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Transient safety analyses of this charge, require a knowledge of the extent of absorber removal by melting initiated by loss of flow or flow instability. This memorandum presents the results of an analysis of damage to the Mark-41 lithium tube during transients caused by loss of flow and indicates no consideration need be given to loss of Mark 41 assemblies provided assembly power is at least 28% of original. Exposures beyond this point will require additional analyses or design modifications.

SUMMARY

Damage to the lithium tube during a transient assembly meltdown is dependent upon the relative power of the PuO_2 and Li tubes at the time of transient initiation. At low exposure (during the first few subcycles), no damage to the lithium is expected because melting of the relatively high-powered PuO_2 tube and channel reflooding occurs before the lithium tube temperatures become high enough to cause melting. However, at high exposures, significant damage to the lithium tube is expected because the power of PuO_2 and lithium tubes is nearly equal and both tubes will melt at nearly the same rate.

DISCUSSION

The analysis of damage to the Mark 41 assembly is based on the following sequence of events:

- 1) Total blockage of the assembly inlet occurs,
- 2) Heat generated in the PuO_2 and lithium tubes boils coolant until channels become completely voided,
- 3) PuO_2 and Li-Al tubes adiabatically heat at a rate dependent on the fission and gamma heat produced in the tubes,
- 4) Adiabatic heating continues until the PuO_2 tube completely melts (The lithium tube may or may not melt during this period),
- 5) The assembly starts reflooding with coolant through the bottom end fitting after all of the PuO_2 tube melts, and
- 6) Steady state reflux cooling occurs when all of the stored thermal energy within the unmelted portion of the assembly has been removed.

Adiabatic heating and melting calculations were made using the AMELT code developed earlier for parametric melting studies. This code is briefly described in the Appendix. Assembly reflooding calculations were made on the basis of heat removal rates by reflux cooling, i.e., vaporization of coolant within the assembly channels and subsequent condensation on internal USH surfaces above the core elevation. This cooling mechanism is conservatively calculated to remove about 340 kw of assembly heat.

Damage to the lithium tube was evaluated by calculating the extent of lithium melting which occurred in the total time required to completely melt the PuO_2 tube plus the time to reflood the assembly and establish reflux cooling. Both of these time periods are dependent on the power produced in the PuO_2 tube which decreases with exposure. The lithium tube power remains relatively constant with exposure. Gamma heating represents a significant fraction of the assembly heat and was evaluated from data given in reference 2.

The time required for assembly reflooding is shown in Figure 1 as a function of the percent of assembly power produced in the PuO_2 tube. Time to reflood increases with exposure (decreasing PuO_2 power) because the time required to completely melt the PuO_2 tube increases with a concomitant increase in the stored thermal energy in the lithium tube which must be removed during reflooding.

The calculated temperature history of the PuO_2 and lithium tubes is shown in Figure 2 at a point early in the exposure of the assembly where the PuO_2 tube is generating about 92 percent of the total assembly heat. The upper graph in the figure indicates that PuO_2 temperatures are calculated to increase linearly for approximately 5 seconds, initial melting occurs at 8 seconds, and complete melting in 13.2 seconds. The lower graph indicates that the maximum temperature of the lithium tube 13.2 seconds after loss of flow is about 350°C . At this point reflooding occurs, and lithium tube temperatures decrease in about 4.5 seconds to the pre-incident temperature of 120°C with no damage to the tube.

Figure 3 shows the calculated temperature of the assembly tubes during melting at the end of the planned exposure. The PuO_2 tube is generating about 66% of the total assembly power at this exposure. The upper graph shows that approximately 77 seconds is required to completely melt the PuO_2 tube based on the previously stated model. The corresponding damage to the lithium tube at this time is about 90 percent and reflooding will not occur in time to prevent complete melting.

Figure 4 summarizes the results of lithium damage calculations made for the range of exposure of the Mark 41 assembly expressed as a percent of assembly power in the PuO_2 tube. As can be seen, no lithium damage occurs for a loss of flow incident at assembly exposures where the PuO_2 power is greater than 81.5 percent of the assembly total. This corresponds to an assembly power equivalent to 26% of initial power. At greater exposure where the PuO_2 power percentage is below this value, lithium damage increases, ultimately reaching total damage before the planned end of assembly exposure.

Damage to the lithium tube initiated by a flow instability is expected to be significantly less than the estimated damage due to a loss of flow. First of all, an adverse flow instability would most likely occur when the assembly has the highest heat generation to flow ratio. This occurs at the beginning of exposure where no lithium damage is expected if melting occurs. At greater exposures, propagation of flow instability becomes less likely because total assembly power

is reduced. Secondly, some heat is removed from the assembly during flow decay and steam flow conditions. This heat removal is expected to account for most, if not all, of the heat generated by the assembly at the end of exposure where lithium tube melting for a total loss of flow is the most severe. Finally, because of the larger pressure in the plenum than in the tank, the flow recovery time for a flow instability is considerably faster than the reflood times for a loss of flow which will limit lithium tube damage if melting occurs.

Alternatives exist in the design and operation of the Mark 41 assembly which can be used to reduce damage to the lithium tube. The capacity for stored thermal energy in the lithium tube can be increased by increasing the cross-sectional area of the tube. This effectively reduces the ultimate tube temperature at the point of reflooding. Preliminary calculations for 1.5 inch inner diameter lithium tube (present I.D. is 1.995 inches) indicate that lithium melting will not occur during a loss of flow incident until the PuO_2 tube is generating only 71 percent of the total assembly heat. A 1.0 inch inner diameter tube is calculated not to melt at any point in the planned exposure.

