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NUCLEAR HEATING IN He-3 FAST SCRAM RODS (U)

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NUCLEAR HEATING IN He-3 FAST SCRAM RODS (U)

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Westinghouse Savannah River Company
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INTRODUCTION

Nuclear heating occurs in the He-3 fill gas of the fast SCRAM rods as a result of the very neutron captures which make the rods operative. This heating gives rise to a pressure rise within the rod. If severe enough this heating could present a structural problem, but more importantly the pressurization always causes a partial backflow of the fill gas. This, in turn, reduces the residual gas content and thus reduces the effectiveness of the rod. If enough gas were expelled, the rod would no longer have the required reactivity shutdown margin. This memorandum discussès the bases for determining the heat input and estimating the resultant temperatures, pressures, and backflows to be expected under various assumed design and operational conditions. A method for mitigating the effect by means of heat-conducting fins on the interior surface of the rods is discussed and evaluated.

SUMMARY

Heat input and thermodynamic response are evaluated for the Mark-22 lattice at nominal full power operation and for the proposed low power verification tests. For all of these conditions the pressure increase poses no structural problems and backflow is modest enough that it can be compensated by an increase in the He-3 reservoir pressures. The use of interior fins reduces the nuclear-induced temperature and pressure increases by a factor of five or more. Use of finned tubes would give a large safety factor for Mk-22 or Mk-16 operation, and would permit the system to be used without modification on a wide range of other lattices.

This report consists of three distinct sections:

1) An evaluation of the heat input under SCRAM conditions. By N. P. Baumann

2) An estimate of maximum temperature/pressure rise and backflow under asymptotic conditions (long-time, temperature/pressure equilibrium) using handbook equations. By N. P. Baumann

3) A computation of the transient response through the SCRAM sequence using numerical techniques. By G. P. Flach

The heat input numbers derived in the first section are believed to be quite accurate with no known biases. These are the last in a series of three estimates, each being a more accurate and less conservative estimate than its predecessor. The final best values were used for the asymptotic estimates of the second section in the Discussion. The second set was used for the numerical transient responses of the third section since the final values were not available at the time these computations were performed. Despite the added conservatism, the results of this third section indicate a workable system. It was thus not deemed worth the considerable time and effort required to repeat the computations using the more exact lower heat inputs. In order to assure that the asymptotic values were consistent with the numerical computations, asymptotic computations were also run for the higher heat input. The agreement was very good. This suggests that the asymptotic results of this report can be used to give a reasonable estimate of maximum gas temperatures and pressures, with the numerical computations giving a good indication of the time dependence.

All of the methods used in this report for estimating gas properties have obvious limitations. They do not treat the dynamics of gas transport nor do they include thermodynamic cooling and heating associated with expansion and compression of the gas. Despite these limitations, the present results define the essential operating conditions well enough for the design of a final system. A much more rigorous analysis should be made before final installation and operation of a working system in order to obtain maximum benefit in terms of increased reactor power. Since the SRS has no good gas dynamics code nor recognized experts in the field, a suitable contractor should be found to perform such studies once a design is finalized. Such studies would also provide the basis for setting operating parameters such as initial reservoir pressures.

DISCUSSION

I. Heat Input to Rods

The neutron absorption rate in the He-3 was computed using the GLASS code (Reference 1). The lattice pattern was that devised by W. E. Graves specifically for the purpose of calculating safety rod worths. It consists of a supercell of six fuel and one control rod cluster with each normal 7.00 inch cell divided into three subcells on a 4.04 inch pitch. A Mk-22 assembly (or a control rod cluster) containing almost no exterior moderator makes up one of the three subcells in each set. The spacing is so tight that the USH housing must be omitted in order for the entire assembly to be confined to its subcell. This omission increases the reference reactivity of the lattice but has almost no effect on the computed worth of the safety rods. The remaining cells contain either moderator alone or moderator with a safety rod or instrument thimble at the center. A description of this lattice was first published in a report by W. R. Ferrara (Reference 2). This report also gives the ASSEMBLY records used for the computations presented here.

