INTEGRATED THERMAL MANAGEMENT
OF
ADVANCED AIRCRAFT

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The objective of the proposed effort was to evaluate the U.S. Air Force sponsored Vehicle Integrated Thermal Management Analysis Code (VITMAC) for: i) including an optimization/expert systems architecture for analyzing thermal/fluid network configurations at the component, subsystems, and system level, and ii) coupling VITMAC with engine performance and cycle codes to provide a more integrated mission analysis capability as well as more accurate definitions of thermal loads. This effort resulted in the inclusion in VITMAC of a flow condition optimization method which automatically determines component operation to match user-specified thermal circuit operating conditions. This was the first step in implementing a plan for a multi-level optimization method which was developed for a Phase II program. Various engine performance and cycle models where evaluated which resulted in the recommendation that VITMAC be linked with APL's RJPA ram/scramjet engine performance code as well as NASA's CEA rocket performance model and NNEP turbine engine cycle code. Finally, a plan for commercializing VITMAC was developed which includes: i) enhancing the graphical user interface (GUI) to make it more user friendly and robust, ii) organizing workshops to provide industrial experts with influence on and knowledge of VITMAC capabilities, iii) providing end-user support and training and, iv) developing a market plan for transferring the technology for aircraft and non-aircraft applications.

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1.0 INTRODUCTION

The Aero Propulsion and Power Directorate has, under several initiatives, been pursuing the development of innovative approaches for advancing propulsion systems, turbine engines, and electric concepts. Significant progress has been achieved to date under the Integrated High Performance Turbine Engine Technology (IHPTET) program, the More Electric Aircraft (MEA) programs, the Scramjet Component Technology (SCT) and HyTech programs, to mention only a few. Exploratory development of new concepts is still needed either through analysis or experimentation which may lead to even greater performance enhancements and/or the development of new concepts/systems.

As new aircraft (or generic platforms) evolve, new design problems will occur requiring integration of new and existing technologies for thermal management. The subsystem design requirements are often brought into the design cycle after the airframes and propulsion systems engineers have established an optimal aerodynamic configuration. A design process is required that will meet the platform mission profiles, affirming feasibility and assessing risks while still in the conceptual stage and insures total system integration of the airframe/propulsion system to the many subsystem thermal suites. Modeling and simulation enables planners to identify and optimize conceptual configurations during the initial design phase rather than to incur costly fixes during prototype development and production.

A Phase I investigation was conducted to determine the feasibility of enhancing the Vehicle Integrated Thermal Management Analysis Code (VITMAC) for a thermal management design tool that will assist the Air Force in new concept assessments, integrated system analysis, subsystem interaction assessments, design of actively cooled thermal management systems, and in support of experimental efforts. Since advanced aircraft/propulsion systems are required to utilize the fuel, and, perhaps, other coolants as for absorbing and dissipating the generated heat in convectively cooled circuits, the research efforts will necessarily focus on concepts that integrate the fuel/cooling circuits with the airframe/propulsion systems.

Thermal loads and control requirements imposed on current and future high-performance aircraft continue to increase, thereby stressing the energy collection, distribution, and dissipation capabilities of onboard thermal management systems. The increasing propulsive, aerodynamic and internally generated heat loads experienced by these aircraft coupled with their stringent weight constraints and fuel temperature levels, necessitate the use of highly efficient, coupled, state-of-the-art thermal management models (Van Griethuysen et al., 1996).

A design problem common to high-speed aircraft is the efficient management of thermal loads with minimum weight or performance penalties. As noted above, these penalties can often be attributed to the manner in which thermal management design has traditionally been relegated to the final stages of the overall vehicle design process. When heat loads become sufficiently large, such that cooling becomes a significant performance driver, thermal management can no longer be relegated to the final stages of the design cycle. In the past, thermal management analysis methods did not allow for timely tradeoff analyses to affect overall system designs. The development of a design tool that allows users to easily investigate concepts and conduct parametric trade studies with quick turn around results can help alleviate the problems associated with unoptimized thermal management systems.

To design and optimize advanced aircraft and propulsion systems, engineers must utilize modeling and simulation tools capable of assessing the performance of various vehicle cooling schemes and thermal protection systems in an integrated fashion. A principal requirement of such a tool is the ability to couple vehicle aerodynamic and internally generated heat loads with the coolant network thermal-hydraulic response. Such an integrated computational capability is contained in the basic VITMAC code, developed by Science Applications International Corporation (SAIC) for the U.S. Air Force (Issacci et al., 1992, 1995a, 1995b, 1996; Wassel et al., 1995a, 1995b).

VITMAC is an easy-to-use, general purpose analysis tool, developed for analyzing fluid networks. VITMAC contains many of the features needed to evaluate and design thermal management systems of advanced aircraft. However, it lacks a mechanism by which it could automatically perform optimization analysis. The Phase I effort identified an optimization methodology that would allow for the identification of improved fluid network operating conditions and configurations from the component to total system level. An architecture was defined that uses traditional optimization schemes to optimize the total system effectiveness. Phase I also investigated engine performance and cycle codes that could be linked with VITMAC to provide a more accurate assessment of the integrated engine thermal loads. A workshop was organized with WL/POP and engine company experts to help identify and define engine model requirements. At the same time, the requirements were identified for enhancement of the graphical user interface (GUI) to make the VITMAC design tool more robust and user friendly.

These Phase I results are described in the following sections, as well as the techniques that will be required to implement these results into VITMAC.

2.0 OVERALL TECHNICAL OBJECTIVES

The primary objective of this program is to enhance the PC-based version of VITMAC to include an optimization scheme, to permit industry-standard engine performance calculations, and to upgrade the graphical user interface (GUI) for an improved user friendly environment for simulation of thermal networks, input data, and display of the results. The effort focused on the development of a software package that will provide thermal designers with a tool to design thermal management systems at their optimum conditions based on mission profile figures of merit (such as minimum weight), which satisfy the system cooling requirements.

The specific task objectives of the Phase I effort included the following tasks:

Task 1: Development of Optimization Scheme
Task 2: Investigation of Engine Performance/Cycle Codes
Task 3: Identify GUI Requirements
Task 4: Development of Phase II Plan

The Phase I investigation featured a workshop at the Wright-Patterson Laboratory which brought together the potential users of the VITMAC code, as well as addressing issues relevant to two major tasks of the program, namely, optimization and engine performance codes. It became clear, for example, that different levels of optimization will be required at various stages of a thermal management system design.

Also, designing an aircraft thermal management system (TMS) requires a capability for estimating the engine thermal load using simple and fast running performance codes. Such codes are available (RJPA, Johns Hopkins), or under development (APCAT, WL/POP), for ram and scramjets. For turbojet engines, a thermodynamic cycle code such as NEPP (NASA Engine Performance Program; Klann and Snyder, 1994) was identified. These codes can be linked to VITMAC (Phase II) to provide a capability to design an integrated thermal management system for different engine types and for different conditions from design point operating conditions to a complete mission analysis.

Furthermore, in order to make the code more user friendly, VITMAC users were consulted for their input and feedback. A list of user requirements for graphics enhancement has been compiled and are being incorporated into the code. In Phase II, a continuation of GUI upgrades will be made while VITMAC users will be solicited for additional advice that will help the code be user friendly as well as be robust.

3. PHASE I RESULTS

This section presents the results of the feasibility study during the Phase I of this program, as well as the recommendations for continuing this effort in Phase II.

3.1 Optimization Architecture

An optimization analysis, needed for finding optimum operating conditions of a thermal management system, requires specification of: the objective function (figure of merit), design variables, and constraints. Optimization of a thermal network should be carried out on a component level, as well as a system level. At the component level, an exergy analysis will be used to identify the optimum operating conditions of components such as: heat exchangers, pumps, compressors, turbines, etc.. At the subsystem and system levels, optimization can be done at three different levels which involve increasingly complicated analysis. These levels are: optimum operating conditions, optimum network design, and optimum network configuration/expert system. It is anticipated that the optimization schemes will provide a unique capability in VITMAC as a design tool and enhance VITMAC as a commercial product.

