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Thermal-Hydraulic Analysis of TFE Verification Test UFAC-1

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Prepared for the U.S. Department of Energy
Assistant Secretary for Nuclear Energy

Westinghouse
Hanford Company Richland, Washington

Hanford Operations and Engineering Contractor for the
U.S. Department of Energy under Contract DE-AC06-87RL10930

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ABSTRACT

The Experimental Breeder Reactor No. II (EBR-II) irradiation test Uninstrumented Fueled Accelerated (UFAC)-1 of seven encapsulated thermionic test pins was analyzed with the code COBRA-SFS. The model predicted coolant and material temperatures for three conditions of interest: Steady state full power, response to the unlikely loss of flow transient, and decay heat cooling by forced down flow of argon. Modeling assumptions and a summary of results are included.

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THERMAL-HYDRAULIC ANALYSIS OF TFE VERIFICATION TEST UFAC-1

1.0 SUMMARY AND CONCLUSIONS

The Uninstrumented Fueled Accelerated (UFAC)-1 thermal performance is compared to the performance requirements as shown in Table 1.

The Experimental Breeder Reactor No. II (EBR-II) requirements for the UFAC-1 are easily met for all operating conditions analyzed. This covers the sodium flow range from 1,000-5,000 lb/h. Argon cooling requirements for orificing to 2,050 lb/h sodium flow are also met, even with only one day of decay time. This permits removal and reconstitution immediately, without concern for overheating. Extrapolation of the temperature calculations for argon cooling to the orificing associated with the lowest sodium flow analyzed (1,000 lb/h) shows marginal performance. Further analyses to demonstrate acceptable cooling during short decay transfers will be necessary if sodium flows approaching 1,000 lb/h are required in the future.

2.0 PROBLEM DEFINITION

The objective of the Thermionic Fueled Element Verification Program is to demon-

strate the lifetime capability of thermionic components and initiate prototype testing of a thermionic element in a fast reactor. One part of this program is the EBR-II irradiation of fueled emitters to determine emitter deformation. The first series of such tests is designated the Uninstrumented Fueled Accelerated (UFAC) tests.

The requirements for all irradiation experiments in EBR-II include the following:

- Test assembly exit temperature must be within 100 °F of the average of surrounding assemblies
- Temperatures during designated over-power and under cooling transients must not approach conditions of sodium boiling or fuel element rupture
- Temperatures during forced down flow argon cooling after removal from reactor must not cause damage to the experiment. At least a 20 min margin for loss of cooling is required.

Capsule bowing must also be characterized to anticipate the impacts on disassembly and reconstitution following scheduled interim examinations.

The UFAC capsule is illustrated

Table 1. Uninstrumented Fueled Accelerated-1 Requirements and Performance.

EBR-II requirement	UFAC-1 performance
Exit temperature within 100 °F of average of surrounding assemblies.	Meets this requirement for the flow rates of interest, 1,000 - 5,000 lb/h.
Temperatures during loss of flow transients must be below boiling.	Peak temperature calculated (at 1,000 lb/h flow rate) is about 100 °F or 500 °F below boiling.
Temperatures during argon cooling must not damage the experiment (limit is 1000 °F to prevent cladding degradation).	Peak temperature if orificed to a sodium flow of 2,050 lb/h is 660 °F after only one day of cool down. Extrapolation if orificed to 1,000 lb/h is 975 °F, marginally acceptable.
Argon cooling requires 20 min margin to limit on loss of flow.	About 9 h is required before reaching the 1000 °F limit for a sodium flow of 2,050 lb/h, which easily exceeds the requirement. Acceptability for flows as low as 1,000 lb/h will require analysis for confirmation.

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schematically in Figure 1. The short fuel column is centered axially on the EBR-II core mid-plane. Below the fuel pin is a solid steel shield section and above is a large fission gas plenum. The fuel region is characterized radially by the UO_2 pellet, the tungsten emitter, a wide helium-argon mixture gas gap, the niobium collector, a narrow helium-filled gas gap, and the outer stainless steel capsule. The two types of UFAC assemblies are illustrated in Figure 2. The prototype pin has a 0.5 in. OD emitter and a 1.83 in. long fuel column. The accelerated burnup pin features a 0.25 in. OD emitter and a 1.00 in. long fuel column. At comparable linear powers, the accelerated pin accumulates burnup at four times the rate of the prototype pins.

Surrounding the prototype assembly in position 7F1 are three EBR-II driver assemblies on the core side and three blanket assemblies outboard. The accelerated burnup assembly located in position 5E2 is surrounded by 91 pin metal fueled driver assemblies. Both the steady state and the transient response of the test assemblies are affected by the surrounding assemblies. The test assembly power, flow, and temperatures are much lower than the driver assemblies. Consequently, the heat flow between assemblies is important in determining the test assembly temperatures.

3.0 MODEL DESCRIPTION

The UFAC thermal performance was characterized with the COBRA-SFS code.⁽¹⁾ Both steady state and transient conditions were predicted for both up flow with sodium and down flow with argon. The UFAC test geometry was modeled with three types of elements:

- Flow channels
- Slabs for conduction heat transfer
- Rods to simulate fuel pins.

