APPLYING THE RELIABILITY THEORY TO THE INVESTIGATION AND OPTIMISATION OF THE COMPLEX GEOTHERMAL USES

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ABSTRACT

Through complex geothermal uses (CGU) one understand thosc equipment that offer the possibility of exploitation of geothermal energy in three ways: electricity production, space heating and low temperature uses (health treatment, biomass prcduction).
In the first part of the paper the principles (from the hardware point of view) of CGU are described.. offering the input and output values and the possible variations with respect to the structure. In the second part it is defined the "reliability" function of the system and of its subsystems. The mathematics model of the evaluation of safety and availability indicators for CGU, is elaborated based on similar indicators of elements and subsystems.

The final part contains references for "objective" function of CGU type system and far the way of applying the "maximum economic efficiency" criteria, with the purpose of optimization the diagram and the momentary operating structure of the CGU.

1. THE OPPORTUNITY OF THE PROJECT

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

- the improvement of energy conversion efficiency;
-efficient technologies for decreasing the pollutants (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 technologies (solar, geothermal, hydro, wind, biomass and waste).

In the area of renewable energies, recently, special attention is given to the preoccupation and achievements in geothermal area done under the umbrella of the International Geothermal Association (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 as combined processes.
Such preoccupation is on actuality now in Romania (Cohut, 1994). At the University of Oradea (Maghiar et al., 1991) there is a pilot plant that uses the geothermal water energy in a complex way: electric power generation and space heating. Soon to these uses will be added new ones: biomass production and medical treatment. The economic, environmental and enqetic advantages of geothermal waters when one discusses just of house heating are of no doubt. The aspects of utilisation with other purposes (electric power generation, biomass prodcution and medical treatment) have a character of technical and scientific researches that must be subjected tu economic analysis.
The industrial applications involve, besides solving of technical problems, making a proper economical analysis related with their economical efficiency in comparison with the classic technologies (Friedleifsson, 1994). Using CGU that can facilitate the parallel or alternate use of the geothermal energy delivered by the source (well, group of wells) in useful processes as those mentioned above represent a very efficient way of their utilisation. With CGU one can obtain economic advantages, because:
- such utilisation generally allows the increase of thermal capacity which is recovered from the geothermal water, on the basis of increasing of AT 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 some methodological aspects of reliability analysis and the optimisation of the execution and operation structure of CGU.

2. THE STRUCTURE OF CGU

CGU mean those installations (systems) that offer the possibility of alternate or parallel development of geothermal energy (GE) in different ways: electricity generation, house heating, biomass production and medical treatment.

The block diagram of CGU system is shown in figure 1. The authors considers 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 literature

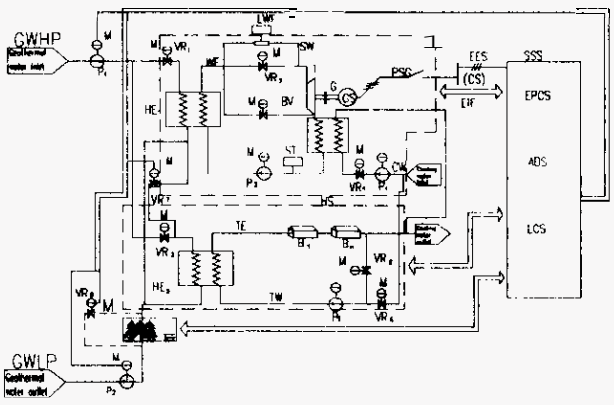

Figure 1 - The block diagram of CGU

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

- the electric energy generation subsystem (EEGS) that makes the thermal, mechanical and electrical energy conversion. The inputs in this subsystem are: the geothermal water with high potential (GWHP), the working fluid (WF) and the cooling water (CW). The EEGS output is the electric energy delivered to the electroenergetic system (EES) or delivered to a consumer (CS) isolated from the EES. The storage lank (ST) is designed to replenish the WF if necesary. There are also two safety elements lor EEGS, due to high prcssurc in the WF cloecd circuit (sometimes higher than m classical power plant): the by-pass valve (BY) and the safety valve (SV). There in also a storage tank to

avoid the leakage of the WF;
- the heating subsystem (HS), that has a simpler structure than EEGY, designed to delivere the thermal energy (TE) to the buildings (B_1, B_2,..., B_n). In the heat exchanger (HE_3) the heat from GWHP is transferred to the industrial water (TW). This subsystem can work, in respect with the TW, "closed" or "open";
- the low potential utilisation subsystem (LPUS), which is even simpler. Here is accomplished the thermal bio- and chemical energy conversion;
- the self services subsystems (SSS), containing: electric power circuits subsystem (EPCS), designed to deliver EE to the main consumers of EEGS (pumps, valves); the autonomous delivering subsystem (ADS) for vial consumers and the leading and checking subsystem (LCS), that measures, *signals*, commands, checks and adjusts (including automatic adjustment based *on* a preestablished software). The links between SSS and the other three subsystems provides the transmission of energetic and informational flows (EIF);
- the interface subsystem (wells, CW towers, GW pumps, by-passes between subsystems).

