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Technical Evaluation Report on Propulsion and Energetics Panel 44th Meeting

on

Power Plant Controls for Aero Gas Turbine Engines

by

K.Bauerfeind and C.D.McCarthy

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TECHNICAL EVALUATION REPORT ON PROPULSION AND ENERGETICS PANEL 44th MEETING ON POWER PLANT CONTROLS FOR AERO GAS TURBINE ENGINES

by

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Technical Evaluation Report on
44th Propulsion and Energetics Panel Meeting on
Power Plant Controls for Aero Gas Turbine Engines

by

Dr. Klaus Bauerfeind
C. Deane McCarthy

1. INTRODUCTION

The 44th meeting of the Propulsion and Energetics Panel on "Power Plant Controls for Aero Gas Turbine Engines" was held at Ustaoset Hoyfjellshotell, Norway, from 9th to 13th September 1974. The meeting had been organized to discuss advances and trends in the aero gas turbine engine controls together with appropriate techniques for the design of optimum controls. The background was provided by the tremendous progress made in the past decade in the field of aero gas turbine engines resulting in more complex control requirements in particular for the multispool bypass engines with and without afterburning and variable geometry. In parallel with the growth of the control requirements, new design methods have evolved in order to make full use of the new types of control system hardware available today.

The meeting was divided into six sessions with a total of 29 papers. The first two sessions dealt with both steady state and transient performance of aero gas turbine engines in a general fashion to provide the ground work for session three, where typical control requirements were discussed. The next two sessions were on control concepts and on simulation techniques, while the last session was devoted to control system hardware.

There was a lively interest in the topics of this meeting as indicated by the official discussions at the end of each paper as well as by the numerous talks about specific problems in the evenings. The meeting made it very clear that the field of engine controls comprises many highly specialized and advancing technological areas, such that keeping up to date will be a real requirement and challenge for every control system engineer. In particular, a very close collaboration between performance and control system engineers is absolutely essential.

2. REVIEW OF MEETING

In this section, the papers of this meeting will be commented upon with an attempt to summarize the principal message of each paper and highlight areas which could make an impact on future developments.

2.1 Steady State Engine Thermodynamics

J.E. Scott [1] began this meeting with a survey paper on the performance characteristics of aero gas turbine engines. The paper dealt with the fundamental working equations in a very generalized form in order to acquaint the audience with the steady state mechanisms of aero gas turbine engines, in particular with the independent and dependent variables that could be used for control purposes. It was stressed that the paper should be considered as an introduction and a basis for the following papers in particular on transient performance and on simulation techniques. The author suggested considering a recommendation for common symbols and units for future PEP meetings.

2.2 Transient Engine Performance

Thomson [2] gave a survey on the basic transient effects of aero gas turbine engines. He demonstrated that a comprehensive transient model of an engine must include a number of typical transient effects on top of the steady state characteristics of the components if a representative simulation of the important engine transients is required. The most important transient effect is the heat exchange between the gas flow and the engine material during load changes in either direction. This means that energy is lost or added at the various points of the thermodynamic cycle. On one particular two-spool bypass engine energy equivalent to some 30 % of the overfuelling was "lost" during a fast acceleration. Test results agreed well with predictions. Other important effects caused by the transient temperature changes of the components are component efficiency changes due to changes of seal clearances and interstage cooling or heating respectively. There are also other effects which mainly affect the high frequency spectrum such as packing lags in the flow swept volumes and delays in the combustion chamber, depending on the type of injection system used. All these effects have been approximated in a practical way to allow their incorporation in a normal engine performance computer programme. A question was asked concerning the accuracy of the predicted transient effects. The author replied that this computer programme had been used on a number of different engine projects with good agreement between prediction and test results, the only critical area being the effects of the transient seal changes particularly in the turbine area, which in some cases have to be treated as an updating process using information from actual engine running on a sea level test bed. However, the possible lack of information does not invalidate the approach, since during the early design stage also the steady state performance of the components when running in the engine is usually not known very precisely.

