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June 1968

Westinghouse Astronuclear Laboratory

MODEL STATUS REPORT - 1967

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TABLE OF CONTENTS

	<u>Page</u>
TABLE OF CONTENTS	iii
LIST OF FIGURES	v
LIST OF TABLES	vii
SUMMARY	i
I. INTRODUCTION	2
II. NUCLEAR REACTOR SUBSYSTEM MODEL	
A. Reflector Analysis	
1. Sectionalization studies using the CAM Reflector Model	3
2. Sectionalization studies including flow work and detailed hydrogen properties	5
B. CAM Nuclear Subsystem Model With Detailed Hydrogen Properties (No additional axial sectionalization)	21
C. CAM Nuclear Subsystem Model With Detailed Hydrogen Properties and With Detailed Material Properties in Support Element (No additional axial sectionalization)	21
D. Support Element Analysis	22
III. CONCLUSIONS	
Summary of Results	33
Suggestions for Further Study	35
APPENDIX: MODELING TECHNIQUES	38
A. Computation of Hydrogen Properties When Input Variables Other than Pressure and Enthalpies are known	39
B. Computation of Power Fractions	40

TABLE OF CONTENTS (Cont'd.)

	<u>Page</u>
C. Computation of Loss Coefficients	42
D. Multiparallel Flow Channels	44
REFERENCES	46

LIST OF FIGURES

<u>Figure</u>	<u>Title</u>	<u>Page</u>
1.	Effect of Axial Sectionalization on the Transfer Function, Reflector Exit Enthalpy/Reflector Inlet Enthalpy (Design Power)	13
2	Effect of Axial Sectionalization, Hydrogen Properties and Flow Work on the Transfer Function, Chamber Pressure/Reflector Inlet Pressure (Design Power)	15
3	Effect of Axial Sectionalization on the Transfer Function, Reflector Exit Temperature/Reflector Inlet Flow Rate (Design Power)	16
4	Transfer Function - Tie Rod Exit Gas Temperature/Total Power (Design Power)	30
5	Transfer Function - Tie Rod Exit Gas Temperature/Tie Rod Inlet Enthalpy (Design Power)	31
6	Iteration Scheme to Compute E and P, Given U and ρ	41

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LIST OF TABLES

<u>Table</u>	<u>Title</u>	<u>Page</u>
1	Operating Conditions (NRX-A5)	4
2	Nomenclature for Reflector, Shield, Core, and Tie Rod	6
3	Numerical Values of the Constants Used in the Reflector, Shield, Core, and the Tie Rod Simulations	9
4	Static Differences Between Various Models at Design (Nuclear Subsystem)	19
5	Static Differences Due to Radial Sectionalized Tie Rod Model (Nuclear Subsystem)	28
6	Static Differences Between Tie Rod Model and TNT Data at Different Operating Points	29

SUMMARY

This report presents a discussion of the results of computer studies made during 1967 with models more rigorous than the Common Analog Model (CAM). These studies were made as part of a continuing effort to provide the simplest and most accurate CAM models for use in systems and control studies and to lay the foundation for a more rigorous digital systems dynamic model for use in verifying the adequacy of the simpler CAM models. Previous reports have documented the basic Common Analog Models used for official test predictions of the NRX/EST and NRX systems.^{1,2,3}

This report presents, in particular, a discussion of a study of the dynamic effects of the inclusion of more complex equations and more detailed hydrogen property simulations in the reflector. Similar studies with the shield and reactor core have yet to be done. Also, a discussion of the results obtained with a more complex support element simulation is presented. Comparisons of these more rigorous models with the CAM are given, and conclusions which can be drawn from these comparisons presented. A detailed description is also presented in the Appendix of various modeling techniques developed and used in the studies presented in this report.

1. INTRODUCTION

This report should be used in conjunction with Reference 1, which gives the status of the system analysis model development as of September 1966. The main task of the model study presented herein is to improve the accuracy and, if possible, simplicity of the CAM models. These studies are directly applicable to the R-1 analysis model except that the support system is different. However, the same modeling conclusions can be made in either case.

This report contains a detailed discussion of the following models and presents results illustrating the comparative accuracy of these models with CAM. (The reflector was chosen as the representative component but conclusions drawn here may not be applicable in the shield and core).

1. Multi-axially sectionalized CAM model of the reflector.
2. Multi-axially sectionalized reflector with inclusions of detailed hydrogen properties and flow work terms.
3. The total nuclear subsystem CAM model with the inclusion of hydrogen properties.
4. The total nuclear subsystem CAM model with the inclusion of hydrogen properties in all components and material properties in the tie rod.
5. Radially sectionalized tie rod support system with inclusion of hydrogen and material properties.

On the basis of comparisons using the above models, various conclusions are drawn and recommendations for further study postulated.

The various modeling techniques used in the study of the above models are given in the appendix.

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II. NUCLEAR REACTOR SUBSYSTEM MODEL

The model evaluation task during the year 1967 has been to investigate effects of parameter variation, increased axial and radial sectionalization, and the use of detailed hydrogen and material properties codes on the WANL nuclear subsystem model. The Common Analog Model (CAM) equations for the nuclear subsystem are used as a reference model with slight modifications to the system equations. These are indicated where they are initially referenced.

Digital computer analysis, using the TAF computer code for the CDC 6600, is used for the studies. Frequency and transient responses are obtained and compared to determine the optimum degree of sectionalization and best parameter values. All transfer functions and transient analysis are made with reflector inlet pressure and nuclear power as perturbing variables. Similar studies have yet to be made with the shield and core. The CAM-A5 equations are chosen for static and dynamic model comparisons.

Each component of the model is analyzed at four different operating conditions of the NRX-A5 performance map. These operating conditions are outlined in Table I, in terms of core power and nozzle chamber conditions.

A. Reflector Analysis

Primarily, the different model formulations investigated included expanded axial sectionalization and a more detailed description of the heat transfer using the para-hydrogen properties code. Two reflector models were extensively investigated:

- 1) A multi-axially sectionalized model of the reflector without use of the detailed hydrogen properties code and no flow work terms.

TABLE I
OPERATING CONDITIONS
(NRX-A5)

	<u>Power</u> <u>MW</u>	<u>P₈</u> <u>psia</u>	<u>T₈</u> <u>(°R)</u>	<u>Comment</u>
1	1100	574	4090	Design Operation
2	550	380	2480	50% power on the 1\$ reactivity feedback line
3	340	174	4090	Structural operating line at design chamber temperature
4	55	65	1000	5% power

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- 2) Multi-axially sectionalized model of the reflector with inclusion of detailed hydrogen properties code and flow work terms.