The UFAC pin geometry to be modeled is illustrated in Figure 3. This geometry dictates the fine structure needed to simulate the pins. A one-twelfth section of the test assembly is modeled and one sixth of the adjacent driver assembly. The resulting cross section model is

illustrated in Figure 4. One-half of the outer capsule closest to core center is modeled, i.e., pin position number 10 in Figure 2. One-twelfth of the center pin (pin position number 5) is also modeled. These pins differ only in their emitter thickness, being 25 mils on pin 10 and 20 mils on pin 5. All external boundaries are adiabatic. Forty-three axial segments are specified, as listed in Table 2. All dimensions represent the steady state, full power conditions in the reactor, and are not changed during the transient or for the decay heat cases.

In order to include radiation heat transfer between the emitter and collector, the radial gas gap heat transfer is modeled with a gap coefficient. Gas conductance and emitter to collector radiation are included as parallel heat transfer paths. All remaining heat transfer is by conduction in the slabs and conduction and convection in the fluid channels.

The clearance between the UFAC capsules and the duct is about 12 mils, or about an average of 3 mils if the seven capsules are uniformly spaced. The radial temperature gradients on the outer capsules will cause outward bowing during steady state conditions, restrained by contact with the duct. Therefore, the model geometry sets the outer capsules against the duct wall and maintains the inner capsule centered.

4.0 CODE MODIFICATIONS

4.1 COBRA-SFS DESCRIPTION

The COBRA-SFS (Spent Fuel Storage) is a generalized computer code developed by Pacific Northwest Laboratory (PNL)⁽¹⁾ to evaluate the thermal-hydraulic performance of a wide variety of systems. Even though the code was refined and specialized for spent fuel storage system analyses, it is designed to predict flow and temperature distributions under a wide range of flow conditions, including mixed and natural convection. The COBRA-SFS code is structured to perform both steady-state and transient calculations.

The COBRA-SFS provides finite-volume solutions to the equations governing mass, momentum, and energy conservation for incompressible flows. Although it is assumed that the backfill medium is incompressible,

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Figure 1. Uninstrumented Fueled Accelerated Capsule Design.

Figure 2. Uninstrumented Fueled Accelerated Subassembly Schematic.

Figure 3. Uninstrumented Fueled Accelerated Model Geometry.

Table 2. Uninstrumented Fueled Accelerated Axial Segments.

Segment no.	Hot length (in.)	Constituents	
		UFAC	Driver
(66.376 in.)			
43	1.833	Outlet Hex	Outlet Hex
42	1.629	Outlet Hex	Shield Rod
41	1.629	Outlet Hex	Shield Rod
40	1.856	End Plug	Shield Rod
39	1.856	End Plug	Shield Rod
38	0.829	End Plug	Hex Shield
37	2.162	Plenum	Hex Shield
36	2.162	Plenum	Hex Shield
35	2.162	Plenum	Hex Shield
34	1.164	Plenum	Gap/End Plug
33	2.658	Plenum	Plenum
32	2.658	Plenum	Plenum
31	2.658	Plenum	Plenum
30	2.658	Plenum	Plenum
Top of Core (38.362 in.)			
29	2.735	Plenum	Fuel
28	2.735	Plenum	Fuel
27	0.100	Nb Plate	Fuel
26	0.050	Nb	Fuel
25	0.101	Ta	Fuel
24	0.101	Nb	Fuel
23	0.101	Nb	Fuel
22	0.261	Spring	Fuel
21	0.121	Pedestals	Fuel
20	0.170	Fuel	Fuel
19	0.170	Fuel	Fuel
18	0.170	Fuel	Fuel
Core Mid-plane (31.647 in.)			
17	0.170	Fuel	Fuel
16	0.170	Fuel	Fuel
15	0.170	Fuel	Fuel
14	0.035	Pedestal	Fuel
13	0.036	W End Cap	Fuel
12	0.134	Gas Gap	Fuel
11	0.157	Nb Plate	Fuel
10	0.140	Transition	Fuel

Table 2. Uninstrumented Fueled Accelerated Axial Segments.
(cont.)

Segment no.	Hot length (in.)	Constituents	
		UFAC	Driver
Core Mid-plane (31.647 in.) (cont.)			
9	1.003	Transition	Fuel
8	1.070	Shield Rod	Fuel
7	1.510	Shield Rod	Fuel
6	2.265	Shield Rod	Fuel
Bottom of core (24.787 in.)			
5	1.133	Shield Rod	Transition
4	7.235	Shield Rod	Hex Shield
3	7.392	Shield Rod	Shield Rod
2	5.692	Shield Rod	Hex Shield
1	3.335	Inlet Hex	Inlet Hex

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COBRA-SFS uses a thermally expandable flow model to calculate buoyancy-driven circulating flows within a system. Analyses are conducted using a subchannel approach in which the flow areas of assemblies are divided axially into discrete control volumes for which the conservation equations of mass, momentum, and energy are written. These equations are then solved using an iterative implicit method. The energy equations for the coolant, rod cladding, fuel, and structural members (walls) are solved simultaneously in a plane. Axial conduction in the structural members is included. A nonparticipating, gray body radiation heat-transfer model also allows two-dimensional radiant heat exchange among all solid members in an enclosure and is iteratively coupled to the rod and wall energy equations.

