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GEOTHERMAL MATERIALS ADVISORY SYSTEM

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ABSTRACT

DSIR corporate knowledge of materials selection and use for geothermal energy applications is being captured using a PC-based expert system. The expert system will include a knowledge base designed to assess the corrosivity of new and existing geothermal fields and to give advice on materials for pre-planning and problem solving.

Advice will be based on corrosion predictions derived from thermodynamic principles of corrosion and on a database of materials testing results and experience. The initial target audience for the system will be materials engineers with limited experience in geothermal applications. This paper reviews the development procedures used, the status of the prototype and plans for future development.

INTRODUCTION

Initial development of computerised materials information systems began with abstract storage and searching programmes in the 1960's followed by a steady increase in the number of systems being made publicly available from the 1970's (Matteson, 1981; Anthony and Mildern, 1985). The use of computers in more direct corrosion control applications also increased dramatically over this same time period and into the 1980's (NACE, 1986). Examples of applications-oriented computer products which have now become standard tools for many corrosion control technologists include:

- Abstracts and Text Searching
  - corrosion and materials information (Matteson, 1981; Anthony and Mildern, 1986; Anderson, 1990)
- Data Logging
  - corrosion measurements and calculations (NACE, 1986)
- Database Information System
  - data storage, manipulation and reporting (NACE, 1986; Anderson, 1990; ASM, 1990; IMMA, 1990)
- Modelling
  - corrosion process modelling (NACE, 1986; Anderson, 1990)
- Expert Systems
  - materials selection and performance advice (NACE, 1986; Anderson, 1990; MTI-EFC-NACE, 1990).

Expert systems have been the last application to see increased development activity. Widespread use of the technology which is seen as an application of Artificial Intelligence was initially limited by hardware developments. The symbolic representation techniques used to describe entities or attributes and their values in expert systems require large amounts of memory and early systems were restricted to large computer system capable of operating in LISP or PROLOG. The increasing availability of faster, smaller (and larger) but generally less expensive hardware together with the development of expert system software tools suitable for use by non-programmers has spawned a proliferation of in-house and commercial expert systems (Harmon and King, 1985; Waterman, 1986).

Recent surveys conducted by an international Working Party on Expert Systems in Materials Engineering (MTI-EFC-NACE, 1990) identified 66 expert systems being developed by 62 companies specifically for materials selection and performance advice. Eleven of the surveyed systems were being offered for sale. The great majority of these active developments are by small groups considering narrow knowledge domains (areas of expertise) and are being implemented using commercially available expert system development shells which provide a programme structure designed to accept a knowledge base.

Recent developments have included expert system capable of handling more generalised corrosion and materials domains and incorporating additional features such as materials performance databases and text searching capabilities (MTI-EFC-NACE, 1990).

DSIR have maintained geothermal materials performance databanks and modelling programmes for some years. DSIR activity in the development of expert systems for materials selection began in 1988 with an expert system module for selection of materials for sucker rod pumps for the US oil and gas industry - PETRO*COR™[1] (Lichti et al, 1989), a joint development with the National Association of Corrosion Engineers (NACE) and the National Institute of Standards and Technology (NIST) under the auspices of the NACE-NIST Corrosion Data Centre. This development combined DSIR and oil and gas industry experience in materials selection with NACE-NIST expertise in development of databases and expert systems for the corrosion community (Sturrock and Pollock, 1989; Anderson, 1990).

This paper describes initial efforts to develop a geothermal materials advisory system by combining the capabilities of several commercial software packages into one system: an expert system shell, KES™[2], a relational database, Paradox™[3], and a corrosion process modelling programme.

INTEGRATED SOFTWARE IN MATERIALS ENGINEERING

The increasing use of expert systems and user friendly databases arises from a demand for evaluated data which has been interpreted and placed in context for a particular application.

The process of "evaluating" data involves (Anderson, 1989):

- assessing accuracy and reliability
- assessing experimental techniques and associated errors
- comparison with other experimental or theoretical values
- recalculating derived results and accepted models
- comparison with service experience
- comparison with current industry practice
- selective acceptance and statistical manipulation
- assignment of probable error or reliability

[1] PETRO*COR™ NACE, Houston, Texas, USA.
[2] KES™ Software A&E, Arlington, Virginia, USA.
[3] Paradox™ Borland Intl., Scotts Valley, California, USA.

