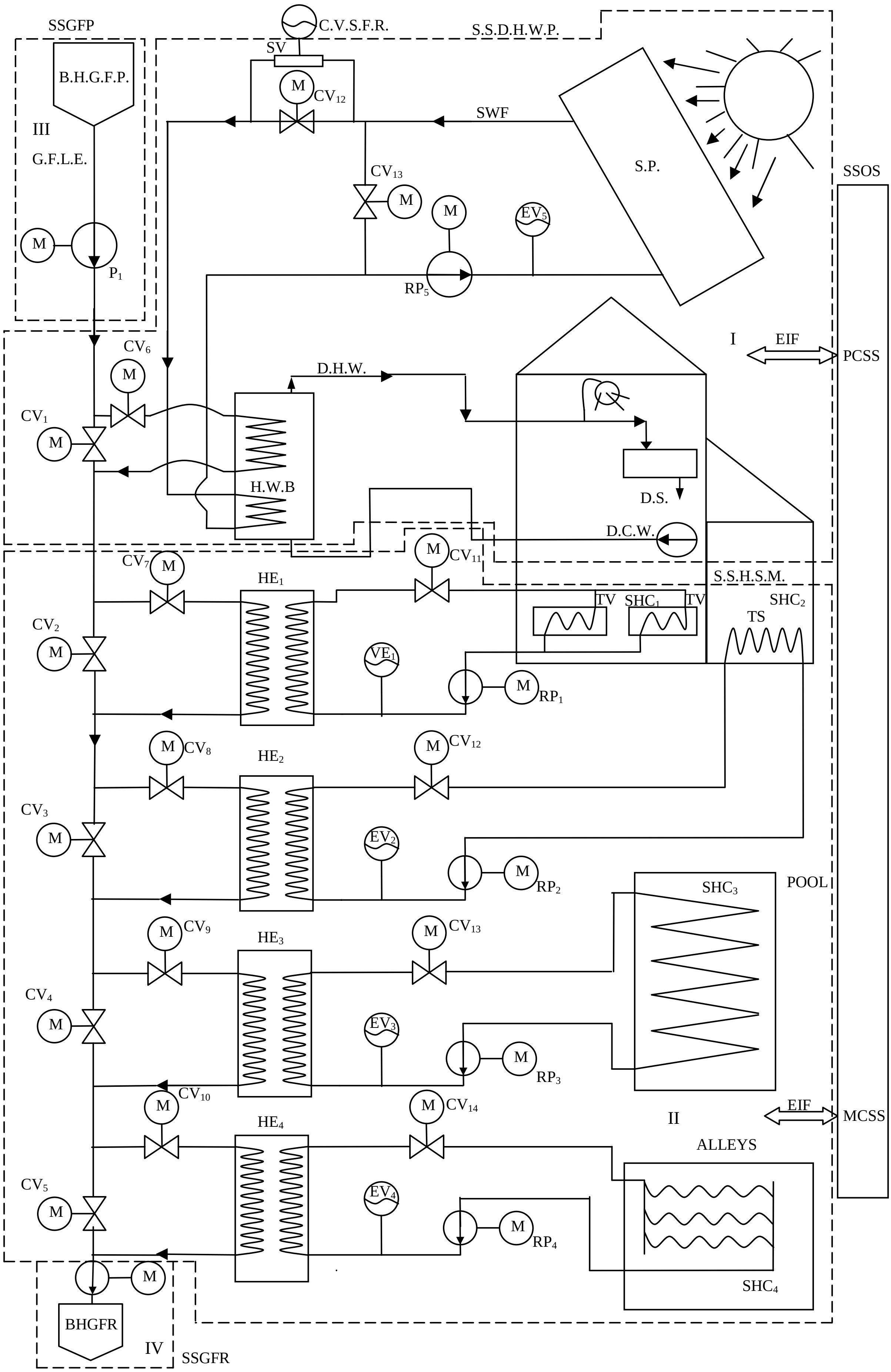

Figure 1: Block diagram of CGU system

The security function of SSDHWP can be as follows:

$$P_{SEC} = 1 - (1 - P_{MP}) \cdot (1 - P_{CV_{13}}) \cdot (1 - P_{SV} \cdot P_{CVSFR}) \quad (3)$$

Where:

P_{MP} – probability to maintain pressure under the permissible value (probability of good operation of the monitoring and controlling subsystem of pressure)

$P_{CV_{13}}, P_{SV}, P_{CVSFR}$ - probability of good operation (intrinsic safety of the elements CV, SV, RR)

b) The intrinsic safety (intrinsic reliability) of the CGU subsystems needs a more elaborated discussion.

