N94-23636

AN ENGINEERING CODE TO ANALYZE HYPERSONIC THERMAL MANAGEMENT SYSTEMS

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INTRODUCTION

Thermal loads on current and future aircraft are increasing and as a result are stressing the energy collection, control and dissipation capabilities of current thermal management systems and technology. The thermal loads for hypersonic vehicles will be no exception. In fact, with their projected high heat loads and fluxes, hypersonic vehicles are a prime example of systems that will require thermal management systems (TMS) that have been optimized and integrated with the entire vehicle to the maximum extent possible during the initial design stages. This will not only be to meet operational requirements, but also to fulfill weight and performance constraints in order for the vehicle to takeoff and complete its mission successfully. To meet this challenge, the TMS can no longer be two or more entirely independent systems. Nor can thermal management be an after thought in the design process, the typical pervasive approach in the past. Instead, a TMS that has been integrated throughout the entire vehicle and subsequently optimized will be required. To accomplish this, a method that iteratively optimizes the TMS throughout the vehicle will not only be highly desirable, but advantageous in order to reduce the manhours normally required to conduct the necessary tradeoff studies and comparisons.

This paper will discuss a thermal management engineering computer code that is under development and being managed at Wright Laboratory, Wright-Patterson AFB. The primary goal of the code will be to aid in the development of a hypersonic vehicle TMS that has been optimized and integrated on a total vehicle basis.

BACKGROUND HISTORY

Prior to high speed flight, thermal loads on aircraft were not overtaxing the capabilities of existing cooling approaches, coolants or structural material temperature limits. Consequently, thermal management was not on overriding design consideration. With the advent of high speed flight, this is changing. Previously, aeroheating prediction methods were undergoing development and did not have the fidelity that we are witnessing today. As a result, the extent of thermal protection needed was not apparent during the initial design stages for vehicles, such as the space shuttle. Consequently, some of the solutions for thermal protection of the shuttle were "fix-it" solutions, ultimately resulting in payload loss potential. With hypersonic vehicle development, we can not afford to take this approach.

Between the lessons learned from previous programs, such as the shuttle, and the current heat loads that are anticipated for hypersonic vehicles, thermal management can no longer be relegated to the tail end of the design cycle. Instead, there must be active involvement during the early design cycle. Furthermore, to enhance the overall vehicle performance and to aid in meeting weight constraints, an integrated engine/airframe thermal management system will have to be developed. This leads to the need for a computer code that will aid in that process.

After a review of available codes and identification of computational requirements, it was decided to base an integrated thermal management code on an engineering code that was under development by Science Applications International Corporation known as HYSTAM (Hypersonic Structural Thermal and Acoustic Management). The primary author submitted a proposal, during autumn 1990, to further develop and enhance the code to meet requirements for a hypersonic vehicle program. The proposed program was approved January 1991 and the effort was under contract before the end of August 1991.

To differentiate HYSTAM from the resulting code to be developed during this effort, a new name was derived and the code became known as the Vehicle Integrated Thermal Management Code or VITMAC. In addition to the code's technical capabilities, it was necessary that it be non-proprietary. This was to ensure that it would be available to the government and government contractor's associated with thermal management for the hypersonic vehicle program in the near term, and eventually to a wider user base. An additional attractive feature of this code was its modularity which easily facilitates the incorporation of non-proprietary codes, subroutines or algorithms from the various sources involved with the program.

CODE ARCHITECTURE

The design approach that went into the development of VITMAC was to simulate a vehicle's thermal management system as a network of open and closed fluid loops with adjacent structures, which may experience external or internal heat loads.[1] Since the networks also included components, such as pumps, tanks, heat exchangers, cooling panels, piping, fittings and turbomachinery, the ability to add them was incorporated into the code. This was possible due to the modular design of VITMAC.

Originally, VITMAC had three primary modules, a general cooling network thermal-fluids response module, a structure thermal response module, and a heat loads module. The heat loads module, for example, contained the capability to compute aerothermal heat loads and to calculate the heat flux on external surfaces of an earth-orbiting body.[2] After contract initiation, the heat loads module was expanded to include internally generated heat loads. In addition, new modules were added and included a fuel tank module and a component performance module. The role of the fuel tank module is to predict thermal-hydraulic response of the cryogenic tanks and inlet conditions to the cooling networks. The purpose of the component module is to calculate component performance and thermal response and provide coupling with the cooling networks. Figure 1 outlines the code module architecture. A generic VITMAC cooling network is presented in Figures 2 and 3. Figure 2 is a generic cooling network showing various components, with aero-heating and internal heat load inputs and thermal outputs. Figure 3 is the same cooling network that is broken down further to show control volumes, branching and merge points, structure breakout and heat sources and sinks. A more detailed description of the modules follows.

