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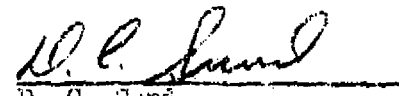
ANALYSIS OF REDUCED FFM COOLING EFFECTS ON
THE PERFORMANCE, ICELLING, AND THERMAL
CHARACTERISTICS OF THE MARQUARDT APOLLO
SM-LM RCS ENGINE

CONTRACT NAS 9-7281, TASK II

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REDUCED FILM COOLING ANALYSIS

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I. SUMMARY

Existing and new TMC analytical capabilities were used in making the required analyses. Part of the new work included the development of two IBM 360/40 computer programs, a preigniter rocket engine hydraulic program and a steady state performance program. When used with existing capabilities, these programs provided a strong base from which comprehensive analyses of the effects of reduced film cooling could be made.

Results of the analyses showed that in no cases would loss of performance result, and improved performance would be realized, for some fuel cooling flow configurations. The analyses also indicated that good ignition will occur in all cases. In addition, reduced film cooling will reduce the amount of fuel accumulated on chamber walls during pulsing operation with resulting reduction in combustion residue formation and subsequent ignition overpressures.

II. INTRODUCTION

As part of the Apollo SM-LM RCS Engine Product Improvement Program, an evaluation is being conducted on the effects of reducing the amounts of fuel cooling on both the combustion chamber and the preigniter walls. This evaluation will consist of both analysis and test efforts. An engine design modification has been performed to allow efficient testing with several combinations of preigniter and chamber coolant flow, including zero flow in both cases.

In support of the design and test phases of this program, analytical studies were made to predict the effects of reduced film cooling on combustion residue formation and ignition characteristics, engine thermal characteristics, and engine performance. The results of these analytical studies are presented in this report.

III. DISCUSSION

Whenever possible, existing TMC capabilities were used in the accomplishment of the analyses required in this reduced film cooling study. When existing capabilities were inadequate, new tools were devised to perform the required analyses.

A 360/40 computer program, described in Section IIIA was written to study the hydraulics of preigniter rocket engines. Another 360/40 computer program described in Section IIIB was written to study steady state performance of rocket engines. Three existing TMC 360/40 computer programs, described in Section IIIC, were used to study the effects of reduced film cooling on the thermal characteristics of the R-4D engine for steady state conditions and soakback conditions. An existing TMC Quiktran computer program, described in Section IIID, was used to study the effect of reduced film cooling on pulse performance of the R-4D engine.

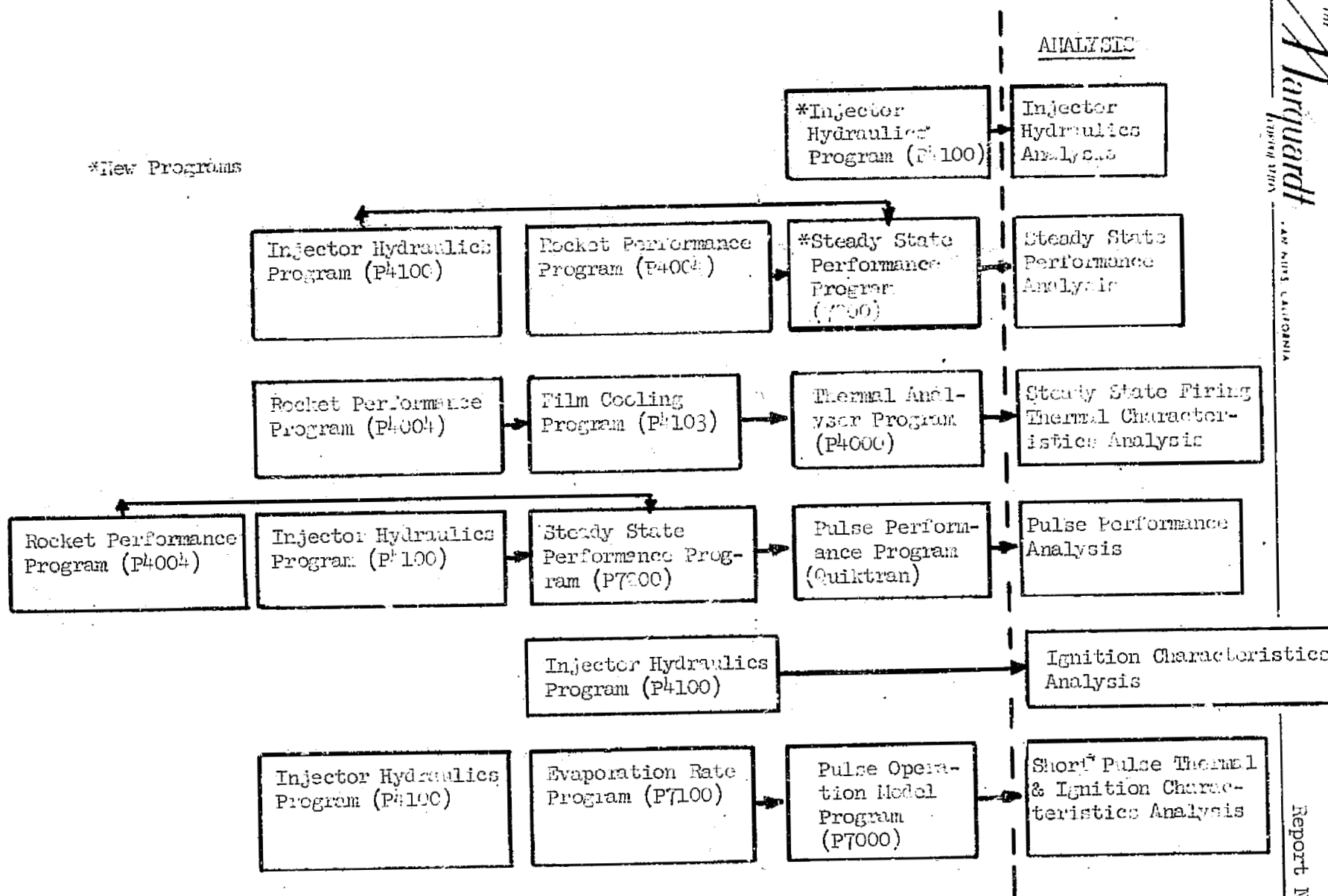
From existing test data, a criterion for determining ignition characteristics, described in Section IIIE, was established. Output from the hydraulics program was used with this criterion to predict ignition limits. To study the effects of reduced film cooling on residue accumulation, two existing TMC 360/40 computer programs, described in Section IIIF, were used. The analytical model is based on a large body of test data.

A flow chart showing the interrelationship between the computer programs used in these analyses is shown in Figure 1.

A. Injector Hydraulics

A computer program was developed which calculates the various flow distributions and internal pressures in a preigniter rocket engine under initial transient and steady flow conditions of operation. This program was initiated several years ago when the first preigniter engines were being developed; however, it was never completely operational. The program was completed as part of the present study. The program handles the following cases:

- Case 1. Propellants are flowing to the preigniter; neither the preigniter nor the main chamber are lit; the hydraulic delay passage is filling (but not full); both preigniter and chamber pressure are zero.
- Case 2. NOTE: As much as possible, the nomenclature used is the same as the original program. Case 2 considered water flow and was not included in the new program.
- Case 3. The preigniter is lit and the preigniter exit is choked; the main chamber is not lit, but the main chamber throat is choked; the hydraulic delay passage is filling.



COMPUTER PROGRAM FLOW DIAGRAM

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Case 4. Same as Case 3, except the hydraulic delay passage is full.

Case 5. Steady state firing - both preigniter and chamber are lit; preigniter exit is unchoked.

The program solves the hydraulic circuit shown in Figure 2. The list of nomenclature for this figure is shown in Figure 3. The basic set of equations for which the analysis was made is as follows:

$$\begin{array}{ll}
 PTF - PSF = KLF (WTF)^2 & (1) \\
 PTO - PSO = KLO (WTO)^2 & (2) \\
 PSF - PJF = KVF (WTF)^2 & (3) \\
 PSO - PJO = KVO (WTO)^2 & (4) \\
 PJF - PDF = DWF (WTF)^2 & (5) \\
 PJO - PDO = KWO (WTO)^2 & (6) \\
 PDF - PC = KBF (WBF)^2 & (7) \\
 PDF - PC = KBC (WBC)^2 & (8) \\
 PDF - PC = KDF (WDF)^2 & (9) \\
 PLO - PC = KMO (WMO)^2 & (10) \\
 PJF - PP = KIF (WTF)^2 & (11) \\
 PJO - PI = KIO (WTO)^2 & (12) \\
 WTF = WMF + WIF & (13) \\
 WTO = WMO + WIO & (14) \\
 WMF = WMP + WBC + WDF & (15) \\
 WP = WIF + WIO & (16) \\
 WT = WMO + WMF + WP & (17) \\
 WP = KP (PP) & (18) \\
 WT = KC (PC) & (19)
 \end{array}$$

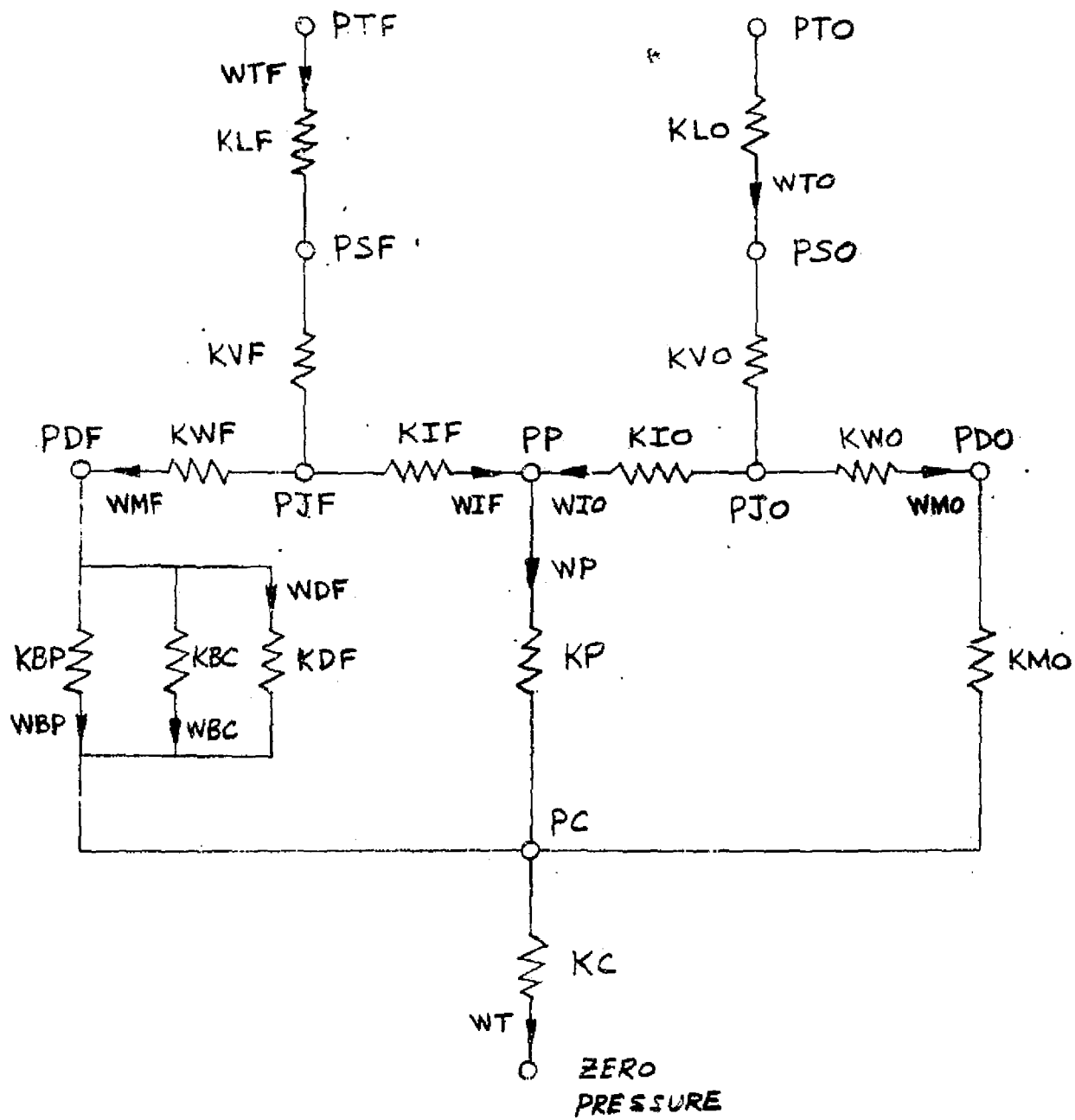
In all cases, it is assumed that the external or exhaust pressure is 0 psia.