The flow field may be either user prescribed or internally calculated as a function of the gravitational and dynamic pressure losses. Specifications of heat losses from the boundary may vary circumferentially and axially, and can include both radiation and convection heat transfer. It is also possible to model axial heat transfer from the subchannel model to plenum regions (regions above and below the fuel assemblies).

4.2 CODE MODIFICATION DESCRIPTION

To accurately model the UFAC-1 pin geometry, modifications were made to the released version of the COBRA-SFS code. Most of these modifications were required to add flexibility in the solid structure modeling capabilities. Features added to the code include:

- Temperature-dependent solid thermal conductivities
- Solid heat generation vs. time as a function of material type
- Axially varying material types
- Material dependency of solid-to-fluid connections
- Temperature-dependent heat transfer coefficient.

Each of these features is described in more detail below.

4.2.1 Temperature-Dependent Solid Thermal Conductivities

Solid material properties, such as thermal conductivity, are specified as constants for each material type in the original version of COBRA-SFS. For materials used in the UFAC-1 test, the temperature range for some of the materials used in the pin was large enough to cause a significant variation in thermal conductivity from one location to another. For this reason, the code was modified to allow the solid thermal conductivity for each solid material type to be expressed as a function of temperature using the polynomial expression:

$$k = C_0 + C_1 \times T + C_2 \times T^2 + C_3 \times T^3$$

where C_0 , C_1 , C_2 and C_3 are user specified constants, and T is the temperature in $^{\circ}\text{R}$.

The flow and temperature equations were solved iteratively at each time step. For each iteration, the solid thermal conductivities are updated to reflect the current temperature distribution.

4.2.2 Solid Heat Generation vs. Time

The original version of COBRA-SFS did not provide for variation of solid heat generation as a function of time, except in the case of fuel rods. The UFAC-1 test contains both fuel and materials that are heated by gamma radiation. As a result, decay heat as a function of time varies from one material to another. For this reason, a modification was made to allow specification of the transient heat generation profile as a function of material type.

4.2.3 Axially Varying Material Types

In the original version of COBRA-SFS, the geometry, including solid material types, was assumed to be uniform in the axial direction. In the fuel region of the UFAC-1 test there were as many as thirteen different solid material zones occupying the same cross-sectional location. For this reason, an option was added to specify material types as a function of axial location. The material type

for each node is used to calculate material properties, such as thermal conductivity.

4.2.4 Solid-to-Fluid Connections

The thermal connection between a solid node and subchannel consists of two parts: (1) the thermal resistance between the center of the solid node and the wetted surface, and (2) the resistance between the surface and center of the subchannel. In the original version of COBRA-SFS, the thermal resistance in the solid node must be specified directly. Since modifications were made to allow varying material types and temperature dependent conductivity for solid nodes, this method for specifying resistance was inadequate for many situations. For this reason, an option was added to specify the resistance in terms of a geometry shape factor similar to those used in the solid-to-solid thermal connections. The thermal conductivity of the node was determined based on material type and temperature, and was then used to calculate the thermal resistance.

4.2.5 Heat Transfer Coefficients

The solid-to-solid thermal connections in COBRA-SFS allow the specification of a gap resistance between the surfaces of adjacent nodes. In the original version of COBRA-SFS, the gap resistance was assumed to be constant and uniform in the axial direction. In the UFAC-1 test there was a helium-argon mixture gas gap, which was critical in determining the peak temperatures in the fuel. The dimensions and characteristics of this gap vary as a function of axial location. For this reason, the code was modified to directly specify the gap resistance at each axial location. The resistances were written in terms of temperature and added directly to the energy solution subroutine.

4.3 CODE MODIFICATIONS

As a result of the modifications to the COBRA-SFS code described in Section 4.2, changes were made to the COBRA-SFS input structure. These changes are described in Appendix A on a line-by-line basis. The input description format used is similar to that used in the COBRA-SFS user's manual.⁽¹⁾

A list of the code update changes is presented in Appendix B.

5.0 STEADY STATE PREDICTIONS

The UFAC-1 experiment was orificed for 5,000 lb/h flow in EBR-II Run 144, its initial irradiation. It was reorificed to 2,050 lb/h following interim examination for its second irradiation in Runs 146 and 147. Later irradiations may require reorificing to as low as 1,000 lb/h. Steady state calculations for flows of 5,000, 2,000 and 1,000 lb/h were made to cover the range of interest. The temperatures of interest are shown in the following figures and tables. Figure 5 illustrates that the UFAC exit temperature always fell within the allowable range. Figure 6 charts the radial temperature profile at mid-plane. The assumption of zero gap between the emitter and fuel is evident. The purpose of reorificing at interim exams was to maintain emitter temperatures near design values. Both fuel burnup and emitter deformation tended to lower the emitter temperature with time. The results in Table 3 present the sensitivity of emitter temperature to reorificing.

Table 3. Emitter Sensitivity to Sodium Temperatures.