The following is description of the optimization schemes which address these issues. This task comprises one of the major tasks of the proposed effort and its objectives will be achieved by completion of the following optimization schemes: component optimization, network optimization.

3.1.1 Component Optimization

In development of this scheme, second-law analysis methods such as exergy analysis and entropy generation minimization (EGM) methods will be used to provide performance optimization of components. The fact that these second-law methods can be used in optimizing the energy usage of systems and in establishing realistic upper limits for their thermodynamic performance, make them extremely attractive.

Exergy is the available energy of a reservoir or a flow that can be fully converted to work in an ideal (reversible) thermodynamic cycle in which no entropy is generated (Bejan, 1988, 1996; Bejan et al., 1996). In real systems, entropy is generated and part of exergy is wasted. In an exergy analysis of a system, the entropy generation and the lost exergy are calculated for each component along with the system, and optimum configurations are identified for which the entropy generation is minimum to guarantee the performance conditions (Bejan, 1982).

In a conventional analysis, the emphasis is mainly on balancing energy (1st law of thermodynamics) where entropy generation (2nd law of thermodynamics) is accounted for by assigning efficiencies for each component of the system. In exergy analysis, the energy balance and entropy generation are considered simultaneously. Combination of the 1st and 2nd laws of thermodynamics yields the exergy equation which accounts for the energy balance as well as exergy loss (or entropy generation). This approach allows for full coupling between the components of a system and provides a systematic analysis of the performance of the entire system under consideration. In a system, the total entropy generation is the summation of its counterparts in every process involved in the system. Examples of processes are shown in Table 1 along with the entropy generation and exergy lost in each process.

Table 1. Processes and Their Entropy Generation and Exergy Loss

Process	Process Parameters	Entropy Generation	Exergy Lost
Heat Transfer	Heat flux $\dot{Q}$, Temps T_L T_H	$\dot{S}_{gen} = \dot{Q}/T_L - \dot{Q}/T_H$	$\dot{E}_{lost} = \dot{Q}(1 - T_L / T_H)$
Internal Flow	Mass flow rate $\dot{m}$	$\dot{S}_{gen} = -\dot{m}\int_{in}^{out} (1/\rho T)_h dP$	$\dot{E}_{lost} = \dot{m}[(h - T_o s)_{in} - (h - T_o s)_{out}]$
Thermoelectric	Heat Q, and Current I	$S_{gen} = Q/T + I^2 R/T$	$E_{lost} = T_o(Q/T + I^2 R/T)$
Melting, freezing	Phase change enthalpy Δh	$S_{gen} = \Delta h / T$	$E_{lost} = T_o \Delta h / T$
Radiation	Heat Q, Temperature T	$S_{gen} = \varepsilon A F \sigma (T^4 - T_o^4)$	$E_{lost} = \varepsilon A F \sigma (3T^4 - T_o^4 - 4 T_o T^3)$

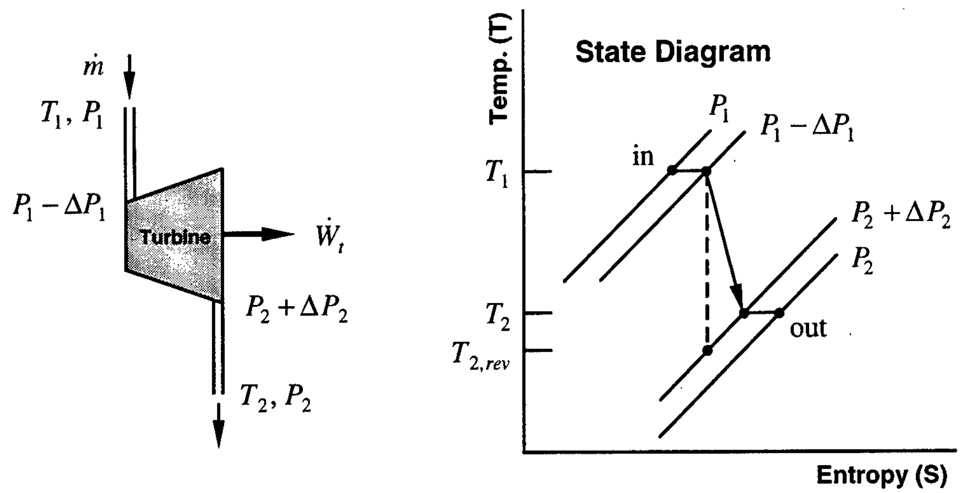


Figure 1. State Diagram Shows Entropy Generation Through Turbine with Inlet and Discharge Pipes

Two examples are presented below to illustrate the basics of the optimization method based on exergy analysis: one for a turbine and the other for a heat exchanger. The configuration used in the first example, which contains three components: a gas turbine and the ducts leading into and out of the turbine, is shown in Figure 1. The overall pressure difference is fixed. The assembly has three sources of entropy generation: a pressure drop associated with the inlet pipe, losses through the turbine stages, and another pressure drop associated with the exit pipe. The turbine power output can be maximized by adjusting the flow rate, which is equivalent to optimizing the distribution of pressure drops along the flow path from P_1 to P_2.

Another simple example is a system that relies on one or more heat exchangers. When the total weight of the heat exchangers is fixed, or must be minimized, there is an optimal way of allocating the area among the heat exchangers such that the system reaches its realistic upper limit of thermodynamic performance (Bejan, 1982). Optimization approaches of this type can be applied at the conceptual design-level when assessing new or postulated subsystem components.

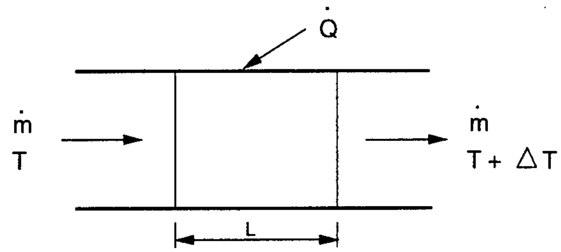


Figure 2. A Heat-Exchanger Passage

The entropy generation minimization method can also be applied to a given component. As an example, this optimization method is applied here to a heat-exchanger passage to find the optimum passage diameter. A heat flux $\dot{Q}$ is applied to a duct with length L and a mass flux $\dot{m}$ flowing through it (see Figure 2). The entropy generation in this process will be due to both heat transfer, as well as pressure drop due to friction. That is,

$$\dot{S}_{gen} = (\dot{S}_{gen})_{heat-transfer} + (\dot{S}_{gen})_{pressure-drop} \tag{1}$$

It can be shown that (Bejan, 1988)

$$\dot{S}_{gen} = \frac{\dot{Q}^2 \,\mathrm{Re}^{-0.8}}{0.023\pi L k T^2 \,\mathrm{Pr}^{0.4}} + \frac{0.0524\mu^5 \,\mathrm{Re}^{4.8}}{L\dot{m}^2\rho^2 T} \tag{2}$$

where, the flow Reynolds number, Re, and Prandtl number, Pr, are defined by $\mathrm{Re} = 4\dot{m}/\pi\mu D$ and $\mathrm{Pr} = \mu c_p/k$, respectively. The fluid properties in Eq. (2) are the thermal conductivity, k, viscosity, μ, and heat capacity, c_p.