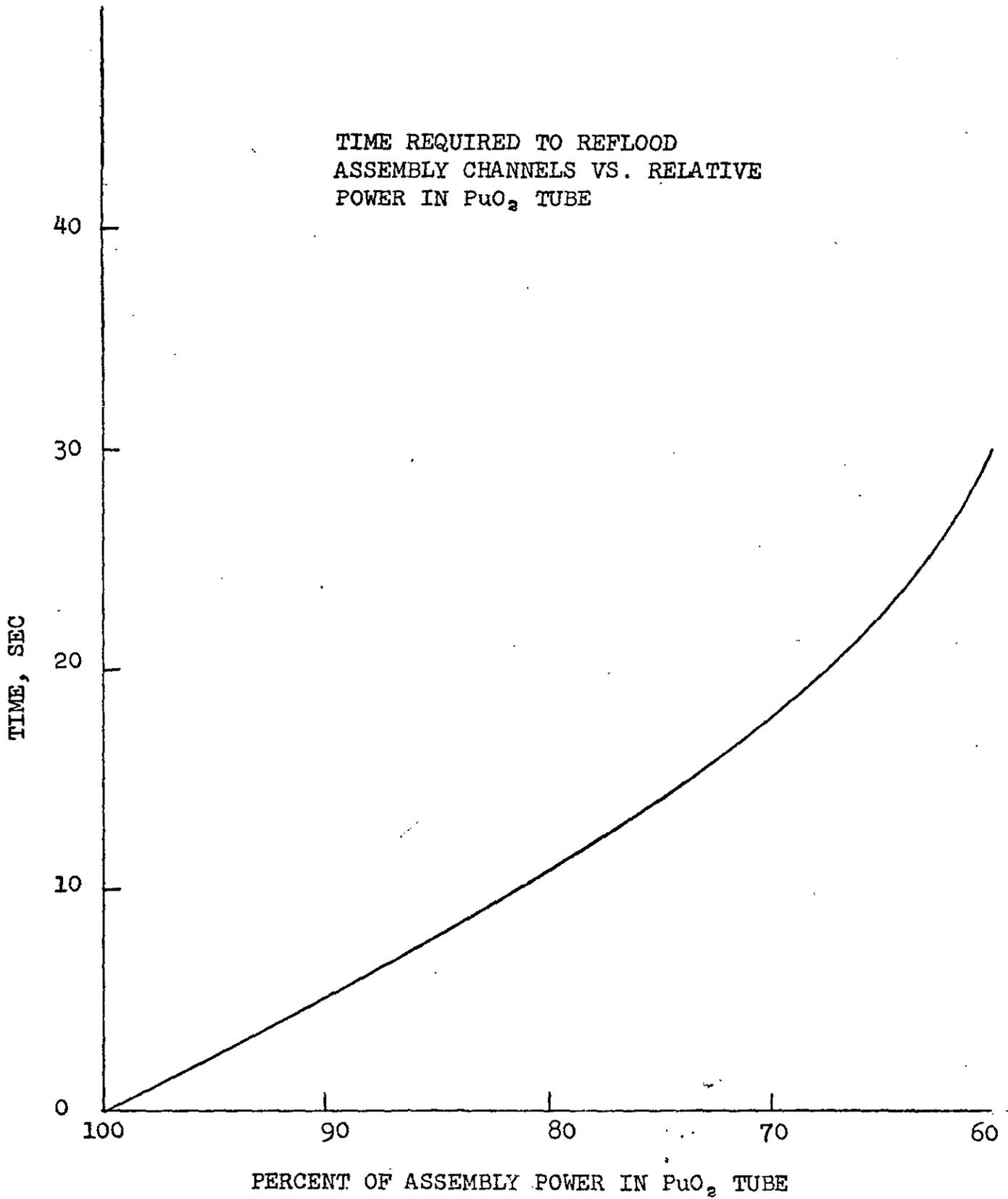
Accident analysis calculations are planned to determine if damage to the lithium tubes will have an adverse affect on an unscrammed transient. These calculations will indicate whether or not additional alternatives have to be explored.

REFERENCES

1. Baker, W. H., "Development Program for Producing High ^{242}Pu , DPST-74-350 (SECRET).
2. Hootman, H. E., "Bismuth Target Design," DPST-67-264 (SECRET).