1) SECTIONALIZATION STUDIES USING THE CAM REFLECTOR MODEL

The first model is an extension of the CAM equations to include from two to six axial reflector sections. The generalized CAM-A5 multi-axially sectionalized reflector equations with initial conditions can be written down with the help of the figure below and the nomenclature and numerical values of the constants in Tables 2 and 3.

$$\left. \begin{aligned} E_{rb}(0) \\ P_{rb}(0) \end{aligned} \right\} = \begin{aligned} E_5 \\ P_5 \end{aligned} \quad (1)$$

Linear enthalpy variation is assumed with each reflector axial section.

$$E_{rb}(i) = 2E_r(i) - E_{rb}(i-1) \quad i = 1, n \quad (2)$$

$$P_{rb}(i) = R \left(\frac{E_{rb}(i)}{3.67} + 44 \right) (1 - 0.1712 p_{rb}(i))^{-1} p_{rb}(i) \quad (3)$$

$$T_r(i) = 0.2725 E_r(i) + 0.03218 \frac{[P_{rb}(i-1) + P_{rb}(i)]}{2} + 44 \quad (4)$$

$$HD_r(i) = 0.165 + 0.000833 T_r(i) \quad (5)$$

$$\dot{W}_r(i) = \frac{144 A_r g}{L_r} \{ P_{rb}(i-1) - P_{rb}(i) \} - d(i) \frac{W_r^2(i)}{p_{rb}(i)} \quad (6)$$

TABLE 2
NOMENCLATURE FOR REFLECTOR, SHIELD, CORE, AND TIE ROD

Constants

A	Cross-sectional flow area, ft. ²
c _p	Specific heat at constant pressure, BTU/lb. _m - °R
d(i)	Loss coefficients along reflector axis, lb/ft. ³
D	Diameter, in.
g	Gravitational acceleration, ft./sec. ²
J _e	Joule's mechanical equivalent of heat, ft. - lb/BTU
k	Thermal conductivity (may also be variable), BTU/sec. - ft. - °R
K	Empirical heat generation constant, BTU/sec. - %
L	Length, ft.
m	Number of radial sections in the structural graphite
M	Mass, lbs.
n	Number of axial sections in the reflector
N	Number of radial sections in the pyrolytic graphite
R	Gas constant for hydrogen, ft./°R
V	Volume, ft. ³
α	Heat transfer surface area, ft. ²
Δ	Width, in.

Variables

E	Enthalpy of fluid, BTU/lb. _m
H	Enthalpy of component, BTU/lb. _m
P	Fluid pressure, psia
S _n	Power, %
t	Time, sec.

TABLE 2 (Cont'd.)

Variables (Cont'd.)

T	Fluid temperature, °R
U	Internal energy of fluid, BTU/lb.
W	Weight flow rate, lb. _m /sec.
ρ	Fluid density, lb. _m /ft. ³
φ	Temperature of material, °R

Station Designations

5	Reflector inlet plenum
5a	Reflector exit plenum
6	Core shield inlet plenum or reflector shield exit
7	Core inlet plenum
8	Thrust chamber or core exit plenum and entrance to hot-bleed port

Component and Flow Channel Identification

c	Fueled graphite channels in the core
pg	Pyrolytic graphite sleeve in tie rod channel
s	Core shield
sg	Structural graphite support element
ss	Stainless steel liner in tie rod channel
tr	Tie Rod

Qualifying Sub-subscripts

e	Exit
g	Gas
H	Hot side
H ₂	Hydrogen gas

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TABLE 2 (Cont'd.)

Qualifying Sub-subscripts (Cont'd.)

i	Inlet
j	Surface at inside radius of component
o	Surface at outside radius of component
r	Reflector
ra	In the radial direction in reflector
rb	Indicates exit of axial division in reflector
x	In the axial direction

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TABLE 3

NUMERICAL VALUES OF THE CONSTANTS USED IN THE
REFLECTOR, SHIELD, CORE, AND TIE ROD SIMULATIONS

Reflector

A	=	-162 BTU/lb.
A _r	=	0.595 ft. ²
B	=	-0.06514 BTU-in. ² /lb. ²
c	=	3.67 BTU/lb. - °R
c _r	=	2.237 lb/ft. ³
D	=	0.263 in.
g	=	32.2 ft./sec. ²
J	=	5.403 ft.-lb/BTU
k _l	=	.655
k _r	=	0.0006823
K _r	=	234.4 BTU/% - sec.
L _r	=	4.46 ft.
M _r	=	4246 lb.
R	=	5.32 ft./°R
V _r	=	2.65 ft. ³
(V _r +V _{5a} +V ₆)	=	8.7 ft. ³
α _r	=	609 ft. ²

Tie Rod

A	=	.55
B	=	.1
C	=	.025

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TABLE 3 (Cont'd.)

Tie Rod (Cont'd.)

D	=	.117 in.
D _j	=	.364 in.
D _{jpq}	=	.246 in.
D _o	=	.753 in.
D _{opq}	=	.357 in.
L _{sq}	=	52 in.
M _q	=	11.6466×10^{-5} lbs.
M _{H2}	=	$.575 \times 10^{-5}$ lbs.
X	=	52 in.
Δ _H	=	.002 in.
Δ _{H2}	=	.0035 in.
Δ _{pq}	=	.056 in.
Δ _{sq}	=	.195 in.
Δ _{ss}	=	.005 in.
ρ _{pg}	=	.08 lb/in. ³
ρ _{sq}	=	.0671 lb/in. ³

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$$H_r(i) = \frac{nK_r}{M_r} F(i) \left[k_1 S_n + 6.409 \left(\sum_{j=1}^3 Q_j \right) \right] - \frac{k_r}{M_r} \alpha_r \cdot HD_r(i) \cdot W_r(i) \cdot 0.8 \left[\phi_r(i) - T_r(i) \right] \quad (7)$$

$$\dot{\rho}_{rb}(i) = \frac{n}{V_r} (W_r(i) - W_r(i+1)) \quad (8)$$

$$S = S_n + Q_1 + Q_2 + Q_3 \quad (9)$$

$$\dot{\rho}_6 = \frac{1}{\left(\frac{V_6}{n} + \frac{V_r}{n} \right)} [W_r(n) - W_s] \quad (10)$$

$$E_6 = E_{rb}(n) \quad (11)$$

$$P_6 = P_{rb}(n)$$

$$T_6 = \frac{E_6}{3.772} + 0.03218 P_6 + 45$$

$$\begin{aligned} \dot{E}_r(i) = & \frac{1}{\rho_{rb}(i)} \left[2 \cdot \frac{n}{V_r} W_r(i) (E_{rb}(i-1) - E_r(i)) \right. \\ & \left. + \frac{k_r \alpha_r}{V_r} HD_r(i) W_r(i) \cdot 0.8 (\phi_r(i) - T_r(i)) \right] \end{aligned} \quad (13)$$

$$P_r(i) = \frac{P_{rb}(i) + P_{rb}(i+1)}{2} \quad (14)$$

The reflector material temperature is computed from a new energy balance equation as given in equation (7). This equation contains an $F(i)$ term multiplying the source term to include the power fraction weighting of the source at different axial locations in the reflector. This is very necessary because of multi-axially sectionalization. This is mentioned in more detail in the Appendix on Modeling Techniques.