Cooling Network Thermal-Fluid Module.- This module determines the thermal and hydraulic response of a user-defined active cooling network. This module is coupled to the Structure Thermal Response Module. Contained within this module is the capability to have multiple cooling flow loops with multiple coolant sources (i.e. tank) and sinks (i.e. combustor, film cooling). Variable time dependencies can be accepted for the source and sink conditions. Multiple branching and merge points within the loops to simulate parallel flow is also present. Individual coolant loops can thermally interact through designated heat exchangers, as well as allow for coolant (fluid) mass addition and subtraction. The fluid flow can be simulated as being either once-pass through, as in an open system, or recirculating flow, as in a closed system. The code also allows for flow reversal.

VITMAC is currently set up to handle the computation of heat transfer coefficients and friction factors for various flow areas. These include smooth and rough wall for pipe flow and flow between parallel plates for laminar, turbulent and transitional flow. Heat transfer coefficients are based on Nusselt number correlations. Also contained within this module is a loss coefficient library containing several plumbing components, such as valves, tees, elbows and bends. These are listed in Table 1 and can be expanded as needed.

The ability to include pressure drops has been generalized to account for pressure losses due to both skin friction and form drag within the network components. Also contained within this module is the capability to determine hydrogen property data. To accomplish this, NASA Lewis Research Center's code GASPLUS has been coupled with VITMAC as well as built in hydrogen property functions and tables. In addition, a separate submodule for tank operating conditions for hydrogen, oxygen and helium has been developed.

This module is being updated to include correlations for predicting the heat transfer and losses associated with various cooling concepts. Further, industry data pertinent to configuration and conditions will be incorporated.

Structure Thermal Response Module.- This module predicts structure temperature history and heat loads to the cooling networks. It performs in-depth conduction and radiation heat transfer calculations and convection heat transfer calculations with the coolant, to determine structure thermal response, including through gaps. The module takes a multi-one dimensional approach during its calculations. Further, it takes into account convective, radiative or heat addition boundary conditions. The structures themselves can be actively or passively cooled or heated. In addition, multi-layer composite materials with gaps can be simulated. Thermo-physical properties, such as density and temperature-dependent conductivity and specific heat, for a number of structural materials have been incorporated in with this module. The current list of materials is shown in Table 2. There are plans to expand this list.

Heating Loads Module.- This module addresses aeroheating and internally generated heating loads. The aeroheating portion is based on a cold wall spatial distribution as a function of altitude, while hot wall aeroheating is extracted from surface temperature and edge recovery enthalpy during the flight trajectory. The user has the option to either use the aeroheating module to generate the external heat loads or to input the data directly from other sources. The user has the option to utilize attached boundary layer aeroheating loads generated from a 2-D version of the SAIC 3-D MEIT/3-D inviscid code. The 2-D version was selected to help keep the run times down. A comprehensive survey of the heating effects due to shock boundary layer interaction has been completed, including defining classes of interactions. Development of an algorithm for the code was underway, but due to current funding limits and other priorities, incorporation into VITMAC will be delayed.

Internal heat loads can be either steady-state or transient. VITMAC currently provides the user with three options for specifying internal heat loads on structures. The first option allows the heat loads to be included as part of the input file, i.e. a namelist file, in tabular form. These loads are directly applied to the structure surfaces as specified in the input deck. The second and third options permit the user to define the heat loads on the structures in separate input files, one each for the vehicle's upper and lower surfaces. These heat loads are treated as cold wall aeroheating loads and corrected to hot wall aeroheating loads when read into VITMAC. The second option derives these files from the TRAJIQ code, while the third option requires the user to manually generate these files in the TRAJIQ output file format employing own data.

Algorithms that were previously developed for internal heat generation, such as generic engine heat generation rates and electronic heat generation will be incorporated into VITMAC.

Fuel Tank Module.- This module solves the time-dependent forms of the mass and energy conservation equations for gas, liquid and solid phases for hydrogen and oxygen within a tank. This can be coupled with the injection of a binary gas such as helium for ullage pressure control. Further, the ullage pressure, fuel mass, and fuel level within the tank are predicted as a function of specified heating, venting and recirculation rates. Also, the code has the capability to model equilibrium with phase transition due to heat leakage. Tank pressure can currently be depicted by a pressure-time table. The tank module will be fully integrated with VITMAC and expanded to include heat transfer to local structures and insulation.

Component Performance Module.- This module calculates component responses and provides coupling with the cooling network. The code currently includes simple models for pumps, compressors, and turbines, based on generic component performance and thermodynamic relationships. Pump performance is obtained from head-discharge curves. Compressor performance is based on compression ratio and efficiency. Turbine performance is calculated from expansion ratio and efficiency, coupled with compressor and pump power requirements. The capability to determine power balance between several compressors, pumps and turbines is included. The capability to conduct a complete system power balance will be taking place in the near future.

Engine Module.- VITMAC does not currently support a fully dedicated engine module. However, the code can model at a simplified level, the fuel side of the system. This work was originally scheduled to be developed in FY93. However, funding cutbacks currently preclude the addition of this module. Nonetheless, it is hoped that this can be added in the future.

Input/Output.- While working with the code, it became clear that an alternative approach for inputting the data was needed. The process of inputting a network in a data file was very time consuming. In addition, the learning curve associated with the code was longer than desired. Because of the limited available manpower at contractor and government facilities to conduct cooling network design trade-off and analysis studies, an easier and faster approach to input data into VITMAC was needed. To fulfill this need, the use of a computer graphical user interface (GUI) was recommended.