The process of building an expert system involves evaluation of the knowledge base and the advice given. System developed for non-experts do not require on-line access to supporting data as simple explanations are generally sufficient. Combining materials advisory expert system with database facilities can provide experienced users with direct access to the evaluated data which has been used to develop the knowledge base and give the system advice so that they can independently evaluate the relevance of the date for their current application.

GeoMat OBJECTIVES

The GeoMat expert system is being developed to capture DSIR corporate knowledge on the provision of advice for the selection and use of materials for geothermal energy applications. The system will incorporate DSIR results and experience gained since 1956 in testing materials and giving advice for geothermal energy applications(Braithwaite and Lichti, 1980; Wilson and Lichti, 1982; Lichti and Wilson, 1983). The primary audience will be DSIR materials and corrosion engineers having limited expertise in geothermal systems.

The final expert system will provide:

- a formal tabulation of existing data and experience
- a formal review of DSIR results and experience
- a collation of expertise held by several individuals
- a broad base of individuals with access to the knowledge
- the ability to continue to give advice in geothermal energy applications without an active research programme
- a structure for capturing additional knowledge as it is obtained.

GeoMat SYSTEM OVERVIEW

GeoMat consists of three separate computer software packages which are to be accessed via a single user interface. Figure 1 gives an overview of the anticipated design structure for the system. The primary user interface will automatically provide the user with access to the various software packages as they are required and will facilitate movement of information between the software packages.

The expert system will obtain or define the relevant corrosion chemistry and physical parameters for the area of interest indicated by the user and give advice on the selection and use of materials. The corrosion process modelling programme will provide a graphical presentation of a theoretical equilibrium potential-pH (Pourbaix) diagram from which the user will obtain information on the predicted stability of corrosion products. This information will be required by the expert system to give materials advice. The materials performance database will include practical experience and exposure results on which the advice is based.

PROTOTYPE IMPLEMENTATION STRATEGY

Initial prototyping effort has been directed at development of the user interface and the individual programmes for the three distinct activities identified above. The KES™ expert system shell is being used to implement the user interface and to develop the expert system structure. Corrosion chemistry calculations are done within the expert system shell. A small subset of rules which give materials advice for a limited number of steam field applications have been written in order to test the user interface and system operation. A programme designed to calculate equilibrium potential-pH diagrams is available but requires development of a permanent database for typical geothermal steam applications. A preliminary structure for a geothermal materials performance database of corrosion results has been developed. Sample materials results have been entered to test the reporting facilities which are needed to justify materials advice given by the expert system.

Effort is now required to expand the knowledge base for provision of materials advice and to integrate the software to avoid the need for users to be intimately familiar with each of the software packages used.

PROTOTYPE DEVELOPMENT

Primary User Interface and Expert System Implementation:

Figure 2 illustrates the current system architecture and control structure for GeoMat. Screens presented to the user during a sample consultation are summarised in Appendix A. Figure 2 together with the sample consultation given in Appendix A illustrate: user identification of application of interest, user input of steam chemistry, system calculation results for high temperature corrosion chemistry, user entry of results obtained from equilibrium potential-pH diagram and final provision of advice followed by the system change menu. The change menu will permit repeated interrogation of the system to ascertain the influence of variation of input conditions on final materials advice.

Justification of advice from the change menu will ultimately include automatic access to or at minimum a reference to the materials database on which the advice is based.

Potential-pH (Pourbaix) Diagram Programme Implementation:

Corrosion process modelling using equilibrium potential-pH (Pourbaix) diagrams helps experienced technologists to describe equilibrium corrosion reactions expected to occur when carbon steels for example are exposed to geothermal steam condensate (Lichti and Wilson, 1983). Figure 3 illustrates such a diagram for the steam condensate chemistry obtained for the example in Appendix A. (These results represent the corrosion chemistry of

