THERMAL ENERGY SYSTEM SYNTHESIS

the origin and development of a scientific procedure for the design of thermal energy systems

by

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THERMAL ENERGY SYSTEM SYNTHESIS

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THERMAL ENERGY SYSTEM SYNTHESIS.

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SUMMARY.

Thermodynamics is a necessary but insufficient science for the design of thermal energy systems. A theorem for design is proposed to overcome this insufficiency. The design method requires simulation of the energy functions of a real system in the precise terms of a radiant model system. A combination of this design method with methods of numerical optimisation leads to a discipline and procedure for system synthesis.

The synthesis procedure is formulated in unified terms for both steady systems and time-varying systems, with or without energy storage. The key is a representation of system function on a diagram of temperature co-ordinates and energy-rates for each time-interval. Engineering constraints and objective functions remain process oriented. Computing methods are developed directly from this formulation.

The engineering and optimising features of synthesis are both demonstrated by an application to solar heating systems. The synthesis methods themselves are shown to be satisfactory but solar design requires further study. The optimum (cost) relation between solar collector area and storage capacity is exposed.

Present limitations on the application of system synthesis are outlined as a plan for future work. The work will be justified by its significance to professional engineering practice – promising an improved faculty for decision and design in the field of thermal energy.

THERMAL ENERGY SYSTEM SYNTHESIS.

STATEMENT OF ORIGINALITY.

This thesis contains no material which has been accepted for the award to me of any degree or diploma in any University and, to the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made in the text of the thesis.

(G.M.Tostevin)

PREFACE

Thermal Energy System Synthesis will be explained over a wide range of thought, from scientific foundation to engineering practice. Rather than take each aspect of synthesis as it arises through this whole range of explanation, this thesis presents its subject in four main progressive steps:

. An ARGUMENT to establish a basis for synthesis in present thermodynamic knowledge — Section 2.

. A DISCIPLINE and formulation of the synthesis procedure in its own terms — Sections 3 to 5, Part A.

. The PRACTICE of synthesis, particularly its computing methods — Sections 6 to 11, Part B.

. A DEMONSTRATION of the synthesis procedure by an application to solar heating — Sections 13 to 16, Part D.

An intermediate commentary on the relation of the work to that published by others is contained in Section 12, Part C. The thesis concludes with a discussion of the effectiveness, the limitations and the future of synthesis, Part E.

The style of writing in Parts A, B and D is deliberately *instructional* to support the introduction of synthesis into engineering practice.

Diagrams and tables are grouped at the end of each main section to which they refer. References to published work, an index of definitions and a glossary of symbolic names are included at the end of the thesis.

The work was done in the Department of Mechanical Engineering of the University of Adelaide under the supervision of Professor R.E.Luxton between February 1975 and May 1978. Professor Luxton's unfailing enthusiasm and perceptive comment were of tremendous support throughout the period and I am indeed grateful to him.

Although founded in the knowledge of Mechanical Engineering, the discipline of synthesis particularly makes that knowledge accessible to methods of Operations Research. I appreciate the discussions I have had with Professor R.B.Potts, of the Department of Applied Mathematics, on those methods.

I am indebted to the University for the use of its central computer and I appreciated the routine help given by the staff of the Computing Centre. For help with editing I am grateful to Mr. W.H.Schneider, also of the Department of Mechanical Engineering. I value the opportunity to have consulted with the staff of C.S.I.R.O., Division of Mechanical Engineering at Highett, Victoria, about solar heating and to have observed part of their experimental program.

G.M.TOSTEVIN.
19 May 1978

1.0 INTRODUCTION

Most of our industrial history stems from the combustion of coal, gas and oil. Within little more than a century, man has developed ingenious methods of harnessing the thermal energy released by combustion - for power generation, for transport and for the heating, cooling and other needs of a modern industrial society. This is the work of the professional Mechanical Engineer.

There has been much for him to learn and master - the physics and chemistry of materials, thermodynamics, mechanics of material behaviour, fabrication of machinery, lubrication and much more. Each is a life's study on its own. Yet to harness thermal energy the Mechanical Engineer has to organise and apply the knowledge of all these disciplines, together and harmoniously - always in a way which is socially and economically acceptable.

Great advances have been made in each of the disciplines individually. But in 1972 I began to realise that their integration into thermal energy systems requires much more than a knowledge of the individual subjects; that many system design procedures have been merely 'handed down' as the experience of 'practical' men; and that design solutions are often subjective and dependent on such experience. A wholly scientific procedure for system design did not appear to exist and I could see that the Mechanical Engineer had to accept the limitations of 'experienced' procedures to supplement his scientific training. It appears that the results have been accepted only because his whole activity evolved in, and was continued in, a world of cheap and convenient sources of energy.

In 1973, the world's energy situation rapidly changed. Evaluation and introduction of less convenient energy sources and their new technologies is now a necessary part of system design. There is little or no experience to support such design and the need for a scientific procedure is emphasised - if not essential - for continued professional competence. Such a procedure should be as soundly based as the component disciplines it seeks to integrate.

In summary, I consider that the 'experienced' procedures for design are now inadequate, perhaps even misleading, in a world of changing energy values and changing social expectations. This leads me to pose the question

> WHERE IS, AND WHAT IS, THE ULTIMATE
>
> SCIENTIFIC PROCEDURE FOR THE DESIGN
>
> OF THERMAL ENERGY SYSTEMS?

If such a procedure can be found, the immediate benefits would be greater precision and certainty in design. More importantly, it would improve the ability of the professional mechanical engineer to make correct decisions about thermal energy in many new situations.

The need for improved design methods has already been outlined by others (e.g. Ref.3, Preface) and some of the improved methods which have been proposed will be discussed later. (Sections 2.12 and 12.1). In the meantime, however, those methods do not appear to provide an answer to the above question.

My search for a scientific procedure began in 1975 in the science of thermodynamics. The essence of such a procedure emerged in a particular *organisation* of thermodynamic and mechanical knowledge - an organisation which is remarkably compatible with methods of numerical optimisation.

In this dissertation, the resulting synthesis procedure is shown to:

. Strip an engineered thermal energy system of its machinery, its working substance and all other physical constraints while still (notionally) preserving the essential energy functions of its processes;

. Identify those essential energy functions in universal scientific terms applicable to the stripped condition;

. While retaining the scientific identity of the essential functions at all times, rebuild the system back to a practical level by a scientific procedure - by a disciplined sequence of information and decision processes which leads to (or synthesises) the optimal system.

The synthesis procedure is demonstrated to be applicable in engineering practice to both steady systems and time-varying systems. The optimal capacity for energy storage is readily specified by the procedure for time-varying systems so the functional roles of storage are exposed and are discussed at length. The procedure requires that all its technical information should be presented on a unified basis. Far from being a handicap, however, such a unified information base is shown to be the key to a wide application of synthesis.

Two sets of limitations on the synthesis procedure are explained. One set is merely associated with the present state of development and can be expected to be overcome with further experience and with refinement of computing methods. The second set appears to restrict the use of synthesis in situations for which information is uncertain and decision criteria are not precisely defined; and these limitations require further research.

The second set of limitations does not restrict the imminent use of synthesis for the design of 'optimal' thermal energy systems based on certain knowledge. To that extent, the objective of the work has been achieved – a scientific design procedure for use by the engineering profession.

2.0 A FOUNDATION FOR SYNTHESIS.

The starting point for synthesis is shown in this section to be consolidated in a theorem for design of thermal energy systems. (p15). The reasoning to support the theorem is creative rather than analytical – a deliberate construction from elements of common knowledge.

Synthesis is shown to require a somewhat different way of thinking than is usual in mechanical engineering – requiring a functional rather than a process perspective. This section also introduces and explains this 'reversed' point of view.

Much of the philosophical view which forms the foundation of the present work has existed for at least forty years. Bridgman (Ref.1,p5) asks, among other questions, "Why is it that (thermodynamics) is so impotent to deal with irreversible processes?", and proceeds to explain a view of energy and thermodynamics which has universal significance. Such a philosophy is not used directly to develop the argument which follows – but its presence is compelling. Reference is made where the connections between the philosophy and argument are tangible.

2.1. Definitions.

"*Thermodynamics* is the science which deals with energy and its transformations and with relationships between the properties of substances." It includes "the study of substances in dynamic motion". (Ref.2,p13).

"Energy is the capacity, either latent or apparent, to exert a force through a distance." (Ref.2,p15). "Energy in various forms is considered to be a *companion of mass* . . . ." (Ref.2,p16). "When *changes* in energy occur without mass transfer, the energy is pictured as 'flowing' to or from the mass under consideration . . . the transitory forms of energy are called *heat* and *work* . . . concepts not tied to mass . . . ." (Ref.2,p17).

"The system is a specified region, not necessarily of constant volume, where transfers of energy and/or mass are to be studied." "The actual or hypothetical envelope enclosing the system is the boundary of the system." "The region outside the system is the surroundings." (Ref.2,p22-23).

"State is the condition of the system (or a part of the system) at an instant of time as described or measured by its properties." "A process occurs whenever a system undergoes either a change in state or an energy transfer at a steady state." (Ref.2, p26-27).

For the present, a *thermal energy system* is defined as one across the boundary of which heat or work or both are being transferred - with or without transfer of other forms of energy or transfer of mass. (Fig.1,p20)

If a thermal energy system is to include more than one process, each process will be considered to occur within a separate region of the system. Each process may then be visualised as a sub-system.

A *steady* thermal energy system is defined as one for which the transfers of heat or work or both occur at a steady rate over a definite time-interval, no matter how large or small. A *time-varying* system is defined as one for which such transfers occur at varying rates over a definite time-interval.

2.2. System Functions.

The *function* of a thermal energy system (or *system function*) is defined as the purposeful effect of its processes on its immediate surroundings; where *purpose* expresses the intention of the mechanical engineers who design and build the system.

A particular system function will be specified by the quantity, direction and form of energy transferred - with or without a simultaneous transfer of mass. Heat or internal energy or flow energy or work or a combination may, for example, be transferred in various quantities in either direction. Internal energy is defined (Ref.2,p16) as "energy of mass composition" and "a fundamental axiom of modern thermodynamics is that internal energy is a property of matter". Flow energy is defined (Ref.2,p63) as the pressure x volume property of a flow stream (of matter).

Functions accompanied by a (purposeful) transfer of mass are derived from a system defined as an *open system*. (Ref.2,p60). Functions without (purposeful) transfer of mass are derived from a system defined as a *closed system*. (Ref.2,p47).

A purposeful transfer of energy

. *into* a system is defined as a *source* function and

. *out* of a system is defined as a *demand* function.

Either or both or a number of source and demand functions may occur simultaneously at the boundary of a system, each associated with a particular process. (Fig.2,p21).

Another kind of function associated with the 'heat sink' required for heat and work conversion processes is defined as a *residual* function.

The following *general equation* states the relation between functions and processes of a thermal energy system with a compressible working substance, pressure P, volume V;

Function Process

$$\Delta Q - \Delta W = \Delta E = \Delta(U+PV)$$

This equation applies for all steady systems where:

- ΔQ and ΔW are heat and work quantities, respectively, transferred across the boundary to provide function.
- ΔE is the total change in all forms of energy within the system.
- $\Delta(U+PV)$ is the change, due to the process, of the sum of internal energy and flow energy of the system's working substance.

Such an equation between function and process is dictated by the First Law of Thermodynamics. (Ref.2,p45).

Each different kind of thermal energy system will be associated with a particular form of the general equation, depending on purpose, e.g.

$$\Delta Q = \Delta U \quad (P\text{constant}, V\text{constant}, W=0)$$
$$\Delta Q = \Delta(U+PV) \quad (\Delta W = 0)$$
$$\Delta W = \Delta(U+PV) \quad (\Delta Q = 0)$$
$$\Delta Q - \Delta W = \Delta(U+PV)$$

More particularly, each function of a steady system for a given time-interval may be defined by a particular algebraic combination of the above terms. Some examples are:

Closed System Functions

Purpose	Demand		Source	Residual
Heating	$+Q_D$	=	$-Q_S$	
Work	$+W$	=	$-Q_S$	$+Q_R$
Cooling	$-Q_D$	=	$-W$	$+Q_R$

Open System Functions

Heating	$+(U_D+P_DV_D)$	=	$-W$	$-(U_R+P_RV_R)$
Work	$+W$	=	$-(U_S+P_SV_S)$	$+(U_R+P_RV_R)$
Cooling	$-(U_D+P_DV_D)$	=	$-W$	$+(U_R+P_RV_R)$

Signs refer to surroundings.

Whatever the combinations of terms, all functions of a thermal energy system are seen from the above equations to require a transfer of heat or internal energy, the latter usually, but not necessarily, accompanied by a transfer of flow energy for an open system. Also transfers of work occur only with transfers of heat or flow energy. Thus transfers of heat and/or internal energy are seen as necessary components of all system functions while transfers of work and/or flow energy are seen as optional components, depending on purpose.

"Energy function" (Ref.1,p115) is a general term defined for the present work as a nett transfer of energy of *any* given form across the boundary of a system. Energy functions necessarily occur as a part or as the whole of all system functions but they are not confined to such (purposeful) functions.

Transfers of mass accompany transfers of (U+PV) in the functions of an open system. (p5). Transfers of potential and kinetic energy accompanying such transfers of mass may be determined separately if required - they are excluded from discussions in the present work.

2.3. Thermodynamics - a Basis for Design.

Engineers design thermal energy systems for definite functions required by industry and commerce, e.g. for power generation and refrigeration.

Design is the creative organisation and specification of the required system and its processes from knowledge of the

- thermodynamic processes themselves, and the
- mechanics of the machinery needed to contain them.

Two observations may be made about the sufficiency of thermodynamics for the design of thermal energy systems:

(1) The best *thermodynamic* design provides the required function with minimum expenditure of "available energy", (Ref.2,p83), i.e. with minimum increase of "entropy". The best *industrial* design provides the required function with minimum total expenditure of a number of commodities - available energy, capital, materials and so on. Thus the *scale of value*, by which different design solutions may be compared, is different. The thermodynamic scale by itself gives insufficient, and therefore possibly misleading, guidance for design in industrial practice.

(2) Thermodynamics is based on a dual concept – that of the ideal and that of the real. The "*ideal or perfect state*" of a system is considered to be one of "vanishing density" of its working substance i.e. its density and pressure both approach zero. (Ref.2,p38). Processes occurring in such a system are defined by only a few thermodynamic variables; and the system can be readily designed for a given function because the end-result of a choice of values for these variables is clearly determined. Although obtainable in a laboratory (Joule's experiment at low pressures), such systems of 'perfect' state serve no purpose in industrial practice – where substantial densities and pressure of 'real' working substances are indeed required for practical function.

In addition to the few thermodynamic variables of the 'perfect' state, a designer of a practical system of real processes must also choose the:

- Working substance and its chemical composition for each process (and usually there is a sequence of processes) e.g. water, air, gas or even a mixture.
- Physical states of the working substance for each process e.g. density or phase.
- Physical details of the machinery and materials needed to contain and transport the working substance – since these determine, for example, friction, turbulent dissipation of energy or resistance to corrosion.

Thus a system of real processes gives rise to many more variables than a system of 'perfect' processes, all because of the presence and containment of a real working substance. The additional variables react with the thermal processes themselves and with each other. The complexities are now such that thermodynamics no longer suffices to determine the precise end-result of a choice of values for all these variables. Compared with a system of the 'perfect state', design solutions are difficult to obtain. The difficulty multiplies as the number of required processes increases.

With the inadequacy of thermodynamics itself to guide and determine design solutions precisely, there is an apparent gap in scientific procedure for the design of thermal energy systems. In the past, designers have closed this gap with the aid of experience, experiment and intuition.

2.4 A Proposition for Design.

It is my thesis that a wholly scientific procedure potentially exists for the design of thermal energy systems. It must be founded in present thermodynamics but this will either have to be extended or its insufficiency supplied by other procedures.

The observations (1) and (2) on pages 7-8 may now be summarised as follows:

(1) Whatever the inadequacy of the *scale of value* for design, the required functions of a system are independent of such a scale because function is the given requirement in design, no matter how it is achieved.

(2) The functions of a system of 'perfect state' will be independent of the complexities arising from a real working substance.

Although the (purposeful) functions of a real system cannot be derived from a 'perfect state', it will be shown shortly that *energy functions* generally can indeed be derived.

Thus a *proposition* emerges as a possible basis by which the difficulty with the design of thermal energy systems can be overcome:

The energy functions of a real system, when expressed as precisely the same energy functions of a defined 'perfect' model system, will be independent of the scale of value for design and independent of the working substance.

The *proposition* will be demonstrated here as it is expanded. The essential steps in the demonstration are:

(1) Replace the usual engineering consideration of process by a consideration of function. (p5-7).

(2) Replace each energy function of each process in a real system by precisely the same energy function of a 'perfect' process. (Section 2.5).

(3) Define the model system in which such 'perfect' processes can occur. (Section 2.6).

(4) Express the energy function of each (real or 'perfect') process in terms of that model system. (Section 2.7).

(5) Establish the relation between the (purposeful) functions of the real system and the associated energy functions of the model system. (Section 2.8)

At this point it should be said that the elements of knowledge used to construct the *proposition* are already well understood. It is rather the explicit statement of the proposition, and the purpose which it later serves, which appear to be original.

It should also be said that the intention of the *proposition* is not the well known procedure of using an 'ideal' process as a simplified model of a real process from which approximate design solutions are determined. (Ref.2.p38). By replacing process with function, a precise equivalence is maintained between the real and 'perfect' situation.

2.5 Real and 'Perfect' Processes.

A particular function of a real system will be accompanied by energy functions associated with the same (purposeful) process. The form and direction of those energy functions will also be determined by purpose.

The same energy functions may conceivably be provided by a different process in a different system. The only requirement is that the value and direction of the energy functions should be the same in both systems.

If a 'perfect' process can be uniquely determined to provide precisely the same energy functions, each process of a real system may conceivably be replaced by such a 'perfect' process.

2.6. A Model System.

While the 'perfect' thermodynamic state is approached as the density and pressure in a system approach zero, processes in such a system are still dependent on the molecular structure of the (residual) working substance. If the 'perfect' processes are to be independent of the working substance (proposition,p9) it will have to be removed altogether.

The only thermal energy system which appears to exist without a working substance is one in which energy is transferred by radiation in an evacuated space. The elementary form of such a 'radiant system' of steady states is shown in Fig.3,p22. The system comprises a 'couple' of identical 'black body' emitters/absorbers in an evacuated region. Radiation between the bodies is confined to a linear path of section area A. The nett transfer of energy (QN) in unit-time for a steady system of this kind is given by the Stefan-Boltzmann relation (Ref.2.pp404-411) as

$$QN = \sigma.A.(T1^4-T2^4) \qquad (T1>T2)$$

where T1 and T2 are the temperatures of the 'black bodies'. Such a thermal energy system is maintained by a source function (heat, QS) and a given demand function (heat, QD). The *general equation* (p6) for such a steady, unit-time system without a working substance is

$$QS = QD$$

The values of the incoming and outgoing energy functions at the boundary (QE1 and QE2 respectively) are defined by

$$QE1 = QS$$
$$QE2 = QN = \sigma.A.(T1^4-T2^4)$$

with direction defined by T1>T2

Generally, all energy functions of such a 'radiant system' may be expressed as

$$Q = FUNC(TT,SIZE)$$

where TT is the "state couple" (Ref.1,p84) of 'black body' temperatures and SIZE is a parameter, the value of which is equal to the area (A) of the 'black body' radiation openings. For the present work, the essential fact about such a system is that for particular values of TT and Q, the value of SIZE is *precisely determined*.

Based on the foregoing explanation, a *model system* (as it applies to the present work) is defined as one in which only 'perfect' radiant processes between 'black body' couples can occur; with all energy functions precisely determined for each couple by the temperatures and area of radiation openings. The processes shall be steady and extend over a definite time-interval, however large or small.

A network (or sequence) of processes may occur in a model system, each process occurring between a separate 'black body' couple, such that an outgoing energy function of one body is an incoming energy function of the next. (Fig.4,p23). The energy functions of each couple, and therefore of the whole network, will be precisely expressed by the relations:

$$Q = FUNC(TT,SIZE).$$

2.7. Simulation of Energy Functions.

Recalling section 2.5,p10, it will now be said that a process in a model system may be chosen to 'simulate' precisely the same energy functions (QE) as those of each process in a real system. Such a simulation in practice would require only

. 'connection' of the radiant paths of each 'black body' couple in the same arrangement as the connected processes and energy functions in the real system, and

. adjustment of the temperatures (T1 and T2) of the bodies and their SIZE (of openings) until the direction and value of each QE is the same for all processes in both the real and model systems.

There is no intention to construct a physical model to conduct such a simulation. But a mathematical or "paper and pencil" procedure (Ref.1,p7) could presumably be devised to do so. In fact it should be possible for a digital computer to take-up the task readily because

. only three variables, T1, T2 and SIZE, precisely determine the value and direction of QE for all bodies of the model system, and

. the same set of variables will determine QE for all bodies in a whole network, no matter how extensive.

For a given arrangement of processes and given values of QE in the real system, the computer would merely search for the particular combinations of temperatures and areas of openings which precisely determine the equilibrium condition of the whole (steady) model system. Thus a very large number of relatively simple arithmetical computations will be required - a task for which the digital computer is particularly suited.

A similar model view of a thermal energy system is recorded by Bridgman (Ref.1,p79) as a philosophical observation. His model is "pairs" of "pieces of matter" and his observation is that, for such a model, the "energy functions are over-determined" i.e. that "the number of possible combinations in different conditions of the various substances is much greater than the number of the aggregate of possible energy functions". The model system for the present work is a 'perfect' radiant system, so chosen as to exclude the working substance; and for such a model the energy functions are precisely determined by values of TT and SIZE alone.

2.8. Synthesis Simulation.

With the energy functions of a real system simulated by the model system - and with the energy functions of the model system independent of any working substance - it now remains to establish the relations between such a simulation and the (purposeful) functions of the real system. The *proposition* (p9) will only be demonstrated when this is done.

The diagram of the single-couple model system (Fig.3,p22) is now developed into a series of diagrams of various real (steady) systems in each of which a purposeful process occurs as follows:

- . Thermal conduction,
- . Liquid cooling,
- . Liquid to vapour phase-change,
- . Gas expansion for work, and
- . Combustion of fuel for heating.

The diagrams are shown in Figs.5-10,pp24-29, and each is intended to be self-explanatory in terms of the key diagram, Fig.5. Each diagram is shown as a single *state-couple* i.e. as a single process which occurs between an initial and a final state of the system's working substance.

In summary, the diagrams (Figs.5-10) show that each real system is a member of a family of similar systems such that:

(1) The form and direction of all system functions is defined by purpose;

(2) The values of the system functions are related to each other by a particular form of the *general equation* (p6);

(3) The process of each system is defined by the values of a set of parameters;

(4) Each system has an incoming and an outgoing energy function (QE1 and QE2 respectively), while a third energy function (QE3) may occur depending on purpose;

(6) If the value of one QE is given then the value(s) of the other QE will be determined by the values of a set of *functional parameters* (Fig.5,p24 and Section 2.10,p16) which includes the parameters of (3) above;

(7) The set of functional parameters is similar for all systems such that a set of QE,TT and SIZE are always included while up to five more parameters (P1, P2, C1, C2 and PATH) may be included in the set depending on purpose;

(8) The values of all energy functions (QE) are extracted for simulation in terms of the model system.

One fact should be clarified at once - the values of the TT and SIZE parameters in a real system will not be the same as the value of those parameters in the model system. The requirement of simulation is that the direction and value of the energy functions (QE) be the same, regardless of how they are achieved. Nevertheless the *presence* of the QE1, QE2, TT and SIZE parameters of whatever value is shown by the diagrams (Figs.5-10) to be *essential* for the determination of all (purposeful) functions of *all* thermal energy systems, whatever the presence or combination of the other functional parameters.

It has been said (p12) that the simulation of the energy functions (QE) of a real system could be taken-over from the model system by a computer. If this is done, the dependence of the simulation on the characteristic 'black body' radiation equation (p11) can be relaxed - in the sense that a different equation of values of the TT and SIZE parameters could be used, as long as the same direction and value of each QE is obtained. A *convention* will be adopted for such a computer simulation so that

. the direction of each QE will be defined by the (purposeful) functions of the real system;

. the value of each QE will be determined by a correct equation of TT and SIZE; and

. the equation (of TT and SIZE) will be the one which prevails in the real system.

The demonstration of the *proposition* (p9) has then reached the point where

. the radiant model system will be set aside;

. a computer will maintain the simulation of both the direction and value of the energy functions of the real system; and

. the temperatures associated with the simulation will be those of each state-couple of the real system itself.

Such a computer simulation of the functions of a real system in terms of state-couple temperatures and energy functions is defined as a *synthesis simulation*. The terms of a synthesis simulation are to be known as TT,Q and the simulation is to be accompanied by:

. A definition of purpose.

. A (purposeful) set of functional parameters for each state-couple of the real system.

Like the model system from which it evolved, a synthesis simulation will still be independent of the working substance because:

(1) For a particular combination of values of TT and Q (for both the real and simulated systems) the value of the parameter SIZE is 'over-determined' for all except the 'perfect' radiant system, which has no working substance;

(2) The value of SIZE is therefore free to be determined for all other real systems by a *selection* of values of the set of other functional parameters associated with the given purpose - including the parameters of the working substance.

The *proposition* (p9) may now be stated as a *theorem for design* of thermal energy systems:

THE ENERGY FUNCTIONS OF A REAL SYSTEM, WHEN EXPRESSED AS PRECISELY THE SAME ENERGY FUNCTIONS IN TERMS OF THE DEFINED SYNTHESIS SIMULATION, ARE INDEPENDENT OF THE SCALE OF VALUE FOR DESIGN AND INDEPENDENT OF THE WORKING SUBSTANCE.

For the present work, the essential value of the theorem is that is provides a method of *functional simulation* which is *universal* for *all* thermal energy systems.

A synthesis simulation will apply to a network (or sequence) of real systems, where each 'sub-system' is an identifiable state-couple. It only requires that the values of certain functional parameters be matched at each point of connection. This is a practical matter to be discussed in Part A.

2.9 Flow Energy and Work.

A synthesis simulation will readily account for the energy functions which occur in a real system as transfers of heat or internal energy alone, without the presence of flow energy. Such energy functions will be determined directly from simple arithmetical equations in Q terms alone. A synthesis simulation will not so readily account for flow energy or work components of energy functions because the values of such components must first be calculated in terms of other functional parameters, e.g. pressure. But the series of diagrams (Figs.5-10,pp24-29) also illustrates the earlier discussion (p7) about the relation of different components of energy functions as follows:

(1) A steady system requires at least two energy functions, each of which includes a transfer of heat or internal energy, with or without flow energy.

(2) Such transfers of heat or internal energy have a certain continuity of direction through a system even if their value changes due to flow energy or work.

(3) The presence, and direction of transfer, of flow energy or work will be defined by purpose.

(4) The value of flow energy or work components will either be a given requirement of design or the value of the heat or internal energy component will be given. In either situation the *general equation* (p6) applies and the value of the unknown component has to be determined by a solution of that equation in terms of the functional parameters.

A general view of the above relationship is that energy functions of heat and/or internal energy form an essential continuum through a network (or sequence) of processes in a real system while

. flow energy is (purposefully) superimposed upon such energy functions and

. work functions are (purposefully) localised at particular state-couples. (Fig.11,p30).

As such, flow energy and work may be accounted for locally and independently of the synthesis simulation being conducted in TT,Q terms alone. Such a view is consistent with the fact that the synthesis simulation is independent of the working substance - because PV and W components of function can only be derived in the presence of a (compressible) working substance.

2.10. Functional Parameters.

Before leaving the subject of synthesis simulation for the time being, its functional parameters (Fig.5,p24) will be fully defined as follows:-

Essential Parameters.

QE1, QE2, etc. Energy functions, at least two, the value of one being given and the value of the other(s) to be determined for each state-couple of both the real and simulated systems.

TT. The state-couple temperatures (T1, T2) of both the real and simulated systems where T1>T2, T1=T2 or T1<T2 depending on the process in the real system.

SIZE. The parameter (defining the 'size' of a process), the value of which is determined for each state-couple of the real system when the values of the set of all other functional parameters are known.

State Parameters (additional to TT).

P1, P2. The pressure of the working substance at the initial and final states of the process in the real system.

C1, C2. The physical and chemical composition of the working substance at the initial and final states of the process in the real system, e.g. a knowledge of the composition as it determines thermal conductivity, specific heats and specific enthalpy when the values of T and P are known.

PATH. A parameter to describe both the physical and thermodynamic 'route' of the change of state of the working substance i.e. the 'route' by which energy (and mass if applicable) is transferred 'through' a process from the initial to the final state. PATH should strictly be expressed in terms of the differential changes which occur in the values of T, P and C during a process. But it may often be more convenient to express PATH in familiar engineering terms. In the thermal conduction example (Fig.6,p25) PATH is merely the length of the conductor - a simple factor of physical construction. In the gas expansion example (Fig.9,p28) PATH may be considered to be determined by the value of a polytropic exponent n of an equation of state of the process such that $PV^n =$ constant.

The values of PATH may depend on values of other functional parameters. The expression of PATH must then include such terms; and the use of the expression in practice will require re-iterative procedures to determine a solution for each process.

The parameters SIZE, C and PATH may take *any appropriate form* as long as that form is defined for each state-couple and such parameters correctly relate to each other and to the other parameters Q, TT and P. Examples are given in Part B, pp82-83.

A knowledge of PATH for each process will be obtained from the analytical and experimental procedures of mechanical engineering science. Such knowledge may be expressed in any degree of detail - whether as a mathematical model or as a set of experimental data. Except where it is required for explanation and demonstration in Parts B and D, the detailed knowledge of process PATH is not a subject of this thesis. It is expected that such knowledge will be available for each process from a reliable source.

2.11 Design Procedure.

Thermodynamics generally views the effects of real working substances as a degradation of what would otherwise be ideal or 'perfect' processes. The usefulness of the *theorem for design* (p15) is only realised by taking a reversed point of view - that the simulated 'perfect' energy functions can be obtained by changes in the values of the functional parameters associated with the real working substance. This permits the synthesis simulation to be maintained independently (in TT,Q terms alone) as the additional variables of the real system are introduced.

The procedure for system design will be:-

(1) Specify the required *functions* of the system.

(2) Define the *scale of value* for design.

(3) Define the *arrangement* of purposeful processes of the real system required to provide function.

(4) *Simulate* (in TT,Q terms) the energy functions of the same arrangement of processes.

(5) *Examine* all combinations of TT,Q terms which can support the required functions of design; and determine the values of the functional parameters for each combination.

(6) *Measure* the 'value' of each combination according to the scale of value for design.

(7) Select, and adopt as the *design solution*, the combination (of energy functions and values of functional parameters) which ranks best on the scale of value for design.

I contend that this is already the basis of a scientific procedure for the design of thermal energy systems. But it can be developed further.

2.12. System Synthesis.

Recent attempts to formulate an improved method of system design have

. started with a mathematical simulation of the performance of the real system (Ref.3,p78),

. then subjected that mathematical simulation to a procedure for direct optimisation. (Ref.3,p104).

Such a method is discussed further in Section 12.1 (p108). Generally I see that the method becomes increasingly difficult, both to formulate and to optimise, as the extent or complexity or time variation of the real system increases. This is the situation for which a scientific procedure is most needed. Nevertheless, the method suggests an improvement on the procedure for design outlined above.

The difficulty with mathematical simulation arises mostly for the reasons of thermodynamic complexity outlined on page 8. This complexity can be reduced by changing to the synthesis simulation described in Section 2.8. (p14). Further, methods of optimisation can conceivably be built into steps 5, 6 and 7 of the above procedure for design. Those methods and those steps can be expected to be unified for all systems because they will all be conducted in the universal (TT,Q) terms of the synthesis simulation. In this way the whole procedure can be organised to converge progressively to the one best design solution. This is a *synthesis* of the optimal system - "the ultimate in design technique". (Ref.4,p10).

It is this synthesis procedure, for application to all kinds of thermal energy systems, which I consider to be the answer to my initial question on page 2: "Where is, and what is, the ultimate scientific procedure for the design of thermal energy systems?" The remainder of this thesis will illustrate and demonstrate this answer.

2.13. Presentation.

"Thermal system design is gradually emerging as an identifiable discipline." (Ref.3,px). I support this view - that system synthesis requires a special discipline of thought. This is mostly due to the functional rather than process perspective required for the synthesis simulation. But it is also due to the inclusion (later) of unified optimisation procedures.

Thermal Energy System Synthesis will therefore be presented as a separate discipline in its own right - and the text will change to an instructional style. Some terms will be redefined, some new terms will be established and the discipline will be formulated in those terms. This is not a departure from present thermodynamic and mechanical knowledge - only a particular *organisation* needed for a scientific design procedure.

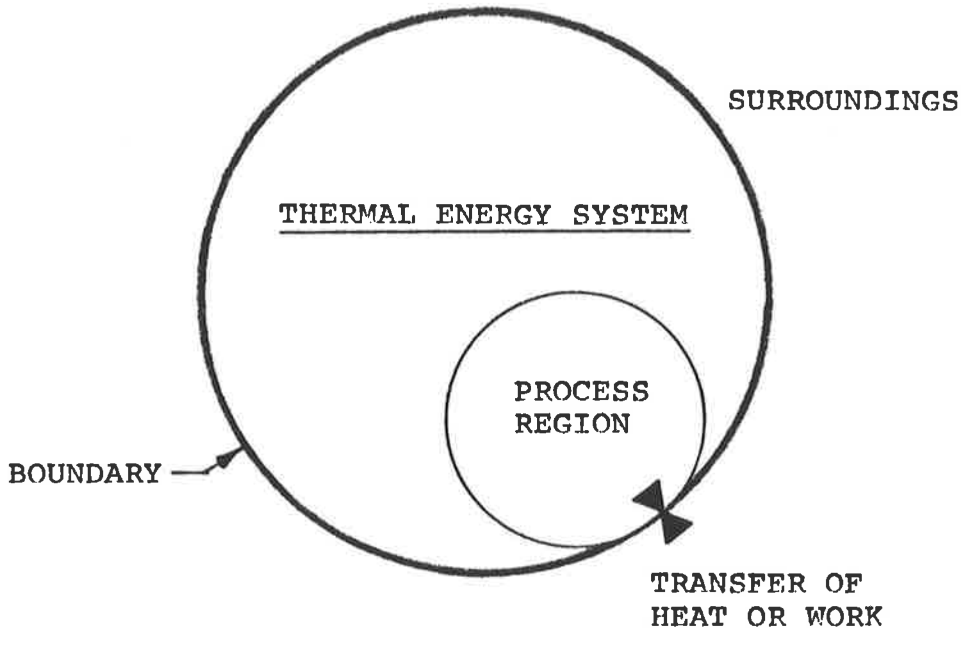

SURROUNDINGS
THERMAL ENERGY SYSTEM
PROCESS
REGION
BOUNDARY
TRANSFER OF
HEAT OR WORK

FIG 1

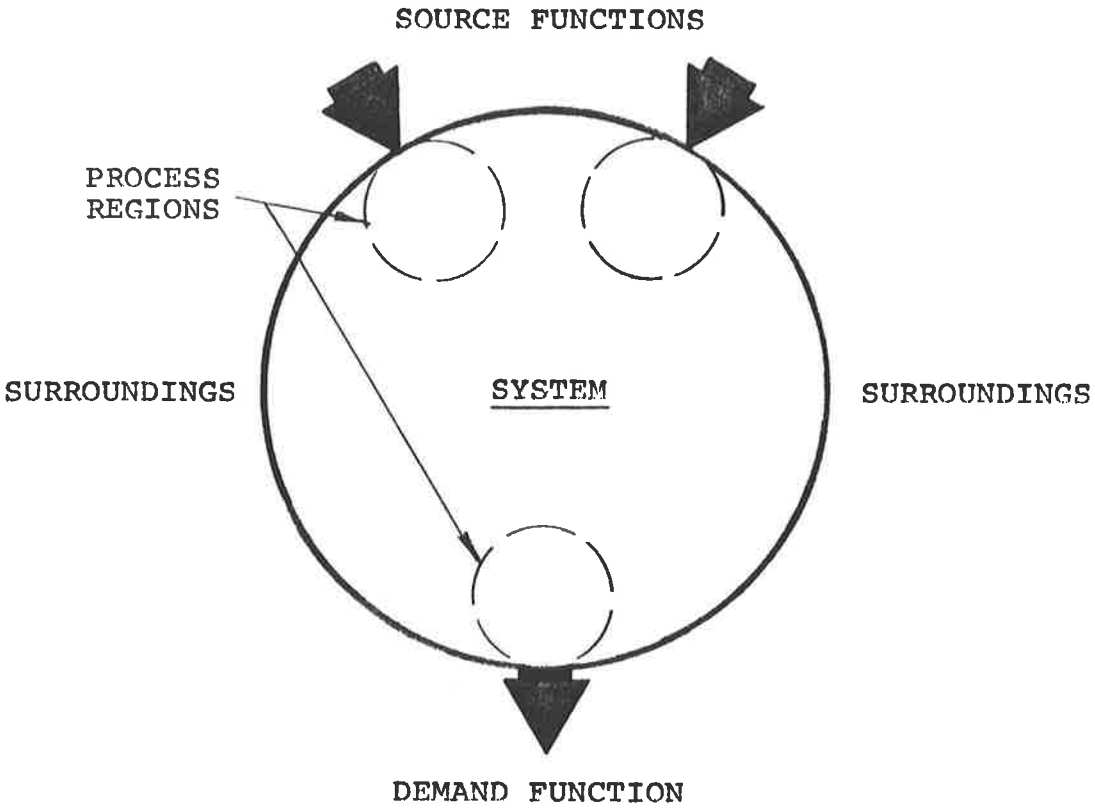

SOURCE FUNCTIONS
PROCESS REGIONS
SURROUNDINGS
SYSTEM
SURROUNDINGS
DEMAND FUNCTION

FIG 2

MODEL SYSTEM.

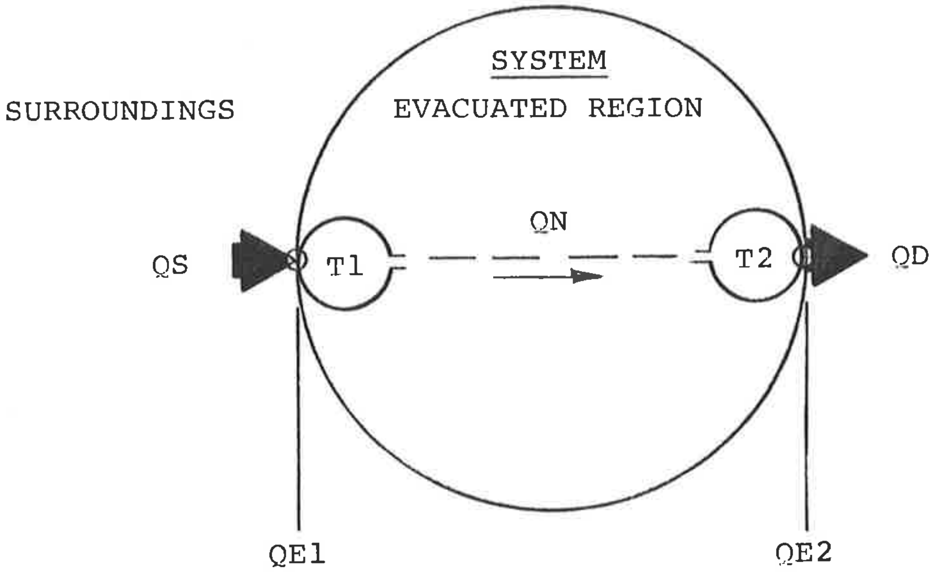
'PERFECT' RADIANT PROCESS.
STEADY SYSTEM, UNIT TIME.

Two 'black body' emitters/absorbers, Kirchhoff construction, form a single couple.

Equilibrium temperatures T1 and T2, where T1 > T2.

Openings in bodies same area A, with radiation between the openings confined to a linear path.

Process: nett transfer of heat, QN.



SYSTEM FUNCTIONS.

Source, heat, QS
Demand, heat, QD (given)
QS = QD (General Equation)

ENERGY FUNCTIONS.

Incoming, QE1 = QS
Outgoing, QE2 = QN
$= \sigma.A.(T1^4 - T2^4)$ (Stefan-Boltzmann)

or, writing generally,

$$Q = FUNC(TT,SIZE)$$

where Q, TT and SIZE are parameters as follows:

Q	energy function.
TT	state-couple temperatures.
SIZE	area A (for the 'perfect' radiant process)

Value of SIZE is precisely determined for particular values of TT and Q.

FIG 3

MODEL SYSTEM.

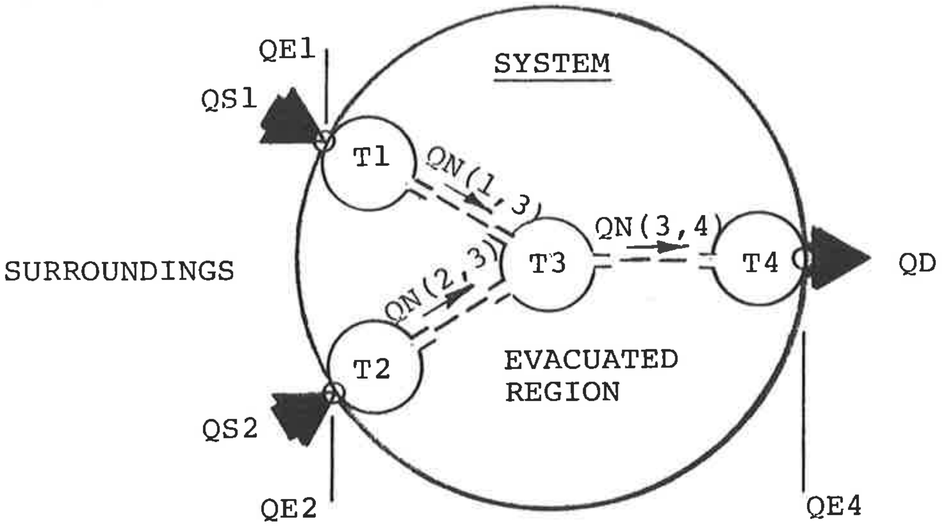
NETWORK OF 'PERFECT' RADIANT PROCESSES.
STEADY SYSTEM, UNIT TIME.

Four 'black body' emitters/absorbers, Kirchhoff construction, form three couples.

Equilibrium temperatures T1, T2, T3 and T4, where T1 > T3, T2 > T3 and T3 > T4.

Openings in bodies, area for each couple being A(1,3), A(2,3) and A(3,4), with radiation in each couple confined to a linear path.

Processes: nett transfers of heat QN(1,2), QN(2,3) and QN(3,4).



SYSTEM FUNCTIONS.

Source 1, heat, QS1
Source 2, heat, QS2
Demand, heat, QD (given)
QS1 + QS2 = QD (General Equation)

ENERGY FUNCTIONS.

Incoming, QE1 = QS1 = QN(1,3)
QE2 = QS2 = QN(2,3)
Outgoing, QE4 = QN(3,4)

or, writing generally as in Fig.3,

Q(1,3) = FUNC(TT(1,3),SIZE(1,3))
Q(2,3) = FUNC(TT(2,3),SIZE(2,3))
Q(3,4) = FUNC(TT(3,4),SIZE(3,4))

All values of SIZE are precisely determined for particular values of TT and Q for each state couple.

FIG 4

REAL SYSTEMS - KEY DIAGRAM FOR FIGS. 6 - 10.

PURPOSEFUL PROCESS IN A WORKING SUBSTANCE.

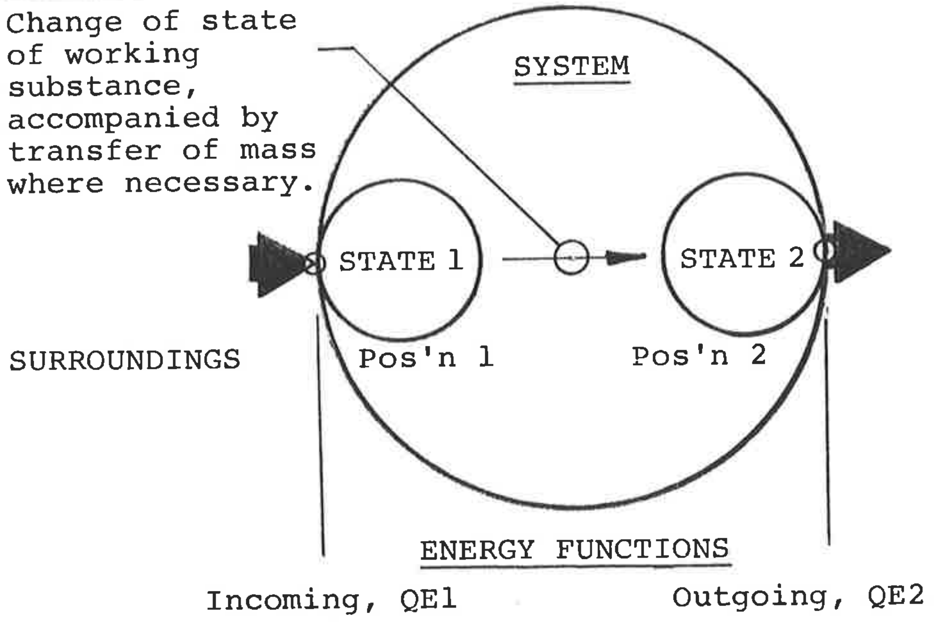
STEADY SYSTEM, UNIT TIME.