From Eq. (2) it is clear that increasing the flow Reynolds number (by increasing the flow mass flux or decreasing the duct diameter) will have counter effects on the total entropy generation. The heat-transfer entropy generation decreases while the internal-flow entropy generation increases due to the increase in pressure drop. For a given heat flux and mass flow rate, the entropy generation can be minimized for an optimum passage diameter by finding an optimum Reynolds number which yields minimum entropy generation, i.e.,

$d\dot{S}_{gen} / d\mathrm{Re} = 0$, which results in $\mathrm{Re}_{opt} = 2.023\,\mathrm{Pr}^{-0.071}\left(\dfrac{\rho^2 \dot{m}^2 \dot{Q}^2}{L^2 \mu^2 k T}\right)^{0.1785}$ (3)

Or, in relative terms

$$\frac{\dot{S}_{gen}}{\dot{S}_{gen,\min}} = 0.856\left(\frac{\mathrm{Re}}{\mathrm{Re}_{opt}}\right)^{-0.8} + 0.144\left(\frac{\mathrm{Re}}{\mathrm{Re}_{opt}}\right)^{4.8} \tag{4}$$

where, $\dot{S}_{gen,\min} = \dot{S}_{gen}(\mathrm{Re}_{opt})$. This relationship is shown in Figure 3. At Re = Re_{opt}, the entropy generation is minimum. For pipe diameters larger or smaller than the optimum value the entropy generation is larger.

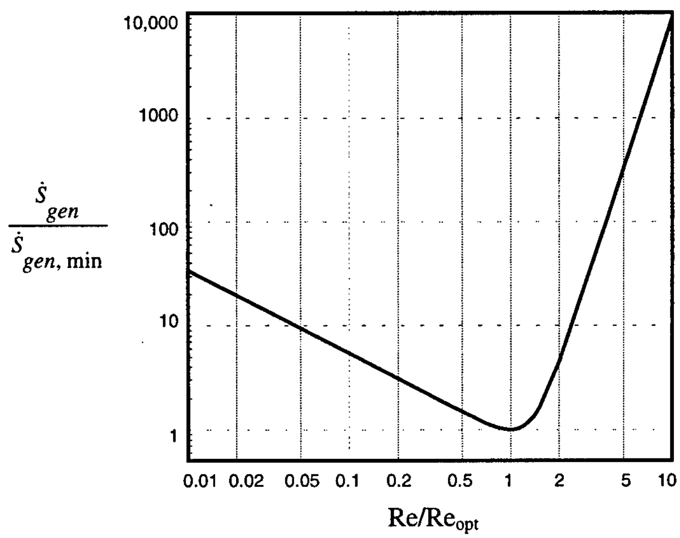


Figure 3. The Relative Entropy-Generation Rate for a Heat-Exchanger Passage

Furthermore, the optimum passage diameter for minimum irreversibility may not coincide with minimum entropy generation for each mechanism heat transfer and pressure drop separately. To investigate this issue for the above example, an irreversibility ratio, ϕ, is defined as

$$\phi = \frac{fluid - flow - irreversibility}{heat - transfer - irreversibility} = \frac{(\dot{S}_{gen})_{pressure - drop}}{(\dot{S}_{gen})_{heat - transfer}} \quad (5)$$

At optimum conditions (Re = Re_{opt}), $\phi_{opt} = 0.168$. That is, the optimum trade-off between $(\dot{S}_{gen})_{pressure - drop}$ and $(\dot{S}_{gen})_{heat - transfer}$ does not coincide with perfect balance between the two irreversibilities. Such an optimization analysis could be applied to all of the components within a system to determine the overall best performance.

In this task, optimization schemes based on exergy analysis will be developed for components and systems as well. As a top level analysis, the optimization routine will call VITMAC calculations and evaluates the entropy generation at each component. Calculated flow characteristics will be fed to component-level optimization routines, to evaluate the optimum conditions at each component. The optimized parameters of the components will then be fed to VITMAC for the next iteration of the calculations. The calculations will stop after the prescribed convergence criteria are met.

3.1.2 Network Optimization

Based on the Phase I work, an optimization architecture was structured that considered a flowpath network optimization methodology. While traditional methods can be used to optimize at the component level, they cannot be effectively used at the subsystem and total system level until the optimized network has been identified. Accordingly, network configurations were identified based on expert knowledge that would be generically used to establish system optimization for thermal management. These basic configurations can be easily modified to meet user requirements; hence providing an architecture for the optimization process.

At the system and subsystem levels, optimization can be done at three different steps, from simple to a complicated analysis. These steps are: optimum operating conditions, optimum network design, and optimum network configuration. Using the optimum operation analysis, for a given thermal network, the operating conditions can be found to satisfy the constraints such as set limits on temperature, pressure or flow rate at a given junction in the network. For optimum network design, the optimization analysis will use the network layout but allows for choosing different components in the network which will satisfy the thermal constraints on the coolants as will as the subsystem constraints such as minimum weight or minimum volume. The optimum network requires development of a complicated optimization scheme which allows for selection of not only alternative components of the network, but also different layouts for the optimum network. The following presents the description of these levels of optimization.

Optimum Operating Conditions A simple optimization analysis may involve determination of optimum operating conditions of an existing thermal network for a set limit on the temperature, pressure, and/or mass flow rate (constraint parameters) at one or more locations in the network. These conditions can be satisfied by controlling the network conditions such as a valve setting, the fluid source pressure, pump conditions, or/and a component heat load (control parameters). An optimization model was developed and integrated into VITMAC which provides calculations for optimum conditions of a thermal management system with one constraint and one control parameter. In this task, this optimization model will be enhanced to allow for at least two constraint parameters and two control parameters. The following example describes an optimization analysis for network optimum operation conditions for generic thermal management network (Figure 4.)

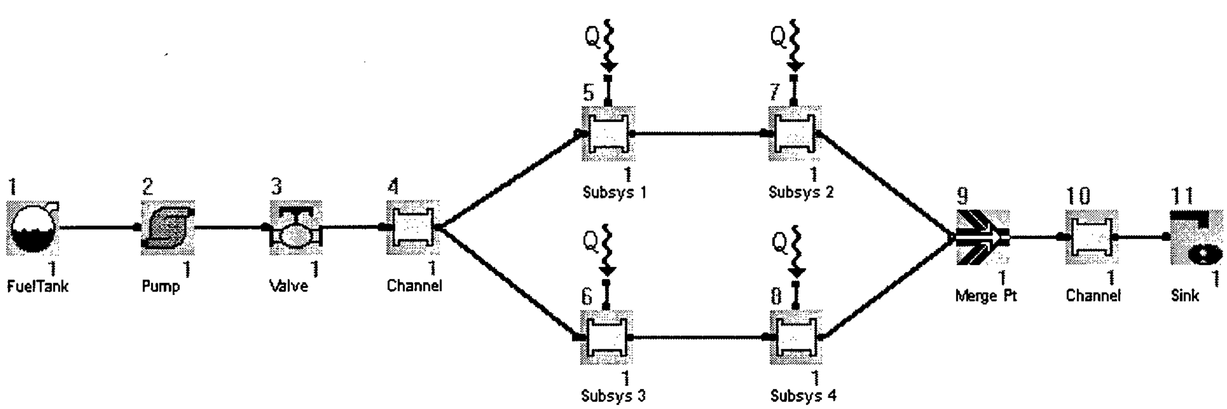


Figure 4. A generic thermal management system

This network consists of a fluid source, such as a fuel tank, a pump, a valve, a flow channel, four subsystems, a flow channel, and a deposition point, designated as the sink. The fuel, JP-7, is heated in the subsystems by subjecting each one to a heat load of 58 Btu/sec. With the specified network flow characteristics the fuel temperature at the merge point is calculated to be about 940 R. If it is required that the fuel temperature at the exit of this network be under 850 R, the valve setting can be changed to allow for more fuel flow in the network to reduce the exit temperature. The optimization calculations show that the valve loss coefficient (K_{loss}) should be reduced from its original value of 12 to 0.2 (about fully open valve) to satisfy the operating conditions and the temperature limit.

If the valve setting cannot be changed to its calculated optimized value, the fuel tank pressure can be increased to allow for higher flow rate. The optimized source pressure was found to be 15.3 psi (an increase of 0.6 psi from its atmospheric pressure). If the increase in the tank pressure is not a viable option, the heat load on each one of the subsystems may be reduced. The required heat load was found to be about 15 Btu/sec on each one of the subsystems to ensure that the fuel exit temperature is just under 850 R.