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Fig. 1



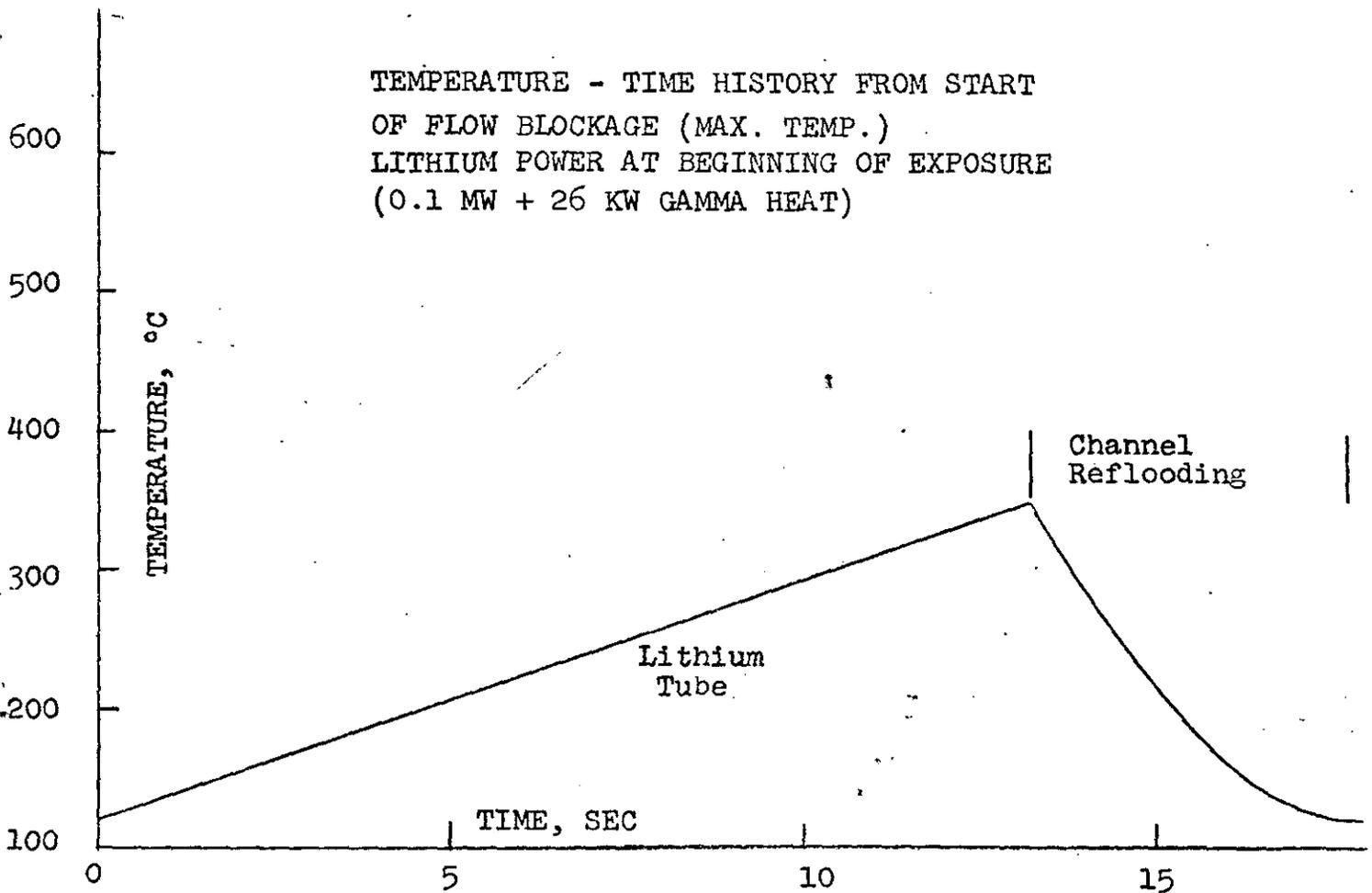
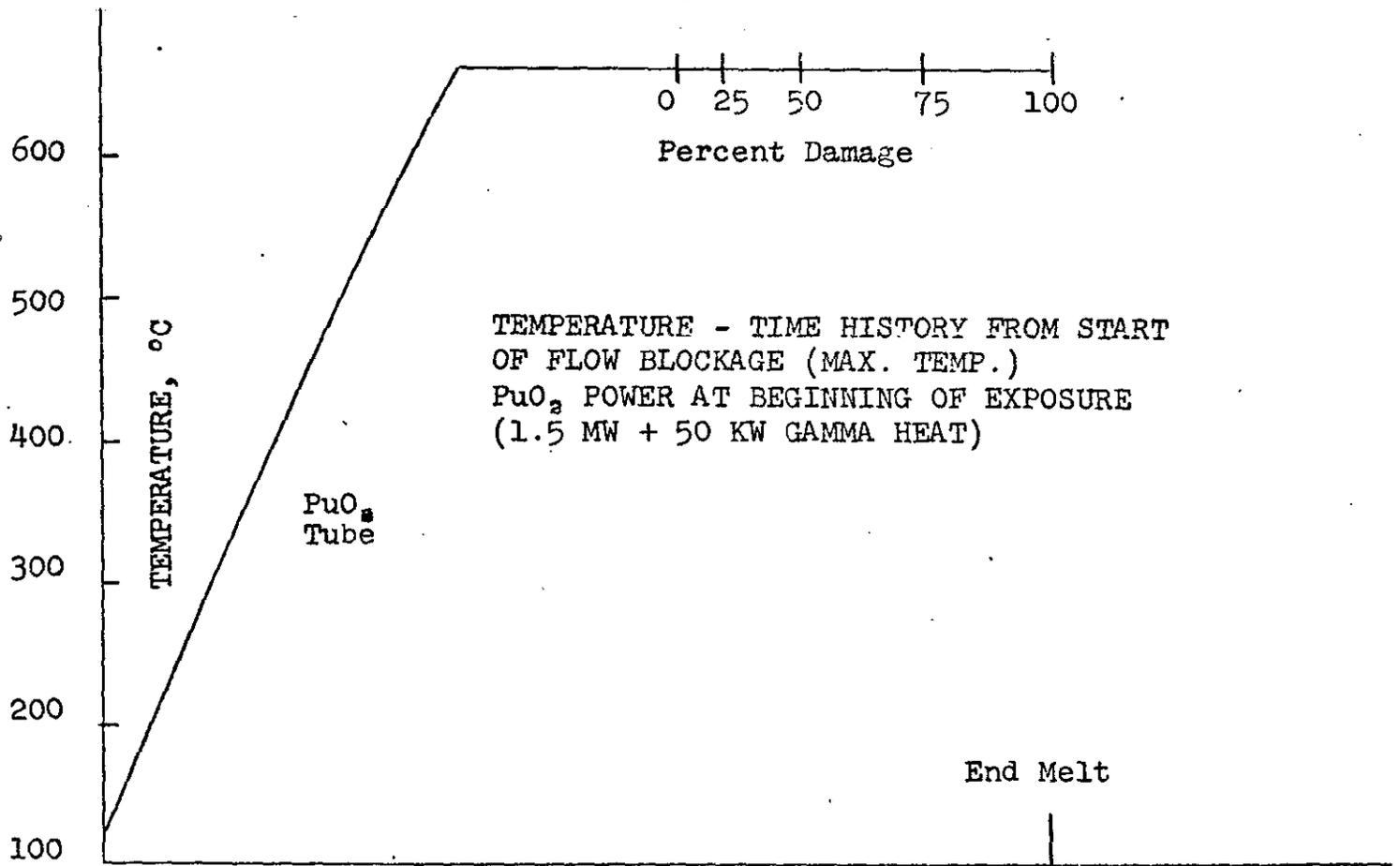