The GLASS code has many edit options. One of these gives total neutron capture rate in the He-3 rod relative to the total fission rate in the six Mk-22 assemblies within that rod's supercell. These rates require only the energies of the reactions (0.75 Mev for He-3 capture vs. 200 Mev for U-235 fission) to give a power ratio of 0.0003127. A reactor power level of 2400 Mw with 400 effective tubes, which is typical for a Mk-22 lattice, is equivalent to an average Flat-Zone fuel power of 0.5 Mw/ft. This fuel power gives a He-3 power density of 938 w/ft length. With a rod ID of 1.08 inches, the He-3 volume per foot length is 180.1 cc, and the power density in the gas is 5.21 w/cc. Assuming a 40% power drop during the transient (Reference 4) and including energy losses from direct interaction of the reaction particles with the wall the power density is reduced to 2.69 w/cc (or 0.64 cal/sec/cc). This wall interaction is discussed in the next paragraph.

Wall losses occur because the ranges of the He-3 reaction products (a proton and a triton) are not negligible with respect to the linear dimensions of the rod. Neutron captures which occur in the gas near the walls will usually result in one of the two reaction products striking the wall before all of its kinetic energy is expended. A numerical computation of this effect, using known energy-range relations for the particles, is possible but is very laborious with the added complication that the captures are not spatially uniform. An easy estimate of the effect can be made using published characteristic pulse-height distributions which have been measured for He-3 neutron detectors. One source of such data is Reuter-Stokes in promotional literature provided for their line of He-3 detectors. Their 1.0 inch diameter neutron detector tubes at a fill pressure of 10 atmospheres are a very close approximation to the SRP He-3 rod design. In a pulse-height distribution for a detector of this type, the full energy peak includes all events in which both proton and triton deposit all of their kinetic energy within the gas. The low energy "tail" is a result of one or the other of the particles depositing part of its energy in the wall. The energy lost to the wall is simply the distance below the peak, in energy units, at which the pulse occurs. The derived loss fraction for the detector was 0.14 and this value was used for the estimates of heat input to the He-3 rods.

The GLASS results can also be expressed in terms of effective thermal neutron fluxes and cross sections. At a power of 1440 Mw, or 40% below 2400Mw, the unperturbed thermal neutron flux is 0.9E14 /sq cm/sec, with a depression factor of 0.30 in the He-3 rod. The computed thermal cross section in the rod is 2817 barns. This severe reduction from the 5333 barn value at 2200 m/sec is primarily a result of spectrum hardening due to the "1/E tail" below 0.625 eV which GLASS includes as part of the thermal flux. An added source of spectrum hardening arises from the selective low-energy neutron absorption from the 1/v character of the He-3 cross section. If the thermal cross section is augmented to include all absorption, including epithermal, one obtains an effective value of 3540 barns. These values produce the same final heat input of 0.64 cal/cc/sec.

II. Asymptotic Estimates of Temperature/Pressure and Backflow

To estimate the maximum temperature and pressure, the following assumptions are made:

- Asymptotic values are computed, i.e., no credit is taken for the possibility that safety rods may drop before maximum temperature and pressure are attained.

- The initial insertion of the gas is so fast that no heating occurs during this phase and it is assumed that the gas is at room temperature and at uniform pressure everywhere in the system at the start of the transient. The initial gas pressure (150 psia for the no-rib tube) is taken to be at 30 deg C, the assumed ambient temperature at the reservoir. The numerical treatment of the third section references this pressure to be that of the aluminum tube, or 90 deg C.

- The gas has a uniform heat input of 0.64 cal/sec/cc for each of 12 rods at an operating reactor power of 2400 MW (complete installation at full power) and 0.38 cal/sec/cc for each of 3 rods at an operating power of 1050 MW (anticipated test conditions).

- Thermodynamic gas temperature changes resulting from expansion and compression are ignored.

  The method of solution for the BASIC code listed in Appendix A is equivalent to the following physical assumptions in addition to those above.

- Immediately after the gas is introduced, it is treated as if there were a barrier seal in the tube at the edge of the reactor core.

- An equilibrium temperature and pressure are computed for the gas in the sealed tube.

- The seal is then broken. The rate of heat input and the temperature of the gas which remains within the tube are taken to be unchanged. The pressure is equilibrated in the system assuming all the gas inside the tube remains at the sealed tube temperature and all of the gas in the lines and reservoir is at process room ambient (30 deg C). This gives a pressure reduction below that for the sealed tube. The pressure reduction is simply related to the fractional backflow.