The author was asked as to the type of computer used and the execution time for a typical transient from idle to maximum rating. The computer used is an IBM 370 and the time factor for a complex three spool bypass engine is approximately 4 to 5 relative to real engine acceleration time.

The next paper by MacIsaac [3] and Saravanamutto dealt with transient performance and variations of certain kinds of parameters including their effects on transient response. It is well recognized that aircraft gas turbines should be designed to respond instantly to input changes whether they be from the pilot or from changes in the operating environment. The problem is first to understand the engine performance. If the engine could be perfectly represented by a computer, one would have available a tool which would greatly simplify the performance analysis and greatly simplify the analysis and design of an adequate control system. Current trends for improving acceleration response include fuel schedule changes which provide maximum accelerating torque without causing surge or overtemperature problems and the introduction of variable geometry at appropriate air flow control points throughout the engine such as inlet guide vanes and exhaust nozzle.

The authors claim that a closed loop acceleration control on turbine inlet temperature improves the engine response rates drastically was challenged by stating that if a good acceleration potential in terms of surge margin and temperature reserves is available then also a fuel schedule type control could provide the extra acceleration fuel flow with a similar result.

Nardone and Ripoll [4] emphasized the possibilities of using a high altitude test chamber to investigate typical transient engine phenomena such as compressor surge lines with and without intake distortion,in-flight reignition of engine and afterburner, open and closed loop transfer functions as well as to carry out stability checks of the total power plant.

2.3 Control System Requirements

Kamber[5] made the point that commercial transport manufacturers must give attention to and specify requirements for advanced engine controls and engine/airframe interfaces that will help improve the overall operational economy of commercial aviation. He stresses that, in addition to accurate and stable control of the engine and full-time protection against overtemperature and overboost, attention must be given to a selective allocation of service bleed as a means of extending engine life for a mix of nominal and deteriorating engines while preserving a desirable thrust distribution. In addition, he emphasizes the need for what he terms a "rating command control" by which thrust commands by the pilot are automatically maintained at the desired level by appropriate combinations of sensed parameters even though these parameters may change with flight conditions. Kamber, having stated the need for more complete engine/airframe control considerations, continues his message by concluding that electronic control technology must be employed in a "full authority" sense to provide the flexibility and permit required interfaces with other aircraft systems so that the desired results of operational economies can be achieved.

In the discussion it was suggested to Kamber that civil engine life is not just a function of material creep at elevated temperature levels. The author replied that more sophisticated electronic control systems could also take care of things like thermal shocks etc. if required.

Johnson[6] concluded that the flat rating of an engine is necessary to optimize engine life in terms of payload times distance flown. To achieve this without excessive pilot workload, it is necessary to incorporate some type of automatic control system which may take a variety of forms depending on the accuracy of selection of the engine rating desired to be achieved by the control. A pneumatic mechanical flat rating system was chosen for the RB 211. Follow-on studies have shown the possibility of controlling the desired rating more accurately by the use of electronics which may also affect the choice of control parameters.

Prue[7] gave a good description of a low-cost engine-mounted, closed loop electronic control system for the air-breathing engine used on the Harpoon missile. One stringent requirement had to do with the acceleration control system which must avoid overtemperature and surge while permitting the most rapid possible acceleration of the engine under any environmental or flight condition. A mode independent of inlet distortion was desirable since the missile has a flush inlet and the attitude of the aircraft is not precisely known during light-off and missile acceleration. The selected EGT versus N mode represents the best overall address to the above. It was the opinion of Prue that no control system hydraulics have ever been concepted for aircraft engine applications that are so fast in response, so lightweight, and so low cost as that arrived at for this engine. It was surprising to many of the audience to learn that in spite of the requirement for low cost, a closed-loop, full-authority, electronic control had been chosen. Low cost of the electronics was achieved by utilizing conservative design techniques where component tolerances are not critical and by using electronic components already in volume production for other programs.