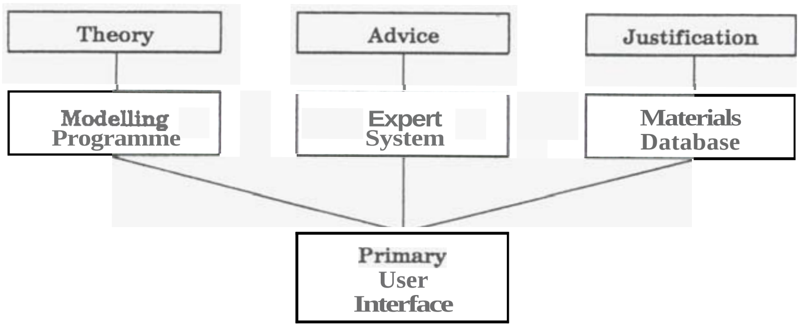

FIGURE 1 DSIR GeoMat Integrated Software Overview.

the Broadlands geothermal well BR22 in 1983.) The diagram shown in Figure 3 illustrates:

- environment steam chemistry
- steam condensate pH calculated by the expert system
- approximate corrosion potential taken as the potential of the point of intersection of the steam condensate pH with the H_2 - H^+ equilibrium line
- the difference in pH between the steam condensate pH and the pH where Fe^{++} is stable at the assumed corrosion potential.

These values are used by the expert system in making a materials recommendation.

Sets of electrochemical free energy data required to calculate the potential-pH diagrams have been assembled for the various species involved in the reactions shown on the diagram. Automatic selection of the correct set for the desired conditions has yet to be implemented and the present programme can only be operated by experienced users.

Database Implementation:

Materials results are available for over 20 differing alloy types exposed in up to 8 differing geothermal test environments (Braithwaite and Lichti, 1980; Lichti and Wilson, 1983). An initial materials test results database has been developed for ASTM surface corrosion coupons using the relational database Paradox™. The database includes basic materials parameters, descriptions of forms of corrosion, corrosion rate and pitting results. Figure 4 illustrates a sample output of results for a plain carbon steel exposed to four geothermal environments.

It is intended to use graphical presentations wherever possible although tabulated results will be available for inspection. Much work remains in design of the database for the differing results available. It is also intended to tabulate experience gained in materials selection for actual plant although this information will be inherent in the expert system knowledge base.

PROTOTYPE REVISION I

The initial prototype module has focused on bringing together expertise pertaining to corrosion rates. This emphasis reflects the quality of both emperical corrosion rate data and the theoretical framework relating alloy performance to environmental parameters. Other significant modes of alloy degradation are pitting corrosion and stress corrosion cracking and it is intended that later developments of GeoMat will incorporate expertise in these two areas.

In that the intended use of an expert system is the prediction of materials performance, the development of GeoMat has highlighted areas of materials performance where the quality of information is of a lower standard.

For pitting corrosion and stress corrosion cracking there is currently a qualitative theoretical model relating alloy performance/resistance to environmental parameters. In some isolated instances there is semi-qualitative emperical data linking alloy performance *to* environmental parameters, but generally the link between environmental parameters and alloy performance data is at best qualitative.

Progress in this area requires improve theoretical models for both pitting corrosion and stress corrosion cracking in chloride-free environments but containing hydrogen sulphide and oxygen. Research on this aspect is proceeding in parallel with the expert system development with the initial objective of defining the threshold of acceptable performance in terms of the assessable environment parameters of temperature, pH and H_2S content (McIlhone and Wilson, 1990).

CONCLUSIONS AND FUTURE TARGETS

The basic structure for an integrated software package for provision of advise on materials selection and use for geothermal energy applications has been designed.

Discrete prototype software packages for a user interface/expert system, a potential-pH diagram calculation and a relational database have been prepared.