Fig. 3

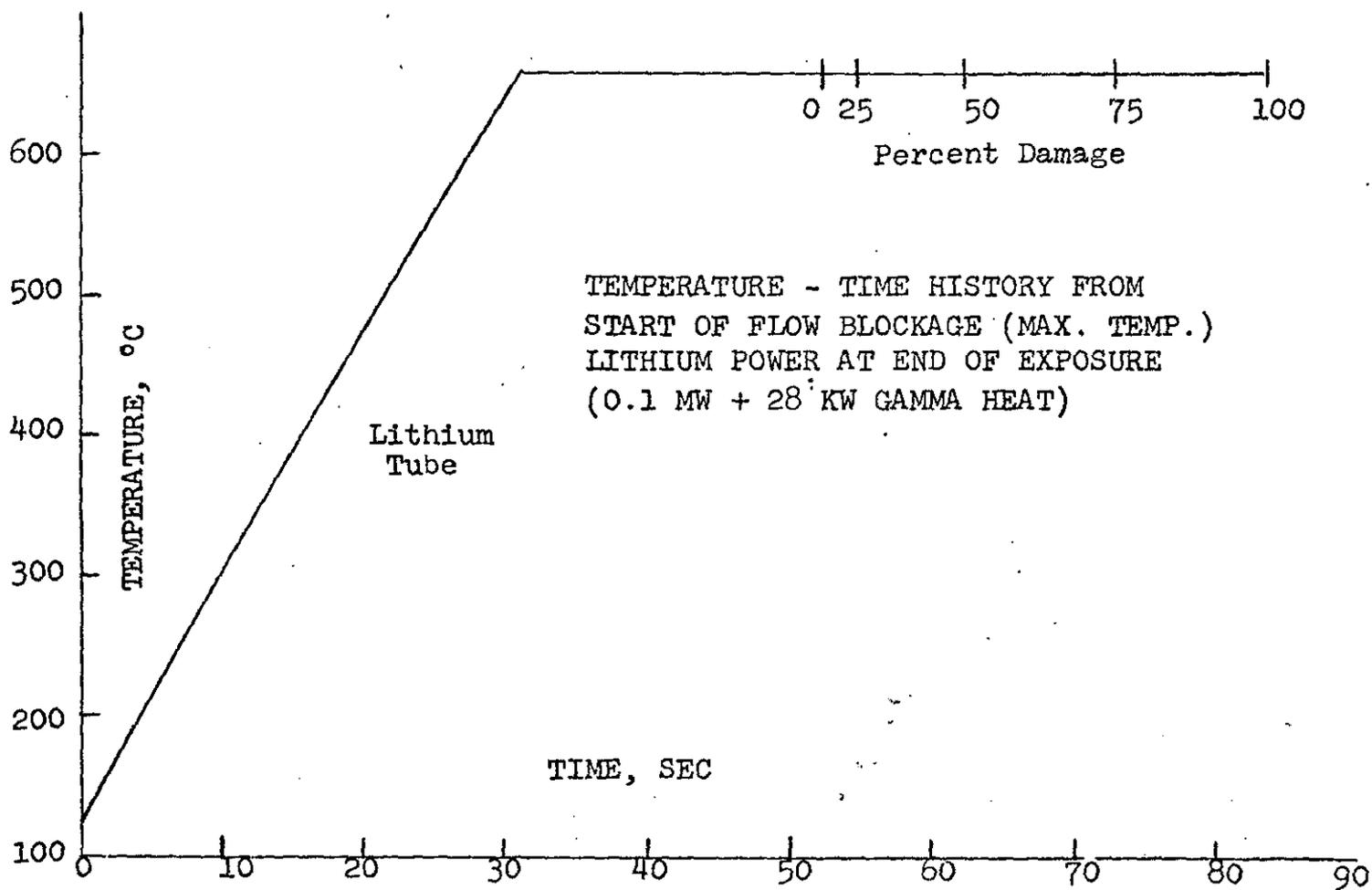