The flame resistances KP and KC are functions of the actual C* values for combustion in the preigniter and the main chamber. These actual C* values in turn are dependent on the O/F ratio and an input C* efficiency. Theoretical values of C* vs. O/F are part of the program input. In addition, KP is modified by an unchoked flow correction factor, dependent on the ratio PP/PC when necessary.

For Case 1, the set of equations to be solved consists of 1, 2, 3, 4, 5, 6, 11, 12, 13, and 14 with the additional constraints that:

$$\begin{array}{ll}
 PDF = 0 & (20) \\
 PDO = 0 & (21) \\
 PP = 0 & (22) \\
 PC = 0 & (23)
 \end{array}$$

This results in a nonlinear system of twelve equations with twelve unknowns and is solved easily by algebraic substitution.



SCHEMATIC HYDRAULIC CIRCUIT

NOMENCLATURE FOR HYDRAULIC CIRCUIT

PTF - fuel tank pressure
 PTO - oxidizer tank pressure
 WTF - total fuel flow
 WTO - total oxidizer flow
 KLF - fuel line resistance
 KLO - oxidizer line resistance
 PSF - fuel supply pressure
 PSO - oxidizer " "
 KVF - fuel valve resistance
 KVO - oxidizer " "
 PJF - fuel junction pressure
 PJO - oxidizer " "
 KIF - fuel preigniter resistance
 KIO - oxidizer " "
 WIF - fuel preigniter flow
 WIO - oxidizer " "
 PP - preigniter pressure
 WP - total preigniter flow
 KP - preigniter flame resistance
 KWF - fuel window resistance
 KWO - oxidizer " "
 WMF - fuel manifold flow
 WMO - oxidizer " "
 PDF - fuel doublet pressure
 PDO - oxidizer " "
 KDF - fuel doublet resistance
 WDF - fuel doublet flow
 KBC - chamber bleed resistance
 WBC - chamber bleed flow
 KBP - preigniter bleed resistance
 WBP - " " flow
 KMO - oxidizer manifold resistance
 PC - chamber pressure
 KC - chamber flame resistance
 WT - total propellant flow

All pressures are in psia
 " flows " " lb/sec
 " resistances are in $\text{psi}/(\text{lb}/\text{sec})^2$

For Case 3, it is assumed that the C^* efficiency is the same in the main chamber as in the preigniter. This case consists of equations 1, 2, 3, 4, 5, 6, 11, 12, 13, 14, 16, 17, and 18 with the additional constraints that:

$$\begin{aligned} PDC &= PC & (24) \\ PDF &= PC & (25) \\ WP &= (KC) (PC) & (26) \end{aligned}$$

This results in a nonlinear, nonconstant coefficient, system of 16 equations with 16 unknowns and is solved by an iteration procedure with PP (preigniter pressure) as the iterate.

For Case 4, it is assumed that the propellants injected into the main chamber through the doublets and cooling holes are not combusted, that is, they make no contribution to chamber pressure. It is, again, assumed that the C^* efficiency is the same in the main chamber as in the preigniter. This case is similar to Case 3 except that equations 24, and 25 are replaced by equations 7, 8, 9, 10, and 15 resulting in a system of 19 equations with 19 unknowns.

This system is also nonlinear with nonconstant coefficients and must be solved by the same iteration procedure as used in Case 3.

Case 5 consists of the basic set of equations 1 through 19. This set of 19 equations in 19 unknowns is also nonlinear with nonconstant coefficients but must be solved by a double iteration procedure (PP/PC being the iterates).

A complete listing of the program is given in Figure 4. A completed input form corresponding to the following results is given in Figure 5. Figure 6 is a sample of the results of cases 1, 3, 4, and 5 for a nominal engine (i.e., normal coolant flow, $O/F = 2.03$, $P_c = 97$ psia).

The program can be used to determine required inlet pressures and/or flow resistances for specified chamber pressures and O/F ratios. The program was used in this manner to determine the injector orifice diameters (which are related to flow resistance) and inlet pressures required to achieve certain reductions in film cooling flows while maintaining overall steady state O/F ratio and chamber pressure at their nominal values. The procedure used was as follows. With some or all film cooling holes plugged or made smaller, the total fuel flow decreased while the flow through the remaining holes increased, when compared with the nominal condition. The overall O/F increased and the chamber pressure decreased. The tank pressures and flow resistances of the film cooling orifices were adjusted until both the desired flows and nominal performance were achieved.

To convert flow resistances into orifice diameters, the basic flow equation was used.

```

      C      MAIN
0001      COMMON PIF,PTD, PUF,PJO,PC,PP,PFC,PCGES,DF,DFP,WTF,WID,WIF,WID,
      1,P,ASTAR,APSTAR,CEFF,CPEFF,CTHED,CPHED,CSTAR,CPSTAR,IMAX,DFTAB(20
      2),CTAB(20),BKVF,BKVD,AKIF,AKIC,AKWF,AKWD,AKLF,AKLD,BKWD,BKWF,AKMD,
      3,AKED,AKBP,AKBC,AKDF,NFLAG,GAM
0002      DIMENSION TITLE(13)
0003      10 FORMAT(6E12.6)
0004      1 READ(5,2),END=78) TITLE
0005      N=1
0006      21 FORMAT(13A4)
0007      READ(5,10)AKIC,AKVD,AKLF,AKVF,AKWD,AKWF,AKIC,AKIF,AKBP,AKBC,AKDF,
      1AKMD,PCJOM,PTNUM,GAM
0008      READ(5,20) IMAX,ICASE
0009      20 FORMAT(2I2)
0010      READ(5,10) (DFTAB(I),CTAB(I),I=1,IMAX)
0011      77 READ(5,10)ASTAR,APSTAR,CEFF,CPEFF,PTD,PTF
0012      READ(5,30) N1,N3,N4,N5
0013      30 FORMAT(4I1)
0014      AKED=1./((1./SQRT(AKBP)+1./SQRT(AKBC)+1./SQRT(AKDF))*2
0015      BKVD=AKVD+AKLD
0016      BKVF=AKVF+AKLF
0017      BKWD=AKWD+AKMD
0018      BKWF=AKWF+AKDF
0019      PCGES=PCJOM**2/(2.*(PTD+PTF))*(SQRT(1.+2.*(PTD+PTF))*(PTNUM-
      1PCNUM)/PCNUM**2)-1.)
0020      WRITE(6,22) TITLE
0021      22 FORMAT(1H1,5X,13A4)
0022      WRITE(5,11) AKLD,AKLF,AKVD,AKVF
0023      11 FORMAT(1H0, 5X,5HKLD =,F10.1,30X,5HKLF =,F10.1,/,10X,5HKVD =,F10.1
      1,50X,5HKVF =,F10.1)
0024      WRITE(6,12) AKWD,AKIC,AKIF,AKWF,AKBP,AKMD,AKBC,AKDF
0025      12 FORMAT(5X,5HKWD =,F10.1,5X,5HKIC =,F10.1,5X,5HKIF =,F10.1,5X,5HKWF
      1 =,F10.1,/,60X,5HKBP =,F10.1,/,5X,5HKMD =,F10.1,40X,5HKBC =,F10.1,/,
      2,60X,5HKDF =,F10.1,/)
0026      WRITE(6,14) PCNUM,PTNUM,GAM
0027      14 FORMAT(7,10X,'NOMINAL CHAMBER PRESSURE = ',F8.3,/,10X,'NOMINAL
      ITANS PRESSURE = ',F8.3,/,10X,'GAMMA = ',F6.3)
0028      WRITE(6,13) (DFTAB(I),CTAB(I),I=1,IMAX)

```

FIGURE 4a

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0029      13 FORMAT(//,20X,5H DZB ,10X,5H CSHR1,//,(20X,F6.3,9X,F7.1))
0030      NFLAG=0
0031      IF (N1.EQ.1) CALL CASE1
0032      IF (N3.EQ.1) CALL CASE34(1)
0033      IF (NFLAG.GT.0) GO TO 75
0034      IF (N4.EQ.1) CALL CASE34(2)
0035      IF (NFLAG.GT.0) GO TO 75
0036      IF (N5.EQ.1) CALL CASE5
0037      76 N=N+1
0038      IF (N.GT.1000) GO TO 1
0039      GO TO 77
0040      78 CALL LX11
0041      STOP
0042      END

```

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FIGURE 4b

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C      SUBROUTINE CASE1
0001      SUBROUTINE CASE1
0002      COMMON PTF,PTO,   PJF,PJO,PC,PP,PPC,PCGES,OF,DFP,WTF,VTO,WIF,WIO,
      1WP,ASTAR,APSTAR,CEFF,CPEFF,CTHEO,CPTHEO,CSTAR,CPSTAR,IMAX,OFTAB(20
      2),CTAB(20),BKFV,BKVO,AKIF,AKIO,AKVF,AKWO,AKLF,AKLO,BKWF,BKWD,AKMO,
      3AKEJ,AKBP,AKBC,AKDF,NFLAG,GAM
0003      WRITE(6,11)
0004      11 FORMAT(1H1,54H CASE 1 RESULTS - NOTHING LIT, DELAY PASSAGE NOT FU
      1LL)
0005      PJF=(PTF
      1SQRT(AKIF)+1./SQRT(AKWF))**2)
      2)/(1.+BKVF*(1./
0006      WTF=SQRT((PTF-PJF)/BKVF)
0007      WIF=SQRT((PJF
      1)/AKWF)
0008      WIF=WIF-WMF
0009      PSF=PTF-AKLF*WTF**2
0010      PJO=(PTO
      1SQRT(AKIO)+1./SQRT(AKWO))**2)
      2)/(1.+BKVO*(1./
0011      WTO=SQRT((PTO-PJO)/BKVO)
0012      WMO=SQRT((PJO
      1)/AKWO)
0013      WIO=WTO-WMO
0014      PSO=PTO-AKLO*WTO**2
0015      OF=WTO/WTF
0016      DFP=WIO/WIF
0017      WRITE(6,12)PTO,PTF,PSO,PSF,PJO,PJF
0018      12 FORMAT(/,10X,54HPTO =,F10.3,30X,5HPTE =,F10.3,/,10X,5HPSO =,F10.3,
      130X,5HPSE =,F10.3,/,10X,5HPJO =,F10.3,30X,5HPJF =,F10.3,/,20X,
      215HPDO=PDF=PP=PC =,F10.3)
0019      WRITE(6,13)WTO,WTF,WMO,WMF,WIO,WIF
0020      13 FORMAT(/,10X,5HWTO =,F10.5,30X,5HWTF =,F10.5,/,10X,5HWMO =,F10.5,
      130X,5HWMF =,F10.5,/,10X,5HWIO =,F10.5,30X,5HWIF =,F10.5)
0021      WRITE(6,14)OF,DFP
0022      14 FORMAT(/,15X,5HOF =,F10.5,10X,6HDFP =,F10.5)
0023      RETURN
0024      END