In the above example, only one control parameter was allowed to be changed at a time. It may be necessary to simultaneously change more than one parameter to control a set limit on the flow characteristics. Accordingly, this expanded capability will be recommended in the proposed Phase II program.

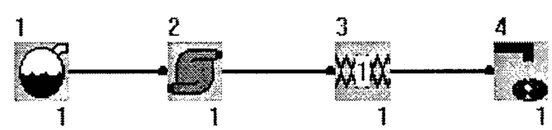


Figure 5. A section of a thermal management network to be optimized with alternative pump and heat exchanger

Optimum Network Design A thermal management network design for a specified cooling capacity may be optimized to have minimum weight by selecting alternative components of the flow network. Figure 5 shows a section of a thermal management network which includes a pump and a heat exchanger. In a given heat exchanger, the applied heat load may require a high flow rate, which may require a pump with high pressure head, and consequently, high weight. The developed optimization scheme in this task will provide a model for selection of the optimized set of a pump and a heat exchanger, from a list of available components, which has the least weight among all the available options. For these calculations, weight of each component is required. A data base can be developed to provide weight for pipes, fittings, and components used in thermal management systems (Phase II recommendations).

Optimum Network Configuration/Expert System Optimum network configurations require the development of a complicated optimization scheme which allows for selection of not only alternative components of the network, but also different layout to reach an optimum thermal management system. Artificial intelligence and neural networking were identified as appropriate approach for the required optimization scheme. One practical outgrowth of artificial intelligence research has been the development of expert systems which have become a well developed commercial technology. By textbook definition, they are: "... a class of computer programs that can advise, analyze, categorize, consult, design, diagnose, ...test and tutor." Examples known to PC owners are the Apple Guide and Microsoft Wizards which, in addition to a documented help database, can provide step-by-step onscreen instructions on using various program functions. Such expert system concepts can provide a useful aid to developing an optimum thermal management system, for example, when used in conjunction with the formal optimization procedures to be implemented in VITMAC. As a result, part of the optimization task in Phase II will be devoted to exploring the implementation of expert system concepts for use in the setup and execution of a VITMAC model.

The development of a thermal management system (TMS), and a VITMAC model thereof, usually starts with the heat loads which must be accommodated and a single fluid loop. The mass flow rate, for example, must be determined so that the fluid operating temperatures are within certain limits. The solution of this first-step problem provides the motivation for the first level optimization implemented in VITMAC and described above. Implemented as a program-user interaction it essentially represents a simple "production system" which is a type of expert system based on "if-then-else" rules. In this case, the program "suggests" an operating condition (flow rate regulated by a pump pressure, tank pressure or valve setting) based upon querying the user concerning desired maximum loop temperature, for example. The TMS design subsequently grows by the addition of additional fluid loops and heat exchangers, structures and cooling panels between the heat loads and the primary coolant loop. Numerous additional design and operating parameters are introduced which then must be varied, leading to an optimum design. Formal component level and circuit level optimization procedures will be developed in the Phase II effort and the development of expert system "rules-of-thumb" will complement the user interaction with these procedures.

Production systems consist of the rules database along with a control system to interpret the rules and to use them for something productive. In VITMAC it is envisioned that these production system rules will be implemented as suggestions to the user as part of the GUI, which provides the control system to interact with the user. The suggestions will be implemented conditionally, executed to show their benefit and implemented finally only with user concurrence. Paralleling the formal optimization procedures, component level and network level suggestions will also be developed in Phase II. On the component level, examples could include suggestions for the type, size and material for heat exchangers or cooling panels, for example, or for secondary loop operating conditions to maximize component effectiveness. For circuit level optimization a myriad of possibilities exist; some rule based suggestions, implemented as dialog boxes with user selected conditional buttons or data entry fields, are the following:

"Try transient solution (in Set Network menu) with $\Delta t = .1$ sec"

"Valve N has a K_{loss} that may result in unphysical operation; reduce to 2.5?"

"Use Hypertherm-X as fluid in loop N to enhance system effectiveness"

"A higher flow rate in loop N will result in a higher heat exchanger M effectiveness"

Some rules or suggestions will be general and leave it up to the user to implement while others will be specific with specific suggestions for operating conditions or configuration changes.

The VITMAC guide must be useful but innocuous; i.e. it must help the user develop an optimum design without interfering with the creative design process. The development and recommendations summarized here can clearly be an open ended project, however, we envision a first step in the indicated directions as an aid to the VITMAC user and as a necessary adjunct to providing a commercial product.

3.2 Engine Thermal Management

In advanced aircraft, the engine is a major source of heat load on the structure of the vehicle. As flight speed increases to above approximately Mach 4, the ambient air temperature relative to the aircraft is too high to utilize ram air as an effective coolant. As the heat sink capability of the air disappears, the aircraft fuel becomes the primary cooling resource, providing cooling capacity for absorbing components heat load and/or for cooling the ram air before it is used in the engine cooling systems (Van Griethuysen et al., 1996).

The thermal management of an advanced engine must address both the air-side (engine internal flow) and coolant-side (thermal-network flow). The air side deals with predicting the heat loads on engine compartment structural surfaces, while the coolant-side deals with the absorption, distribution, and rejection of engine heat loads, aeroheating loads, if applicable, and other subsystem heat loads. The coolant side utilizes the fuel as the main coolant, and involves single or multiple loops, turbomachinary to circulate the fuel into the heat exchangers, heat exchangers/reactors (in case of endothermic fuels), and cooling panels. Additional non-fuel coolants may be used depending on the design and cooling configuration proposed.

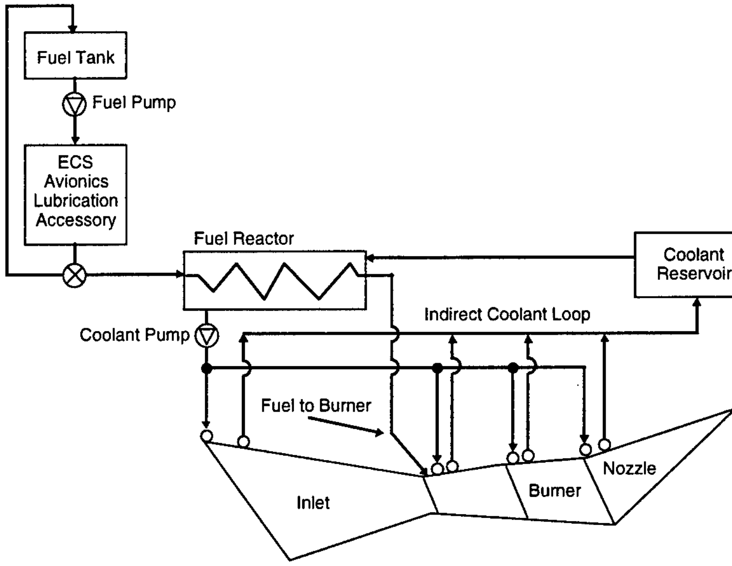


Figure 6. Scramjet thermal management scheme

An example of scramjet thermal management scheme (Spadaccini et al., 1993), shown in Figure 6, represents a configuration for cooling both the vehicle auxiliary and propulsion subsystems. The fuel is first used to cool the aircraft environmental control system (ECS), avionics, lubrication system, and accessory subsystems. The fuel is then circulated through a heat exchanger/reactor to cool the secondary cooling fluid prior to being injected into the burner. The secondary cooling fluid absorbs the heat load from the engine components, namely, the inlet, burner, and nozzle, in a closed-loop configuration. The heated secondary fluid is circulated in the heat exchanger where it is cooled by the fuel. One of the objectives of analyzing such a scheme is the determination of the required mass flow rates, in both the fuel and coolant loops, necessary to keep the fluids temperature below set limits. Also, in a parametric study, different flow channels can be investigated to find an optimized cooling network with the minimum pressure drop in the loops. With lower pressure drop in the loops, smaller pumps can be used, which in turn results in a system with lower weight and volume.