The possibility of coupling GUI technology with VITMAC was investigated and determined to be highly feasible. The question then became, whether to include GUI capability as soon as possible or to wait until the end of code development. The decision was made to incorporate the GUI during code development. This would make it easier and faster for the user to learn the code, while taking less time to input data. Further this would facilitate feedback to the developer on capabilities, strengths, weaknesses, and areas needing change while the code was still under development. A contract modification was completed in late August 1992 to add this capability.

Figures 4, 5, and 6 demonstrate generally how the GUI will be used with VITMAC. It is clearly obvious that with the use of the GUI, the network from figures 1 and 2 can literally be generated on the computer screen. This not only aids in visualizing the network, but also aids in input error detection. The GUI will also be used for displaying output, as seen in figure 7 as an example. As a result of these changes, VITMAC is being transitioned to the UNIX operating system, with an XWindows environment.

GENERAL CAPABILITIES

VITMAC has been developed to enable the user to select steady-state, quasi-transient or transient operation. Procedures for ensuring numerical stabilities have been developed and incorporated into the code. These include operations involving division and logarithms, and input error detection. Procedures to minimize storage (i.e. Jacobian matrix within the thermal-fluid module) and run time requirements have been developed. Thermophysical property data for hydrogen and structural materials has been extrapolated to 9000°R, to provide the user with information which may prove helpful during modeling refinement. This is not intended to extend the response of the coolant and materials to this high a temperature. Currently the maximum number of control volumes per loop is 100 and the maximum number of structures is 70 during simulation. This capability can be easily expanded by updating the appropriate parameter statements and recompiling the code.

Several cases, of varying degrees of complexity, were run to assist in the development and checkout of the thermal-fluid network, structure thermal response and tank modules. With the aid of industry in supplying data, several specific simulation cases were performed for both the airframe and engine. The VITMAC User Manual is revised as the code is updated. A manual on the theory of the code will be generated as part of the final report. The code is in the process of being transitioned from a VAX environment to a SUN Workstation environment and should be completed prior to this meeting.

CURRENT STATUS

Mid October 1992, this effort received a drastic budget cut of 76% for FY93. As a result, a stop work order had to be placed on the contract to prevent over expenditure. Damage control was initiated to determine what we could afford to complete and what had to be eliminated, yet still result with a product that would be useful. Downscoped statements of work were written, while budget levels fluctuated. One key area that had to be sacrificed was the engine heat loads module. Since the scope of work had to be reduced to such a large extent, the contract had to be modified and renegotiated. This was finally completed mid March 1993 and work has been reinitiated at the reduced level. The current contract is scheduled to be completed the end of January 1994. It is hoped that funding will be restored, as a minimum, to the level before the budget cut, in order to complete the originally scoped effort.

CONCLUSION

Despite the uncertainties surrounding the future of hypersonic programs, the need for an engineering computer code that integrates overall thermal management systems remains. This is true, now more than ever, due to the manpower cuts experienced by both airframe and engine companies, particularly in the thermal management community. Not only is the industry personnel base in thermal management small, the same is true for the government in both DOD and NASA. Regardless of whether hypersonic vehicle programs continue, or if there are sub orbital research vehicle programs, or a high speed propulsion system development program, thermal management issues still exist and remains an enabling technology. To conduct complete integrated engine/airframe analyses and trade-off studies to develop an optimum TMS, a code such as VITMAC, is required.

REFERENCES

1. Issacci, F.; Wassel, A.T.; Farr, J.L., Jr.; Wallace, C.E.; and Van Griethuysen, V.J.: "A Thermal Management Assessment Tool for Advanced Hypersonic Aircraft." SAE Aerotech '92, Oct. 1992, p. 2.
2. Wallace, C.E.; Wassel, A.T.; Laganelli, A.; and Carlson, D.: "Systems Integrated Thermal Management Assessment Tool." Science Applications International Corp., Jul. 1990, p. 3.

TABLE 1. Loss Coefficient Library

Component Type	K_{loss}
Elbows:	
Regular 90°, flanged	0.3
Regular 90°, threaded	1.5
Long radius 90°, flanged	0.2
Long radius 90°, threaded	0.7
Long radius 45°, flanged	0.2
Regular 45°, threaded	0.4
180° Return Bends	
Flanged	0.2
Threaded	1.5
Tees:	
Line flow, flanged	0.2
Line flow, threaded	0.9
Branch flow, flanged	1.0
Branch flow, threaded	2.0
Union, threaded	0.08
Valves:	
Globe, fully open	10.0
Angle, fully open	2.0
Gate, fully open	0.15
Gate, 1/4 closed	0.26
Gate, 1/2 closed	2.1
Gate, 3/4 closed	17.0
Swing check, forward flow	2.0
Swing check, backward flow	∞
Ball valve, full open	0.05
Ball valve, 1/3 closed	5.5
Ball valve, 2/3 closed	210.0
Pipe Entrances:	
Inward projecting	0.78
Sharp edged	0.50
Slightly rounded	0.23
Well rounded	0.04
Pipe Exits:	
Projecting	1.0
Sharp edged	1.0
Rounded	1.0