```

FIGURE 4c

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      SUBROUTINE CASE 34
0001  SUBROUTINE CASE 34 (NCASE)
0002  COMMON PTF,PTD, PJE,PJY,PC,PP,PPC,PCSES,DF,DFP,WTF,WTO,WIF,WID,
      1,P,ASTAR,APSTAR,CEFT,CPLFF,CTHED,CPTPEG,CSTAR,CPSSTAR,IMAX,OFTAB(20
      2),OTAB(20),BKVF,BKVD,AKIF,AKIL,AKWF,AKWD,AKLF,AKLD,BKWD,BKWF,AKMU,
      3AKF),AKBP,AKBC,AKDF,NELAG,GAM
0003  EXTERNAL FUN3
0004  GO TO (3,4), NCASE
0005  3 BKWD=AKWD
0006  3 AKWF=AKWF
0007  3 WRITE(6,11)
0008  11 FORMAT(1H1,97H CASE 3 RESULTS - PPEIGNITER LIT AND CHOKED, CHAMB
      1IF NOT LIT BUT CHOKED, DELAY PASSAGE NOT FULL)
0009  GO TO 7
0010  4 WRITE(6,12)
0011  12 FORMAT(1H1,93H CASE 4 RESULTS - PPEIGNITER LIT AND CHOKED, CHAMB
      1IF NOT LIT BUT CHOKED, DELAY PASSAGE FULL)
0012  7 A=C.
0013  B=AMINI(PTD,PTF)
0014  PPGES=.4*B
0015  XABSER=.1
0016  XREFLER=.002
0017  FABSER=1.E+06
0018  XBOUND=100.
0019  X2CODE=50.
0020  NPRINT=1
0021  NCOUNT=50
0022  NCONV=1
0023  NSERCH=-1
0024  NLEVEL=1
0025  CALL SOLVE(PPX,PRINT,A,B,PPGES,XABSER,XREFLER,FABSER,XBOUND,X2CODE,
      1NPRINT,NCOUNT,NCONV,NSERCH,NLEVEL,4HFUNCTION3,FUN3,ARRAY,NEERRR)
0026  IF(NERROR.NE.1) GO TO 77
0027  PP=PPX
0028  WTD=SQRT((PTD-PJE)/BKVD)
0029  WTF=SQRT((PTF-PJE)/BKVF)
0030  WT=WTD+WTF
0031  WMD=SQRT((PJG-PC)/BKWD)

```

12

FIGURE 4a

FORTRAN IV 3 LEVEL 0, MOD 0

CASE 34

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0032      WMF=SQRT((PJE-PC)/3KMF)
0033      CF=WTQ/WTB
0034      PSQ=PTD-AKLD*WTB**2
0035      PSF=PTF-AKLF*WTF**2
0036      WRITE(6,17)PTD,PTF,PSQ,PSF,PJD,PJF
0037      17 FORMAT(7,10X,5HPDQ =,F10.3,30X,5HPTF =,F10.3,7,10X,5HPSQ =,F10.3,
13 130X,5HPSF =,F10.3,7,10X,5HPJD =,F10.3,30X,5HPJF =,F10.3)
0038      IF(NCASE.EQ.2) GO TO 5
0039      WRITE(6,15) PP,PC
0040      16 FORMAT(7,30X,4HPP =,F10.3,77,20X,12 HPC=PDF=PC= ,F10.3)
0041      GO TO 5
0042      5 PDD=PJD-AKLD*WMF**2
0043      PDF=PJF-AKLF*WMF**2
0044      WBP=SQRT((PDF-PC)/AKBP)
0045      WBC=SQRT((PDF-PC)/AKBC)
0046      WDF=SQRT((PDF-PC)/AKDF)
0047      WRITE(6,15)PDD, PP,PDF,PC
0048      15 FORMAT(710X,5HPDD =,F10.3,11X,4HPP =,F10.3,10X,5HPDJ =,F10.3,77,30
1X,4HPC =,F10.3)
0049      6 WRITE(6,13)WTQ,WT,WTB,WMD,WMF,WID,WP,WIF
0050      13 FORMAT(7,10X,5HWTQ =,F10.5,11X,4HWT =,F10.5,10X,5HWTB =,F10.5,7,10
1X,5HWMD =,F10.5,35X,5HWMF =,F10.5,7,10X,5HWID =,F10.5,11X,4HWP =,
2F10.5,10X,5HWIF =,F10.5)
0051      IF(NCASE.EQ.2) WRITE(6,20) WBP,WBC,WDF
0052      20 FORMAT(760X,'WBP' =,F10.5,7,60X,'WBC' =,F10.5,7,60X,'WDF' =,F10.5)
0053      WRITE(6,14)OF,UEP,CPTHEO,CPEFF,CPSTAR
0054      14 FORMAT(7,10X,5HOF =,F10.5,15X,6HUEP =,F10.5,7710X,9HCP*THEO =,
1F10.1,5X,8HCP*EFF =,F10.4,5X,5HCP* =,F10.1)
0055      GO TO 1
0056      77 NFLAG=14
0057      1 IF(NCASE.EQ.2) GO TO 2
0058      BKWD=AKWD+AKMD
0059      BKWF=AKWF+AKFD
0060      2 RETURN
0061      END

```

FIGURE 4e

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C      FUNCTION FUN3
0001      FUNCTION FUN3(ICOUNT, PPTAB, FPKIOF, NFRRF, NCODE, ARRAY, NLEVEL)
0002      COMMON PTF, PTO, PPF, PJO, PC, PP, PPC, PGGES, OF, OFP, WTF, WTD, WIF, WIO,
      1WP, ASTAR, APSTAR, CPEFF, CPEFF, CTHED, CPTHEO, CSTAR, CPSTAR, IMAX, DFTAB(20
      21, CTAB(20), BKVF, BKVD, AKIF, AKIO, AKWF, AKWD, AKLE, AKLD, BKWD, BKWF, AKMO,
      3AKFD, AKBP, AKBC, AKDF, NFLAG, GAM
0003      DIMENSION PPTAB(1), PPTRY(50), F3TRY(50)
0004      GO TO (2000, 3000, 4000), NCODE
0005      2000 PP=PPTAB(NLEVEL)
0006      PPTRY(ICOUNT)=PP
0007      PC=PP*APSTAR/ASTAR
0008      AF=(1./BKVF+1./AKIF+1./BKWF)**2-4./((AKIF*BKWF)
0009      CF=(PP+PC)/((AKIF*BKWF)-PTF/BKVF*(1./BKVF+1./AKIF+1./BKWF-PP/AKIF+
      1(1./BKVF+1./AKIF)-PC/BKWF*(1./BKVF+1./BKWF)
0010      CF=PTF**2/BKVF**2+2.*PTF*PP/(BKVF*AKIF)+2.*PTF*PC/(BKVF*BKWF)+
      1PP**2/AKIF**2+PC**2/BKVF**2-2.*PP*PC/(AKIF*BKWF)
0011      IF(BF**2-AF*CF)2,3,3
0012      2 FUN3=10.
0013      GO TO 4
0014      3 AO=(1./BKVD+1./AKIO+1./BKWD)**2-4./((AKIO*BKWD)
0015      BO=(PP+PC)/((AKIO*BKWD)-PTO/BKVD*(1./BKVD+1./AKIO+1./BKWD)-PP/AKIO*
      1(1./BKVD+1./AKIO)-PC/BKWD*(1./BKVD+1./BKWD)
0016      CO=PTO**2/BKVD**2+2.*PTO*PP/(BKVD*AKIO)+2.*PTO*PC/(BKVD*BKWD)+
      1PP**2/AKIO**2+PC**2/BKWD**2-2.*PP*PC/(AKIO*BKWD)
0017      IF(BO**2-AO*CO)5,6,6
0018      5 FUN3=10.
0019      GO TO 4
0020      6 PJO=(-B)-SQRT(BO**2-AO*CO)/AO
0021      PJF=(-BF)-SQRT(BF**2-AF*CF)/AF
0022      WIO=SQRT((PJO-PP)/AKIO)
0023      WIF=SQRT((PJF-PP)/AKIF)
0024      OFP=WIO/WIF
0025      CPTHEO=ENTRP(OFTAB,CTAB,OFP,IMAX,2)
0026      CPSTAR=CPTHEO*CPEFF
0027      WP=APSTAR*32.174*PP/CPSTAR
0028      FUN3=WTD+WIF-WP
0029      4 F3TRY(ICOUNT)=FUN3
0030      GO TO 4000

```

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FIGURE 4f

FORTRAN IV - LEVEL 3, MOD 5

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```
0031      3000 WRITE(6,3100) (PTRY(I),FTRY(I),I=1,100000)
0032      3100 FORMAT(10I24H PTRY FTRY ,12D16.8)
0033      4000 RETURN
0034      END
```

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FIGURE 4a

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```

0001 SUBROUTINE CHOKED
0002 SUBROUTINE CHOKED
      COMMON /PPF,PTD,PJF,PJG,PC,PP,PPC,PJGES,OF,DEP,WTF,WTD,WIF,WID,
      IWP,ISTAR,APSTAR,CFF,CFFE,CFFE,CFFE,CSTAR,CPSTAR,IMAX,OFIAB(20
      2),CTAB(20),BKVF,AKVD,AKVF,AKVD,AKVF,AKVD,AKVF,AKVD,AKVF,AKVD,
      BAKVD,AKBP,AKBC,AKD,NFLAT,SAM
0003 EXTERNAL FUN6
0004 A=1.
0005 B=2.
0006 NLEVEL=1
0007 XABSER=.001
0008 XRELER=.0005
0009 FABSER=100.
0010 XBOUND=100.
0011 X2CODE=50.
0012 NPRINT=1
0013 NCDUNT=20
0014 NCONV=1
0015 NSERCH=1
0016 PPCGES=1.144
0017 CALL SOLVE(PPP,FPRINT,A,B,PPGES,XABSER,XRELER,FABSER,XBOUND,X2
      1CODE,NPRINT,NCDUNT,NCONV,NSERCH,NLEVEL,4HFUN6,FUN6,ARRAY,NEERRR)
0018 PPC=PPP
0019 IF (NEERRR.NE.1) GO TO 77
0020 PP=PPC*PC
0021 WT=WTD+WIF
0022 WME=SQRT((PJF-PC)/BKVF)
0023 WMD=SQRT((PJG-PC)/BKVD)
0024 PSF=PFF-AKVF*WTF**2
0025 PSD=PTD-AKVD*WTD**2
0026 PDF=PJF-AKVF*WME**2
0027 PDU=PJG-AKVD*WMD**2
0028 WBP=SQRT((PDI-PC)/AKBP)
0029 WPC=SQRT((PDF-PC)/AKBC)
0030 WDF=SQRT((PDI-PC)/AKDF)
0031 WRITE (6,12)
0032 12 FORMAT(3HICASE 5 RESULTS - STEADY STATE FIRING, CHAMBER CHOKED, P
      1KIGNITER LIT BUT UNCHOKED,/)

```

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FIGURE 4b

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FORMAT IV G LEVEL 10,

CASE

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```

0033      WRITE(6,19) ASTAR,CTHED,CPEFF,CSTAR,APSTAR,CPTHEO,CPEFF,CPSTAR
0034      19 FORMAT(10X,7HASTAR =,F10.5,5X,8HC*THEO =,F10.1,5X,7HC*EFF =,F6.4,
      15X,4HC* =,F10.1,/,9X,6HAPSTAR =,F10.5,4X,9HCP*THEO =,F10.1,4X,
      2HCP*EFF =,F6.4,4X,5HCP* =,F10.1,/)
0035      20 WRITE(6,13) PTD,PTF,PSD,PSF
0036      13 FORMAT(10X,5HPTD =,F10.3,30X,5HPTF =,F10.3,/,10X,5HPSD =,F10.3,30X
      1,5HPSF =,F10.3)
0037      WRITE(6,14) PDC,PJC,PJF,PDF,PP,PC
0038      14 FORMAT(5X,5HPDC =,F10.3,5X,5HPJC =,F10.3,5X,5HPJF =,F10.3,5X,5HPDF
      1 =,F10.3,/,35X,4HPC =,F10.3,/,35X,4HPC =,F10.3)
0039      WRITE(6,15) WTD,WTF,WF
0040      15 FORMAT(//,10X,5HWTD =,F10.5,10X,5HWTF =,F10.5,10X,5HWF =,F10.5)
0041      WRITE(6,16) WMD,WIF,WMF
0042      16 FORMAT(5X,5HMD =,F10.5,5X,5HIF =,F10.5,5X,5HMF =,F10.5,5X,5HMF
      1 =,F10.5)
0043      WRITE(6,17) WBP,WP,WBC,WDF
0044      17 FORMAT(60X,5HWBP =,F10.5,/,35X,5HWBP =,F10.5,10X,5HWBC =,F10.5,/,
      160X,5HWDF =,F10.5)
0045      WRITE(6,13) OF,OFF
0046      18 FORMAT(//,20X,5HOF =,F10.4,20X,5HOF =,F10.4)
0047      77 RETURN
0048      END