The computations utilize a standard textbook formalism (c.f., Reference 3) which was developed for laminar flow but is velocity independent and thus is presumed to be valid as velocities approach zero. (From the results of the numerical computations of the final section of this report it appears that the limiting case of zero axial flow may actually have a heat transfer rate about a factor of two higher). This formalism uses a dimensionless quantity called the Nusselt number, Nu, which is defined for a cylindrical fluid-filled tube as

$$Nu = hD/k$$

This expression and those that follow are valid in any consistent set of units. In this application cgs units are used. The Nusselt number is a dimensionless number with a normal value of about 4.0 depending on the details of the problem. The case of a constant (time and space) heat input is considered to be appropriate with a value of 4.364. Cases were also run with a Nusselt number of 8.0, a value derived in the final section of this report as being applicable to the convection model in the limit of zero velocity. D is the diameter of the interface, k is the conventional thermal conductivity of the fluid, and h is the heat transfer coefficient of the fluid. The coefficient h is related to the areal heat flux at the wall, q"w, by the following expression:

$$q"w = h(Tw - Tb)$$

Here Tw is the wall temperature and Tb is the bulk (volume averaged) temperature of the fluid.

An exact treatment of the coolant fins requires a numerical solution. A good first order estimate can be made using the hydraulic diameter approximation. The hydraulic diameter, Dh, is given by

$$Dh = 4V/S$$

where V is the gas volume and S is the total fluid/tube interface surface area.

The conductivity of helium increases strongly with temperature. As a result, it is necessary to iterate to find the equilibrium temperature. The BASIC code, included in Appendix A, evaluates this temperature for various possible numbers of fins. In this code, the tube ID is taken to be 1.08 inches, as in the current design, and the fins are 0.375 inch long with a tapered thickness varying from 0.060 at the base to 0.040 inch at the tip. The initial fill pressure is taken to be 150 psia for the reference no-fin case. With fins, the initial pressure is increased so as to maintain the same initial total helium inventory within the tube.

The derived values using values for both Nusselt numbers, 8.0 and 4.364, are shown on the computer printouts of first data sheet in Appendix A. Even the values for the worst case (full 2400 mw power in the Mk-22 with 12 He-3 rods, Nusselt number = 4.364) are acceptable in that the 20% backflow could be compensated by a fractional increase of the initial He-3 fill pressure. This condition, however, allows little margin for possible higher reactor fluxes at some later time. It is proposed that an 8-fin design be substituted. Finned tubes would provide very comfortable margins.

The second data sheet of Appendix gives the irreducible minimum pressure rise and backflow from heating due solely to to the hot moderator. With fins, these values are about half those due to the combined nuclear and moderator heating. There is thus little motivation to further reduce the effect of nuclear heating.

The data sheet of Appendix B gives the results of asymptotic computations for conditions more nearly consistent with those for the convection model of the numerical analysis of the third section of this report (Figures 1b, 2b, 3b, 4b, and 5b). The major differences from the conditions of Appendix A are that the nuclear heat input is higher (1.07 vs 0.64 cal/cc/sec) and the initial reference pressure is taken at the temperature of the moderator (90 deg C) instead of that of the reservoir (30 deg C). The agreement is quite good considering implicit differences in the modeling. The asymptotic computations give a slightly larger backflow fraction with a resultant lower maximum pressure.

III. Numerical Time Dependent Analysis of the Fast Scram System

System Description

The system for these computations are taken to be consistent with those of the preceding section except for the previously noted difference in input heat rate and initial gas temperature. Another irrelevant difference is that the tapered fins of the second section are taken to be rectangular with the same volume. The system characteristics are summed in Table I.

Heat Transfer Models

Two relatively simple heat transfer models were constructed to conservatively estimate the transient He gas heat losses to the surroundings. In both models, He-4 is assumed to occupy the 1 in aluminum tube volume from the onset. At the start of the heat transfer calculations, the gas is assumed to be at the equilibrium pressure that would result if no nuclear heating occurred. In order to avoid having to solve a complex fluid flow problem, the tube is assumed to be sealed off from the supply tank and line at the start of nuclear heating. The *conduction* model treats the He gas as a solid with constant thermal properties evaluated at a nominal temperature; that is, fluid motion is neglected. Conduction is also modelled in the aluminum tube. Since fluid motion increases the heat dissipation, the conduction model is a conservative one. Heat generation in the gas is assumed to be uniform in space and over a 1 s time interval. This assumption is also conservative since more neutron absorption occurs in the gas close to the cool aluminum tube. The aluminum tube outer surface is allowed to dissipate energy to the moderator through a convection boundary condition with h = 1000 BTU/h-ft^2-F. The HEATEL finite element heat conduction computer code is the primary tool used for the conduction analysis (Reference 5).