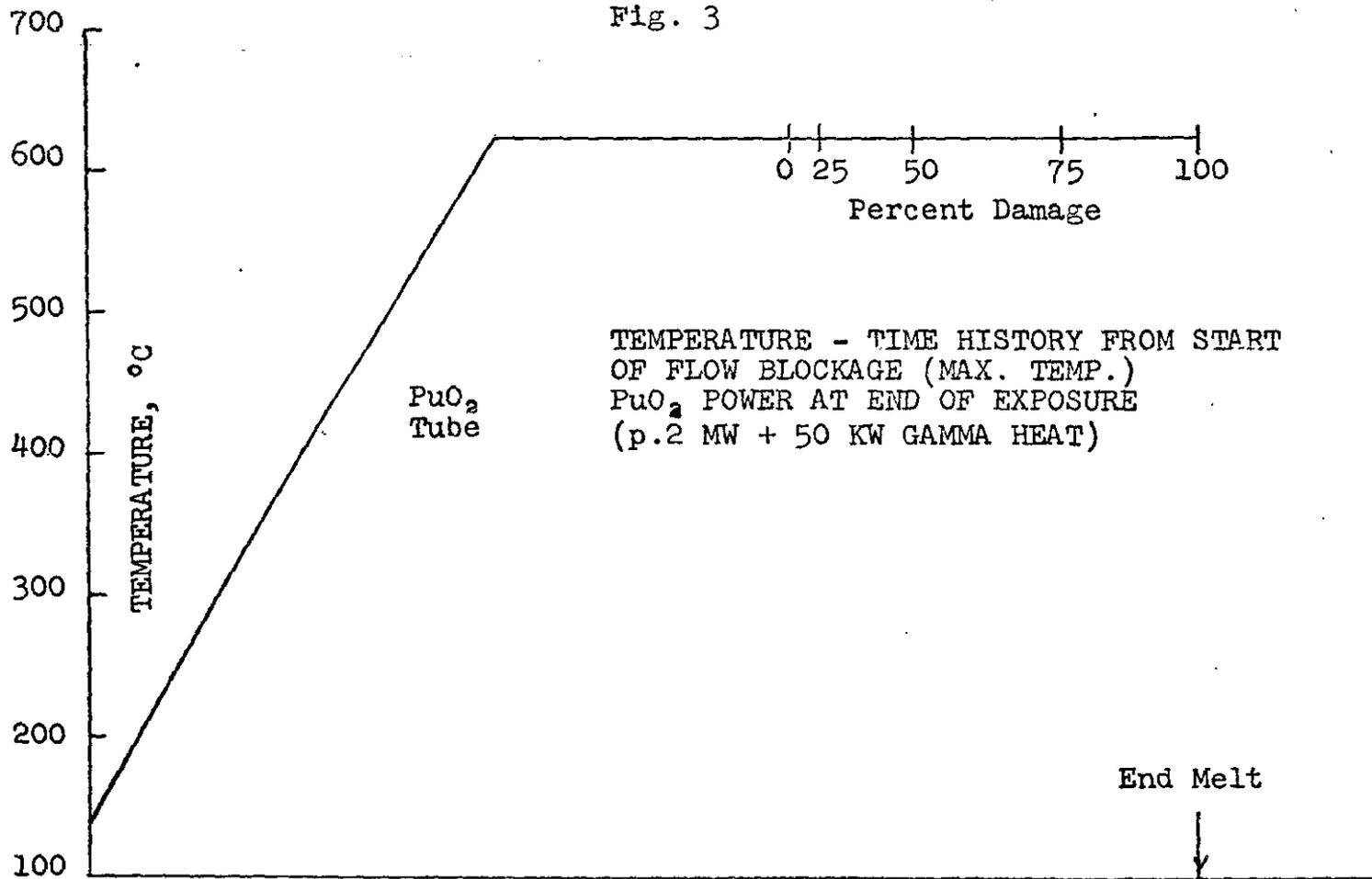
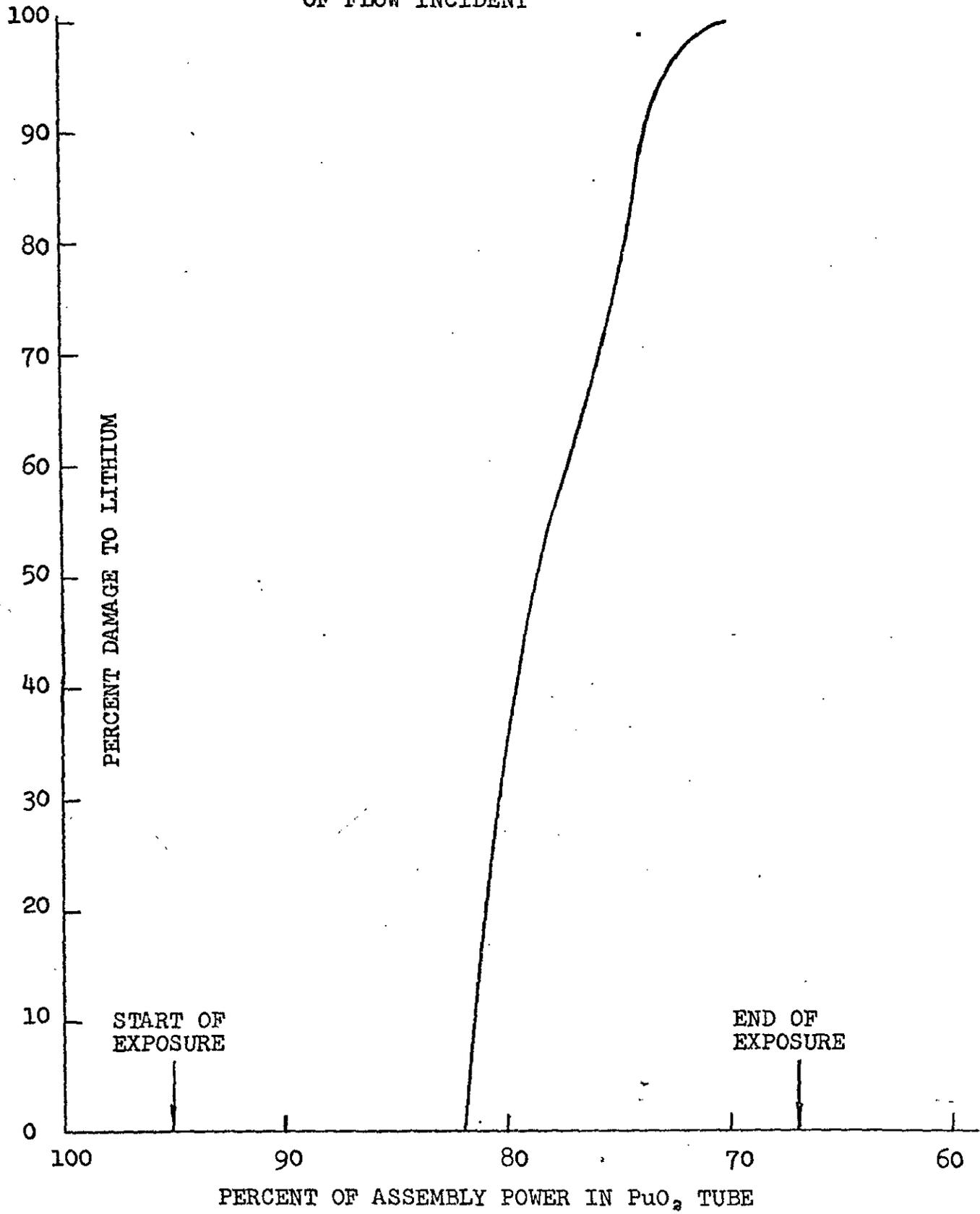