```

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FIGURE 44

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FIGURE 4.1

```

C      FUNCTION FUN5
0001      FUNCTION FUN5(ICOUNT,PPCTAB,PPCTRY,NERRR,FUNCODE,ARRAY,NLEVEL)
0002      COMMON PTF,PTO,PJA,PJB,PC,PP,PPC,PGES,DF,DFP,WTF,WTO,WIF,WID,
      1WP,ASTAR,APSTAR,CEFF,CPEFF,CTHEO,CPTHEO,CSTAR,CPSTAR,IMAX,GFTAB(20
      2),CTAB(20),BKVF,BKVO,AKIF,AKIO,AKWF,AKWO,AKLF,AKLO,BKWO,BKWF,AKMO,
      3AKFO,AKBP,AKBC,AKDF,NELAS,GAM
0003      COMMON/MIKE/BX,CX
0004      DIMENSION PPCTAB(5),PPCTRY(20),F6TRY(20)
0005      EXTERNAL FUN5
0006      GO TO (1000,3000,3000),NCODE
0007      2000 PPC=PPCTAB(NLEVEL)
0008      PPCTRY(ICOUNT)=PPC
0009      Z=0.
0010      R=AMIN1(PTO,PTF)
0011      BX=1
0012      XABSER=.05
0013      XRELER=.0005
0014      FABSER=1.E+05
0015      XBOUND=100.
0016      XZCODE=50.
0017      NPRINT=1
0018      NCOUNT=50
0019      NCONV=1
0020      NLEVEL=2
0021      NSERCH=-1
0022      PGES=AMIN1(PGES,.9*(P-A)/1.144)
0023      CALL SOLVE(PX,FROOT,A,B,PGES,XABSER,XRELER,FABSER,XBOUND,XZCODE,
      1NPRINT,NCOUNT,NCONV,NSERCH,NLEVEL,4HFUN5,FUN5,ARRAY,NERRR)
0024      IF(CX.GT.0.) GO TO 2500
0025      PC=PX
0026      FUN6=PP-BID-WIF
0027      F6TRY(ICOUNT)=FUN6
0028      GO TO 4000
0029      2500 ICOUNT=ICOUNT
0030      FUN6=(50.-FCOUNT)*.2
0031      GO TO 4000
0032      3000 WRITE(6,3100) (PPCTRY(I),F6TRY(I),I=1,ICOUNT)
0033      3100 FORMAT(1H1,10X,25H PPC          FUN6          ,(2E15.8))

```

FORTRAN IV 6 LEVEL 0.1 400

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0034 4000 RETURN

0035 END

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FIGURE 4k

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FIGURE 42

```

0001      C      FUNCTION
0002      C      FORT (ICOUNT, PCTAB, FORTIC, IERR, NCODE, ARRAY, NLEVEL)
0003      C      COMMON /PCTAB, PTF, PJE, PJJ, PC, PP, PPC, PCGES, CF, WPF, WTD, WIF, WID,
0004      C      IERR, ASIAK, APSTAK, CFF, CPEFF, CTRFD, CPTHEO, CSIAK, CPSTAK, IMAX, CPTAB(20
0005      C      2), CTAH(20), BKVF, BKV, AKIF, AKIL, AKWF, AKMD, AKLF, AKLO, BKWD, BKWF, AKMD,
0006      C      BAKED, AKKP, AKBC, AKDF, NPLAS, GAM
0007      C      COMMON /IERR, CX, CX
0008      C      DOUBLE PRECISION AS, BI, CI, AF, PI, CF
0009      C      DIMENSION PCTAB(5), PCTRY(50), FITRY(50)
0010      C      GO TO (2000, 3000, 3000), NCODE
0011      C      2000 PC=PCTAB(NLEVEL)
0012      C      PC=PCTAB(1)
0013      C      IF=PP*PC
0014      C      IF(PP.GT.3X) GO TO 2500
0015      C      CX=0.
0016      C      PCTRY(100000)=PC
0017      C      AF=(1./BKVF+1./AKIF+1./PKWF)**2-4./((AKIF*PKWF)
0018      C      BF=-((1./BKVF+1./AKIF+1./PKWF)*(PTF/BKVF+PP/AKIF+PC/BKWF)+2.*(PP+PC
0019      C      1)/(AKIF*PKWF)
0020      C      CF=(PTF/BKVF)**2+(PP/AKIF)**2+(PC/BKWF)**2+2.*(PTF/BKVF*(PP/AKIF+PC
0021      C      1/BKWF)-2.*PP*PC/(AKIF*PKWF)
0022      C      IF(BF**2-AF*CF)2,3,3
0023      C      2 FUN5=-10.
0024      C      GO TO 4
0025      C      3 AC=(1./BKVC+1./AKIQ+1./BKWC)**2-4./((AKIQ*BKWD)
0026      C      BC=-((1./BKVC+1./AKIQ+1./BKWC)*(PTD/BKVC+PP/AKIQ+PC/BKWD)+2.*(PP+PC
0027      C      1)/(AKIQ*BKWD)
0028      C      CC=(PTD/BKVC)**2+(PP/AKIQ)**2+(PC/BKWD)**2+2.*(PTD/BKVC*(PP/AKIQ+PC
0029      C      1/BKWD)-2.*PP*PC/(AKIQ*BKWD)
0030      C      IF(CC**2-AC*CC)5,6,5
0031      C      5 FUN5=-10.
0032      C      GO TO 4
0033      C      6 PJD=(-BC-DSQRT(CC**2-AC*CC))/AC
0034      C      PJE=(-BF-USQRT(BF**2-AF*CF))/AF
0035      C      WPF=SQRT((PTF-PJE)/BKVF)
0036      C      WTD=SQRT((PTD-PJD)/BKVC)
0037      C      WIF=WTD/WPF
0038      C      WIF=SQRT((PJE-PP)/AKIF)

```

FORTRAN IV G LEVEL C, MIN 0

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0031      AID=SQRT((PJD-PP)/AKIL)
0032      PEP=WID/DIF
0033      CTHEO=ENTERP(MTAN,CTAB,PE,IMAX,2)
0034      CPTHEO=ENTERP(MPTAB,CTAB,CPE,IMAX,2)
0035      CSTAR=CTHEO*CPEF
0036      CPSTAR=CPTHEO*CPEF
0037      AK=ASTAR*32.174/CSAR
0038      PCP=(2./(GA+1.))*((GAM/(GA+1.))
0039      IF (PP/PC-1./PCR)/7.7,0
0040      7 FUDPE=SQRT(2.-(PP/PC)**((GAM-1.)/GAM)-1.)/(GA+1.)/(2.*(PP/PC)**
      1((GA-1.)/GAM)/(GA+1.))*((GAM+1.)/(2.*(GAM-1.)))
0041      GO TO 3
0042      8 FUDPE=1.
0043      9 AKP=APSTAR*32.174*FUDPE/CPSTAR
0044      KP=AKP*PP
0045      FUN5=SQRT((PJE-PC)/BKWF)+SQRT((PJD-PC)/BKWD)+AKP*PP-AK*PC
0046      4 FITRY(ICOUNT)=FUN5
0047      GO TO 4000
0048      2500 FUN5=0.
0049      CX=14.
0050      GO TO 4000
0051      3000 WRITE(6,3100)(PCTRY(I),FITRY(I),I=1,ICOUNT)
0052      3100 FORMAT(1H1,10X,29H      PC      FUN5,50(1,2E15.8))
0053      4000 RETURN
0054      END

```

P

FIGURE 4m

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Report No. E-894

IBM 704 INPUT FORM
FORM TMC A1545

JOB NO. P 4100	CUSTOMER	EXTENSION	DEPT.	CHARGE NO.	PAGE OF
JOB NAME PREIGNITER ROCKET ENGINE HYDRAULICS PROGRAM				ESTIMATED RUNNING TIME	EST. PAGES OF OUTPUT

TITLE						SEQUENCE
SAMPLE R-4D-1 ENGINE UNDER NOMINAL OPERATING CONDITIONS						1
KLO	KVO	KLF	KVF	KWO	KWF	2
0.9	455.2	0.2	970.6	755.8	4556.3	3
KLO	KIF	KBP	KBC	KDF	KMP	4
1.1679.4	9040.1.7	62860.1.9	1.6948.9	3600.1	640.1	5
P NOMINAL Z NOMINAL GAMMA						6a
97.0	170.	1.12				6b
IMAX = NO. OF PAIRS IN TABLE BELOW; ICASE = NO. OF RUNS WITH SIMILAR INPUT (SEE BOTTOM)						6c
C* VS. C/F TABLE IN PAIRS (20 MAXIMUM) OF FIRST AND MONOTONICALLY INCREASING						etc
0.0	4.019.0	1.0	5389.0	1.4	5663.0	7
1.6	5706.0	2.0	5656.0	2.5	5777.0	8
3.0	5303.0	3.5	5135.0	4.0	4786.0	
5.0	4717.0	20.0	682.0			
A* CHAMBER A* PREIGNITER Z* CHAMBER Z* PREIGNITER PTD. DTE						
.5915	.0762	.924	.7	170.	170.	
IF USE = 1 CASE OF SAME NUMBER WILL BE EXECUTED						
1 3 4 5						
1 10 20 30 40 50 60 70 72						
INPUT ICASE (NUMBER) LOTS OF THESE CARDS BEFORE LOOPING BACK TO TITLE						

Merguardt
 VAN NUYS, CALIFORNIA
 Part No. 0-001

SAMPLE R-4D-1 ENGINE UNDER NOMINAL OPERATING CONDITIONS

KLE = 0.0 KLF = 0.0
 KVD = 455.2 KVF = 970.6
 KWD = 755.3 KID = 11879.4 KIF = 190401.7 NWF = 4556.3
 KMD = 640.1 KBP = 62860.9
 KBC = 16948.9
 KDE = 3600.1

NOMINAL CHAMBER PRESSURE = 97.000
 NOMINAL TANK PRESSURE = 170.000
 GAMMA = 1.200

C/F	C*THEO
0.0	4010.0
1.000	5389.0
1.400	5663.0
1.600	5706.0
2.000	5656.0
2.500	5477.0
3.000	5303.0
3.500	5135.0
4.000	4986.0
5.000	4717.0
20.000	682.0

PERFORMER ROCKET ENGINE HYDRAULICS PROGRAM OUTPUT

The
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 CORPORATION

VAN NUYS CALIFORNIA

Report No. S-894

CASE 1 RESULTS - NOTHING LIT, DELAY PASSAGE NOT FULL

PTD =	170.000	PTF =	170.000
PSD =	170.000	PSF =	170.000
PJD =	87.284	PJF =	132.396

PEO=PDF=PP=PC = 0

WTD =	0.42626	WTF =	0.19683
WMD =	0.33983	WME =	0.17041
WID =	0.08645	WIF =	0.02637

U/F = 2.16569 S/EP = 3.27838

CASE 3 RESULTS - PREIGNITER LIT AND CHOKED, CHAMBER NOT LIT BUT CHOKED, DELAY PASSAGE NOT FULL

PTD = 170.000
PSD = 170.000
PJQ = 101.467

PTF = 170.000
PSF = 170.000
PJF = 137.419

PP = 77.643

PCD=PDF=PC= 12.628

WTD = 0.38801
WMD = 0.34285
WID = 0.04517

WT = 0.57123
WP = 0.06288

WTF = 0.18321
WMF = 0.16550
WIF = 0.01772

O/F = 2.11781

O/FP = 2.54903

CP*IBED = 5459.7

CP*EFF = 0.7000

CP* = 3821.8

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FIGURE 6c

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CASE 4 RESULTS - PREIGNITER LIT AND CHOKED, CHAMBER NOT LIT BUT CHOKED, DELAY PASSAGE FULL

PTD =	170.000		PTF =	170.000	
PSD =	170.000		PSF =	170.000	
PJU =	120.256		PJF =	143.063	
PDU =	62.673	ap =	85.498	PDJ =	41.631
		PC =	13.905		
WTD =	0.33057	WT =	0.4017	WTF =	0.16659
WML =	0.27602			WMP =	0.14920
WID =	0.05455	WP =	0.07194	WIF =	0.01739
				WBP =	0.02100
				WBC =	0.04045
				WDF =	0.08776
O/F =	1.98433	O/FP =	3.13742		
CP*THEO =	5254.9	CP*EFF =	0.7000	CP* =	3678.5

CASE 5 RESULTS - STEADY STATE FIRING, CHAMBER CHOKED, PREIGNITER LIT BUT UNCHOKED

ASTAR = 0.59150 C*THEU = 5645.0 C*EFF = 0.9240 C* = 5216.0
 APSTAR = 0.09620 CP*THEU = 5153.0 CP*EFF = 0.7000 CP* = 3607.1

PTU = 170.000 PTF = 170.000
 PSD = 170.000 PSF = 170.000
 PDU = 118.748 PDU = 144.367 PUF = 158.742 PDF = 109.864

PP = 111.337

PC = 97.050

WTD = 0.23730 WT = 0.35418 WTF = 0.11688
 WMD = 0.18411 WID = 0.09318 WMF = 0.10143
 WIF = 0.01544
 WBP = 0.01428
 WBC = 0.02750
 WDF = 0.05966
 WP = 0.06846

O/F = 2.0304

O/FP = 3.4437

Where:

$$\dot{w} = AC_d \sqrt{\rho \Delta P} \quad (27)$$

$\dot{w}$ = flow rate
 A = flow area
 C_d = discharge coefficient
 ρ = density
 ΔP = pressure drop

Equation (27) can be written as:

$$\Delta P = K \dot{w}^2 \quad (28)$$

Where:

K = flow resistance.

Substitution of equation (27) into equation (15) and simplifying the fact that:

$$D \propto A^{1/2} \quad (29)$$

Where:

D = orifice diameter

The relationship:

$$D = \frac{1}{K^{1/2}} \quad (30)$$

is obtained, assuming constant C_d and ρ .

Written another way:

$$D_{\text{actual}} = D_{\text{nominal}} \left(\frac{K_{\text{nominal}}}{K_{\text{actual}}} \right)^{1/2} \quad (31)$$

Figure 7 is a tabulation of the results for the five different coolant flow configurations that have been selected for testing. These configuration involve combinations of zero and 50% of nominal chamber wall coolant and zero preigniter wall coolant. The desired hole sizes and inlet pressures are given.

ORIFICE DIAMETERS & INLET PRESSURES FOR REDUCED FUEL COOLING CONFIGURATIONS

Configuration No.	O/F	Chamber Pressure (psia)	Chamber Cooling % of Nom.	Preigniter Cooling % of Nom.	Chamber Cool.Hole Diameter (inches)	Preigniter Hole #1 Diameter (inches)	Preigniter Holes #2-8 Diameter (inches)	Oxidizer Tank Pressure (psia)	Fuel Tank Pressure (psia)
1	2.03	97	100	100	0.01865	0.0201	0.0100	170	170
2	2.03	97	0	100	0.0	0.1777	0.00884	170	180
3	2.03	97	100	0	0.01645	0.0	0.0	170	172
4	2.03	97	50	100	0.01229	0.01864	0.00927	170	173
5	2.03	97	0	0	0.0	0.0	0.0	170	179

B. Steady State Performance

An analysis was conducted to determine the effects of reduced film cooling on the performance of the R-4D rocket engine. A computer program was written to determine rocket engine performance taking into consideration the variation in O/F ratio across the combustion chamber. To implement the program, the injector face is divided into areas in which the propellant jets mix together upon ejection. The propellant emitted from each of the areas is assumed to expand isentropically out its own nozzle within a streamtube which does not mix with the other streamtubes.

The propellant flow rate in each streamtube is assumed to be proportional to the total orifice area included by the tube. Specific injector hydraulics are considered by inputting discharge coefficients and pressure drops across each injector orifice. The equivalent I_{sp} of each streamtube is determined after calculating the O/F ratios of the tubes. The equivalent I_{sp} is interpolated from I_{sp} vs. O/F data which is input into the program for the appropriate propellants, chamber pressure, chemical kinetics, and area ratio.

The total I_{sp} is determined by mass flow averaging as follows:

$$I_{sp} = \frac{\sum_{i=1}^n W(i) I_{sp}(i)}{W_T} \quad (32)$$

Where:

$I_{sp}(i)$ = equivalent I_{sp} of streamtube i

$W(i)$ = propellant flow rate of streamtube i

W_T = total propellant flow rate

This expression is a linearization of a more exact expression which takes into account the effect of the variation in the specific heat ratio between streamtubes. It has been shown in Reference 1 that this linearization introduces no significant inaccuracies.

A complete listing of the Steady State Performance Program is shown in Figure 8.

The program was applied to the R-4D engine burning N_2O_4/MMH . A chamber pressure of 100 psia was assumed, and an expansion ratio of 40/1 was used. Shifting equilibrium was assumed to the throat with frozen flow from the throat to the nozzle exit. The injector face of the R-4D engine was divided into three streamtube areas, one including the chamber cooling orifices, another the preigniter, and the other the doublets and preigniter cooling orifices. An I_{sp} efficiency of 100% was assumed for the chamber cooling, 100% for the doublets, and 90% for the preigniter. The I_{sp}

STEADY STATE PERFORMANCE PROGRAM LISTING