Using VITMAC, a thermal network such as that shown in Figure 6, can be analyzed in two ways (Issacci, 1995a; Van Griethuysen and Issacci, 1996): 1) the engine heat loads are specified and only the coolant side is considered, 2) the engine internal flow is analyzed and directly coupled to the coolant side. For the second approach, VITMAC offers calculations based on a fundamental thermodynamic approach. It is recommended that in Phase II, an engine performance code or a thermodynamic cycle code be integrated with VITMAC to allow for better estimates of the engine heat loads.

The Phase I investigation identified performance codes that can be used, namely, JHU/APL's RJPA model, and NASA's CEA and NEPP models. Moreover, linkage interface requirements were identified as well as a methodology for developing an unique module. A database had also been identified (NASP, and the WL/POP HyTech and SCT programs) to help formulate the heat loads for the engine module. The JHU/APL will provide services to develop the module as well as the required linkage of the performance codes to VITMAC. This effort will provide an engine model in VITMAC that can be integrated into the total system thermal management design/analysis. With the optimization routines, the commercial potential for engine companies, government, and universities will be significantly enhanced since no other thermal management tool is available at this level for design.

The following is a description of different elements, required for development of the VITMAC's engine module. These elements are: 1) integrated engine module, 2) linkage between VITMAC and an engine performance code, and 3) linkage between VITMAC and a cycle code.

3.2.1 Integrated Engine Module

Based on the Phase I effort and the discussions at the workshop at WL, it became clear that a simple engine performance calculation is required for a top level thermal analysis. The VITMAC engine module at its current status provides engine performance calculations for ramjet, scramjet, turbojet and turbofan engines. The analysis is based on thermodynamic cycle calculations and correlations. It is recommended that the current VITMAC engine module be modified to include trade off analysis as well as on-design and off-design calculations based on the approach outlined in Matingley (1996). The developed engine module will allow thermal management design of an engine using its cycle performance calculations and the thermal characteristics of the cooling circuit.

3.2.2 Link with an Engine Performance Code

As described above, the trend in thermal management analysis in general and VITMAC integrated thermal management, in particular, is to emphasize the "integrated" in the sense of implicitly linking the thermal management system (TMS) with models for the heat generating system; in the present case of interest, namely, the engine. In response to this direction, a key part of a proposed Phase II program will involve linking VITMAC with a suite of engine models. For present purposes these are categorized as engine performance models for ramjet/scramjet and rocket engines and engine cycle models for general turbofan/turbojet engines. Proposed activities to link VITMAC with "industry standard" models in each category are discussed in this subsection and the next respectively.

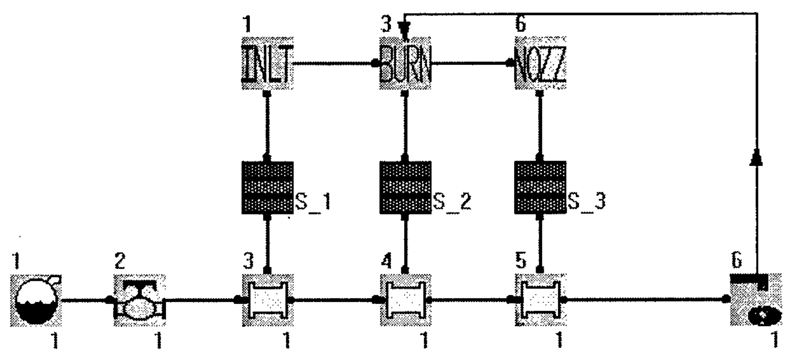


Figure 7. VITMAC Generic Scramjet Cooling Network

For initial assessment purposes, a preliminary version of a ramjet-scramjet model (Mattingly, 1996) has been implemented in VITMAC. A rudimentary TMS circuit for cooling a scramjet engine is presented in Figure 7, which illustrates the coupling of the principal scramjet components—inlet, combustor and nozzle—with a VITMAC cooling loop. In this simplified case, engine cooling is provided by a fuel loop consisting of a tank (source) of fuel leading to three cooling panels which cool respective engine components through a multilayered structure. VITMAC provides for a range of user selectable heat transfer surfaces within the cooling passages and within the intervening structure. Endothermic fuel reactions, which provide an additional "heat sink" to magnify the effectiveness of the cooling system, can also be modeled. After cooling the engine, the heated fuel ultimately is injected into the combustor to power and perhaps film-cool the combustor, as shown in the diagram.

The principal reason to link an engine model with VITMAC is to automatically predict the heat loads with which the TMS must deal during a conceptual or preliminary design study or in a "mission analysis" of an existing design concept. However, other links are also of interest. For example, in the above case, the rate of fuel flow needed to provide adequate cooling may be more than the engine needs to operate at the specified condition (e.g., thrust level). Hence the fuel mass flow rate should be inherently linked to the engine operation and appropriate measures to return fuel to the tank or use it for other purposes must be provided for. Currently, the links between the engine model and the TMS loop(s) are limited in both type and quality. Subsidiary models to predict the heat loads for each engine component are currently lacking as are intimate links of TMS fluids (principally the fuel) with the engine. Both deficiencies will be examined and remedied in the proposed Phase II program.

During the Phase I effort, several available government/industry ramjet/scramjet models have been examined in some detail. In addition to the aforementioned Mattingly derivative, the RJPA model of Billig and Pandolfini (1990, 1992), and the APCAT model have been examined. APCAT uses engineering level approximations (ala Mattingly) resulting in a robust model which can treat a wide range of ramjet and scramjet configurations quickly and easily. RJPA uses a next level of approximation implementing a one-dimensional integral method for the engine flow path and making liberal use of empirical correlation's based on an extensive database. Because of its inherent capability, as described in the following paragraphs, and its wide use, RJPA has been recommended for linking to VITMAC in a Phase II program.

The Johns Hopkins University Applied Physics Laboratory (JHU/APL), which will assist UNISTRY in the proposed effort, has designed, tested, and analyzed ramjet and scramjet engines for over fifty years, performing design and evaluation of ramjet/scramjet inlet, isolator, combustor, and nozzle engine components in addition to performing complete engine free-jet and flight test evaluations. JHU/APL's work on ramjets/scramjets has encompassed engine designs for supersonic/hypersonic missiles and hypersonic aircraft.

An engineering tool for the investigation of hypersonic engines has been under continual development at JHU/APL for over thirty years. The Ramjet Performance Analysis (RJPA) code computes stream-thrust-averaged flow quantities at the component interfaces in a hypersonic engine using specified engine component efficiencies and heat loads (Pandolfini and Friedman, 1992). The RJPA code has matured through its use in the JHU/APL's experimental hypersonic engine programs. The code has been used to estimate the performance of scramjets, dual-combustor ramjets, rockets, and subsonic combustors and has been a major component of JHU/APL's hypersonic engine system analysis capability. RJPA incorporates an integral analysis technique to compute hypersonic engine performance using a general equilibrium chemistry package that allows for the analysis of any fuel/oxidizer combination.

In order to compute hypersonic engine performance and the associated stream-thrust-averaged flow quantities at the component interfaces, both the component efficiencies and their associated heat loads must be known. Typically, for hypersonic inlet/isolator configurations, computational fluid dynamics (CFD) is used to estimate the component heat load. A large database was generated for the National Aerospace Plane (NASP) program that would allow the development of an empirical correlation for inlet heat load for hypersonic inlets. This database can be used to calibrate CFD codes so that these codes can be used to fill in the database for configurations of interest for which detailed test data does not exist. In Phase II, a mechanism will be developed to couple this inlet test database with CFD results, and create a correlation that will be used in the VITMAC engine module.

Currently, an empirical correlation exists for the estimation of hypersonic combustor heat loads up to a flight Mach number of about 8. This correlation (Orth et al., 1992) was developed at JHU/APL using results from a number of scramjet combustor experiments for both hydrogen and hydrocarbon fuels. Heat transfer measurements from scramjet combustor experiments performed during the NASP program with hydrogen fuel can be correlated to extend the heat load database up to about Mach 12. In Phase II, a mechanism will be developed to compile both databases into a combustor heat load correlation to be used in the VITMAC engine module. The NASP database will be augmented by including the data generated by the on-going Scramjet Component Technology (SCT) program sponsored by WL/POP via the HyTech program.