White[8] discussed the reliability aspects of modern control systems. This discussion included some of the classic concepts of reliability engineering, a suggested definition of the control system to be evaluated, a review of some of the fundamental design parameters of reliability and comments on reliability programs and reliability assurance. He stressed reliability demonstrations must be based upon an accurate failure mode analysis. White also stressed the point that those who establish requirements must avoid specifying unrealistic demands either outside the potential of instrumentation and measurement capability or outside the available financial or time resources needed for accomplishment. As system complexity increases, reliability must be considered as important as any other performance parameter.

2.4 Control Concepts

Leeson[9] reviewed in his survey paper some of the various main fuel control concepts used in the last two decades mainly in the USA. Mechanical systems have achieved very high levels of reliability (up to and more than 10,000 hours between overhauls). In spite of the sophistication added to the mechanical and pneumatic computing devices in the past, some of the control requirements for modern aero gas turbine engines cannot be satisfied any longer with the potential of these systems. Obvious alternatives are fluidics and electronics used both in analog and digital control systems. While the progress made with fluidic elements in the aerospace industry is disappointingly slow, very significant advancements are being made on electronic control systems. Some of the present systems employ analog techniques but the future seems to be with the digital systems because of their accuracy and flexibility. Contrary to the present hydromechanical situation, where an immense number of completely different approaches in terms of hardware have been used in order to fulfill in many cases more or less identical requirements, sometimes resulting in very high development costs for a limited number of units produced, the control systems of the future appear to converge towards a more standard arrangement with the digital computer providing the computation and programming capability to satisfy the ever increasing complexity of requirements. Accurate, high-response rate, reliable sensors are an absolute key part of any modern control system.

Bentz[10] dealt with the question of how to use the benefits of the electronic control systems best, i.e. whether a full integration with all the other control tasks of an airplane is to be preferred to the dedicated computer for the propulsion system alone. He came to the conclusion that the latter approach is to be preferred for cost, complexity and reliability reasons. Apart from basically technical reasons, a fully integrated system would create additional contractual problems with respect to the question "who is responsible for the engine performance during the qualification and acceptance tests if the brains of the engine control system is under the responsibility of the airframe contractor?" And even more important is the question of vulnerability of the airplane's capability to stay in the air with all of the plane's propulsion and flight management controls contained in one black box.

The author was asked to comment on the choice of digital versus analaog computers and replied that in the limit of sampling and computing the digital computer acts like an analog controller. However, its storage capacity and computing flexibility together with high accuracy, low weight and cost make it very attractive for future applications involving complex tasks. A second question as to the extent of cooling problems for the described base line system was answered by the author in that the study had not revealed any cooling problems with this particular arrangement where fuel between the boost and main pump had been used to cool the electronics. He also suggested that new families of computers will have a heat load reduced by 40 - 50 %. The next question was related to the possible benefits to be gained when integrating the control functions of inlet and engine in terms of performance. The author claimed that in one particular case the gains in performance ranged from 5 to 10% in thrust and up to 5 % in TSFC improvement. In addition, aircraft manoeuverability can be improved in certain areas.

Tervo and Tringali [11] dealt with the control requirements of engines with an increased number of control variables. Since it is generally accepted that at least part of future engine performance improvements will be achieved by the introduction of more control variables in the form of variable geometry at the fan, compressor, and turbine, this paper was of considerable interest. It was shown that there are many possible ways of how to arrange the control loops. The question of which variable should be used to control certain engine parameters to achieve optimum steady state performance in conjunction with good overall stability and improved overall response of the powerplant will ask for very detailed performance studies before the control system engineer can embark on the control system design. The paper lists a number of possible approaches for the calculation of these multi-variable feedback controller functions including the use of several optimal control techniques.

Bauerfeind[12] proposed a new control system concept, where the acceleration is controlled along a defined run-up line in the H.P. compressor, just below the surge line. With such a direct control it should be possible to either improve the acceleration performance for a given surge margin or to reduce the required surge margin for a required acceleration time, resulting in possible fewer compressor stages. Control concepts of this type will probably be the contenders for the next generation of digital controls.