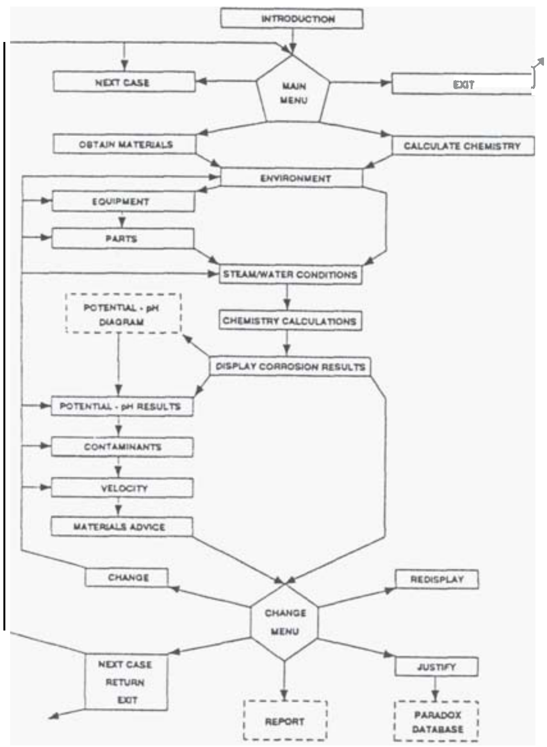

FIGURE 2 DSIR GeoMat Expert System Architecture and Control Structure.

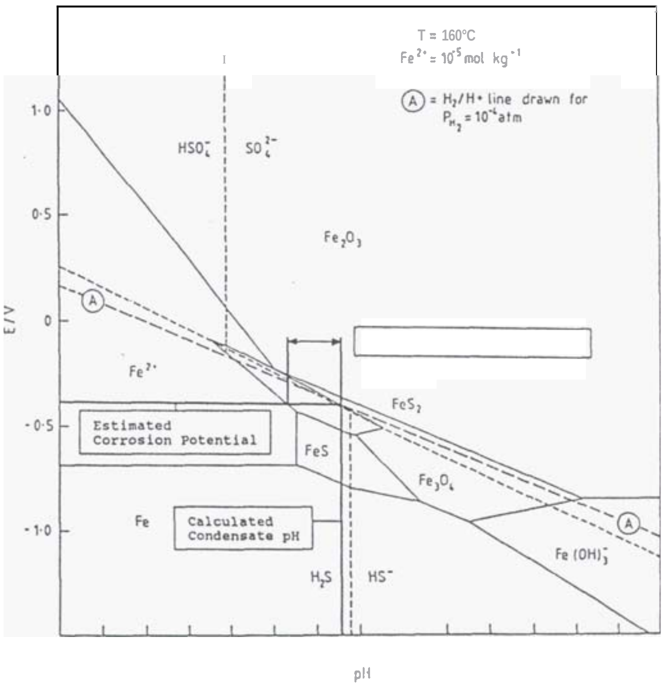

FIGURE 3 DSIR GeoMat Equilibrium Potential-pH (Pourbaix) Diagram Illustration of Values Used to Give Materials Advice.

Future work on these packages will involve:

- expanding the expert system knowledge base for provision of materials advice
- preparing a file structure for the electrochemical free energy database required to calculate the equilibrium potential-pH diagrams
- adding an on-line graphics presentation package for equilibrium potential-pH diagrams
- capturing corrosion test results using the relational database

Integration of the software to avoid the need for users to be intimately familiar with each of the software packages used will involve expansion of the user interface software.