A second *convection* model treats the gas as a lumped mass at the average gas temperature with internal heat generation and convection heat loss to the surrounding aluminum tube. Temperature dependence of the thermal properties is included since the extra effort is minimal. The aluminum tube is assumed to be isothermal at the moderator temperature; scoping analysis with the conduction model indicates the temperature rise in the aluminum tube is insignificant relative to the rise in the gas temperature and can be neglected. The convection coefficient can be determined from an appropriate Nusselt number correlation, if available. Some effort was spent searching for such a Nusselt number correlation but none based on experiments similar to the present physical situation was located. However, an analytical conduction analysis yields a lower bound of Nu = 8; this value is used to generate the numerical results. The choice of Nu = 8 means the conduction and convection models will effectively give identical steady-state results if identical thermal properties are used. Thermal radiation as a mode of heat dissipation was initially considered but subsequently neglected for two reasons. Adequate treatment of thermal radiation heat transfer would require a longer term effort that possible for this study. Also, the radiative losses are probably smaller than one would normally expect since Helium is a monotonic gas. It is our understanding that unlike most gases, monotonic gases emit significant thermal radiation only at high frequencies and therefore temperatures. Since the goal is to keep the He temperature relatively low to minimize backflow, radiative heat transfer will presumably be small. In any case, neglecting radiative heat transfer is conservative.

Thermodynamic Model

Both heat transfer models assume the initial quantity of Helium at the onset of nuclear heating becomes trapped in the 12 ft tube to make the analysis tractable; that is, no backflow into the supply tank and line is allowed. During this phase the gas is assumed to obey the perfect gas law. The fraction of He remaining in the tube during the actual heating process can be estimated by opening the hypothetical seal at any desired stage in the heat transfer computations and computing the equilibrium amount of mass remaining in the tube. The thermodynamic model for this process is based on conceptually dividing the He gas into two chambers separated by a movable barrier. The gas is again assumed to be ideal. All walls and the movable barrier are modelled as adiabatic. No work is allowed to leave the composite system although work transfer is allowed between the two internal subsystems. Initially, the gas in the 12 ft tube is at higher pressure than the gas in the supply tank and line. When the seal is broken (the separating barrier is allowed to move) the gas in the tube expands and compresses the remaining gas until both sides are at an equal pressure to be computed. The problem is thermodynamically indeterminate at this point. To close the formulation, the gas occupying the supply tank and line is assumed to undergo an isentropic (reversible, adiabatic) compression. The expansion process is therefore irreversible.

Model Assessment

The composite model consisting of heat transfer and thermodynamic calculations is obviously a simplified one constructed to produce timely results. In both heat transfer models, fluid motion, which will significantly increase the desired heat losses, has been neglected: the conduction model treats the gas as a solid and the convection model uses a Nusselt number based on a conduction analysis. Also, the tube is considered sealed off from the supply tank and line during the heat transfer computations. Backflow is estimated indirectly by allowing the seal to be broken and computing the amount of gas leaving the tube until the pressures are equal. Therefore the subsequent computed results should be viewed as approximate but probably biased towards a conservative estimate of heat losses and backflow.

Results and Discussion

The conduction and convection model results are given in parallel. Transient temperature and pressure traces during the heat transfer phase of the computations are illustrated in Figures 1 and 2, respectively. Recall that the tube is considered sealed off from the supply tank and line for Figures 1 and 2. Assuming the seal is broken and the supply tank pressure and tube pressure equilibrate according to the previously discussed thermodynamic model, the transient temperature and pressure vary as shown in Figures 3 and 4, respectively. The corresponding fraction of He mass remaining in the tube relative to the initial amount is shown in Figure 5. Clearly the 8-ribbed tube greatly augments heat dissipation and yields a minimum mass fraction of He remaining in the tube of about 96%. The nonribbed tube results in a minimum mass fraction of approximately 86%. Again, since both models are effectively based on a conduction analysis, these values are expected to be conservative.

REFERENCES

1) H. C. Honeck, "The JOSHUA System", DP-1380, April 1975.