TABLE 2. Structural Material List

Aluminum 2219	Beryllium	Carbon-Carbon
Fibermax	Graphite/Epoxy	Haynes 188
Haynes 230	Incoloy 754	Incoloy 909
Incoloy 956	Lockalloy	Mo-50/Re
Narloy-Z	Niobium	Q-fiber/He purge
Stainless Steel	Titanium 6Al-4V	Titanium 1100

FIGURE 1. VITMAC Architecture

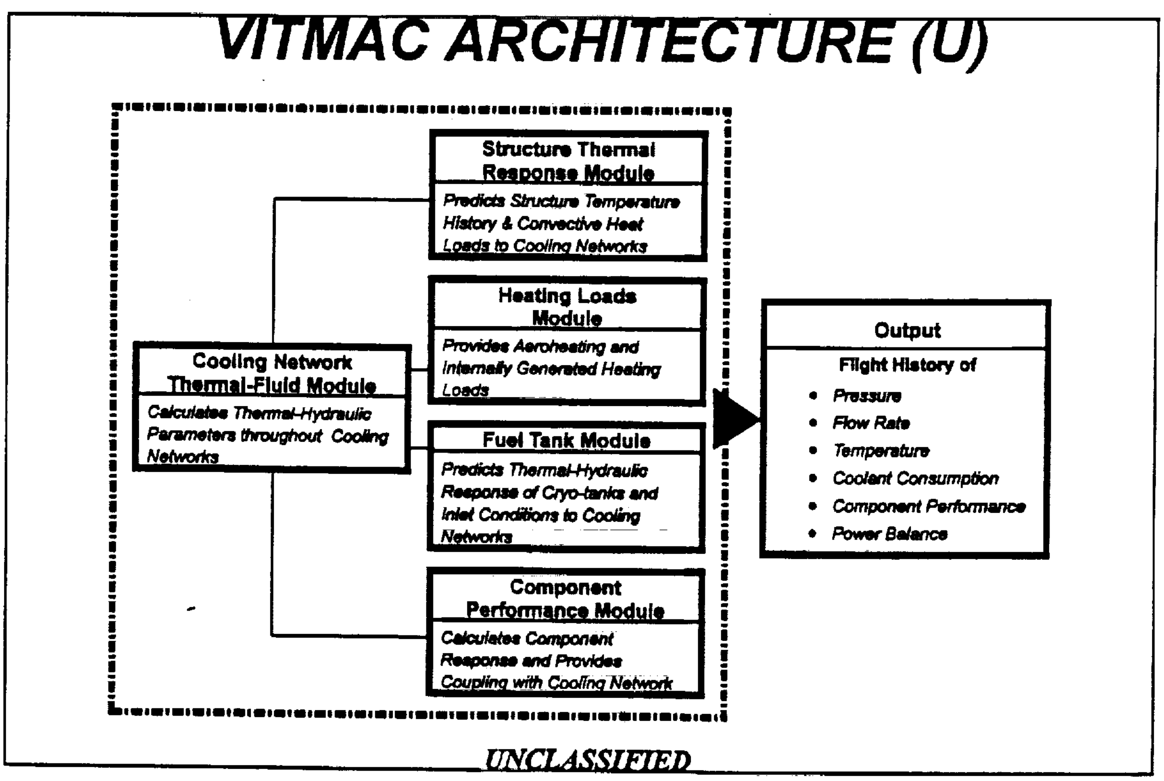

FIGURE 2. VITMAC Cooling Network

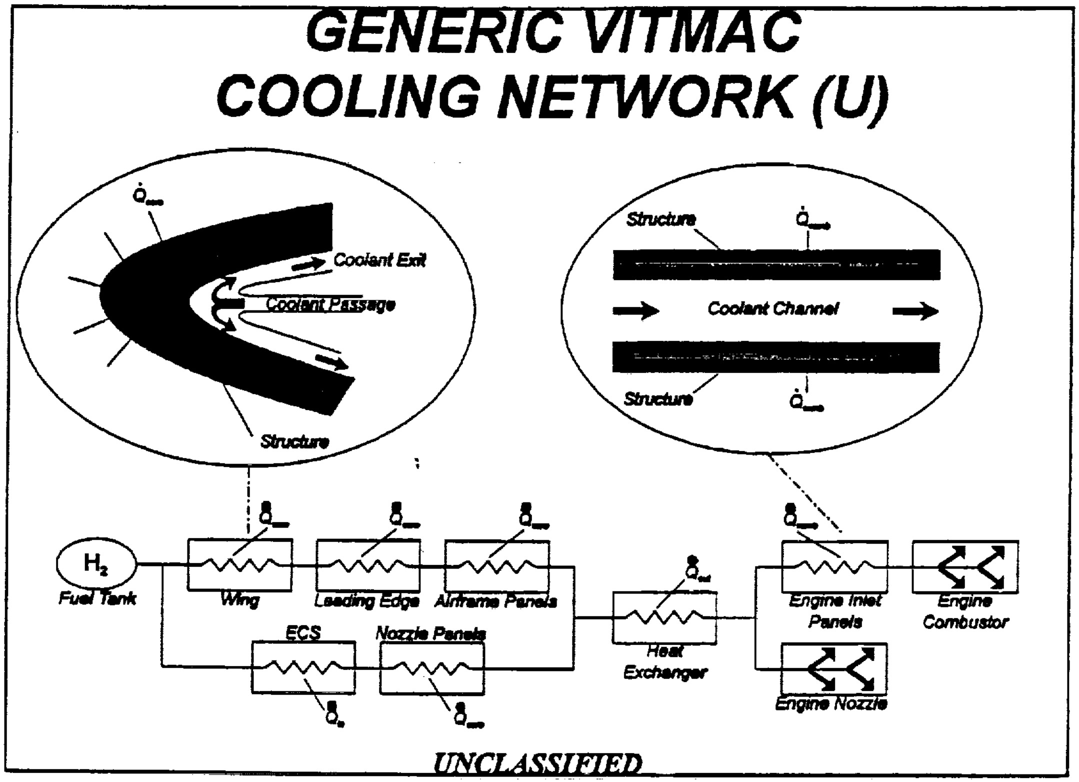

FIGURE 3. Generic Cooling Network

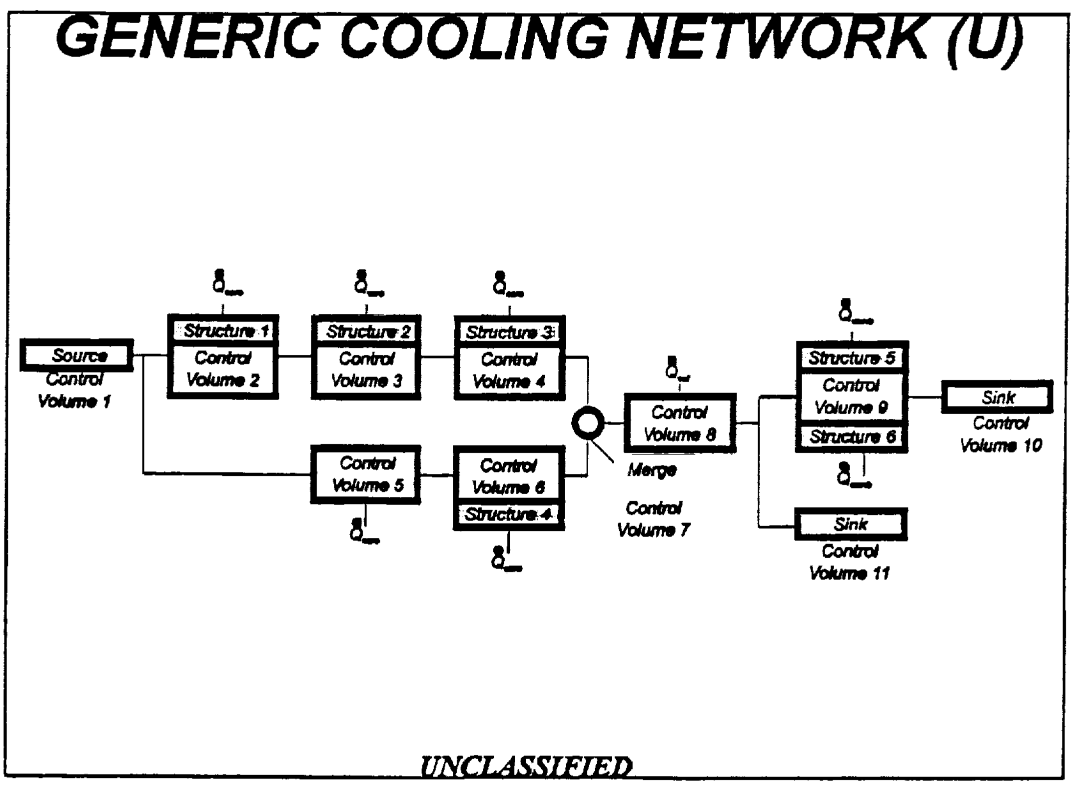

FIGURE 4. VITMAC GUI Generic Cooling Network

VITMAC GUI GENERIC COOLING NETWORK (U)