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 LCS, on the basis of a preestablished software, related with the mathematic model of the process and taking into account the physical structure of the system;
- design and execution of the following working possibilities for the EEGS and HS subsystems: parallel (VR_2 - open; VR_1 - closed) and serial (VR_2 - closed, VR_1 - open) adjusting the GWHP input parameters of each subsystem;
- upgrade the *operators* to the technical level of CGU, in order to be able to operate in all CGU subsystems.

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 (Nitu, 1994).

Concerning the qualitative aspect, the CGU reliability represents its capacity to accomplish the designed task, at a *given* time and in a certain period.

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

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

where:
t = time variable;
T = design operation period,
UE_{ij} - useful effect of subsystem "i" (i = {EEGS, HS, LPUS}), 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 solicited at a *given* time (t_j) are able to accomplish the specific tasks, we can evidently write:

$$R_S = R_{EEGS} \cdot R_{HS} \cdot R_{LPUS} \quad (2)$$

The reliability functions of the subsystems (R_{EEGS}, R_{HS}, R_{LPUS}) are defined similarly with the reliability function of the system (RS), implying, evidently, the good operation of the SSS parts.
Thus defined, the reliability function of CGU involves the following functions: security, availability, intrinsic and associate safety

a) the security problem arises *only* m relation with EEGS, m two aspects:
- avoiding the explosion danger in the WF circuit (P_s – HE, – VR_s – T – HE_3) when exceeding the admissible pressure limit, by losing control of regulation elements;
- avoiding the leakage of WF - if the fluid can affect the operators or the environment - after the action of the SV, in LWR.

The securily function of EEGS can be as follows:

$$P_{SEC} = 1 - (1 - P_{MP})(1 - P_{BV})(1 - P_{SV}) \times P \quad (3)$$

where:
P, – the probability of maintaining the pressure under the admissible value (the probability of proper operation of the checking and adjusting pressure system);
P_{BV}, P, PLWR – the probability of proper operation (intrinsic safety) of the elements (BV, SV, LWR).

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

The problem of the intrinsic reliability arises from the design phase ox m operation (when the long term assessments of useful effects are made). It is the role of the analyst to assess the so called "predictable intrinsic reliability" (PIR) 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 the subsystems of a certain CGU are requested by the assessment of the damages produced by the decrease of the useful effects under the established values (UEij < UEcij). The damages' characteristics of the mentioned utilities can be as those shown in figure 2

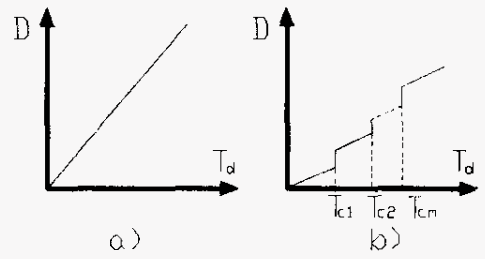

Figure 2. Damage characteristics of the utilities served by CGU {D - damage [monetary units]; Td - interrupt period [time units]; T_{ck} - critical moments (ck = 1, m)}

A characteristic like the one in figure 2.a. is typical for LPUS and for the majority of HS applications and the one in figure 2.b. is typical for EEGS (more specific on *CS)* and for certain application with HS

When the damage is proportional with the period of interruption (figure 2.a.) it is enough to determine the following reliability indicators:
- the probability of good functioning (P_{GF});
- the total period of interruption in the analysed interval [$v(T_A)$].

When the damage depends both of the period of interruption and the number of interruptions (figure 2.b.), besides the mentioned indicators. it is necessary to evaluate the following indicators as well:
- numher of failures over the analysed interval [$\beta(T_A)$];
- the mean time between failures (MTBF) and the average stopage timc respectively (MTR).