Single 'state couple' i.e. process occurs between thermodynamic states 1 and 2.

No other but the purposeful process occurs.

Changes of potential energy and kinetic energy are nett zero in the unit time.

PROCESS:



Change of state of working substance, accompanied by transfer of mass where necessary.

FUNCTIONAL PARAMETERS.

QE1,QE2	A set of energy functions, at least two, written as Q in general expression.
T1,T2	Temperatures of working substance at states 1 and 2. Written as TT, the state-couple temperatures.
SIZE	Value determined when the values of all other functional parameters are known.
P1,P2	Pressures of working substance at states 1 and 2.
C1,C2	Physical and chemical composition of the working substance at states 1 and 2.
PATH	Physical and thermodynamic 'route' of the change of state of the working substance.

FIG 5

REAL SYSTEM.

THERMAL CONDUCTION.

Refer Key Diagram, Fig.5.

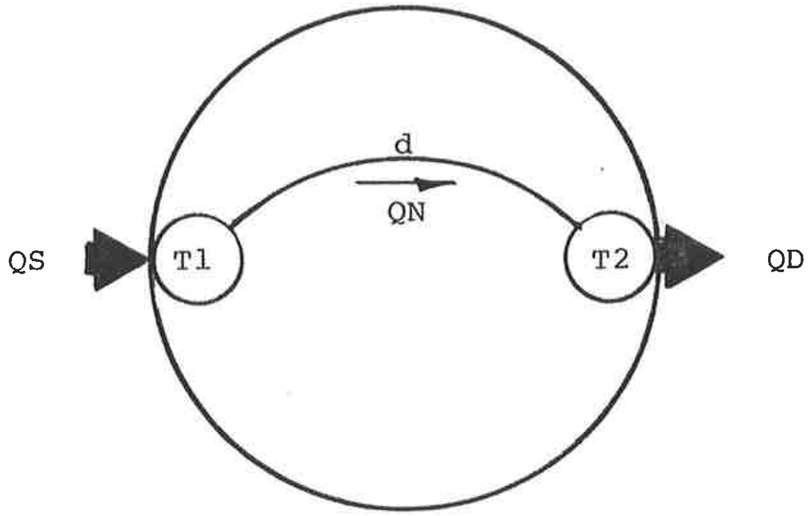
Two bodies at T1 and T2, T1 > T2.

Metal rod between bodies, rod section area A (SIZE = A), various lenghts d (PATH = d).

Metal composition C (C1 = C2), thermal conductivity k.

PROCESS:

$$QN = \frac{(T1-T2).A.k}{d}$$



SYSTEM FUNCTIONS.

Source, heat, QS
Demand, heat, QD (given)
QS = QD (General Equation)

ENERGY FUNCTIONS.

QE1 = QS
QE2 = QN
= FUNC(TT,SIZE,C,PATH)

For given values of QE2 and TT, value of SIZE is determined by selection of values of C and PATH.

FIG 6

REAL SYSTEM.

LIQUID COOLING.

Refer Key Diagram, Fig.5.

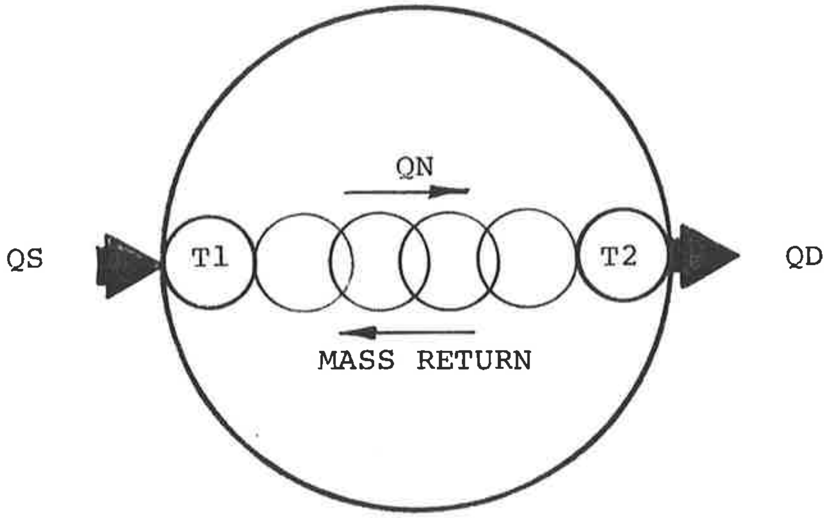
Liquid mass M (SIZE = M) in container at position 1 receives QS, moves straight to position 2, releases QD and returns straight to position 1, all in unit time.

Liquid states T1, T2 and P (P1 = P2), T1 > T2.

Liquid composition C (c1 = C2), specific heat CP.

PROCESS:

QN = (T1-T2).M.CP



SYSTEM FUNCTIONS.

Source, heat, QS
Demand, heat, QD (given)
QS = QD (General Equation)

ENERGY FUNCTIONS.

QE1 = QS
QE2 = QN
= FUNC(TT,SIZE,P,C)

For given values of QE2 and TT, value of SIZE is determined by selection of values of C and P, where P is required particularly to ensure that the liquid does not change phase.

FIG 7

REAL SYSTEM.

LIQUID TO VAPOUR PHASE CHANGE.

Refer Key Diagram, Fig.5.

Open System, container volume V.

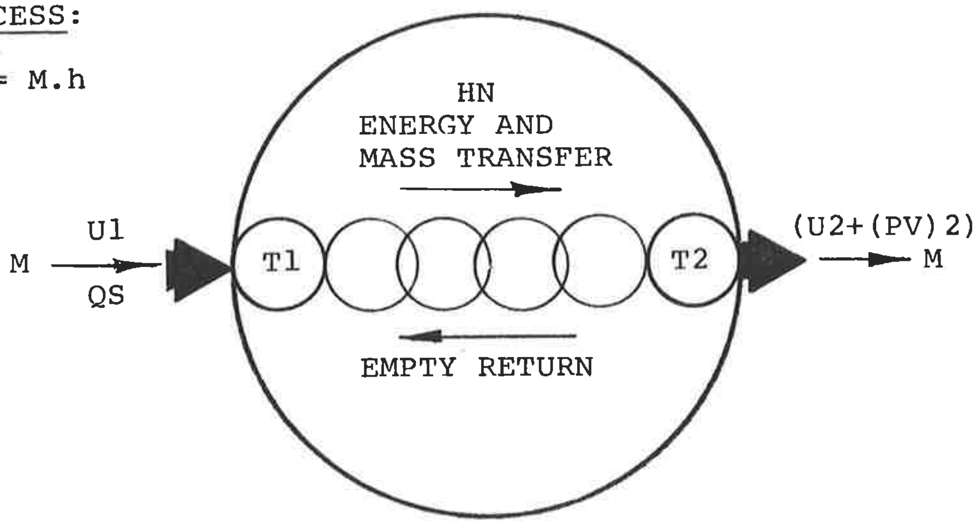
Small volume of liquid mass M (SIZE = M) enters (system and) container at position 1, receives QS, simultaneously evaporates to saturated vapour (volume V) as container moves straight to position 2. Vapour leaves (system and) container at position 2 after which container returns empty to position 1. All in unit time.

Liquid state T1, P1
Vapour state T2, P2
(T1 = T2 and P1 = P2 = P)

Liquid composition C1, vapour composition C2, specific enthalpy change, C1 to C2, is h.

PROCESS:

HN = M.h



SYSTEM FUNCTIONS.

Source, heat, QS
Demand, internal and flow energy, (U2+(PV)2) (given)
QS + U1 = (U2+(PV)2) (General Equation)

ENERGY FUNCTIONS.

QE1 = U1 = FUNC(T1,SIZE,P,C1)
QE2 = HN = FUNC(TT,SIZE,P,C1,C2)
QE3 = QS = QE2 - QE1

For given values of QE2 and TT, value of SIZE (and then values of QE1 and QE3) is determined by selection of values of P, C1 and C2.

FIG 8

REAL SYSTEM.

GAS EXPANSION FOR WORK.

Refer Key Diagram, Fig.5.

Open System, container of variable volume.

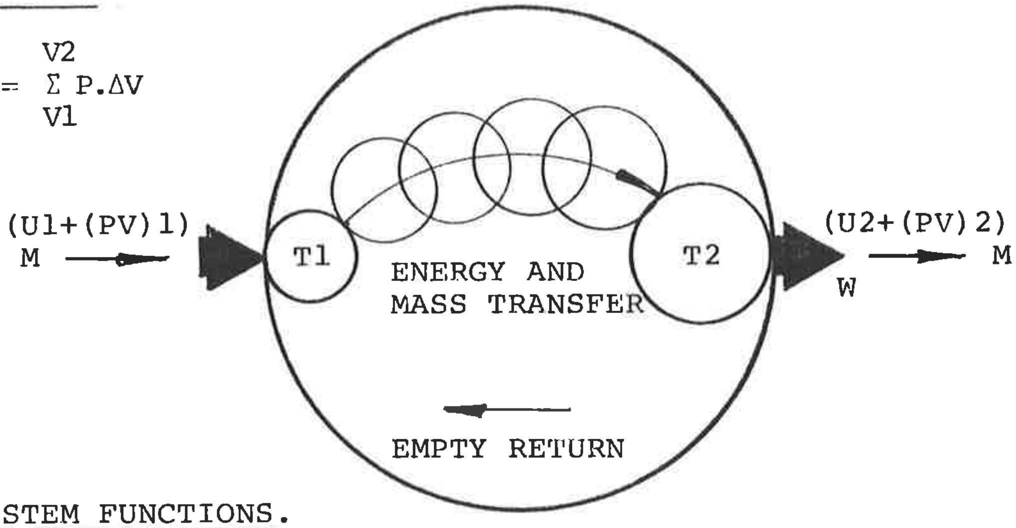
Gas mass M (SIZE = M) enters (system and) container (volume V1) at position 1, simultaneously expands by thermodynamic PATH as container moves to position 2 (volume V2). Gas leaves (system and) container at position 2 after which container returns empty to position 1. All in unit time.

Gas state 1, T1, P1
Gas state 2, T2, P2 (T1 > T2 and P1 > P2)

Gas composition, C (C1 = C2)

PROCESS:

$$W = \sum_{V1}^{V2} P.\Delta V$$



SYSTEM FUNCTIONS.

Source, internal and flow energy, (U1+(PV)1)
Demand, work, W (given)
Residual, internal and flow energy, (U2+(PV)2)
(U1+(PV)1) = W + (U2+(PV)2) (General Equation)

ENERGY FUNCTIONS.

QE1 = (U1+(PV)1) = FUNC(T1,SIZE,P1,C)
QE2 = (U2+(PV)2) = FUNC(T2,SIZE,P2,C)
QE3 = W = FUNC(TT,SIZE,P1,P2,C,PATH)

For given values of QE3 and TT, value of SIZE (and then values of QE1 and QE2) is determined by selection of values of P1, P2, C and PATH.

FIG 9

REAL SYSTEM.

COMBUSTION OF FUEL FOR HEATING.

Refer Key Diagram, Fig.5.

Open System, container of variable volume.

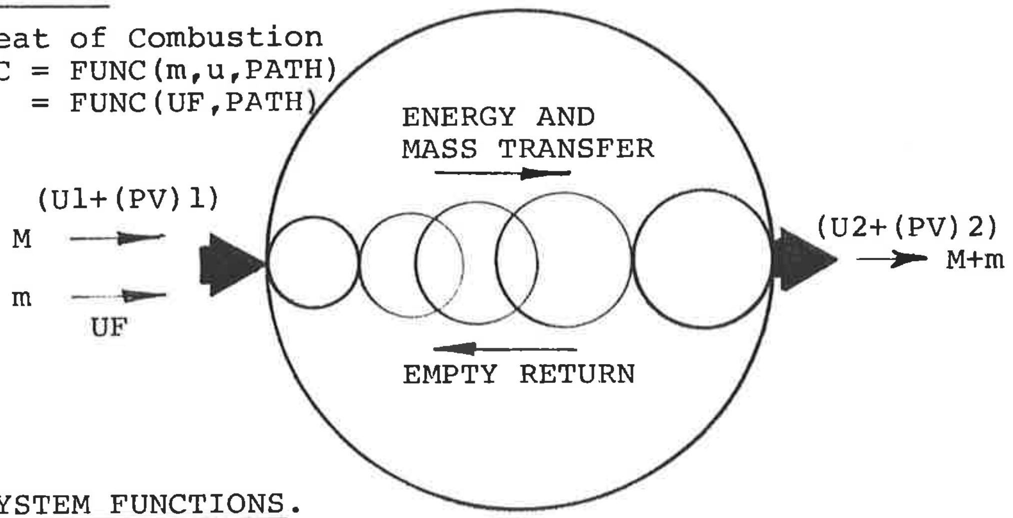
Air mass M (SIZE = M) enters (system and) container (volume V1) at position 1. Fuel mass m, specific heating value u, also enters container at position 1. Simultaneous combustion of fuel to gas as container moves to position 2 (volume V2), without work (W = 0). Gas leaves (system and) container at position 2 after which container returns empty to position 1.
All in unit time.

Air state, T1, P1
Gas state, T2, P2 (T1 < T2)

Air composition C1, gas composition C2, reaction PATH, C1 to C2.

PROCESS:

Heat of Combustion
QC = FUNC(m,u,PATH)
= FUNC(UF,PATH)



SYSTEM FUNCTIONS.

Source, internal energy of fuel, UF,
and internal and flow energy of air, (U1+(PV)1)
Demand, internal and flow energy of gas, (U2+(PV)2) (given)
QC + (U1+(PV)1) = (U2+(PV)2) (General Equation)

ENERGY FUNCTIONS.

QE1 = (U1+(PV)1) = FUNC(T1,SIZE,P1,C1)
QE2 = (U2+(PV)2) = FUNC(T2,SIZE,P2,C2)
QE3 = UF = FUNC(QC,PATH)
= FUNC((QE2-QE1),PATH)
= FUNC(TT,SIZE,P1,P2,C1,C2,PATH)

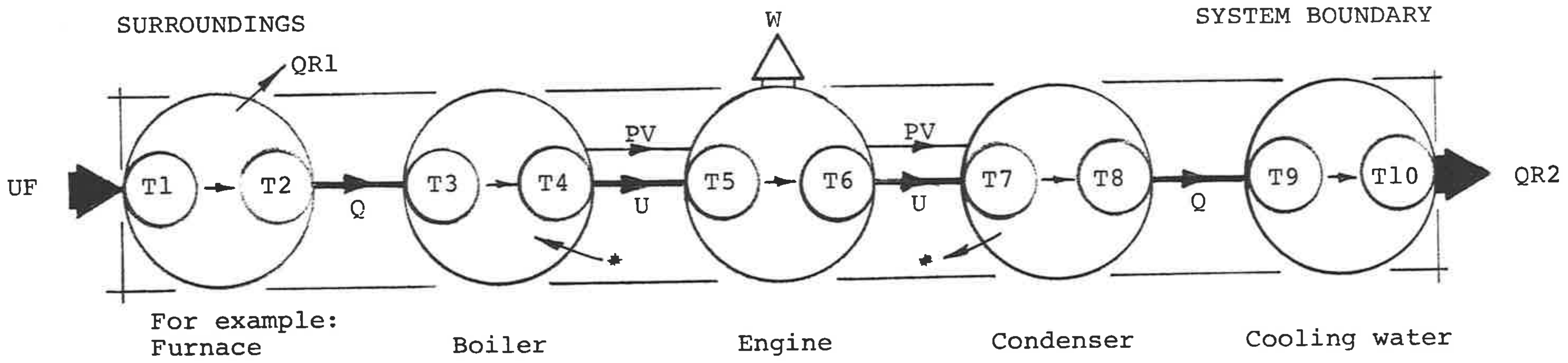
For given values of QE2 and TT, value of SIZE and values of QE1 and QE3 are determined by selection of values of P1,P2,C1,C2 and PATH.

FIG 10

FLOW ENERGY AND WORK.

SUPERIMPOSED ON ENERGY FUNCTIONS OF HEAT AND INTERNAL ENERGY.

Five processes, five state-couples, diagrammatic only.



SYSTEM FUNCTIONS

Source, fuel, UF
Demand, work, W
Residual, heat, QR1 & QR2
UF = W + QR1 + QR2

SYNTHESIS SIMULATION

Accounts for all energy functions in Q terms alone, at all points.

FLOW ENERGY

Accounted for as PV = FUNC(T,SIZE,P,C) at points 4,5,6,7.

WORK

Accounted for as W = FUNC(TT,SIZE,P5,P6,C5,C6,PATH) at state-couple (5,6) alone.

FIG 11

THERMAL ENERGY SYSTEM SYNTHESIS

PART A

DISCIPLINE - A METHOD OF THINKING ABOUT THERMAL ENERGY SYSTEMS AND THEIR SYNTHESIS.

3.0 SYSTEM STRUCTURE.

We have established a theorem as a scientific starting point for synthesis and we have outlined a plan to use the theorem. (Section 2). But we still have a big task ahead of us to turn that plan into a practical procedure. In this Part A we will be content to formulate such a procedure in general terms – leaving many of the practical details to be taken-up later in Part B.

Many of the terms established as part of the foundation of synthesis will continue to be used. But we will now develop some of them further. At the outset there is a need to organise a basic view of the 'active' structure of thermal energy systems.

3.1. System Space.

A system has been defined previously as a physical 'region' within which processes are occuring. (p4). A process or sequence of processes in a steady system is maintained by a source function and a demand function at the boundary. (p5).

In design, demand functions are a *given* requirement and source functions have to be derived from one or more available sources of energy. We will now abbreviate the names of such functions to *demand* and *source*.

Between a given demand and all available energy sources, many combinations of processes may conceivably occur. The only requirement (for a steady system) is that the general equations (p6) be maintained not only for any combination of processes between source and demand but also for each process.

For synthesis, a *thermal energy system* (or *system*) will be defined as a particular set of purposeful processes which energy undergoes in its transition from source to demand. No conflict is intended with the earlier definition of a thermal energy system (p5) because a physical region is still required and transfers of heat or work or both still occur. But it is the functional activity of processes in the region which is now to be emphasised, rather than the region itself.

The combined set of all possible systems between a given demand and all available energy sources will be defined as the energy systems' *feasible space*. (Fig.A1,p36). Any one system which forms a design solution must then be expected to be found somewhere within that feasible space. For example,

- the demand may be the heating needs of a factory,
- the source may be a supply of natural gas, and
- the necessary combustion and heat-transfer processes are those which occur within the feasible space to link the source to the demand.

Although shown diagrammatically as a circle (Fig.A1,p36), the limits of the feasible space will always be defined (or 'constrained') by the scientific laws governing the system's processes. When we engineer a system, the limits of the feasible space will also be 'constrained' by the technical and physical characteristics of that engineering. It is the whole set of such *constraints*, taken together, which define the feasible space in relation to the surroundings. Constraints are discussed further in Section 4.6(p43).

3.2. System Elements.

Man has to engineer his systems from a set of available processes of which there appears to be just two fundamental kinds:

- Processes which *change the form* of energy at the boundary of a system, e.g. chemical to thermal energy in combustion or flow energy to work in steam expansion. These will be classified as *conversion processes*.
- Processes which exchange energy from one working substance to another, or from one phase of the same working substance to another phase, e.g. heat from furnace gas to water, or condensation of steam to water respectively. These will be classified as *exchange processes*.

Engineering applies these two fundamental kinds of processes by building *conversion elements* e.g. furnaces and steam engines and *exchange elements* e.g. water-heaters and condensers. Such *engineering elements* are built in a wide variety of shapes and sizes. Thermal energy systems are then assembled from a logical set of such elements, each element having the capacity to contain and conduct one or more particular processes. We may use the word 'plant' to describe such engineering assemblies but will always reserve the word 'system' for the set of processes which can occur (within such plant) between source and demand.

The extent to which processes can occur within an element will be constrained by that element's engineering e.g. a steam engine restricts its (purposeful) process to one of steam expansion and the 'size' of the cylinder restricts the volume of steam which can be expanded during one revolution.

The set of all possible processes which can occur within an element will be defined as that element's *feasible field*. The whole feasible space of an engineered thermal energy system will then be the combined set of the feasible fields of its component elements. The element fields must at least connect with each other, if not overlap, for continuity from source to demand. (Fig.A2/1,p37). Consistent with our names for the two kinds of elements themselves, we will view the feasible space as a combination of

- conversion fields and
- exchange fields.

3.3. Operation and Control.

A particular set of functions which are derived from one or more of a (steady) system's processes will be defined as a particular *operation* of that system.

Within the limits of the feasible space and each element's feasible field a wide range of different operations may be obtained. But it is a feature of man's energy systems that he controls them – for stability, predictability and safety. We will view *control* as an additional set of imposed constraints, made available through physical engineering and often exercised by human decision, to determine a specific operation (of a system) within the feasible space. (Fig.A2/2,p37).

3.4. Mechanical Work.

Most of man's thermal energy systems are engineered to obtain mechanical work e.g. steam power stations. Many systems also utilise work to derive particular heat functions e.g. refrigeration systems.

Most such industrial systems are continuous thermodynamic 'cycles' of processes. (Ref.2,p55). But the mechanical work functions themselves are localised to particular processes and those processes will be contained in particular conversion elements e.g. in a steam engine cylinder.

Thus, when associated with a conversion element, mechanical work is to be viewed as another source or demand at a particular point on the boundary of a system. The set of work functions available from a particular conversion element will be related to the feasible field of that element; and that field continues to be integrated with the feasible fields of the other elements of such a system. (Fig.A3,p38).

3.5. Summary.

It is borne out in practice that man can

- engineer his required thermal energy systems from an assembly of particular energy sources and engineering elements, and
- control the operations of those systems to maintain specific processes of energy transition from source to demand – within a space made feasible both by the nature of the processes themselves and by the engineering elements which contain them.

This summarises the foregoing definitions and upon this basic 'spatial' view we will now develop a method of system and space identification.

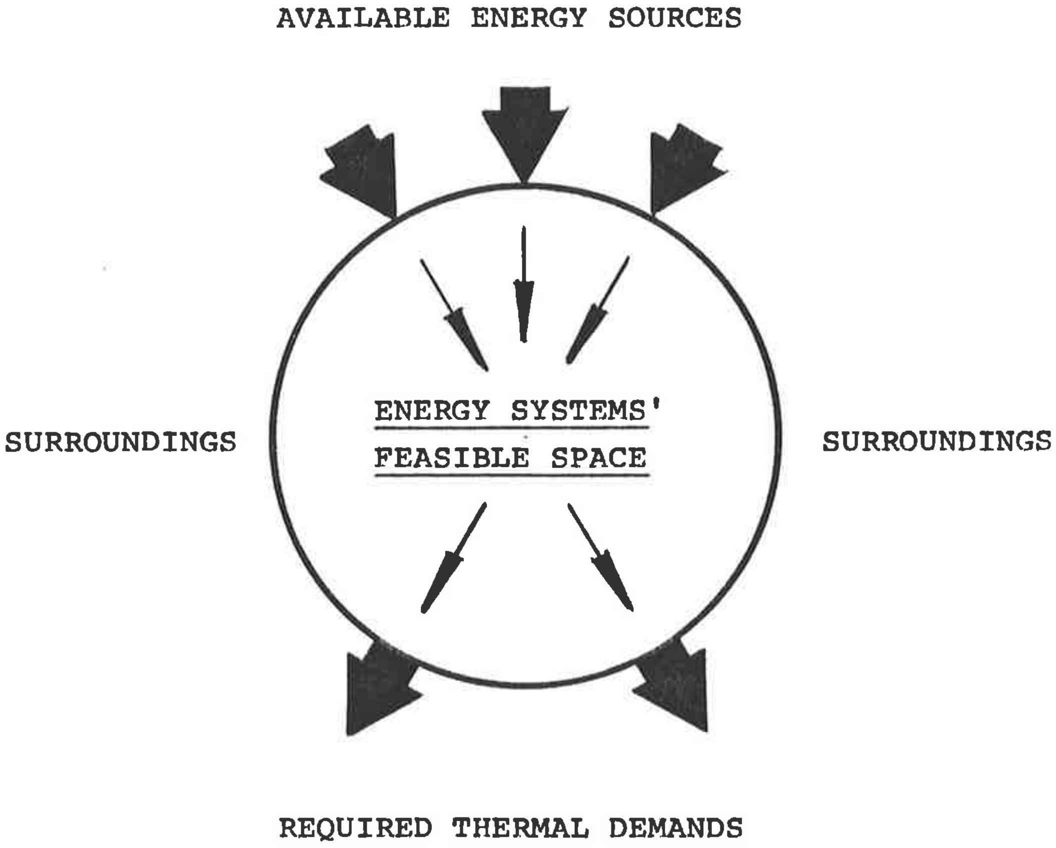
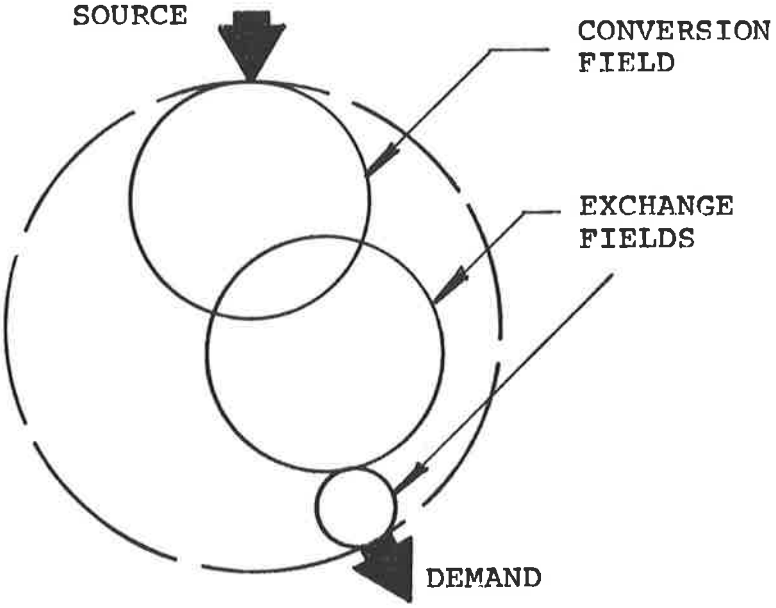
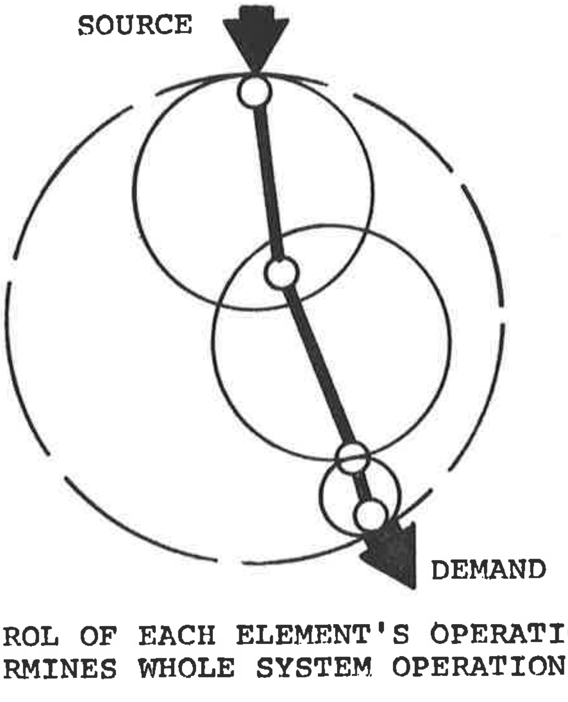

AVAILABLE ENERGY SOURCES
SURROUNDINGS
ENERGY SYSTEMS' FEASIBLE SPACE
SURROUNDINGS
REQUIRED THERMAL DEMANDS

FIG A1



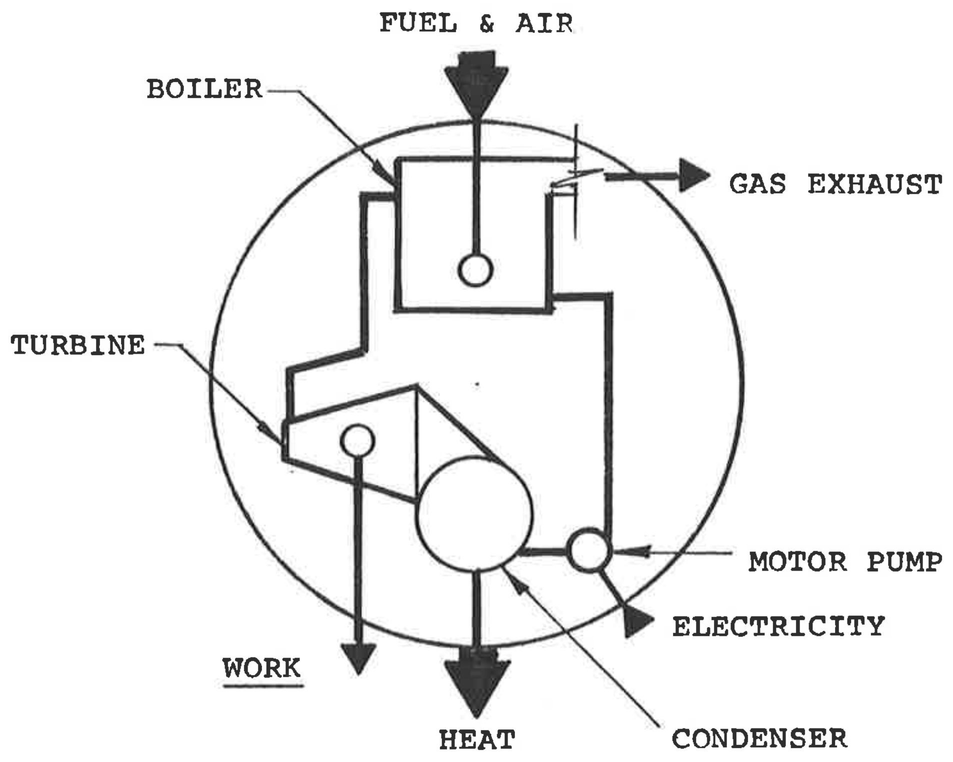
A2/1 SET OF ELEMENT FIELDS DEFINES THE SYSTEM'S FEASIBLE SPACE.



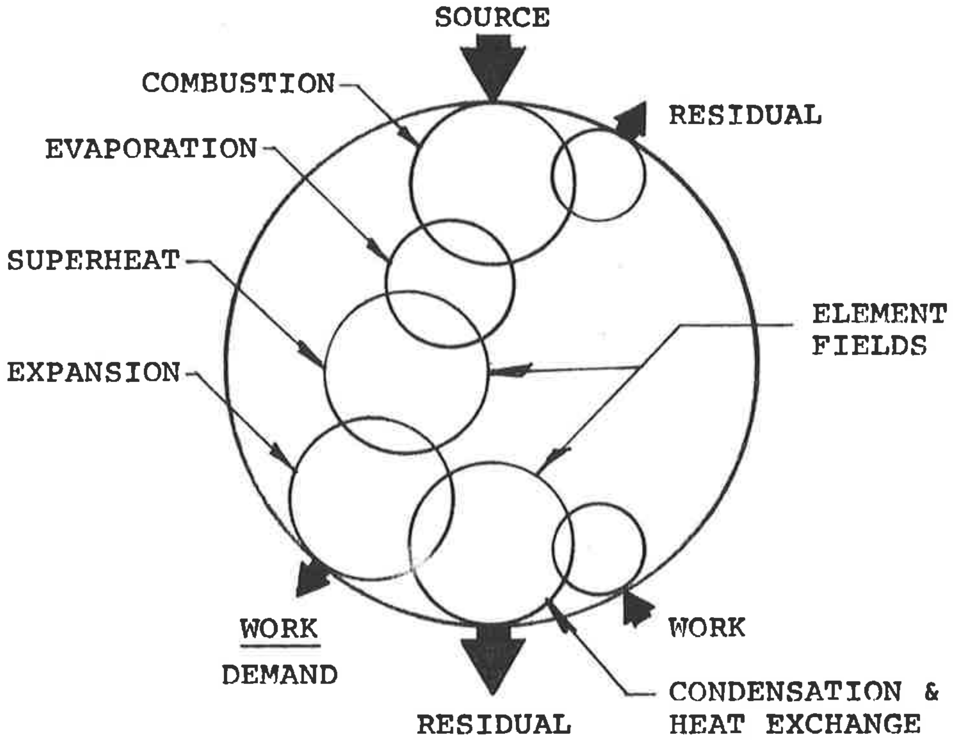
A2/2 CONTROL OF EACH ELEMENT'S OPERATION DETERMINES WHOLE SYSTEM OPERATION.

FIG A2

THERMAL ENERGY SYSTEM ENGINEERED FOR WORK



MECHANICAL VIEW



'SPATIAL' VIEW

FIG A3

4.0. SYSTEM IDENTIFICATION.

We recall now the theorem for design of thermal energy systems. (Section 2.8,p15). Based on the argument by which it was established, the theorem can now be described in general terms as follows:

(1) All thermal energy systems are maintained by a set of energy functions;

(2) All systems can be expressed in the first instance in terms of the state-couple temperatures (TT) and the energy functions (QE) of their component processes, i.e. in (TT,Q) terms of the synthesis simulation;

(3) The values of the SIZE parameters of only a 'perfect' radiant system are precisely defined by values of the above (TT,Q) terms;

(4) The values of the SIZE parameters of all other (real) systems are determined by a selection of the values of a set of functional parameters (p16) additional to the above (TT,Q) terms.

The (TT,Q) terms of the synthesis simulation will now be used to construct a visual *frame of reference* by which all systems, their feasible space and their operations will be *identified.*

4.1. Size, Energy-rate and Time.

Up to the present, we have only spoken of steady systems. The value of an energy function has been determined by the value of SIZE alone, the value of all other functional parameters being known.

But most systems are required in practice to operate with a demand source (or both) which vary with time. The value of the energy functions of such time-varying systems will strictly be instantaneous values, requiring integration over a particular time-interval. For synthesis, however, we

. define the value of an energy function as an *energy-rate,* considered to occur for a steady system over a particular *unit time-interval* (I) however large or small, and

. use a numerical procedure for integration of the values of such 'steady' energy-rates over an *extended time-interval* (L). (Fig.A4,p46).

Thus a time-varying system will be viewed as an aggregate of steady systems - so maintaining the relevance of all previous definitions and discussions, applicable as they are to steady systems. But energy storage within a time-varying system will be discussed separately. (Section 5.9,p58).

The first step in identifying a system in our proposed new frame of reference is therefore to specify its (notionally steady) energy-rate for each unit time-interval of the whole extended time-interval. We adopt a convention that the energy-rate to be specified for identification will be the *demand-rate* (QD) – given as a design requirement for each unit time-interval, (I).

4.2. TT Diagram.

With QD specified for each I, the frame of reference (for system identification) is reduced to a method of identifying the state-couple temperatures (TT) of all processes between source and demand. For the time being (Sections 4.2. to 4.4.) we will restrict the discussion of such a method to a 'perfect' radiant system.

For any such system the highest and lowest temperatures will be those at source and demand respectively. This pair of temperatures can be plotted as a point between two similar rectangular co-ordinates representing the value of the high (THI) and low (TLO) temperature respectively. (Fig.A5/1.p47). Provided their demand-rates (QD) and unit time-intervals (I) are the same, two 'perfect' systems identified by this one TT point will be similar as far as the source and demand functions are concerned.

Such a diagram (Fig.A5/1) of TT points plotted between THI and TLO co-ordinates will be called a *TT diagram*. Each TT diagram applies to a particular demand-rate (QD) and a particular unit time-interval (I). Such a diagram completes the identification of a 'perfect' thermal energy system in the first instance.

Note that the space below the line 00' (Fig.A5/1) is not available for plotting as it implies that THI is less than TLO. But a point on the line 00' may occur, to indicate that the values of the state temperatures are equal.

The scales of the co-ordinates (THI and TLO) shall be the same and, unless noted to the contrary, shall be graduated in DEG C, to represent measured state temperatures.

4.3. TT Tracking.

While we can identify a whole 'perfect' system by a single TT point, such a system may include a sequence (or network) of different processes between source and demand. But each process also occurs between its own pair of state-couple temperatures - so each process can also be identified by its own TT point for the same QD and I. (Fig.A5/2,p47). The whole set of such process points must span between the THI and TLO co-ordinates of the single point originally plotted. (Fig.A5/1). The co-ordinates of each extreme point must identify the state temperatures of the processes at source (TTC) and demand (TTD) respectively. The *demand point* (TTD) will always be on the line 00' as it identifies the process which transfers the demand-rate (QD) to the surroundings without (as far as the system is concerned) any further reduction of temperature.

Having plotted the TT point for each process we can now visualise that energy 'tracks' across the diagram from point to point, source to demand. (Fig.A5/3,p47). Such a *track* on a TT diagram represents a particular operation of a particular system for a given value of QD and I. In effect, the track indicates the 'relocation' or 'transfer' of energy from one process to another within the feasible space.

For each track through a sequence (or network) of TT points, the energy-rates at the source, at the demand and through each point must meet the simple arithmetical equations of continuity. Each point is therefore associated with particular energy-rates i.e. those of the energy functions of the process represented by that point. In the 'perfect' (no losses to surroundings) system shown in Fig.A5/3

$$\begin{matrix} TTC & & TT2 & & TT1 & & TTD \\ QC & = & Q2 & = & Q1 & = & QD \end{matrix}$$

4.4. Space Identification.

Each process of a system will be able to exist only within certain limits of temperature if (purposeful) system function is to be maintained. In a 'perfect' system such limits of temperature will be determined solely by the temperatures of the adjacent processes. Thus in Fig.A5/3, if the co-ordinates of TT1 and TTC are fixed, the co-ordinates of TT2 are limited by

$$THI1<TLO2<THI2<TLOC$$

The use of the TT diagram can be extended to indicate such limits. (Fig.A5/4.p47). The 'areas' bounded by the limiting co-ordinates will be said to define the feasible *TT field* of each process. The combination of the TT fields of all feasible processes then defines the whole feasible space between source and demand, for given QD and I.

4.5. Real System Identification.

The above method of identification of a 'perfect' radiant system on a TT diagram also applies to real systems provided a restriction is observed.

The restriction arises from the determination of the initial and final states of the working substances in a real system. Such states are no longer determined by temperature alone (as in a 'perfect' radiant system) but also by the composition and pressure of the working substance (parameters C and P, p17).

A convention is therefore adopted for each TT diagram of a real system – that the working substance and its pressure are to be *declared* for each process. Any particular TT point will then continue to identify the process at that point. Such a declaration is to be viewed as part of the definition of 'purpose' of a process e.g. to evaporate water at atmospheric pressure, a process which is then precisely identified on TT diagram by:

THI = TLO = 100 DEG C

The synthesis procedure would be expected to 'search' for values of the C and P parameters, had they not been declared. But their introduction by declaration only changes the sequence and method of such a search and does not in any way inhibit the outcome of the synthesis procedure.

The method of declaration (of C and P) will be shown in Part B (Section 8.2,p76) to be compatible with the organisation of information about engineering elements. Meanwhile, it is essential for the maintenance of the TT diagram – and the TT diagram is justified by the support it gives to the formulation of the whole synthesis procedure in practice.

Some special details also apply to the TT diagram of a real system:

(1) The TT fields of conversion processes are *fixed* upon the TT diagram by particular values of temperatures e.g. by maximum flame and minimum permissible exhaust temperatures of a combustion process at a point TTC such that

$$TLOCMIN \leqslant TLOC < THIC \leqslant THICMAX$$

(2) The TT fields of exchange processes are determined upon the TT diagram by *relative* values of temperatures e.g. by minimum 'difference' and 'approach' limits of two adjacent heat transfer

processes between points TTN and TT(N+1) such that

$$\mathrm{TLON} + \mathrm{TDIF} \leqslant \mathrm{THIN}$$
$$\mathrm{THIN} + \mathrm{TAPP} \leqslant \mathrm{THI(N+1)}$$
$$\mathrm{TLON} + \mathrm{TAPP} \leqslant \mathrm{TLO(N+1)}$$

(3) Energy functions of *heat loss* or heat gain (ΔQN) may occur at each process (depending on the relative temperature of the process surroundings) so that the continuity of energy-rate through the process is then disturbed, e.g. for a process at TTN

$$\begin{array}{ccccc} \text{Incoming} & & \text{Outgoing} & & \text{Loss} \\ Q(N+1) & = & QN & + & \Delta QN \end{array}$$

while for a whole sequence of processes between a point TT(NMAX) and demand (TTD)

$$Q(NMAX) = QD + \sum_{N=1}^{N=NMAX} \Delta QN$$

(4) Relocation of heat and/or internal energy alone from one TT point to another will be shown as single track lines on the TT diagram. When accompanied by a (purposeful) transfer of flow-energy (PV), however, double lines will be shown. Recall (p16) that the synthesis simulation requires separate accounting for transfers of flow-energy and the double lines merely indicate (visually) that such accounting is necessary.

(5) Transfers of all forms of energy at TT points of source and demand are accounted for locally, at those points alone. Such transfers are at once reflected in the values of energy-rates within the system at those points.

The general formulation of a real system in terms of its TT diagram is given later in Section 5.10(p60).

4.6. Physical Constraints.

The (declared) working substance (C) and its (declared) pressure (P) impose constraints upon what would otherwise be 'seen' by a synthesis simulation (in TT,Q terms) as a 'perfect' radiant process. These (C and P) parameters are defined to be *declared constraints* – values of which are essential for the specification of 'purpose' of a real process. The extent of the TT field of a real process will also only be determined when values of these declared constraints are known.

The engineering element which contains each real process will impose further constraints according to the element's physical characteristics. The SIZE of an element particularly constrains the value of its energy-rates. The details of construction of an element will constrain its process to a particular physical or thermodynamic PATH (p17) for what are otherwise given conditions. These (SIZE and PATH) parameters are defined as *element constraints.*

All functional parameters of the synthesis simulation (p16) are now accounted for, either as:

TT Diagram: TT,Q where T1,T2 are the temperatures of the state-couple and Q is the set of values of the energy functions at each process, or as

Constraints: C1,C2, P1,P2, SIZE and PATH where the intention of the simulation is to permit a selection of the values of such constraints for each (TT,Q) point in the system's feasible space.

Two classes of constraint deserve identification:

(1) Constraints which restrict the feasible field of an element's process for either functional and/or practical reasons, e.g. the minimum permissible temperature of exhaust from a furnace to avoid corrosion. These are defined as *field limits.*

(2) Constraints which are associated with the interconnection of fluid flow between two 'open-system' elements, e.g. the fluid mass flow-rate connecting two heat-transfer processes. Such connections require a knowledge of the temperature (T), composition (C) and pressure (P) of the fluid but the connecting fluid is most often the process working substance so the values of these parameters are readily determined. The process in each 'open system' element is always constrained by the values of such interconnection parameters - defined as *system constraints.*

But *all* constraints are to be seen as having a 'physical' effect on what would otherwise be a 'perfect' radiant system determinable in TT,Q terms alone. All constraints acting at a particular process point (TTN) on the TT diagram are therefore defined as the set of *physical constraints* (PHYSN) acting at that point.

4.7. Unified Information.

A synthesis simulation (in TT,Q terms) requires that the effect of all possible values of all physical constraints be determined for each process. The different kinds of constraints have already been classified above. (Section 4.6). But the organization of constraints can be taken further by

- consolidating them into a separate body of information about each kind of process or engineering element and
- ordering that information for each process or element so that its use (as a set of constraints) by a synthesis simulation is facilitated.

This subject will be discussed further in Part B. (Section 8,p75). In the meantime, however, it may be said that all such information, for all processes and all elements, becomes unified in its relation to the TT,Q terms when such an organisation is undertaken. The particular organisation of mechanical engineering knowledge on such a basis is defined as a *unified information base*.