```

0001      C ISP CONSIDERING C-F DISTRIBUTION
          DIMENSION D(20,2,90),A(20,2),W(20,2),CF(20),RISP(50),DF1(50),
          1AREA(2),ETISP(20),CEFF(20),XMAX(20,2),CD(20,2,90),DELTAP(20,2,90),
          2OVCF(20)
0002      READ (5,102) MAX
0003      102 FORMAT (I3)
0004      READ (5,101) (OVCF(L),L=1,MAX)
0005      101 FORMAT (6F12.8)
0006      READ (5,100) IMAX,N,WDCIT
0007      100 FORMAT(2I3,2E12.8)
0008      DO 180 L=1,MAX
0009      OET=OVCF(L)
0010      WRITE (6,135) IMAX,N,WDCIT,OET
0011      135 FORMAT (1H1,14X,21HNO. OF STREAMTUPES = ,I2,12X,
          121HNO. OF DATA POINTS = ,I2/14X,18HTOTAL FLOW RATE = ,F8.4,9X,
          214HOVERALL C/F = ,F5.3//)
0012      READ (5,119) ((KMAX(I,J),I=1,IMAX),J=1,2)
0013      119 FORMAT (24I3)
0014      DO 120 I=1,IMAX
0015      DO 120 J=1,2
0016      KK=KMAX(I,J)
0017      DO 120 K=1,KK
0018      120 READ (5,121) D(I,J,K),CD(I,J,K),DELTAP(I,J,K)
0019      121 FORMAT (6E12.8)
0020      C CALCULATE THE TOTAL AREA OF J HOLES IN STREAMTUP I
          DO 122 I=1,IMAX
0021      DO 122 J=1,2
0022      122 A(I,J)=0.0
          DO 123 I=1,IMAX
0023      DO 123 J=1,2
0024      IF (KMAX(I,J).NE.0)KK=KMAX(I,J)
0025      IF (KMAX(I,J).EQ.0)KK=1
0026      DO 123 K=1,KK
0027      123 A(I,J)=A(I,J)+.7854*CD(I,J,K)*SQRT(DELTAP(I,J,K))*10(I,J,K)**2
0028      C CALCULATE TOTAL ORIFICE AREA
          DO 115 J=1,2
0029      115 AREA(J)=0.0
0030      DO 103 J=1,2
0031      103

```

```

0032      DO 103 I=1,IMAX
0033      103 AREA(J)=AREA(J)+A(I,J)
0034      WDOT1=WDOTT*(OFT/(1.0+OFT))
0035      WDOT2=WDOTT/(1.0+OFT)
      C CALCULATE W(I,J)
0036      DO 104 I=1,IMAX
0037      104 W(I,1)=A(I,1)*WDOT1/AREA(1)
0038      DO 105 I=1,IMAX
0039      105 W(I,2)=A(I,2)*WDOT2/AREA(2)
      C CALCULATE OXIDIZER-FUEL RATIOS
0040      DO 107 I=1,IMAX
0041      OF(I)=W(I,1)/W(I,2)
0042      107 CONTINUE
0043      READ(5,109) (OF1(I),RISP(I),I=1,N)
0044      109 FORMAT (6E12.8)
0045      DO 110 I=1,IMAX
0046      FIISP(I)=ENTRP(OF1,RISP,CF(I),N,1)
0047      110 CONTINUE
0048      READ(5,112) (CEFF(I),I=1,IMAX)
0049      112 FORMAT(6E12.8)
      C CALCULATE TOTAL ISP
0050      TISP=0.0
0051      DO 113 I=1,IMAX
0052      113 TISP=TISP+((W(I,1)+W(I,2))*FIISP(I)*CEFF(I))/WDOTT
0053      WRITE (6,136)
0054      136 FORMAT (20X,9HINPUT C/F,23X,9HINPUT ISP/)
0055      WRITE (6,137) (OF1(I),RISP(I),I=1,N)
0056      137 FORMAT (21X,F6.3,31X,F6.2//)
0057      DO 146 I=1,IMAX
0058      WRITE (6,138) I
0059      138 FORMAT (1H1,1X,11HSTREAMTUBE ,I2)
0060      WRITE (6,139) KMAX(I,1),KMAX(I,2)
0061      139 FORMAT (12X,24HNO. OF OXIDIZER HOLES = ,I2,
        15X,24HNO. OF FUEL HOLES = ,I2/)
0062      WRITE (6,140)
0063      140 FORMAT (10X,1HK,10X,25HDIAMETER OF OXIDIZER HOLE,10X,
        12HDISCHARGE COEFFICIENT,10X,7HDELTA P)
0064      KS=KMAX(I,1)

```

FORTRAN IV C LEVEL C, MOD 0

MAIN

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```

0065      DO 141 K=1,KS
0066      141 WRITE (6,142) K,D(I,1,K),CD(I,1,K),DELTAP(I,1,K)
0067      142 FORMAT (9X,I2,19X,F6.5,26X,F6.4,19X,F6.2)
0068      WRITE (6,143)
0069      143 FORMAT (/,10X,14X,12X,2X,HDIAMETER OF FUEL HOLES)
0070      KT=KMAX(I,2)
0071      DO 144 K=1,K1
0072      144 WRITE (6,145) K,D(I,2,K),CD(I,2,K),DELTAP(I,2,K)
0073      145 FORMAT (9X,I2,19X,F6.5,26X,F6.4,19X,F6.2)
0074      146 CONTINUE
0075      WRITE (6,129)
0076      129 FORMAT (1H1,8X,8H1      ,12HGF(I)      ,
      121HFQUIV. ISP (I)      ,19HGX. FLOW (I)      ,
      220HFUEL FLOW (I)      ,18HISP. EFFICIENCY (I))
0077      WRITE (6,130) (I,GF(I),FIISP(I),W(I,1),W(I,2),CEFF(I),I=1,IMAX)
0078      130 FORMAT (7X,I2,6X,F6.3,11X,F6.2,13X,F8.4,11X,F8.4,16X,F5.3//)
0079      WRITE (6,131) TISP
0080      131 FORMAT (23X,35HISP CONSIDERING O/F DISTRIBUTION = ,F6.2)
0081      140 CONTINUE
0082      STOP
0083      END

```

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FIGURE 8c

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Report No. S-894

due to main chamber cooling flow was primarily a result of the fuel (monomethylhydrazine) decomposing to more elemental molecules, i.e., CH_4 , N_2 , H_2 . The I_{sp} due to the doublets and the preigniter cooling flows was assumed to be normal combustion with the oxidizer (nitrogen tetroxide). The I_{sp} due to the preigniter is also assumed to be normal combustion with the oxidizer.

A sample of the computer output is shown in Figure 9.

Figure 10 shows the resultant calculated engine I_{sp} vs. O/F for various film cooling flows (measured in percent of total fuel flow) for the R-4D engine. Specific predictions of I_{sp} were made for the anticipated test configurations. These predictions which are for an overall O/F ratio of 2.03 and a total flow rate of .354 pounds per second are given below.