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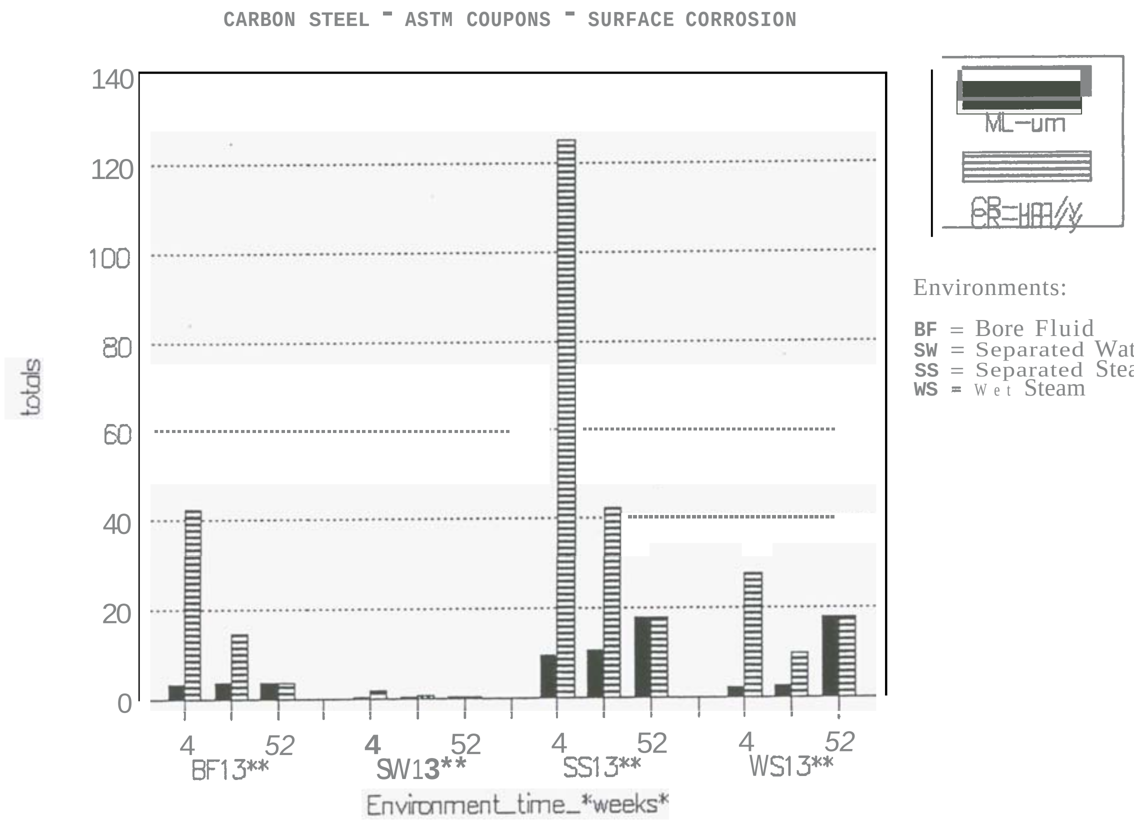

Environments:

BF = Bore Fluid
SW = Separated Water
SS = Separated Steam
WS = Wet Steam

FIGURE 4 **DSIR** GeoMat Database Illustration of Graphically Presented **Results**

APPENDIX A DSIR GeoMat Expert System Prototype Sample Consultation.

```
*************************************************************
*  Welcome to the DSIR Materials Performance Group          *
*        Prototype Expert System                            *
*     for The Selection of Materials for                    *
*      GEOTHERMAL ENERGY APPLICATIONS                       *
*                                                           *
*     This system is being developed to                     *
*        CAPTURE DSIR EXPERTISE                             *
*                                                           *
*  System Developers:                                       *
*     - Industrial Processing DSIR                          *
*     - Information Technology DSIR                         *
*  Principle Contact:                                       *
*     - Keith A Lichti, Lower Hutt, (04) 690-788            *
*************************************************************
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DSIR GeoMat Expert System

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*****************
*  MAIN MENU  *
*****************
```

What do you want to do?

1. obtain materials for geothermal application
2. calculate high temperature/high pressure chemistry
3. do another case
4. exit from expert system

=? 1

What environment do you want to do?
1. dry superheated steam
2. saturated steam
3. wet steam
4. separated water
5. return to previous menu

=?3

What equipment do you wish to select materials for?
1. pipelines
2. steam valves
3. water valves
4. steam/water separators
5. all equipment

(Multiple answers allowed)
=? 1

What parts do you want to select materials for?
1. straight pipe sections
2. pipe elbow
3. valve stem
4. valve body
5. valve plug
6. compensator
7. return to previous menu

=? 1

Is oxygen allowed to enter the environment?
1. yes
2. no

=? 2

What is the CO2 gas concentration in the steam phase?
You must enter a value between 0.001 and 250000 to continue.
eg 841 [mmol gas/100 mmol steam]
(Enter a number)
=?841

What is the H2S gas concentration in the steam phase?
You must enter a value between 0.001 and 25000 to continue.
eg 17.6 [mmol gas/100 mmol steam]
(Enter a number)
=? 17.6

What is the NH3 gas concentration in the steam phase?
You must enter a value between 0.001 and 25000 to continue.
eg 5.4 [mmol gas/100 mmol steam]
(Enter a number)
=? 6.4

What is the H2 gas concentration in the steam phase?
You must enter a value between 0.001 and 2500 to continue.
eg 6.6 [mmol gas/100 mmol steam]
(Enter a number)
=? 5.6

What is the N2 gas concentration in the steam phase?
You must enter a value between 0.001 and 2500 to continue.
eg 10.6 [mmol gas/100 mmol steam]
(Enter a number)
=? 10.6