2) W. R. Ferrara, "GLASS GILDA $\Delta\Sigma_{C_2}$ Values, Rapid Shutdown System", DPST-88-454, June 1988.

3) "Handbook of Heat Transfer Fundamentals", Second Edition, p 7-17, McGraw-Hill Book Co., 1983.

4) W. R. Ferrara, "GLASS-GILDA $\Delta_{keff/keff}$ Values, Rapid Shutdown System (He-3)", NEDP-88-04.

5) Hamn, L. L., "HEATEL Finite Element Heat Conduction Code", transmitted from L. L. Hamn to G. P. Flach, February, 1989.

TABLE I

Assumed Fast Scram System Dimensions and Operating Conditions

Quantity	Value
Inner tube diameter	1.08 in
Tube thickness	0.030 in
Rib width	0.375 in
Nominal rib thickness	0.040 in
Tube length	12 ft
Moderator temperature	90°C
Storage tank/line temperature	30°C
Initial He Pressure - No ribs	150 psia
Initial He Pressure - 8 ribs	173 psia
Heat input per unit volume - No ribs	1.07 cal/cm^3
Heat input per unit volume - 8 ribs	1.23 $ca./cm^3$
Nuclear heating duration	1.0s

APPENDIX A-1

BASIC CODE FOR COMPUTING ASYMPTOTIC TEMPERATURES AND PRESSURES

```
100 REM COMPUTE TEMPERATURES AND PRESSURES IN TUBE WITH INTERIOR FINS
110 DIM T(20),K(20)
120 INPUT "FULL POWER WITH 12 RODS (F), or 3-ROD TEST (T)";A$
130 IF A$="f" OR A$="F" THEN PWR=.64:TMOD=90
140 IF A$="t" OR A$="T" THEN PWR=.382:TMOD=60
150 'Power input is in cal/cc/sec, Moderator temperature in deg. Cent.
160 NU=4.364
170 FOR I=1 TO 18:READ T(I),K(I):NEXT I:'HEAT CONDUCTIVITY VS TEMP TABLE
180 FOR I=1 TO 18:K(I)=K(I)/1000:NEXT I
190 INPUT "Number of ribs";N
200 VCYL=5.91
210 V=VCYL - N*9.677001E-02:'VALUES ARE FOR EMPTY TUBE & PER RIB VOLUMES
220 S=8.618 + N*1.854:'SURFACE AREA NUMBERS ARE FOR EMPTY TUBE & PER RIB
230 DH=4*V/S:'HYDRAULIC DIAMETER
240 QW=PWR*5.91/S:'HEAT TRANSFER PER UNIT AREA AT GAS/METAL INTERFACE
250 '*******FIND PROPER TEMPERATURE INTERVAL IN LOOKUP TABLE*******
260 I=0
270 I=I+1
280 H=NU*K(I)/DH
290 DELTAT=QW/H:'ASYMPTOTIC TEMPERATURE DIFFERENCE, GAS TO WALL
300 TKELVIN=273+TMOD+DELTAT:'ASYMPTOTIC GAS TEMPERATURE
310 IF TKELVIN>T(I) THEN GOTO 270
320 '*******LINEAR INTERPOLATION WITHIN INTERVAL*******
330 FOR J=1 TO 10
340 K1=K(I-1)+ (K(I)-K(I-1))*(TKELVIN-T(I-1))/(T(I)-T(I-1))
350 H=NU*K1/DH
360 DELTAT=QW/H
370 TKELVIN=273+TMOD+DELTAT
380 NEXT J
390 LPRINT CHR$(27);CHR$(73);CHR$(3);
400 IF A$="F" OR A$="f" THEN LPRINT "FULL PWR (2400 MW), 12 RODS WITH"N"FINS";
410 IF A$="T" OR A$="t" THEN LPRINT "TEST LOAD AT 45% PWR, (1080 MW), 3 RODS WIT
H"N"FINS";
420 '*******INITIAL PRESSURE P0 IS INCREASED TO OFFSET FIN VOLUME*******
430 P0=150*VCYL/V:'INITIAL PRESSURE AT ROOM TEMPERATURE, PSIA
440 PT=P0*(TKELVIN/303):'PRESSURE FOR HYPOTHETICAL CLOSED TUBE
450 'LPRINT USING "      Nusselt No.= #.###";NU
460 PMAX=P0+.666*P0*(TKELVIN/303 -1):'ASYMPTOTIC PRESSURE IN SYSTEM
470 '*******BACKFLOW ASSUMED ISOTHERMAL*******
480 FRACTION=1-PMAX/PT:'FRACTION OF GAS WHICH BACKFLOWS FROM TUBE
490 LPRINT "TOTAL TEMPERATURE INCREASE IN CENT DEG IS ";
500 LPRINT USING "###.#";DELTAT + TMOD -30
510 LPRINT USING "ABSOLUTE TEMPERATURE IN KELVIN DEG IS ####.#";TKELVIN
520 LPRINT USING "P0 = ###.#";P0;:LPRINT " PSIA";
525 LPRINT USING "    PMAX = ###.#";PMAX;:LPRINT " PSIA";
530 LPRINT USING "    BACKFLOW FRACTION = #.####";FRACTION:LPRINT:LPRINT
540 DATA 100,.175,140,.217,180,.257,220,.295,260,.238,300,.364
550 DATA 350,.407,400,.447,450,.488,500,.526,600,.603,650,.632
560 DATA 700,.666,750,.697,800,.728,900,.790,1000,.847,1200,.966
570 END
```