STEADY STATE I_{sp} FOR REDUCED FILM COOLING CONFIGURATIONS

CONFIGURATION NO	I_{sp} (SEC)	DESCRIPTION
1	280	Nominal
2	298	No chamber cooling
3	283	No preigniter cooling
4	289	50% chamber cooling - 100% preigniter cooling
5	299	No chamber cooling - no preigniter cooling

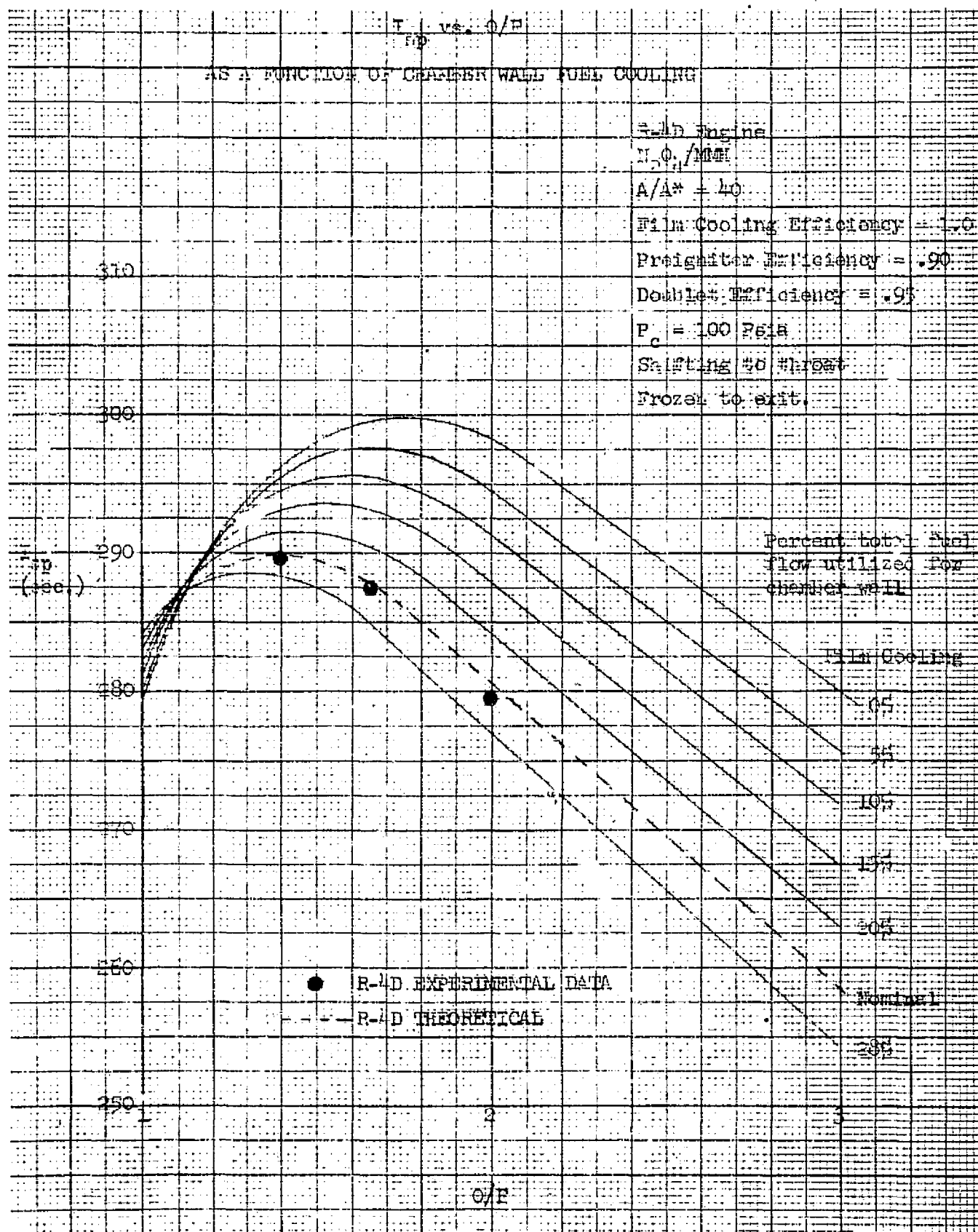
STEADY STATE PERFORMANCE PROGRAM OUTPUT

		Theoretical				
		O/F (I)	Equiv. Isp (I)	Ox. Flow (I)	Fuel Flow (I)	Isp Efficiency (I)
Chamber Cooling	I = 1	0.0	221.77	0.0	0.0	1.000
Doublets	I = 2	1.991	319.56	0.1844	0.0926	0.950
Preigniter	I = 3	2.181	316.08	0.0513	0.0242	0.900

Isp considering O/F distribution = 299.42

CONDITIONS:

1. H_2O_2 /1MH
2. O/F = 2.03
3. No film cooling (Configuration 5)



C. Steady State Firing Thermal Characteristics

An analysis was conducted to better define the effects of film cooling on the thermal characteristics of the R-4D rocket engine. Steady state and soakback temperatures for various parts of the engine were determined as functions of percent combustor wall fuel cooling. Changes in preigniter cooling flow primarily result in potentially damaging preigniter temperatures. This possibility was analyzed as part of the Severe Off-Limits Evaluation Task and is discussed in TMC report S-899. The effects of preigniter cooling flow changes on injector head temperatures is secondary and has not been included in the present analysis.

The analysis was carried out using the Marquardt Thermal Analyzer Computer Program, with effective film temperatures predicted from the Film Cooling Computer Program. The Thermal Analyzer program solves the appropriate heat transfer equations at specified locations (nodes) in the engine by a finite difference technique.

From an energy balance of each node:

$$C_K \frac{dT}{d\theta} = \sum_{j=1}^n T_j A_{j-k} - T_k \sum_{j=1}^n A_{j-k} \quad (33)$$

Or in finite difference notation:

$$\frac{T_{\theta+\Delta\theta} - T_{\theta}}{\Delta\theta} = \frac{1}{C_K} \left\{ \sum_{j=1}^n T_j A_{j-k} - T_k \sum_{j=1}^n A_{j-k} \right\} \quad (34)$$

Where:

C_K = thermal capacity of node K
 T_{θ} = temperature of node at time θ
 $T_{\theta+\Delta\theta}$ = temperature after time interval $\Delta\theta$
 A_{j-k} = reciprocal of thermal resistance for conduction, convection, or radiation between the node sought and an adjacent node J

Figures 11, 12, 13, and 14 show the engine configuration and the thermal networks used in the analysis.

Experimental data obtained from qualification and acceptance tests of R-4D engines were incorporated into the computer model to provide an accurate simulation of the engine. These data, for example, include the heat flux from the gases to the injector head face (0.92 Btu/sec for a 70°F face temperature).

Heat transfer coefficients for the combustion gases were obtained using the modified Bartz equation which follows:

$$h_{cg} = \frac{0.026}{(D^*)^{.2}} \frac{\mu_f^{.2}}{(Pr_f)^{.6}} \left(\frac{W}{A^*} \right)^{.8} \left(\frac{A^*}{A} \right)^{.9} \left(\frac{H_R - H_W}{T_R - T_W} \right) \sigma \quad (35)$$

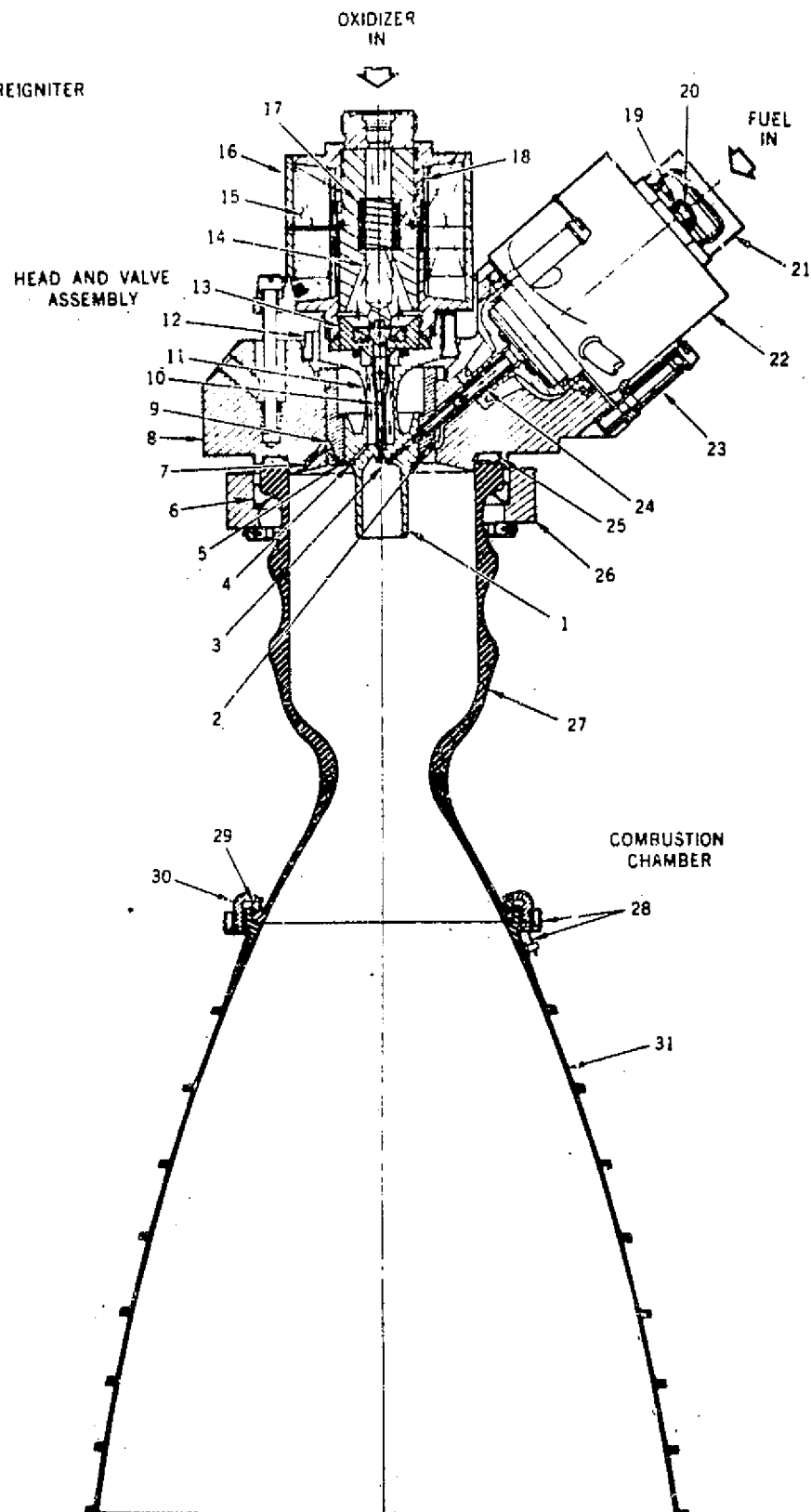
Where:

h_{cg} = heat transfer coefficient
 D = diameter
 Pr = Prandtl number
 μ = viscosity
 W = propellant flow rate
 A = flow area
 σ = correction factor
 H = enthalpy of gas
 T = temperature
 $*$ = throat conditions
 f = film
 R = recovery
 w = wall