A question was asked as to the difficulty in sensing ΔP_2 accurately enough. The author replied that the number of sensing points and their optimal location largely depend on the special application i.e. mainly on the degree of pressure profile in the measuring plane. In the particular case described three probes have been installed which are also fairly insensitive to a certain amount of swirl change over the operational range of the engine. The range of Mach number in this plane is 0.3 to 0.6.

Simonis, Perks[13] gave a survey on the development of helicopter controls in the past with an outlook into the future. They stressed the point that clearer requirements with respect to operation and safety are available now which allow a more effective design approach for future helicopter controls. The major requirements of helicopter control systems plus suggested approaches were discussed. An example for such an advanced system, using a digital computer with considerable built-in flexibility with respect to future requirements was given. The progress made in this field was indicated by claiming that the first generation of helicopter gas turbine controls represented approximately 20 % of engine weight and cost and that later systems representing 10 % of the engine weight and cost have been demonstrated. Future systems further reducing the pilot's workload while at the same time providing more desirable control performance will be still lighter, cheaper, and more reliable than today's concept.

The authors were asked whether the specified 10 micron filtration in the proposed system layout was essential in order to protect the pumps. Simonis replied that this high degree of filtration was required to protect the burners of the small helicopter engines. The author also agreed to the suggestion that the higher cost of a vane pump compared with a gear pump cannot be justified if an additional boost pump is still required.

Waters[14], whose paper was given by Dunham, dealt with one particular scheme for avoiding reheat combustion roughness (buzz) in modern highly loaded afterburner systems with individual fuel injection. Factors affecting the design of an adequate controller were discussed. A buzz detector, sensing vibration amplitudes within characteristic frequency bands, reduces the afterburner fuel flows until safe vibration levels have been achieved. This device allows the afterburner to operate closer to its limits at high altitude and low flight speed conditions.

Robinson[15] gave a comprehensive survey on various afterburner control concepts, discussed the possible control arrangements and briefly dealt with the question of open vs closed loop arrangements for applications, where a fast response is required. Weighing the pros and cons carefully, the recommendation is for a twin open loop system, where the pilot selects a nozzle position and the actually achieved nozzle schedules the rated afterburner fuel flow. To improve steady state accuracy a working line trim of limited authority and slow response can be incorporated. When discussing the required hardware the speaker made a plea to reconsider the sometimes extremely stringent afterburner response requirements in particular, since they add enormously to the complexity of the system.

Barbot[16] reviewed typical problems with the introduction of electronic controls dealing in particular with reliability and safety aspects. He suggested that there will eventually be fewer problems with digital controls when compared with the analog systems.

Peikert[17] described a closed loop control system for a two-dimensional external-compression type intake for an advanced supersonic turbofan engine. The stated purpose of the air intake control system is to position the variable surfaces of the intake in order to match intake air flow to engine demand at acceptable distortion levels to provide the maximum possible installed thrust of the powerplant system under steady state and transient operating conditions over the whole flight envelope, particularly during supersonic flight. During subsonic flight, the inlet geometry remains in a fixed position. Intake operating maps, derived from small scale windtunnel tests, were shown along with a discussion of the resulting selection of control signals and control concepts. The performance of the air intake and the air inlet control system was substantiated by full scale windtunnel tests. It was claimed that a closed loop control on the parameter static pressure above the second ramp over total free stream pressure gives a more precise control with respect to the avoidance of excessive intake distortions for the engine in case the second oblique shock enters the engine. It is interesting to note that the inlet control was fully independent of the engine control in spite of the fact the inlet controlled the air flow to the engine.

Brunet, Laprie [18] described control system studies for a small free turbine emergency power unit resulting in the choice of a digital control system. The various steps of the evaluation of such a control system are presented.