The detailed hydrogen properties code can be called for in the main program by a library subroutine TABHP.⁴ The inputs needed for this subroutine are Enthalpy and Pressure.

Transfer functions were obtained of reflector exit to reflector inlet parameters of enthalpy, pressure, and flow rate. Additional transfer functions were obtained of exit nozzle chamber pressures and temperatures to reflector inlet pressures and enthalpies. For all reflector studies, the CAM-A5 equations of the reactor core, tie rod, and shield were used as a reflector load. Although four different steady-state conditions were investigated, the specific results given here apply primarily to the conditions corresponding to design. Results have been investigated at the other operating points, and the same conclusions can be drawn.

The transfer functions obtained from this reflector model indicated two important results. Outlet-to-inlet reflector transfer functions of slower variables such as temperatures and enthalpies indicate a definite sectional effect. Two sections appear to be adequate. The reflector, however, has little effect on the overall subsystem transfer functions such as P_8/P_5 , T_8/S_n , etc.

The transfer functions of exit to inlet parameters, such as reflector exit enthalpy (E_6) to reflector inlet enthalpy (E_5), illustrated a gain difference between CAM-A5 and a two section reflector model.

However, the CAM formulation showed a 60° phase lag at 10 radians/sec. over the two section model (Figure 1). Additional sectionalization (from 3 to 6 sections) showed no marked differences from the two section model. This indicates that at least two axial sections are necessary for a good dynamic representation of the reflector. In the case of transfer functions P_8/P_5 , P_6/P_5 , W_5/P_5 , W_s/W_{r1} ,

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13

FIGURE 1

Effect of Axial Sectionalization on the Transfer Function
Reflector Exit Enthalpy/Reflector Inlet Enthalpy
(Design Power)

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P_8/W_{r1} , P_6/W_{r1} , T_8/P_5 , no discrepancies were observed due to sectionalization in the region of interest. Differences in amplitude and phase are, however, quite noticeable past 20 rad/sec., for example, in a plot of P_8/P_5 , Figure 2.

The transfer function T_6/W_{r1} (reflector exit temperature to reflector flow rate in the first section) illustrated an interesting sectional effect. The CAM formulation (1 section) demonstrates a resonance between 1.0 and 10.0 radians per second (Figure 3), whereas two sections and greater are identical with CAM out to 1 rad/sec., but do not illustrate resonance beyond 1 rad/sec. This resonance effect appears to be due to the heat transfer coefficient description for the reflector, since with no sectionalization and including hydrogen properties in the CAM model, similar results are also obtained.

Transfer functions P_8/E_5 , P_6/E_5 have a good check with the CAM model up to 2 rad/sec. as far as the gain is concerned, but the phase difference is approximately 40° . Both get progressively worse at higher frequencies. However, the importance of this difference is diminished greatly since the gain at 2 rad/sec. is .015 psi/BTU/lb. and .016 psi/BTU/lb. respectively. Transfer functions E_6/P_5 and T_6/P_5 have a gain difference of about 8 db at 1 rad/sec. and phase difference of 50° . However, the coupling is weak enough to minimize the difference. Transfer functions P_8/S_n and P_6/S_n agree quite well.

2. SECTIONALIZATION STUDIES INCLUDING FLOW WORK AND DETAILED HYDROGEN PROPERTIES

The second reflector model considered was also a multi-axial section model, but included a detailed description of the hydrogen properties and included a number of effects neglected in the CAM model. These are: (1) the flow work terms in the hydrogen gas energy equation, (2) the elimination of the

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Effect of Axial Sectionalization, Hydrogen Properties and Flow Work on the
Transfer Function, Chamber Pressure/Reflector Inlet Pressure
(Design Power)

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16

perfect gas law approximation, and the empirical equation of enthalpy versus temperature and pressure, (3) the inclusion of variable hydrogen density time constants in the gas energy equations, (4) more theoretically accurate computation of the hydrogen property dependent part of the heat transfer coefficient (i.e., computation of HD terms by TABHP), and (5) the inclusion of density and flow rate gradient terms in the hydrogen gas momentum equations. Consistent with the first mentioned requirement,

$$\begin{aligned} \dot{U}_r(1) = & \frac{W_r(1)}{\rho_{rb} A_r} \left\{ U_{rb}(1) - U_r(1) \right\} + \frac{q_{rHD_r}(1)}{M_r} W_r(1) \cdot 0.8 \left(\phi_r(1) - T_r(1) \right) \\ & + \frac{P_r}{J} \frac{2}{\rho_{rb}} \left[\dot{\rho}_{rb} + \frac{W_r}{\rho_{rb} A_r} \left(\rho_{rb}(1) - \rho_{rb}(1 - 1) \right) \right] \end{aligned} \quad (15)$$

The equation relating the internal energy of the fluid U and its enthalpy E is:

$$E_r(1) = U_r(1) + \frac{P_r}{J_e \rho_{rb}} \quad (16)$$

Where J_e is the mechanical equivalent of heat in in.-lb/BTU. Equation (15) is obtained by substituting equation (16) in equation (13).

The transfer functions most meaningful with respect to the control system viewpoint (i.e., T_8/S_n , P_8/P_5 , T_8/P_5 , P_8/S_n , and W_5/P_5) indicate that CAM responds very much like this more accurate model. For transfer functions E_6/E_5 and T_6/W_{r1} , improvements are seen over the previous model. For example, in transfer function E_6/E_5 , no large dip in gain is obtained as compared to the CAM model. Also, phase lags by about 10° from the phase of the two-section model. For transfer function T_6/W_{r1} , this model is slower than the CAM and does not show a resonance between 1.0 and 10.0 radians/sec. Response is flatter in this frequency range as compared to the two section model. However, as in the case of the first

model, no downstream transfer function discrepancies resulted due to this model formulation. Additionally, it was noted that two sections in this model differed from one section considerably with respect to the outlet/inlet transfer functions, but little improvement was observed by going to three or more sections. Static discrepancies attributed to enthalpy fits, gas law approximations and neglected effects were also observed and these can be seen in columns 2 and 6 in Table 4.