The problem of the intrinsic reliability arises from the design phase or in the operation (when the long term assessments of useful effects are made), if the analyst evaluates the so-called "predictable intrinsic reliability" (PIR), respectively in the phase of operational exploitation (checking in operation) as well as when recording the events with the purpose of estimating the "intrinsic operational reliability" indicators (IOR).

The PIR indicators that are necessary to be estimated for a given CGU subsystems, are requested by the assessment of the damages caused by the decrease of the useful effects under the established values ($UE_{ij}<UE_{cij}$). The damage's characteristics of the mentioned utilities can be as those represented in figure 2.

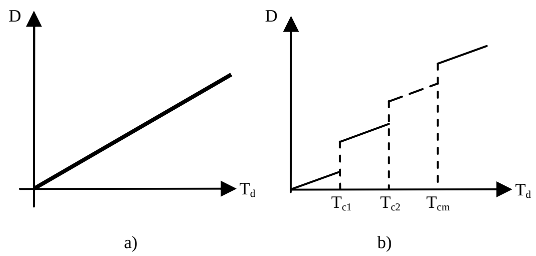

Figure 2: Damage characteristics of the utilities served by CGU

Where: D – Damage [monetary units]; T_d – duration of interruption of the energy supply in time units; T_{ck} – critical moments (k=1…m).

The characteristic in fig. 2 a) is from the SSUPR and the most applications with PH, and the characteristic in fig. 2 b) is typical for EGSS (in this case the CS) and some applications with PH.

For the cases in which the damage is proportional with the duration of interruption (fig. 2 a)) is sufficient to determine the following reliability indicators:

- probability of proper functioning (P_{PF});
- total period of interruption in the analyzed (T_A) interval [$ß(T_A)$];

For the cases in which the damage depends on the duration of interruption and also the number of interruptions (fig.2 b)), besides the mentioned indicators, it is necessary to evaluate the following indicators as well:

- number of failures over the analyzed interval [$\nu(T_A)$];
- average time of proper functioning (MTBF) and of failures (MTTR) (Billinton 1971).

For the evaluation of these indicators at a subsystem level it is considered that the indicators of the component elements are known. In the PIR analysis we can operate with the values from the stationary conditions (constant) of the indicators: λ (failure intensity) and μ (recovery intensity). The most elements of the SCGU are classic components (for which the producers guarantee the values of the λ, μ indicators).

There are some components (P_1, P_2, CV_1, CV_6, HWB, CV_2, CV_7, HE_1, CV_3, CV_8, HE_2, CV_4, CV_9, HE_3, CV_5, CV_{10}, HE_4 and the GW pipes) that involve the specific factors of GW (scaling corrosion). When computing PIR special attention must be paid to the correct introduction of indicators for the SWF circuit elements, which are exposed to the specific factors of SWF. For those elements, knowing the values of the reliability guaranteed indicators in the basic regime (λ_b, μ_b), one can evaluate the indicators in the given conditions ($\lambda=k_\lambda\ \lambda_b$; $\mu=k_\mu\ \mu_b$). the correction factors (k_λ, k_μ) are determined through physical and chemical analyses.

Supposing the elements indicators (λ, μ) as known, the PIR indicators of the subsystems can be determined applying one of the following methods (Billinton, 1971, Felea 1996):

- the equivalent diagram of reliability;
- the events and failure tree;
- the Markov process with continuous time method.

For example, for SSHSM, the equivalent reliability diagram is represented in Figure 3.

The equivalent structure from figure 3 being in series, the equivalent indicators are determined with the relations:

$$\lambda_e = \sum_{i=1}^{33} \lambda_i \qquad \mu_e = \frac{\lambda_e}{\sum_{i=1}^{33} \frac{\lambda_i}{\mu_i}} \quad (4)$$

The other indicators are expressed as follows:

$$P_{BF} = \frac{\mu_e}{\lambda_e + \mu_e}$$

$$\beta(T_A) = \frac{\lambda_e}{\lambda_e + \mu_e} \cdot T_A$$

$$\nu(T_A) = \frac{\lambda_e \cdot \mu_e}{\lambda_e + \mu_e} \cdot T_A$$

$$MTBF = \frac{1}{\lambda_e}; MTR = \frac{1}{\mu_e} \quad (5)$$

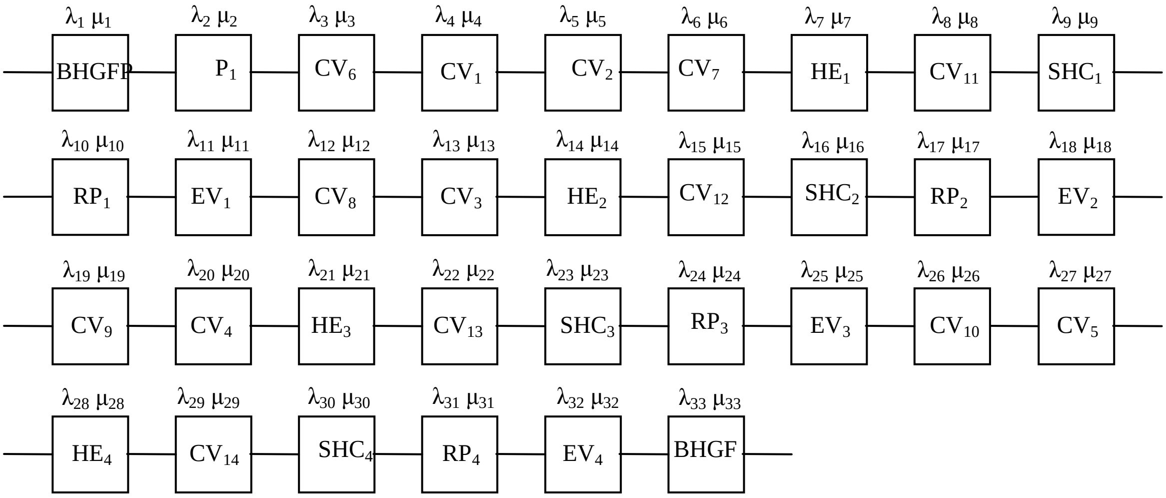

Figure 3: The equivalent reliability diagram of SSHSM

In the subsystem structures that are inside CGU there are also redundant elements (reserves). The equivalent indicators of the respective areas are computed following the model specific to the parallel equivalent schemes (Felea 1996), introduced after computation in the serial equivalent diagram.

The allotment in the design phase of the reliability level for groups of equivalent diagrams (subsystem components) is an optimization method and can be solved applying the accepted methods (Billinton 1971): the proportions' method, the modules' method, or the cost-reliability criteria

In order to establish the intrinsic operational reliability indicators (ORI), it is necessary to build statistics on a time basis, following in operation the components and the CGU. Special attention has to be paid to the elements from GW and SWF circuit, stressing the influence factors of ORI.

c) the associate safety (associate reliability) represents the CGU links' (interfaces) capacity to accomplish their job at a given time or over a period of time. Because these links are input or output ways for energetic agents (EA), beside the time safety (the time variation of safety indicators), at this level, one must solve the problem of the reliability parameters (that means that the EA parameters must be inside the proper limits for a normal functioning of the system). The indicators taken into account and the assessment modality are the same as for intrinsic safety.

d) availability is defined as the capacity of the CGU or of its subsystems to satisfy the specific job, at a given time or over a period of time, considering the combined aspects of safety, maintainability and maintenance.

The availability indicators offer a more complete characterization of the system than safety indicators; allow global assessments (of the intrinsic components and links) and are preferable in optimization methods.

To define the availability indicators in a stabilized regime - indicators that are used in design and forecast - it is first necessary to define the characteristic values for time and power.

For BHGFP, BHGFR, SSDHWP, SSGFR are defined the following characteristics values for time (on T_A interval) and power (at a given time, from T_A):

$$T_A = T_E + T_s + T_{SR} + T_{PM} \tag{6}$$

Where, T_E is effective operation time; T_s is stoppage time (failure, repairing, corrective maintenance); T_{SR} is static reserve time (on dispatcher disposal); T_{PM} is preventive maintenance time.

$$P_N = P_O + \Delta P_{PD} + \Delta P_{FD} \tag{7}$$

Where, P_N is nominal power; P_O is operation power; ΔP_{PD} is programmed decrease of power for revolving reserve; ΔP_{FD} is forced partially decrease of power, given by unavailability, etc.

Time availability (A_T) reflects the system's (subsystem's) capacity to respond to a solicitation:

$$A_T = \frac{T_E + T_{SR}}{T_A} = \frac{T_A - T_s - T_{PM}}{T_A} \tag{8}$$

The power availability (A_p) reflects the system’s (subsystem’s) capacity to ensure, by request, a certain level of power:

$$A_p = \frac{P_O + \Delta P_{PD}}{P_N} = \frac{P_N - \Delta P_{FD}}{P_N} \tag{9}$$

Beside the intrinsic reliability of the components, the availability of CGU is essentially influenced by the maintainability (the promptness of maintenance actions). To increase the CGU maintainability and of its subsystems are mainly recommended:

- proper training of the operators. for this reason one can call, for CGU with a certain importance, the automatic instruction system;
- technical diagnose in operation time for the motion elements;
- the optimization of the reserve stock of spare parts through operative maintenance;
- the maintenance optimization at the level of SSDHWP and of SSHSM, taking into account the

influence factors (reliability, accessibility, information quantity), applying the “objective” function:

$$F_O = \max\left[\frac{\lambda_i}{\sum\lambda_i}\frac{1}{T_i}H\cdot H*\right] \quad (10)$$

Where, λ_i is defect intensity rate for “i” element; T_i is time interval that characterizes the accessibility to element “i”; H, H* is the number of measurements necessary to find a defective element, referred to the total number of elements, when the first measurement is positive (H) or negative (H*).