Flow, lb/h	Mid-plane sodium temperature °F	Mid-plane emitter temperature °F
5,000	740	2821
2,000	783	2839
1,000	837	2861

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The temperature dependent gas conductivity and the increased radiation heat transfer made the emitter temperatures somewhat insensitive to sodium temperature.

Axial temperature profiles are charted in Figure 7. Radial temperature gradients near

the top of the core are charted in Figure 8. The gradients from the driver assembly are near the middle of the hex flat and should be associated with the pin 10 circumferential gradients at 1.73 in., as indicated with the dashed line. The pin 10 circumferential gradients show that the assumption of bowing toward the corner is appropriate for flows higher than about 1,500 lb/h. Below that flow, the temperature gradient probably caused inward bowing. The center pin temperatures for the 1,000 lb/h case were thus lower than what would be expected.

The UFAC edge temperatures were tied closely to driver assembly temperatures in all cases. Figure 9 charts the axial progression of radial gradients for the 5,000 lb/h flow case. The largest gradients developed above the core as the edge temperatures were further increased by heat flow from the driver assembly.

6.0 LOSS-OF-FLOW PREDICTIONS

The safety requirements for EBR-II experiments include surviving the unlikely loss of flow transient. Sodium temperatures must remain below boiling, and capsule temperatures must not threaten capsule integrity. The UFAC capsules operate at only 4 atm at sodium boiling temperatures, with resulting primary hoop stresses of less than 1,000 psi. This stress imposes no threat to capsule integrity. The predicted peak capsule temperatures are charted in Figure 10. Peak temperatures were just above 1100°F for the low flow case, showing that the safety requirement is easily met.

7.0 DECAY HEAT COOLING PREDICTION

The test was cooled by forced convection, downward flowing argon during transfer of EBR-II experiments between the reactor and Hot Fuel Examination Facility (HFEF) hot cells. The capsule temperatures could not

Figure 5. Uninstrumented Fueled Accelerated Sodium Temperatures.

Figure 6. Radial Gradients at Mid-Plane, Pin 5.

Figure 7. Axial Temperature Profiles, Pin 5.

Figure 8. Temperature Gradients Near Top of Core.

Figure 9. Axial Progression of Temperature Gradients.

UFAC-1, Unlikely Loss of Flow Transient

Figure 10. Uninstrumented Fueled Accelerated-1 Peak Transient Cladding Temperatures.

exceed 1000 °F, to ensure there was no significant oxidation of the cladding. The COBRA-SFS code was run with down-flowing argon to confirm that capsule temperatures were acceptable. The conduction connections between the UFAC-1 and the driver assembly were removed, isolating the UFAC-1 test.

Decay heat levels appropriate to a decay time of one day were chosen as follows.

<u>Material</u>	<u>% SS power</u>	<u>Power/watts</u>
SST	0.13	20.0
Ta	6.35	7.3
UO ₂	0.56	12.6
W/Re/Nb	0.0	0.0

The argon flow rate of 5.09 lb/h was supplied by EBR-II for the UFAC-1A orificing. This orificing provides a sodium flow rate of 2,050 lb/h. The argon exit temperature at one-

day decay time was about 660 °F. The axial temperature profile is charted in Figure 11. The capsule temperatures thus easily met the 1000 °F maximum temperature requirement, even after only one day of cooling.

If the argon flow was lost, the heat capacity of the assembly would ultimately maintain a heatup rate from decay heat of about 30°/h. The transient profile after three hours of zero flow is charted in Figure 11. The temperature history of the peak temperature location is charted in Figure 12. The rate of increase at 3 h was about 36 °F/h, approaching equilibrium. About 9 h at zero flow would have been necessary to reach the operating limit of 1000 °F. This allowed adequate time to reestablish argon cooling or transfer the assembly back to sodium.

8.0 REFERENCE

Rector, D. R., C. L. Wheeler, N. J. Lombardo, 1986, COBRA-SFS: A Thermal-Hydraulic Analysis Computer Code, PNL-6049, Volumes 1-3, Richland, Washington.

Figure 11. Temperature Profiles Under Argon Cooling.

Figure 12. Capsule Temperature History After Loss of Flow.

APPENDIX A

COBRA-SFS CODE MODIFICATIONS

The updates used to modify the cycle 0 version of COBRA-SFS are presented below. A description of the modifications to the code and resulting input format changes may be found in Section 3.0.

Input modifications for temperature-dependent solid thermal conductivity and transient heating rate:

PROP.3 (AMAT(I),ANAME(I),CPSOL(I),RHOSOL(I),CONO(I),CON1(I),
CON2(I),CON3(I),NQVT(I),I=1,NSPROP[PROP.1])

Read only if NSPROP > 0 on PROP.1

FORMAT (I5,A5,6E10.0,I5)

<u>Columns</u>	<u>Variable</u>	<u>Description</u>
1-5	AMAT(I)	Solid material type identification number.
6-10	ANAME(I)	Solid material name (for user convenience).
11-20	CPSOL(I)	Specific heat (BTU/lbm-°F) (for transient calculations).
21-30	RHOSOL(I)	Density (lbm/ft ³) (for transient calculations).
31-40	CONO(I)	Coefficients of an expression for solid thermal conductivity (BTU/h-ft-°F) which has the form: $k = \text{CONO(I)} + \text{CON1(I)}*T + \text{CON2(I)}*T^2 + \text{CON3(I)}*T^3$ where T is the temperature in °R.
41-50	CON1(I)	
51-60	CON2(I)	
61-70	CON3(I)	
71-75	NQVT(I)	Transient heating rate forcing function. Corresponds to profiles read in OPER.14 and 15.