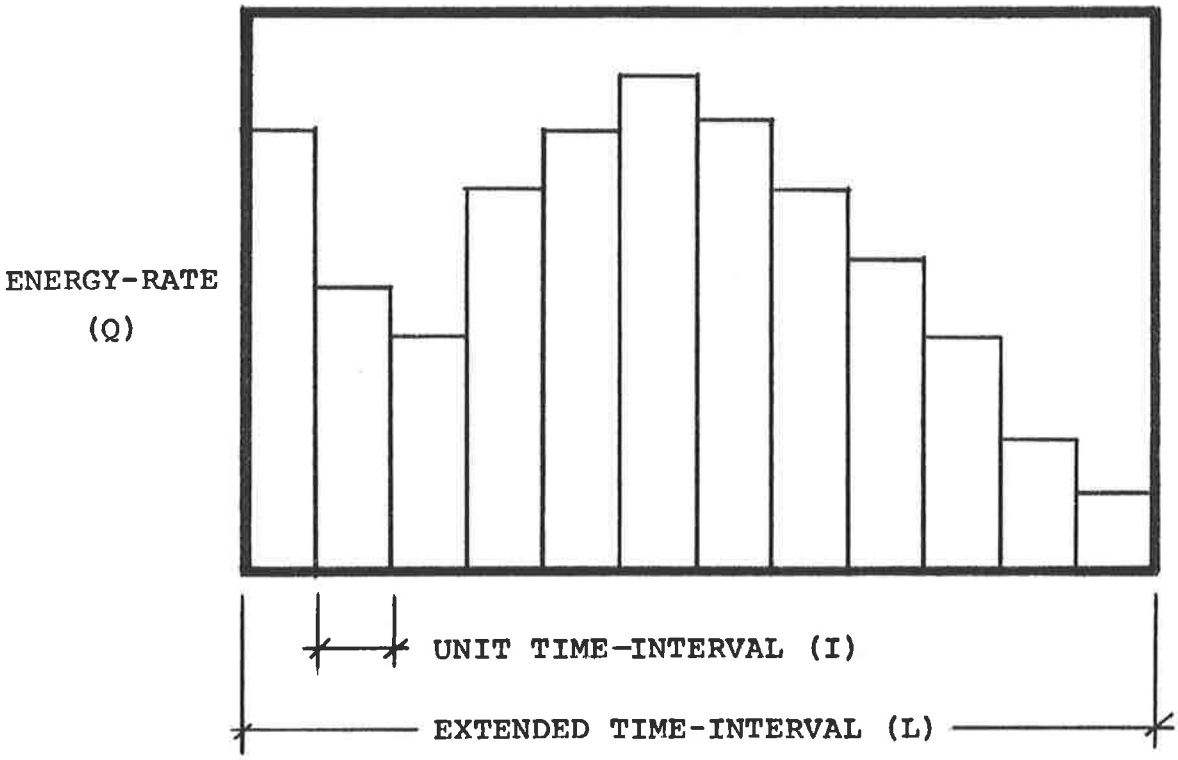
4.8. Summary.

Starting from the foundation established in Section 2, we have deliberately created a special visualisation and method of identification of the structure and operations of an engineered thermal energy system. Such a method is summarised in the TT diagram of a simple heating plant, Fig.A6(p48), and in representative diagrams for other common thermal systems, Fig.A7(p49).

The TT,Q and time base of such a diagram provides a complete unified frame of reference for tracking, directing and accounting for energy movement through the systems' feasible space between source and demand. Based as it is upon recognition of just the six essential factors — source, demand, energy-rates, state-couple temperatures, engineering elements and their constraints — it applies equally well to all kinds of thermal energy systems in all kinds of situations.

It is an *operational view* of thermal energy systems. Functional activity is emphasised while the necessary 'mechanics' of energy conversion, exchange and transport are subordinated to those functions. It is upon this basic view of a thermal energy system and the unified information base that we will now develop methods of decision and synthesis.

THERMAL ENERGY SYSTEM UNDER VARYING CONDITIONS

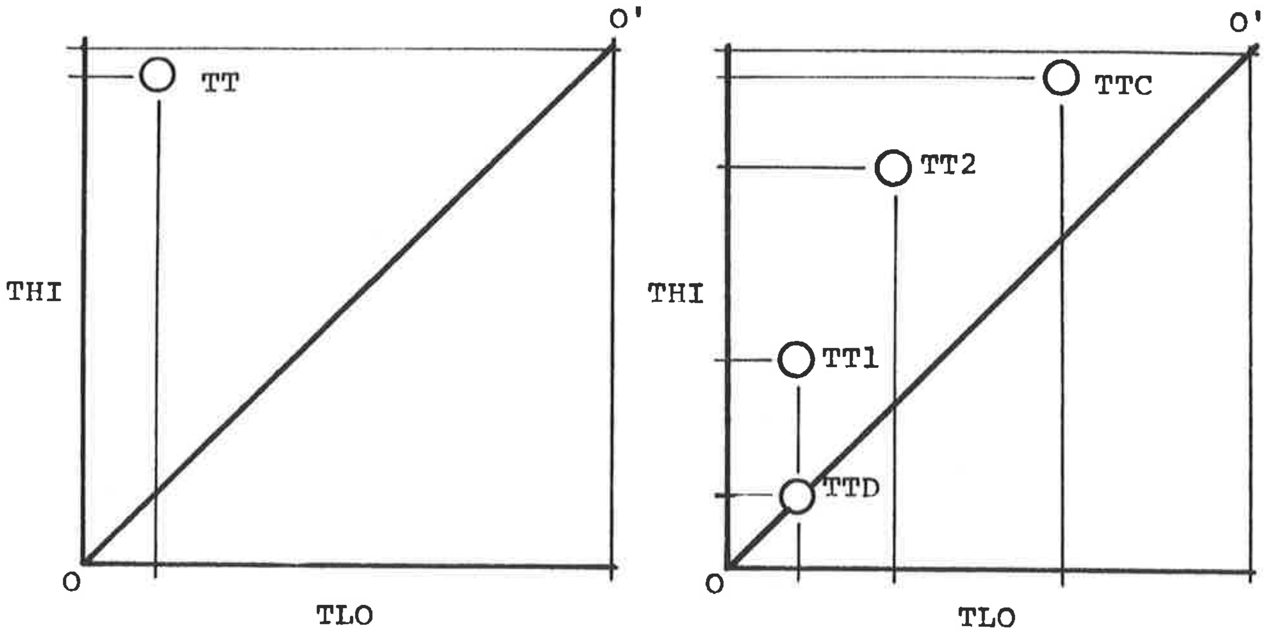


INTEGRATED OVER THE WHOLE
EXTENDED TIME INTERVAL:

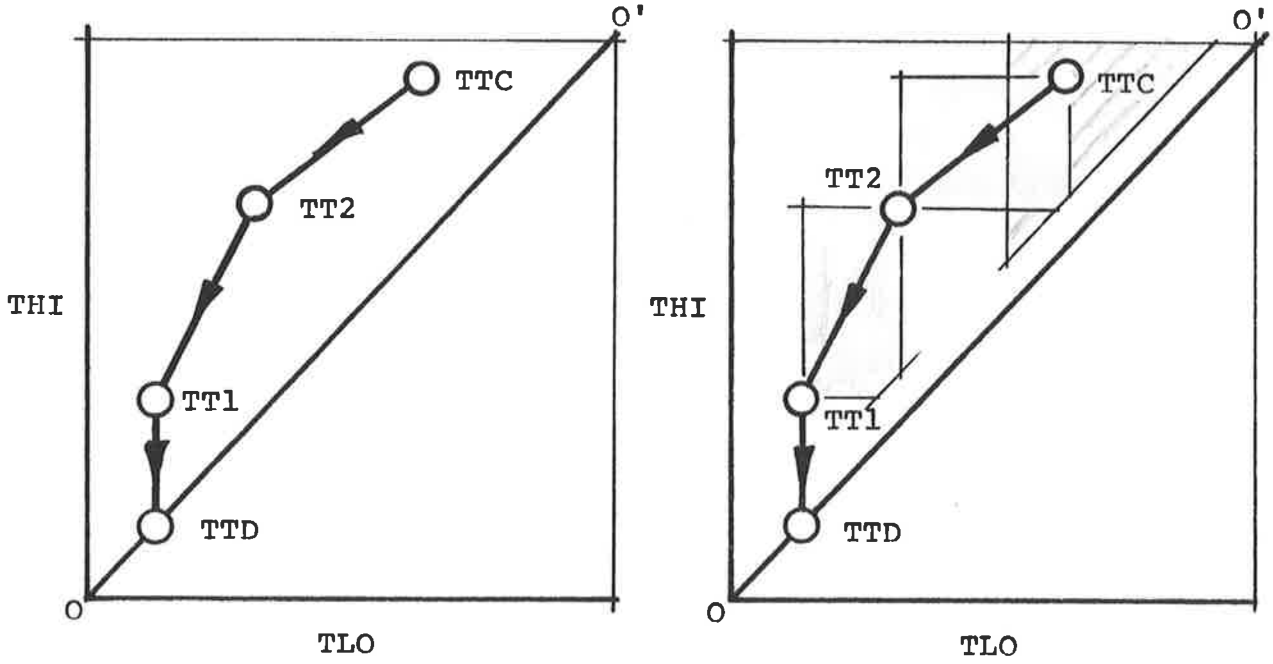
$$\text{EXTQ} = \sum_{i=1}^{i=L} Q_i$$

FIG A4

SYSTEM AND SPACE IDENTIFICATION



A5/1 IDENTITY OF WHOLE SYSTEM A5/2 IDENTITY OF PROCESSES



A5/3 ENERGY TRACK A5/4 PROCESS FIELDS

TT DIAGRAMS

EACH DIAGRAM APPLIES TO
UNIT TIME: I
DEMAND-RATE: QD AT TTD

FIG A5

TT DIAGRAM - AIR HEATING SYSTEM WITH HUMIDIFICATION

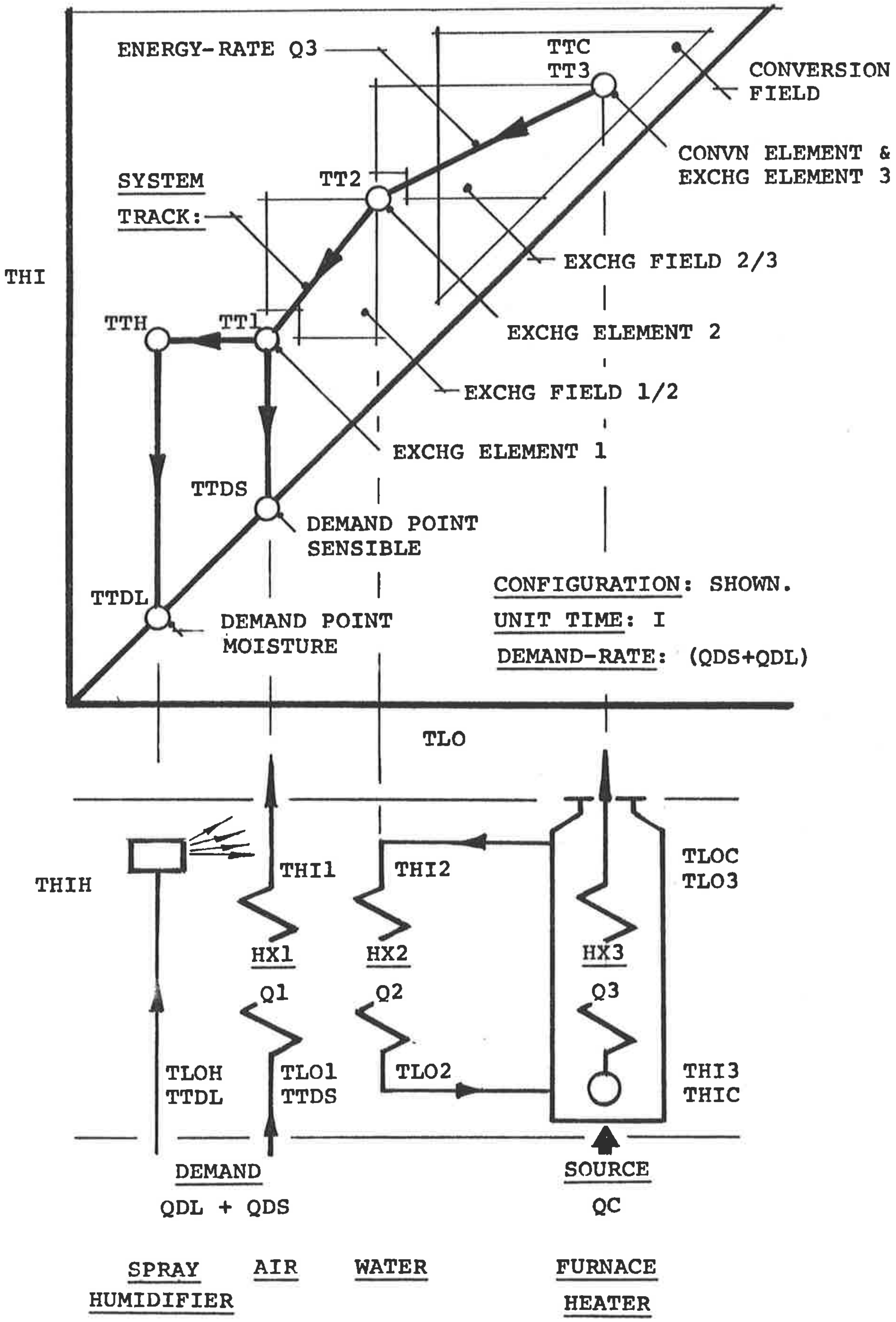
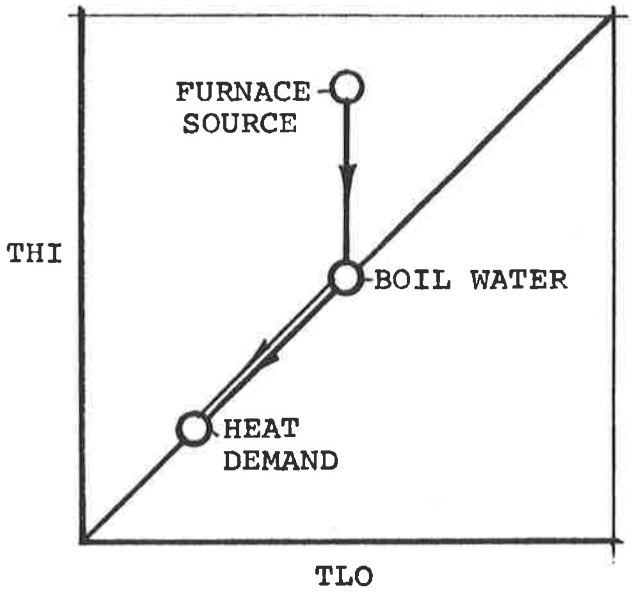
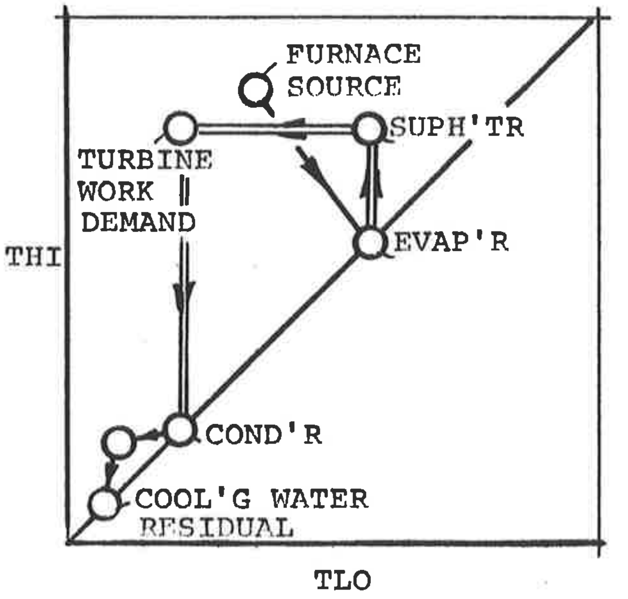


FIG A6

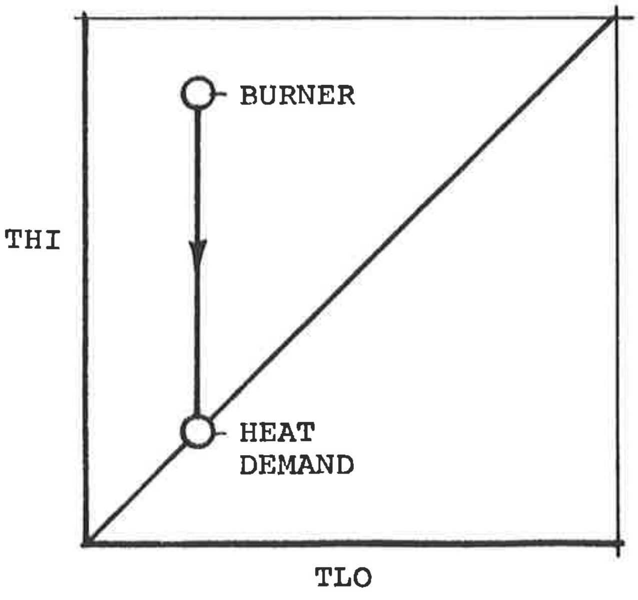
ELEMENTARY TT DIAGRAMS



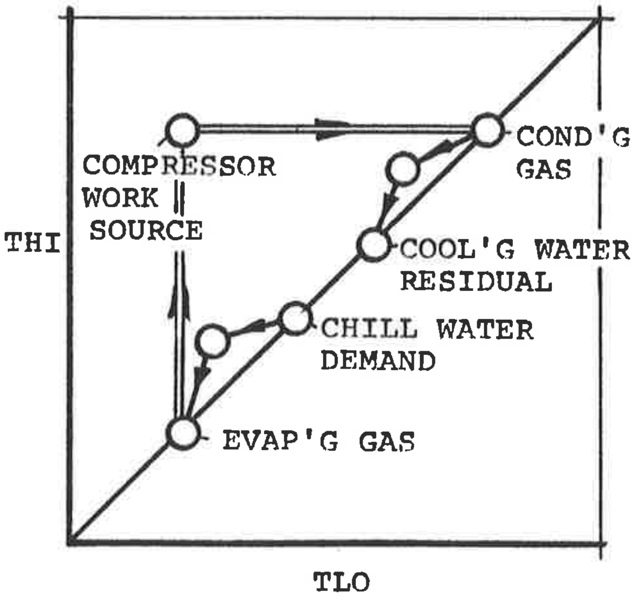
DIRECT STEAM HEATING



STEAM POWER PLANT



DIRECT GAS SPACE HEATING



VAPOUR COMPRESSION REFRIGERATION

⇉ DOUBLE LINE INDICATES
PURPOSEFUL PRESENCE OF
FLOW ENERGY.

FIG A7

5.0 SYSTEM SYNTHESIS.

The world's power plants, propulsion engines, heating and refrigeration installations demonstrate that man can design and build thermal energy systems on a big scale. In each case he has synthesised his system from available resources to produce what he wants.

So system synthesis is as old as thermal engineering itself and this age and wealth of experience has been the mainstay of its success. System synthesis has, of course, been greatly supported by successful research, by the development of modern technologies and by the new engineering elements evolved from them. Yet in this present age we must recognise that our synthesis skills and most of the available technology has been developed from experience gained with sources of cheap energy. We must also realise that such skills and technology may be inadequate to cope with rapid changes in world energy resources. The time is ripe to establish a universal discipline and skill for thermal energy system synthesis – a skill which can use all past experience, present knowledge and the result of future research but keep it all subordinate to rational decision.

5.1. Planning.

System synthesis is a form of detailed planning – how to meet a required demand from available energy resources.

Planning needs a clear objective if it is to have meaning. More specifically, thermal energy system synthesis needs a clear objective such as 'maximise the use of indiginous fuel' or 'minimise the total annual cost'.

Planning and synthesis also need a source of information or they will have no substance. Energy system planning needs scientific, technical, economic and sociological information about the required demands, energy sources, thermal processes, engineering elements and the system's surroundings.

Our whole discussion of synthesis expects that we start with, or first establish, a rational *objective* and a stock of sound *information*.

5.2. An Objective Proposal.

Man synthesises his thermal energy systems by a process of decision-making. Except for the most elementary systems, such decisions involve a selective choice from many available combinations of energy sources, processes, elements and operations. The decisions must be co-ordinated so that, first and foremost, the system demand is precisely satisfied at all times.

From a functional point of view, all different combinations which merely satisfy the demand will be equivalent and they will each result in a different *workable system*. (Ref.3,pll).

Man lives by more than functional criteria, however, and his systems will be judged according to their fuel economy, cost economy, environmental effect, safety, size, space, weight and so on. A 100 KW plant may be functionally similar to a 50 KW plant, if the demand does not exceed 50 KW, but an engineer will usually be censured if he builds the large plant when the smaller one will do. He strives then to synthesise his energy systems so that, while still functionally sound, they at least also lie within acceptable limits of all the other prevailing criteria. He nearly always achieves this.

Acceptable limits, while certainly narrowing the range, will usually still leave many options open for decision in system synthesis. Man appears to be insufficiently equipped merely by his experience to make these decisions. Frequently he may have little more than research knowledge about, say, a new energy source. Alternatively he may have such great personal knowledge of a particular process that it dominates his thinking – his synthesis may then become subjective or even prone to inadequate decisions.

There are many thermal energy systems being synthesised by many people in all parts of the world each day for all kinds of purposes. So it would seem good to establish a general and universal method for the conduct of the whole procedure – one which replaces its subjective aspects with rational objectivity.

Let us anticipate that, in any given case, there will be just one, or only a small number of equal combinations of available energy sources, elements and operations which most closely satisfy the criteria which define the planning objective. Provided we have the essential planning information about all these components, a wholly objective method of synthesis should then lead us to such an 'optimal' solution.

This present work proposes, from the outset, that we should conduct a thermal energy system synthesis, together with all its information and decision processes, in a way which continually pursues and finally identifies this optimal result.

We will now discuss the five principal steps of any method of energy system synthesis before applying them in such an *objective method*.

5.3. Five Steps of Synthesis.

Man builds energy systems to meet a demand. All methods of synthesis must therefore start, as a *first step*, with a statement of that demand in terms of a work-rate, or heat-rate at certain temperatures, for each unit time-interval. Expressed over an extended time-interval, all the unit values define a whole *demand profile* for which the energy system must be engineered and operated. (e.g. Fig.A4,p46). Apart from its demand-rates, a system will also usually be required to supply the demand in a certain physical medium e.g. electricity or hot water, and at a certain location, all of which is essential information for the start of synthesis.

The *second step* is to expose the quantity and quality of all the *energy sources* potentially available to meet all or part of a system demand profile. Many of these will be primary sources, e.g. natural gas, requiring conversion processes as the first stage of their transition to the demand. Other energy sources may already exist in a thermal form, e.g. hot water from an unrelated industrial process.

The *third step* is to link each of the available energy sources to the demand with the minimum number of conversion and exchange processes needed to provide the required functions, e.g. combustion to hot gas, then hot gas to hot water for transport, then hot water to hot air for the demand. (Fig.A6,p48). We define each different set of energy sources and processes as a particular system *configuration*.

The *fourth step* is the nomination of *engineering elements* for the processes in each configuration, matching the required functions to the physical and technical characteristics of both the elements themselves and their interconnection.

The *fifth step* is to *select* one configuration, its elements and its particular set of operations from the whole set of all feasible combinations so that the system to be built and operated is precisely defined, physically and operationally, to meet the required demand profile over the whole specified tine-interval.

5.4. Unified Synthesis Information.

The first four steps in synthesis are a collection and assembly of information about the demand profile, energy sources, processes, elements and their configurations. There is no short cut to this in any method of synthesis. What we can do, however, is organise that information in a way which specially facilitates configuration assembly in the first place while simultaneously making it readily accessible to the fifth step of selection and decision. This is the whole reason for creating the unified and operational view of thermal energy systems in Sections 3 and 4.

The first two steps of synthesis are concerned with information which is to be obtained from a system's surroundings. We define this as *external information* – over which a system has little or no control and over which, for synthesis, we have little or no power of decision. The third and fourth steps are concerned with information over which, for synthesis, we do have the power of decision within the limits of maintaining the required functions. We define this as *internal information*. It includes all the technical information previously organised on a unified base and defined as physical constraints. (p44). It now also includes whatever additional technical, economic or sociological information is associated with each element, and which may be required for evaluation of objectivity during the synthesis procedure.

We will defer until Part B an explanation of how external and internal information is to be managed in practice. But at this stage it will be said that *all* such information will be organised on the unified basis. All information will then be available for common use in all synthesis procedures.

The first four steps of synthesis involve professional decision-making only to the extent that a piece of information or its assembly is, or is not, correct and should, or should not, be admitted. Nevertheless those steps are a fundamentally important preparatory task.

Engineering organisations gather information from research and experience over a long period to suit their own needs. While we are proposing that it should all be brought to a unified basis for objective synthesis, we can perhaps foresee a second major benefit in the rationalisation of all thermal energy information generally.

5.5. Objective Function.

The fifth step of synthesis is the one with which we are most concerned. When this stage has been reached, we may have a large number of alternative configurations to consider – each configuration having a large number of alternative feasible operations for each unit time-interval. We have to decide on just one combination of possibilities from this very large number. Of course we can enlist a computer to help our processing but, more fundamentally, we first have to establish a basis by which we will make our decisions. Such a basis is the *scale of value* for design introduced in Section 2 (p7.) but we will now develop it further.

We have already stated (p51) that man is expected to synthesise his energy systems within limits of prevailing criteria. We have also stated that, instead of just meeting limits, we propose to synthesise the most objective system in terms of specific criteria.

Let it be said at the outset that, except for criteria of the simple yes/no kind, all those of significance to objective synthesis will have to be defined in numerical terms. Economic criteria can, for example, be expressed as costs. In turn, if an energy system is to be evaluated objectively against those criteria then it must be measurable in the same numerical terms, e.g. the cost of operation per hour.

Whatever the *planning criteria* so long as we can measure a system in terms of such criteria, and as long as that measure is a reliable and orderly numerical function for all feasible systems, we can establish an objective target or direction for synthesis. We define such a method of measurement as the *objective function* and recognise that the most objective or 'optimal' thermal energy system will be the one which minimises (or maximises) the value of that objective function.

The essential procedure at the start of the fifth step of synthesis is then:

- Recognise the significant planning criteria.
- Define them numerically.
- Establish the objective function in their terms.

All this is a most important professional task, multi-disciplinary if necessary, upon which the success of the subsequent synthesis procedure will rely.

We will confine the present work to objective functions of a single expression and defer the consideration of synthesis for simultaneous multiple objectives.

5.6. Objective Values.

We can anticipate that, depending on the planning criteria, many or most parts of a thermal energy system, its energy sources, its engineering and its operations will contribute in some way to the objective function, e.g. fuel consumption in terms of its cost will contribute to an objective cost function. In establishing the objective function we will therefore deliberately construct it from a number of small components, one for each element in each configuration. All such components are to be unified by the planning criteria. Subject to the physical constraints of that element, we may then formulate an objective function for each element and compute an objective value for each TT,Q point of operation in a synthesis simulation. We can then add the objective values of all TT points on a system track to obtain an *objective value* (V) for the whole operation represented by that track, e.g. V = V1+V2+V3+VC (Fig.A8,p62).

Formulation of the objective function for each element will require professional skill and experience — a knowledge of both the planning criteria and the engineering elements. Nevertheless it can remain a wholly logical and numerical process by which the objective value of any system track can be readily determined. The essence of correct formulation of the objective function is that it be complete; and that the terms of each of its components be organised on a common numerical base which itself measures the planning criteria.

5.7. Field Search.

The relation between the objective values of different alternative system tracks will measure the relative approach of each track to the planning criteria. In the fifth step of synthesis, for each unit time-interval (I) and its demand-rate (QD) we can then conceivably

. search the whole feasible space of every configuration in sequence in incremental TT steps,

. evaluate the objective value of each track in turn and finally

. identify and record the track of minimum (or maximum) objective value as a principal decision of synthesis, i.e. the one identifying the system which most closely meets the planning criteria.

Such a procedure is defined as a *field search* and decision sequence - a method of numerical optimisation. (Fig.A8,p62).

Two classes of decisions may be seen to apply during a field search:

. *Mechanistic decisions* are those which result particularly from the action of field limits, e.g. at a certain temperature a process must stop and, when it does stop, its function must be zero. Such decisions must take priority over all other possible decisions when they are encountered in a synthesis procedure.

. *Tactical decisions* are those which result from objectivity, e.g. that a particular system track has an inferior objective value to another track and hence is rejected as a synthesis solution. Such decisions are competitive and may be made at any time during the synthesis procedure.

As all feasible systems can be represented and identified on the same unified (TT,Q) base, different (alternative) configurations may be searched concurrently for the same demand-rate and unit time-interval. Tactical decisions can also be made at any time based on the objective values of tracks of different configurations.

If we are concerned only with one unit time-interval, or with a steady system (for which the source, demand and surrounding conditions are constant for the whole extended time-interval) the field search and decision sequence completes the synthesis. The optimal energy source, system configuration, objective values and values of all constraints (engineering elements, operations and control parameters) will be defined by the most objective track.

5.8. Evolutionary Search.

Most industrial thermal energy systems are time-varying systems for which the value of the demand or source functions (or both) change from one unit time to another. (Section 4.1,p39).

While the field search will find the most objective system for one unit time-interval, under such changing conditions it can be expected to find a different solution for the next unit time. If the change from one solution to another could occur without physical constraint, the whole set of unit-time solutions evolved for the whole demand profile would then constitute the optimal system specification. We will define this as a *free evolution* and later use the concept for a special purpose. (Section 10.2,p91).

In practice, however, the physical constraints of a thermal energy system may have only limited ability to adjust to such 'free' operation as external conditions change. The 'free' operation may, in fact, be achieved at times when the values of the constraints are well matched to the optimal condition. Otherwise, as conditions change, the most objective system to be found with the field search will merely be the best available within the 'fixed' physical constraints of the system's engineering. Yet we still have to seek and identify the optimal system in such a situation.

While still conducting the field search for each unit time-interval, and while still identifying the most objective system (and its operation) for that time, we now

- conduct an additional search repeatedly over the whole extended time-interval,
- integrate the most objective value obtained for each unit time-interval into an *extended objective value*,
- incrementally change the values of the physical constraints for each repetition of the search and finally
- identify the set of physical constraints and unit-time operations for a particular configuration, all of which minimises (or maximises) the extended objective value.

Such a procedure is defined as an *evolutionary search* – also a method of numerical optimisation. (Formulation, Fig.A9,p63).

In summary, the task of the evolutionary search is to evolve the physical and operating characteristics of the system which, when built, will most closely meet the planning criteria when considered over the whole extended time-interval.

Mechanistic and tactical decisions still apply within the field search for each unit time-interval. Other mechanistic decisions now apply to integrated aspects of system operations and other tactical decisions may be made according to the extended objective values. In addition, *evolutionary decisions* now have to be made about the extent and direction of change of physical constraints during the evolutionary search.

Satisfactory completion of the evolutionary search defines the energy sources, system configuration, objective values and values of all constraints, operations and control parameters all of which determine the 'optimal' synthesis solution.

5.9. Energy Storage.

For a time-varying system, the notion of adjusting the values of the physical constraints to obtain the desired 'free' operation from time to time, permits the introduction of the concept of energy storage. We could, for example, synthesise an 'optimal' system to operate steadily at the same conditions, its constraints continually well matched, storing its output in a terminal accumulator from which a varying demand can draw at will. It only requires us to ensure that the accumulated output is equal to the integrated demand over the whole extended time-interval. Alternatively, if an energy supply is variable or interruptible, we could store energy at the source so that any variation in supply would have no effect on operation within the system itself. Thus in general, we may expect to

- 'normalise' the engineering and operation of a thermal energy system between its source and a storage point while
- the system operation must continue to respond to any change in demand below that point of storage.

It is a decision to be made during the first four steps of synthesis whether or not, in principle, energy storage is to be admitted to a system configuration. If so, it becomes part of that configuration at a particular point (on the TT track) and both the field search and evolutionary search must take it into account.

The presence and effect of storage is predictable in thermal and technical equations as for any other engineering element although, unlike many of them, it must include the integrated effect of time. For synthesis, the information about such a *storage element* and its constraints is also to be expressed in the unified (TT,Q) terms of the TT diagram such that:

- For unit time-intervals I and extended time-interval L where $1<I\leq L$.

- For 'hot' energy storage at points TTK, between elements at TTN and TT(N+1).

- Storage TT Field limits are

$$\begin{aligned} &TLOK \leq THIK \\ &TLON < TLOK < TLO(N+1) \\ &THIN < THIK < THI(N+1) \end{aligned}$$

- Nett heat (QK) transferred to or from storage in a particular unit time-interval is

$$QK = Q(N+1) - (QN+\Delta QN) - \Delta QK$$

i.e. the simple equation of arithmetical continuity, where ΔQK is the 'heat loss' to surroundings.

- Energy in storage QSTO(I) at a particular unit time-interval (i=I) is

$$QSTO(I) = QSTO(1) + \sum_{i=1}^{i=I} QKi$$

$$0 \leq QSTO(I) \leq QSTOMAX$$

where QSTO(1) is the energy in storage at the start of the extended time-interval and QSTOMAX is an arbitrary maximum limit of storage.

- 'Heat loss' from storage in a particular unit time-interval is

$$\Delta QK = FUNC(TTK,PHYSK,SURR)$$

where PHYSK is the set of physical constraints (mainly those of the working substance and engineering construction) of the storage element and SURR are the surroundings conditions (mainly the ambient temperature).

For synthesis then, *energy storage* is seen from the above relations to be defined as an *arithmetical accumulation* of energy, the quantity and temperatures of which are to be determined from the integrated functions of elements to which the storage element is connected. The functional role of storage is discussed further in Part B (Section 10.5,p93). Hot water storage is discussed in Part D (Section 15.5, p124).

The capacity of the storage element is derived automatically from the evolutionary search. As the physical constraints of the system above storage are incrementally 'tightened', demands which would otherwise be excessive have to be met by storage. Alternatively, if a source is intermittent, as the physical constraints of its conversion element are incrementally 'relaxed', supply in excess of demand may be accumulated in storage.

Energy storage will affect the objective values of other system elements at all times by the changes it makes to their energy-rates. But the objective value of the storage element itself will usually await the derivation of its capacity and then contribute directly to the extended objective value of the system configuration. (Formulation, Fig.A10,p64).

The specification of energy storage, if admitted to a system configuration, is an essential part of the synthesis solution for time-varying systems.

5.10. General Formulation.

Everything that has been discussed can now be consolidated into a *general formulation*, Figs.A11,A12 and Table A1,(p65-67).

The general formulation is the essence of the discipline we have created in Part A for a unified synthesis procedure. Based as it is on the foundation developed in Section 2, it applies to the design of all kinds of thermal energy systems for which the planning criteria are defined numerically.

The formulation is an essential step required at this stage to translate the discipline into computer programs required to conduct the procedure in practice.

5.11. Summary.

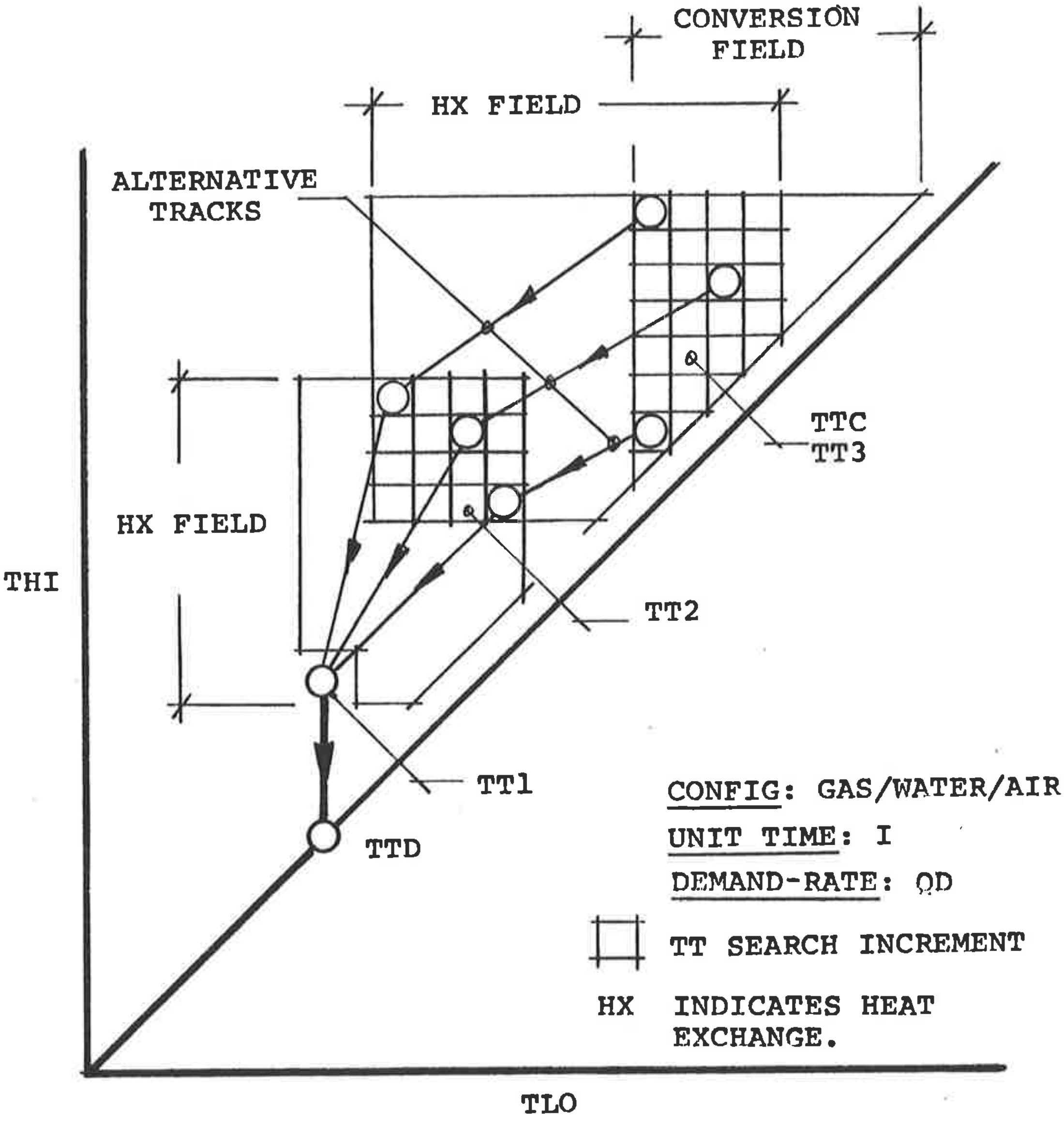
We should not allow the details of the formulation to obscure the basic principles of the synthesis procedure. They may be expressed in simple terms as follows:

. Reduce a thermal energy system to a simulation of its energy functions in universal (TT,Q) terms - free of all physical constraints.

. Organise the knowledge of the effects of all physical constraints on a common basis - unified by the (same TT,Q) terms of the simulation.

- Establish an objective function by which the design of the system can be evaluated.
- While maintaining the simulation at all times, add the necessary physical constraints by a disciplined sequence of mechanistic, tactical and evolutionary decisions so that the 'optimal' system is ultimately synthesised.

Let us now apply these principles to practice.



CONFIG: GAS/WATER/AIR

UNIT TIME: I

DEMAND-RATE: QD

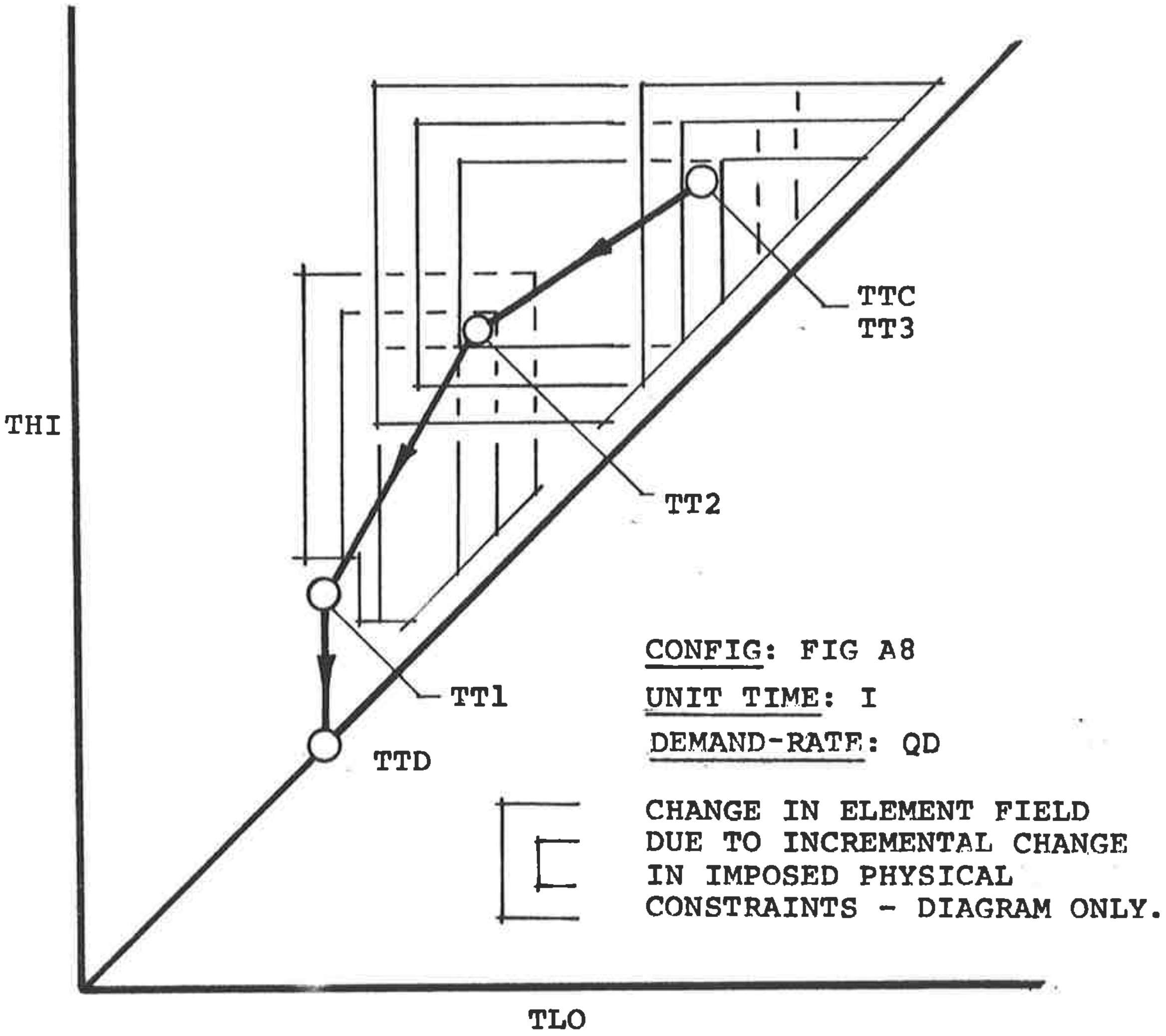
FIELD SEARCH:

TTD GIVEN	
TT1 FIXED	V1 FIXED
THI2 AND TLO2 IN INCREMENTS	COMPUTE V2
THI3 AND TLO3 IN INCREMENTS	COMPUTE V3
THIC = THI3 AND TLOC = TLO3	COMPUTE VC

TRACK VALUE: $V = V1 + V2 + V3 + VC$

MOST OBJECTIVE TRACK: V^*

FIG A8



EVOLUTIONARY SEARCH:

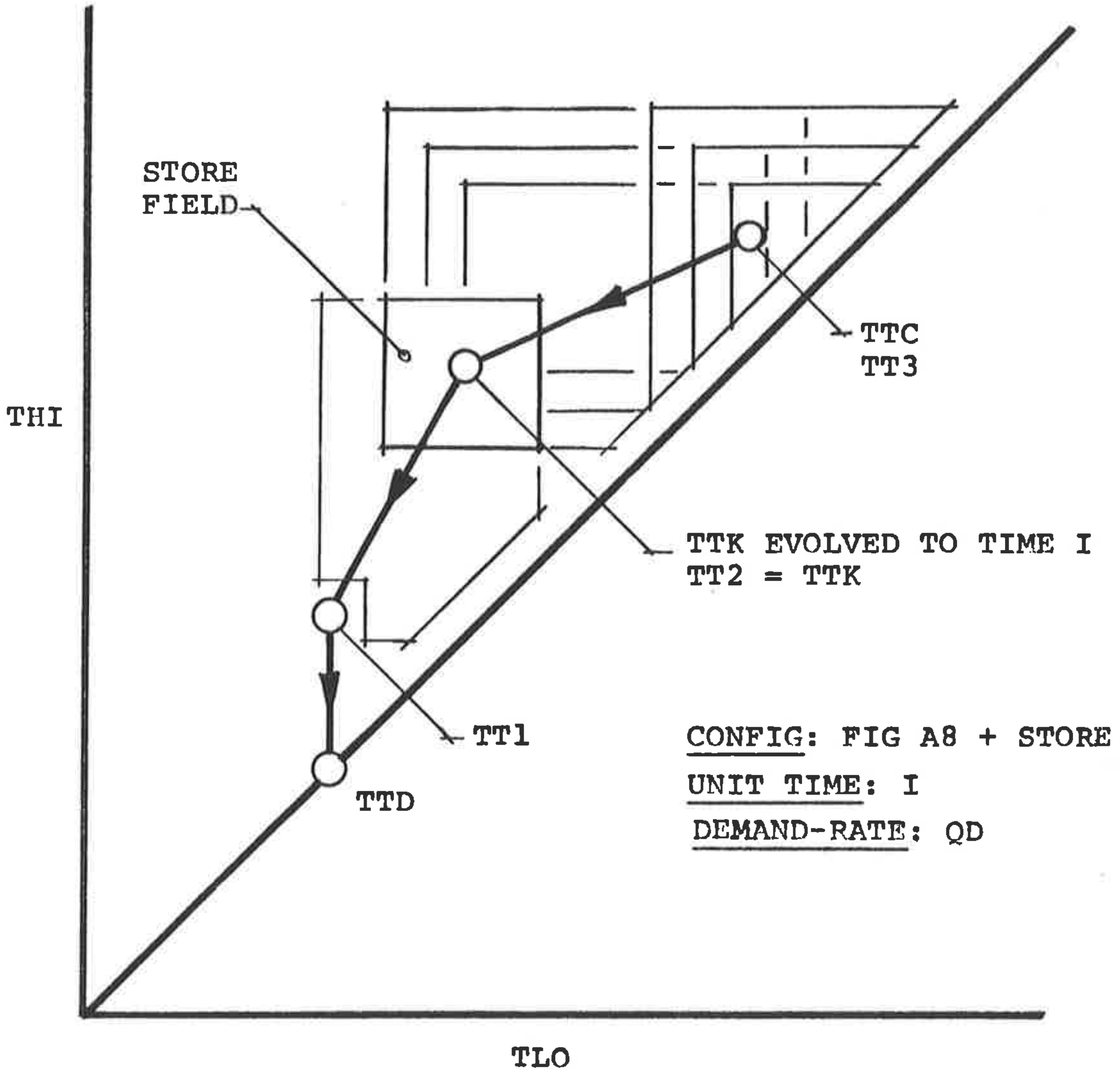
CHANGING QD AND/OR TTD EACH I.
ELEMENT AND SYSTEM CONSTRAINTS IMPOSED.
FIELD SEARCH STILL CONDUCTED EACH I.