2.5 Simulation Techniques

A large number of techniques for the simulation of the transient engine behavior exist. Ravagli,[19] Barbot show that the purpose of the simulation in many cases determines the type of engine model to be considered and the type of simulation method to be used (digital, analog or hybrid). In many cases a hybrid simulation technique has its attraction from a flexibility point of view. Such an approach has been used for both the design as well as the simulation of the behavior of a new control system. Cockshutt[20] indicated the potential of a simulation method which starts with linearization of the governing equations at the design point in order to establish a matrix of engine response influence coefficients. These coefficients are then used to achieve rapid convergence as the cycle iterates to an off-design operating point. The coefficients are used only to expedite the converging procedure. Therefore, the technique is not restricted to the small steps normally associated with linearized analysis. The paper describes the techniques as applied to the simple turbojet cycle but its extrapolation to turbofan cycles is indicated. In the discussion, it was pointed out to the author that some of the influence coefficients used (for instance, a change of the mass air flow for a change of speed) are not really fixed quantities. A question as to the possibility of a matrix becoming singular was answered by the author in that he claimed the engine would normally go outside its physical limits before the convergency technique fails. A further question was raised as to whether influence coefficients had been developed for condition monitoring and health analysis engine programs. The author replied they had not but he considered his approach as very fruitful in providing such programs, assuming high quality instrumentation is available.

Another approach towards a representative engine model is the use of full thermodynamic characteristics, stored in a digital computer. This is the usual approach for the evaluation of steady state performance both at design as well as off design conditions. Sellers [21] and Teren presented such a digital computer program called "Dyngen", which could be used for simulating both the steady-state and dynamic performance of turbojet and turbofan engines. This program possesses significant advantages over traditional methods of digital engine simulation. Specifically, it eliminates the need to operate two separate computer programs to obtain steady state and dynamic results. It can also simulate a wide variety of engine types without reprogramming. It was pointed out to the author that the inclusion of important transient effects like heat transfer, packing lags of flow swept volumes, etc. is a must for many applications if realistic results are to be expected. The author could see no problems in adapting other variables depending, of course, on the capability of developing equations which can accurately model the variables. The author cautioned against including items which might overly complicate the program while at the same time not representing sufficient significance to warrant its inclusion. Another audience input supported the use of analog and hybrid computers for simulation work, starting that all three approaches give results in agreement with engine tests provided that adequate component data are used. This input cited the merits of a "hands on" or visual observation of results as variables were changed as being of considerable value.

Another question had to do with whether "Dyngen" had provision for variable step length. The author replied his system has provision for a variable time step, but the time step must be selected by the user, as a function of time, at execution time. He agreed it would be desirable to have step size varied automatically by the program, and stated the possibility of including such a feature is being studied.

One particular disadvantage of a transient engine model on a digital computer is the fact that the results are not available in real time. Cottington[22] presented in his paper an approach for developing a mathematical model for the performance of a total aircraft powerplant (including engine and air intake) by the use of standard simulation language in a program called DIGISM - a digital computer program used at the National Gas Turbine Establishment. This program can solve with respect to time any set of algebraic and first order differential equations, either linear or non-linear, continuous or discontinuous. This step is then followed by delegation of appropriate parts of the model ot the analogue computer. As an example, dynamic equations, which involve integration, are best suited for the analogue, while non-linear algebra and function generation are more efficiently implemented on the digital system. In view of the fact that some of the engine companies do much of their control analytical work using simulations which do not run in real time, the author was asked to comment on his recommendation. The author agreed that the use of hybrid computers is not a necessary requirement, but that if hybrid facilities are available, they could be used to give the control engineers a better "hands-on" feel of control performance. Another engine company commented that it was working with the author's establishment in a program to represent the control performance of a helicopter engine. In this case, individual input to a real time simulation has been most rewarding.

The next paper by Nye[23] and Vickers demonstrated the application of all these simulation concepts and techniques in industry by dividing a project into 5 phases, i.e. initial concept, definition of control characteristics, development of hardware, production and in flight service problems. The authors made the point that each phase ideally needs a certain type of model in combination with a simulation technique either digital or in real time. Computer models for both the controls and the engine are being used during the early phases but as soon as hardware is available this hardware should be used in the simulation of the closed loop system. A question was asked as to the possible interference caused by the dynamics of the rig, i.e. the response of motor drives, etc. The author agreed that particularly for engines with a fast response, problems do exist and a good compensation network is required in order to minimize these effects as much as possible. A major airframe company representative commented on the author's use of "functional block" programming language to aid engineers steeped in the use of analogue computers to do hybrid simulation work. The referenced representative said his company had tried the same approach with regards to control analysis and abandoned it for two main reasons:

1) The new generation of engineers has little or no experience in analog programming but is generally well-versed in FORTRAN or can easily be taught;
2) Use of the "block" language is more expensive than when loop equations and logic statements are input in FORTRAN from the standpoint of both computing costs and manpower costs.