Input modifications for axially varying material types:

SLAB.1 AGROUP,NKSS,NKSF,NWK,NMAT
FORMAT(A4,1X,13I5)

<u>Columns</u>	<u>Variable</u>	<u>Description</u>
1-4	AGROUP	Enter SLAB.
6-10	NKSS	Number of solid-to-solid thermal connection types.
11-15	NKSF	Number of solid-to-fluid thermal connection types.
16-20	NWK	Number of solid structure nodes.
21-25	NMAT	Number of axial material type profiles.

SLAB.3 (KW,MATTYP(KW,1),WALLXC(KW),QSLAB(KW),NAXK(KW),
NSLAB,(KWAL(L,KW),ICON(L,KW),L=1,NSLAB)

Read only of NWK > 0 on SLAB.1

FORMAT(2I5,2F5.3,2I5,5(I5,I5))

<u>Columns</u>	<u>Variable</u>	<u>Description</u>
1-5	KW	Solid structure node identification number.
6-10	MATTYP(KW,1)	Solid node material type identification number (corresponding to a material type specified on PROP.3) or, if greater than NSPROP[PROP.1], an axial material type profile (corresponding to a profile specified on SLAB.6 and 7).
11-15	WALLXC(KW)	Solid node cross-sectional area (in. ²) for axial conduction. (Enter zero if axial conduction will not be calculated for this problem.)
16-20	QSLAB(KW)	Solid node volumetric heat generation rate (BTU/h-ft ³).
21-25	NAXK(KW)	Identification number of the axial heat generation profile table [specified on OPER.16] to be applied to QSLAB(KW). (Default is 1.)
26-30	NSLAB	Number of thermal connections to adjacent solid nodes with index numbers great than KW.
31-35, 41-45, etc.	KWAL(L,KW)	Identification number of the Lth solid node adjacent to node KW, where KWAL(L,KW) > KW.etc.
36-40 46-50, etc.	ICON(L,LW)	Identification number of the thermal connection type for the connection between node KW and node KWAL(L,KW). (Note: This must correspond to a thermal connection type identified on SLAB.2.)

*** SLAB.3 is read in NWK[SLAB.1] times ***

SLAB.6 MAT,NSET

Read only of NMAT > 0 on SLAB.1

FORMAT (2I5)

<u>Columns</u>	<u>Variable</u>	<u>Description</u>
1-5	MAT	Axial material type profile identification number. (Used in SLAB.3. Must be greater than NSPROP [PROP.1].)
6-10	NSET	Number of sets of material type information.

SLAB.7 (KAX(N),KMAT(N),N = 1,NSET[SLAB.6])

Read only if NMAT > 0 on SLAB.1

FORMAT (4(5X,2I5))

<u>Columns</u>	<u>Variable</u>	<u>Description</u>
6-10 21-25 36-40 51-55	KAX(N)	Number of axial nodes in axial set N. (The total number of nodes must be equal to NDX[CHAN.1].)
11-15 26-30 41-45 56-60	KMAT(N)	Material type for axial set N. (Corresponds to material type specified in PROP.3.)

***SLAB.7 is repeated until all NSET sets are read.

***SLAB.6 and SLAB.7 are read NMAT[SLAB.1] times.

Input modification for material dependency of solid-to-fluid connections:

SLAB.4 (IC,RDIMF(IC)RWAL(IC),WID(IC),IC = 1,NSKF[SLAB.1])

Read only if NKSF > 0 on SLAB.1

FORMAT(I5,2E5.0,e105)

<u>Columns</u>	<u>Variable</u>	<u>Description</u>
1-5	IC	Solid-to-fluid thermal connection type identification number.
6-10	RDIMF(IC)	Geometry factor from the solid structure node to the node surface that faces the channel. (Not used if RWAL is specified for connection IC.)
11-15	RWAL(IC)	Thermal resistance (s-ft ² -°F/Btu) from the solid structure node to the node surface that faces the channel. (Not used if RDIMF is specified for connection IC.)
16-25	WID(IC)	Perimeter of solid node that faces the channel (inches).