EXTENDED OBJECTIVE VALUE: $\text{EXTV} = \sum_{i=1}^{i=L} V_i^*$

RE-EXECUTE OVER WHOLE L WITH INCREMENTED CONSTRAINTS.

MOST OBJECTIVE SET OF CONSTRAINTS: EXTV*

FIG A9



CONFIG: FIG A8 + STORE
UNIT TIME: I
DEMAND-RATE: QD

EVOLUTIONARY SEARCH WITH STORE:

CHANGING QD AND/OR TTD EACH I.
ELEMENT AND SYSTEM CONSTRAINTS IMPOSED.
FIELD SEARCH STILL CONDUCTED EACH I.

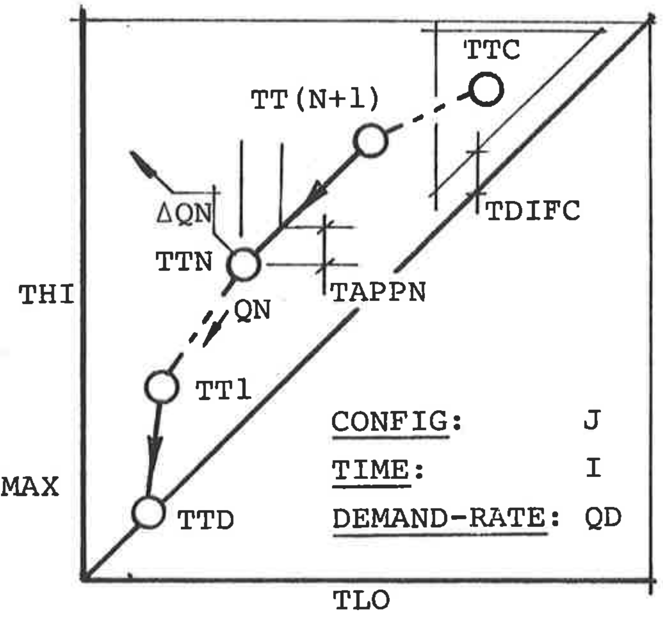
EXTENDED OBJECTIVE VALUE: $EXTV = \left(\sum_{i=1}^{i=L} V_i^* \right) + VK$

RE-EXECUTE OVER WHOLE L WITH INCREMENTED CONSTRAINTS, EVOLVING DIFFERENT STORE AND VK.

MOST OBJECTIVE SET OF CONSTRAINTS: EXTV*

FIG A10

THERMAL ENERGY SYSTEM SYNTHESIS.



GENERAL FORMULATION.

STEADY SYSTEM, UNIT TIME.

TRACK SEQUENCE

TTD,TT1,..,TTN,..TTC

TT,Q RELATIONS

$TTD < TLO1 < TLON < TLOC$
$TTD < THI1 < THIN < THIC$

$0 < QD \leq QN \leq QC$

EXCHANGE ELEMENTS

FIELD LIMITS
$TLON \geqslant TLONMIN$
$TLON + TDIFN \leq THIN \leq THINMAX$
$THIN + TAPPN \leq THI(N-1)$
$TLON + TAPPN \leq TLO(N-1)$

ENERGY-RATES
$QN = Q(N-1) + \Delta Q(N-1)$
$\Delta QN = FUNC(TTN,PHYSN,SURR)$
$QN \leq QNMAX$

OBJECTIVE VALUE
$VN = FUNC(TTN,QN,PHYSN,SURR,OBJN)$

CONVERSION ELEMENT

FIELD LIMITS
$TLOC \geqslant TLOCMIN$
$TLOC + TDIFC \leq THIC \leq THICMAX$

ENERGY-RATES

$$Q(NMAX) = QD + \sum_{N=1}^{N=NMAX} \Delta QN = QC - \Delta Q(NMAX)$$

$QC = FUNC(TTC,PHYSC,SURR)$
$QC \leq QCMAX$

OBJECTIVE VALUE
$VC = FUNC(TTC,QC,PHYSC,SURR,OBJC)$

TRACK VALUE

$$VJ = VC + \sum_{N=1}^{N=NMAX} VN$$

DETERMINE VJMIN BY FIELD SEARCH

SYNTHESIS SOLUTION, STEADY SYSTEM

FOR GIVEN TTD AND QD, MINIMISE V

$$V^* = MIN\left[VJMIN\right]_{J=1}^{J=JMAX}$$

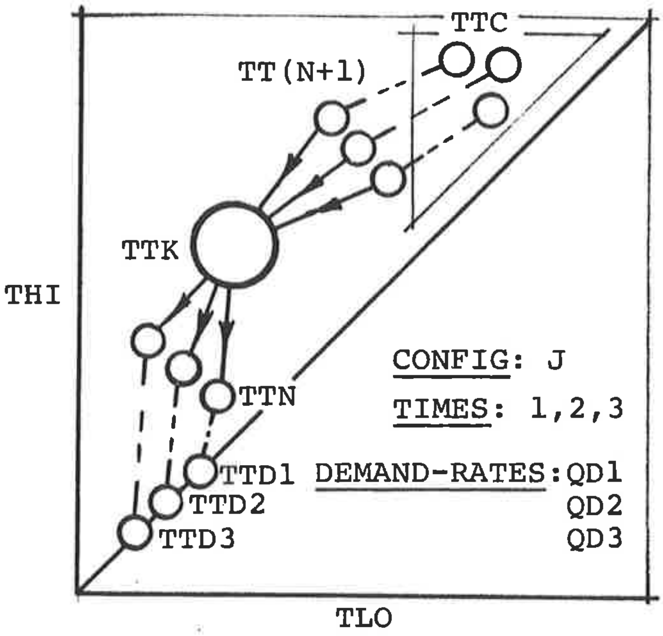
IDENTIFIES OPTIMAL SYSTEM.

FIG A11

THERMAL ENERGY SYSTEM SYNTHESIS.

GENERAL FORMULATION.

TIME-VARYING SYSTEM.



TIME SEQUENCE

$1 < I \leqslant L$

ENERGY STORAGE

FIELD LIMITS
$TLOK \leqslant THIK$
$TLON < TLOK < TLO(N+1)$
$THIN < THIK < THI(N+1)$

EACH UNIT TIME-INTERVAL
$QK = Q(N+1)-(QN+\Delta QN)-\Delta QK$
$\Delta QK = FUNC(TTK,PHYSK,SURR)$

AT TIME I

$$QSTO(I) = QSTO(1) + \sum_{i=1}^{i=I} QK_i$$

$$0 \leqslant QSTO(I) \leqslant QSTOMAX$$

AT TIME L

QSTO(L) = QSTO(1) FOR BALANCE OVER THE WHOLE L

OBJECTIVE VALUE OF STORAGE
VK = FUNC(QSTOMAX,PHYSK,OBJK)

WHOLE CONFIGURATION

FIELD SEARCH CONDUCTED IN EACH UNIT TIME-INTERVAL (FIG A11) WITH THE EFFECT OF CONSTRAINTS, GENERALLY:

EXCHANGE ELEMENTS
QN = FUNC(TTN,PHYSN,PHYS(N-1),PHYS(N+1),SURR)
$QNMIN \leqslant QN \leqslant QNMAX$

CONVERSION ELEMENT
QC = FUNC(TTC,PHYSC,PHYS(NMAX),SURR)
$QCMIN \leqslant QC \leqslant QCMAX$

EXTENDED OBJECTIVE VALUE

$$EXTVJ = \sum_{I=1}^{I=L} VJMIN(I) \quad + \quad VK$$

EXTVJMIN DETERMINED BY
EVOLUTIONARY SEARCH OF PHYSC AND $[PHYSN]_{N=1}^{N=NMAX}$

SYNTHESIS SOLUTION, TIME-VARYING SYSTEM

FOR GIVEN $[TTD(I) \text{ AND } QD(I)]_{I=1}^{I=L}$ MINIMISE EXTV

$EXTV^* = MIN\,[EXTVJMIN]_{J=1}^{J=JMAX}$ IDENTIFIES OPTIMAL SYSTEM.

FIG A12

THERMAL ENERGY SYSTEM SYNTHESIS.

GENERAL FORMULATION.

Refer Figs. A11, A12 (pp65-66)

SYMBOLIC NAMES.

EXTVJ	Extended objective value, configuration J.
FUNC	Numerical function of:
I	Unit-time identifier.
J	Source/configuration identifier.
L	Extended time-interval.
OBJ-	Objective information.
PHYS-	Set of physical constraints.
Q-	Heat-rate, or energy-rate for synthesis generally.
QSTO(I)	Energy in storage element at time I.
SURR	Conditions in system (or element) surroundings.
TT-	State-couple temperatures of process or element.
TAPP-	Minimum temperature approach.
TDIF-	Minimum temperature difference.
V-	Objective value.
VJ	Track value, configuration J.
V*	'Optimal' value of objective function.

- indicates frequent use of symbol with subscript.

Subscripts.

C	Conversion element.
D	Demand.
K	Storage element.
MAX	Maximum value of:
MIN	Minimum value of:
N	Exchange element.

Refer also to the glossary, p175.

TABLE A1.

THERMAL ENERGY SYSTEM SYNTHESIS

PART B

PRACTICE - A COMPUTER-BASED PROCEDURE FOR SYNTHESIS.

6.0 SYNTHESIS IN PRACTICE

Thermal energy system synthesis is practised all over the world every day as a continuing occupation for thousands of professional engineers in the design offices of electricity undertakings, shipyards, chemical industries and many others. Each group of people conducts a procedure of synthesis in its own way, with its own information for all kinds of tasks – from big new systems to small alterations of old systems. On the one hand then, all the substance and activity of synthesis already exists even if its practical methods are diffuse.

On the other hand, there are other groups of people who already apply methods like our objective synthesis procedure in practice. They may, for example, prepare an optimal flight plan for an airways operation from origin to destination in the same way that we propose to find the optimal energy track from source to demand. They will start with a geographical chart while we have to compose a plan of our feasible TT space from technical equations. They may have to optimise a large number of different air operations over a period as we may have to synthesise for an extended time-interval. Exactly like ours, their planning objectives may be technical or economic or sociological.

The present work brings the methods of the second kind of activity to the substance of the first kind, the key being the organisation of thermal energy systems in unified, operational terms.

Every application of such operational methods must be based on its own particular professional disciplines but they all have three essential practical tasks in common:

- Information management,
- Objective processing of information, and
- An executive specification.

Thermal Energy System Synthesis is based on the discipline of mechanical engineering and the discipline just developed in Part A for numerical optimisation. It is strictly within these disciplines that we will now develop procedures for the three practical tasks – all suitable for a digital computer. But first a note about setting objectives.

6.1. Objectives.

Planning objectives originate in man and society according to their many needs and motives but objectives usually need a single executive authority to define them. In the past, one man alone has made energy decisions for his own home, a company for its factory and a government for its people. In each case the authority has been the one with the power, resources and leadership needed to build and operate the required energy system – and their objectives have been almost entirely economic. This is now changing as energy resources dwindle and planning authorities have to contend to a greater degree with ethical and political factors. But it will not change the fact that before synthesis we must co-operate with the appropriate authority and help him define a meaningful energy objective.

Energy planning objectives mainly need directional definition and limits, e.g. minimise one aspect and limit another to a certain maximum. We can compose any rational objective like this from any number of terms so long as we have a common numerical measure for them.

If we set loose objectives the synthesis procedure will not converge to a definite or small set of solutions; it will simply tell us that there are a large number of 'equal' solutions. If we set objectives which are too restrictive, the procedure will tell us that there is no feasible solution. Poor objective setting will not always bring a failure of the method – rather it will mean that the procedure itself can help redefine an objective from the results of early trials. This provides an important aid to the exploration of new energy systems.

One common industrial objective seeks to build an energy system which meets its demand with minimum total annual owning and operating cost in terms of a company's cost equation. For example, the objective function for its energy system may be constructed as follows:

V = CAPITAL COST x CPC
\+ FUEL COST
\+ OPERATING POWER COST
\+ OPERATING LABOUR COST
\+ MAINTENANCE COST
\+ OVERHEAD COST

where all costs are measured in the same units and CPC is the company's required gross annual percentage charge on capital investment of this kind. As we have seen, (p55), the equation has to be further broken down into objective functions for each system element. An example is given in Part D, Table D6,p160.

6.2. Extended Time-Interval.

The choice of an extended time-interval for synthesis depends on the objective. Long-term energy planning may, for example, require synthesis for a period of 25 years while one year is usually the minimum suitable for technical synthesis of land-based thermal energy systems. This is due to their exposure to, perhaps even to their dependence on, seasonal climatic changes. A year has been the usual basis for technical planning of thermal energy systems.

7.0 EXTERNAL INFORMATION

We have to obtain and express the detail of the demand, the available energy sources and the system surroundings as essential *Input Data* for synthesis. This is all *external information*. Neither we nor the energy system have any control over it and it can be expected to be different for every case of synthesis. Our main task is to see that it is correct, complete and compatible with our unified discipline.

7.1. Demand.

The whole profile of the system demand over the extended time-interval is to be derived from technical knowledge of the system's service, whether it is an industrial process, a ship or a city building. The present work is not concerned with its calculation – it requires no change to customary engineering methods. Whether heat-rate or work-rate or a combination of both, each is stated as a single factor in KW for each point of demand during each unit time-interval, specifying also the physical medium required at each demand point and the temperature to be maintained at a thermal demand point. A system required to supply both electric power and process heating may, for example, have its demand stated for a one hour unit time-interval, 1200 to 1300, as:

TIME	ELEC	WATER HEAT	TEMP
1200	450 KWE	50 KWTH	45 DEG C

Demand is a *given* requirement of design and, as such, is expressed as variable Input Data for synthesis.

While we have defined 'demand' as a condition imposed on a system from its surroundings, we will often use the word 'load' to define the energy-rate at which a system or one of its elements is actually working within its feasible space.

7.2. Energy Sources.

The qualities of primitive thermal energy sources like coal and oil can be readily stated in terms of their combustion chemistry. Except for minor variations due to source of supply, their heating value is virtually fixed. Unless they are subject to variable consumption limits, just one set of figures is often sufficient to define them for the whole synthesis period, e.g. heating value, water content and ash. Information like this is fixed Input Data.

The quantity and/or quality of some energy sources may vary, however, and their details must then be stated for each unit time-interval. Waste-heat energy sources and solar energy are in this category. The latter for example may need at least a predicted value of radiation on a horizontal plane at the system locality for each day and hour of the year. This must be stated as variable Input Data, e.g.

DAY	TIME	RADN HORIZ
23 MAY	1200	730 W PER SQ M

while the geographical position, for computation of geometric changes in radiation on other surfaces, is taken into the synthesis as an item of fixed Input Data.

7.3. Surroundings.

Many thermal energy processes and their elements are influenced by the thermal conditions of their surroundings. An engine's performance may vary with air density, a condenser with sea-water temperature, a solar collector with ambient air temperature and so on. All elements also experience some degree of heat gain or loss to the surroundings. These effects must be taken into account in synthesis and we will see later that they have to be included in characteristic technical equations for each system element. The relevant surrounding conditions required by these equations must then all be included as variable Input Data at each unit time-interval, e.g.

TIME	TEMP AMB
1200	25 DEG C

7.4. Objective Data.

Sometimes the external information from which a system's objective value is calculated may change during the period of synthesis. The cost of fuel, for example, may change seasonally. Although it is not to be confused with the technical information just discussed and without which a system cannot be defined, variable objective information such as this must also form part of the Input Data at each unit time-interval.

7.5. Input Data Assembly and Time-Intervals.

All items of Input Data for synthesis are tabulated in an orderly array of figures – fixed data in an initial list; variable data in a separate row for each unit time-interval with a separate column for each parameter. An example is included in Part D, Table D5,p159. The computer can help compile this array from a variety of sources of information.

The synthesis procedure will take each variable Input Data value as a constant (or mean) for each unit time-interval. The unit time-interval must therefore be selected small enough to ensure that these mean values give a sufficiently precise synthesis solution. On the other hand, unnecessarily small unit time-intervals are to be avoided as they merely prolong the procedure without benefit. Unit time-intervals certainly need be no smaller than those needed to span significant variations in input data; recall, in the extreme case of no variation, the extended time-interval itself becomes the single unit time-interval.

Setting the unit time-interval may require some experience with the kind of system being studied but, in any case of doubt or where a lot of repetitive studies are involved, controlled tests can be made by reconstituting the Input Data and observing the effect. It has been customary to base the technical planning, design and operation of commercial thermal energy systems on unit time-intervals of one hour over an annual extended time-interval.

If only *typical input data* is used to represent sub-periods of the extended time-interval, computations from such data must be appropriately amplified. For example, a procedure using hourly data for a typical single day of each month in the year requires multiplication of its accumulation parameters, by a 'days per month' factor. The use of typical input data must be shown to be valid for a particular objective or the precision of the synthesis result must be qualified.

8.0 INTERNAL INFORMATION

Information about energy conversion and exchange processes and their engineering elements must be compiled in advance as a catalog of knowledge. This is permanent *internal information*, from which all synthesis procedures can draw at will.

The essential requirement is that all such information must be compiled on the unified base in terms of TT,Q and the other functional parameters of the synthesis simulation. (Section 2.10,p16).

8.1. Thermal Processes.

The catalog begins with a list of all the different thermal processes we want to consider – classified by their (purposeful) function and working substance. Some examples are:

FUNCTION	WORKING SUBSTANCE
Conversion	
combustion	various gases
compression	various refrigerants
expansion	steam
Exchange	
evaporation	water to steam
condensation	various refrigerants
heat transfer	air

Scientific information about each process or 'family' of similar processes can be organised in the terms of TT,Q and physical constraints. Some examples are shown in Table B1, p82. Note that the constraints shown in Table B1 are only those which arise from the earth's gravity and atmosphere – because the constraints resulting from the engineering elements have not yet been added to the processes.

Many thermal processes occur in mixtures of fluids, the individual components of which have different properties; air and water is an important example. We shall view a process in a mixture as two or more separate coincident processes for each fluid, each process conforming to its own constraints. The formation of clouds as air is lifted, for example, is a combination of an air expansion process and a water condensation process; the two processes have coincident temperatures at saturation and a total energy-rate which is the net sum of that derived from each process.

If the knowledge about thermal processes has been scientifically established, their PATH parameters (p17) may be defined by analytical equations. Analytical information is not essential for synthesis, however, and empirical information can be used, either in equations or numerical arrays.

8.2. Engineering Elements.

For practical use in synthesis, the above information about thermal processes must be accompanied by information about the engineering elements which contain them. This brings material and SIZE constraints to both the TT fields and their (functional) energy-rates. Each process PATH equation is changed. Additional Q terms occur, such as 'heat loss' to surroundings and *transport energy* required to transfer fluids from one process to another e.g. pumping from a condenser to a boiler.

Though still classified by the (purposeful) function of its process and the working substance, each different physical form of an element will now have its own identity and characteristic constraints. Each form of an element should therefore strictly be cataloged separately. But two factors can reduce this need:

- Where the elements are of similar construction, and the differences in values of constraints arise from specific changes in *details* of construction, the elements may be cataloged as a similar 'family'. Air heating coils with different details of their extended surface is an example. Such a 'family' catalog may also include the effect of changes in the working substance e.g. a refrigeration compressor with different (but similar) refrigerants.
- Professional selection may reduce the need to catalog many elements where their functions are known to be inferior to that of other elements in all situations e.g. a co-current shell-and-tube heat exchanger may be omitted in favour of a similar but counter-current heat exchanger.

Unless the applications of synthesis require a large amount of analytical information, it may be sufficient to simplify an element's PATH equation by using simple numerical factors. An ultimate simplification for a conversion element may, for example, be a single number for the element's 'efficiency' over the whole field of operation. But such simplification cannot be taken too far, because the synthesis procedure may then show that there are many 'equal' solutions. Synthesis expects a sufficient and realistic level of formulation to support its search for an optimum.

Many engineering elements contain a sequence of purposeful processes, the function of the whole of which can be identified in terms of the element's state-couple, SIZE and PATH parameters. Depending entirely on the intention of a synthesis procedure – whether we are designing an engine itself or whether the engine is a minor auxiliary in a much larger system – we may choose to catalog information about such elements in which various processes are combined. The procedure is quite general and can be adapted to the information which is either available or appropriate.

Heat exchangers are common elements in thermal systems and each heat exchanger combines two coincident exchange processes. The general formulation (p60) for two such processes at TTN and TT(N+1) is

QN = FUNC(TTN,PHYSN,SURR)
Q(N+1) = FUNC(TT(N+1),PHYS(N+1),SURR)

But for two coincident processes, with 'heat losses' omitted for simplicity, QN = Q(N+1) so that the above two equations may be combined as

FUNC(TTN,PHYSN,SURR) = FUNC(TT(N+1),PHYS(N+1),SURR)

This 'combined' equation expresses a complicated heat transfer relation peculiar to the details of the physical contact between the processes. This equation is often, but need not be, simplified for practical use. Part of the simplification is a classification of combinations of exchange processes we expect to use in thermal energy systems e.g. water/water heat exchangers, water/air cooling coils and steam/water condensers. Combined heat transfer coefficients (CU) are published for such engineering elements where

QN = Q(N+1)
= FUNC(TTN,TT(N+1),SIZE,PATH,SURR) and

where SIZE = Contact Area and PATH = CU.

Such heat transfer coefficients form the basis of the functional information cataloged for such elements. It is still possible to formulate CU in terms of system constraints which may cause its value to vary e.g. fluid flow-rates. For heat exchangers it is also convenient to reduce their FUNC(TTN,TT(N+1)) to FUNC(TTHX) where

THIHX = THI(N+1) - THIN
TLOHX = TLO(N+1) - TLON

Heat exchangers are also subject to approach temperature limits as shown in the general formulation. (p65).

Examples of a catalog of information about some engineering elements are shown in Table B2, (p83). Other, more detailed examples are given in Part D, (p138).

8.3. Constraints.

We have to arrange the information about each element in a way which quickly determines the effects on (purposeful) function of a choice of values of constraints during a synthesis procedure. A certain order of assembly must therefore be observed as follows:-

(1) Element constraints to the extent that they positively limit the TT field.

(2) System constraints which may be dictated by connected 'open system' elements.

(3) Declared constraints, pressure and composition.

(4) PATH, equation or empirical information.

(5) SIZE (of the element) the values of all other parameters being known.

While full knowledge of the effect of constraints on element equations forms part of our catalog of internal information, the values of the constraints do not – they are a subject of decision and evolution in the synthesis procedure itself.

8.4. Supplementary Information.

Most elements will also have other factors associated with their existence and operation which, while not part of their functional performance, must still be cataloged as internal information about that element. Only then can its contribution to all kinds of synthesis objectives be properly computed. Physical data e.g. space and weight, and economic data e.g. present costs, are examples of this. All these details must be expressed in supplementary equations or tables. Examples are given in Part D, Table D6, p160.

8.5. Objective Value Factors.

Apart from technical, physical and economic definition, the whole point of cataloging the information for each element in unified terms is easy, quick assembly into different configurations followed by ready computation of an element's objective value during a synthesis procedure.

Depending on each particular synthesis objective, a whole variety of details of an element may contribute to this computation. For most common industrial objectives, however, these details fall into three main groups dominated by the element's size, its utilisation and its age, for example:-

Size: apart from particularly constraining the element's maximum energy-rate, sets items like space, weight, installation and capital costs.

Utilisation: sets items like fuel and other consumables, operating labour, auxiliary power and their associated costs.

Age: sets items like maintenance, repair, replacement and their costs.

For any synthesis objective the information must be sufficient to compute each item's contribution to the element's objective value at any stage. In turn, it is convenient to formulate these contributions into three *objective value factors*, one for each of the above groups. During synthesis then, the objective value is readily obtained by multiplying these factors by the size, utilisation or age derived for the element at any point in the procedure. For example:

GAS FIRED AIR HEATING FURNACE
ANNUAL OPERATION ... 8760 HOURS
FURNACE VOLUME ... SIZE ... KWTH
CAPITAL COST ... CAP ... $ PER KWTH

ANNUAL CAPITAL RATE ... CPC ... PER CENT
FUEL RATE ... GAS ... CENTS PER MJ
REPAIR RATE ... RPR ... $ PER KWTH PER YEAR

VS = (CAP x CPC)/8760
VU = GAS
VA = RPR/8760

from which the objective value of the element in terms of cost per hour of operation may be readily computed from the main variables SIZE and Q during the procedure as:

V = ((VS+VA) x SIZE) + (VU X Q/100)

This kind of assembly aids the supervision and unification of the computer program.

8.6. Element Subroutines.

All internal information must be cataloged methodically so that it can be easily identified, located, read, used and corrected. We can achieve all this, and at the same time keep it immediately ready for use in synthesis, by compiling it into computer program subroutines, one subroutine for each element. All subroutines are to be compatible, in unified terms, for rapid assembly into different combinations of elements.

There will be a large number of subroutines if all the available thermal processes and their engineering elements are to be cataloged. Each must be researched, compiled, tested and corrected with professional skill before it is made available for synthesis. Each is a complete catalog of technical, physical, economic and all other supplementary information about the element, all compiled in terms of TT,Q and physical constraints. Changes in system constraints, e.g. pressures of a compressible working fluid, or element constraints, e.g. the surface extension of a heating coil, may be tabulated in a readily searched numerical array if the effects of the constraints are not otherwise expressed in characteristic equations.

Each element subroutine will have its own coded identity and a descriptive text in English. Each will use the same computer language, the same dictionary of names and symbols, the same format and the same sequence of information and computation steps. Each step will also include a descriptive text in English. The essential composition of an element subroutine is:

- Identity, and ordered parameter list.
- Dateline, being the date of last change or correction.
- Element description in English.
- Dimensions of arrays.
- Information limits, if any.
- Operating field limits in TT terms and the (mechanistic) decision to make the element 'not feasible' if those limits are exceeded.
- Imposition of system constraints, if applicable.
- Information base, its origin, in English.
- Physical data. (supplementary information).
- Cost data. (supplementary information).
- Objective Value Factors, being the formulation of all factors contributing to computation of V for a particular synthesis objective.
- Shutdown and low limit conditions, with the (mechanistic) decision to comply.

. Set declared constraints, if applicable.

. Equation, or array of information, relating all functional parameters in the form:

Q = FUNC(TT,SIZE,P1,P2,C1,C2,PATH)

. Computation of the values of the element's functional parameters and objective value for given TT,Q conditions and for the three basic situations of a synthesis procedure:

1. No system constraints and no constraint on element SIZE. (free evolution, p57). Compute value of SIZE.
2. Element not operating.
3. System constraints and element SIZE imposed by evolutionary search. (p57). Compute values of energy-rates.

8.7. Summary.

The whole collection of subroutines forms the library of knowledge (of internal information) from which thermal energy systems will be synthesised. It is to be built and maintained with great professional care and skill.

If the task of organising engineering and objective knowledge on this basis seems daunting, let us realise that once done it is done forever. Provided it is properly maintained, the whole store of existing information, and the incoming result of new research, will at once become accessible to rapid computer management, technical evaluation and system synthesis.

THERMAL PROCESSES.

CATALOG IN TT,Q TERMS - EXAMPLES.

UNIT TIME, NO LOSSES, NO ENGINEERING.

COMBUSTION.

QC = FUNC(TTC,SIZE,C,PATH)
= HEAT-RATE

THIC = FLAME TEMPERATURE
TLOC = AMBIENT AIR TEMPERATURE
SIZE = FUEL MASS-RATE
C = AIR/FUEL COMPOSITION
PATH = CHEMICAL EQUATIONS OF COMBUSTION

EXPANSION.

SUPERHEATED STEAM.

QR = FUNC(TTC,SIZE,P1,P2,C1,C2,PATH)
= ENERGY-RATE OF EXHAUST STEAM

SIZE = STEAM MASS-RATE
P1 = INITIAL STEAM PRESSURE
P2 = FINAL STEAM PRESSURE
C1,C2 = INITIAL AND FINAL STEAM COMPOSITION
PATH = THERMODYNAMIC EQUATION OF STATE (OF STEAM)

FIELD LIMITS:
TLOC > SATURATION TEMPERATURE AT P2

FLOW ENERGY AND WORK:
PV = FUNC(T,SIZE,P,C) AT THIC,P1,C1 AND TLOC,P2,C2
W = FUNC(TTC,SIZE,P1,P2,C1,C2,PATH)

FUNC = FUNCTION DERIVED FROM STEAM CHART

CONDENSATION.

SATURATED REFRIGERANT.

QN = FUNC(TTN,SIZE,PN,C1,C2)
= HEAT-RATE

SIZE = CONDENSATE MASS-RATE
PN = CONDENSING PRESSURE
C1,C2 = REFRIGERANT COMPOSITION, VAPOUR AND LIQUID

FIELD LIMITS:
THIN = SATURATION TEMPERATURE AT PN
TLON = THIN

FUNC = FUNCTION DERIVED FROM REFRIGERANT TABLE

TABLE B1

ENGINEERING ELEMENTS.

CATALOG IN TT,Q TERMS - EXAMPLES.

FURNACE, OIL-FIRED, ON/OFF BURNER.

QC = FUNC(TTC,SIZE,C,PATH)
= COMBUSTION HEAT-RATE

THIC = FLAME TEMPERATURE
TLOC = AMBIENT AIR TEMPERATURE
SIZE = BURNER FUEL-RATE
C = SPECIFIC HEATING VALUE OF FUEL
PATH = COMBUSTION EFFICIENCY

FIELD LIMITS:
QC ≤ QCMAX (LIMITED BY FURNACE VOLUME)

STEAM ENGINE CYLINDER, SPEED GOVERNED, BACK PRESSURE.

W = FUNC(TTC,SIZE,P1,P2,C1,C2,PATH)
= INDICATED WORK-RATE

THIC = INLET STEAM TEMPERATURE
TLOC = EXHAUST STEAM TEMPERATURE
P1,P2 = INLET AND EXHAUST STEAM PRESSURES
C1,C2 = INLET AND EXHAUST STEAM CONDITION (DRYNESS)
SIZE = CYLINDER VOLUME (AREA AND STROKE)
PATH = FUNCTION OF THE INDICATOR DIAGRAM

FIELD LIMITS:
P1 ≤ P1MAX (LIMITED BY CYLINDER CONSTRUCTION)

ENERGY-RATE OF EXHAUST STEAM:
QR = FUNC(TLOC,SIZE,P2,C2)

REFRIG. CONDENSER, SAT., SHELL & TUBE, COOLING WATER.

QN = FUNC(TTN,TT(N-1),SIZE,PN,C1,C2,PATH,SURR)
= HEAT-RATE TO COOLING WATER

TTN REFRIGERANT
TT(N-1) COOLING WATER
SIZE = CONDENSER SURFACE AREA
PN = CONDENSING PRESSURE
C1,C2 = REFRIGERANT CONDITION, VAPOUR AND LIQUID
PATH = CONDENSING/HEAT TRANSFER COEFFICIENT
SURR = AMBIENT TEMPERATURE (DETERMINES HEAT LOSS)

FIELD LIMITS:
THIN = SATURATION TEMPERATURE AT PN
TLON = THIN
THIN ≥ THI(N-1) + TAPP
TAPP = MINIMUM APPROACH TEMPERATURE

TABLE B2

9.0 UNIT-TIME PROCEDURE

System synthesis can proceed once its objective is formulated and the external and internal information is assembled. The procedure is conducted by an *executive (computer) program* which, although always similar in logic, requires special preparation for each system according to the energy sources and configurations available to it. For the time being we will exclude discussion of the evolutionary search of a time-varying system. We will confine the procedure to a steady system of constant source and demand which in any event occurs for all systems within each unit time-interval.

9.1. Configuration Assembly.

Common engineering perception can link available energy sources to the required demand in a variety of ways, each with a necessary minimum number of conversion or transfer processes. Strictly, all sources and all feasible configurations can be examined but professionally acceptable rules of experience can reduce this for expediency. Some source-configurations may be rejected outright as non-objective but all others are to be presented to the synthesis procedure, each as a separate, numbered configuration in its own executive program step. For example:

```
SOURCE/CONFIG NUMBER ... J = 1
GAS-FIRED FURNACE AT TTC              (GASHT)
GAS/WATER HEAT EXCHANGE TT3/TT2       (HXGW)
WATER/AIR HEAT EXCHANGE TT2/TT1       (HXWA)
HOT AIR DEMAND AT TTD
```

This specifies the configuration in Fig.B1,p87, taking gas as the energy source, heating water for energy transport and finally heating air at the point of demand. Note that the whole track sequence is defined from one TT point to the next.

As all element subroutines are compiled on a common TT,Q base, their assembly into various configurations is only a matter of establishing and linking their

- feasible fields on the TT diagram,
- track continuity relations in Q terms, and
- system constraints where applicable.

Ultimately the computer can be expected to support this task, particularly when multiple tracks are being considered. At present, however, it is a manual task which is greatly supported by visual representation on the TT diagram and the unified formulation of element subroutines. (Fig.B1).

9.2. Field Search.

For each configuration, the feasible TT field of each element is divided into an incremental temperature grid. Starting from the demand point TTD, which is given and fixed, the field search then connects all grid points in each element field in sequence to examine each feasible system track between source and demand. Objective values are computed for each element at each grid point and added to make up the track values for all combinations. The lowest (or highest) track value identifies the physical detail and the operating conditions of the most objective system obtainable from the configuration. The field search embodies the whole pattern of decisions needed to identify the configuration's most objective operation as rapidly as possible.

The essential steps of the field search procedure are shown in Fig.B2,p88 for the configuration of Fig.B1,p87. In practice, the developing track value (VJ) is progressively tested against the developing bounds of BEST VJ, to abort the search procedure as soon as its result is inferior. Tests and indicators are also included for special conditions like non-feasibility, system shutdown and equal solutions.

9.3. Solution and Specification.

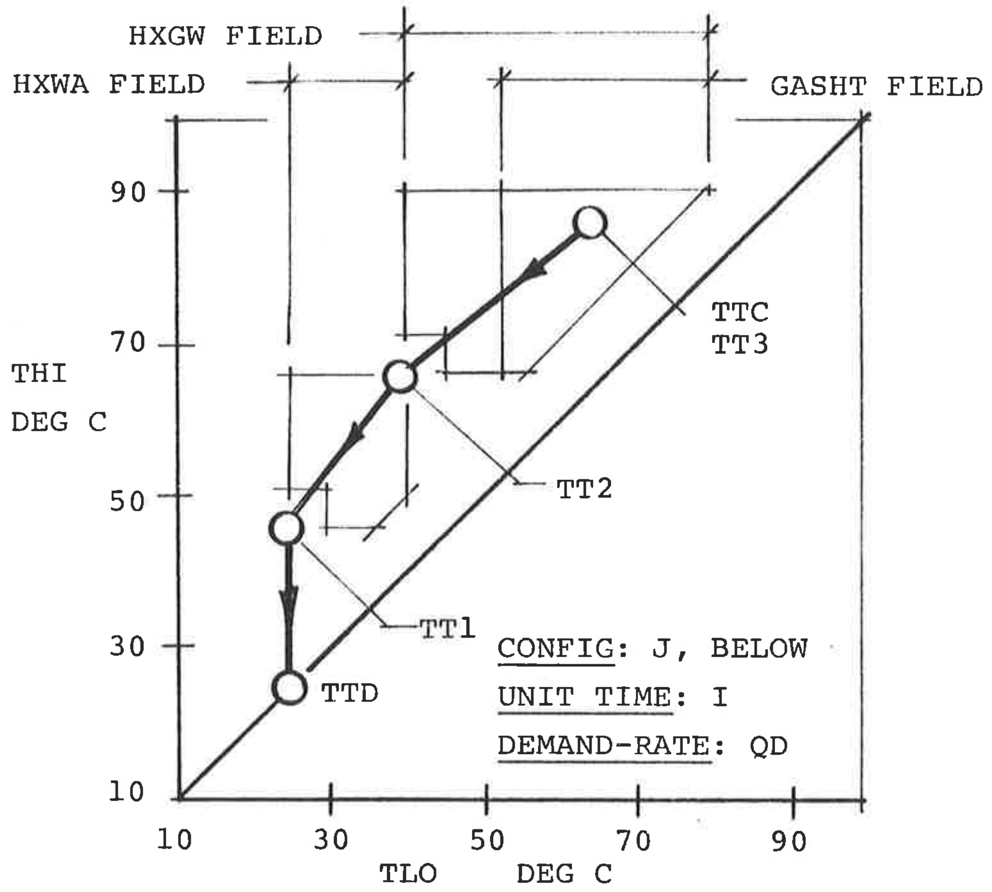
The executive program conducts a field search like this for each configuration. The program continually compares the result of each of them to select one configuration and its most objective track as the unit-time synthesis solution. The whole procedure is a logical sequence of informed (mechanistic and tactical) decisions to synthesise the most objective system by rapid, progressive elimination of inferior systems.

On completion, every detail of information associated with the TT,Q track and configuration of the solution, including all the information in its elements' subroutines, is available as an executive specification, e.g.

- Energy Source, identity, consumption, cost.
- Engineering elements, identity, interconnection, operating temperatures and energy-rates, sizes and other physical characteristics, fixed costs.
- Working substances, pressures, fluid flow-rates and control parameters generally.
- Operating times, operating costs.

This is a specification of the one combination of all these variables which meets the system demand most objectively. It is the essence of an engineering specification for subsequent detail design, construction and operation.

ORGANISATION OF FIELD SEARCH



SOURCE/CONFIGURATION

GAS HEAT/WATER/AIR/HEATING DEMAND

FIELD	TRACK	RATE	CONSTRAINTS
DEMAND	TTD GIVEN TDEL GIVEN	QD GIVEN	
DELIVERY	THI1=TTD+TDEL TLO1=TTD	Q1=QD	
HXWA THI2MAX=90 THI2MIN=THI1+TAPP TLO2MIN=TLO1+TAPP THI2 ≥ TLO2+TDIF	FIELD LIMITS	Q2=Q1	
HXGW THI3MAX=90 THI3MIN=THI2+TAPP TLO3MIN=TLO2+TAPP THI3 ≥ TLO3+TDIF	THI3=THIC TLO3=TLOC	Q3=Q2	FM3=FM2
GASHT THICMAX=90 TLOCMIN=52 THIC ≥ TLOC+TDIF	FIELD LIMITS	QC= FUNC(TTC,PHYSC,SURR) FOR REQUIRED Q3	

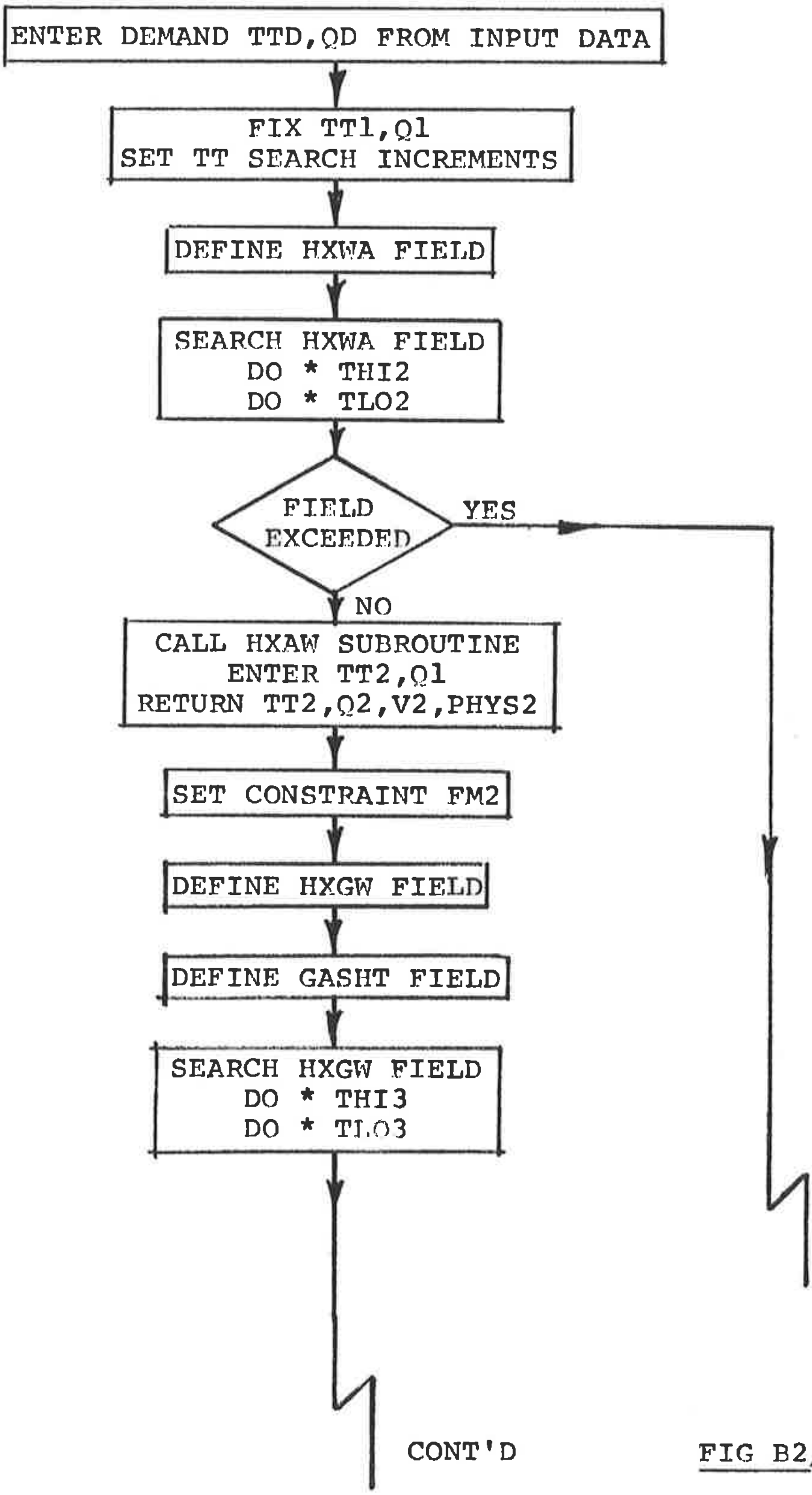
SEARCH INCREMENT: TTINCR = 5 DEG C

LOSSES EXCLUDED. FM = FLOWRATE.