2.6 Control System Hardware

Since the economical realization of new control concepts depends primarily on the availability of suitable hardware, this session took a good look at new components that could make an impact on future developments.

Griffiths[24] and Powell emphasized the flexibility of the digital control system approach. Control loops treated as separate and independent systems as main engine, reheat, nozzle and variable intake controls can now be integrated and optimized in the digital computer. The safety philosophy adopted is: Use of two independent self monitoring lanes - fail operative with the fault in the first lane and fail safe with subsequent fault - self monitoring of each lane - provision of a "last ditch" overspeed governor. Approximately 15 - 20 % of the store capacity is used for self check of the computer. The author also claimed that the use of a digital intake/engine control system for the Concorde engines could save a substantial portion of the present analog control system weight of 785 kg for the 42 black boxes together with the associated cabling. A question was asked how possible transducer failures such as medium to fast drift rates could be monitored without making the self detecting system oversensitive. The author proposed individual rather than general solutions such as limits on the absolute values, on the rates, or even using more than one transducer, depending on the failure consequences. Nevertheless the monitoring of transducer failures is a very difficult task.

A precise indication of the turbine gas or metal temperature is very important for the rating control of modern engines. It is obvious that a direct measurement of this quantity is preferable to a "computed" temperature, based on a temperature measurement downstream of the hot inlet section.

Compton,[25] Rohy and Duffy describe in their paper (no presentation at the meeting) two types of optical systems for measuring turbine blade temperatures. They are a lens system where an objective lens is used to focus the radiation onto a field aperture defining target size and shape, and a light pipe system where the light is accepted within a cone of half angle, usually equal to 15 - 30 degrees, thus defining a target area on the blade surface. Both types are already in operation and in one particular case an optical pyrometer is already used in an advanced technology engine for the closed loop temperature control. The authors also report on an analysis with respect to promising candidates for a turbine inlet gas temperature measurement up to 2200 K. Three concepts with the required potential have been found. They are: beta ray probe, optical immersed target pyrometer and the ultrasonic air gap method. All three systems still need basic development. From a thermodynamic point of view the beta ray probe is most attractive since it measures (radial) mean temperatures.

Dini[26] and Santochi claimed that fluidics may replace electronics in certain areas. In particular a new type of rotational speed sensor, two types of exhaust gas temperature sensors and an airflow sensor had been tested in the laboratory and are proposed for use in an integrated system either for control duties or for health monitoring purposes. Both the turbulent jet type as well as the capillary tube type temperature sensor appear, however, limited to temperature levels below 1400 K.

The introduction of electronic control systems for the computing duties necessitates a good look at the most suitable hydraulic hardware to be used in conjunction with the electronics. Since most of the present systems have been designed to carry out at least some computing either mechanically, pneumatically or hydraulically, a new approach is required in order to arrive at cost effective solutions. Holzem[27] presented the design criteria and development experience of such a lightweight fuel control system. Attention had to be paid in particular to the accuracy and reliability of the electrical interface and to a low weight and volume of this system. The present system employs the metering area principle, a closed loop flow meter system is being studied in parallel. Estimated weight and volume of this 1250 g/s max flow unit are 8 kg and 4 liters respectively.

The last two papers dealt with fuel pumping systems. Miles[28] demonstrated that the choice of the pumping arrangement including the oil coolers depends in many cases on the heat generation characteristics. The advantages of fueldraulic drives for the in-tank booster pumps has been pointed out. For a good backing pump performance in terms of both head rising as well as suction capability a combination of the radial type with the Francis type impeller is suggested. For the high pressure main engine fuel pumping, positive displacement pumps (mainly gear pumps) are the favorite candidates mainly because of simplicity, weight and cost, while at least in Europe, the vapor core pump dominates among the afterburner pumping devices. In response to a question the author stated, that the inlet throttle of the vapor core pump is rather insensitive to dirt and lubrication problems.