*** SLAB.4 is read in NKSF[SLAB.1] times ***

APPENDIX B

COBRA-SFS UPDATE LISTING

The updates used to modify the cycle 0 version of COBRA-SFS are presented below. A description of the modifications to the code and resulting input format changes may be found in Section 3.0.

```

*id param
*/
*/ dimensioning parameters
*/
*d specs.71,79
  parameter(ma=37,mc=49,mx=44,me=44,liroll=0,mg=60)
  parameter(mi=6,mj=1,mk=2,ml=6,lmm=31)
  parameter(mn=6,mp=27,mq=1,mr=18)
  parameter(ms=49,mt=4,mv=3,mw=193,mh=5)
  parameter(my=5,nd=3,no=1,nv=1)
  parameter(lnz=1,id=25,ie=20,lif=1)
  parameter(lip=2,iq=1,lir=3,lit=2,iu=2)
  parameter(liw=9,lix=1,liz=67,ih=9)
  parameter(la=1,lb=1,llic=1,ld=1,le=1,lf=1)
*id mat
*/
*/ these updates change variable mattyp to a two-dimensional array
*/
*d walls.5
  2          icon(mh,mw),rwal(liz),wid(liz),qgen(mw,mx),
*i energy.67
  qres(jx+1) = 0.0
*i energy.72
  if (nrod.eq.0) qres(2) = 0.0
*i energy.432
  xdumy = amax1((x(jx)-0.5*dx(jx))/z,0.0)
  do 780 n=1,naxp
    call curve (qax,xdumy,axial(1,n),y(1,n),nax(n),ierror,1)
780    vscm(n) = qax/.0036
*d energy.435
  mat = matj(mattyp(k),jx)
*d energy.445,460
  tdown = twall(k,jm1)
  tup = twall(k,jp1)
*d energy.463,471
  if (iterat.le.1.and.ipart.eq.1) go to 175
  axkpl = 0.
  if (jx.eq.ndxpl) go to 51
  matpl = matj(mattyp(k),jx+1)
  tw = twall(k,jp1)+459.67
  conpl = con0(matpl)+con1(matpl)*tw+con2(matpl)*tw*tw
  $+con3(matpl)*tw*tw*tw
  axkpl = 2*wallxc(k)/(dx(jx)/conw(k)+dx(jx+1)/conpl)
51 continue
  axkml = 0.
  if (jx.eq.2) go to 52
  matml = matj(mattyp(k),jx-1)
  tw = twall(k,jm1)+459.67
  conml = con0(matml)+con1(matml)*tw+con2(matml)*tw*tw
  $+con3(matml)*tw*tw*tw
  axkml = 2*wallxc(k)/(dx(jx)/conw(k)+dx(jx-1)/conml)
52 continue
  uwal(1,k) = uwal(1,k)+(axkpl+axkml)/dx(jx)
  qwal(k) = qwal(k)+(axkpl*tup+axkml*tdown)/dx(jx)

```

```

        if (jx.eq.ndxpl.or.ipart.eq.2) go to 60
        caxld(jx,3) = caxld(jx,3)-axkpl
        caxld(jx+1,1) = caxld(jx+1,1)-axkpl
        qlevel = qlevel-axkpl*(twall(k,j)-twall(k,jpl))
*d energy.482
    * dxwall/conw(k))*(1./areaxcp(ii)))/dx(jx)
*d energy.518,519
    if (rdima(ic).eq.0.) go to 174
    ka = min0(k,k1)
    kb = max0(k,k1)
    rser(ic) = rdima(ic)/conw(ka)+rdimb(ic)/conw(kb)
174 continue
*d exprop.180
    $conw(mml))*(1./areaxcp(nb)))
*i setin.88
    do 155 jj=2,mx
        matj(j,jj) = j
155 continue
*i setin.454
    nmat = n4
*i setin.551
    if (nmat.eq.0) go to 120
    do 770 j=1,nmat
        read (i2,9030) mat,nset
        nlist = 3*nset
        read (i2,9030) (izdum(i),i=1,nlist)
        k1 = 2
        k2 = izdum(2)+1
        do 750 n=1,nset
            do 740 jj=k1,k2
                matj(mat,jj) = izdum(3*n)
740 continue
            k1 = k1+izdum(3*n-1)
            k2 = k2+izdum(3*n+2)
750 continue
770 continue
*d setin.1432
    9030 format (12i5)
*id qtran
*/
*/   these updates add transient heat generation functions to
*/   slabs as a function of material type
*/
*i props.20
    4          nqvt(id),conw(mw),matj(id,mx),mattyp(mw),
*d energy.436
    lq = nqvt(mat)+1
    qgen(k,j) = wallxc(k)*vscm(naxk(k))*qslab(k)*powr(lq)
*id rodtrn
*/
*/   these updates fix the rod transient terms
*/
*d fuels.17
    3          hgapl(mt),lri(lir,mc),troid(m7,mr,mx),rtran,endf12