FIG B1

FIELD SEARCH

REFER FIG B1



CONT'D

FIG B2/1

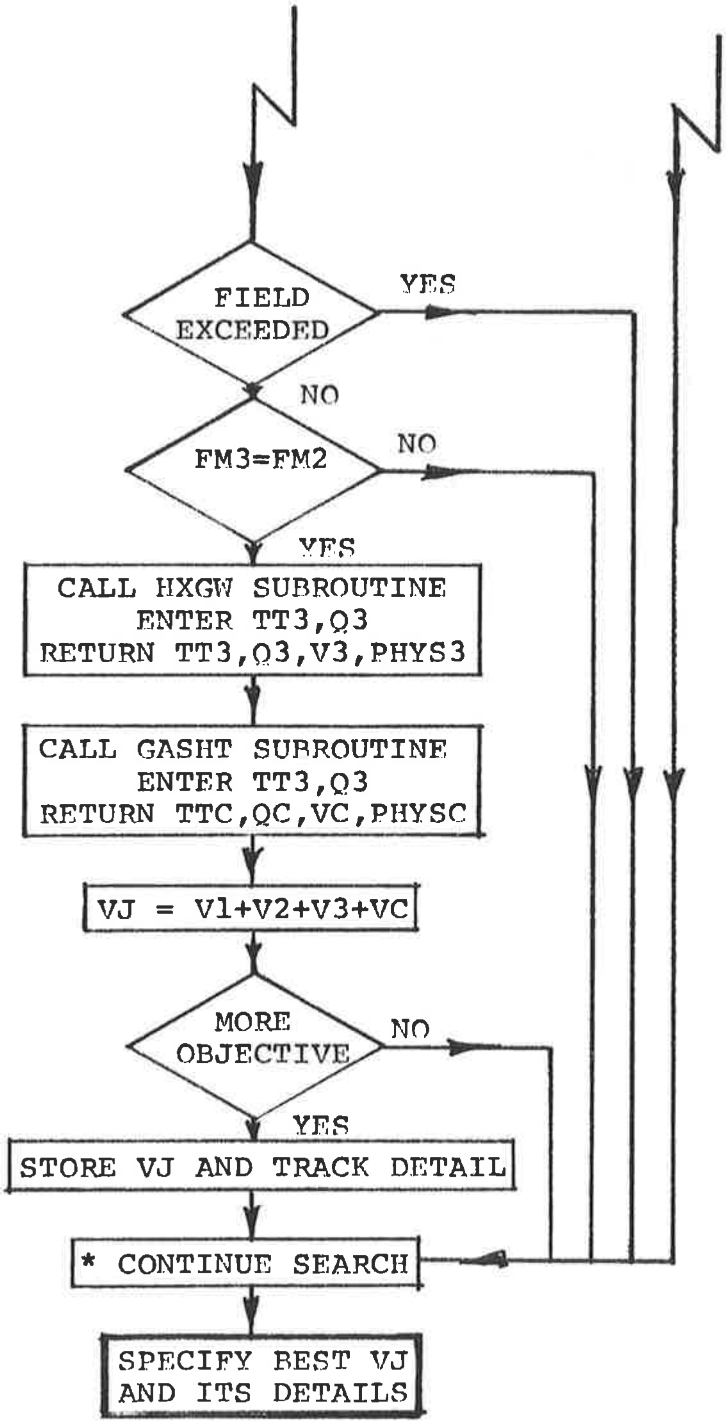

FIELD EXCEEDED
YES
NO
FM3=FM2
NO
YES
CALL HXGW SUBROUTINE
ENTER TT3,Q3
RETURN TT3,Q3,V3,PHYS3
CALL GASHT SUBROUTINE
ENTER TT3,Q3
RETURN TTC,QC,VC,PHYSC
VJ = V1+V2+V3+VC
MORE OBJECTIVE
NO
YES
STORE VJ AND TRACK DETAIL
* CONTINUE SEARCH
SPECIFY BEST VJ
AND ITS DETAILS

FIG B2/2

10.0 EXTENDED-TIME PROCEDURE

When the system demand-rate varies with time, the field search is still conducted for each configuration in each unit time-interval but the objective results are accumulated until the whole extended time-interval is examined.

The series of field searches is initially conducted as a *free evolution* which allows independent element and system constraints to adjust freely to their most objective value from one unit time-interval to the next, e.g. element sizes and control conditions. Although such a 'free' system can be approached in practice by only a few limited adaptive measures, the free evolution nevertheless establishes a datum condition for each configuration. Seeking, as it does, the most objective element sizes and operating conditions throughout the period, the free evolution will indicate datum values for element sizes and controls from which a subsequent evolutionary search of these constraints should start.

The evolutionary search then begins by imposing these datum size and control values in each configuration and executes the series of field searches again through the extended time-interval. In the same way that one set of element sizes and controls accompanies one particular system track in free evolution, just one track will match source to demand when particular values of these constraints are imposed. The field searches are, in fact, greatly curtailed during this imposed evolution because they are aborted as soon as a track is found to be unmatched. Generally there will be just one solution for a matched track of each configuration in each unit time-interval and, again, the objective results for each are accumulated for the whole extended time-interval.

The evolutionary search continues by incrementally changing the configuration constraints in a logical pattern about their datum values, then executing another imposed evolution through the whole extended time-interval. This continues until the most objective accumulated result is obtained for every configuration. The executive program continually maintains an objective comparison of these results. Upon completion of the search, the most objective source/configuration, its TT,Q operating track for each unit time, its physical engineering constraints and its objective values are specified as the synthesis solution.

10.1. Synthesis Classification.

When demand-rates vary through the extended time-interval, the synthesis solution may conceivably select from the available energy sources and configurations in three basically different ways, Fig.B3,p97:

A. Either/Or. One single energy source and configuration operating throughout the whole period.

B. Alternate. One or more energy sources and their configurations, changing from one to the other from time to time for functional or objective reasons.

C. Combined. One or more energy sources operating together through a combined configuration throughout the period.

At the time of configuration assembly, common engineering perception will often indicate which class of synthesis solution to pursue for a particular objective. If necessary, all configurations of all classes can be examined.

The executive program sequence is different for each class, as follows:

A. Comparison and selection of configurations awaits the accumulation of objective results for the whole extended time-interval.

B. Comparison and selection of separate configurations which are permitted to operate alternately is made at the end of each unit, or other defined time-interval. If a Class A configuration is also feasible, it may be examined concurrently.

C. Objective results are accumulated to the end of the extended time-interval for the common part of the configuration between the demand point and point of combination. Comparison and selection of the separate source/configurations above the point of combination is made at the end of each unit time-interval – the selected result is then added to the former accumulation.

10.2. Free Evolution.

The whole purpose of the initial free evolution is the examination of behaviour of constraints for each configuration as TT,Q conditions change through the extended time-interval and then to set datum values for their subsequent evolutionary search.

The essential computing steps of the free evolution are shown in Fig.B4,p98. In practice, a special condition has to be recognised for Classes B and C in which a particular configuration is excluded by another through the whole period, thus evolving zero datum element sizes. It has to be given at least a 'second chance' after setting its competitors' imposed sizes to their own datum and re-trying the free evolution for the excluded configuration. It may then correctly appear as the most objective configuration at some times and thereby correctly derive datum sizes for its elements.

10.3. Datum Setting.

Datum values for element sizes, controls and other engineering constraints can be derived directly during the free evolution on an objective or functional basis according to any strategy we like to set in the executive program. Datum setting of element sizes at a maximum value corresponding to maximum demand is a simple example.

The closer the datum is set to the values later found in the synthesis solution, the shorter will be the evolutionary search. This provides an incentive to program the datum-setting strategies with as much rational thought, experience and care as the case allows. Such discretionary control is to be used only with great professional skill, however, as it must not restrict the effectiveness of the evolutionary search – only improve its efficiency. If in any doubt, though, it is necessary to study the whole behaviour of the value of all constraints as they change through the free evolution before setting datum values.

There is no practical need to search constraints that are seen to have little effect on system operation or objective. On the other hand, physical element sizes are by far the most significant constraints in systems of widely varying energy sources or demand profile; so the value of SIZE will usually require to be searched. Computer methods can be expected to be developed for examining the free evolution, for setting datum values and for planning the evolutionary search.

The design of the evolutionary search pattern itself has to be co-ordinated with the datum setting strategy. Recall, however, that no evolutionary search and no datum setting is required for steady systems which will be entirely resolved by the free evolution itself.

10.4. Imposed Evolution.

Physical sizes, controls and other constraints are imposed on each element of each configuration during the evolutionary search, initially at their datum values. Element subroutines compute the energy-rates and objective value corresponding to the imposed size and constraints at each TT condition of field search. The computed energy-rates are tested at once for a match to the required energy-rate at the TT point, within the tolerance of the TT field search increment. Matched tracks are admitted and their objective solutions accumulated or compared, Classes A or B and C respectively. Unmatched tracks are rejected. Failure to obtain a match or the occurrence of a multi-match within any configuration in any unit time-interval is immediately indicated and stops the procedure until the condition is resolved.

Depending on the range of variation of system energy-rates in relation to imposed element sizes through the extended time-interval, a match may not be obtained within a configuration without some adaptive measures. Three of those particularly available in practice are:

. Multi-unit elements, some units being shut-down at times of reduced energy-rate;

. Deliberate physical control of system constraints, particularly the flow-rates, temperatures or pressures of fluids which interconnect adjoining elements;

. Intermittent operation of the energy source or conversion element where this can be tolerated at the point of demand.

The need for some or all of these adaptive measures will be indicated by the behaviour of the values of constraints through the free evolution. Such measures can be readily detailed into each configuration's executive program step if required.

The essential computing steps for each configuration in the imposed evolution, without energy storage, are shown in Fig.B5,p99.

10.5. Energy Storage.

Storage is defined (p59) as the arithmetical accumulation of energy during times of excess at a point on a system track from which it is utilised later during times of deficiency at that point. One physical analogy is an expanding and contracting volume of hot water but it may take any equivalent form in practice - thermal, mechanical or chemical.

Engineering perception will identify physical opportunities for storage and include them in each appropriate configuration assembly, specifying the TT track point of storage and corresponding working substance.

As demand-rates vary through the extended time-interval, the extent of system storage utilisation becomes a function of the operations on the supply side of the store-point, more particularly a function of the element sizes which are imposed above that point during the evolutionary search. As element sizes are reduced, for example, maximum supply energy-rates will be decreased and the system has to utilise stored energy at times of high demand. Over the whole storage period, however, the supply-side elements must at least be able to make-up at times of low demand the total energy drawn from store, otherwise the configuration at the imposed conditions is not feasible. This is *active storage*, an additional element essential to configuration feasibility, derived from the evolutionary search strictly on a *functional* basis.

A different condition of system energy storage may occur when a configuration includes a storage element merely to accumulate surplus energy derived from a particular source, later to release it to the demand, but which is not essential to system operation if an alternative energy source is available, e.g. Class B or C. This is *passive storage*, also to be derived from the evolutionary search but strictly on an *objective*, not functional, basis.

Computing procedures are different for active and passive storage:

- Active storage requires Input Data entry in reverse time sequence – working backwards through the extended time-interval. It also requires verification that the nett delivery to store is at least equal to the nett draw from store over the whole period, or some other defined store period. It also requires re-iteration through the period, (to make the storage computation continuous) if the period ends with nett storage unsatisfied. All this is needed to 'tie-up' the function of active storage before it, or its accompanying configuration can be examined objectively.
- Passive storage requires Input Data entry in forward time sequence. Verification of the equation of delivery and draw is not required as a draw occurs only when storage is in fact available. Similarly, re-iteration through the

extended time-interval is not required, merely the indication of any store excess at the end of the period and a small objective adjustment made if required.

- Both procedures are necessary if a single (Class B or C) configuration contains a single storage element to support one source actively and another passively. The passive procedure is executed first and then the active procedure, both for the same set of constraints.

These storage strategies are detailed into the executive program in each of the configuration steps to which storage is admitted and in the accumulation step exercised at the end of the extended time-interval. The capacity or size of storage evolved, its objective value and its corresponding contribution to the accumulated objective result of each configuration is specified at the end of each imposed evolution. An example of passive storage is inclined in the demonstration to follow in Part D.

10.6. Evolutionary Search.

The imposed evolution is executed again and again with incrementally changed, imposed physical constraints until the most objective set of values is found for each configuration.

Imposed constraints, particularly element sizes, are changed from their datum by a designed evolutionary search pattern. An elementary pattern shown in Fig.B6,p100, is an initial 'straddle' test of two constraints for improved objectivity, incrementally above and below their datum values, followed by movement of the straddle in the direction of improvement. The increments can be set at will, e.g. 10% of datum sizes or 5 DEG C of control temperature. Element sizes should strictly be changed one at a time, but initially this can be done in two principal groups on a simple functional basis:

- Between demand and storage, element sizes remain at their datum, e.g. to meet maximum demand.
- Between storage and source, element sizes change together in similar proportion.

The evolutionary search pattern for Class A must change the constraints of each configuration simultaneously for each imposed evolution. The pattern for Class B and C (competitive) cases must change constraints in one configuration at a time. Configurations are not re-searched when the pattern straddles imposed conditions which have already been searched.

The results of changes imposed during the evolutionary search may be recorded in terms of objective sensitivity. Such results may then be used either to change the increments or to re-direct the search pattern according to a logical strategy founded in sound knowledge of the thermal processes involved. In any case of doubt, however, the evolutionary search should be exhaustive over a wide range. The subject is further discussed in Part C, p110.

The essential computing steps of the evolutionary search are shown in Fig.B7,p101.

10.7. Synthesis Solution.

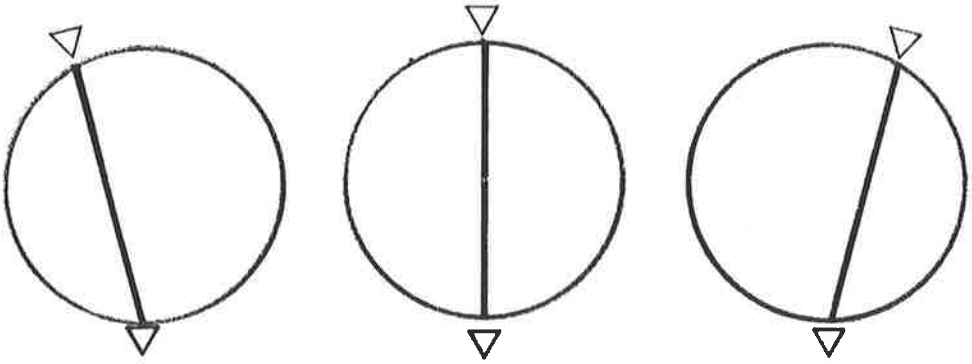
When the evolutionary search is satisfied for all configurations the most objective accumulated result identifies one energy source/configuration, its storage, physical engineering, controls, operations and objective values as the synthesis solution. If necessary the evolutionary search pattern can be executed again about this solution in smaller increments to refine its detail. Within the limits of the available information and the precision of its processing, we will regard this most objective solution as the *optimal system* for the given demand and objective.

In practice, rather than store in the computer the large amount of detail as the solution evolves, it is convenient to execute the program again, with the solution constraints imposed, particularly to obtain the executive engineering specification.

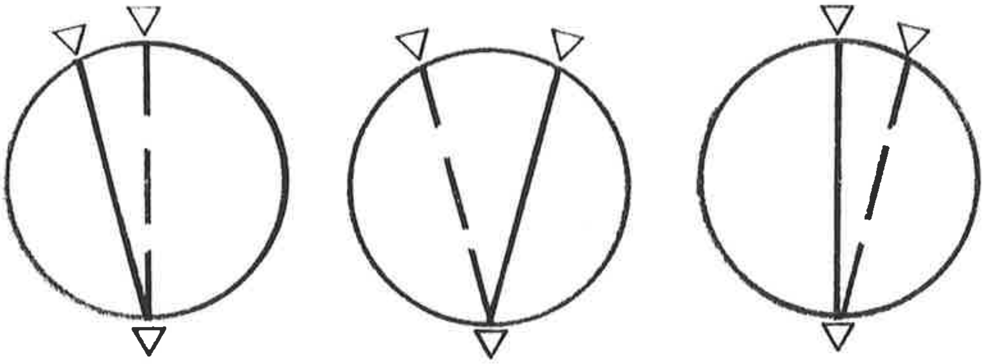
10.8. Summary.

The computing procedures just outlined are a practical expression of the discipline and formulation of thermal energy system synthesis developed in Part A. They are universally applicable and made possible only by organisation of our knowledge and decision-making on a unified basis. It is a premise of the present work (p1) that the effort of such organisation is not only justified but necessary for professional engineering practice in a world of rapidly changing energy values.

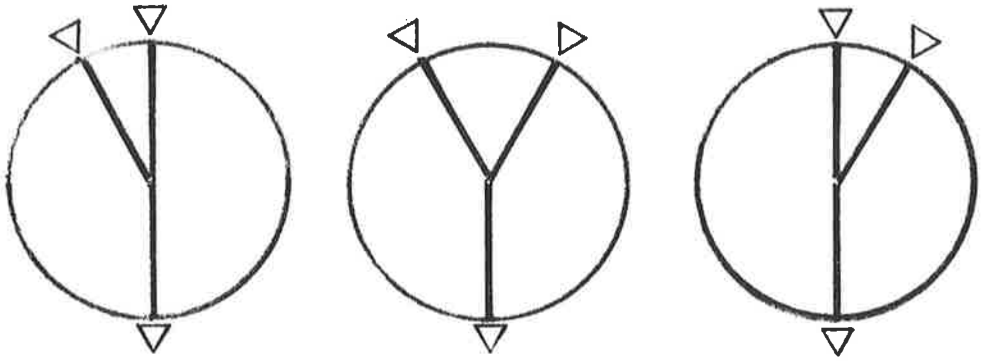
THREE CLASSES OF SYNTHESIS



CLASS A: EITHER SOURCE/CONFIG 1 OR 2 OR 3



CLASS B: ALTERNATELY 1 & 2 (OR 1 & 3) (OR 2 & 3)



CLASS C: COMBINED 1 & 2 (OR 1 & 3) (OR 2 & 3)

FIG B3

FREE EVOLUTION

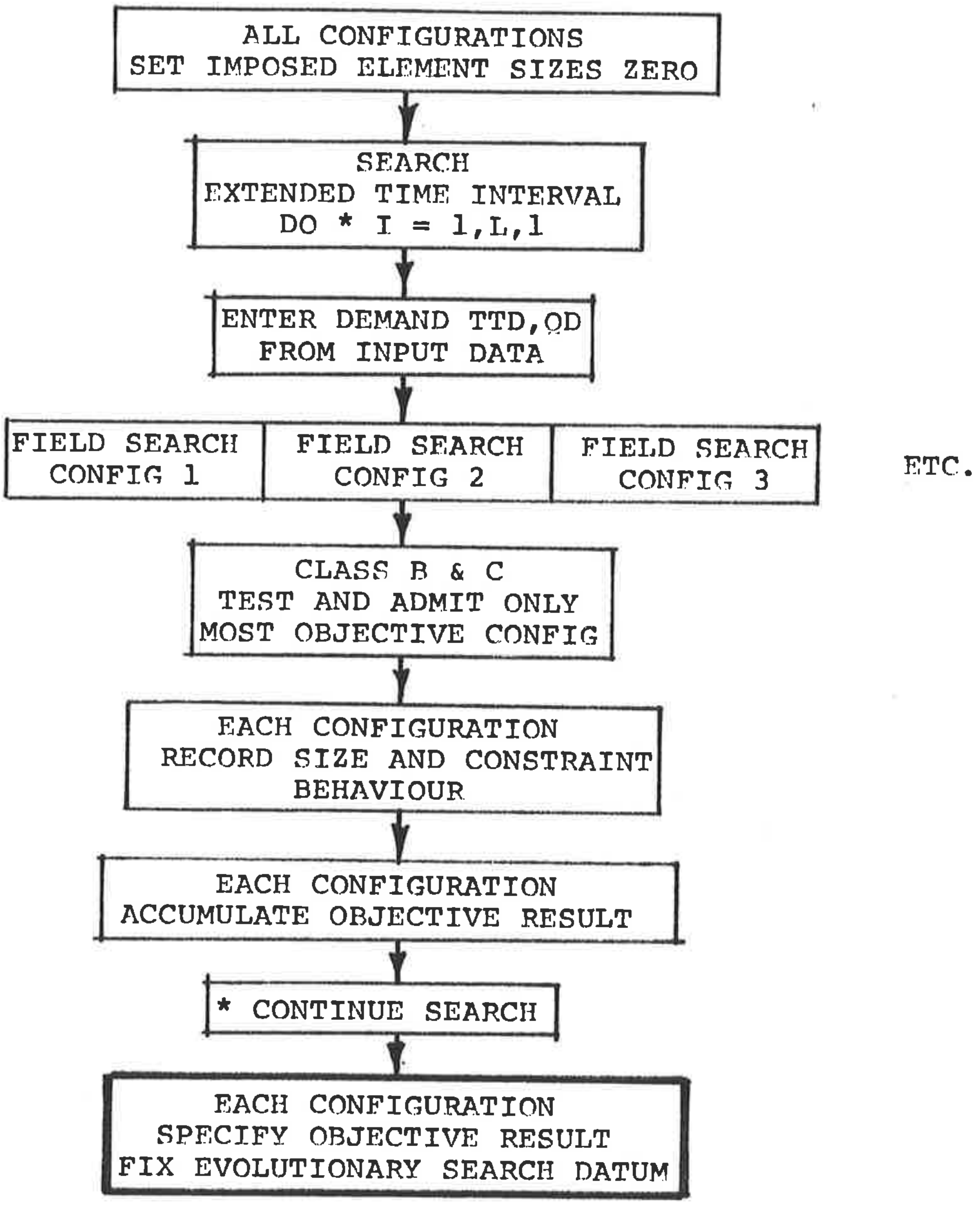
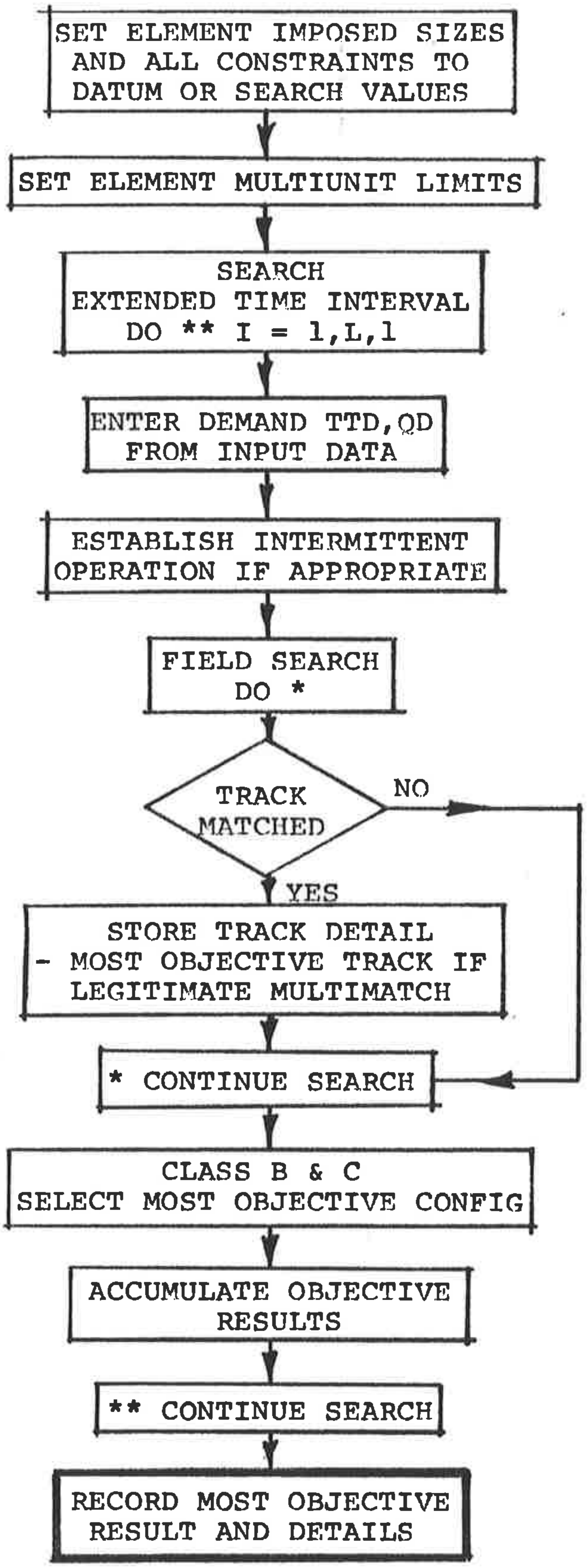


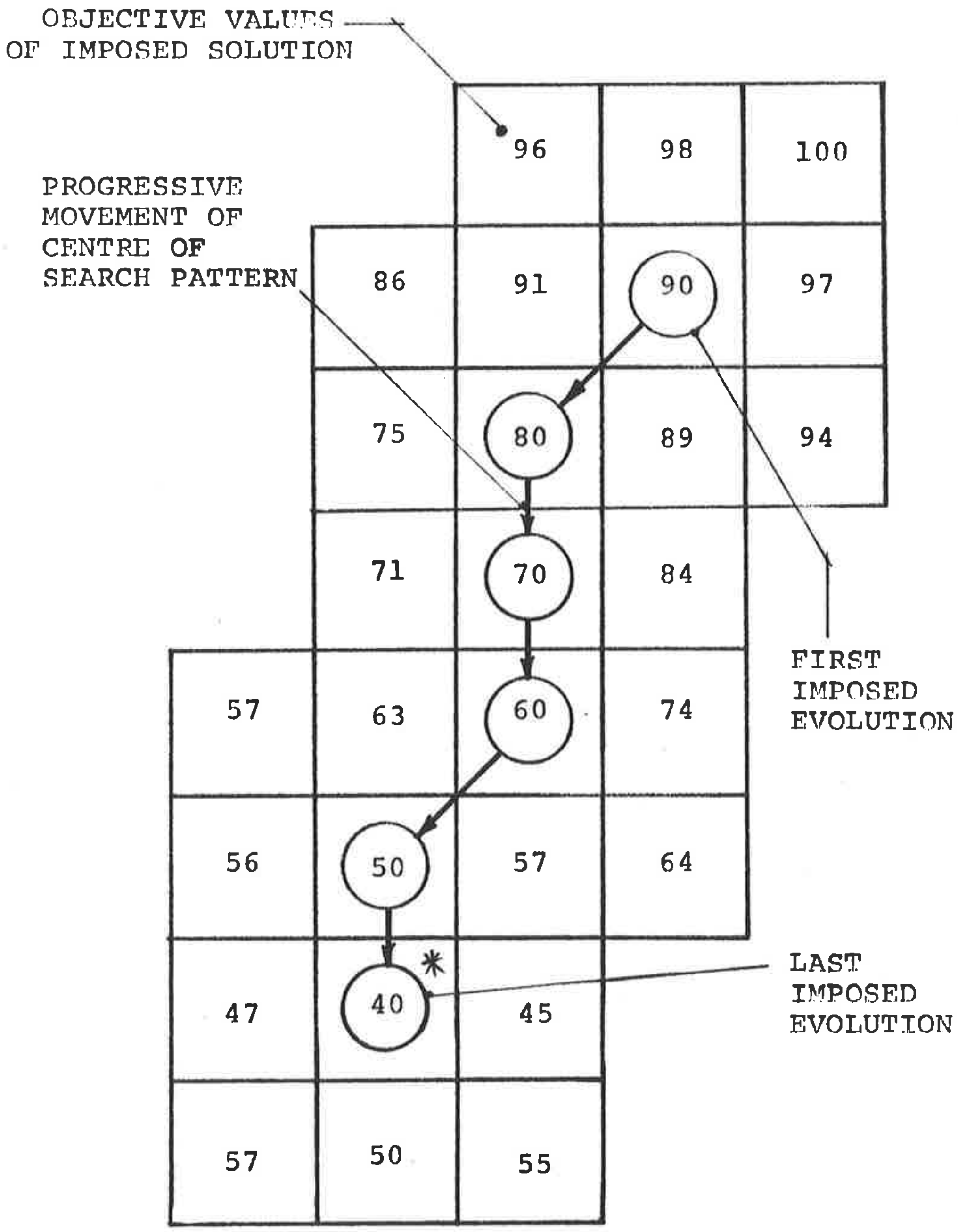
FIG B4



EACH CONFIGURATION.
NO ENERGY STORAGE.

FIG B5

EVOLUTIONARY SEARCH PATTERN



TWO CONSTRAINTS SEARCHED SIMULTANEOUSLY.
* IDENTIFIES OPTIMAL SET OF CONSTRAINTS.

FIG B6

EVOLUTIONARY SEARCH

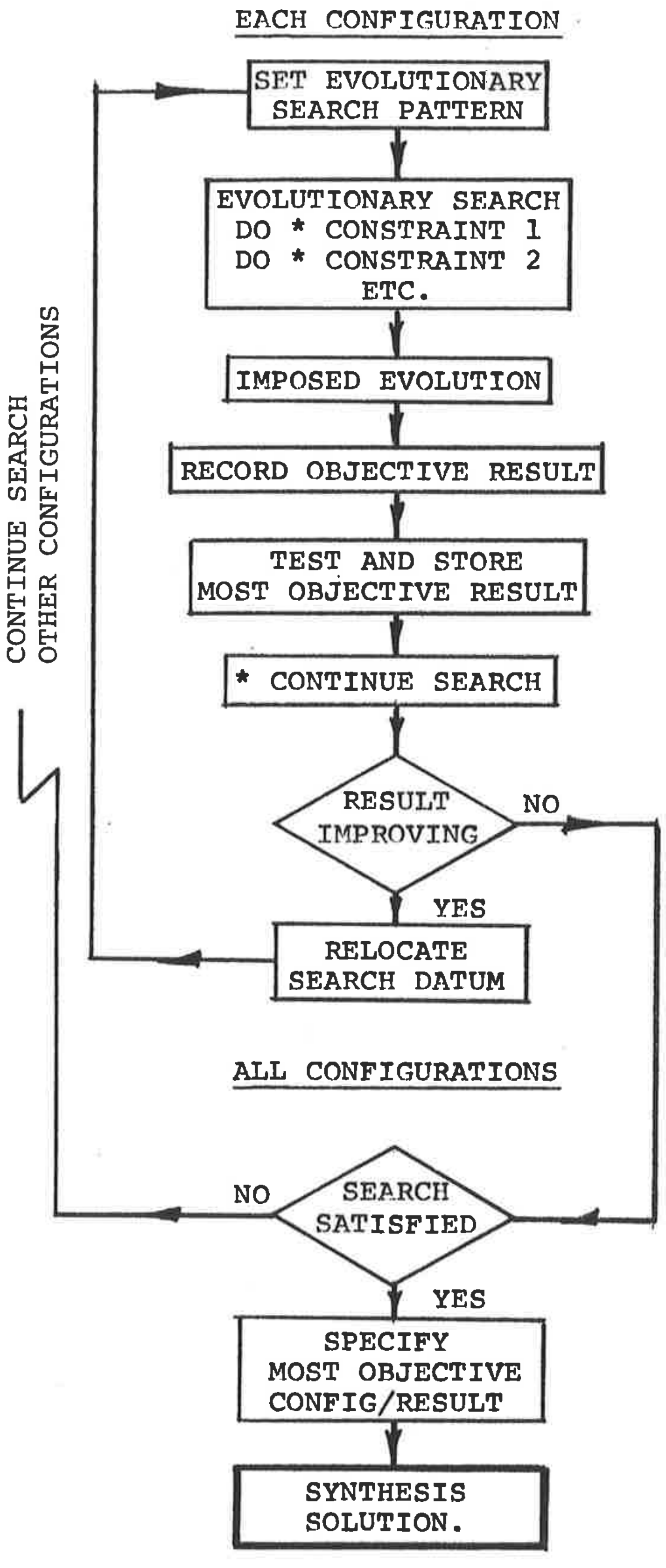


FIG B7

11.0 COMPUTING DEVELOPMENT

Computing began as soon as the synthesis discipline was formulated in November 1975. (Ref.8). All the essential procedures were programmed and a good system synthesis achieved by July 1976. (Ref.9). Experience with subsequent test and demonstration programs brought refinement.

The work is written in FORTRAN, all composed and executed from an interactive visual terminal operating with INTERCOM on the University of Adelaide CDC6400 computer.

11.1. Development Program.

Development was based on a synthesis which involved:

- An annual space/air heating demand.
- Two available energy sources.
- One configuration a combustion process followed by four heat exchange processes and no storage. The other configuration a radiant heating source and two heat exchange processes, with active storage.
- An objective to build and operate the energy system which minimises total annual owning and operating cost.

This needs all the procedures just outlined for information handling and synthesis so it became a complete prototype of an executive computer program.

The development program is supported by three special subroutines for common use by all configurations during their field search:

TACDEC, for (tactical) decision on the most objective track, subject to prior minimisation of active storage if it applies, and for recording the selected track details.

STOADJ, for adjustment of energy storage levels and temperatures, for applying thermal losses and applying capacity limits.

MATCH, for testing an element's match to the system energy-rate during imposed evolutions.

The development program also includes a number of special algorithms and sub-procedures, most of which are required in all executive programs:

- Input Data testing.
- Amplification of typical Input Data.
- Free and Imposed Evolution control.
- Evolutionary Search Pattern control.

- Imposed constraint setting and testing.
- Demand Limits and Store Limits.
- Field Search control.
- Zero Demand condition.
- Intermittent operation.
- Multi-unit element operation.
- System Control: Flow-rates, temperatures, pressures.
- Energy Source 'shut' condition.
- Mismatch and Multimatch identification.
- Operating Hours computation.
- Cost computation.
- Storage evolution control.
- Configuration non-feasibility.
- Constraint Datum setting.
- Free Evolution re-try.
- Evolutionary Search stops.

Apart from essential output-file headings, informative messages and a specification of the synthesis solution, the development program is equipped to trace the detail procedure by writing many output options, exercised in four levels. This is needed for examining, testing and proving each stage of an executive program during assembly, for example:

- Values of selected parameters presented to TACDEC in each configuration during the field search.
- Specification of the most objective track of each configuration in each unit time-interval, including specification of tracks of equal objective value or multimatch.
- Values of constraints and accumulating parameters at the end of each unit time-interval through the whole extended time-interval.
- Summary of the most objective result, overall and for each configuration, evolved to the end of each free or imposed evolution.

Re-imposition of a synthesis solution to obtain its full executive engineering specification for the whole extended time-interval is also exercised as an output option.

The development program required subroutines for two conversion elements and two heat exchange elements. With these it totalled 20000 words of FORTRAN, requiring 15 CP seconds to compile on the CDC6400 before execution.

11.2. Execution-Time Control.

Program execution-time increases with smaller unit time-intervals or smaller search increments or both. On the other hand, smaller unit time-intervals and search increments increase the precision of the synthesis solution. The additional cost and delay for precision therefore has to be justified and it is very often limited by the precision of the Input Data itself.

Unit-time setting has already been discussed, (p74). The use of a short assembly of typical input data keeps execution time short during initial program assembly and testing. It then only requires attachment of a full Input Data assembly (and change of data amplifying factors) to execute a final synthesis result. A typical 24 hour day for example may be sufficient to work-up a program which will later compute a result of 8760 hours in a full year.

The free evolution accounts for almost the whole execution-time for a steady system and 50%-70% of the time for a time-varying system. Although the free evolution's unconstrained field searches are shortened by developing bounds, they are potentially exhaustive. The number of TT tracks to be examined increases rapidly with the number of elements in a configuration and improved program strategies are certainly required with more than four elements. The time spent on field searches can, however, always be controlled by the choice of TT increments. Initially they can be coarse (about one-fifth of each element's field range) and later be refined for greater precision as the synthesis solution is evolved and the field is reduced.

Time spent on field searches is not great during imposed evolutions as unmatched tracks are quickly rejected. Execution-time is then most sensitive to the setting of the increments of change in constraints during the evolutionary search. Small increments require a larger number of imposed evolutions to traverse from their original datum to the most objective solution. Again, these search steps can be set coarse initially (about one-fifth of datum values) and then refined for precision.

Execution-time is readily controlled by a detail in the executive program which facilitates changes in the setting of time-intervals and search increments. The development program was entirely built with short, amplified data and coarse (one-fifth) search increments requiring about 15 CP seconds execution-time. Changing to data and search precision sufficient for commercial space heating (hourly values for a typical day in each month), execution-time increased to about 400 CP seconds.

11.3. Program Testing.

The sheer task of creating the prototype executive program generated an acute sensitivity to procedural irregularity. It appears to expose itself at once in erratic behaviour of the value of the objective function, either that found within a configuration itself during its field searches or within accumulated values during the evolutionary search. This at once suggests a valuable practical test on a program - plotting or tabulating objective values and its main contributing factors for examination over a wide range of program execution followed by diagnosis of any irregularity. Conversely, it cannot be said that a regular and/or explicable plot of these values guarantees that a program procedure is correct - it may, for example, breach the discipline of mechanical engineering. Program composition and application is, however, a professional task and the plot of values is equally subject to examination from an engineering point of view. A regular plot of output values depends on a degree of regularity in component functions but this is to be expected in thermal energy systems whose processes are founded in physical nature even though highly constrained by their engineering.

All executive programs and their subroutines also require elementary tests of their decision structure and their numerical computation. A set of Test Input Data serves well for this, with values specially chosen to give easy manual checking of solutions. It is good practice, however, to use a special test program to verify the behaviour of each element subroutine independently before attaching it to an executive program.

Apart from the regularity tests applied to a synthesis program, the question arises of independent mathematical proof of the computing procedure. Contrary to early expectation (Ref.7) such a proof has not been developed. Mathematical testing would presumably mean the compilation of a large number of simultaneous equations, one for each system element and its interconnecting fluid flow at certain imposed conditions, finding the solution for each unit-time and integrating over the extended time-interval. It is demonstrated in Part D that the mechanism of synthesis provides a similar solution to that obtained from such a mathematical method for a particular synthesis program. But a general method of mathematical testing would appear to be as big a task as synthesis itself for even simple systems and simple objectives. Such a method is therefore considered redundant in the face of a direct *engineering* examination of the behaviour of the synthesis program. Independent proof of the numerical optimisation of a synthesis program would presumably require the substitution of artificial for real subroutines to generate special proof patterns of objective values. Unless the proof is of similar nature to the behaviour of the real system, however, it would appear to be of little value. It seems better to expose the synthesis program itself to direct *numerical* examination in familiar engineering values. The above examinations are demonstrated in Part D.

11.4. Present Limitations.

Computing times are too high at present to synthesise with reasonable precision a solution from more than two or three configurations, each of three or four elements, with TT increments finer than one-tenth of their field and with more than three hundred representative unit time-intervals. CDC6400 execution times of up to 800 CP seconds are then experienced. Improved search efficiency, with mathematical programming of the field search and with highly directed methods of evolutionary search, are required either for useful precision from cases with a high count of combinations or high precision from a lower count. Methods of optimisation of engineering constraints within element subroutines are also required.

No matter how well self-protected from computing error, the present individual composition of executive programs for each case of synthesis bring the risk of error of omission. Failure to include or search appropriate configurations or element subroutines and failure to include some components contributing to their objective values are examples of this. It can be said that this is the concern and work of the professional engineer but much of it could be taken up by a supervisory computing program. It will become essential for handling large subroutine libraries, assembling multiple configurations and handling large synthesis tasks.

THERMAL ENERGY SYSTEM SYNTHESIS

PART C

COMMENTARY - THE RELATION OF THE WORK TO THAT OF OTHERS.

12.0. COMMENTARY.

Up to this point, the exposition of the discipline and procedure for synthesis has been based largely on step by step creative argument, reinforced by the practical demands of formulating and building the computer program. That it works in practice for a particular application is demonstrated in Part D. With this much in hand, however, it is now time to comment critically on the relation of this method of synthesis to similar work by others.

12.1. Published Work.

The present work began with the notion that a disciplined method of synthesis for an optimal system should exist; because methods for workable systems already exist and they should therefore only require proper organisation and direction to bring them to optimality. Other published work, now to be discussed, gave insight to many aspects of the task. But such work stopped well short of a method suitable for the design of a time-varying system in all its engineering detail. Nevertheless, the insights were valuable and all contributed to a more demanding specification of what is required and a resolve to find a solution. (Ref.7).

Reference has already been made (p18) to Stoecker (Ref.3). He emphasises the difference between "workable" and "optimum" systems. (Ref.3,p11). For optimisation he explains the need first to be able to

. numerically or mathematically model the performance of each engineering component (Ref.3,p45),

. simulate the performance of the whole system in terms of a solution of such model equations (Ref.3,p78),

. formulate an "objective function" in terms of all the independent variables (Ref.3,p106) and

. write all the system constraints (Ref.3,p106).

Stoecker shows how to organise the engineering knowledge of various systems on such a basis. But he recognises that it is often difficult and "one of the gaps in knowledge . . . to develop the constraint equations in a systematic manner". (Ref.3,p112). By contrast with that approach, the present method of synthesis distinctly separates its simulation of the energy functions (in TT,Q terms alone) from simulation of the effects of the constraints (the engineering elements and working substances), all organised, however, upon the same TT,Q basis. The constraints acting on each element or its interconnection with other elements then remain "process oriented" while still maintaining compatibility for assembly into any kind of feasible system configuration. It appears to provide a systematic method required to close the "gap" while maintaining both an operational and engineering insight, rather than an analytical insight, into the thermal system being optimised. The textbook goes on to describe many classical methods of optimisation, each applicable to different classes of problem and therefore relatively local in scope and usefulness. It also restricts its consideration to steady systems. (Ref.3,p80).

Beveridge & Schechter (Ref.4) formulate the problem of optimisation generally as a definition of an objective function in terms of all its variables, a statement of all the restrictions to which it is subjected and choice of a technique to find its optimal value. While this exposition in general terms is excellent for understanding the nature of the task, such generality in application can well obscure the nature of the problem itself. The Authors clearly recognise, however, that each application must be properly organised in its own way. For thermal system synthesis then, we have the choice of organising the knowledge of mechanical engineering on an exclusive basis for each problem or on a fundamental basis for general application to all problems. We may see the latter as an important professional discipline.

Beveridge & Schechter (Ref.4) draw a clear distinction between analytical and numerical methods of optimisation – the former being suitable only for objective functions which can be expressed mathematically in terms of all the available technical and economic information, are continuous and readily differentiated. While this may be possible for many local aspects of thermal energy systems or even for whole systems to which gross simplifying assumptions are applied, it is not possible for the general practical situation where information may be available only in experimental or empirical form and where discrete functions of engineering and economic practice commonly occur. On the contrary, the text (Ref.4,Ch.6) indicates that numerical methods could well be applied to the optimisation of whole thermal energy systems provided:

- All technical information is organised in a way which correctly represents system operation and its engineering, i.e. that the design 'model' is complete and correct.

- The organisation will admit all objective information without restriction and then permit ready computation of a single value of the objective function for given values of all the system variables.
- The organisation particularly lends itself to logical numerical search procedures.
- The nature of the objective function is unimodal, i.e. that it has only one peak value in the region of search for an optimum.

Organisation of thermal energy systems in terms of the synthesis simulation proved to be the key to this. The unified information methods and the objectively directed search and decision procedures followed from it.

The validity of logical search procedures depends on an understanding of the nature of the objective function. Composed as it usually is for thermal systems from competing factors, it can be expected to be unimodal. Indeed, "the property of unimodality seems to be the rule rather than the exception". (Ref.4,p146). It is not a problem with the steady system, unit-time procedure as the field search is potentially exhaustive. If unimodality is not assured during the evolutionary search, however, the search must be deliberately executed over a wide range of the objective function to establish the fact. If there is any indication of more than one peak, each region must be separately searched.

Hendry, Rudd and Seader (Ref.5) surveyed and summarised the state of the art of chemical process synthesis in 1973. More than fifty contributions are reviewed, and techniques and applications are classified. The Authors identify a particular class of chemical systems which they name "Energy Transfer Networks" – similar to our thermal energy systems. (Ref.5,p8). Bearing in mind our preconceived notion for a solution, one of the reviewed papers of the above class stood alone to indicate an approach to the present work. King, Gantz and Barnés (Ref.6) proposed a method of evolutionary system synthesis, "applied . . . as a succession of alterations involving identification of that portion of the most recent process which could be changed to greatest advantage, followed by generation of the appropriate change for that portion of the process and by an analysis of the new process". (Ref.5,p6). In our present terms it could be said that they started with a workable configuration of workable element sizes and conducted a heuristically directed computer search not only to adjust the element sizes but also to change the configuration itself. Though these practices may conceivably be applied to all systems, the actual procedures will be exclusive to each particular system being studied. Perhaps this is usual for chemical systems anyway and perhaps it accounts for the Author's conclusion that the value of their work lies more in "helping the design engineer to structure his thinking better, rather than in the prospect of an ultimate totally computerised synthesiser". (Ref.6,p282). By contrast, our present method of synthesis confines the action of heuristics, as a matter of expediency only, to initial configuration assembly (p.84) and to the strategies for datum setting in the free evolution, (p.92). In that way the heuristics remain identifiable and clear of the procedure itself, leaving the computation and search procedures of synthesis to be solely directed by objectivity and remain common to all system configurations. Nevertheless the importance of the paper to the present work is its suggestion of successive change to an initial system, the essence of our own evolutionary search. Note, however, that we use the concept only for synthesis of time-varying systems.

All the foregoing publications played a part in organising the present work out of a prior basic knowledge of thermal engineering and a conviction that a fundamentally disciplined approach to thermal system synthesis should exist.

Another published paper has particularly contributed to the subject of system synthesis since the formulation of the present work:

Duff (Ref.19) outlines a method of selecting optimal components for solar thermal systems. It is a synthesis procedure which assembles a system from sub-system stages. The sub-system assembly can then be subjected to the principles of dynamic programming, with each stage being reduced to a set of optimum sub-systems by, say, direct search.