Cygnor[29] explained that future engines will most likely require a further increase of the fuel flow turn-down ratio with subsequent heat generation problems. He therefore concludes that variable displacement pumps which can match the rotational speed-fuel flow requirements of the engines will become more attractive, mainly from a reduced heat generation point of view at low metered flow conditions. The author concludes that variable geometry positive-displacement, fuel pumps which can match the engine fuel system flow and pressure requirements over a wide operating range have been developed.

For a representative main engine installation, the author estimated the weight penalty of the variable displacement pump over a fixed displacement pump to be about 50 % greater and the cost penalty to be about 100 %. The author discussed the Dowty vapor core pump both for reheat as well as the main engine. While the dynamic response of the vapor core pump is adequate to meet the fill modes and operating modes of augmentor fuel systems, it has not been conclusively demonstrated that a vapor core pump and control system can satisfy the amplitude attenuation and phase shift requirements of the gas generator section of an engine. To date, there is no evidence it could not meet the needs. However, a problem would exist in the low speed range of start and idle in that the vapor core pump output pressure would probably be insufficient to supply the needed flow to the engine. A supplementary electric driven positive displacement pump would be required in the low speed regime. The author also described the development of a parallel-flow, two-element, engine mounted boost pump. At low flow conditions, a selective operation of only one of the two elements reduces the temperature rise. A friction clutch is used to couple the high flow impeller to the shaft, when required.

3. CONCLUSIONS

Present research and development work in the field of power plant controls is being greatly influenced by two items, i.e.

- the development of very efficient, aerodynamically highly loaded engines with more variable geometry
- the introduction of electronic computing devices, mainly in form of digital computers.

The resulting tasks for the control system engineer include:

I. Provision of suitable computer engine models for engine and control simulation work. A clearer definition of the handling and accuracy requirements of such models for the different applications would be useful. For steady state design point and off-design performance the simulation methods used all over the world are nearly standard, but for transient simulations they are varied.

II. New control concepts are required in order to cope with the more stringent requirements in terms of accuracy and the increasing number of control variables. A number of present day control concepts have been tailored to make allowance for the natural limitations of the mechanical, pneumatic and hydraulic computing devices. The situation must be reviewed in the light of the potential of the electronic computers. A close collaboration between the engine performance and control system engineers will be required.

III. The general acceptance of electronics for at least the more sophisticated control requirements will also depend to a high degree on further advances in the field of sensors and actuators. Considerable progress in this area is still needed in order to realize the full performance potential of present and future aero gas turbines and to achieve at least some degree of standardization of control system hardware.

4. RECOMMENDATIONS

The meeting provided a worthwile platform for the information and exchange of ideas in the field of power plant controls for aero gas turbine engines. Since the controls of an engine represent a substantial portion of both the total power plant cost and weight respectively, and since there appear to exist so many different solutions for very similar requirements, meetings of this type are considered very effective by the participants. It is recommended that another meeting be held in perhaps two years when the requirements of the new power plants have emerged more clearly and more experience with the operation of electronic controls is available.

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15. Abstract

The 44th Meeting of the Propulsion and Energetics Panel on "Power Plant Controls for Aero Gas Turbine Engines" was held at Ustaoset Hoyfjellshotell, Norway, from 9–13 September 1974. The meeting had been organized to discuss advances and trends in the aero gas turbine engine controls together with appropriate techniques for the design of optimum controls.

The meeting was divided into six sessions with a total of 29 papers. The first two sessions dealt with both steady state and transient performance of aero gas turbine engines in a general fashion to provide the ground work for session three, where typical control requirements were discussed. The next two sessions were on control concepts and on simulation techniques, while the last session was devoted to control system hardware. This Report gives a brief review of the papers presented and the conclusions to be drawn from them.

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