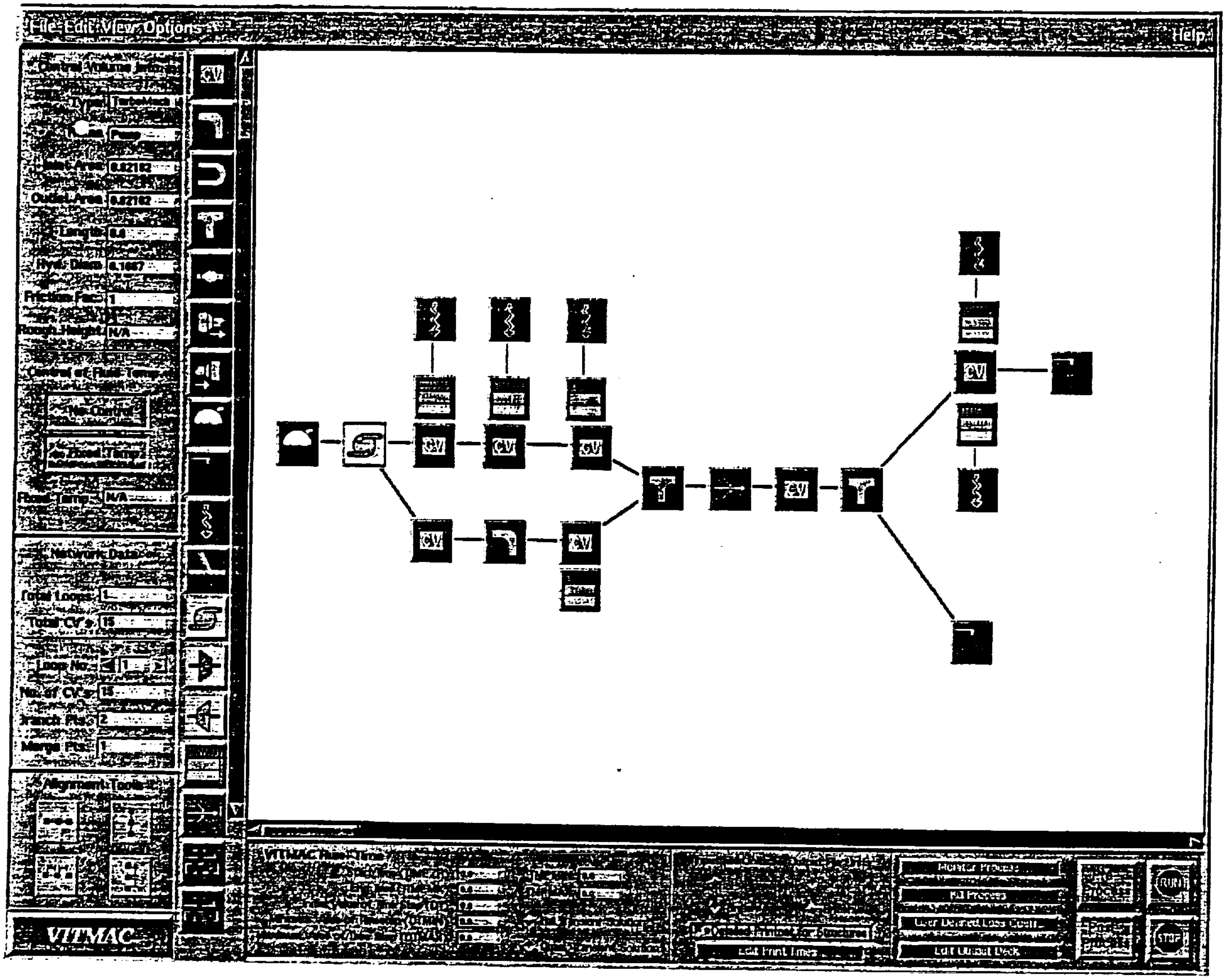

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FIGURE 5. VITMAC GUI Structure Generation

VITMAC GUI STRUCTURE GENERATION (U)