As a static check on each model, Thermal & Nuclear Design supplied TNT runs for the four steady-state conditions of interest. It was observed that the resulting steady-state variables of reflector pressures and temperatures of this model were closer to the TNT predictions than in the CAM type formulation.

TABLE 4
 STATIC DIFFERENCE BETWEEN VARIOUS MODELS AT DESIGN
 (Nuclear Subsystem)

SYSTEM VARIABLES	CAM MODEL I	TABHP IN ALL SUBSYSTEMS II	II + PROTK IN TIE ROD III	I + REFLECTOR SECTIONALIZATION (Two Sections) IV	IV + FLOW WORK TERMS AND TABHP REFLECTOR	TNT DATA
E_5	300.0	300.0	300.0	300.0	300.0	300.0
T_{8d}	4090.0	4090.0	4090.0	4090.0	4090.0	4090.0
P_{8d}	574.0	574.0	574.0	574.0	574.0	574.0
P_5	726.0	731.2	731.2	728.7	726.6	730.0
W_r	71.30	71.30	71.30	71.30	71.30	71.45
ρ_6	0.5675	0.5678	0.5678	0.5458	0.5574	----
W_s	71.30	71.30	71.30	71.30	71.30	71.45
W_{tr}	4.23	4.324	4.288	4.201	4.216	4.287
ϕ_{sg}	3723.0	3616.0	3319.0	3723.0	3723.0	3928.0
ϕ_{pg}	3015.0	2917.0	2158.0	3018.0	3017.0	2622.0
ϕ_{ss}	542.7	490.3	531.9	548.8	545.7	----
ϕ_{tr}	541.3	496.5	443.2	547.3	544.2	470.6
W_c	67.07	66.9	67.01	67.1	67.08	67.16
S_n	93.30	90.81	90.81	93.22	93.26	----
S	100.3	97.6	97.6	100.3	100.3	----
T_6	229.7	223.6	233.6	238.9	277.8	227.2
P_6	693.5	693.4	693.4	694.8	693.7	700.82
T_r	180.9	182.7	182.7	190.8	180.5	175.6
ϕ_r	223.3	226.3	226.3	235.5	230.2	225.0

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TABLE 4 (Cont'd.)

SYSTEM VARIABLES	CAM MODEL I	TABHP IN ALL SUBSYSTEMS II	II + PROTK IN TIE ROD III	I + REFLECTOR SECTIONALIZATION (Two Sections) IV	IV + FLOW WORK TERMS AND TABHP REFLECTOR	TNT DATA
T_7	240.0	223.2	233.2	244.5	242.1	235.7
P_7	687.4	687.4	687.5	687.6	687.5	696.18
ρ_7	0.5386	0.5394	0.5394	0.5287	0.5338	----
T_5	139.5	139.0	139.0	139.4	138.9	139.3
ϕ_s	258.7	251.2	251.2	263.2	260.9	261.3
$\phi_{c.1}$	1523.0	1471.0	1470.0	1525.0	1524.0	1559.0
$\phi_{c.2}$	3362.0	3265.0	3264.0	3362.0	3362.0	3276.6
$\phi_{c.3}$	4243.0	4156.0	4154.0	4242.0	4243.0	4182.2
$T_{c.1}$	952.0	918.1	917.8	955.8	953.8	960.0
$T_{c.2}$	2703.0	2619.0	2619.0	2705.0	2704.0	2545.0
$T_{c.3}$	3993.0	3920.0	3920.0	3993.0	3993.0	4045.8
$T_{c.3e}$	4321.0	4383.0	4281.0	4320.0	4321.0	4277.8
T_{tr}	455.7	406.9	421.1	461.4	458.5	403.0
T_{tre}	671.5	596.7	625.2	678.4	674.9	658.0
ϕ_{tro}	502.0	485.5	432.5	508.4	505.3	----
T_8	4090.0	4090.0	4090.0	4090.0	4090.0	4090.0
P_8	574.0	574.0	574.0	574.0	574.0	574.0
W_8	71.30	71.30	71.30	71.30	71.30	71.45
ρ_8	0.02633	0.02627	0.02627	0.02633	0.02633	----
ρ_{tre}	0.1607	0.1791	0.1711	0.1590	0.1599	----
δk_f	0.004014	0.004847	0.004836	0.004262	0.004149	----

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B. CAM Nuclear Subsystem Model with Detailed Hydrogen Properties (No additional axial sectionalization)

(U) The third model which has been analyzed at the design conditions only was a straightforward extension of the CAM equations. The perfect gas law approximations, enthalpy fits, and hydrogen property dependent heat transfer coefficient approximations, at every station in the CAM equations were replaced by use of the hydrogen properties code. The results of this model indicated a number of static (steady-state) discrepancies arising from these approximations as can be seen from column 3, Table 4. Dynamically, the transfer functions, T_8/E_5 , T_6/W_{rl} , T_8/S_n , etc., responded faster due to the inclusion of hydrogen properties. At lower operating points, inclusion of hydrogen properties is expected to produce the greatest effect. These data have not been obtained as yet. An addendum to this report will be issued as soon as the data are available. As a by-product result of this model, it was discovered that the heat generation rate in the tie rod was in error. This will be elaborated upon in the next section.

C. CAM Nuclear Subsystem Model with Detailed Hydrogen Properties and with Detailed Material Properties in Support Element (No additional axial sectionalization)

(CRD) Finally, a model was formulated in which the hydrogen properties code was utilized at all stations in the CAM equations, but additionally, the tie rod equations were reformulated to include a complete description of the thermal variation of the solid material thermal properties. In this model, material enthalpy energy equations replace material temperature energy equations, thus, removing the restriction of constant material specific heats. A steady-state solution of this model at design (column 4, Table 4) shows a large variation in the temperatures in different components of the tie rod. These are mainly due to

the inclusion of detailed thermal properties of different materials in the tie rod. The thermal properties referred to here are the nonlinear thermal conductivity-temperature relationships.