It is implied that such a method will be able to achieve everything we expect from our own method of synthesis. But it depends on a "concise parametric representation that conveys all the performance information about the sub-systems thus far put together". (Ref.19,p246). The formulation of such a "parametric representation" is not supported by any general organisation or discipline - so the details of the method can be expected to be different for each kind of system. The method (Ref.19) still apears to be one of 'mathematical simulation and direct optimisation' which is made more tractable by dynamic programming. Nevertheless the paper highlights the power of dynamic programming to reduce what would otherwise be a difficult combinatorial problem – a subject which will find application to our field search procedure when the number of elements is high. The paper is confined to steady systems but says that the method will be extended to "explicitly account for . . . dynamic considerations". (Ref.19,p253).

There is considerable activity in modelling and optimisation of energy 'resource systems' (of supply and demand) on a world or regional scale. (Ref.20). Its techniques are stimulating and promise considerable help with the future extension of synthesis. But such work at present appears to have little direct application to system synthesis at engineering level.

12.2. Search for Originality.

In an attempt to establish the originality of the present work, a computer search was made on 21st December, 1977, from the National Library of Australia of the following data files:

SSIE. Smithsonian Science Information Exchange, records since July 1974.

ENERGYLINE. Energy information from "Environment Abstracts", 1971 to 1975, and from "Energy Information Abstracts", since January 1976.

NTIS. United States "Government Reports, Announcements and Index", since 1964.

COMPENDEX. Engineering and technological literature from "Engineering Index", since 1970.

SCISEARCH. Science and technological literature from "Science Citation Index", since 1974.

A total of 465 abstracts were retrieved from the above data files within various search profiles made up from the following key-words:

Thermal
Thermodynamic
Thermonuclear

Energy
Power
Steam
Heating
Cooling
Refrigeration
Nuclear
Solar

System
Process
Operation

Synthesis
Optimum
Optimal
Optimisation

The applications to which these abstracts refer can be classified as follows:

Central Power Generation	101
Chemical Processes	96
Nuclear Reactors	80
Automatic Control	46
Electrical Systems	37
Solar Energy	29
Buildings' Energy Systems	21
Energy Conservation	10
Miscellaneous	45

Virtually all abstracts report on work which is concerned with a particular subject or a particular application, rather than a general application to all thermal energy systems. Of the few which indicate a degree of generality, none proposes a method similar to the present synthesis procedure although papers by Duff (e.g. Ref.19, discussed on p111) are prominent. Nevertheless many of the abstracts indicate opportunities for comparison of the present method of synthesis with other methods of thermal system optimisation. Such a comparative study has not been undertaken - a particular method of demonstration has been chosen instead. (Part D).

Within the context of the present work a search of the following specific key-words gave "zero" return from all data files:

Functional Simulation.
State-couple.
Energy Function.
Temperature Co-ordinates and Energy-rate.

Also, no publication of the present method of synthesis has been found by search of information in the Library of the University of Adelaide and in the State Library of South Australia.

As far as can be reasonably determined, therefore, the present work is original except where reference is made.

THERMAL ENERGY SYSTEM SYNTHESIS

PART D

DEMONSTRATION - SYNTHESIS OF AN
OPTIMAL SOLAR HEATING SYSTEM.

13.0 SYNTHESIS EXAMINATION.

At any level of its development, and for any particular application, we must be prepared to demonstrate and not merely assert that our procedure for system synthesis conforms to the disciplines of mechanical engineering and numerical optimisation within understandable and acceptable limits. This embraces the program tests already outlined (p105) but extends much further, to examine the whole professional competence of the procedure for a given case.

For the present work, the synthesis procedure had to be demonstrated at least at the level of a complete prototype within the computing limitations already outlined (p106). It had to include system and space identification in TT,Q terms, unified engineering information, numerical objective setting and ultimate synthesis of both steady and time-varying systems, with or without energy storage. The prototype application had to be a practical, useful thermal energy system incorporating all these features, not significantly affected by the computing limitations and to which the results of the synthesis procedure could be readily referred. A solar, storage and auxiliary heating system fulfils these requirements and is used to demonstrate the work here.

The solar heating system is programmed as a single configuration, combined energy source, class C case for synthesis, with passive storage. The mechanical engineering discipline of synthesis is demonstrated by relating the behaviour of the system predicted by the program to that:

1. Simulated by an entirely independent computer program of foreign origin,
2. Measured on an experimental plant.

The program's optimising discipline is demonstrated by reconciling changes in the synthesis solution with controlled changes in both the objective function and the physical constraints for such a system.

But first a note about solar heating as an energy source.

14.0 SOLAR ENERGY FOR HEATING

The earth receives a large quantity of solar energy each day but this energy has relatively poor quality. For any particular geographical location it is diffuse and intermittent. Nevertheless it can be harnessed as heat and blended with many industrial and commercial energy systems in the interests of fuel conservation.

14.1. Solar Radiation.

One side of the earth continually receives solar radiation at a beam intensity of about 1.3 KW per SQ.M, distributed in a spectrum from ultra-violet to infra-red, peaked at visible wavelengths. (Ref.10,p27). The atmosphere absorbs and scatters a large proportion, reducing the maximum intensity of direct radiation reaching the earth's surface to about 0.9 KW per SQ.M, half visible and half infra-red. (Ref.10,p38). The scattered proportion is not all lost, however, and can add a diffuse radiation component of up to about 0.11 KW per SQ.M at the surface. (Ref.10,p38). The total radiation which could be received on a horizontal surface in a clear atmosphere with the sun's beam normal to the surface is then a little more than 1 KW per SQ.M - geometrically less on surfaces of other inclination and orientation.

During the day as the sun moves through the sky, the geometric relation between the solar beam and any fixed surface continually changes. The reduction due to absorption and scattering also changes with the obliquity of the beam to the atmosphere. Nevertheless the direct, diffuse and total radiation received on a given surface in a given location with a clear sky can be predicted as a function of annual date and time of day. (Ref.11). Such 'clear sky' radiation is interrupted by cloudy weather, however, and although the consequent 'loss' of radiation over, say, a particular month cannot be predicted with certainty it can be estimated from local long-term records if they are available.

14.2. Flat Plate Solar Collectors.

Surfaces exposed to solar radiation are heated by its absorption. Temperatures rise until the incoming energy-rate equates outgoing energy-rates, the latter either as heat removal or losses. Flat plate solar collectors are good absorbing surfaces which readily transfer useful heat to a water circuit (usually) and which are otherwise built to minimise radiation, convection and conduction losses. (Ref.12,p120). They are usually installed in pipe-connected arrays on a surface of fixed inclination and orientation appropriate to their location and duty – often directed towards the highest point on the celestial equator for good all-round annual heat collection. Their characteristic performance equations have been well formulated and tested.(Ref.13). The useful heat-rate available from a collector of particular construction used in the present demonstration is, for example:

$$Q = G \times A \times (0.61 - 3.07\ (TD/G) - .0036\ (TD)^2/G)$$

where TD = ((THIC+TLOC)/2) - (TAMB-3)
Q is useful heat-rate, KWTH
THIC is water outlet temp., DEG C
TLOC is water inlet temp., DEG C
TAMB is ambient air temp., DEG C
G is total solar radiation on collector surface, KW/SQ M
A is collector area, SQ M

The important facts are that the collector heat-rate

- varies directly with solar radiation and
- varies inversely with water temperatures – losses dominating at high temperatures.

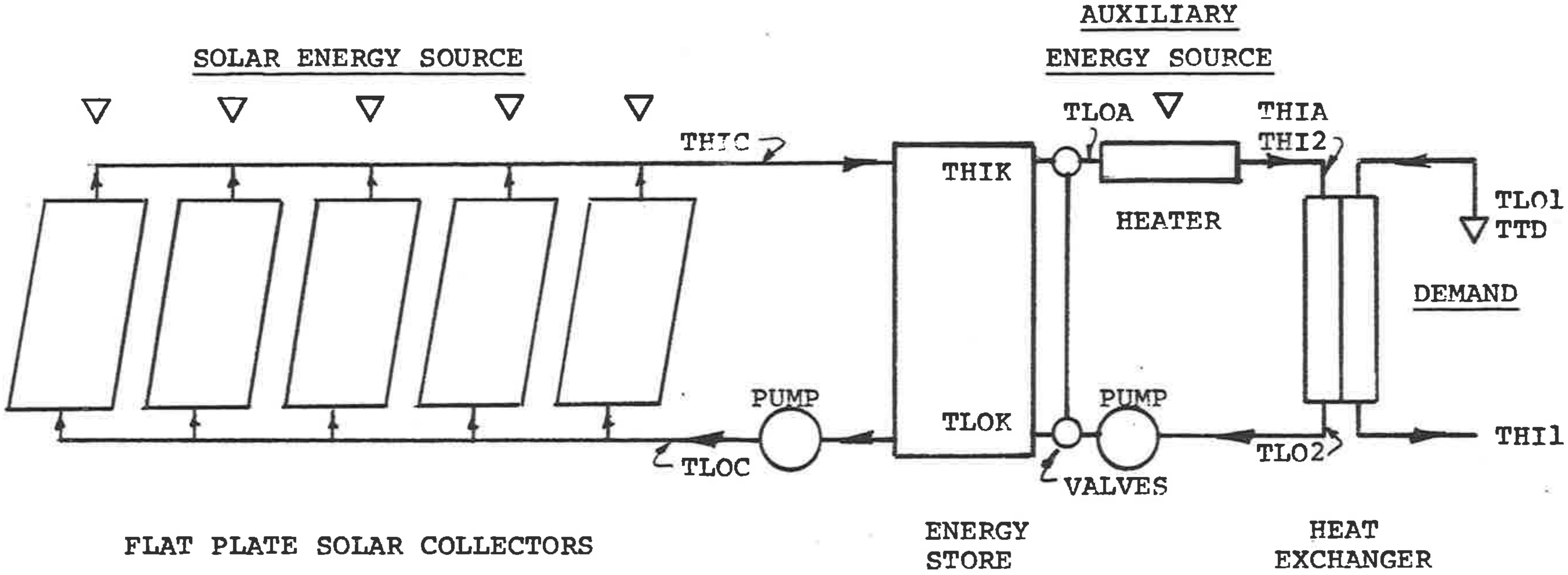
14.3. Solar Heating System.

The energy available to a system from a solar source, using flat plate collectors as a conversion element, will vary through the day according to the time and weather. When used for a definite industrial demand profile, therefore, solar heating must work in combination with another auxiliary energy source or energy storage or both. Various configurations are appropriate, depending on the relation of the energy sources to the demand, and that of Fig. D1,p119, is suited to a solar/stored/auxiliary water heating system suitable for industrial demands up to about 70 DEG C. (Ref.12,p275). It will be used for the present demonstration.

There are many combinations of variables by which a system configuration like this can meet a given heating demand profile, for example

- large collector areas at high temperatures, or small collector areas at low temperatures, each with relatively high use of auxiliary energy, or
- moderate collector areas at moderate temperatures with relatively low use of auxiliary energy, or
- excess collector areas and energy storage during mid-day periods to meet night, early morning or late afternoon demands with lower use of auxiliary energy.

Superimposing the continual daily and annual variation of solar radiation on these features, a designer has quite a problem to decide which particular combination of collector area, storage capacity and temperatures he should specify for a given case. It is a professional engineering task, to which we will apply our method of optimal system synthesis.



TT POINT TEMPERATURES REFER TO FIGS D3 & D4

SOLAR/AUXILIARY WATER HEATING CONFIGURATION

FIG D1

15.0 ENGINEERING DEMONSTRATION

Analytical and experimental research of solar heating has intensified during the last few years as the world becomes conscious of its limited fuel inventory. Improved radiation predictions, improved collection at higher temperatures and improved energy storage methods are important areas of fundamental research. At the same time, system simulation programs and tests on working systems are making significant contributions to applications research and we will use some of them here to demonstrate the engineering aspects of our synthesis procedure. On a broad front, all this activity can be expected to bring more decisive utilisation of solar heating in industry and commerce in the future.

15.1. Experimental Plant.

The Australian CSIRO Division of Mechanical Engineering is operating a 30 KWTH solar, storage and electric auxiliary heating plant at Highett, Victoria. (Ref.14). Commissioned in 1976, it is initially being used to test a mathematical simulation of its flat plate collectors over a wide range of conditions. It is fully instrumented for automatic logging of all significant radiation, temperature and flow measurements at 5 or 10 minute intervals; so a continuous record of performance for the whole system and each of its elements can be readily obtained. While its physical engineering is conveyed by the plant schematic, Fig.D2,p130, some explanation is needed of its intended method of operation.

Whenever solar radiation is sufficient to raise the collector outlet water temperature above inlet temperature, a pumped water circuit transports heat from the collectors to the store tank, at a fixed flow-rate.(1977). Once the pump is running, the collector outlet temperature therefore varies with the solar radiation and the energy collected. Collection temperatures and flow-rate are readily measured from the water circuit at the positions marked, Fig.D2,p130.

Although there will be a degree of mixing, hot water may be expected generally to accumulate in the upper part of the store tank, stratified from colder water at the bottom. Measurement of tank water temperatures at four levels gives a measure of the heat in store above the bottom temperature.

Energy is transported from store to load heat-exchanger by a second pumped water circuit, connected through the auxiliary heater, and also (1977) operating with a fixed flow-rate. Variation in system demand is met by automatic control of a modulating store bypass valve and auxiliary heater steps in sequence, for example:

- Heat-exchanger inlet temperatures less than store outlet are met with part bypass and heater shut.
- Heat-exchanger inlet temperatures equal to store outlet are met with no bypass and heater shut.
- Heat-exchanger inlet temperatures higher than store outlet are met with no bypass and heater operating.
- When there is no energy in store above the heat-exchanger outlet temperature (indicated by an equal or lower store outlet temperature) the demand is met with full bypass and heater operating.

A cooling tower and third pumped water circuit loads the heat-exchanger. The tower circuit also works at fixed conditions at present (1977) but could be programmed later to simulate a given demand profile.

The TT diagram of such a system, unconstrained by any particular element sizes or controls, initially shows the whole feasible space of system operations. (Fig.D3,p131). A synthesis program would initially admit this whole space for a given demand profile and then evolve the optimal values of constraints on an objective basis. During its evolutionary search, however, the procedure must reproduce the performance of a plant built to the constraints which are imposed. This confines the system operation to a definite TT track for a particular store condition when the solar radiation, ambient temperature and demand are given. Furthermore, if the CSIRO engineering detail is imposed, the synthesis program should reproduce the operations expected from the CSIRO plant itself. That it does so within understandable limits over a wide range of varying conditions will be a demonstration of the program's engineering discipline.

15.2. Synthesis Program.

The engineering of the CSIRO plant is reproduced in a synthesis program containing just that one configuration. The free evolution is stopped and the evolutionary search is stopped except for one execution in each unit time-interval in which the CSIRO element sizes, their characteristics and controls are all imposed as constraints.

With the entry of an intial store condition and the entry of solar radiation, ambient temperature and demand as Input Data for each unit time-interval, the program identifies the one matched TT track of system operation for each unit time; and therefore predicts the whole CSIRO plant performance over a given extended time-interval.

The program is detailed to the CSIRO configuration's TT diagram, Fig.D4,p132, expressed in a flowchart, Fig.D5,p133. Engineering information is obtained from on-site examination, physical measurement and manufacturer's ratings. It is listed in Table D1,p138, expressed in unified terms as a separate subroutine for each element. Objective information is not required for the engineering demonstration. Transport (pumping) energy may be included in both the collector and heat exchanger subroutines. Thermal losses may be included in the collector and store subroutines. TT Field search increments, and hence the program precision, is 1 DEG C.

15.3. Simulation by TRNSYS.

In 1975, the Solar Energy laboratory of the University of Wisconsin, Madison, U.S.A., published a computer program TRNSYS for simulation of the performance of a solar heating plant under transient thermal conditions. The program is now available at the University of Adelaide, Version 7.5,1976. (Ref.15). It must be stressed that TRNSYS is only a simulation program, not an optimising or synthesis program.

A TRNSYS simulation of a particular plant is obtained by ordering the engineering detail and interconnection of a number of TRNSYS program modules, one for each element in the plant configuration, then observing the computed change in plant operation with given changes in external variables. Each module is a mathematical equation describing the element's engineering performance. Program modules are connected to each other and to external conditions with a set of prevailing technical and physical variables. For given solar radiation, ambient temperature and demand, the program solves the whole set of interconnected equations simultaneously to identify the plant's operating conditions.

The TRNSYS simulation can be conducted on an ordered time-base, identifying the operating conditions in each unit-time over an extended period under changing external conditions. Time-dependent functions like energy storage are included, together with a solution of their differential equations.

The TRNSYS simulated performance of the CSIRO plant should, of course, be similar to the performance measured from the plant itself. The initial series of CSIRO tests over a long period is intended to examine and report on this.

Valid technical information contained in the TRNSYS program should equally be contained in a corresponding synthesis program. Both programs organise element information into separate subroutines and both can be conducted on a selected time-base. Apart from this, however, the two programs are quite independent in origin and detail. For the present work, no alteration has been made to the standard TRNSYS program.

15.4. Simulated Demonstration.

The CSIRO plant may be expected to show the performance predicted in Table D2,p139 and Fig.D6,p134 for a typical set of clear-sky solar radiation and ambient temperature conditions, with a 30 KWTH (108 MJ PER HR) continuous demand over a 24 hour period. Two sets of predicted figures are given, one obtained from the special synthesis program (S) and one from the TRNSYS simulation (T), both using the same collector and heat exchanger performance characteristics and both on the basis of a TRNSYS type, two-node, hot water storage tank. (Ref.15,p4.4-1).

Early in the morning, at 0700, the demand is met by auxiliary heating (QA) alone because there is initially no heat in store and radiation is too low for solar collection. As collection of solar energy (QC) increases during the day, however, it is delivered to store as hot water, top store temperatures (THIK) increase, the store supplies an increasing part of the demand and auxiliary heating is correspondingly reduced. Top store temperatures and stored heat reach a maximum for the day in mid afternoon at which time auxiliary heating is a minimum. During the remainder of the period, the store supplies a decreasing part of the demand, store top temperatures decrease and auxiliary heating again increases. At 0600, the store is virtually exhausted, with auxiliary heating again supplying nearly the whole demand. Integrated for the day, after setting transport-energy and store losses zero, collector energy (EXTQC) + auxiliary energy (EXTQA) = total demand of 2592 MJ + nett gain in stored energy.

The only significant difference in the performance predicted by the synthesis and TRNSYS programs is the small one of top store temperature (and therefore heat drawn from store) at certain times, leading to a corresponding small difference in auxiliary heating at those times. As store temperatures are rising or falling, TRNSYS predicts slightly lower or higher values respectively. This is because TRNSYS resolves the incoming and outgoing heat-rates as a simultaneous equation while the synthesis program merely adjusts the top store temperature for the incoming rate and outgoing heat-rate in sequence. The synthesis program is an approximation in this case but the effect, particularly over the whole day, is very small. The subject is discussed further in Section 15.5. below.

The important result of this demonstration is that, over a wide range of varying conditions, the ability of the synthesis program to represent the performance of the CSIRO plant in both dynamic and numerical terms is virtually as good as the independent TRNSYS program. Certainly both have been supplied with the same external and internal information but their mechanisms are quite independent and different. Synthesis conducts a search of the TT operating fields of the whole system configuration until, for the imposed constraints, a matched track of system operation is identified. TRNSYS obtains a simultaneous solution of all the given analytical equations by successive substitution and reiteration.

15.5. Hot Water Storage.

The difference between the TRNSYS and synthesis storage behaviour originates with the definition of stored energy for synthesis in Section 5.9,p59 - a concept of accumulation of hot water in a variable volume rather than the TRNSYS concept of accumulating heat in a particular volume. (Ref.15). Although the synthesis condition may be approached by a distinct, two-level tank stratification, such a condition could strictly only occur in the CSIRO tank if the upper hot and lower cold sections of water were separated by a moving or flexible diaphragm. The important fact is that in a synthesis procedure we want to evolve a particular stored energy capacity, not merely impose a particular tank capacity as an engineering constraint. The TRNSYS concept is therefore of little significance in synthesis.

For the present engineering demonstration with TRNSYS, however, we have no alternative but to adjust the synthesis program to conform as closely as possible to the TRNSYS store tank volumes and equations. This is done by accumulating hot water in the usual way but then changing to an equal heat content in the larger TRNSYS volume at a lower temperature. This adjusted store temperature is then the one which is available to meet the demand, after which the heat in store is again adjusted to the TRNSYS tank volume. This sequence is computed in each unit time-interval. As shown in Fig.D6,p134, the result conforms closely to that predicted by TRNSYS.

The predicted performance of the CSIRO plant operating with the synthesis defined hot water storage, with the same Input Data as Fig.D6,p134, but with collector outlet temperature control rather than flow-rate control, is shown in Fig.D7,p135. In this case auxiliary heating varies directly with the difference between the demand and solar collection, no residual storage occurs and the day's total auxiliary heat is similar to that of the former method of storage and control. This is a demonstration of the normal engineering content of a synthesis program for this system configuration. No general comparison between the two collector control methods is justified as the whole approach of synthesis is that there will be one correct solution for each system and each demand profile - that different system constraints or controls require a search for the set which is most objective in each case.

15.6. Measured Test.

It would have been informative to arrange a measured test on the CSIRO plant under similar conditions to those used in Section 15.4. for the relation of the synthesis and TRNSYS programs. The CSIRO test schedule has been concentrated initially (1977) on collector performance, however, and makes no attempt either to set the demand or operate the auxiliary heater or measure the performance at the heat exchanger. The only control exercised is to shut down the collector circuit at times of low or zero radiation, to start the load circuit when the top store temperature has reached a relatively high value and to stop the load circuit when that temperature has fallen close to a partly stabilised load return temperature. In this mode, the whole operation of the plant is passive, being entirely dependent on and subordinate to the collection of solar heat.

A set of test measurements on the collectors, store tank and a passive load on store are available, though, for a few weeks in July and August, 1977. One day, 6th August, is arbitrarily selected from the CSIRO records for detailed examination here. The measured performance of the plant on that day is summarised in Table D3,p140, plotted in Figs. D8 and D9,pp136-137.

Early in the morning at 0700 the heat in store is 100MJ, 2.5 DEG C above the lowest bottom store temperature. Solar radiation (G) and solar heat collection (QC) is intermittent throughout the day due to cloudy weather but the integrated, measured heat collected and delivered to store between

0940 and 1540 is 159 MJ above the measured collector inlet temperatures. Collector flow-rate is virtually constant at 890 KG PER HR although the pump is shut down at times of very low radiation – the total shut time being about 1 hour in the 8 hour radiation period. Heat is discharged from store to a passive load through the heat exchanger between 1200 and 2000, the integrated measured total for the period being 166 MJ above the measured load return temperatures. Load circuit flow-rate is virtually constant at 1660 KG PER HR. By the end of the day, at 2100, the residual heat in store, 2.4 DEG C above the initial bottom store temperature, is 96 MJ, 4 MJ lower than the heat in store at 0700.

Radiation on the collector plane, temperatures and flow-rates are electrically measured and automatically logged at 10 minute intervals. Heat-rates at those times are derived from temperature difference x flow-rate x specific heat of water. Temperatures reported here are measured inside the plantroom, adjacent to the store tank, Fig.D2,p130, so they include the effect of exterior thermal losses at the collectors. They similarly include the effect of pumping energy in the load circuit but exclude measurement of the pumping energy in the collector circuit. Thermal losses from the store tank are about 1.1 MJ per hour, derived from the fall of store temperatures overnight when the plant is shut down. During the day of the test from 0700 to 2100, tank losses of about 15 MJ are therefore almost exactly offset by collector pumping.

The important result of the day's operation is the close equation of the heat collected and nett draw from store (163 MJ) with the heat discharged to load (166 MJ).(Table D3,p140). This is only to be expected from such an uncontrolled, passive test. The balance verifies, however, that the CSIRO temperature and flow measurements are generally correct.

A TRNSYS simulation of the CSIRO plant operating in this passive mode, with the measured solar radiation and ambient temperature, predicts the performance summarised in Table D4,p141, and overplotted in Figs. D8 and D9. In this case the program simulates a 'fully-mixed' storage tank. (Ref.15,p4.4-1). Neither the collection performance nor the load performance predictions conform closely to the measured test and the differences require explanation. Note at once though, that like the measured test, the predicted day's heat collection (279 MJ) is closely balanced by the day's discharge to load plus nett gain in store (276 MJ). This at least verifies that the program simulation is representative of the plant's passive mode of operation.

The predicted day's collection of 279 MJ (Table D4,p141) is much higher than the measured collection of 159 MJ though it must be recalled that the latter is derived from measurements in the plantroom, including the effect of exterior thermal losses, while the TRNSYS program collector equation would expect measurement at the collector itself. The CSIRO log does include temperatures closer to the collectors and they indicate a day's heat collection of 230 MJ but there is some evidence that these measurements are subject to a local heating and cooling error due to their exterior location. Comparison of the predicted and measured collection graphs in Fig.D8,p136, shows the two to have similar transient characteristics, particularly at times of decreasing radiation. At times of increasing radiation, particularly in early morning, the measured collection trails behind the prediction both in time and numerical value. This indicates that the difference may well be due to ambient cooling of the whole collector structure and its contained liquid; which then has to be heated up from overnight temperatures in the early mornings and, to a lesser extent, after solar interruption during the day. This could be aggravated by poor control methods delaying the start of the collector circulating pump. The deficiency will yield to continued experimental investigation and that is the purpose of the CSIRO test program. Meanwhile, the prediction of solar heat collection by TRNSYS (or a corresponding synthesis program) must be considered too high, or at least suspect, for the design of heating systems similar to the CSIRO plant.

The (program) predicted day's load of 233 MJ (Table D4,p141) is also much higher than the measured day's load of 166 MJ but, with passive plant operation, this is a direct consequence of the higher predicted day's heat collection. Top store temperatures are then higher so, for the constant load flow-rate of 1660 KG PER HR, the heat discharged to load is correspondingly higher. It is rather the different character of the load profile (Fig D9,p137) which deserves explanation here. Store temperatures resulting from the fully-mixed tank of TRNSYS are uniform and rise or fall proportionally with the collection and load heat-rates respectively. The rapid fall with a high load and poor collection between 1200 and 1300 reflects this, as does the rise between 1500 and 1600 when the collection rate exceeds the load rate. On the other hand, the measured load profile does not show the same rate of response, partly due to less collection but also due to a considerable degree of stratification of hot water in the upper half of the tank. Stratification is indicated by a record of tank water temperatures at various levels and particularly shows in the rapid fall of load as the upper hot water is exhausted soon after 1800.

Like the earlier demonstration, predictions of the load profile by both TRNSYS and the equivalent synthesis program are virtually identical. This is not tabulated here but, instead, the load profile of the synthesis program operating with the measured, rather than its predicted, solar heat collection is shown in Table D4 and Fig.D9,p137. Approximating the fully mixed tank, the character of the load profile is then still similar to that of TRNSYS but the numerical values now closely correspond to the measured test at both the load starting condition at 1200 and for the whole day's operation. This is a practical level of correlation of the synthesis load profile with that of the measured test - further adjustment of the program for tank stratification will not be pursued in view of the synthesis definition of energy storage, (p59).

15.7. Summary.

All methods of design of thermal energy systems require engineering calculations based on technical knowledge. The synthesis procedure brings that knowledge and those calculations under an organised, unified discipline which permits numerical optimisation. Nevertheless, it remains an engineering design calculation.

TRNSYS is an independent method of engineering calculation which verifies the synthesis method of calculation for solar/auxiliary heating plant over the range of operating conditions demonstrated in Section 15.4. It is only the *method* of calculation which is verified, however, as the measured test:

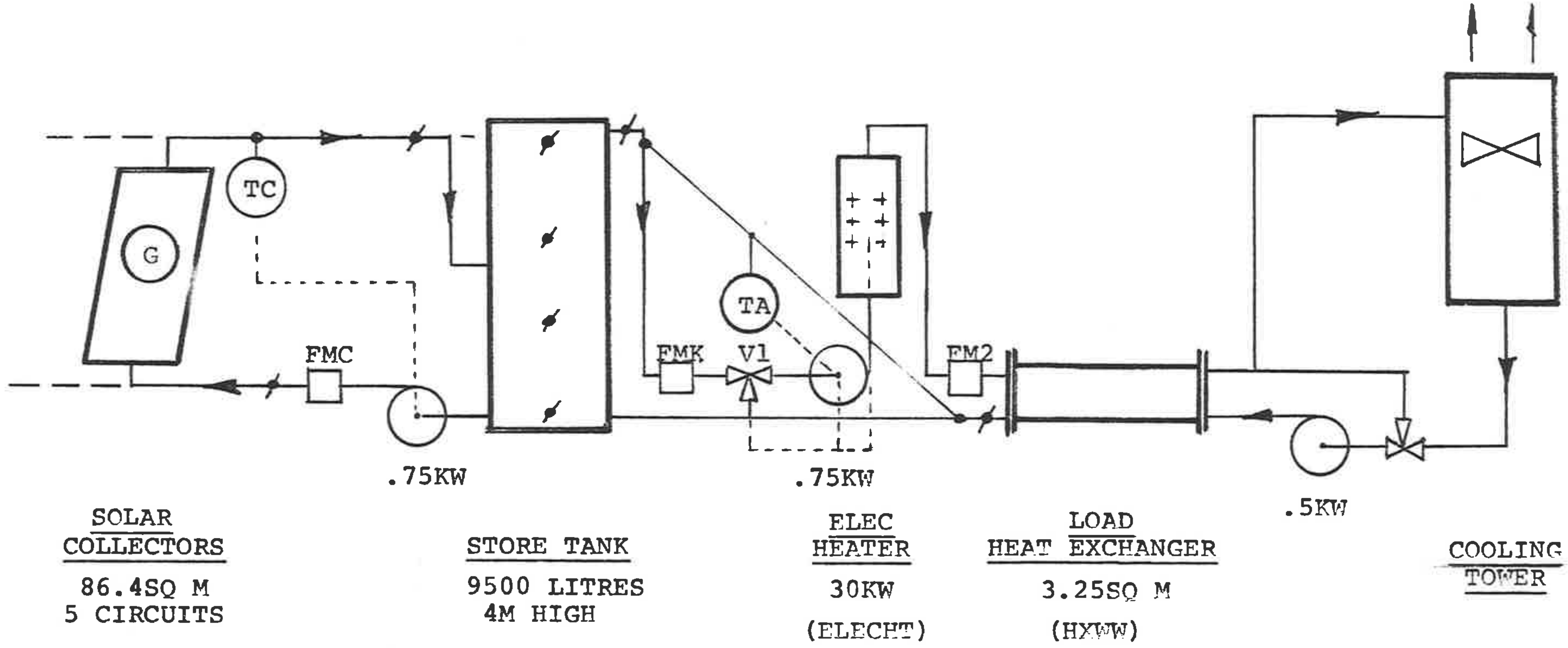
1. Shows there is a significant deficiency in the calculated quantity of heat delivered from the solar collectors;
2. Omits, for CSIRO reasons, all demand setting, auxiliary heating and measurement of the system below the store tank.

In time, the CSIRO experimental program will bring an understanding of the apparent deficiency of the TRNSYS calculation. The findings can then be readily formulated into both the TRNSYS and synthesis programs. Until then the engineering calculations embodied in both programs are partly inadequate for the design of industrial solar heating plant.

The engineering demonstration for the present work is ended by saying that the synthesis method of design calculation for steady and time-varying thermal systems is at least as good as other (1976) methods of calculation for such systems. The demonstration also emphasises that no engineering calculation should be used in practice until it is thoroughly established.

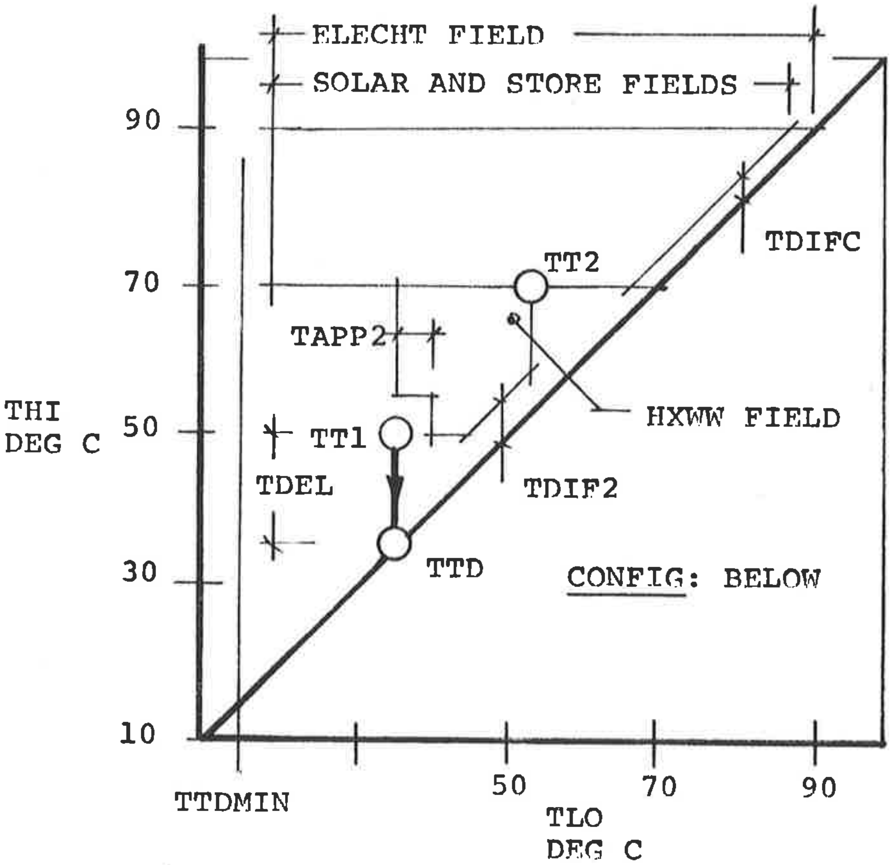
While recognising the above limitation of the synthesis program for design, we can still use the program now to demonstrate that it will identify the optimal system for a given numerical objective and given engineering information.

CSIRO - HIGHETT. 30KWTH PLANT SCHEMATIC.



T- TEMPERATURE CONTROLLER
G SOLAR RADIATION MEASUREMENT
⌀ TEMPERATURE MEASUREMENT
FM- FLOWMETER
V1 STORE BYPASS VALVE

FIG D2

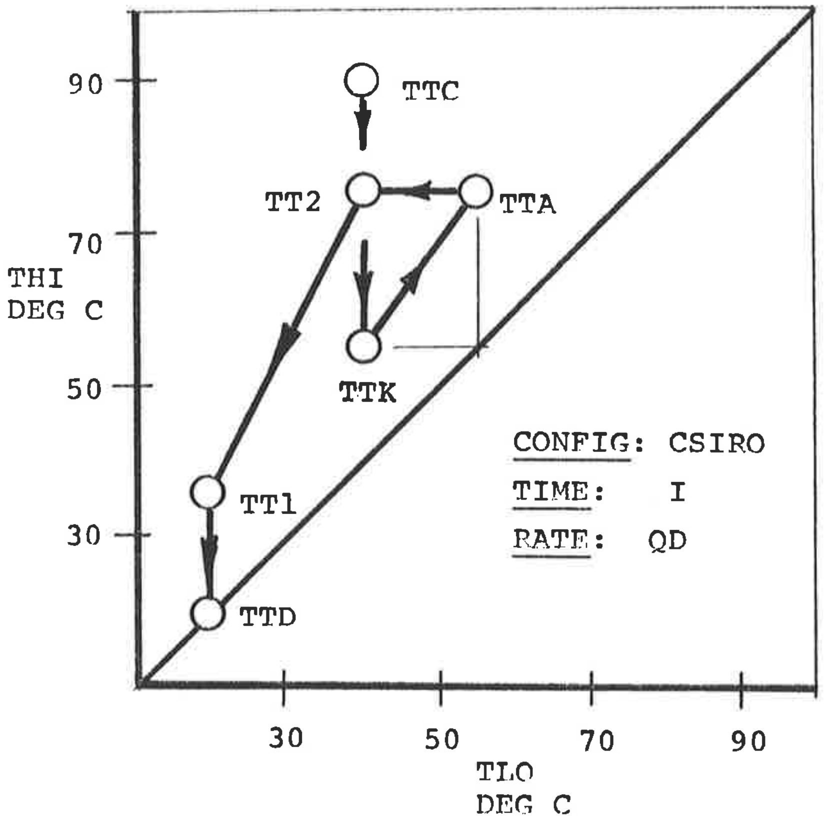


SOLAR/WATER/STORE/AUX ELEC/WATER HEATING CONFIGURATION

TT FIELD DEFINITION

DEMAND	$15 \leqslant \mathrm{TTD} \leqslant 90$
DELIVERY	$5 < \mathrm{TDEL} \leqslant (90-\mathrm{TTD})$
HXWW	$\mathrm{TAPP2}=5$ $\mathrm{TDIF2}=5$ $(\mathrm{THI1}+\mathrm{TAPP2}) \leqslant \mathrm{THI2} \leqslant 90$ $(\mathrm{TLO1}+\mathrm{TAPP2}) \leqslant \mathrm{TLO2} \leqslant (\mathrm{THI2}-\mathrm{TDIF2})$
ELECHT	$\mathrm{THI2} \leqslant \mathrm{THIA} \leqslant 90$ $\mathrm{TLO2} \leqslant \mathrm{TLOA} \leqslant \mathrm{THIA}$
STORE	$\mathrm{TLO2MIN} \leqslant \mathrm{TLOK} \leqslant \mathrm{THIK} \leqslant 90$
SOLAR	$\mathrm{TDIFC}=2$ $\mathrm{TLOK}=\mathrm{TLOC} \leqslant (\mathrm{THIC}-\mathrm{TDIFC}) \leqslant 90$

FIG D3



CSIRO PLANT

TT,Q DEFINITION WITHIN FIELDS OF FIG D3

ELEMENT	TRACK	RATE
COOLING TOWER	TTD=PUMP OUT	QD=Q(TOWER)
HX DEMAND SIDE	TLO1=TTD TDEL=Q1/CP.FM1 THI1=TLO1+TDEL	Q1=QD
HX SOURCE SIDE	FIELD LIMITS	Q2=Q1
ELECTRIC HEATER (HEAT IN STORE)	TLOA⩽THIK THIA=THI2	QA⩾0 QA=(THI2-THIK) x CP.FM2
(NO HEAT IN STORE)	TLOA=TLO2 THIA=THI2	QA=Q2
SOLAR COLLECTOR	TLOC=TLOK TDC=QC/CP.FMC THIC=TLOC+TDC	QC= FUNC(TTC,G,TAMB)
STORE TANK	TTK EVOLVED REF SEC 14.5	QK=QC-(Q2-QA)

PUMP AND LOSS ENERGY EXCLUDED FOR CLARITY
CP WATER SPECIFIC HEAT
FM- WATER MASS FLOW RATE

REFER FIG D1

FIG D4

CSIRO PLANT - SYNTHESIS PROGRAM

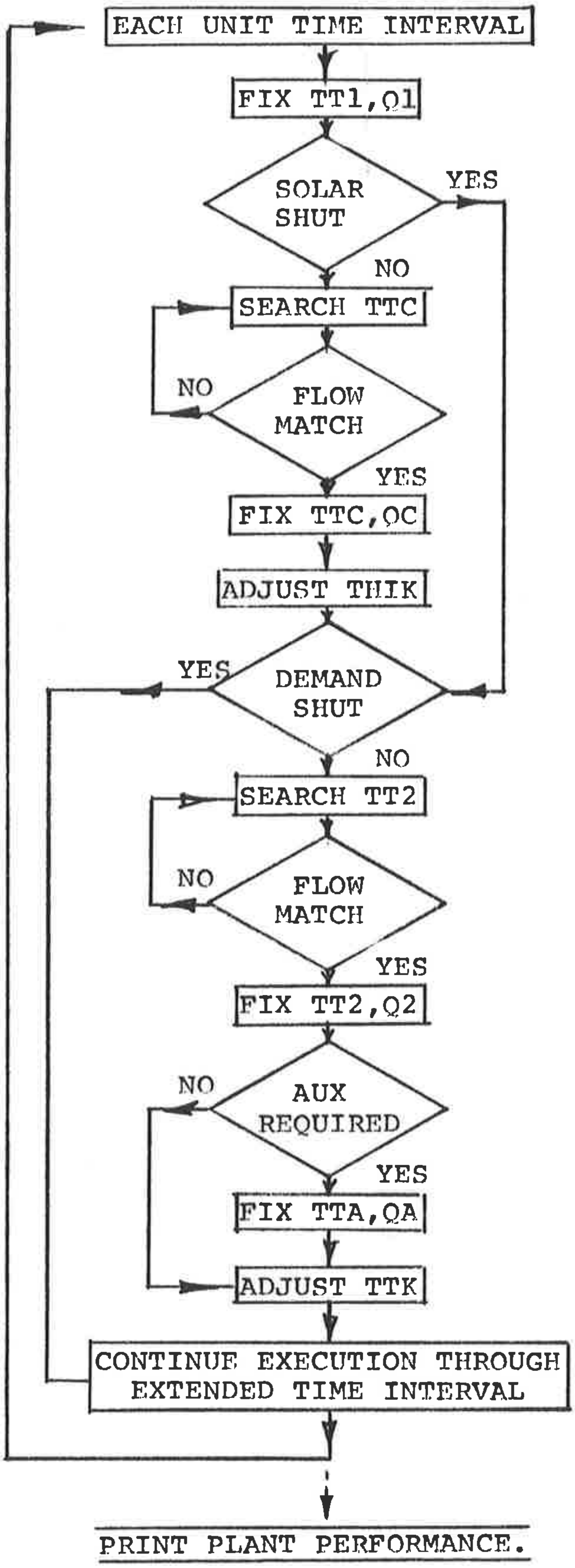


FIG D5

CSIRO PLANT - SYNTHESIS AND TRNSYS PROGRAMS.