4. THE OPTIMISATION OF THE CGU STRUCTURE AND REGIMES

The decision related to the existence and the structure of CGU is taken in the design and execution phases. The essential influence factors are:

- the necessity of the utilities in the target zone;
- the cost of the equipment;
- the conversion efficiency and the useful effects obtained;
- the running cost;
- the development perspectives.

The CGU structure must to be established applying the “maximum discounted economic efficiency” criteria, analytic synthesized as follows:

$$E_a(T) = H_a(T) - G_a(T) \to \max \quad (11)$$

Where, $H_a(T)$ is the discounted value of the economic effects, estimated for the studied period (T); $G_a(T)$ is the estimated discounted value for the existence and running expenses for the studied period (T);

The main terms of the objective function (12) are:

$$H_a(T) = V_{aI}(T) + V_{aUS}(T)$$

$$G_a(T) = I_{aD}(T) + I_{ac}(T) + C_{ae}(T) - R_a(T) \quad (12)$$

Where, $V_{aI}(T)$, $V_{aUS}(T)$ are the discounted values of TE [$V_{aI}(T)$] and of useful effects of LPUS [$V_{aUS}(T)$], estimated for the studied period (T); $I_{aD}(T)$, $I_{ac}(T)$ are the discounted value of direct [$I_{aD}(T)$] and connected [$I_{ac}(T)$] investments, estimated for the studied period (T); $C_{ae}(T)$ is the discounted value of running costs, for the studied period (T); $R_a(T)$ is residual and remnant discounted values for the CGU components, not in function or at the end of the studied period (T).

The computation of the discounted value for a certain term (X_a), knowing the value (X_j) in the year “i” is made according to:

$$X_a = \sum_{i=0}^{T} X_i\left(\frac{1+r}{1+a}\right)^i \quad (13)$$

Where, “r” is inflation rate and “a” is discount rate.

For CGU we can adopt: T=20 years, a=0.08 and r is estimated in relation with the tendency of the hard currency exchange rate in the past years of study.

The operation regime of CGU is defined through the parameters of the useful effects, produced by the subsystems that are in operation at a given time, or in a relatively short period ($\Delta t \ll T_A \ll T$), in respect with the nominal parameters.

From all possible regimes, the optimum one is obtained applying the “maximum economic efficiency” criteria (MEE).

$$E(\Delta t) = H(\Delta t) + G(\Delta t) \to \max \quad (14)$$

Where,

$$H(\Delta t) = V_I(\Delta t) + V_{US}(\Delta t) \quad (15)$$

$$G(\Delta t) = C_{ep}(\Delta t)\cdot C_{eAE}(\Delta t) + C_{eM}(\Delta t) + D(\Delta t)$$

Where, $V_I(\Delta t)$, $V_{US}(\Delta t)$ is the TE value and of useful effects in US, on Δt interval; $C_{ep}(\Delta t)$, $C_{eAE}(\Delta t)$, $C_{eM}(\Delta t)$, $D(\Delta t)$ are exploitation expenses referred to the personnel [$C_{ep}(\Delta t)$], energetic aspects [$C_{eAE}(\Delta t)$], maintenance [$C_{eM}(\Delta t)$] and damages [$D(\Delta t)$], on Δt interval.

The part of a certain factor (X), for Δt interval is determined knowing its value during the analyzed period, as follows:

$$X(\Delta t) = \frac{\Delta t}{T_A}\cdot X(T_A) \quad (16)$$

Evidently the reliability of CGU and of its components is reflected in the “objective” function of the optimization criteria.

CONCLUSIONS

Under the current conditions when the share of renewable energy is globally increasing the preoccupation and achievements related with the use of the geothermal energy have a special evolution.

For applications focused on relatively rich geothermal resources it is justified to use these resources in a complex way (CGU) for house heating, heating of technical spaces, domestic hot water production, drying of alleys (ice and snow melting), low potential uses (medical treatment, biomass production). The installed system (established in design and execution) and the momentary scheme of CGU system must be established applying an optimization criterion. In this paper it is proposed to apply the “maximum economic efficiency” criteria (MEE). The “objective” function of MEE criteria stressed the main factors of the momentary scheme of operation for CGU the necessity to use the resource locally and temporarily, the cost of the equipment, the conversion efficiencies, the equipment reliability, the running cost. In this paper the reason of reliability is understood in a large range (security, availability, intrinsic and associate safety). The general theory of reliability must be adapted to the level of CGU. It is possible to program the algorithm and the mathematical model on computers.

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