D. Support Element Analysis

(CRD) In the previous study of the tie rod model, certain discrepancies existed between the CAM model results and the experimental data^{5,6} with respect to amplitude and frequency responses. At the outset it was discovered that the description of the heat transfer coefficient needed to be modified, as the existing equation was beyond the limits of its validity. The equation used is:⁷

$$h = \frac{(HD)W_T^{.8}}{D^{1.8}} \left(\frac{T}{T_w} \right)^{-A} \left(1 + \frac{X}{D} \right)^{-B} \quad (17)$$

WHERE:

(U) A, B, and C are constants

D is channel diameter

h is convective heat transfer coefficient

k is thermal conductivity

T is hydrogen bulk temperature

T_w is wall temperature

W is flow rate

X is channel length

γ is the absolute viscosity

At design, the heat transfer coefficient, h, as defined by (17) reduces

to: $h = 0.00199 W_T^{.8}$

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(CRD) Compare equation (2) with $h = 0.00177 W_T^{.8}$ used in the CAM model. This coefficient of the equation, however, is intended to be an average coefficient. This is more correct for hydrogen and valid in the ranges of Reynolds & Prandtl numbers encountered. The model investigation here not only includes this new description of the heat transfer coefficient but also includes consideration of hydrogen and material properties. Heat generation rates were recomputed from the XE data book and were found to be 0.728°R/sec. and 0.664°R/sec. for structural and pyrolytic graphite as opposed to 0.97°R/sec. for both in the CAM model. The heat generation rate and the size of the gap between the fuel and structural graphite were varied in the CAM model purposely to yield a 3750°R design temperature of the structural graphite. The 400°R rise observed at design between the fuel and structural graphite cannot be calculated strictly on the basis of the thermal conductivity equation which is involved.

(U) Also, to yield a better description of the tie rod, radial sectionalization of the tie rod was considered as the next logical step. The generalized tie rod equations are given below.

$$(U) \quad \dot{H}_{sg_{i+1}} = F_{sg_{i1}} (\phi_{sg_i} - \phi_{sg_{i+1}}) + F_{sg_{i2}} (\phi_{sg_{i+2}} - \phi_{sg_{i+1}}) + \frac{K_{sg} S_n}{M_{sg_i}}; i=1, m \quad (19)$$

(CRD) Where the structural graphite has m sections. Also,

$$\phi_{sg1} = \phi_{c,2} \quad \text{and} \quad \phi_{sgm+2} = \phi_{pg1}$$

$$(CRD) \quad \dot{H}_{pg_{j+1}} = F_{pg_{j1}} (\phi_{pg_j} - \phi_{pg_{j+1}}) + F_{pg_{j2}} (\phi_{pg_{j+2}} - \phi_{pg_{j+1}}) + \frac{K_{pg} S_n}{M_{pg_j}}; j=1, N \quad (20)$$

(CRD) Where the pyrolytic graphite has N sections. Also,

$$\phi_{pg_{N+2}} = T_{H_2}$$

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$$F_{sg11} = \frac{2\alpha_{sg10} k_{sg1} k_{H1}}{M_{sg1} (\Delta_{sg} k_{H1} + 2m k_{sg1} \Delta H)} \quad (21)$$

$$F_{sg1i} = \frac{2\alpha_{sg10} k_{sg1} k_{sg1-i}}{M_{sg1} \Delta_{sg} (k_{sg1-i} + k_{sg1})} \quad i = 2, m \quad (22)$$

$$F_{sg12} = \frac{2\alpha_{sg1j} k_{sg1} k_{sg1+1}}{M_{sg1} \Delta_{sg} (k_{sg1} + k_{sg1+1})} \quad i = 1, m-1 \quad (23)$$

$$F_{sgm2} = \frac{2\alpha_{sgmj} k_{sgm} k_{pg1}}{M_{sgm} (\Delta_{pg} k_{sgm} + k_{pg1} \Delta_{sg})} \quad (24)$$

ALSO:

$$F_{pg11} = \frac{2N\alpha_{pg10} k_{pg1} k_{sgm}}{M_{pg1} (\Delta_{pg} k_{sgm} + k_{pg1} \Delta_{sg})} \quad (25)$$

$$F_{pgj2} = \frac{2N\alpha_{pgji} k_{pgj} k_{pgj+1}}{M_{pgj} \Delta_{pg} (k_{pgj} + k_{pgj+1})} \quad j = 1, N-1 \quad (26)$$

$$F_{pgj1} = \frac{2N\alpha_{pgjo} k_{pgj} k_{pgj-1}}{M_{pgj} \Delta_{pg} (k_{pgj-1} + k_{pgj})} \quad j = 2, N \quad (27)$$

$$F_{pgN2} = \frac{2N\alpha_{pgNj} k_{pgN} k_{H2}}{M_{pgN} (\Delta_{pg} k_{H2} + N\Delta H_2 k_{pgN})} \quad (28)$$

Thermal properties code⁸ PROTK is used to determine the thermal conductivities of materials and the hydrogen properties code TABHP is used to determine hydrogen properties. The masses are calculated in the following manner:

Structural Graphite

$$\text{Width of structural graphite} = \frac{D_o - D_j}{2}$$

$$\text{Width of structural graphite per section} = G = \frac{D_o - D_j}{2m}$$

Where m is the number of sections:

$$\begin{aligned} A_i &= 3.464 \left(\frac{D_o}{2} \right)^2 - \pi (D_o - G)^2 \\ A_i &= \pi \left(\frac{D_o}{2} - (i-1)G \right)^2 - \pi \left(\frac{D_o}{2} - iG \right)^2 \quad i = 2, m \quad (29) \\ V_i &= A_i L_{sg} \\ M_{sg i} &= \rho_{sg} A_i L \end{aligned}$$

Pyrolytic Graphite

$$\text{Width of pyrolytic graphite per section} = G_{pq} = \frac{D_{opq} - D_{j pq}}{2N}$$

$$A_j = \pi \left(\frac{D_{opq}}{2} - (j-1)G_{pq} \right)^2 - \pi \left(\frac{D_{opq}}{2} - jG_{pq} \right)^2 \quad j = 1, N \quad (30)$$

$$V_j = LA_j$$

$$M_{pqj} = \rho_{pq} V_j$$

The surface areas are calculated in the following manner:

Structural Graphite: At the various interfaces, the following equation holds true:

$$\begin{aligned} \alpha_{sgio} &= \alpha_{sg(i-1)j} \quad i = 2, m \\ \alpha_{sgio} &= \pi L \left(D_o - 2(i-1)G \right) \quad i = 1, m \quad (31) \\ \alpha_{sgmj} &= 3.464 D_j L \end{aligned}$$

Pyrolytic Graphite:

Interface conditions here are given by:

$$\alpha_{pgJo} = \alpha_{pg(J-1)j} \quad J=2, N \quad (32)$$

$$\alpha_{pgJo} = \pi L(D_{opg} - 2(J-1)G_{pg}) \quad J=1, N$$

$$\alpha_{pgNj} = \pi D_j L.$$

The energy balance in the hydrogen gap between pyrolytic graphite and the stainless steel liner yields the following differential equation:

$$\dot{E}_{H2} = \frac{2\alpha_{H2} k_{H2} k_{pg}}{M_{H2}(k_{H2}\Delta_{pg} + \Delta H_2 k_{pg})} (\phi_{pg} - T_{H2}) + \frac{F_6}{M_{H2}} (\phi_{ss} - T_{H2}). \quad (33)$$

Also:

$$\dot{H}_{ss} = F_7(T_{H2} - \phi_{ss}) + 681.8 h_o(T_g - \phi_{ss}) + 0.2388 S_n \quad (34)$$

and the differential equation for the hydrogen gap between stainless steel liner and Inconel is:

$$\dot{E}_g = \frac{1}{M_g} 2W(E_7 - E_g) + h_o \alpha_{ssj}(\phi_{ss} - T_g) + h_i \alpha_{tro}(\phi_{tro} - T_g). \quad (35)$$

Also the following equations are written down from WANL-TME-1491 (Reference 1):

$$\phi_{tro} = \phi_{tr} + 0.0275 \frac{h_i}{k_{tr}} (T_g - \phi_{tro}) \quad (36)$$

$$\dot{H}_{tr} = 0.441 \times 10^4 k_{tr} (\phi_{tro} - \phi_{tr}) + 0.2105 S_n \quad (37)$$

$$T_{tre} = 2T_g - T_7 \quad (38)$$

$$T_{tr} = T_g$$

$$F_6 = 2\alpha_{sso} \frac{k_{H2} k_{ss}}{(\Delta_{ss} k_{H2} + \Delta H_2 k_{ss})} \quad \text{Figure 16, WANL-TME-1491} \quad (39)$$

$$F_7 = \frac{F_6}{M_{ss}} = 17F_6 \quad (40)$$

(CRD) $\phi_{ss} = f(H_{ss})$ (Figure 17, WANL-TME-1491) (41)

(CRD) $T_g = f(E_g)$ (Figure 19, WANL-TME-1491) (42)

(CRD) $h_i = h_o = h$

(CRD) The input needed for the solution of the above tie rod equations are the values of E_7 , W_{tr} , S_n , and $\phi_{c,2}$. The steady-state values obtained for various combinations of sectioned structural and pyrolytic graphite are given in Table 5. Variable hydrogen and material properties are used in each case. It is apparent from Table 5 that the tie rod exit temperature is greatly affected in going from one to two radial sections in the pyrolytic graphite but not much is gained in going from 2 to 6 radial sections. Thus, it would seem reasonable to consider one section in the structural graphite and two sections in the pyrolytic graphite along with hydrogen and material properties for better analysis of the tie rod model. Not much is gained in going to more radial sections. Comparison with the TNT data at various operating points is shown in Table 6. The differences observed are probably due to the fact that the coefficients in the heat balance equations are calculated on the basis of the geometry and are not adjusted on the basis of yielding a design temperature. Also, this model considers a new description of the heat transfer coefficient and different values of the heat generation rates as pointed out earlier. Hence, the comparison should be viewed with these differences in mind.

(CRD) Transfer function data are represented in Figures 4 and 5. Transfer functions T_{tre}/S_n and T_{tre}/E_7 show a small gain difference for the two cases of $m=1$, $N=1$, and $m=2$, $N=6$. The phase difference is also quite small.

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TABLE 5
 STATIC DIFFERENCES DUE TO RADIAL SECTIONALIZATION - TIE ROD MODEL
 (Nuclear Subsystem)

SYSTEM VARIABLES	RADIAL SECTIONALIZATION						CAM MODEL
	M = 1 N = 1	M = 2 N = 2	M = 2 N = 3	M = 2 N = 4	M = 2 N = 5	M = 2 N = 6	
S	100.0	100.0	100.0	100.0	100.0	100.0	100.7
ϕ_{sg1}	3426.0	3401.0	3422.0	3435.0	3442.0	3445.0	-----
ϕ_{sg2}	-----	3384.0	3427.0	3455.0	3469.0	3475.0	3725.0
ϕ_{pg1}	-----	-----	-----	-----	3410.0	3450.0	-----
ϕ_{pg2}	-----	2898.0	3149.0	3324.0	3269.0	3384.0	-----
ϕ_{pg3}	-----	-----	-----	3029.0	3039.0	3272.0	-----
ϕ_{pg4}	2648.0	-----	2542.0	2564.0	2585.0	3047.0	3018.0
ϕ_{pg5}	-----	1799.0	-----	1688.0	1734.0	2605.0	-----
ϕ_{pg6}	-----	-----	1641.0	-----	-----	1779.0	-----
T _{H2}	1110.0	894.2	858.5	873.4	887.8	901.7	-----
ϕ_{ss}	556.3	460.3	446.6	452.3	457.8	463.2	542.2
T _{tr}	458.9	393.2	384.1	387.9	391.6	395.2	455.3
ϕ_{tro}	484.2	418.6	409.5	413.3	416.9	420.5	541.1
ϕ_{tr}	515.2	451.0	442.1	445.8	449.4	452.9	502.0
T _{tre}	682.4	551.1	533.0	540.5	547.8	555.0	670.7
W _{tr}	4.247	4.247	4.247	4.247	4.247	4.247	4.247

* Temperatures shown here are temperatures at physical radial locations in the tie rod.

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TABLE 6

STATIC DIFFERENCES BETWEEN TIE ROD MODEL AND TNT DATA
 AT DIFFERENT OPERATING POINTS

SYSTEM VARIABLES	DESIGN POWER		50% OF DESIGN		STRUCTURAL LIMIT POWER	
	2 Sections in Pyro*	TNT Data	2 Sections in Pyro*	TNT Data	2 Sections in Pyro*	TNT Data
ϕ_{sg}	3446.0	3928.0	2005.0	2225.6	3194.0	3362.0
ϕ_{pg1}	2945.0	3575.0	1778.0	2000.0	2755.0	3100.0
ϕ_{pg2}	1818.0	1625.0	1250.0	1475.0	1834.0	1600.0
T_{H2}	897.9	----	730.4	----	1121.0	----
ϕ_{ss}	461.7	----	396.1	----	859.9	----
T_{tr}	394.2	403.0	337.3	313.6	704.0	635.2
ϕ_{tro}	419.6	----	353.5	----	727.4	----
ϕ_{tr}	451.9	470.6	370.3	356.2	735.4	728.0
T_{tre}	553.1	658.0	482.1	494.7	1175.0	1314.2
W_{tr}	4.247	4.287	3.465	3.465	1.1325	1.1325

*Pyrographite

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31

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FIGURE 5
TRANSFER FUNCTION: Tie Rod Exit Gas Temperature/Tie Rod Inlet Enthalpy
(Design Power)

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Thus it would seem reasonable to consider one section in the structural graphite and two sections in the pyrolytic graphite along with hydrogen and material properties for better analysis of the tie rod model. Not much is gained in going to more radial sections.