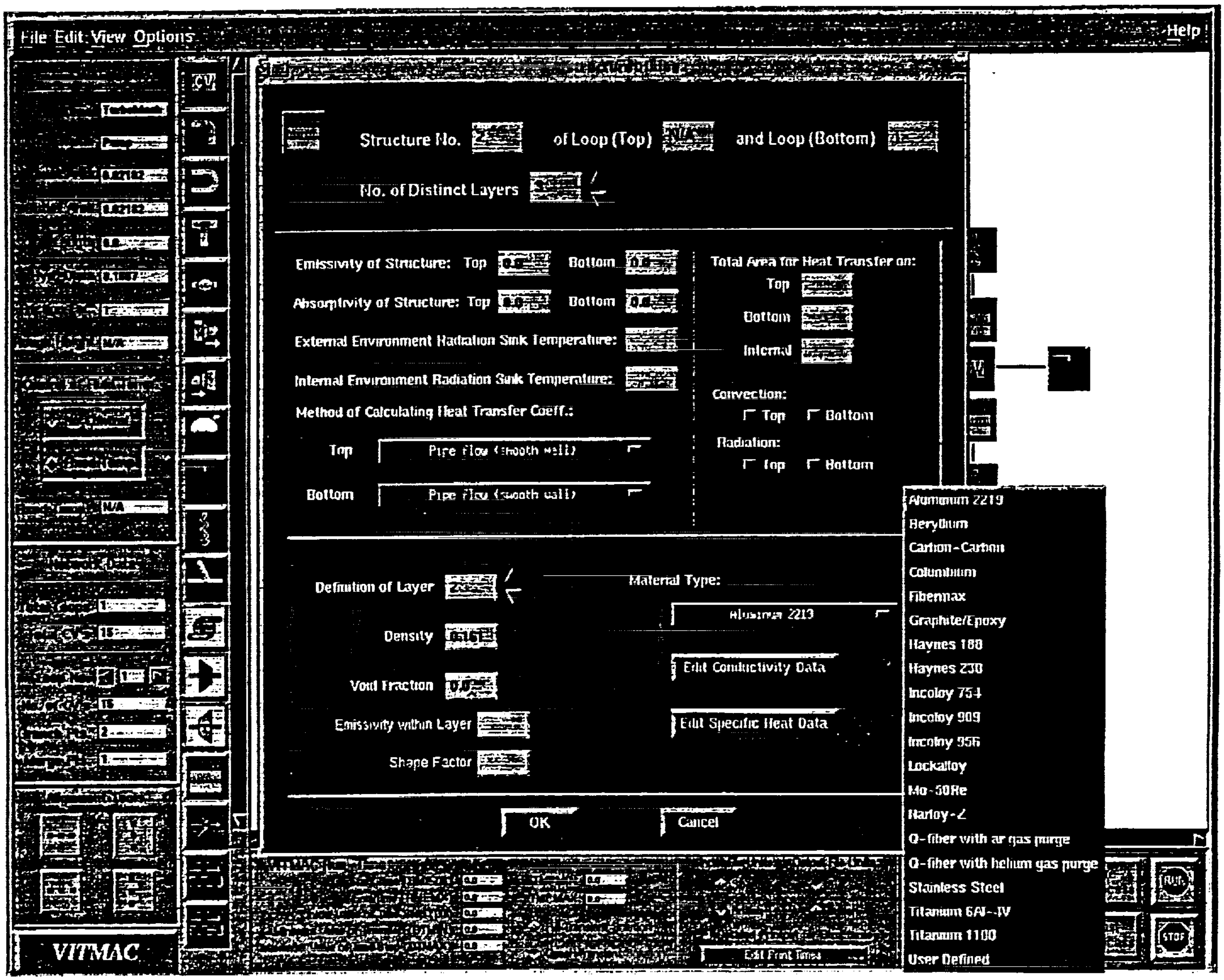

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FIGURE 6. VITMAC GUI Component Generation

VITMAC GUI COMPONENT GENERATION (U)