Fig. 4

PERCENT LITHIUM DAMAGE
 VS. PERCENT ASSEMBLY POWER
 IN PuO_2 TUBE AT TIME OF LOSS
 OF FLOW INCIDENT



APPENDIX

The assembly melting code AMELT calculates the transient temperature, melting profiles and molten material transport within tubular assemblies for either cosine or saddle power shapes normalized to any desired amplitude. A listing of the code is provided in the back of this appendix.

The basic equations used in the code are the finite difference form of the following equations:

$$\rho C_p^s \frac{dT}{dt} = S(x) - Q(x) \quad T^0 \leq T \leq T^m \quad (1)$$

$$\rho \Delta H_f \frac{dY}{dt} = S(x) - Q(x) \quad T = T^m \quad (2)$$

$$\rho C_p^l \frac{dT}{dt} = S(x) - Q(x) \quad T > T^m \quad (3)$$

where,

T = metal temperature, T^*

Y = melt fraction, $0 \leq Y \leq 1$

T^0 = thermodynamic reference temperature, T

T^m = melting temperature of metal, T

ρ = metal density, M/L^3

$C_p^{s,l}$ = metal heat capacity, Q/MT (solid and liquid)

ΔH_f = heat of fusion, Q/M

t = time, t

x = axial elevation, L

$S(x)$ = axial radiolitic heat source function, Q/L^3

$Q(x)$ = axial volumetric heat loss from surface heat transfer, Q/L^3t

* Units are shown in generalized form and any consistent set of units may be employed.

The axial radiolitic heat source function is given by:

Cosine power shape:

$$S(x) = \frac{P}{V} \frac{\cos\left(\frac{x-x_L}{x_L}\pi\right)}{\sin\left(\frac{L/2-x_L}{x_L}\pi\right)} \quad (4)$$

Saddle power shape:

$$S(x) = \frac{P}{V} \left\{ 1 + \frac{2(R-1)L}{(x_p^2 L + \frac{L^3(R-1)}{6} - \frac{L^5(R-1)}{60x_p^2})} \left[x^2 - \frac{x^4}{2x_p^2} - \frac{L^2}{12} + \frac{L^4}{160x_p^2} \right] \right\} \quad (5)$$

- where,
- P = overall assembly power, Q/t
 - V = overall volume of assembly, L³
 - R = peak to minimum ratio
 - L = assembly core length, L
 - X = assembly elevation, $-L/2 \leq x \leq L/2$
 - X_p = elevation corresponding to saddle peak, L
 - X_L = assembly length extrapolated to power = zero, L