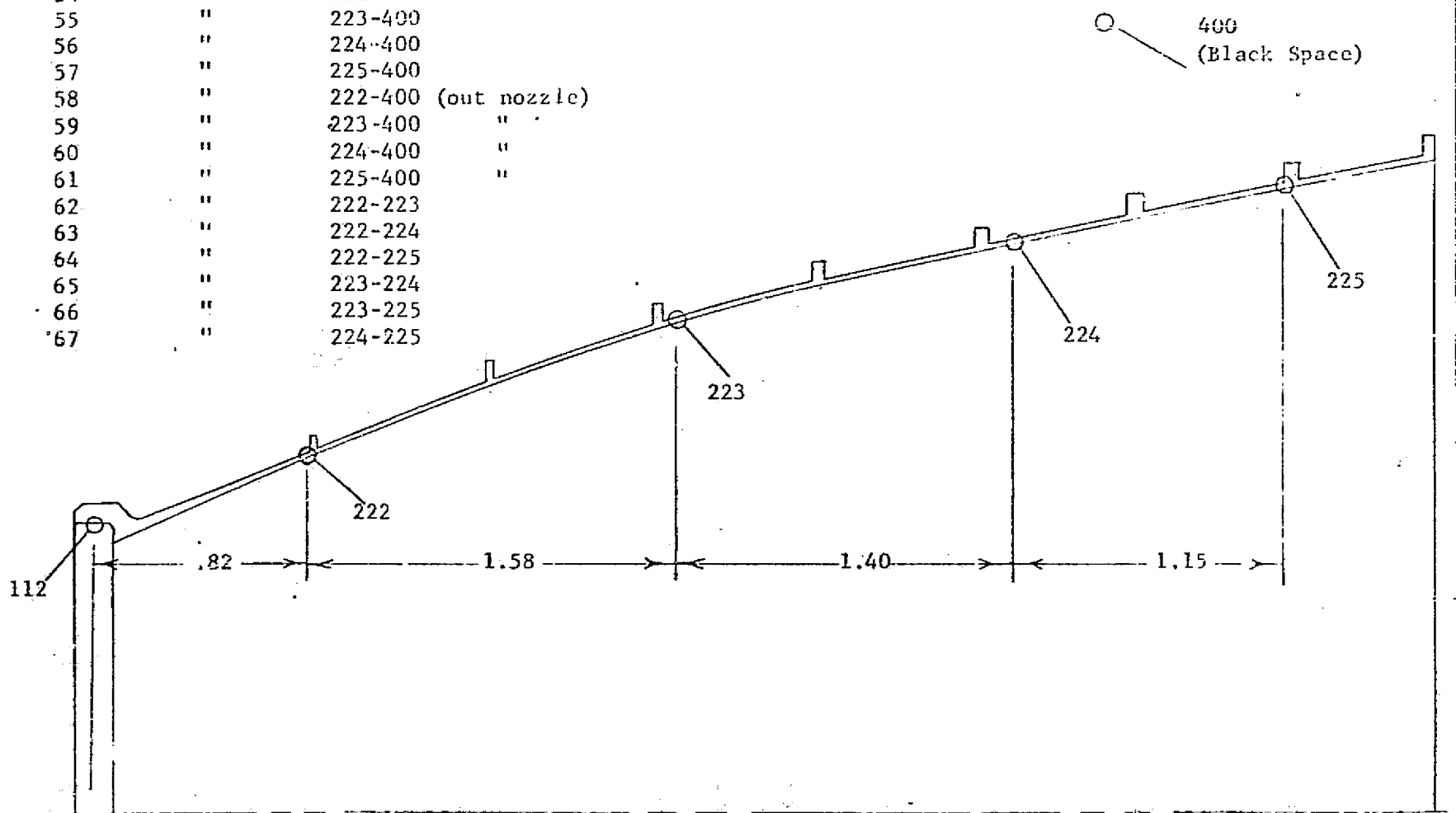
ROCKET ENGINE DIAGRAM

LEGEND

- 1 PREIGNITER
- 2 INTERMEDIATE MIDDLE RING EIGHT PREIGNITER FUEL COOLING ORIFICES
- 3 PREIGNITER CHAMBER ORIFICES
- 4 INNERMOST RING EIGHT PRIMARY OXIDIZER ORIFICES
- 5 MIDDLE RING EIGHT PRIMARY FUEL ORIFICES
- 6 SPLIT RING
- 7 OUTERMOST RING EIGHT CHAMBER WALL FUEL COOLING ORIFICES
- 8 INJECTOR HEAD ASSEMBLY
- 9 ANNULUS
- 10 OXIDIZER PREIGNITER TUBE
- 11 INSERT ASSEMBLY
- 12 INSULATOR
- 13 SEAT ASSEMBLY
- 14 ARMATURE
- 15 DIRECT COIL
- 16 OXIDIZER VALVE ASSEMBLY
- 17 SPRING
- 18 AUTOMATIC COIL
- 19 FUEL ORIFICE
- 20 RETAINING RING
- 21 CAP
- 22 FUEL VALVE ASSEMBLY
- 23 SPACER
- 24 FUEL PREIGNITER TUBE
- 25 COMBUSTION CHAMBER SEAL
- 26 ATTACH RING
- 27 COMBUSTOR
- 28 LOCK RING
- 29 WASHER
- 30 ATTACH NUT
- 31 BELL



RESISTOR	TYPE	CONNECTING
14	Conduction	112-222
15	"	222-223
16	"	223-224
17	"	224-225
29	Convection	112-312 (gas node)
30	"	222-322 " "
31	"	223-323 " "
32	"	224-324 " "
33	"	225-325 " "
53	Radiation	112-400
54	"	222-400
55	"	223-400
56	"	224-400
57	"	225-400
58	"	222-400 (out nozzle)
59	"	223-400 " "
60	"	224-400 " "
61	"	225-400 " "
62	"	222-223
63	"	222-224
64	"	222-225
65	"	223-224
66	"	223-225
67	"	224-225



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BELL - R-4D ENGINE: HEAT TRANSFER NODES

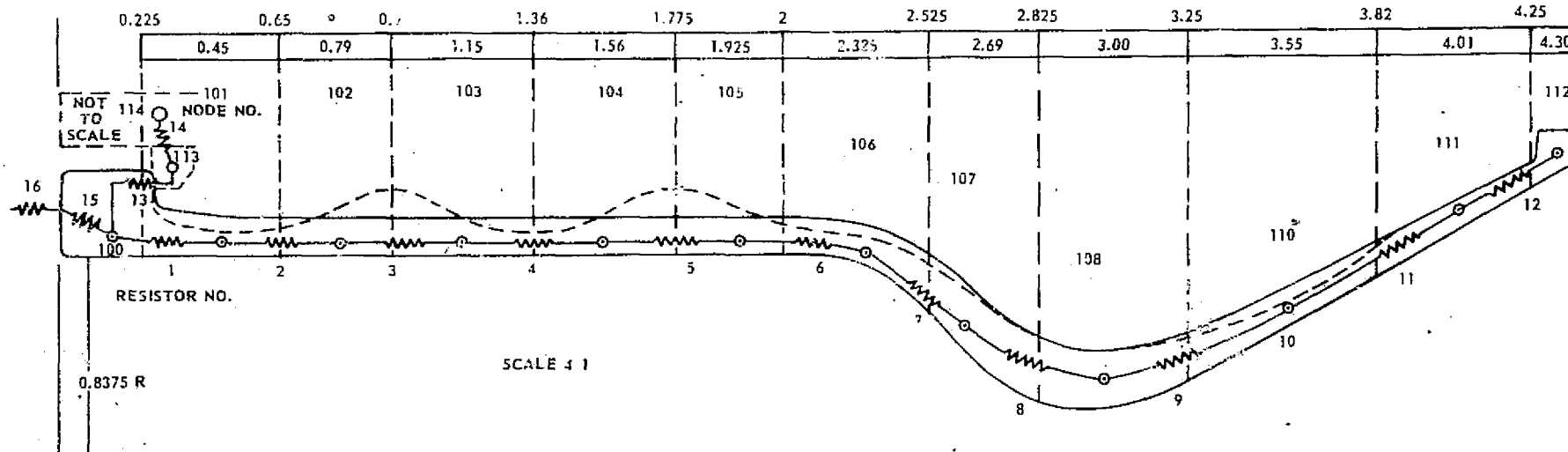
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FIGURE 12

COMBUSTOR HEAT TRANSFER NODES

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DISTANCE OF NODE FROM END OF CHAMBER (IN)



41

FIGURE 13

RESISTOR	NODES	LENGTH (IN.)		AREA (IN. ²)	
		STRAIGHT WALL	WAVE SHAPED WALL	STRAIGHT WALL	WAVE SHAPED WALL
1	100 - 101	0.3085	0.3085	0.770	0.615
2	101 - 102	0.3375	0.3375	0.589	0.546
3	102 - 103	0.3660	0.3660	0.589	0.745
4	103 - 104	0.4040	0.4040	0.589	0.700
5	104 - 105	0.4055	0.4055	0.589	0.733
6	105 - 106	0.3665	0.3665	0.589	0.610
7	106 - 107	0.3500	0.2940	0.617	0.565
8	107 - 108	0.4650	0.4130	0.522	0.557
9	108 - 110		0.527		0.387
10					
11	110 - 111	0.4520	0.3885	0.323	0.303
12	111 - 112	0.3250	0.2835	0.408	0.383
13	101 - 113	ADMITTANCE 0.00113 BTU SEC °F			
14	113 - 114	ADMITTANCE 0.00082 BTU SEC °F			
15		LENGTH 0.137 IN.		AREA 1.47 IN. ²	
16		ADMITTANCE 0.001 BTU SEC °F			

NODE	VOLUME (IN. ³)		INSIDE SURFACE AREA (IN. ²)		OUTSIDE SURFACE AREA (IN. ²)	
	STRAIGHT WALL	WAVE SHAPED WALL	STRAIGHT WALL	WAVE SHAPED WALL	STRAIGHT WALL	WAVE SHAPED WALL
100	0.338	0.338	1.2	1.205		
101	0.266	0.208	2.235	2.235	2.08	2.05
102	0.200	0.252	1.89	1.89	2.11	2.31
103	0.231	0.279	2.18	2.18	2.43	2.67
104	0.245	0.286	2.31	2.31	2.57	2.75
105	0.1741	0.2553	1.77	1.77	2.00	2.11
106	0.3209	0.2425	2.615	2.615	2.867	2.577
107	0.225	0.209	1.449	1.449	1.792	1.322
108	0.230	0.213	1.306	1.306	1.691	1.871
110	0.241	0.155	2.68	2.68	2.89	2.85
111	0.145	0.145	3.05	3.05	3.10	3.18
112	0.121	0.121	1.04	1.04	(INCLUDING END) 2.23	(INCLUDING END) 2.23
TOTAL	2.738 IN. ³	2.728 IN. ³	23.730 IN. ²	23.730 IN. ²	25.77 IN. ²	26.42 IN. ²
113	CAPACITY 0.0073 BTU °F					
114	CAPACITY 0.342 BTU °F					

NOTE: VALUES OF RESISTORS 13, 14, 16 AND NODES 113 AND 114 OBTAINED FROM IM 153-75-31
VALUES FOR WAVE SHAPED WALL OBTAINED FROM THERMAL SEAL PROGRAM WORK BY C. HILL

4/6/69-3

APOLLO R-4D INJECTOR HEAD HARDWARE THERMAL NETWORK

NODE	CAPACITY - BTU °F
1	1.47×10^{-3}
2	3.19×10^{-3}
3	4.95×10^{-3}
4	4.95×10^{-3}
5	3.19×10^{-3}
6	4.87×10^{-3}
7	4.87×10^{-3}

NOTE:

RESISTANCES IN SEC. °F BTU

NODE 8 IS THE PROPELLANTS,
ASSUMED TO BE A CONSTANT
TEMPERATURE HEAT SINK.