DEMAND TTD 15 DEG C, QD 108 MJ/HR (30KWTH) CONTINUOUS, TDEL 40 DEG C
REFER TABLE D2

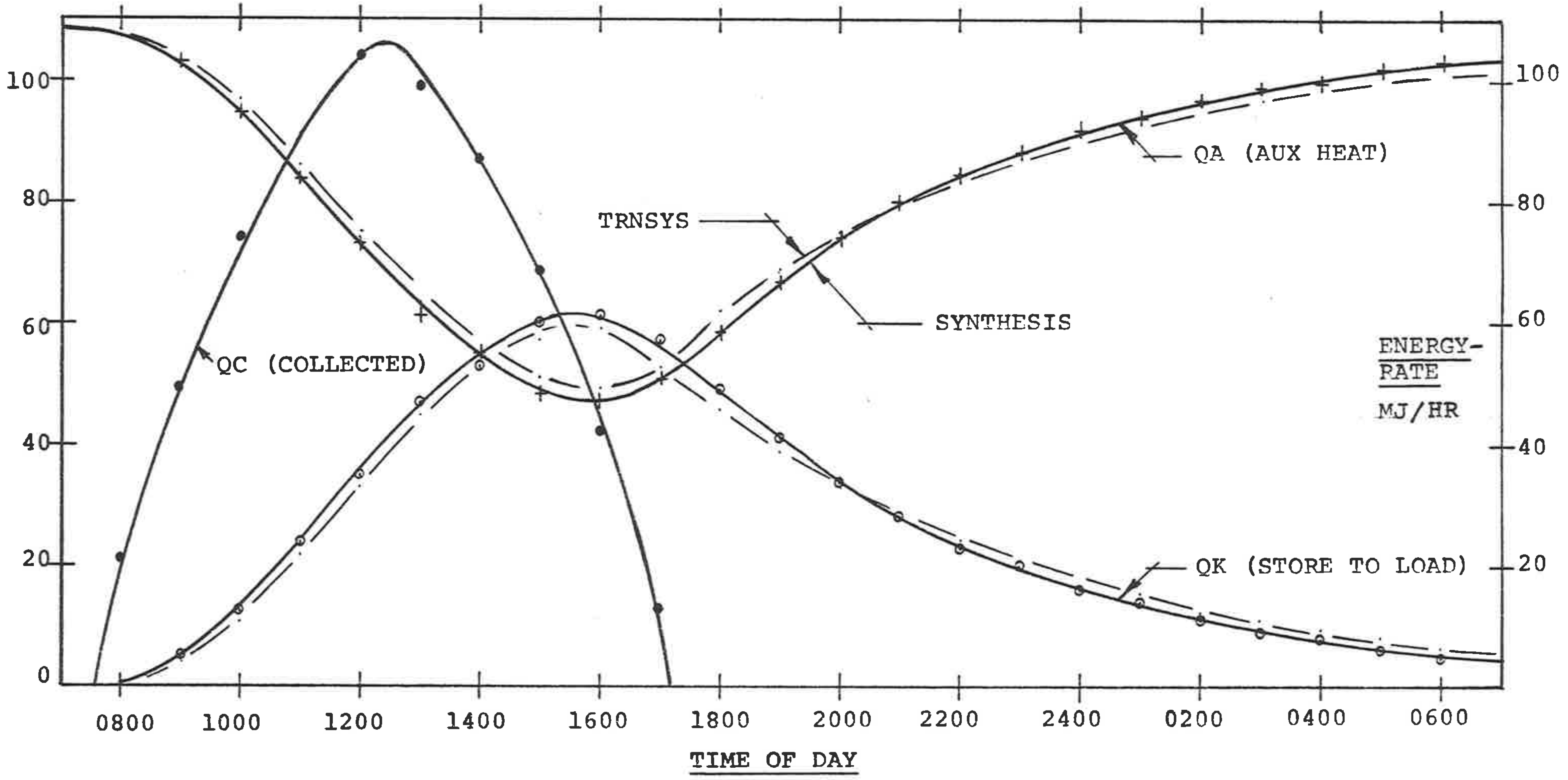
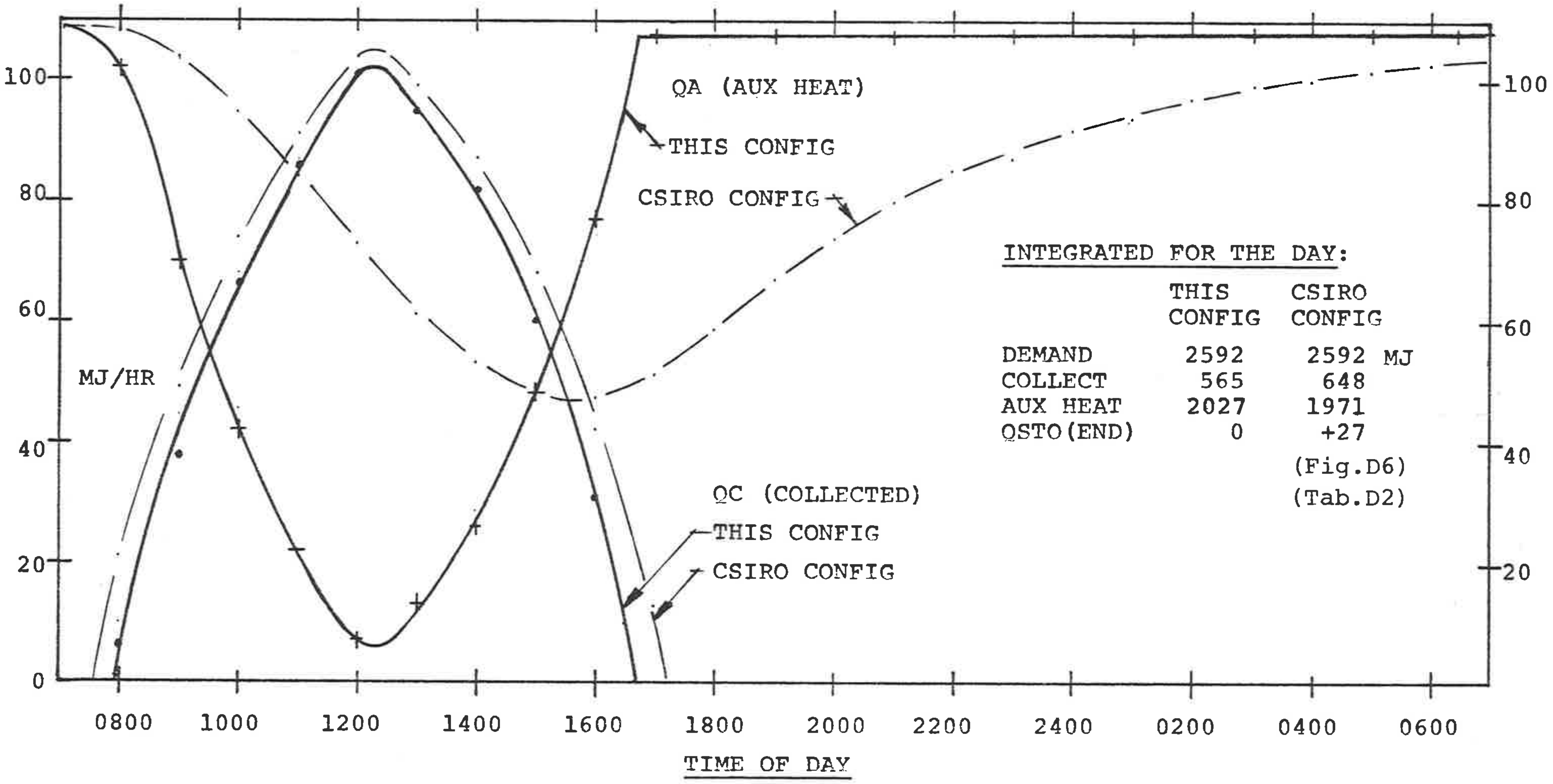


FIG D6

SOLAR/AUXILIARY WATER HEATING PLANT - SYNTHESIS PROGRAM.

DEMAND TTD 15 DEG C, QD 108 MJ/HR (30KWTH) CONTINUOUS, TDEL 40 DEG C
THIC 65 DEG C CONTROLLED, FMC VARIABLE. ACCUMULATOR STORAGE.
OTHERWISE CSIRO PLANT, G AND TAMB TABLE D2.



INTEGRATED FOR THE DAY:

	THIS CONFIG	CSIRO CONFIG	
DEMAND	2592	2592	MJ
COLLECT	565	648	
AUX HEAT	2027	1971	
QSTO(END)	0	+27	
		(Fig.D6) (Tab.D2)	

FIG D7

CSIRO SOLAR HEATING PLANT AT HIGHETT

MEASURED TEST 6 AUGUST 1977 - SOLAR COLLECTOR PERFORMANCE.

REFER TABLE D3. 10 MIN VALUES PLOTTED HERE.

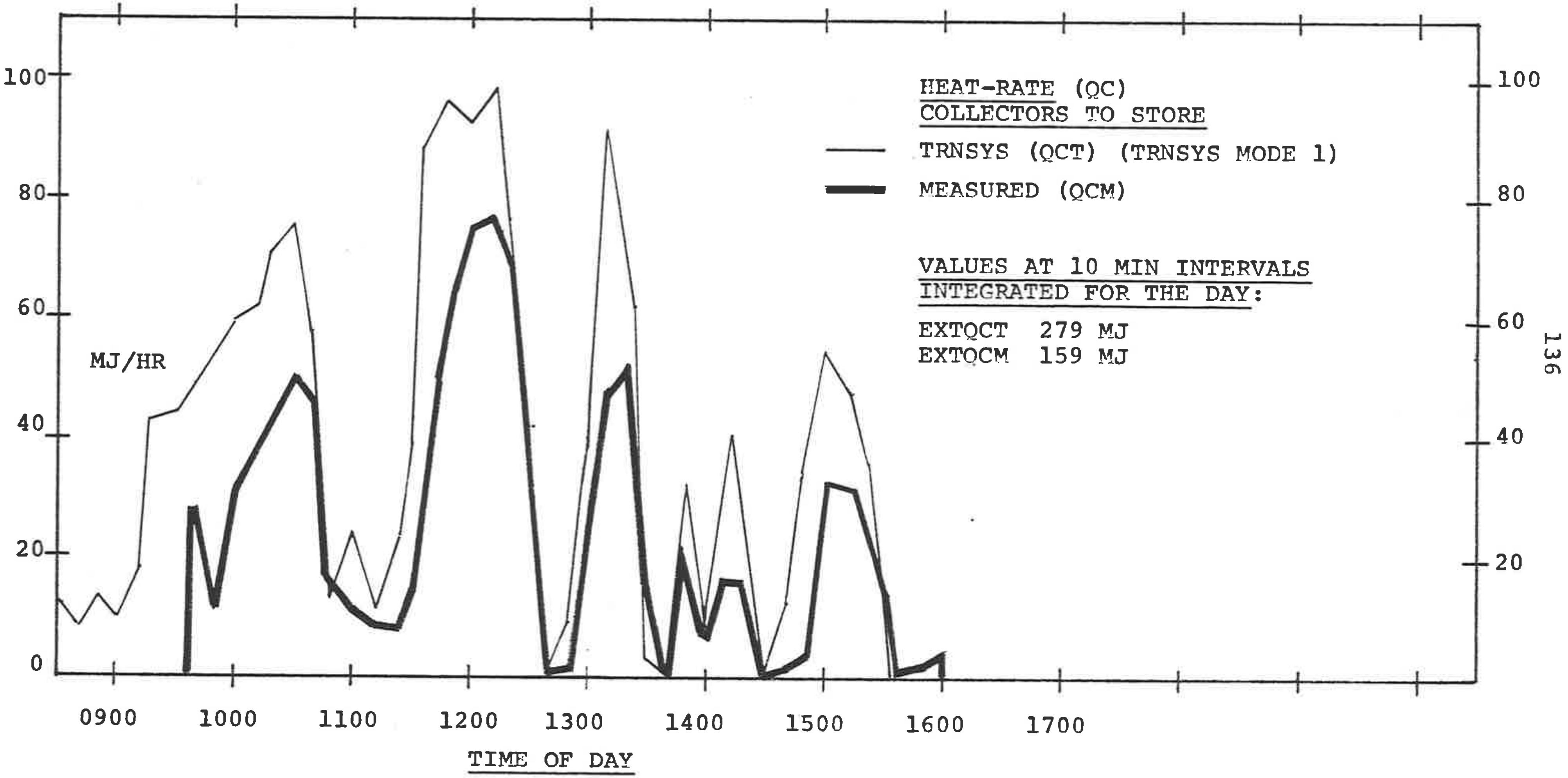


FIG D8

CSIRO SOLAR HEATING PLANT AT HIGHETT

SIMULATION OF MEASURED TEST - 6 AUGUST 1977

LOAD PROFILE. REFER TABLE D4

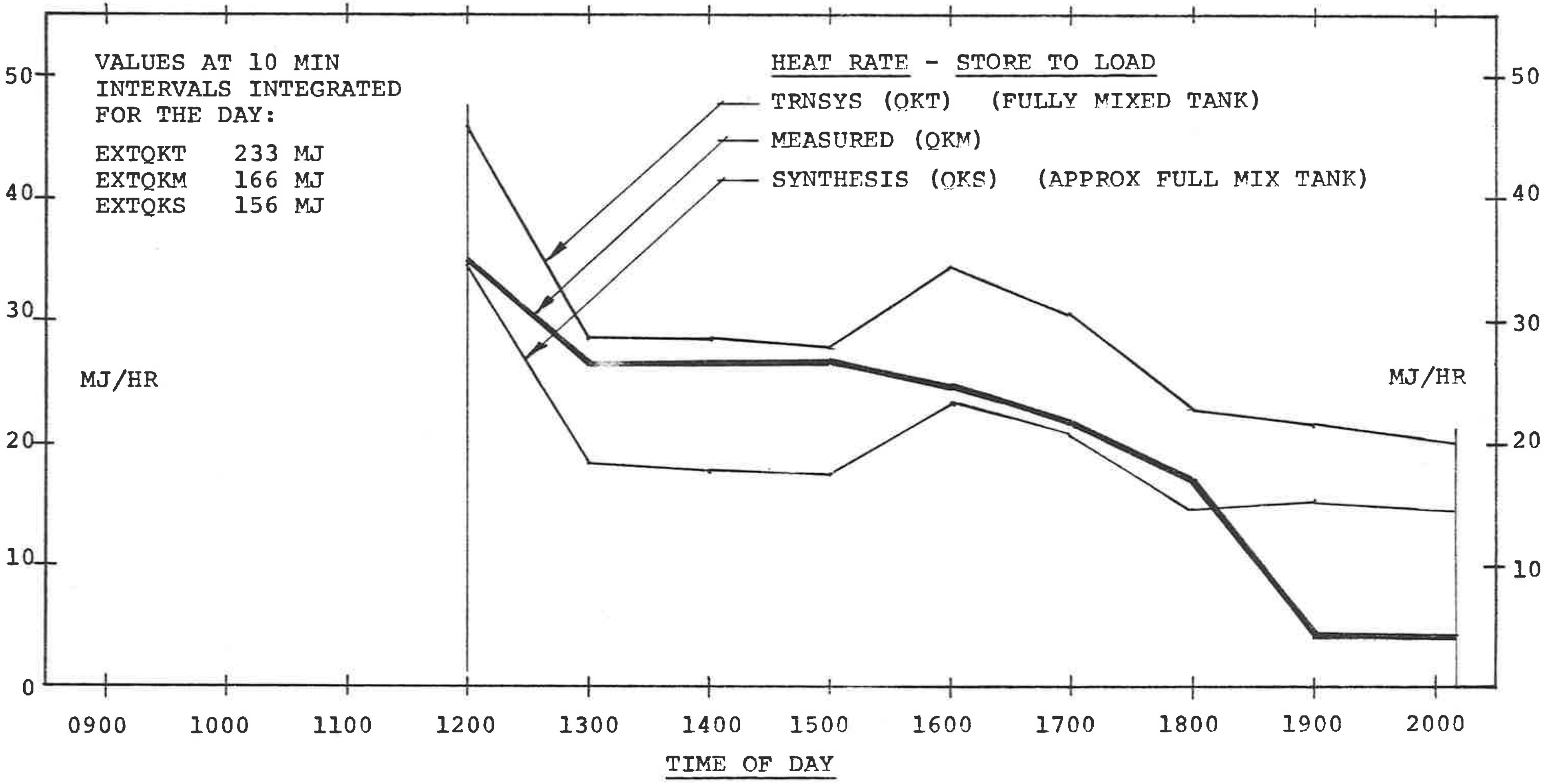


FIG D9

CSIRO PLANT

SYNTHESIS PROGRAM - TECHNICAL INFORMATION

ELEMENT SUBROUTINE

SOLAR COLLECTOR

```
ENTRY  G     (W/SQ M)          F1=0.97
       TAMB  (DEG C)           TA=(0.71*0.89) }TRNSYS(REF.15)
       FMC   (933 KG/HR)       UL=12.42
       TTC                     CP=4.19 (KJ/KG DEG C)
                               SZC=86.4 (SQ M)
MATCH  THIC
                               X1=-F1*UL*SZC/(FMC*CP)
RETURN TTC                     X2=1-(2.7183**X1)
       QC                      FR=FMC*CP*X2/(SZC*UL)

                               QC=((G*SZC*3.6)*(FR*TA))
                                  -(SZC*FR*UL*(TLOC-TAMB))
```

ELECTRIC HEATER

```
ENTRY  FM2   (859 KG/HR)       CP=4.19
       TTA
                               QA=FM2*(THIA-TLOA)*CP
RETURN TTA
       QA
```

HEAT EXCHANGER

```
ENTRY  TT1                     SZ2=3.25 (SQ M)
       Q1                      CU=700 (W/SQ M DEG C)
       FM2                     CP=4.19

MATCH  Q2                      TDM=(THIHX-TLOHX)/
                                   ALOG(THIHX/TLOHX)
RETURN TT2
       Q2                      Q2=SZ2*CU*TDM
```

HOT WATER TANK

```
ENTRY  TTK                     TANK=9500 (KG)
       QSTO (TLOK)             NN=2 (APPROX TRNSYS 2 NODE)
       THIC,QC                 CP=4.19
       OR
       TLO2,FM2                VOL=TANK/NN

RETURN TTK                     QSTO=QSTO+QC-(Q2-QA)
       QSTO(TLOK)              THIK=(QSTO/(VOL*CP))+TLOK
                               TLOK=TLOK
                               OR
                               TLOK=TLOK
                                    +(FM2*(TLO2-TLOK))/VOL
                               QSTO=VOL*CP*(THIK-TLOK)
```

* Indicates MULTIPLICATION
** Indicates EXPONENTIATION

TABLE D1

CSIRO PLANT. SYNTHESIS AND TRNSYS PROGRAMS.

DEMAND TTD 15 DEG C, QD 108 MJ/HR (30KWTH) CONTINUOUS, TDEL 40 DEG C.
FMC 933 KG/HR, FM2 859 KG/HR. INITIAL STORE ZERO, TLOK 35 DEG C THROUGHOUT.

			COLLECTORS				AUX/ELEC			STORE TO LOAD		
AT TIME	G	TAMB	THICS	THICT	QCS	QCT	QAS	QAT	THIKS	THIKT	QKS	QKT
0700	85	14.	.	.	0	0	108	108	35.	35.	0	0
0800	232	15.	40.	40.	21	21	108	108	35.	35.	0	0
0900	395	16.	47.	48.	49	49	103	104	36.	36.	5	4
1000	532	18.	54.	54.	74	73	95	97	39.	38.	13	11
1100	638	18.	58.	58.	91	91	84	86	41.	42.	24	22
1200	710	19.	61.	62.	104	104	73	75	45.	44.	35	33
1300	672	20.	60.	60.	99	99	61	63	48.	47.	47	45
1400	599	21.	57.	58.	87	87	53	55	50.	50.	55	53
1500	482	21.	52.	53.	68	67	48	51	51.	51.	60	57
1600	328	21.	46.	46.	42	41	47	49	51.	51.	61	59
1700	161	20.	38.	39.	13	13	51	53	50.	50.	57	55
1800	31	20.	.	.	0	0	59	62	48.	48.	49	46
1900	0	19.	.	.	0	0	67	69	46.	46.	41	39
2000	0	.	.	.	0	0	74	75	44.	44.	34	33
2100	0	.	.	.	0	0	80	80	43.	43.	28	28
2200	0	.	.	.	0	0	85	84	41.	42.	23	24
2300	0	.	.	.	0	0	88	88	40.	41.	20	20
2400	0	.	.	.	0	0	92	91	39.	40.	16	17
0100	0	.	.	.	0	0	94	93	39.	39.	14	15
0200	0	.	.	.	0	0	97	96	38.	38.	11	12
0300	0	.	.	.	0	0	99	97	38.	38.	9	11
0400	0	.	.	.	0	0	100	99	37.	37.	8	9
0500	0	.	.	.	0	0	102	100	37.	37.	6	8
0600	8	.	.	.	0	0	103	102	36.	37.	5	6
VALUES AT ONE HOUR UNIT TIMES					EXTQC		EXTQA				EXTQK	
INTEGRATED FOR THE 24 HOUR DAY:					648	645	1971	1985			621	607

EXTQA + EXTQK = EXTQD = 2592 MJ/DAY
EXTQC - EXTQK = QSTO AT END OF DAY

S: SYNTHESIS. T: TRNSYS.

TABLE D2.

CSIRO SOLAR HEATING PLANT AT HIGHETT

MEASURED TEST 6 AUGUST 1977 - SAMPLE.

FMC 890 KG/HR. FM2 1660 KG/HR. TEMP DEG C. Q MJ/HR. G W/SQ M.

			COLLECTORS			STORE TO LOAD		
AT TIME	G	TAMB	TLOCM	THICM	QCM	TLO2M	THIKM	QKM
0700	0	8.6	.	.	0	.	.	0
0800	163	10.1	.	.	0	.	.	0
0900	266	11.5	24.7	32.9	0	.	.	0
1000	548	14.7	48.1	56.3	30.6	.	.	0
1100	345	15.2	48.7	51.8	11.6	.	.	0
1200	751	17.0	47.4	67.5	75.0	46.4	51.4	34.8
1300	430	16.7	49.1	56.0	25.7	49.0	52.8	26.4
1400	243	16.0	49.6	51.4	6.7	49.2	53.0	26.4
1500	524	17.2	50.0	58.7	32.4	49.1	52.9	26.4
1600	28	15.6	45.6	46.7	0	48.0	51.5	24.3
1700	0	13.4	.	.	0	47.7	50.8	21.6
1800	0	14.4	.	.	0	48.1	50.5	16.7
1900	0	13.6	.	.	0	47.7	48.3	4.2
2000	0	13.3	.	.	0	47.4	48.0	4.2
2100	0	10.5	.	.	0	44.5	.	0

VALUES AT 10 MIN UNIT INTERVALS
INTEGRATED FOR THE 15 HR DAY: 159 166

HEAT IN STORE ABOVE INITIAL
BOTTOM STORE TEMP: 0700 100 MJ
2200 96 MJ

NETT DRAW FROM STORE: +4

163 MJ 166 MJ

TABLE D3

CSIRO SOLAR HEATING PLANT AT HIGHETT

SIMULATION OF MEASURED TEST - 6 AUGUST 1977

FMC 890 KG/HR. FM2 1660 KG/HR. TEMP DEG C. Q MJ/HR.
M: MEASURED. T: TRNSYS PROGRAM. S: MEASURED COLLECTION/SYNTHESIS PROGRAM LOAD.
REFER TABLE D3.

	COLLECTORS				STORE TO LOAD					
AT TIME	THICM	THICT	QCM	QCT	THIKM	THIKS	THIKT	QKM	QKS	QKT
0700	.	.	0	0	.	.	.	0	0	0
0800	.	.	0	0	.	.	.	0	0	0
0900	32.9	52.0	0	9.9	.	.	.	0	0	0
1000	56.3	65.9	30.6	59.0	.	.	.	0	0	0
1100	51.8	58.2	11.6	24.2	.	.	.	0	0	0
1200	67.5	77.4	75.0	92.6	51.4	51.4	53.0	34.8	34.5	45.9
1300	56.0	63.5	25.7	38.4	52.8	51.6	53.1	26.4	18.3	28.5
1400	51.4	55.2	6.7	7.2	53.0	51.8	53.3	26.4	17.8	28.3
1500	58.7	67.6	32.4	54.5	52.9	51.6	53.1	26.4	17.5	27.8
1600	46.7	51.1	0	0	51.5	51.4	53.0	24.3	23.2	34.2
1700	.	.	0	0	50.8	50.7	52.1	21.6	21.0	30.5
1800	.	.	0	0	50.5	50.2	51.4	16.7	14.8	22.9
1900	.	.	0	0	48.3	49.9	50.9	4.2	15.3	21.6
2000	.	.	0	0	48.0	49.5	50.4	4.2	14.8	20.1
2100	.	.	0	0	.	.	.	0	0	0
VALUES AT 10 MIN INTERVALS INTEGRATED FOR THE 15 HR DAY:			159	279 MJ				166	156	233
NETT CHANGE IN QSTO:								-4	+10	+43
								162	166	276 MJ

TABLE D4

16.0 OPTIMISATION DEMONSTRATION

The diffuse nature of solar energy requires large, new and costly engineering to harness its heat even at relatively low temperatures. The intermittent nature of solar energy requires that it be combined with other energy sources for all but the most passive applications. All this implies that the sound introduction of solar energy into industry is not a matter of replacement of traditional thermal energy systems but rather an optimal blend of the two. Every design can be expected to be different so it is a subject to which our procedure for system synthesis can be well applied.

The CSIRO plant configuration will be suited to many industrial applications involving a heating demand below atmospheric water boiling temperature. We have demonstrated the mechanical engineering aspects of a synthesis program for this configuration. We will now use the program to demonstrate that it will prescribe the optimal system and its associated engineering plant over a wide range of conditions from the point at which solar energy is utilised to a maximum extent up to the point at which it is positively rejected.

The demonstration case for system synthesis is that of a small factory in Adelaide requiring a liquid product heating process, the demand profile for which is known. (Fig.D10,p151). Two energy sources are available, natural gas and solar. For physical reasons, energy is to be transported around the factory as hot water. Solar hot water storage is admitted. The factory's objective is economic – that the total annual owning and operating cost of the energy system should be minimised in terms of the factory's own cost equation.

With this sole statement of requirements, availabilities and objective, the synthesis procedure must be shown to prescribe the optimal combination of energy sources, engineering plant, storage capacity and operating conditions throughout the year.

16.1. Objective.

Industrial objectives for investment in thermal energy systems may well need to be strategic but we will confine them to economic measures for the present purpose. Even with this limitation, a major investment in solar energy should be evaluated many years into the future based on projected costs of alternative energy sources. It will be a clearer demonstration, however, if we pursue here the simple annual cost objective just outlined. The objective function in use is that expressed in Section 6.1,p70, as follows:

V = ANNUAL CHARGE ON CAPITAL (CPC) x CAPITAL COST
+ FUEL COST
+ OPERATING POWER COST
+ OPERATING LABOUR COST
+ MAINTENANCE COST
+ OVERHEAD COST

The structure of the objective function is fixed in the synthesis program and for any given case for synthesis its cost rates would also be fixed. For demonstration, however, one of its most important cost rates, annual charge on capital (CPC), is to be entered as a variable. This has the effect of changing the industrial cost equation, for exploration of the nature of the optimal solar heating system over a wide range of the objective function.

16.2. Input Data.

As in the engineering tests on the synthesis program, solar radiation, ambient temperature and demand are to be entered as Input Data for each unit time-interval of the extended period. Unit time-intervals of one hour are used, to obtain a reasonably good representation of collector performance through each transient daily cycle of radiation and ambient temperature.

Radiation and ambient temperatures vary not only each hour but also seasonally through the year so every single hour of the year's operation should strictly be computed separately. But this is too long for the present level of computing development. While aware of its limitations, the present demonstration is therefore based on hourly data for an average day in each of the twelve months of the year in Adelaide.

Radiation information is derived from 13 years' records of average daily horizontal totals for each month, published by the Waite Agricultural Research Institute of the University of Adelaide. (Ref.16). This is converted to estimated average hourly horizontal values for each month by the methods of Liu and Jordan (Ref.17) then geometrically to a particular collector plane, NORTH, 35 DEG. (Ref.12,p15). It is a wide extrapolation, perhaps typical of that made necessary for locations with poor radiation records. While this data is sufficient for the present demonstration, it can be used for design only with great reservation. The generation of long-term hourly radiation records for Adelaide is an important subject for the future application of solar heating. A monitoring station will be operating in 1978 at the South Australian Institute of Technology at The Levels, north of Adelaide. The result of three years' study of radiation at Flinders University, south of Adelaide, is also being published in 1978. Ultimately, when long-term hourly records are in fact available, there is the statistical task of extracting a 'typical year' from them for system design.

Hourly ambient temperatures are derived from average monthly maxima, 0900 and 1500 values, published for Adelaide. (Ref.18).

The demand energy-rate (QD) is 30 KWTH, initially 24 hours a day, to heat the product liquid 40 DEG C (TDEL) above its incoming temperature of 15 DEG C (TTD). A change in demand is examined later.

A typical month's average Input Data is shown in Table D5,p159.

16.3. Synthesis Program.

The demonstration program is virtually the same as that used for the engineering tests in Section 15 but now, of course, with the CSIRO plant constraints removed and with the free evolution and evolutionary search now operating. TT field increments are 5 DEG C and element size increments are 5% of datum. The annual extended time-interval is 8760 hours, amplified from 288 hours, the latter representing the 24 hour average day for each of 12 months.

The program is based on the synthesis definition of storage and the collector outlet temperature control explained in Section 15.5,p125.

Technical information in element subroutines is similar to that used previously, Table D1,p138, but now without the CSIRO constraints. But a change is made in the collector performance characteristic to simplify computing – the Cooper form listed in Section 14.2,p117, being used instead of the TRNSYS form, Table D1,p138. The two are compared in Fig.D11,p152, but the main reason for the choice of the Cooper form is its independence of collector area, a desirable form for synthesis which imposes TT and Q conditions to obtain an area.

In view of the measured test result, Section 15.7,p128, both equations may be inadequate for large scale industrial plant. In any case they apply only to collectors of the particular CSIRO (Beasley Industries) construction. They are used here only for demonstration – normally a collector subroutine would include an array of information about different details for search and objective selection during the free evolution.

Objective (cost) information is now also contained in each element subroutine, Table D6,p160. Each subroutine also includes the formulation of its objective value factor according to the structure of the objective function, Section 16.1,p143. Solar collector costs are set at $100 PER SQ.M. The gas (fuel) rate is set at 0.5 CENTS PER MJ but a change is examined later. Installed costs are derived in an approximate way as 1.5 x element prime costs. Direct operating labour does not apply to plant of this kind but maintenance requirements are estimated and costed in each element subroutine. Transport energy is included for pumping in the collector and heat exchanger subroutines, costed at a nominal rate for electricity. Overhead costs are omitted for simplicity.

Datum values are set for both collector area and heat exchange area at the maximum values encountered during the free evolution. A search or datum is not required for the auxiliary heater size as it is to be 30 KWTH, capable of meeting maximum demand in the event of prolonged bad weather leading to total loss of solar or stored heat.

The collector outlet temperature datum is set at the value corresponding to the collector area datum. The program retains a fixed flow-rate in the auxiliary heater circuit, the datum value of which is set to correspond to the heat exchanger area datum.

The orientation and inclination of the solar collector plane are constraints which normally deserve inclusion in the free evolution as they can be expected to require matching to the system's annual demand profile. The plane is fixed here, however, at NORTH, 35 DEG (latitude) to the horizontal, as a reasonable plane for satisfactory annual total heat collection in Adelaide. (Ref.12,p55).

A limit may be set in the program on the system's storage capacity – the effect of this is a subject of the demonstration.

16.4. Tests and Demonstration.

A long series of synthesis solutions is obtained from the program with all external and internal information as described except that the annual charge rate on capital investment, CPC, is deliberately varied over the range from zero to 8.6% a year. The values of the objective function and sizes and costs of the main variables of the solution are listed in Table D7,p161, plotted in Fig.D12,p153. Each solution is a specification of the optimum solar/gas heating system for the particular cost equation set by the value of CPC.

For this series of solutions, a high limit of 24 hours at full load is placed on the system's energy storage capacity. Below and up to this limit, optimal storage capacity is evolved in association with optimal collector area on an objective basis.

The most important result is the regular behaviour of the value of the objective function, V, over the whole range. (Fig.D12/1,p153) The value results primarily from a competition between investment in solar collectors and the annual cost of auxiliary fuel. When the capital charge is low, the evolved collector area is high, auxiliary fuel consumption is low and the value of the objective function is low. At the other end of the scale, if the capital charge exceeds a limit of about 8.5% a year in this case, investment in solar collection is abandoned, all heating is done with auxiliary gas and the value of the objective function is high. The regular behaviour of the objective function shows that, whatever the nature of the engineering solution being evolved by the program, the numerical search and optimisation procedures are working reliably. This is also borne out by observation of the progressive improvement in the objective value of the solution obtained at each step of evolutionary search and by the frequent experience during program development that errors in the search procedures are exposed at once by its irregular behaviour. That the values of the objective function are numerically correct, that they are in fact the total annual cost of the energy system specified as the solution, is verified by simple arithmetical calculation.

Once we are satisfied that the objective search procedures are correct, we can turn our attention to the nature of the engineering solutions which they pose. Again, the regularity of the values of the engineering constraints over a wide range of solutions is a necessary indication of the reliability of the evolutionary procedure. The values will change in steps, however, because they are extracted in discrete increments – whether the 5 DEG C TT increment of the field search, or the 5% size increment of the evolutionary search used in this demonstration.

Solar collector area, storage capacity and collector outlet operating temperature are the three variables which essentially specify each engineering solution. (The effect of changes in other engineering constraints is small.) The first two are tabulated, and plotted in Fig.D12/2,p154, for a constant collector outlet temperature of 65 DEG C, a value set throughout the range of solutions at its free evolutionary datum. We will examine changes in this operating temperature later but exclude them at first to expose the detailed behaviour of the collector area and storage capacity solution by itself.

While it is only to be expected that the optimum collector area should increase as the cost of its capital investment decreases, there is a distinct point of discontinuity in its rate of increase over the solution range. There are two such points in the value of storage capacity and they all require explanation. The nature of this behaviour is explored by conducting the synthesis over the same range:

1. With the storage capacity limit at 6 hours of full demand (instead of 24 hours) and at zero, i.e. with storage suppressed altogether. The three sets of solutions are plotted as collector area in Fig.D13,p155.
2. With *stereotype* input data (constant radiation 400 W PER SQ M and constant ambient temperature 18 DEG C from 0700 to 1800 throughout the year) also for the same three different limits on storage. (Fig.D14,p156.)

The first set of solutions is based on input data representing (approximate) annual solar radiation, different each month, so different search datums are evolved under different conditions and the precise steps of the evolutionary search are partly obscured. The stereotype tests eliminate these differences, always setting the same datum. They show the precision of the collector area search steps and the way in which the sets of solutions merge at the points of discontinuity.

It is seen that the point of discontinuity occurs only when storage is admitted and that its position depends on the extent of the storage limit; The explanation is as follows:

- Without storage, the optimum collector area can only be a function of direct utilisation of solar energy during daylight hours - as CPC decreases the area increases steadily up to a maximum value limited only by the demand profile itself and the small effect on objective value of operating and maintenance costs. (Point A, Figs.D13 and D14, pp155,156).

- With 6 hours store limit, optimum collector area increases rapidly as soon as the cost of excess daytime collection and its consequent storage becomes objectively favourable for utilisation at night – recalling that the demand is 30 KWTH for 24 hours a day. Once the store limit is fully utilised, however, the rapid increase is arrested. (Point B, Figs.D13 and D14). Further increase in collector area is again only a function of direct solar utilisation in daylight hours.

- With a large (24 hour) store limit the rapid increase in collector area (supported by storage) is arrested by objectivity, not by the store limit. (Point C, Figs.D13 and D14). The stereotype solutions indicate this sharply – collector area increases until fuel consumption is negligible after which any further increase of area is redundant. With seasonal radiation (Fig.D13) a redundancy of collector area first begins to take (objective) effect in winter months. But summer utilisation continues to support further increase of area (and storage) until the store limit is reached at CPC = 2%. This is the second point of discontinuity in the plot of storage capacity. (Point D, Fig.D12/2). As may be expected, there is indication of such a second discontinuity in the plot of collector area (Fig.D13 at CPC =2%) but it is partly obscured by the search steps.

A present empirical rule for design of solar water heating systems is that storage capacity should be 50 to 75 litres per sq.m collector area. (Ref.21,p120). Such a value is approached (as a maximum) in the range of solutions of Table D7,p161. At CPC = 2%, storage is 55 litres per sq.m. At lower or higher values of CPC, storage per sq.m is less due to the imposed store limit and lesser objectivity respectively. The use of synthesis to explore the nature of storage capacity generally may prove to be a valuable subject of solar energy research.

There is a limitation on the precision of the solution for collector area and storage capacity which is related to the Input Data used for the demonstration. The use of an average day of radiation for each month would suggest to the program that solar heating is available on every day of the year, even if quantitatively adjusted to take into account the days of little or no radiation. As outlined in Section 16.2, p143, the use of a full, typical year's radiation data would overcome the limitation but extend the present computing times beyond reason. That the engineering solution is sensitive to the present limitation is indicated by the broken line plotted in Fig.D12/2, p154. This is a set of solutions obtained by arbitrarily discarding the energy in store at the end of each month, thus simulating a monthly occurrence of a period of prolonged bad weather. While the objective value of the solution is little affected by this, the engineering in terms of collector area and storage capacity is changed over the range of solutions for which energy storage is significant.

Notwithstanding the qualification due to the Input Data, there is still a demonstration here that the synthesis procedure is generating engineering solutions regularly over a wide range. Each solution will be 'optimal' for the given conditions, for the engineering constraints searched and within the precision of the program search steps. That a solution is numerically correct is verified by simple arithmetical calculations.

Up to this point we have searched only for the most objective collector area and its associated storage, holding all other engineering constraints at their datum values set in the free evolution. If the datum-setting strategies are based on sound experience, and changes in unsearched constraints are known to have little objective significance, we may choose to accept the present level of optimisation. Before a thermal energy system is committed to construction, however, the procedure must be executed again in the region of the likely solution - with changes in all significant constraints searched in fine increments. We can demonstrate this here by including now a search of collector outlet control temperature for the same conditions as Table D7,p161.

The results of two tests are shown, at CPC = 3% and 5% respectively. (Fig.D15,p157). The solutions marked X are those obtained previously with the collector temperature held at its datum of 65 DEG C. The solutions marked Z are now more objective when the temperature constraint is searched concurrently with collector area. Both tests show an improvement in objective value accompanied by a change in collector area and operation at 75 DEG C. No general conclusions may be drawn from these curves as they all apply only to this demonstration case. They simply indicate the sensitivity of the solution to collector outlet temperature and show again the regularity of the optimisation procedure. A further refinement could be a search for the optimal control temperature for each month of the year.

We will end the demonstration of the numerical optimisation by examining the behaviour of the synthesis solution, in terms of collector area, when:-

1. The fuel rate is changed from 0.5 to 0.3 and 0.7 cents per MJ. (Fig.D16/1,p158). The curve shape is maintained as it is displaced - investment in solar collection being functionally similar but merely less objective as fuel costs are decreased.

2. The demand profile, still at a steady 30 KWTH, is changed from 24 hours, to 16 hours and 8 hours a day, from 0800. (Fig.D16/2,p158). The curve is now suppressed as it is displaced - investment in solar collection being both functionally inhibited and less objective as system utilisation is decreased.

In both these examples the end of month storage has been discarded. (p149).

16.5. Summary.

Exploration, examination and an understanding of the behaviour of a range of solutions like that just described is an essential part of a synthesis procedure. Once a program is established in this way it can be used within its limitations to evolve and specify the optimal system design for many similar applications. Design solutions can then be obtained directly from an interactive computing terminal and each solution can be expected to be unique.

If the proving and establishment of a synthesis program appears cumbersome, this is due partly to the long explanation and partly to the unfamiliar nature of solar energy. That the methods are in fact highly organised, unified and readily executed is a consequence of the underlying discipline of Part A and the practical methods of Part B.

While we have demonstrated here that the synthesis program for a solar/gas process heating system is working reliably and in one sense ready for use, we recall from Section 15 that its prediction for solar heat collection is suspect. We also recall that the radiation data for Adelaide is only an approximation. Both these problems require research and resolution before we can obtain real synthesis solutions for design and construction of solar heating systems in Adelaide. Meanwhile, we have exposed something of the nature of optimal solar heating systems, particularly the interrelation of optimal collector area and energy storage capacity.

DEMONSTRATION CASE FOR SYNTHESIS.
FACTORY - LIQUID PRODUCT HEATING SYSTEM.

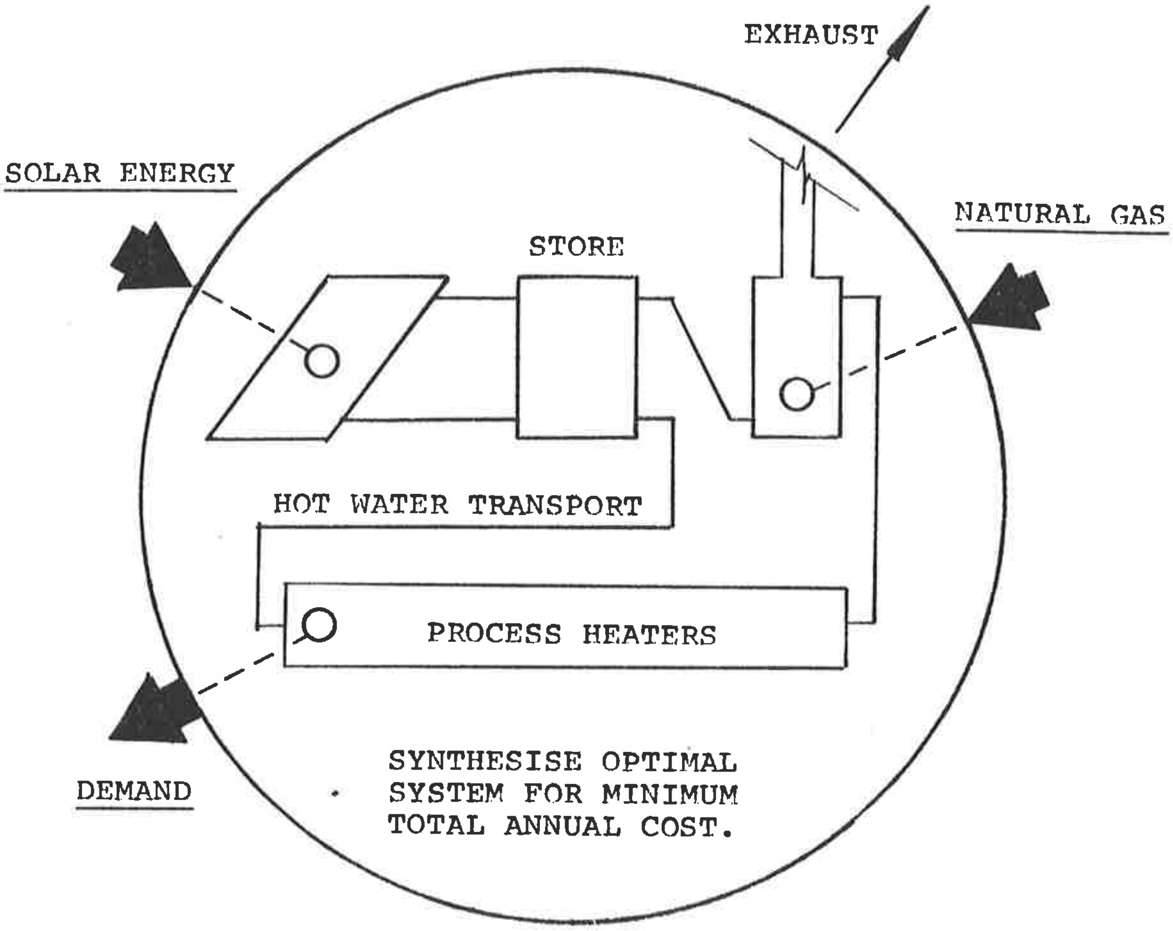


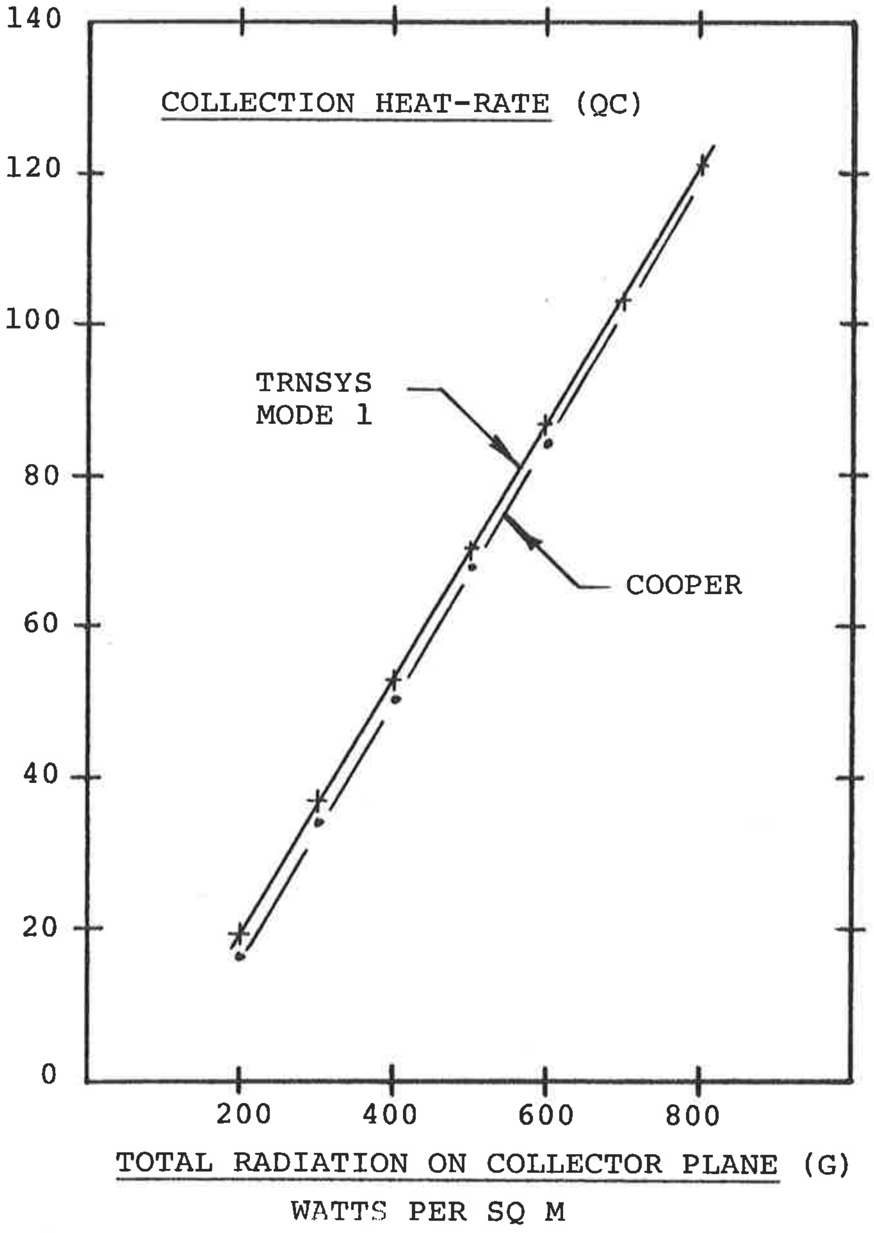
FIG D10

CSIRO SOLAR COLLECTORS.

PREDICTED PERFORMANCE

AT TAMB = 20 DEG C, TLOC = 35 DEG C,
WATER FLOW-RATE (FMC) = 933 KG PER HR.

AREA = 86.4 SQ M, FIVE CIRCUITS.