To assess these indicators at the subsystem level one considers the elements' indicators as known. When *analysing* PIR, one can operate with the indicators' stationary regime values (constants): λ (failure intensity) and μ (restore intensity). For the majority of CGU elements, the values of these indicators are well k n o w being classical components (the producing companies guarantee the values for λ and μ). There are some components (P_1, P_2, VR_1, HE_1, VR_2, HE_2, VR_7, VR_8) and the GW p i p 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 WF circuit elements, that works at high pressure. For those elements, knowing the values of the reliability guaranteed indicators m 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):

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

In the subsystem structure 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 equivalents chemes (Nitu et al., 1994), 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 (Pages and Goudran, 1980): 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 WF 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 function 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, maintenability and maintenance.

The availability indicators offer a more complete characterisation 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 LPUS it is enough to assess the safety indicators. Concerning the EEGS, HS and CGU are defined the following characteristic values for time (on T_A interval) and power (at a given time, from T_A):

$$T_A = T_F + T_d + T_{RS} + T_{MP} \quad (4)$$

where,

T_F - effective operation time;
T_d - stoppage time (failure, repairing, corrective maintenance);
T_{RS} - static reserve time (on dispatcher disposal);
T_{MP} - preventive maintenance time.

$$P_N = P_F + DP_r + DP_f \quad (5)$$

P_N - nominal power;
P_F - operation power;
DP_r - programmed decrease of power for revolving reserve;
DP_{RS} - forced partially decrease of power, given by unavailability, decrease of EA parameters, etc.

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

$$A_T = \frac{T_F + T_{RS}}{T_A} = \frac{T_A - T_d - T_{MP}}{T_A} \quad (6)$$

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

$$A_p = \frac{P_f + \Delta P_{RT}}{P_N} = \frac{P_N - \Delta P_{RF}}{P_N} \quad (7)$$

The energy availability (A_W) reflects the capacity of the system (subsystem) to satisfy the energy demand for the utility (CS, B_j) for a time period:

$$A_W = A_P A_T = \frac{(P_F + \Delta P_{RT})}{P_N} \frac{(T_F + T_{RS})}{T_A} = \frac{W_F + \Delta W_{RT} + \Delta W_{RS}}{W_N} \quad (8)$$

or,

$$A_V = A_P A_T = \frac{(P_N - \Delta P_{RF})}{P_N} \frac{(T_A - T_d - T_{MP})}{T_A} = \frac{W_N - (\Delta W_{IOF} + \Delta W_{IMP} + \Delta W_{IRF})}{W_N} \quad (9)$$

The expression (9) can be also write as follows:

$$A_W = 1 - \frac{\Delta W_{IOF}}{W_N} - \frac{\Delta W_{IMP}}{W_N} - \frac{\Delta W_{IRF}}{W_N} = 1 - (I_{Wd} + I_{WMP} + I_{WRF}) = 1 - I_W \quad (10)$$

The parameters that are involved in (8), (9) and (10) have the following meaning:

W_N - nominal energy (maximum demanded);
ΔW_{IOF}, ΔW_{IMP}, ΔW_{IRF} – unavailable energy because of: forced stops (ΔW_{IOF}); preventive maintenance (ΔW_{IMP}) and forced decreasing of power (ΔW_{IRF});
I_{Wd}, I_{WMP}, I_{WRF} -- unavailable energy because of: breakings (I_{Wd}), preventive maintenance (I_{WMP}), and forced decreasing of power (I_{WRF});
I_W -- total unavailable energy.

The factors I_{Wd}, I_{WRF} have probabilistic character and I_{WMP} has determinist character (in the classic variant of preventive maintenance, after a normalised operation time) and, respectively, I_{WMP} has semi-random character (in the variant of establishing the time of preventive maintenance beginning through the real technical status diagnose by the CGU elements).

The factors that are involved in (8), (9) and (10) are shown in figure 3.

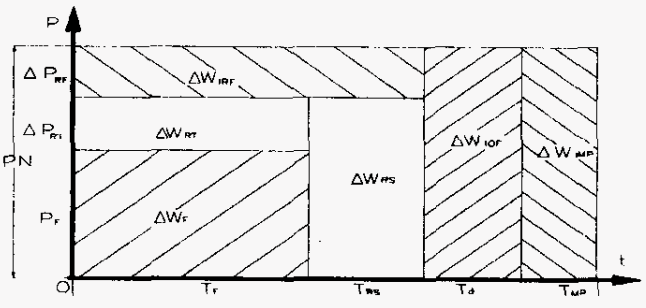

Figure 3. The characteristic factors of time, power and energy for CGU or for the EEGS, HS subsystems

other useful indicators in the design and operation of CGU and of its component subsystems:

$U_T = T_F/T_A$ – the utilisation in time coefficient;
$U_E = W_F/W_N$ – the utilisation in energy coefficient.