```

```

*d recirc.189
    call hotrod (j,jx)
    qside(jx) = qside(jx)+pi*rtran*dx(jx)
    qres(jx) = qres(jx)-pi*rtran*dx(jx)
*d hotrod.2
    subroutine hotrod (j,jx)
*d hotrod.19
    rtran = 0.0
*d hotrod.24,39
    trod(nod,nth,j) = ring(nth)+rang(nth)+rung(nth)*hsurf(nth,j)
    $ *trod(nod+1,nth,j)
    if (nodf.le.0) go to 230
    rtran = rtran+rcclad(nt)*dsqr(nod,nt)*(trod(nod,nth,j)-
    $ trold(nod,nth,jx))/phitot(n)
    trold(nod,nth,jx) = trod(nod,nth,j)
    do 210 ja=1,nodf,1
    jb = nodf - ja + 1
    trod(jb,nth,j) = (zx(jb,nth)-bx(2,jb,nth)*trod(jb+1,nth,j))
    $ /bx(1,jb,nth)
    rtran = rtran+rcfuel(nt)*dsqr(jb,nt)*(trod(jb,nth,j)-
    $ trold(jb,nth,jx))/phitot(n)
    trold(jb,nth,jx) = trod(jb,nth,j)
    210 continue
    230 continue
    flux(nth,j) = hsurf(nth,j)*(trod(nod,nth,j)-trod(nod+1,nth,j))
    240 continue
    250 continue
*d reheat.250
    zx(1,nth) = (rcfuel(nt)*trold(1,nth,jx)+qfuel)*dsqr(1,nt) +
*d reheat.269
    zx(na,nth) = (rcfuel(nt)*trold(na,nth,jx)+qfuel)*dsqr(na,nt) -
*d reheat.286
    ring(nth) = (rcclad(nt)*trold(nod,nth,jx)+qcld)*dsqr(nod,nt)
*i reheat.321
    trtemp = trod(nod,nth,j)
*d reheat.325
    & trod(nod,nth,j) + (1.-accrod)*trtemp
*d reheat.327
    qrtemp = abs((trod(nod,nth,j)-trtemp)/trod(nod,nth,j))
*d reheat.329
*d reheat.335
*id vector
*/
*/ general vectorization of code
*/
*i prop.176
    dummy = 1.0
    if (iterat.gt.1) dummy = accrho
*d prop.179,181
    rho(i,j) = (1.0/v(i))*dummy+rho(i,j)*(1.-dummy)
*id kvary
*/
*/ these updates allow temperature dependent solid conductivities
*/

```

```

*d props.19
  2          npwcon,con0(id),con1(id),con2(id),con3(id),cpsol(id),
*i differ.47
  if (nwk.eq.0) go to 160
c
c   calculate slab thermal conductivities
c
  do 155 k=1,nwk
    mat = matj(mattyp(k),jx)
    tw = twall(k,j)+459.67
    conw(k) = con0(mat)+con1(mat)*tw+con2(mat)*tw*tw+con3(mat)*tw**3
  155 continue
  160 continue
*d setin.86
  read (i2,9020) amat(j),aname(j),cpsol(j),rhosol(j),con0(j),con1(j)
  $,con2(j),con3(j),nqvt(j)
*d setin.88
  con0(j) = con0(j)/3600.
  con1(j) = con1(j)/3600.
  con2(j) = con2(j)/3600.
  con3(j) = con3(j)/3600.
*d setin.1431
  9020 format (i5,a5,6e10.0,i5)
*d setout.39
  conl = con0(i)*3600.
*d energy.481
  mat = mattyp(ii)
  tp = tpsave(ii)+459.67
  conp = con0(mat)+con1(mat)*tp+con2(mat)*tp*tp+con3(mat)*tp**3
  axconk = 1./((dxplen(ii)/conp +
*d exprop.179
  mat = mattyp(nb)
  tp = tpsave(nb)+459.67
  conp = con0(mat)+con1(mat)*tp+con2(mat)*tp*tp+con3(mat)*tp**3
  axconk = 1./((dxplen(nb)/conp + dxwall/
*/
*/   changes to add material dependency to solid-to-fluid connections
*/
*d walls.4
  1          kwal(mh,mw),icf(nd,mw),twsave(mw),rdimf(liz),
*d differ.59
  rw = rwal(ic)
  if (rw.eq.0.) rw = rdimf(ic)/conw(k)
  uwall(nsid,k) = 1./(rw+1./(hfilm(ii)*wid(ic)*.083333))
*d setin.493
  read (i2,9110) ic,rdimf(ic),rwal(ic),wid(ic)
*d setin.1441
  9110 format (i5,2e5.0,e10.5)
*did misc
*/
*/   miscellaneous changes
*/
*d clear.193
  wbegl(1)=0

```

```

*i cobra.365
    xc = 0.5*(x(jx-1)+x(jx))
    if (xc.gt.zend(n,kk)*z) go to 400
*i energy.21
    xflag = 1.0
*i energy.159
c
c    compute the rod dependent terms
c
*d energy.167
    dong = hsurf(n,j)*rung(n)-xflag
*d energy.170,171
    hah(1,i) = hah(1,i)+(1.0-xflag)*ding/(cp(i)*phitot(n))
    dhdx(i) = dhdx(i)-(1.0-xflag)*ding*tmh(i)/phitot(n)
*d energy.176,177
*d recirc.201,202
*d setup.56
    if (x(ndx+1).gt.z) x(ndx+1) = z
*d setin.465
    radgap(ic) = (1./ema(ic)+1./emb(ic)-1.)/(sb*arad(ic))
*d setin.743
    read (i2,9320)
*d setin.16
    real zdum(48)
*d setin.18,20
    character*8 format(1,1)
    dimension izdum(48)
*d setin.32,33
    data format(1,1)/ '(12e5.0)' /
*i setin.1098
    exittod(2) = exitt
*d setin.1271
*i recirc.151
    if (sparev(2).eq.0.) go to 217
*d recirc.619
    if (clerr.le..05.and.qeerr.lt.qerror.and.emax.lt.ferror.and.
        $qoh.lt.herror) recall = 1.
*/
*/  changes to add transient terms to total energy comparison
*/
*i energy.267
    qside(jx) = 0.0
*d energy.403
*d energy.437,441
    utran = wallxc(k)*cpsol(mat)*rhosol(mat)*dti
    qwal(k) = qwal(k)+qgen(k,j)+utran*twold(k,j)
    uwal(1,k) = uwal(1,k)+utran
    qtotal = qtotal + qgen(k,j)*dx(jx)
    qres(jx)=qres(jx)+(qgen(k,j)-utran*(twall(k,j)-twold(k,j)))*dx(jx)
    qside(jx) = qside(jx) + utran*(twall(k,j)-twold(k,j))*dx(jx)
    caxld(jx,2) = caxld(jx,2)+utran*dx(jx)
*i energy.93
    ftran = 0.0
*i energy.106