APPENDIX A-2

ASYMPTOTIC HEAT TRANSFER FOR NU=8.0 (MODERATOR HEAT INCLUDED)

FULL PWR (2400 MW), 12 RODS WITH 0 FINS   Nusselt No.= 8.000
TOTAL TEMPERATURE INCREASE IN CENT DEG IS 307.2
ABSOLUTE TEMPERATURE IN KELVIN DEG IS 610.2
PO = 150.0 PSIA   PMAX = 251.3 PSIA   BACKFLOW FRACTION = 0.1681

FULL PWR (2400 MW), 12 RODS WITH 8 FINS   Nusselt No.= 8.000
TOTAL TEMPERATURE INCREASE IN CENT DEG IS 99.3
ABSOLUTE TEMPERATURE IN KELVIN DEG IS 402.3
PO = 172.6 PSIA   PMAX = 210.3 PSIA   BACKFLOW FRACTION = 0.0825

TEST LOAD AT 45% PWR, (1080 MW), 3 RODS WITH 0 FINS   Nusselt No.= 8.000
TOTAL TEMPERATURE INCREASE IN CENT DEG IS 200.0
ABSOLUTE TEMPERATURE IN KELVIN DEG IS 503.0
PO = 150.0 PSIA   PMAX = 215.9 PSIA   BACKFLOW FRACTION = 0.1328

TEST LOAD AT 45% PWR, (1080 MW), 3 RODS WITH 8 FINS   Nusselt No.= 8.000
TOTAL TEMPERATURE INCREASE IN CENT DEG IS 55.5
ABSOLUTE TEMPERATURE IN KELVIN DEG IS 358.5
PO = 172.6 PSIA   PMAX = 193.7 PSIA   BACKFLOW FRACTION = 0.0517

ASYMPTOTIC HEAT TRANSFER FOR NU=4.364 (MODERATOR HEAT INCLUDED)

FULL PWR (2400 MW), 12 RODS WITH 0 FINS   Nusselt No.= 4.364
TOTAL TEMPERATURE INCREASE IN CENT DEG IS 453.5
ABSOLUTE TEMPERATURE IN KELVIN DEG IS 756.5
PO = 150.0 PSIA   PMAX = 299.5 PSIA   BACKFLOW FRACTION = 0.2002

FULL PWR (2400 MW), 12 RODS WITH 8 FINS   Nusselt No.= 4.364
TOTAL TEMPERATURE INCREASE IN CENT DEG IS 128.5
ABSOLUTE TEMPERATURE IN KELVIN DEG IS 431.5
PO = 172.6 PSIA   PMAX = 221.4 PSIA   BACKFLOW FRACTION = 0.0995

TEST LOAD AT 45% PWR, (1080 MW), 3 RODS WITH 0 FINS   Nusselt No.= 4.364
TOTAL TEMPERATURE INCREASE IN CENT DEG IS 301.8
ABSOLUTE TEMPERATURE IN KELVIN DEG IS 604.8
PO = 150.0 PSIA   PMAX = 249.5 PSIA   BACKFLOW FRACTION = 0.1667