What is the CH4 gas concentration in the steam phase?
You must enter a value between 0.001 and 2500 to continue.
eg 0.79 [mmol gas/100 mmol steam]
(Enter a number)
=? 0.79

What is the desired calculation temperature?
You must enter a value between 20 and 250 to continue.
eg 160 [degrees celsius]
(Enter a number)
=? 160

What is the desired calculation pressure?
You must enter a value between 0.024 and 4000 to continue.
eg 620 [kPa]
(Enter a number)
=? 620

USER DEFINED **CONDITIONS:**

Calculation Temperature = 160 degrees celsius
Calculation Pressure = 620 kPa
C02 gas concentration = 841 mmol gas/100 mol steam
H2S gas concentration = 17.60000038 mmol gas/100 mol steam
NH3 gas concentration = 5.4000001 mmol gas/100 mol steam
H2 gas concentration = 5.6999999 mmol gas/100 mol steam
N2 gas concentration = 10.60000038 mmol gas/100 mol steam
CH4 gas concentration = 0.79000002 mmol gad100 mol steam

SYSTEM DEFINED CONDITIONS:

m(CO2) in condensate = 0.0004619 mol/kg
m(HCO3-) in condensate = 0.00022212 mol/kg
m(H2S) in condensate = 3.27965208e-005 mol/kg
m(HS-) in condensate = 1.49969819e-005 mol/kg
m(NH3) in condensate = 0.00034975 mol/kg
m(NH4+) in condensate = 0.00024656 mol/kg
m(H2) in condensate = 3.31249396e-007 mol/kg
m(N2) in condensate = 4.01560982e-007 mol/kg
m(CH4) in condensate = 6.13218205e-008 mol/kg
condensate pH = 6.52213335

An equilibrium Potential-pH type diagram based on the above information is now required. Use DSIR Pmgram.

Exit from system?
1. yea
2. no
=?2

Is stable corrosion product formation predicted?
1. yes
2. no
=? 1

What is the corrosion potential at pH(T)?
You must enter a value between -1.0 and 1.0 to continue.
eg -0.2
(Enter a number)
=? -0.4

What is the maximum pH of the Fe(++) stability area at the corrosion potential?
You must enter a value between 0.0 and 14.0 to continue.
eg 4.8
(Enter a number)
=?5.2

What is the level of chloride ion in the steam condensate?
eg 1.5 mg/kg You must enter a value between 0.0 and 300.0
(Enter a number)
=? 1.5

What is the minimum silica content in steam condensate?
You must enter a value between 0.0 and 10.0 to continue.
eg 1.5 mg/kg in condensate
(Enter a number)
=? 1.5

What is the steam condensate velocity in your system?
eg 0.5 Enter a value between 0 and 11.0
(Enter a number)
=? 0.5

PARAMETERS AND **VALUES** USED **FOR MATERIALS** ADVICE:

calculation temperature = 160 degrees celsius
calculation pressure = 620 degrees celsius
oxygen entry = no
chloride content of steam = 1.5 ppm [mg/kg]
condensate velocity = 0.5 meters per second
condensate pH(T) = 6.52
neutral pH(T) = 5.77
pH(T) - neutral pH(T) = 0.76
stable corrosion product8 = yea
E(corr) at pH(T) = -0.4 volts
pH max for Fe(++) at E(corr) = 5.2
pH(T) - pH max for Fe(++) = 1.32

For applications of the type:

environment = wet steam
equipment = pipelines
parts = straight pipe sections

The following materiala have been used successfully used in similar environments:

UNS G10XX0 Plain carbon steel, seamless or welded having a maximum hardness of Rockwell C 22. Corrosion allowance of 2 to 3 mm is often pmvided as pitting corrosion is predicted as a consequence of air ingress at startup and shutdown.

Warning:

Monitoring by visual inspection at annual shutdowns is recommended to confirm formation of stable protective corrosion products and absence of damaging erosion corrosion.

```
***********************
*    CHANGE MENU      *
***********************
```

What do you want to do?
1. re-display all values for chemistry or materials
2. justify conditions or advice
3. change a user specified condition
4. return to main menu
5. do another case
6. exit from expert system
=? 6