For hypersonic vehicles that use the fuel to cool any part of the structure, the engine operation is directly coupled to the vehicle cooling requirements. The methodology discussed above allows the vehicle and engine heat loads to be coupled with an integral analysis of the engine to determine the engine operating conditions and heat load in a fully coupled fashion.

In addition to air-breathing engines, rocket engines are also subject to similar thermal management needs and approaches. Engine surfaces must be protected from high heat loads in the combustion chamber, throat and exhaust nozzle either by film cooling, or regenerative cooling by fuel loops within the structures, or both. Thus the coupling of the engine and TMS is equally intimate as in air-breathing engines. Since there is likely to be significant interest in using VITMAC in this manner, and as a result commercial potential, a portion of the Phase II effort will be devoted to coupling VITMAC to an available rocket performance model. In this case, a recognized industry standard model has been in existence for some time, namely, the well known Gordon and McBride (1976, 1988, and 1994) chemical equilibrium program which has been updated to include rocket performance calculations (Chemical Equilibrium with Applications, CEA code, Gordon and McBride, 1994). The model, of course, includes an extensive list of chemical species resulting from combustion of almost any propellant mixture. The model assumes a one-dimensional expansion of the combustion product mixture from specified chamber conditions through a throat to a specified nozzle expansion ratio. The fluid state throughout is thus accurately determined and will be coupled to an extensive database of heat transfer correlation's (available from NASA and the Air Force, Van Griethuysen, 1997) to specify the heat loads to the VITMAC

TMS components. It is not anticipated that VITMAC will be utilized to model a liquid fueled rocket turbomachinery system although it could do so in at least a rudimentary fashion. Rather, subsidiary links between the TMS and the engine model will be provided to exchange cooling fluids at specified or model-determined flow rates. As in the scramjet case, liquid rockets use the fuel as the principal cooling fluid so that the mass exchange links will likely couple to the performance model. VITMAC includes hydrocarbon and cryogenic, however, hypergolic propellants and specialized cooling fluids will have to be added as part of the engine model development task.

The principal effort required for coupling a ramjet/scramjet/rocket engine performance model to VITMAC will be determining and executing the type and number of links between the engine model and the VITMAC TMS loops. The engine model, either RJPA or CEA, can be implemented as a FORTRAN subroutine which is compatible with the core VITMAC model. It will be important to communicate a general parameter list between each routine and of course allow the user to select and quantify these parameter links. As mentioned before, the heat load on VITMAC components is the primary quantity to be "linked" but the coolant/fuel fluid links must also be permitted in a general fashion. In the current engine model, each engine component is required to interact with the coolant loop through a structure to which the engine-defined heat load is applied (see Figure 7). It is anticipated that this will be generalized to include multiple structures and to provide for using a portion of the fuel (coolant) to modify the heat load via film cooling. Additional links which modify the fuel flow rate depending on engine performance or vice versa will also be investigated.

In previous interactions with VITMAC users, an often heard request was to permit interaction with a "user defined subroutine" allowing the VITMAC user to implement a call to a subroutine, which models, for example, proprietary engine or heat exchanger. The requirement to implement RJPA and CEA into VITMAC in Phase II will be a first step in this direction since its success will illuminate the path for more general implementations of this type.

3.2.3 Link with a Cycle Code

Advanced turbojet and combined cycle engines are also increasingly dependent on the fuel subsystem, as well as specialized vapor cycle subsystems, for the thermal management of general engine and heat producing subsystems (ECS, high power electronics, etc.). It is thus incumbent upon a Phase II effort to provide for coupling of VITMAC to an industry standard turbine engine (turbojet/turbofan) cycle code or model. In Phase I, two such models were evaluated in some detail and the NEPP was selected for the proposed Phase II implementation. The motivation, needs and activities involved in this effort are discussed in this section.

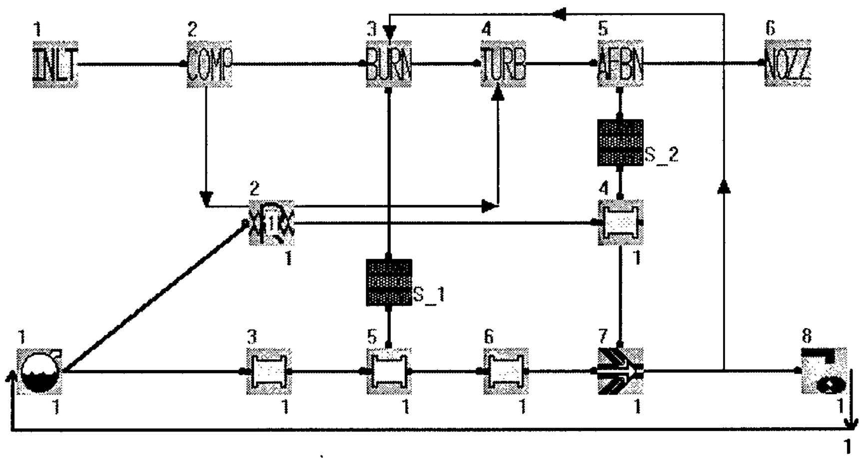


Figure 8. VITMAC Generic Turbojet Engine Cooling Network

Figure 8 illustrates the interaction of an elementary VITMAC TMS model with a preliminary turbojet model which has been previously implemented in VITMAC. The engine model shown, contains all of the engine components, from inlet to nozzle, which could potentially interact with the TMS. In the present case, such interaction consists of direct heat load exchange from the combustor and afterburner, through structural surfaces, to respective cooling panels through which the fuel passes. Also indicated on the TMS of Figure 8 is the use of compressor bleed air, cooled by a heat exchanger/reactor, and reintroduced into the turbine for active cooling of turbine blades or hot-section surfaces. Upon completing its coolant function, the fuel is injected into the combustor and/or afterburner to complete its propulsion function. A real TMS and engine system would possess additional interacting fluid loops involving ram air and perhaps vapor cycle loops and, of course, a complex fuel management system including boost pumps and control valves for shuttling fuel throughout the aircraft. In the proposed program, the VITMAC engine module will be upgraded to the industry standard NEPP model and the engine/TMS interactions mentioned here, at a minimum will be included. By way of summarizing these task activities, the available engine models which were examined in the Phase I program will now be described.

Of the numerous engine models, two public domain codes were found to standout, NEPP, mentioned above, and ROCETS (ROCket Engine Transient Simulation); other models considered were either proprietary in their most complete versions or they were teaching tool oriented. Both NEPP and ROCETS are quite similar in their approach and capabilities; both consider the engine as a user selected combination of engine components: compressors, turbines, inlets, nozzles, combustor, etc. Almost any engine configuration can be simulated by combining components and specialized component models can be more simply upgraded. The ROCETS code was originally developed for rocket engine simulations as its name suggests, and was expanded to include turbine engines by adding turbine engine component models (principally turbines and compressors) to the available combustion chamber and nozzle components. This expanded modeling range of capability provides a strong reason for using ROCETS as the proposed engine module but the detailed component capability, mission analysis capability and industry standard reputation provided the compelling reasons for choosing NEPP at this time.

Much akin to the VITMAC model, NEPP performs a steady one-dimensional thermodynamic analysis of a turbine engine which is modeled as interacting components. NEPP provides a set of standard components including; inlet, compressors, turbines, burner, gas generator, nozzle, water injector, heat exchanger, splitter, ejector, loads or propellers, and shafts. As expected, these components can be connected to simulate a wide range of turbine engine cycles from turboprops/jets/fans to air-turbo-rocket and supersonic cruise variable cycle engines. In addition, secondary air paths such as compressor bleed and ram air can be simulated including their cooling and reinjection into the primary air path. This capability should simplify the integration of such flow loops with the similar VITMAC TMS loops. Off design performance, important to mission analyses, is calculated using performance maps which can be modified and input by the user. Of principal import are the compressor and turbine performance maps which are scaled to design-point mass flow, pressure ratios and efficiency. A multimode engine option is also provided which permits the simulation of an engine that may change its configuration over the course of a mission. Properties of general fuel and high temperature air mixtures (dissociation included) are simulated in detail using the Gorden and McBride CEC model, thus providing some redundancy with the rocket performance model, CEA described earlier, which uses the same chemical equilibrium model. Finally, NEPP already implements a mission analysis capability as well as an engine weights estimation routine which will dovetail with the proposed optimization investigations.