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CONCLUSIONS

Summary of Results:

Numerous digital TAF studies have been made with models more rigorous than the Common Analog Model (1) as part of a continuing effort to provide the simplest and most accurate CAM models, and (2) to lay the foundation of a more rigorous model for use in verifying the adequacy of the simpler CAM models.

Several important conclusions have been drawn from the work:

- (1) At least two axial sections are needed in the reflector to insure an accurate relationship between input and output variables. However, the reflector has little effect on the overall subsystem transfer functions such as P_8/P_5 , T_8/S_n , etc. Therefore, for normal control studies no increase in axial sections will be made in the CAM model of the reflector.* It is anticipated that this could have an important effect, particularly in some of the fast malfunction transient studies where flow rates are changed rapidly.
- (2) Studies with the rigorous reflector model indicated no appreciable effect on the important reactor transfer functions. The results in Item (1) above all apply.
- (3) Studies of the CAM model with hydrogen properties at all stations indicated a number of static (steady-state) differences, but these were not considered to be significant. Dynamically, the transfer functions T_8/E_5 , T_6/W_{r1} , T_8/S_n , etc., had a wider bandwidth due to

* The importance of calculating an accurate set of dome conditions is greater in an engine configuration. This will be elaborated upon further in the section on Recommendations.

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the inclusion of hydrogen properties. At lower operating points, inclusion of hydrogen properties is expected to produce the greatest effect.

- (U) However, the changes in the response due to these modifications are small enough so that no change in the CAM model is indicated at this time. It may be mentioned here that, with some effort, the hydrogen and material properties can be incorporated in the hybrid-analog model where the properties can be looked up from a digital table, thus affording a more accurate analog simulation capability.⁹
- (U) (4) Studies with an improved set of material properties in the support element indicate no appreciable effect on the important reactor variables.
- (CRD) (5) The support element study has shown that the CAM model representation of the pyrographite must be increased from one to two radial sections.
- (U) (6) The support element study has also shown that CAM coefficients must be modified to reflect the latest heat generation rate data. The heat transfer coefficient will also be slightly modified.
- (U) An important by-product of these studies is the development of the foundation of a detailed transient digital model of the nuclear subsystem with which various simplifications can be investigated. Various important effects are included in this model which are not in the CAM representations as, flow work, variable hydrogen and material properties, etc.
- (U) In all the models studied here, although a considerable amount of additional computer calculations are required, in no instance did the digital

(U) computer time required for solution of a given set of calculations exceed twice the corresponding solution time for the simplified CAM formulation. The number of iterations required to obtain a steady-state solution does not appear to increase appreciably with the numerical complexity of the equations.

Suggestions for Further Modeling:

(U) Considering the results of this study, the suggestions offered in this section are intended to improve the CAM equations and to indicate what is considered important for further investigation.

(U) It is essential that all future CAM equations include the decay heat formulation. The need for these equations was demonstrated during the NRX-A5 post-test model evaluation.¹⁰ These equations retard temperature responses during startups and more accurately predict all component (especially tie rod) temperature responses during shutdowns.

(U) It would be desirable to review the power fractions in all nuclear subsystem components to insure that the design power of 1120 Mwt is attained.

(CRD) An energy imbalance exists between the core material and the tie rod structural graphite. Although the structural graphite energy equations reflect the pick-up of heat by conduction from the core, the core energy equations do not reflect the corresponding heat loss. Preliminary studies indicate that this imbalance is dynamically unimportant to the core region. Since there are three axial sections in the core and only one tie rod axial section, any heat removed from the core by the tie rod is contributed by each of the three core sections. One formulation is to divide this total heat loss in three segments, weighted by the power profile and include this heat as one additional term to the present CAM core material energy equations. This will be further investigated.

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The loss coefficients associated with each momentum equation should be constantly updated to reflect the latest steady-state pressure drops across each component at design conditions.

The following future studies are indicated from the work:

- (1) The importance of two axial reflector sections on the engine bleed system response will be investigated before finally deciding upon retaining one section in CAM for XE models.
- (2) Further work is needed involving the support element to determine what thermal properties, if any, can be held constant and yet yield reasonable results using a reasonable amount of analog equipment.
- (3) The more complex nuclear subsystem model up to date must be "tied together" and the coefficients and equations modified to give both an XE and R-I type configuration.
- (4) The use of internal energy (and thus flow work) in all components, including core and tie rod, should be incorporated and the effect examined.
- (5) The use of hydrogen and material properties in all components of the nuclear subsystem should be included and evaluated.
- (6) The determination of an adequate dynamic feedback reactivity function should be made from test data.
- (7) The use of gas flow dynamic momentum and continuity equations in the various plena should be investigated to reflect the gas accumulation effects of these components.

- (8) Radial sectionalizing of the reflector has not yet been investigated but may be more important to the overall model evaluation than the reflector studies to date.

APPENDIX

Modeling Techniques:

In order to keep a mathematical model simple, especially for analog programming, many simplifying assumptions must be utilized. Where possible, empirical relationships are reduced to linear equations, the perfect gas law is assumed and variable time constants are fixed. Many variables, such as thermal conductivities and specific heats, are fixed in the vicinity of their optimum values (for example, near the design value) and numerical approximations to partial differentiation are kept linear. All of these approximations reduce, to some degree, the static and dynamic accuracy of the resultant model.

Digital computer models need not strictly adhere to these limitations to remain simple. In the models utilized in the previous section, advantage was taken of the digital mode of solution to increase the response accuracy where possible. Extensive use was made of tabular digital interpolation sub-routines to obtain:

- (a) hydrogen properties as functions of enthalpy and pressure,
- (b) material temperature as a function of material enthalpy,
- (c) thermal conductivities as functions of material temperatures, and
- (d) component power fractions as functions of the number of sections for a given component.

Numerical iteration schemes were required in many instances. The techniques used in the model study are briefly illustrated below as an aid to future modeling.

A. Computation of the Hydrogen Properties When Input Variables are Unknown

Using the hydrogen properties code, TABHP, when the independent variables of either (or both) enthalpy, E , and pressure, P , are unknown. This requires iteration with exactly two variables which are known. One example of this is the case where the known variables (differential equation initial conditions) are internal energy, U , and gas density, ρ (from the continuity equation). From these variables, using TABHP, one must obtain the additional variables of E , P , and T (temperature).