Molten material was assured to adhere to the tubes until accelerated into the coolant channels as calculated by the following particle transport expression:

$$\frac{dV_p}{dt} = 0.375 \frac{\rho_s}{\rho_p D} (V_s - V_p)^2 + g \quad (6)$$

- where,
- V_p = particle velocity, L/t
 - V_s = steam velocity, L/t

g = gravitational constant, L/T^2

$\rho_{s,p}$ = density of steam and particle, M/L^3

D = particle diameter, L

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COMPILER OPTIONS - NAME= MAIN,OPT=00,LINECNT=58,SIZE=0000K,
SOURCE,EBCDIC,NGLIST,NODECK,LCAD,MAP,NCEDIT,IC,XREF
DIMENSION E(125),Y(125),T(125),AT(45),P(125),IS(125),V(125)
DIMENSION FM(125),MAT(125),RAT(125),ML(45),IAT(125),RATE(400)
C ** READ NO OF ASSEMBLY TUBES
READ(5,5000) NT
5000 FORMAT(I3)
DO 1000 I=1,NT
KC=0
MLAST=0
C ** READ ASSEMBLY TUBE INFORMATION
READ(5,5010) ISH,H,EXH,XP,PWR,R,PEAK,VOLC,HU,FUS,TI,TM
READ(5,5015) PSIZ,PCEN,STD,SVEL,DT,AWGT
5010 FCRMAT(I3,11F5.1)
5015 FORMAT(8F5.1)
C ** SETUP INITIAL VALUES
IPRINT=0
TIME=0.0
VCLI=VOLC
WL=H
NZ=120
ZN=120.
ZHU=HU/ZN
ZFUS=FUS/ZN
ZWGT=AWGT/ZN
C ** CALCULATE INITIAL ELEVATIONS
X=H/NZ
E(1)=X/2.0+(EXH-H)/2.0
Y(1)=E(1)
DO 20 I=2,NZ
E(I)=E(I-1)+X
20 Y(I)=E(I)
C ** CALCULATE INITIAL TEMPERATURES
DO 40 I=1,NZ
RAT(I)=TI
40 T(I)=TI
C AVG TEMPS
DO 50 J=1,40
ML(J)=3
50 IAT(J)=TI
C INITIAL MELT, VELOCITY, MELT FRACTION
DO 60 I=1,NZ
IS(I)=1
V(I)=0.0
60 FM(I)=0.0
C INITIALIZE MATERIAL ACCOUNT
DO 70 J=1,NZ
70 MAT(J)=1
C PRINTOUT AT TIME =0
WRITE(6,6010)PWR,R,PSIZ,PCEN,SVEL
WRITE(6,6011)
6010 FCRMAT(IH1,1X,'P=',F5.3,'(1.0+',F5.2,'*DT) PART DIA=',F6.3,
*'IN. PART SPGR=',F5.1,' STEAM VEL=',F6.1,'FT/SEC'/)
6011 FCRMAT(IH0,5X,'TIME = C.00')
WRITE(6,6020)(ML(I),I=1,40)
WRITE(6,6021)(IAT(I),I=1,40,2)

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WRITE(6,6C22)(IAT(I),I=2,40,2)
MZ=0
MTEF=0
999 CONTINUE
TIME=TIME+DT
PWR=PWR*(1.0+R*DT)
C ** TRANSIENT STATE OF ASSEMBLY
C TEST FOR DEGREE OF MELTING
IF(MTEF.GE.117) GO TO 900
C ** CALCULATE INITIAL AXIAL SEGMENT POWER
GO TO (80,100), ISF
C COSINE PROFILE
80 CGN=PWR/(2.0*SIN(3.1416*F/(2.0*EXH)))
SUMP=0.0
DO 90 I=1,NZ
X1=E(I)-X/2.0
X2=E(I)+X/2.0
TERM1=SIN(3.1416*(2.0*X2-EXH)/(2.0*EXH))
TERM2=SIN(3.1416*(2.0*X1-EXH)/(2.0*EXH))
P(I)=CGN*(TERM1-TERM2)
90 SUMP=SUMP+P(I)
GO TO 120
C SADDLE PROFILE
100 C1=XP*XF*H+F**3*(PEAK-1.0)/6.0-F**5*(PEAK-1.0)/(80.0*XP*XP)
SUMP=0.0
DO 110 I=1,NZ
X1=E(I)-X/2.0-H/2.0
X2=E(I)+X/2.0-H/2.0
T1=(X2-X1)/H
T2=2.0*(PEAK-1.0)/C1
T3=H**4*(X2-X1)/(160.0*XP*XP)
T4=F*H*(X2-X1)/12.0
T5=(X2**3-X1**3)/3.0
T6=(X2**5-X1**5)/(10.0*XP*XP)
PELP=T1+T2*(T3-T4+T5-T6)
P(I)=PELP*PWR
110 SUMP=SUMP+P(I)
C SUBMERGED ASSEMBLY POWER
120 SAP=SUMP*WL/H
C ** CALCULATE BLOWDOWN OF COOLANT IN ASSEMBLY CHANNELS
IF(VCLC.LE.1.0E-5) GO TO 150
VCLC=VCLC-SAP*DT*13.83
IF(VCLC.LT.0.0) VCLC=0.0
WL=VCLC*H/VCLI
C NOW HAVE WETTED LENGTH OF ASSEMBLY
C ASSEMBLY ELEVATIONS ABOVE THIS WETTED ELEVATION ARE ASSUMED TO
C ADIABATICALLY HEAT--ASSEMBLY HEAT BELOW THIS ELEVATION WILL GO
C TO FURTHER VAPORIZE REMAINING COOLANT IN CHANNELS
C IS(I), INDEX OF ASSEMBLY STATUS IS AS FOLLOWS
C IS(I)=1 METAL IS IN CONTACT WITH COOLANT
C IS(I)=2 SOLID BELOW MP NOT IN CONTACT WITH COOLANT
C IS(I)=3 SOLID AT MELTING POINT
C IS(I)=4 LIQUID AT OR ABOVE MP
150 CONTINUE
DO 160 I=1,NZ
IF(IS(I).EQ.1.AND.E(I).GE.WL) IS(I)=2