Based on lessons learned with the preliminary engine models, as well as the evaluation summarized here, the coupling of NEPP and VITMAC will proceed in the Phase II program in a straightforward albeit challenging fashion. The incorporation of the NEPP FORTRAN subroutines will be straightforward after deciding which or how much of its inherent capability to implement. For example, NEPP contains an additional program library which contain more sophisticated performance maps and component descriptions for expanding its basic component model capability. Implementation of these will be based upon future user interaction to balance user needs against unnecessary model complication. The primary effort will parallel the discussion of the previous section regarding implementation of a complete and robust suite of links to VITMAC. Fuel flow rate tied to engine performance and cooling requirements is one obvious link but, as mentioned previously, links to ram air flow rate, compressor bleed and reinjection for turbine cooling are others. Of course, direct heat loads to the TMS will also be provided but as in the scramjet engine these will require additional effort to define required heat loads as functions of engine configuration and operating conditions as well as TMS configuration and operating conditions. Finally, the VITMAC graphical user interface will be modified to guide the user through the selection of: steady state or full transient mission parameters (altitude, speed, engine thrust level etc.), engine configuration parameters, as well as the all-important interaction parameters which "link" the TMS model with the engine model.

3.3 Graphical User Interface (GUI)

Currently, VITMAC employs a PC Windows based graphical user interface which provides a user friendly environment for thermal network simulation, input data, and graphical display of the simulation results. In Phase I, several GUI features were developed and incorporated into VITMAC. One of these features is the capability to group a set of components and graphically represent them as a subsystem icon. With such a capability, a more complicated network can be shown by using subsystem icons where each icon represents a set of components. A subsystem icon can be expanded for updating its components' attributes.

Also, the GUI was enhanced to accommodate the optimization analysis outlined in Section 3.1. The network optimization options can be accessed by selecting *Network Options* from the VITMAC *Set* menu. After selecting YES for Optimization in the Network Options dialog box, the three optimization options will appear, as shown in Figure 9.

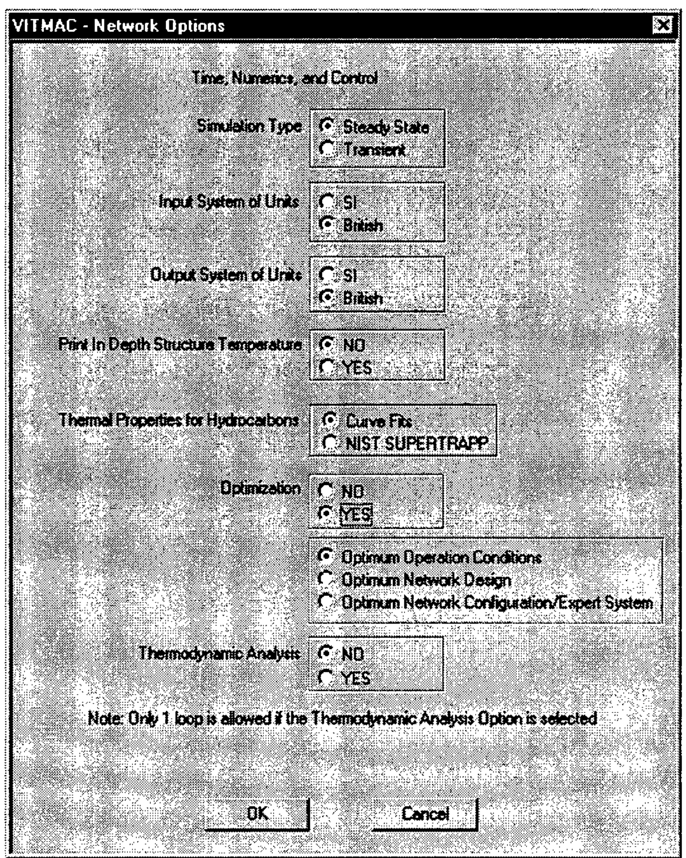


Figure 9. Network options dialog box with optimization selected

Selecting the Optimum Operating Conditions option, displays the Optimum Operating Conditions dialog box, as shown in Figure 10. For each loop, one constraint and one control parameter are allowed. For multi-loop systems, it is possible to run one or more loops with optimization and one or more loops without optimization in the same simulation. To implement the optimum operating conditions option for a particular loop, select a constraint parameter from the drop down list (Figure 11a), the component number in which the constraint parameter is to be controlled, select a control parameter from the drop down list (Figure 11b), and the component number in which the control parameter is to be varied to satisfy the constraint parameter.

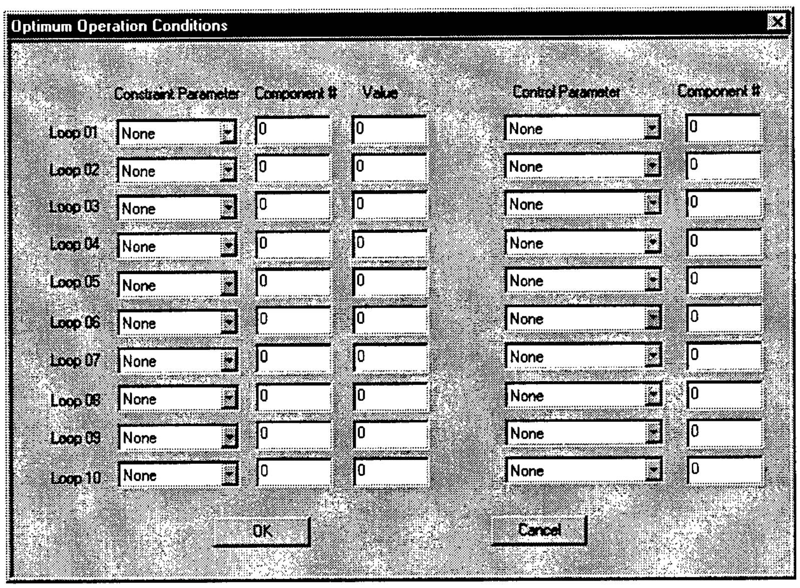
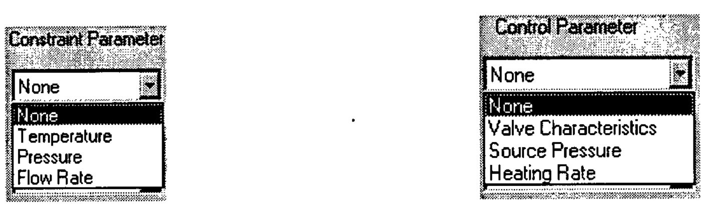


Figure 10. Optimum operating conditions dialog box



(a) (b)

Figure 11. (a) Constraint parameter drop down list. (b) Control parameter drop down list

The GUI will be further enhanced in Phase II to include all the modeling development accomplished in optimization and engine modules. Also, via close collaboration with current and potential users of VITMAC, additional required features will be identified for further development of the GUI, as well as identification of the current GUI areas that need improvement.

A candidate GUI feature to be added during Phase II will be the development of a dynamic link between the calculation module (the FORTRAN code) and the GUI. For transient calculations, this feature allows for the simultaneous display of the results and their consequent changes in time.

3.4 Commercialization Plan

A commercialization plan will be developed in Phase II for packaging VITMAC as a commercial code for applications in aerospace as well as other disciplines, such as Army ground vehicles, automotive industry, power plants, etc.. The commercialization plan will identify sources of Phase III funding for specific applications, and determine requirements for transferring VITMAC as a product to the market place.