TEST LOAD AT 45% PWR, (1080 MW), 3 RODS WITH 8 FINS   Nusselt No.= 4.364
TOTAL TEMPERATURE INCREASE IN CENT DEG IS 75.0
ABSOLUTE TEMPERATURE IN KELVIN DEG IS 378.0
PO = 172.6 PSIA   PMAX = 201.1 PSIA   BACKFLOW FRACTION = 0.0663

NUCLEAR HEAT TURNED OFF, HEATING FROM MODERATOR ONLY

FULL PWR (2400 MW), 12 RODS WITH 0 FINS
TOTAL TEMPERATURE INCREASE IN CENT DEG IS 60.0
ABSOLUTE TEMPERATURE IN KELVIN DEG IS 363.0
P0 = 150.0 PSIA PMAX = 169.8 PSIA BACKFLOW FRACTION = 0.0552

FULL PWR (2400 MW), 12 RODS WITH 8 FINS
TOTAL TEMPERATURE INCREASE IN CENT DEG IS 60.0
ABSOLUTE TEMPERATURE IN KELVIN DEG IS 363.0
P0 = 172.6 PSIA PMAX = 195.4 PSIA BACKFLOW FRACTION = 0.0552

TEST LOAD AT 45% PWR, (1080 MW), 3 RODS WITH 0 FINS
TOTAL TEMPERATURE INCREASE IN CENT DEG IS 30.0
ABSOLUTE TEMPERATURE IN KELVIN DEG IS 333.0
P0 = 150.0 PSIA PMAX = 159.9 PSIA BACKFLOW FRACTION = 0.0301

TEST LOAD AT 45% PWR, (1080 MW), 3 RODS WITH 8 FINS
TOTAL TEMPERATURE INCREASE IN CENT DEG IS 30.0
ABSOLUTE TEMPERATURE IN KELVIN DEG IS 333.0
P0 = 172.6 PSIA PMAX = 184.0 PSIA BACKFLOW FRACTION = 0.0301

ASYMPTOTIC HEAT TRANSFER FOR NU=8.0 WITH A NUCLEAR HEAT INPUT OF 1.07 cal/cc/sec AND OMITTING HEAT INPUT TO GAS RESULTING FROM TUBE WALLS BEING 60 DEG C HOTTER THAN GAS IN RESERVOIR.

(These conditions put the results on a basis directly comparable with the numerical time-dependent transient computations in the final section of the Discussion.)

THE FOLLOWING LINES WERE CHANGED IN THE BASIC PROGRAM LISTING:

```
130 IF A$="f" OR A$="F" THEN PWR=1.07:TMOD=90
440 PT=P0*(TKELVIN/(273+TMOD)):'PRESSURE FOR HYPOTHETICAL CLOSED TUBE
460 PMAX=P0+.666*P0*(TKELVIN/(273+TMOD)-1):'ASYMPTOTIC PRESSURE IN SYSTEM
500 LPRINT USING "###.#";DELTAT
535 LPRINT USING "CLOSED TUBE PRESSURE IN PSIA ###.#";PT:LPRINT:LPRINT
```

```
FULL PWR (2400 MW), 12 RODS WITH 0 FINS     Nusselt No.= 8.000
TOTAL TEMPERATURE INCREASE IN CENT DEG IS 367.4
ABSOLUTE TEMPERATURE IN KELVIN DEG IS  730.4
P0 = 150.0 PSIA    PMAX = 251.1 PSIA    BACKFLOW FRACTION = 0.1680
CLOSED TUBE PRESSURE IN PSIA 301.8

FULL PWR (2400 MW), 12 RODS WITH 8 FINS     Nusselt No.= 8.000
TOTAL TEMPERATURE INCREASE IN CENT DEG IS  63.1
ABSOLUTE TEMPERATURE IN KELVIN DEG IS  426.1
P0 = 172.6 PSIA    PMAX = 192.6 PSIA    BACKFLOW FRACTION = 0.0494
CLOSED TUBE PRESSURE IN PSIA 202.6
```

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A. A. Zagrodnik, 786-58A
C. E. Apperson, 773-59A
J. D. Bickley, 723-A
R. C. Brown, 723-A
F. P. Hennessy, 707-C
J. H. Hinton, 707-C
R. H. Finley, 707-C
D. W. Steward, 723-A
M. B. Wood, 723-A
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