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160	CONTINUE	15.2
	KC=KC+1	15.3
C	CALCULATE TRANSIENT TEMPS	15.4
	DO 180 I=1,NZ	15.5
	J=IS(I)	15.6
	GO TO (180,165,175,165),J	15.7
165	T(I)=T(I)+P(I)*DT/ZHC	15.8
	IF(IS(I).GT.3) GO TO 180	16.0
	IF(T(I).GE.TM) GO TO 170	16.1
	GO TO 180	16.2
170	IS(I)=3	16.3
	FP=(T(I)-TM)*ZHC/DT	16.4
	FM(I)=FM(I)+FP*DT/ZFUS	16.5
	T(I)=TM	16.6
	GO TO 180	16.8
175	FM(I)=FM(I)+P(I)*DT/ZFUS	17.1
	IF(FM(I).LT.1.0) GO TO 180	17.2
	IS(I)=4	17.3
180	CONTINUE	17.4
C	CALCULATE AVG TEMPS	17.5
	N=0	17.6
	DO 200 J=1,NZ,3	17.7
	N=N+1	17.8
200	AT(N)=(T(J)+T(J+1)+T(J+2))/3.0	18.1
C	CALCULATE VELOCITIES OF MELTED ZONES	18.2
	CIAF=PSI7/12.	18.3
	PTD=PDEK*62.4	18.4
	DO 210 J=1,NZ	18.5
	IF(IS(I).NE.4) GO TO 210	18.6
	ACC=0.375*STD*(SVEL-V(I))**2/(PTD*CIAF)+32.2	18.7
	V(I)=V(I)+ACC*DT	18.8
	IF(V(I).GT.SVEL)V(I)=SVEL	19.1
210	CONTINUE	19.2
C	CALCULATE ELEVATIONS	19.3
	DO 220 J=1,NZ	19.4
	IF(IS(J).NE.4) GO TO 220	19.5
	E(J)=E(J)-V(J)*DT	19.6
	IF(E(J).LT.0.0)E(J)=0.0	19.7
220	CONTINUE	19.8
C	UPDATE MATERIAL FCIT	20.1
	DO 230 I=1,NZ	20.2
	RAT(I)=0.0	20.3
230	MAT(I)=0	20.4
	DO 250 I=1,NZ	20.5
	DO 240 J=1,NZ	20.6
	EDIF=ABS(E(I)-Y(J))	20.7
	IF(EDIF.GT.X) GO TO 240	20.8
	MAT(J)=MAT(J)+1	21.1
	RAT(J)=RAT(J)+T(I)	21.2
	GO TO 250	21.3
240	CONTINUE	21.4
250	CONTINUE	21.5
	KNT=0	21.6
	DO 280 I=1,NZ,3	21.7
	KNT=KNT+1	21.8
	ST=0.0	22.1

AV=3.0	22.
DO 260 J=1,3	22.
KL=J-1	22.
IF(MAT(I+KL).EQ.0)GO TO 270	22.
ST=ST+PAT(I+KL)/MAT(I+KL)	22.
GO TO 260	22.
270 AV=AV-1.0	22.
260 CONTINUE	23.
IF(AV.EQ.0.0)GO TO 290	23.
AT(KNT)=ST/AV	23.
GO TO 280	23.
290 AT(KNT)=0.0	23.
280 CONTINUE	23.
KK=0	23.
DO 300 I=1,NZ,3	23.
KK=KK+1	24.
300 ML(KK)=MAT(I)+MAT(I+1)+MAT(I+2)	24.
MTEF=0	24.
MZL=0	24.
DO 320 I=1,NZ	24.
IF(E(I).EQ.0.0)MTEF=MTEF+1	24.
320 CONTINUE	24.
MZ=0	24.
DO 340 I=1,NZ	25.
IF(IS(I).NE.4) GO TO 340	25.
IF(MZL.EQ.0)MZL=I	25.
MZ=MZ+1	25.
340 CONTINUE	25.
MZH=MZL+MZ	25.
IF(MTEF.EQ.0)TMELT=TIME	25.
WRITE(6,5050)TIME,MZ,MZL,MZH,MTEF,SUMP,WL	25.
6050 FORMAT(1H0,5X,'TIME = ',F6.2,5X,I5,' LAYERS MELTED BETWEEN',I5,	26.
*' AND',I5,2X,I5,' IN ENDFITTING',5X,'POWER=',F7.2,	26.
*' WETTED LENGTH=',F5.1)	26.
WRITE(6,6020)(IS(I),I=2,NZ,3)	26.
WRITE(6,6020)(ML(I),I=1,40)	26.
6020 FORMAT(1H0,5X,40I3)	26.
DO 360 J=1,40	26.
360 IAT(J)=AT(J)	26.
WRITE(6,6021)(IAT(I),I=1,40,2)	27.
WRITE(6,6022)(IAT(I),I=2,40,2)	27.
6021 FORMAT(1H0,3X,20I6)	27.
6022 FORMAT(1H0,6X,20I6)	27.
MLAST=MTEF	27.
GO TO 999	27.
900 CONTINUE	27.
TFIN=KC*DT	27.
1000 CONTINUE	28.
STOP	28.
END	28.