As another means of commercialization and providing user support, a World Wide Web (WWW) page is recommended which will provide a relatively straightforward and quick method of obtaining additional exposure to VITMAC. Accessible over the Internet, a WWW site allows people the world over to access information, download and upload files, access technical support information, and participate in discussion groups regarding VITMAC.

Creating a state-of-the-art VITMAC web site is well within the capabilities of the proposed team. Some of the features routinely implemented are the following:

- Index Service: This allows users to perform searches within a particular web site for specific information. The results of such a search are displayed in a custom, dynamically created web page as links.

- Java Applets and CGI Scripts: Interactivity and information exchange is greatly enhanced by utilizing programming or scripting languages such as Java and CGI. These techniques can also be used to communicate with databases.
- Secure Sockets Layer: Using 128-bit keys over a secure sockets layer, allows an acceptable level of security for those transactions which require it.
- Adequate Bandwidth: Based on the usage log files and the number of hits the site gets, the bandwidth will be adjusted for the site in order to ensure adequate response times for users while minimizing operating costs.

Several different topics are envisioned for the VITMAC web site. First, the commercial pages will be dedicated to advocating VITMAC to the thermal management public at large. On-line brochures giving top-level and detailed descriptions of VITMAC, sample VITMAC screens, and on-line demonstrations will be included in this area of the web site. With a web browser, a user can double click on an icon and see an interactive demonstration of VITMAC's capabilities right over the Internet.

Another area of the web site will be dedicated to existing users. Here, technical support information, frequently asked questions (FAQ) and answers, bug lists, and contact information will be given. A news area will also be included which will allow users to post questions to the VITMAC staff and to other users. All correspondence in the news area is posted on a public page for all to read, much like the Usenet newsgroups on the Internet. This will allow the VITMAC community to keep in touch and up to date. An area for patches, bug fixes, and other utilities will be created. This will allow users to download these files over the Internet for immediate use. If necessary, security measures can be implemented such as requiring a user name and password so that only registered users are allowed access. A restricted area for VITMAC personnel only will be created. Security measures will be implemented in order to deny access to others. Program information such as status reports and current issues may be posted on these pages. Finally, an area for file exchanges will also be created, for transferring VITMAC input decks which require support and or demonstrate new model features

4.0 POTENTIAL POST APPLICATIONS/FUTURE R&D

4.1 Potential for the Federal Government

The proposed effort will provide the Federal Government with a reliable design tool capable of optimizing thermal management schemes for platforms including aircraft/missiles/UAV's, ground vehicles, and marine applications. Characterization of the total integrated system with component and subsystem levels will provide a more cost effective process during the initial design stages, avoiding the costly fixes/redesigns at the prototype or production stage. Total system integration allows for definition of thermal management issues for the platform. For aircraft, this includes airframe/engine designs, ECS, high power electronics, working fluids (including fuel), and the ability to address low and high cycle fatigue that will benefit hot section life and performance. With the advent of advanced military hybrid electric power systems, thermal management becomes a key issue for the integration of prime power, energy storage, energy distribution, pulse power (flywheels), power electronics, ECS, and energy/power management. As new platforms evolve, new design problems will require improved thermal management techniques for the optimal integration of new and old technologies.

4.2 Potential for the Commercial Sector

The proposed investigation will provide the commercial sector with similar advantages as the Federal Government. A reliable design tool will be available to optimize thermal management configurations for a variety of platforms. Since the commercial sector represents component and subsystem development as well as the platform total integrated system, the proposed work will help provide the necessary specifications for hardware to meet mission requirements. Moreover, the design tools developed in Phase II can be used by the commercial sector to enhance their product lines to meet more demanding requirements as new emerging technologies push the design envelopes of current state-of-the-art hardware. Finally, the opportunity to have a benchmark design tool used by both the commercial sector as well as the military can eliminate duplication of design efforts and unwarranted and costly testing due to use of proprietary design tools not widely available to the commercial sector as a whole.

4.3 Relationship with Future Research or R&D

The anticipated results of this investigation will provide the U.S. Air Force, as well as other DoD, NASA, and commercial agencies, with the foundation of a reliable and validated tool for integrated thermal management of aircraft systems. It will permit designers to optimize thermal management components, subsystems, and systems relative to mission profile figures of merit. The development of such a design tool will allow analysts to easily investigate concepts and conduct parametric trade studies with quick turnaround results to impact the design process. The optimization techniques together with the graphical user interface allows modeling and simulation for designers to identify conceptual configurations that are truly optimal from a total system point of view. A successful product can provide both timely and cost effective designs in the initial planning phases when changes may be effectively accomplished. Moreover, experimental definition will be properly identified to avoid costly trial and error testing.

The proposed effort will provide a basic thermal management design tool that can be adapted to a number of military and civil platforms. Phase III development of VITMAC can lead to enhancements to the program to be tailored to specific user needs. Examples would be ground vehicle applications (such as CHPS), marine applications (Arsenal ship, Advanced Amphibious Assault Vehicle), and aircraft/missile/UAV's. The open architecture of VITMAC will easily accommodate the addition of capabilities and enhancements in thermal management, and accept data from other sources. This advancement in the current state-of-the-art enables: 1) the development of a library of optimum operation conditions, network designs, and network configurations, 2) the selection of components, materials, and working fluids, 3) the rapid configuration and manipulation of thermal management system components and the ability to model a myriad of configuration and operating conditions, and 4) the use of a GUI for hands-on control.

As new aircraft (or generic platforms) evolve, new design problems will occur requiring integration of new and existing technologies for thermal management. The subsystem design process is often brought into the loop after the airframer and propulsion systems engineers have established an optimal aerodynamic configuration. VITMAC can be effectively used during the initial design phase to insure total system integration of the airframe/propulsion system with the many subsystem thermal suites. Consequently, Phase III will focus on commercializing the basic program while accommodating specific user needs. Operation, maintenance, and technical support for the basic program will be provided while specialization of the design tool will be provided for specific applications.

The ability to address new design problems during the initial phases of a concept will require enhancements to the design code to meet component and subsystem integration issues. These enhancements can be adapted into the VITMAC architecture for a total optimized system to meet mission requirements. Moreover, the flexibility of the architecture allows for technology transfer to other platforms such as vehicular and marine applications, in particular hybrid electric power systems. Enhancements to the basic code to provide total systems thermal management integration for these applications will further solidify the foundation for research and development. Cross fertilization of new design tool enhancements will benefit the various branches of the DoD as well as the commercial sector.

5.0 CONCLUDING REMARKS

A Phase I feasibility investigation was conducted that focused on development of an optimization scheme, and engine thermal management. The following is a summary of the Phase I findings:

- Optimization should be performed on the component, subsystem and system levels.
    - An exergy analysis is recommended for component level optimization.
    - Network optimization schemes should include: optimum operating conditions, optimum network design, and optimum network configuration/expert systems.
- Engine thermal management requires linking VITMAC to an engine module with the following features:
    - Engine performance calculations to allow for a simple cycle analysis and provide required information to estimate the engine heat load
    - A link to an engine performance code (such as RJPA), for ramjet and scramjet configurations, to provide estimates of the engine performance, and heat load
    - A link to an cycle analysis code (such as NEPP) for cycle calculations of jet engines including turbojet, turbofan, and turboshaft engines
- A commercialization plan is recommended to include: i) enhancements to the graphical user interface (GUI), ii) VITMAC workshops to allow for direct interaction with the users and Beta testers, iii) the setup of a World Wide Web (WWW) page to provide up-to-date information on the development of VITMAC, and iv) providing end-user support.
- Phase II Program Plan was developed that focused on the following tasks as a continuation of the successful Phase I effort:
    - Task 1: Develop Optimization Architecture
    - Task 2: Engine Thermal Management
    - Task 3: Develop the GUI
    - Task 4: Validation and Verification of VITMAC
    - Task 5: Phase III Commercialization Plan

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