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

- proper training of the operators. For this reason one can call, for CGU with a certain importance, the automatic mining system (Nitu et al., 1994);
- technical diagnose in operation time for the motion elements (T,

G, P,) of EEGS through vibration transducers. in the measurement, filtering and comparison networks;
- the optimization of the reserve stock of spare parts through operative maintenance;
- the maintenance optimization at the level of EEGS and of HS, taking into account the iniluence factors (reliability, accessibility, information quantity), *applying* the "objective" function:

$$F_0 = \max\left[\sum_{\lambda_i}\frac{\lambda_i}{T_i}\frac{1}{HH^*}\right] \qquad (11)$$

where,
λ_i – defect intensity rate for "i" element;
T_i – time interval that characterises the accessibility to element "i";
H, H* – the number of measurements necessary to find a defective element. referred io 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 iniluence factors are:
- the necessity of the utilities in the target zone;
- the cost ofthe equipment;
- the conversion efficiency and the useful effects obtained ;
- the connection characteristics (lengths of links, accessibility io EES);
- the running cost;
- the development perspectives.

The CGU structure must to he established applying the "maximum discounted economic efficiency" criteria, analytic synthesised as follows:

$$E_a(T) = H_a(T) - G_a(T) \rightarrow \max \qquad (12)$$

where,
$H_a(T)$ – the discounted value of the economic effects, estimated for the studied period (T);
$G_a(T)$ - the estimated discounted value for the existence and running expenses for the *studied* period (T);

The main terms of the objective function (13) are:

$$H_a(T) = V_{aE}(T) + V_{aH}(T) + V_{aLPU}(T)$$
$$G_a(T) = I_{aD}(T) + I_{aC}(T) + C_{ac}(T) - R_a(T) \qquad (13)$$

where,
$V_{aE}(T)$, $V_{aH}(T)$, $V_{aLPU}(T)$ – the discounted values of EE [$V_{aE}(T)$], TE [$V_{aH}(T)$] and of useful effects of LPUS [$V_{aLPU}(T)$], estimated for the studied period (T);
$I_{aD}(T)$, $I_{aC}(T)$ – the discounted value of direct [$I_{aD}(T)$] and connected [$I_{aC}(T)$], estimated for the studied period (T);
$C_{ac}(T)$ – the discounted value of running costs (related to the personnel, EA, maintenance and *damages),* for the studied period (T);
$R_a(T)$ – residual and remnant discounted values for the CGU components, not in function.

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

$$X_a = \sum_{i=0}^{T} X_i\left(\frac{1+r}{1+a}\right)^i \qquad (14)$$

where,
r – inflation rate;
a - discount rate.

For CGU we can adopt: T = 20 Years, a = 0.08 and r is estimated in relation With the tendency ofthe hard currency exchange rate (US Dollar recommended) 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 Lime, 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).

$$E(\Delta T) = H(\Delta T) - G(\Delta T) \rightarrow \max \qquad (15)$$

where

$$H(\Delta t) = V_E(\Delta t) + V_H(\Delta t) + V_{LPU}(\Delta t)$$
$$G(\Delta t) = C_{ep}(\Delta t) + C_{eEA}(\Delta t) + C_{eM}(\Delta t) + D(\Delta t) \qquad (16)$$

where:
$V_E(\Delta t)$, $V_H(\Delta t)$, $V_{LPU}(\Delta t)$ – the EE, TE values and of useful effects m LPU, *on* Dt interval;
$C_{ep}(\Delta t)$, $C_{eEA}(\Delta t)$, $C_{eM}(\Delta t)$, $D(\Delta t)$ – exploitation expenses refmed to the personnel [$C_{ep}(\Delta t)$], energetic agents [$C_{eEA}(\Delta t)$], maintenance [$C_{eM}(\Delta t)$] and damages [D(Dt)], on AI interval.

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

$$X(\Delta t) = \Delta t\frac{X(T_A)}{T_A} \qquad (17)$$

Evidently the reliability of CGU and of its components is reflected in the "objective" function of the optimisation criteria, through: $H(H_a)$, $C_{eM}(C_{eaM})$ and $D(D_a)$, e.g.:

$$V_E(\Delta t) = W_F K_W \frac{\Delta t}{T_A} = W_N A_W K_W \frac{\Delta t}{T_A} \qquad (18)$$

where,
K_W – the specific cost of EE [monetary units/kWh]

5. CONCLUSIONS

The preoccupation and the 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. electricity generation, law potential uses (medical treatment, biomass production). The installed system (established m design and execution)and the momentary scheme of *CGU system must* be established applying an optimisation criterion. In this paper it is proposed to apply the "maximumeconomic 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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