COOPER: REFER SECTION 14.2 (p117)

TRNSYS: REFER TABLE D1 (p138)

FIG D11

SOLAR/GAS HEATING SYSTEM SYNTHESIS

DEMONSTRATION CASE

SOLUTION SCHEDULE - TABLE D7

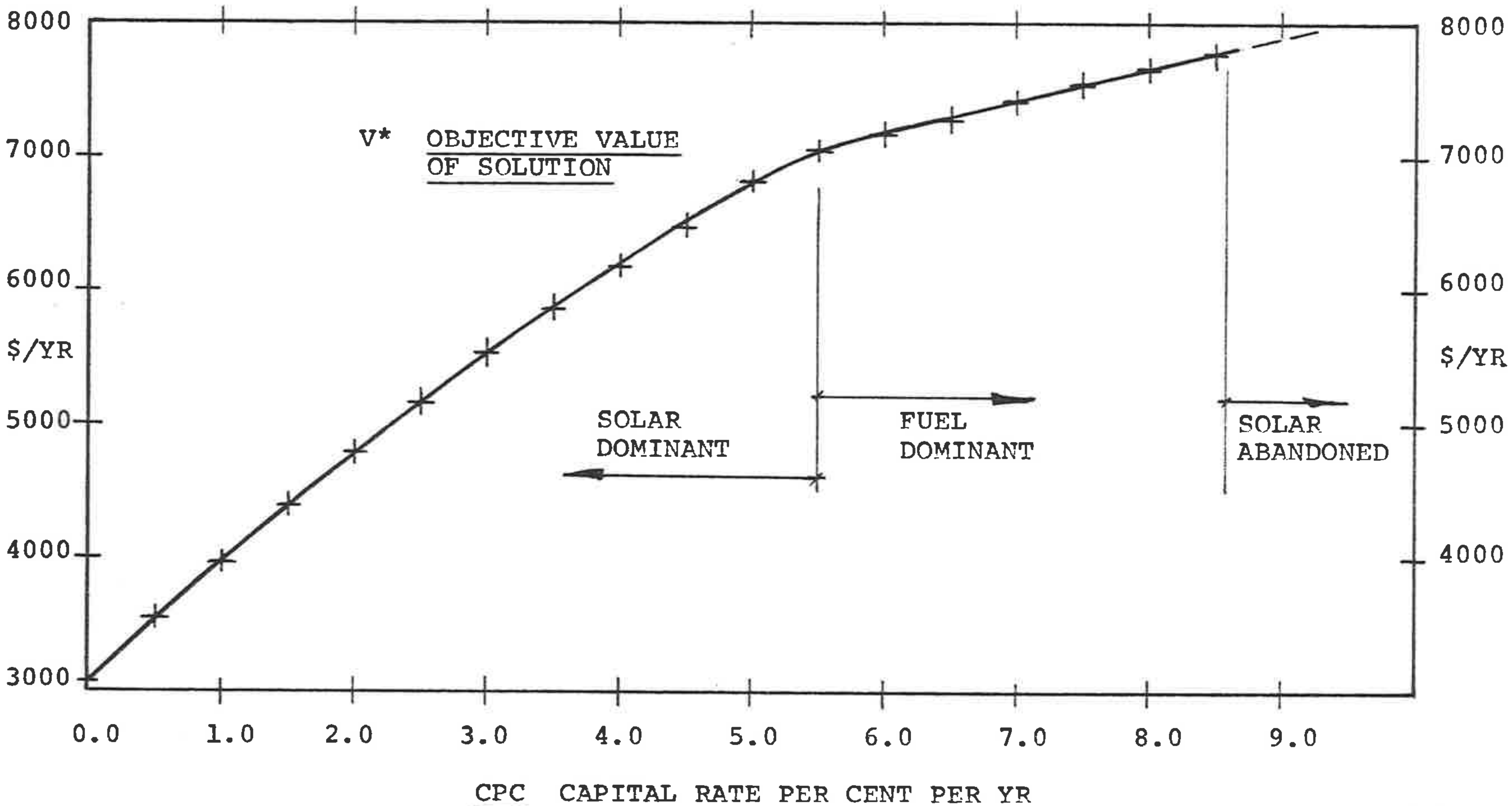
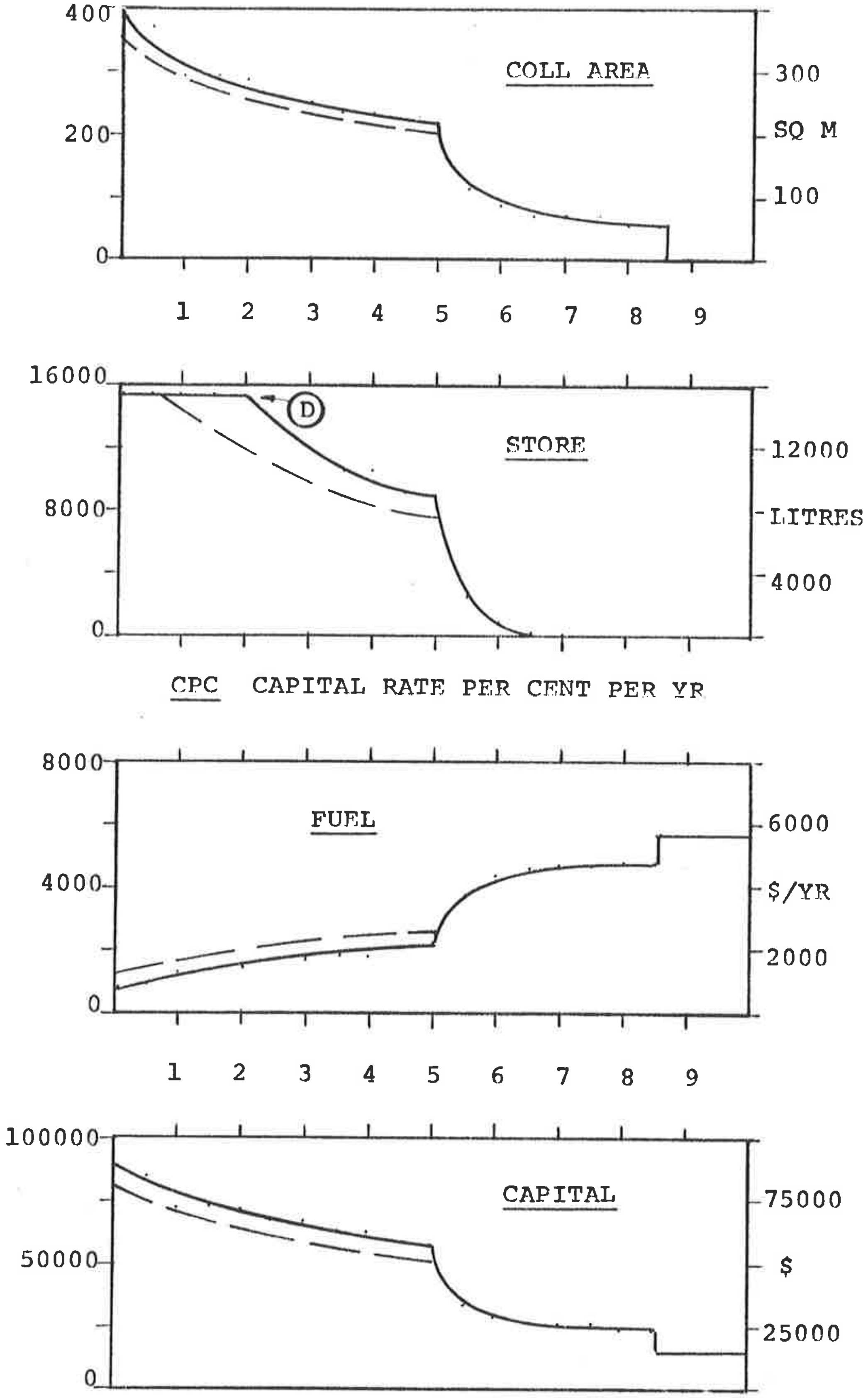


FIG D12/1

SOLAR/GAS HEATING SYSTEM SYNTHESIS

DEMONSTRATION CASE - SOLUTION SCHEDULE TABLE D7.



— — — Indicates end-of-month
discard of energy in store. (p149)

FIG D12/2

SOLAR/GAS HEATING SYSTEM SYNTHESIS

DEMONSTRATION CASE

SOLUTION SCHEDULES - EFFECT OF STORE LIMIT

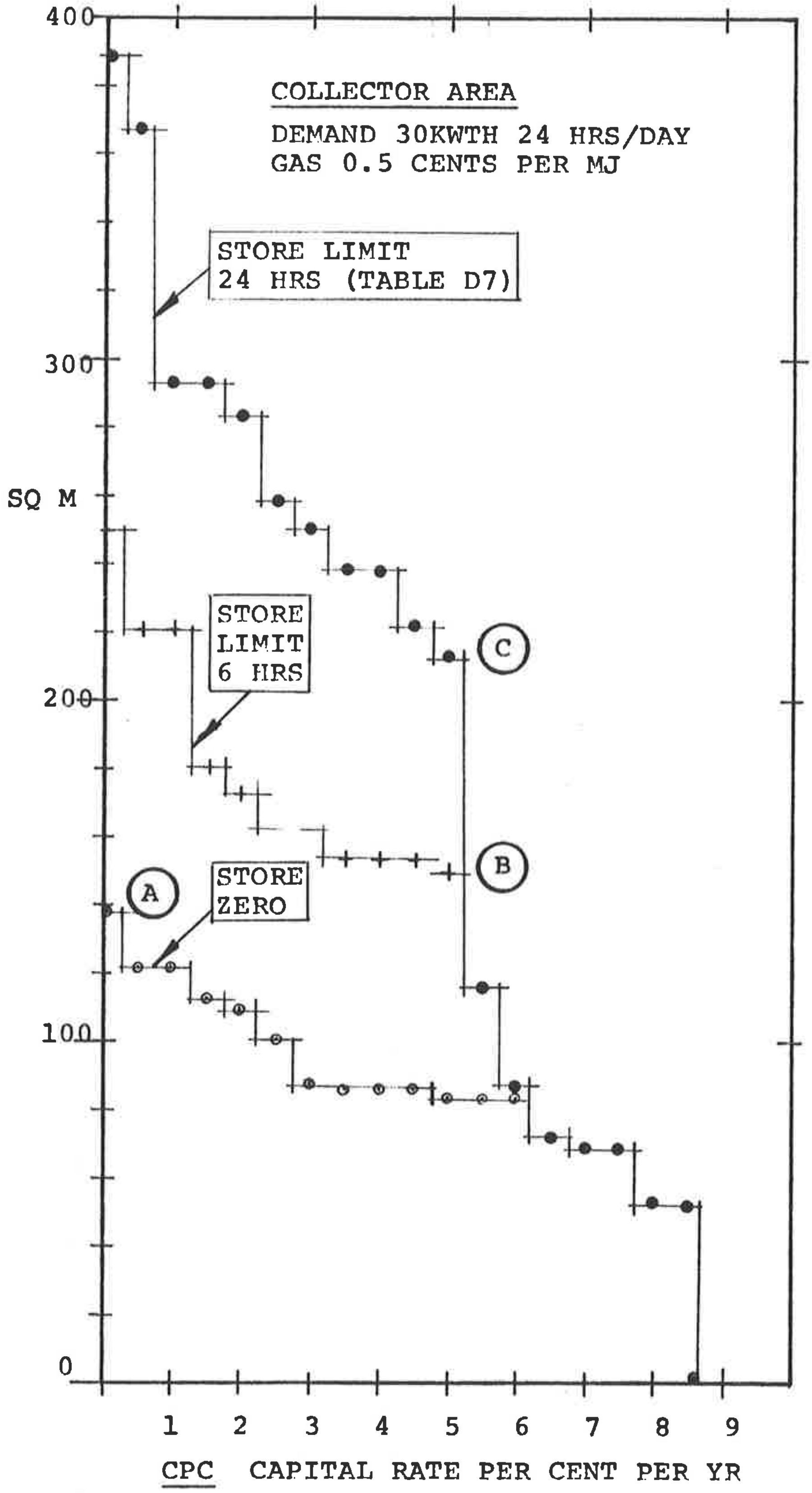


FIG D13

SOLAR/GAS HEATING SYSTEM SYNTHESIS

DEMONSTRATION CASE

EFFECT OF STORE LIMIT - STEREOTYPE DATA

SOLAR RADIATION CONSTANT 400W/SQ M 0700 TO 1800.

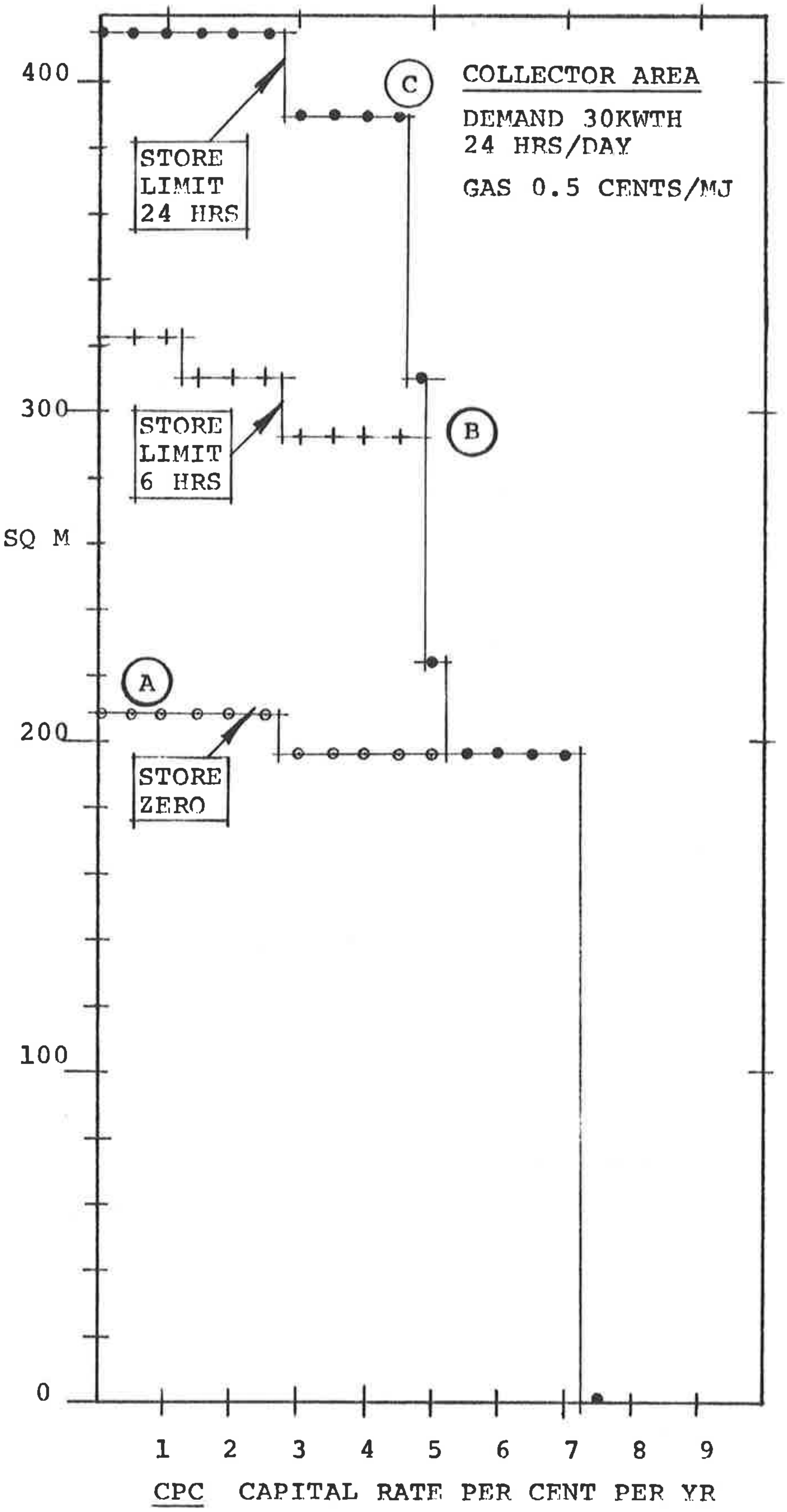
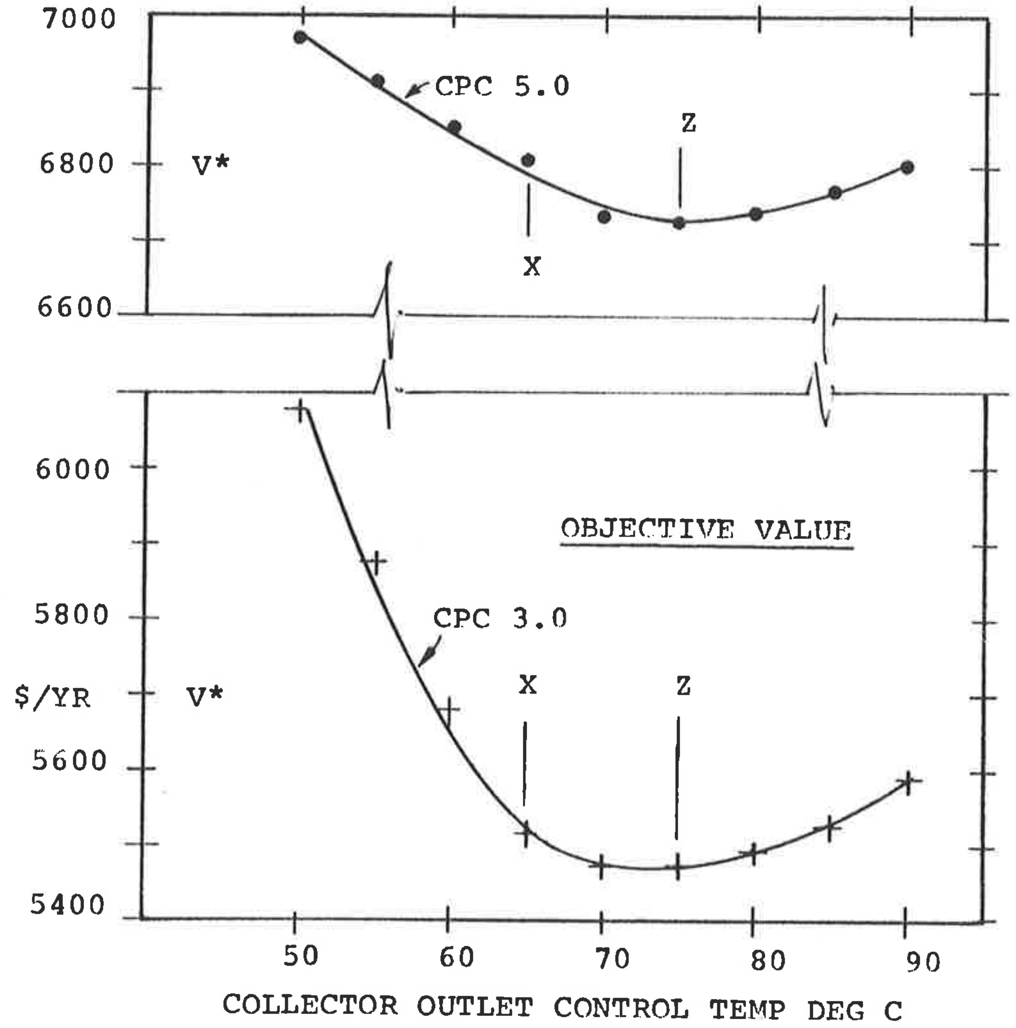


FIG D14

SOLAR/GAS HEATING SYSTEM SYNTHESIS

DEMONSTRATION CASE

COLLECTOR OUTLET TEMPERATURE SEARCH



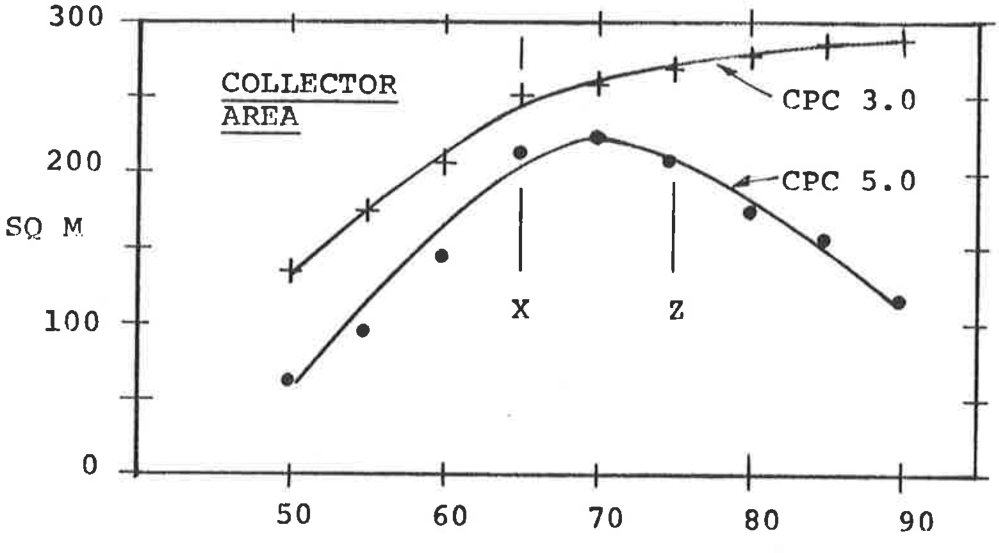
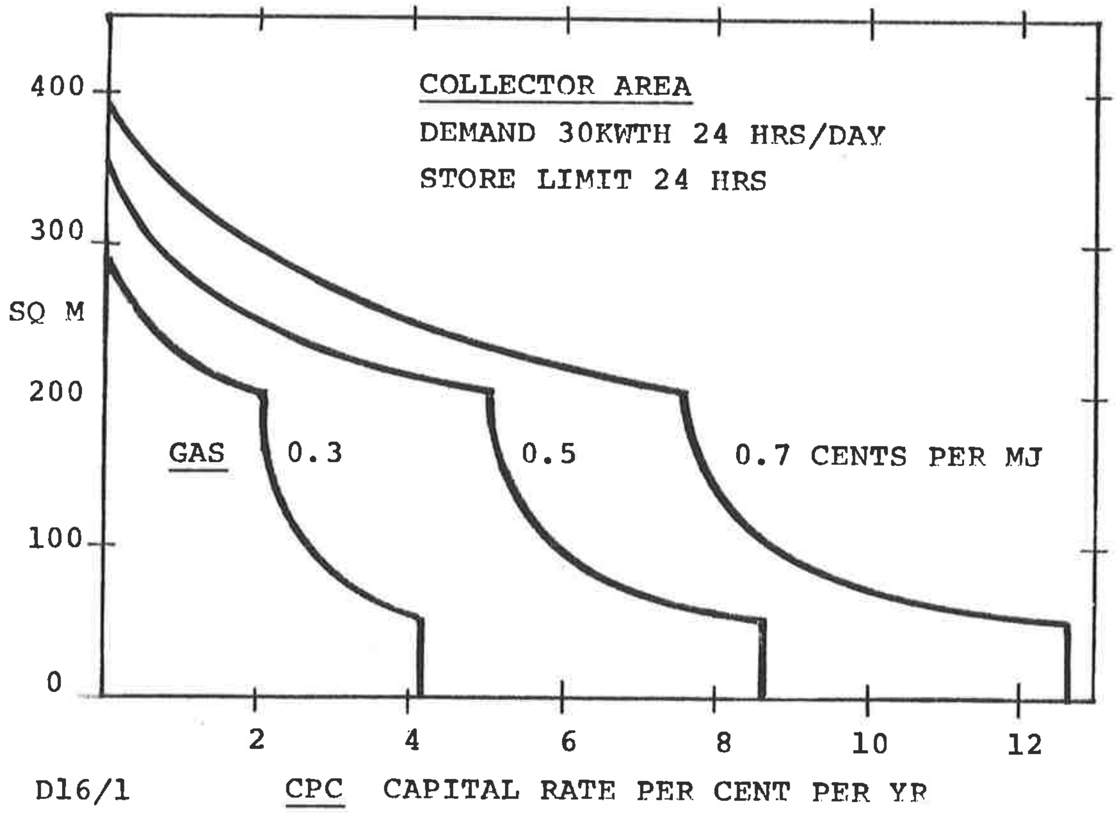
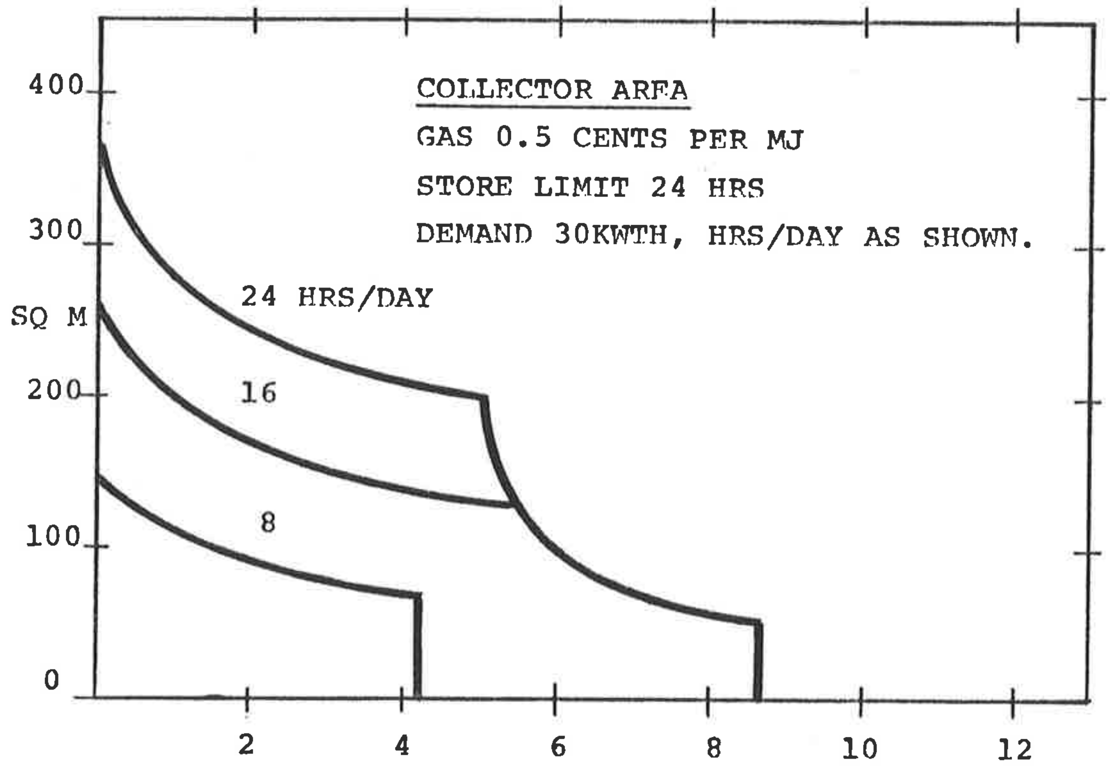


FIG D15

SOLAR/GAS HEATING SYSTEM SYNTHESIS
DEMONSTRATION CASE
EFFECT OF CHANGE OF GAS RATE AND DEMAND PROFILE



D16/1



D16/2

FIG D16

SOLAR/GAS HEATING SYSTEM SYNTHESIS
DEMONSTRATION CASE
INPUT DATA - SAMPLE

ADELAIDE, SOUTH AUSTRALIA.
AVERAGE DAY IN MARCH.

I	TTD	QD	TDEL	TAMB	G
03 0700	15.	30.0	40.0	18.	87
03 0800	15.	30.0	40.0	19.	260
03 0900	15.	30.0	40.0	20.	475
03 1000	15.	30.0	40.0	22.	641
03 1100	15.	30.0	40.0	23.	766
03 1200	15.	30.0	40.0	24.	854
03 1300	15.	30.0	40.0	25.	836
03 1400	15.	30.0	40.0	25.	749
03 1500	15.	30.0	40.0	26.	617
03 1600	15.	30.0	40.0	25.	439
03 1700	15.	30.0	40.0	25.	224
03 1800	15.	30.0	40.0	24.	47
03 1900	15.	30.0	40.0	23.	0
"	"	"	"	"	"
03 0600	15.	30.0	40.0	17.	0

I	TIME OF DAY, PRECEDED BY MONTH NUMBER.
TTD	DEMAND TEMPERATURE, DEG C.
QD	DEMAND ENERGY-RATE, KWTH, PROCESS LIQUID.
TDEL	DEMAND DELIVERY TEMP, SET BY PROCESS, DEG C.
TAMB	AMBIENT TEMPERATURE (COLLECTORS), DEG C.
G	SOLAR RADIATION, TOTAL ON COLLECTOR PLANE, AVERAGE FOR THE MONTH, W PER SQ M. COLLECTOR PLANE FIXED, NORTH, 35 DEG ABOVE HORIZ.

TABLE D5

SOLAR/GAS HEATING SYSTEM SYNTHESIS

DEMONSTRATION CASE

OBJECTIVE INFORMATION AND ANNUAL OBJECTIVE VALUE FACTORS.

CAP-	CAPITAL COST PREFIX
CPC	CHARGE ON CAPITAL, PER CENT PER YR
TRANS	TRANSPORT ENERGY, ELECTRIC MOTOR DRIVEN
RPR	MAINTENANCE COST
SZ-	ELEMENT SIZE
Q	ELEMENT ENERGY-RATE, SOURCE SIDE, KWTH
CINST	INSTALLED/PRIME COST MULTIPLIER, 1.50.
ELEC	MOTOR POWER COST, 3.0 CENTS PER KWH.

SOLAR COLLECTORS

CAPSOL = 100.0 $ per SQ M COLLECTOR AREA
TRANS = 7.5 WATTS PER SQ M AREA
RPR = 3.0 $ PER SQ M AREA PER YR

VC = (CPC*SZC*CAPSOL*CINST) + (RPR*SZC) (QC≥0)
+ (TRANS*SZC*ELEC/100000) (QC>0)

HOT WATER STORE

CAPSTO = 1.0 $ PER LITRE CAPACITY

VK = (CPC*SZK*CAPSTO*CINST)

GAS WATER HEATER

CAPGAS = 250.0 $ PER KWTH MAX RATING
RPR = 10.0 $ PER KWTH MAX RATING, PER YR
GAS = 0.5 CENTS PER MJ

VG = (CPC*SZG*CAPGAS*CINST) + (RPR*SZG) (QG≥0)
+ (GAS*QG*3.6) (QG>0)

PROCESS HEATERS

CAPHX = 600.0 $ PER SQ M HEATING SURFACE
TRANS = 250.0 WATTS PER SQ M HEATING SURFACE
RPR = 50.0 $ PER SQ M SURFACE PER YR

VHX = (CPC*SZHX*CAPHX*CINST) + (RPR*SZHX) (Q2≥0)
+ (TRANS*SZHX*ELEC/100000) (Q2>0)

- - - - - - - - -

* INDICATES MULTIPLICATION

TABLE D6

SOLAR/GAS HEATING SYSTEM SYNTHESIS.

DEMONSTRATION CASE

SYNTHESIS SOLUTION SCHEDULE - RANGE OF CPC

DEMAND 30KWTH (108 MJ/HR) CONTINUOUS
STORE LIMIT 24 HRS FULL LOAD
GAS 0.5 CENTS PER MJ

CPC	V*	COLL	STORE	FUEL	CAPITAL
0.0	3042	388	15466	797	88818
0.5	3525	366	15466	895	85539
1.0	3968	293	15466	1255	74546
1.5	4379	293	15466	1255	74557
2.0	4787	283	15466	1322	72960
2.5	5164	258	13299	1561	67102
3.0	5517	250	12022	1672	64573
3.5	5848	238	10590	1829	61413
4.0	6182	238	10590	1829	61413
4.5	6494	221	8944	2094	57266
5.0	6803	213	8509	2217	55625
5.5	7005	116	2404	3794	34855
6.0	7153	87	878	4268	28993
6.5	7286	72	286	4506	26233
7.0	7412	69	163	4559	25628
7.5	7541	69	163	4559	25628
8.0	7663	53	0	4821	23086
8.5	7778	52	0	4838	22937
8.6	7797	0	0	5702	15107

CPC	CHARGE ON CAPITAL, PER CENT PER YR
V*	OPTIMAL SOLUTION, OBJECTIVE VALUE, $/YR
COLL	EVOLVED COLLECTOR AREA, SQ M
STORE	EVOLVED STORAGE CAPACITY, LITRES
FUEL	ANNUAL FUEL COST, $/YR
CAPITAL	INSTALLED COST OF WHOLE PLANT, $

THIC, THIK, THI2 65 DEG C (COLLECTOR OUTLET)
TLO2, TLOK, TLOC 25 DEG C (LOAD RETURN)

TABLE D7

THERMAL ENERGY SYSTEM SYNTHESIS

PART E

CONCLUSION

17.0 CONCLUSION.

The present work began with a question in search of a scientific procedure for the design of thermal energy systems. (p2). Subject to the permanency of 'black body' radiation as a foundation, I contend that the question has been answered in two ways:-

(1) The synthesis procedure *is* scientific because it is based on the precise laws governing the 'perfect' radiant system and has then been shown by a series of logical steps to apply to all thermal processes for which a state-couple can be identified. Those processes can be small enough and elementary enough to be expressed also in scientific terms – as determined by the best methods of mechanical engineering science.

(2) I am conscious that steps of scientific progress are not necessarily absolute. Nevertheless, for the present state of knowledge, the proposed synthesis procedure appears to be *the* scientific procedure because it is wholly determined (as a search of TT,Q to determine SIZE) for a 'perfect' radiant system and therefore excludes all other methods of synthesis for such a system. The same procedure (search of TT,Q to select the values of the other functional parameters which determine SIZE) is then preserved as the working substances and other physical constraints are introduced during the synthesis of all real systems.

The question arises whether 'black body' radiation is a sufficiently fundamental premise on which to state the above conclusions. The exploration of this question is of considerable importance to the foundation of the whole science of thermodynamics. Such an exploration is prompted by Bridgman's "two strong impressions (of thermodynamics): first of a subject not yet complete or at least of one whose ultimate possibilities have not yet been explored, so that perhaps there may still be further generalisations awaiting discovery; and secondly and even more strongly as a subject whose fundamental and elementary operations have never been subject to an adequate analysis". (Ref.1,p6). But for our present state of knowledge I rely on:-

- The 'black body' and other radiation laws of Prevost, Wien, Kirchhoff and Planck – summarised as far as the present work is concerned by the Stefan-Boltzmann relation applied to a state-couple.(p11).

- "The success of thermodynamics in (cavity radiation) circumstances (as being) perhaps the strongest evidence we possess for regarding the laws (of thermodynamics) as valid in all physical situations to which they can be applied." (Ref.22,p77).

The rigidity of my answers, (1) and (2) above, may appear to have been weakened by discussions about setting objectives (p70), engineering elements (p76) and computing methods (p104). But those discussions are concerned with the *application* of synthesis to man's practical tasks; and any such weakness is due only to the compromise he must often make to obtain acceptable results from limited information within limited available time. The fundamental nature of the synthesis procedure is not affected by such a compromise; and much of the present weakness promises to be overcome by further development in practice. (Section 17.1, below).

Even at its present level of development, the synthesis procedure appears to have accomplished a result of immediate practical value. The 'optimal' cost relation between solar collector area, collection temperature, storage capacity and auxiliary fuel consumption can be readily synthesised for a given situation. (Section 16.4,p146). While it has been well known that such a relation exists (Ref.12,p215), and many solar 'optimisation' studies have been undertaken, the explicit solutions indicated by Fig.D12/2(p154) and Fig.D16(p158) do not as yet appear to have been published. Such synthesis solutions can be used at once to support decisions about solar heating in industry – subject to the availability of correct design information and reliable radiation data. (Section 15.7,p128).

In addition to the above specific result, the synthesis procedure appears to further our knowledge about:

- The 'optimisation' of time-varying systems – where so much published work is restricted to steady systems (e.g. Refs.3 and 19).
- The functional role of energy storage e.g. the difference between the 'active' and 'passive' roles discussed in Section 10.5(p94) and the relative inadequacy (for 'optimal' system design) of 'mixed' hot water storage discussed in Section 15.5 (p124).

Synthesis also alerts us to the potential value of organising thermal information generally on a unified basis. (p53). This does not in any way reduce the continuing need for analytical studies of thermal processes – because those studies are the *source* of such information. But the unified basis means that the results of those studies can be quickly made available to a wide field of practice.

17.1. Limitations and Future Study.

On the debit side of a claim for the present value of synthesis is the fact that its demonstration has so far been limited to but a simple application. (Part D). This has been due to the

- limitations of present computing development (Section 11.4,p106) and the
- need for independent verification of the development application (by TRNSYS and by experiment, Section 15,p120).

Synthesis has not yet been demonstrated with thermal processes involving phase-change, flow energy, cooling and mechanical work. This is an important step which will be undertaken as soon as possible. The need was foreseen at an early stage (Ref.7) but capital for the required experimental plant was not available.

Even after demonstration of rationality, every step in applying synthesis to the design of industrial and commercial systems must be taken cautiously – with great professional care – until all practical details of the procedure are thoroughly established.

The computing limitations (Section 11.4,p106) have to be overcome and methods continually improved for rapid, efficient synthesis.

A whole library of subroutines about thermal processes and engineering elements has to be investigated, programmed and tested to become a broad information base for general synthesis applications. It is not new knowledge – rather it is the conversion of existing information into the unified terms which is needed. No store of knowledge is necessarily complete, however, and all applications of synthesis will be limited by the scope or accuracy of the information available.

The foregoing limitations appear to pose no problems which cannot be overcome with an immediate effort. The synthesis procedure may then be applied widely at an engineering level. But some limitations (to be discussed below) remain to be studied before it can be said that the synthesis procedure has universal application to the whole of man's endeavour in the field of thermal energy systems.

Our synthesis procedure assumes we have the power of decision over all the system relations within their known constraints. This may be so for many common industrial or commercial applications. Some decisions may have a behavioural aspect, however, such as the extent of fuel combustion affecting the environment, depleting the population and reducing the demand for the system's services. We may have some information about such relations and we may try to predict them but we do not have the power of decision over them. To that extent the optimality of our synthesis solution is weakened. It is hoped that intelligent use of predicted information and tests of the sensitivity of the results will aid the solution of many problems like this. Strictly, however, a procedure based on, and requiring, rigorous decisions cannot be applied to systems involving significant behavioural relations. The adaptation of synthesis for this is a subject for further study.

Even when rigorous technical decisions are valid, we may frequently have incomplete information about some of the system relations. We do not know, for example, exactly how much solar energy will be available in a given month. We may predict it within limits, but we cannot be certain, and the optimality of our synthesis is again weakened. If there is only one incomplete item of information, and the solution is not too sensitive to it, we can perhaps still evolve a sound synthesis. Strictly, however, the synthesis procedure is not yet able to handle such a situation and the subject awaits further study and development. One great incentive to this, if it be possible, is extrapolation of the work into optimal planning of energy systems for the future, taking strategic and forecast information into account, with their probabilities.

The synthesis procedure requires that the objective, and the system variables contributing to it, be defined in the same numerical terms e.g. dollar costs. A minimum cost objective is then quite compatible with, say, an attempt to minimise effluent from a furnace provided the effluent rate is also expressed in cost terms. It is not compatible with a simultaneous objective to minimise the rate of effluent in physical terms and yet that may be exactly what is required. Development of synthesis to manage such multiple objectives is also a subject for further study.

17.2. Significance.

The Institution of Engineers, Australia, recently received the report of its Task Force on Energy. (Ref.23). It represents the gathering of knowledge, the generation of understanding and the projection of wisdom for the engineering profession's management of energy. All this will become effective in practice only through the decisions of men – whether at the strategic, planning, design or operating levels of energy utilisation. Modern energy decisions are difficult. In almost every situation there are many conflicting alternatives. Very often the greater the knowledge of the decision-maker, the more complex his decisions become. So we must face one major consequence of the work of the Task Force – that we have to improve our faculty for energy decision-making.

Strategic energy decisions today belong to the field of international ethics. However sound they may be at one time, we can be sure that their basis will continually change. In addition to its familiar short-term engineering decisions, the profession therefore also has to be equipped for sound decision-making in a directional or 'navigational' sense. In essence this means the evaluation of all feasible alternatives in a given situation, the preservation of some as options, their reduction to positive decisions for action, continual monitoring of options for subsequent decisions and, at all times, avoidance of irreversible error. Founded as they are in a whole discipline of energy operations and decision procedures, our methods of synthesis promise much support to this complex and dynamic task.

In all walks of life, the word 'profession' means a discipline of thought and action – of conscience, decision, skill and timing. So the organisation of knowledge and procedures presented here for thermal energy system synthesis complements the decisions and work of the engineer practising in this field. In his everyday task of assessing and deciding on energy sources, engineering plant, investment, energy storage and operations for industry and commerce he will have the combined power of knowledge, the computer and his own executive action brought together by a common objective discipline.

Supported in every way by the synthesis discipline, an engineer will:

- Conceive a thermal energy plant only after he has helped its owner define its demand profile and formulate a rational objective.
- Gather factual information about the availability and quality of all feasible energy resources.
- Carefully maintain, improve and apply his stock of technical and objective information about available thermal processes and their technology.
- Synthesise and study the nature of the optimal energy system before committing it to construction or operation.
- Continually monitor and adjust the operating system to optimality as its future objectives or conditions change.

He aspires to this now, of course, but is overwhelmed by the traditions and presence of cheap energy technology, of consequent *ad hoc* methods of system design and the sheer magnitude of undisciplined optimisation tasks. The procedure for synthesis will help him achieve his aspiration with greater certainty.

The work of a profession also includes its own advancement, by research and education. Energy decisions have to be made here also because research resources are limited and everything we want cannot be pursued at once. The discipline and procedure for synthesis will provide a unified basis not only for prior evaluation of energy projects but also for reporting their results – thus supporting decisions on the allocation of resources and project co-ordination.

The engineering work available for synthesis is wide. It can be used to:

- Prescribe new thermal systems for new factories, buildings and institutions.
- Prescribe alterations and additions to existing systems.
- Re-optimise the operations of existing systems as technical or economic conditions change.
- Expose and prescribe objective opportunities for energy storage in all systems.
- Provide a uniform and rational organisation of knowledge and procedures within energy departments of government, industry and commerce.

This is the field in which it will grow through application, hard work and experience.

Proficiency and results will not come overnight. The synthesis discipline and procedures need study and training. The stated limitations have to be overcome. Nevertheless, the basic structure is complete and a joint effort of practice, development and research will build on it. A professional engineer can already begin to think in this way, to organise his information, to train staff, to replace inferior methods and to contribute his own effort to its development.

Yet he must realise it will not resolve all his problems. Outside a thermal system, in its surroundings, lie biological and social systems and constraints of which he is becoming increasingly aware. Possibly he will then see his new discipline not just as an end in thermal systems but as a start to the coupling of mechanical engineering knowledge with other world knowledge – and thermal systems with other world systems. That is the goal which remains to be pursued by the engineering profession in concert with other professions on an international scale. This thesis is offered as an opening contribution.

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THERMAL ENERGY SYSTEM SYNTHESIS.

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INDEX OF DEFINITIONS

indicating the page number at which the principal terms of Thermal Energy System Synthesis are defined or explained.

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THERMAL ENERGY SYSTEM SYNTHESIS.

GLOSSARY OF SYMBOLIC NAMES.

A	Area
C	Composition of working substance
CP	Specific heat of working substance
CPC	Charge on capital, per cent per year
CU	Heat transfer coefficient
G	Total solar radiation on collector surface
EXTQ-	Energy-rate integrated over time
EXTV-	Extended objective value
FM-	Mass flow-rate
FUNC	Numerical function of:
HX-	Heat exchange element
I	Unit time identifier, and as subscript i or (I)
J	Source/configuration identifier
L	Extended time-interval
M	Mass
OBJ-	Objective information (about process and element)
P-	Pressure of working substance
PATH	Functional parameter, p17.
PHYS-	Set of physical constraints
PV	Flow energy of working substance
Q-	Heat-rate, or energy-rate for synthesis generally
QA	Auxiliary heat-rate
QC	Q, conversion element C
QD	Q, demand-rate
QE	Energy function specifically
QK	Q, storage element K
QN	Q, exchange element N
QR	Q, residual function
QS	Q, source
QSTO(I)	Energy in storage element at time I
SIZE	Functional parameter, p16, process or element size
SURR	Conditions in system surroundings
SZ-	Abbreviation of SIZE
T-	Temperature of working substance
TAMB	Ambient temperature
TAPP-	Minimum temperature approach (e.g. heat exchange)
TDEL	Temperature difference of final delivery to TTD
TDIF-	Minimum temperature difference (e.g. heat exchange)
THI-	High temperature of TT state-couple
TLO-	Low temperature of TT state-couple
TT-	State-couple temperatures of process
TTC	TT, conversion element C
TTD	TT, demand point
TTINCR	Increment of TT for field search
TTK	TT, storage element K
TTN	TT, exchange element N
TT,Q	Terms of the synthesis simulation, p14.
U-	Internal energy of working substance
V-	Objective value. (or volume where defined locally)
V*	'Optimal' value of objective function
VJ	Track value, configuration J
W	Work-rate

Excludes symbols used only locally and defined locally.

\- Indicates frequent use of symbol with subscript 1,2,C,N etc.