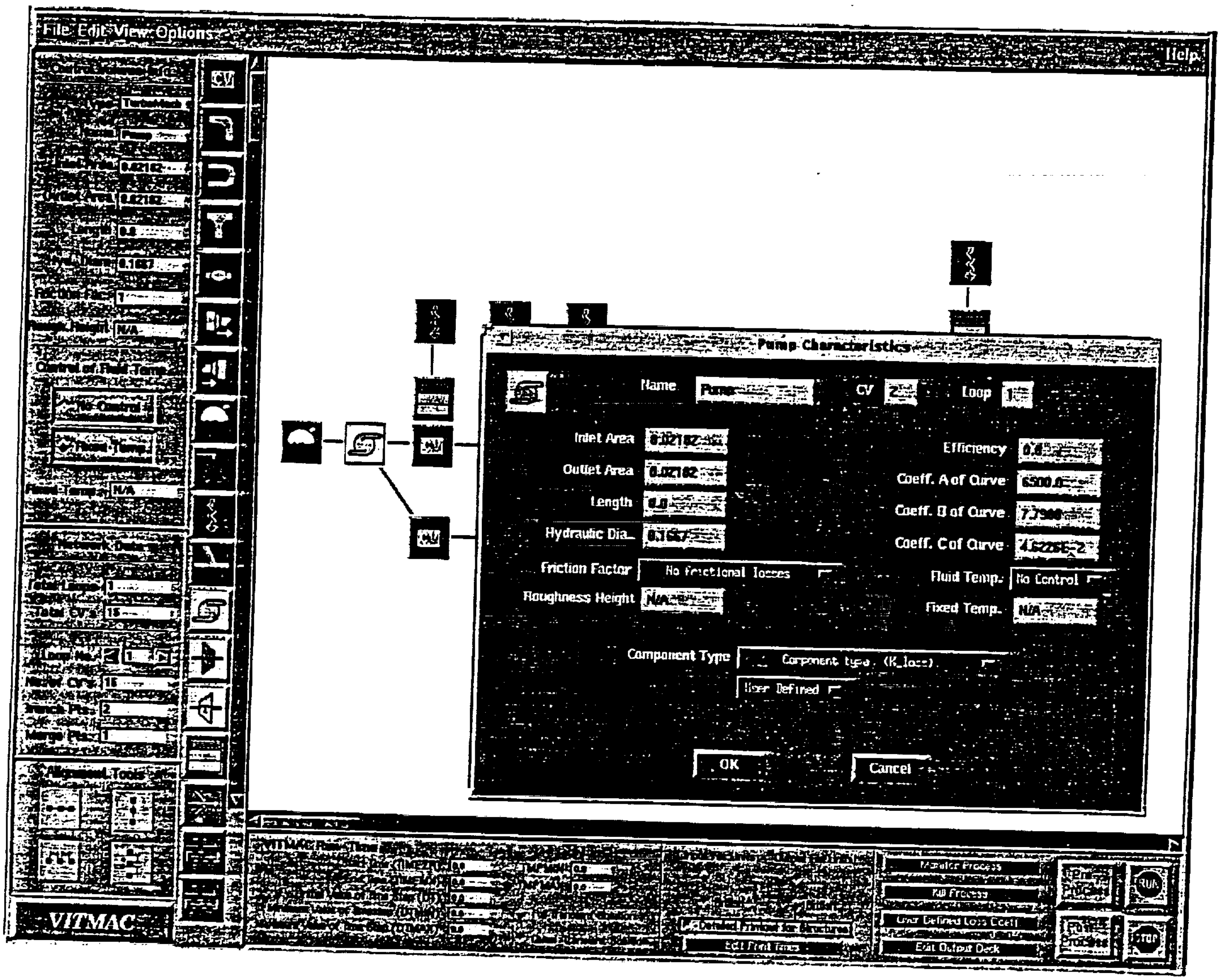

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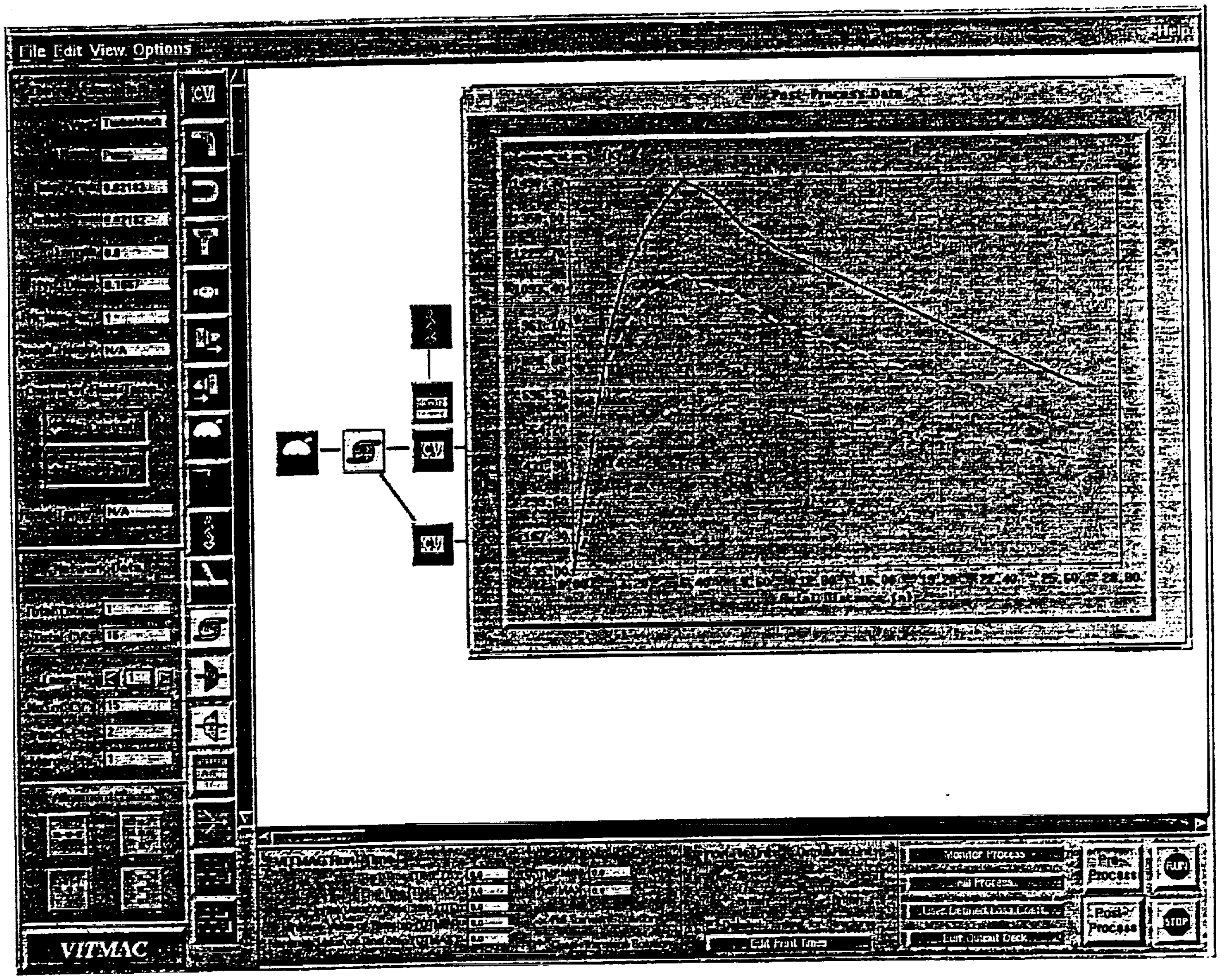
FIGURE 7.   VITMAC GUI Output

VITMAC GUI OUTPUT EXAMPLE (U)



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