```

```

      ftran = ftran+aav*rho(i,j)*(h(i,j)-hold(i,j))
      caxld(jx,2) = caxld(jx,2)+aav*rho(i,j)*cp(i)*dti*dx(jx)
*i energy.418
      qside(jx) = qside(jx)+ftran*dti*dx(jx)
*/
*/ clean-up input summary
*/
*d setout.134,135
      if (nc.gt.4) write(i3,1341) nc
*d setout.756,763
*i setout.343
      if (nbttyp.eq.0) go to 620
*d setout.681
      1005 format (2x,i3,4x,i2,2x,f8.4,5x,f8.3,8x,i3,6x,4(a1,2(i3,a1),1x),4x,
*d setout.39,40
      c0 = con0(i)*3600.
      c1 = con1(i)*3600.
      c2 = con2(i)*3600.
      c3 = con3(i)*3600.
      write (i3,995) i,aname(i),cpsol(i),rhosol(i),c0,c1,c2,c3
      115 continue
*d setout.655,657
      2 "cpsol",8x,"rhosol",10x,"thermal conductivity"/32x,
      3 "(btu/hr-f)",5x,"(lbm/ft3)",11x,"(btu/hr-ft-f)")
      995 format (10x,i2,9x,a5,5x,f10.4,4x,f10.4,5x,1pe10.3," + ",e10.3,
      $"t + ",e10.3,"t**2 + ",e10.3,"t**3")
*d setout.289
      586 write(i3,999) i,rdimf(i),rwal(i),wid(i)
*d setout.295
      585 write(i3,997) i,rdimf(i),rdimb(i),rser(i),rpar(i),ema(i),emb(i),
      $ zdum(1)
*d setout.659,673
      998 format(1h1///" solid-to-fluid thermal connection type table",/1x,
      *50(1h-),/1x,"connection",5x,"geometry",5x,"slab-fluid",5x,
      *"slab wetted",5x,/6x,"type",7x,"factor",6x,"resistance",6x,
      *"perimeter",
      1 /28x,"(ft-f-s/btu)",8x,"(in)")
      996 format(1h1///" solid-to-solid thermal connection type table",/1x,
      *50(1h-),/1x,"connection",7x,"geometry factors",2(5x,"slab-slab"
      *),7x,"em1",5x,"em2",8x,"arad",/4x,"type",31x,
      *"resistance",4x,"resistance",25x,"(in)",
      1 /40x,"-series-",5x,
      *"-parallel-",/37x,"(ft-f-s/btu)",3x,
      *"(ft-f-s/btu)")
      997 format (3x,i3,10x,f7.3,2x,f7.3,7x,f7.2,8x,f7.2,4x,f7.2,1x,f7.2,5x,
      *f7.2)
      999 format (7x,i3,6x,f7.3,8x,f7.3,8x,f7.3)
*/
*/ changes to add temperature dependent heat transfer coef.
*/
*b energy.520
      if (ic.ne.4.and.ic.ne.27) go to 177
      if (jx.ge.2.and.jx.le.9) rpar(ic) = 259.19
      if (jx.eq.10.or.jx.eq.11) rpar(ic) = 18936.

```

```

      if (jx.eq.12) rpar(ic) = 76.937
      radgap(ic) = 0.0
      if (jx.lt.13.or.jx.gt.25) go to 176
      tm = 0.5*(twall(k,j)+twall(k1,j))
      if (ic.eq.27) rpar(ic) = 2923.6/(.08426+7.040e-5*tm)
      if (ic.eq.4)  rpar(ic) = 2923.6/(.07537+6.149e-5*tm)
      radgap(ic)=(1.8085/(.0599+8.889e-5*twall(ka,j))-0.8085)*7.640e14
176  continue
      if (jx.eq.26) rpar(ic) = 73.829
      if (jx.ge.27.and.jx.le.40) rpar(ic) = 1.e8
      if (jx.ge.41) rpar(ic) = 259.19
177  continue
*d  prop.57
      call curve (qax,xdumy,axial(1,n),y(1,n),nax(n),ierror,1)
*d  reheat.32
      call curve (qax,xdumy,axial(1,n),y(1,n),nax(n),ierror,1)
*d  setin.1290
      if (itstep.gt.1) call load (yt,ft,zdum,itstep,n3,12,2,format(1,1),

```


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