Given: U and ρ

Find: E , P , and T , using TABHP and some iteration method.

Using the perfect gas law approximation and a linear enthalpy fit equation versus pressure and temperature, the guess of E and P can be obtained.

$$P = \rho RT \quad (\text{Perfect gas law})$$

$$E = aT + bP + c \quad (\text{Linear fit})$$

$$\text{Thus, } E = aP/\rho R + bP + c \quad (43)$$

$$\text{and } U = aP/\rho R + bP + c - P/J_e \rho \text{ by definition} \quad (44)$$

Solving for P_1 (initial guess) in terms of U and ρ

$$P_1 = (U - c)(a/\rho R + b - 1/J_e \rho) \quad (45)$$

and from equation (43) we now have an initial guess for E_1 . The iteration scheme presented in Figure 6 is therefore:

- (1) Using E_N and P_N find ρ_N , and T_N from TABHP
- (2) Compute U_N

(3) If U_N does not equal U , update E by the equation:

$$E_{N+1} = E_N(2 - U_N/U_{N-1})$$

(4) Return to statement (1) until U_N and U do not differ by more than a specified error criterion.

(5) If ρ_N does not equal ρ , update P by the equation:

$$P_{N+1} = P_N(2 - \rho_N/\rho)$$

(6) Now return to statement (1) again. Eventually both U_N and ρ_N should converge to U and ρ with the error criteria specified.

B. Computation of Power Fractions:

Component power fractions, specified by Reactor Analysis in WANL-TME-483¹¹, must be distributed according to the axial power profile when axial sectionalization of that component is performed. For example, if the reflector were sectioned into N equal axial components, the power fraction for each section would be weighted according to the power profile.

Assume a total component power factor, PF_{TOT} , and a power profile given by the following curve.

This profile could be a digital table of points x and y inserted into the data. Manipulation of these data to determine weighting factors is done by substituting for y , the value of the area under the curve at x by numerically integrating the curve on the computer and storing the areas.

FIGURE 6

Iteration Scheme to Compute E and P, Given U and ρ

The area in the i^{th} segment is:

$$a_i \approx \frac{(x_i - x_{i-1})(y_i + y_{i-1})}{2} \quad i=1, \text{NTOT (Total No. of profile points)}$$

The total area up to the i^{th} segment is:

$$A_i \approx A_{i-1} + a_i = \sum_{i=1}^{\text{NTOT}} a_i$$

where: $A_0 = 0$

Now, in the table where the y 's were first stored, store $y_i = \frac{A_i}{A_{\text{NTOT}}}$
(thus normalizing all areas to 1).

The power factor corresponding to each of the N axial component sections is then determined by the equation:

$$\text{PF}_i = \text{PF}_{\text{TOT}} \left[Y(L_i) - Y(L_{i-1}) \right] \quad i=1, N$$

The term in the bracket represents the fractional area of the curve from L_{i-1} to L_i .

C. Computation of Loss Coefficients

Loss coefficients and component power fractions must be determined empirically from data of pressure drops and gas or material temperatures. A way to establish what their values are for any given model is to continuously update these parameters until the demanded pressure drops and temperatures are attained in the steady state. This updating process can be numerically performed during the solution of a steady state in the TAF code.

Consider the problem of determining the coefficient in the reflector momentum equation which would exactly yield a pressure drop across that component of DP_P . This equation is:

$$\dot{W}_r = K_R \left(DP_{\text{computed}} - \frac{C_L W_R^2}{\rho_R} \right)$$

If the coefficient C_L is not correct, DP_{computed} will not equal DP_D in the steady state as desired. Since the value of C_L is empirical, nothing is sacrificed by artificially changing it until $DP_{\text{computed}} = DP_D$.

In TAF, C_L may be changed in one of two ways: (1) by linearly changing C_L with each iteration as DP_{computed} is determined, i.e.,

$$C_{L_i} = \frac{C_{L_{i-1}} (2 - DP_{\text{computed } i-1})}{DP_D}$$

or (2) by making a controller differential equation of C_L to utilize the steady-state calculational approach of TAF, i.e.,

$$\frac{dC_L}{dt} = K_{CL} (DP_D - DP_{\text{computed}})$$

In this case, the gain (K_{CL}) must be determined such that the system is numerically stable.

Either of these approaches is simply applied and greatly assists in obtaining model accuracy. Of course, an initial guess of C_L must be supplied. In the same way, all component channel loss coefficients can be determined to match the corresponding desired static pressure drops.

The technique by which one can obtain specified material and gas temperatures is basically the same as above. Update the component power fractions until the desired temperatures are attained. However, additional restraints must be considered. The sum total of all component power fractions must equal unity and each power fraction must be positive. Therefore, if N power fractions are to be determined,

$$PF_{N+1} = 1 - \sum_{i=1}^N PF_i$$

where $PF_i > 0 \quad i=1, N+1.$

D. Multi-parallel Flow Channels:

Finally, an example is given to illustrate how multi-parallel flow channels with gas mixing in the plenum can be modeled. This example is illustrated in the core and tie rod formulation and is useful to have at hand.

Given two channel gas inlet conditions, say E_{IN} and P_{IN} , the following approach is useful:

Also given are the differential equation initial conditions for the energy equations, continuity equations, and momentum equations. These are the variables E_1 , E_2 , w_1 , w_2 , w_{out} , and p_{out} .

$$\text{Assume } E_{1e} = 2E_1 - E_{1N}$$

$$E_{2e} = 2E_2 - E_{1N}$$

$$\text{and } E_{out} = \frac{(W_1 E_{1e} + W_2 E_{2e})}{W_{out}}$$

Knowing E_{out} and ρ_{out} obtain P_{out} and T_{out}

Now assume that

$$P_1 = P_2 = \frac{(P_{1N} + P_{out})}{2}$$

Knowing E_1 and P_1 obtain ρ_1 and T_1 .

Knowing E_2 and P_2 obtain ρ_2 and T_2 .

Having determined the above mentioned variables, all of the model differential equations for each channel can be solved. This can be extended to N parallel channels by computing E_{out} accordingly.

$$\text{i.e., } E_{out} = \sum_{i=1}^N \frac{(W_i E_{ie})}{W_{out}}$$

It is sometimes convenient to replace the above equation by:

$$E_{out} = \sum_{i=1}^N \alpha_i E_{ie}, \sum \alpha_i = 1$$

where α_i is a constant representing the steady-state fraction of total flow in the i^{th} channel.

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