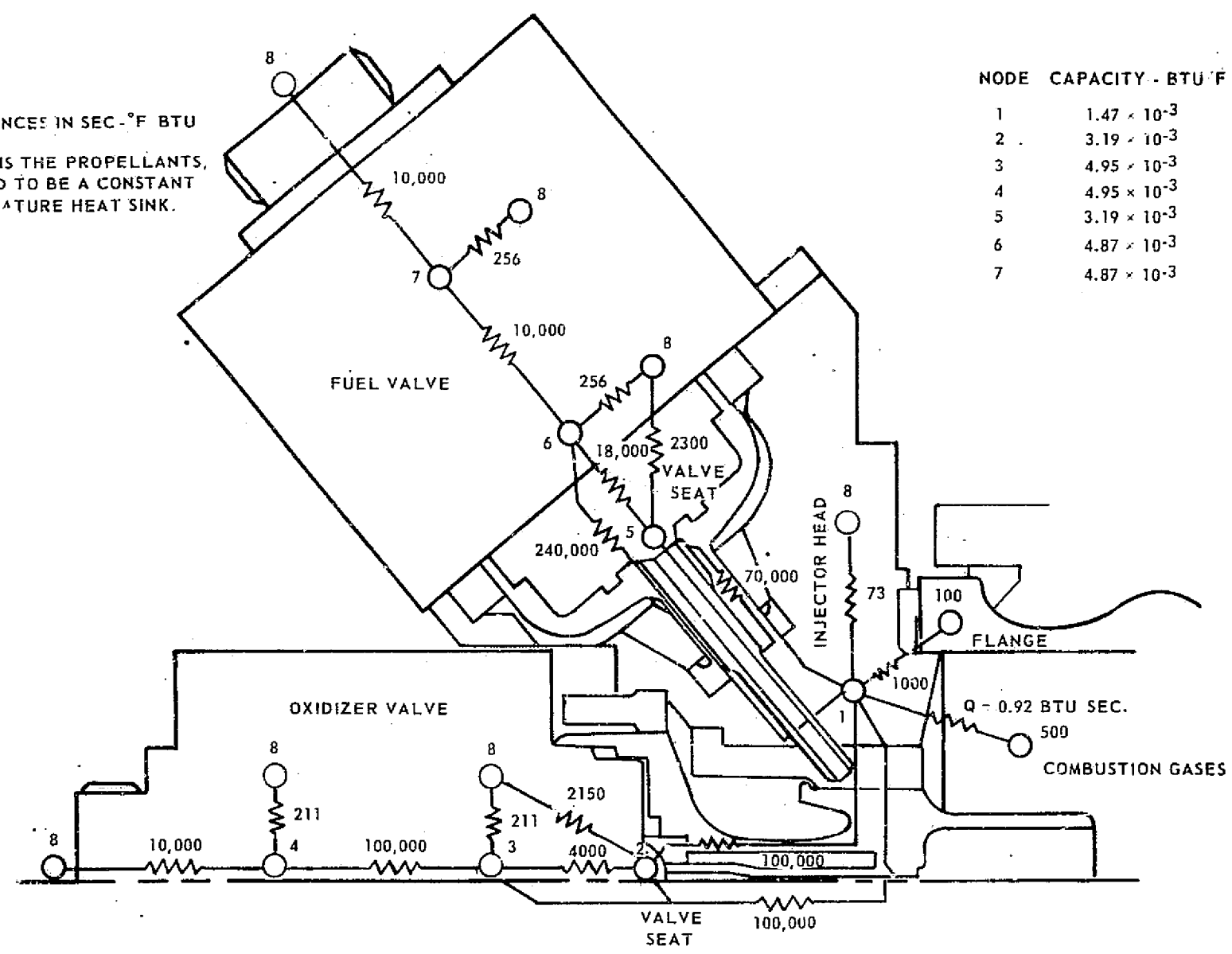
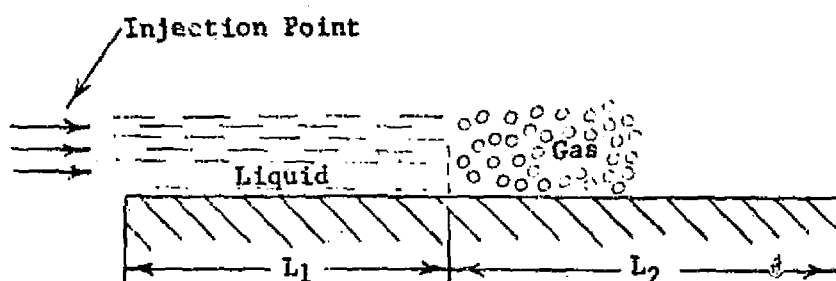


Figure 15 is a plot which shows the resultant convective heat transfer coefficient in the combustor and expansion bell as a function of axial distance from the injector face for the nominal R-4D engine.

The heat transfer from the combustion gases to the chamber and nozzle depends upon the gas temperature at the edge of the boundary layer as well as the heat transfer coefficient. These temperatures have been predicted using the Marquardt Film Cooling Program.

The chamber and nozzle are film cooled by the fuel which is injected along the walls of the chamber. The liquid layer cools a major portion of the chamber and the gaseous film cools the convergent section of the nozzle. The evaporative film cooling correlations have been derived for the simplified physical model shown below:



The equation for the length of the liquid portion of the film coolant is:

$$L_1 = C \left[\frac{W_{fc} C_{pL} (T_V - T_i)}{Ph_{cg} (T_R - T_V)} + \frac{W_{fc} \Delta H_v}{Ph_{cg} (T_R - T_V)} \right] \quad (36)$$

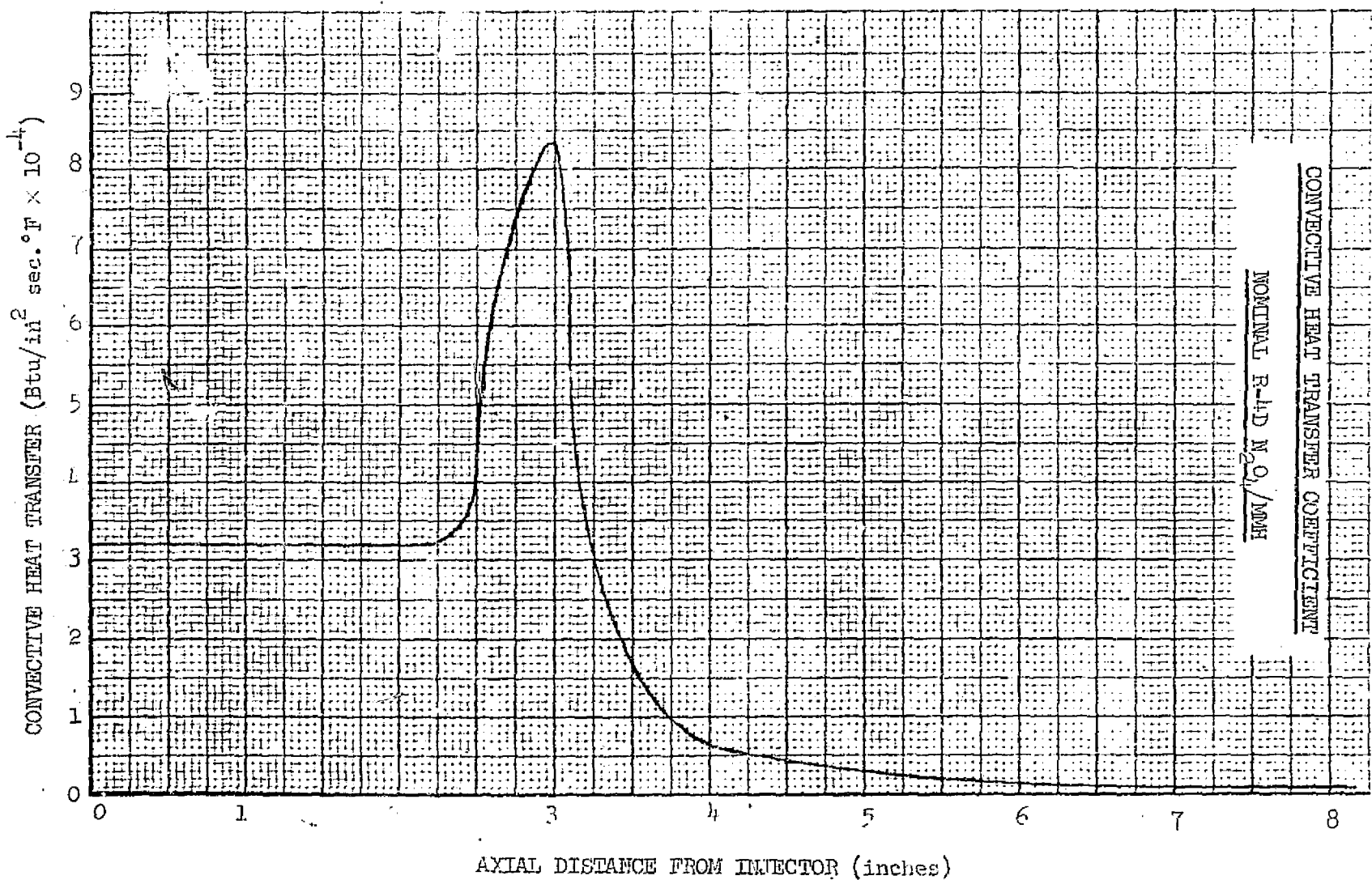
Where:

- C = mixing constant (1.0 - 1.5)
- W_{fc} = weight flow of coolant
- C_{pL} = Specific heat of coolant
- T = temperature
- P = chamber perimeter
- h_{cg} = heat transfer coefficient
- ΔH_v = heat of vaporization
- T_V = vapor temperature at saturation pressure.

Subscripts:

- R = recovery
- i = initial

At L_1 , the liquid film coolant is vaporized and is assumed to be saturated vapor. The equations used to predict the effective temperature in the gaseous region are shown below:



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FIGURE 15

$$\frac{T_R - T_{eff}}{T_R - T_v} = e^{-\left[\frac{h_{eff} A}{\phi C_{p_g} W_{fc}}\right]} \quad (37)$$

and,
$$\frac{1}{\phi} = \left(\frac{SV_g}{\alpha_c}\right)^{1/8} f\left(\frac{V_g}{V_c}\right) \quad (38)$$

For:
$$\frac{V_g}{V_c} \leq 1.0, \quad f\left(\frac{V_g}{V_c}\right) = \left(\frac{V_c}{V_g}\right)^{1.5} \left(\frac{V_c}{V_g} - 1\right) \quad (39)$$

For:
$$\frac{V_g}{V_c} > 1.0, \quad f\left(\frac{V_g}{V_c}\right) = 1 + 0.4 \tan^{-1} \left(\frac{V_g}{V_c} - 1\right) \quad (40)$$

Where:

- A = Interwall chamber surface area
- S = Film height
- V = velocity
- α = thermal diffusivity
- ϕ = efficiency factor
- C_{p_g} = constant pressure specific heat for a gas

Subscripts:

- g = gas
- c = coolant
- eff = effective

These equations were programmed for the IBM 360/40 to predict effective gas temperatures at various distances from the injector face. The typical program output for 35% fuel cooling is reproduced as Figure 16. Figure 17 shows the calculated effective gas temperatures vs. distance from the injector face for 5, 10, 15, 20, 25, and 30% chamber wall fuel cooling.

To more accurately model the thermal characteristics of the engine, the thermal conductivity and heat capacity of the molybdenum chamber were input into the thermal analyzer program as functions of temperature. These functions are presented here as Figure 18.

TYPICAL FILM COOLING PROGRAM OUTPUT

N2O4/MMH PC=100PSIA C#=95 PERCENT R-4 ENGINE

FILM COOLING PERCENT = 35.00 COOLANT FLOW RATE = 0.0402285

EFFECTIVE GAS TEMPERATURE (F)	FILM COEFFICIENT (BTU/IN ² -SEC-F)	VELOCITY OF CORE GAS (FT/SEC)	DISTANCE FROM INJECTOR FACE (IN)
92.4	0.000274	386.98	0.10
114.7	0.000274	387.00	0.20
136.8	0.000273	387.00	0.30
158.7	0.000272	387.00	0.40
180.4	0.000271	387.00	0.50
201.9	0.000270	387.00	0.60
223.3	0.000269	387.00	0.70
244.5	0.000268	387.00	0.80
265.5	0.000268	387.00	0.90
286.4	0.000267	387.00	1.00
295.0	0.000266	387.00	1.10
295.0	0.000266	387.00	1.20
295.0	0.000266	387.00	1.30
295.0	0.000266	387.00	1.40
295.0	0.000266	387.00	1.50
295.0	0.000266	387.00	1.60
295.0	0.000266	387.00	1.70
295.0	0.000266	387.00	1.80
295.0	0.000266	387.00	1.90
295.0	0.000266	387.00	2.00
295.0	0.000266	387.00	2.10
295.0	0.000266	387.00	2.20
295.0	0.000283	414.47	2.30
295.0	0.000301	445.31	2.40
295.0	0.000375	568.37	2.50
295.0	0.000481	752.86	2.60
295.0	0.000611	991.62	2.70
301.5	0.000802	1925.72	2.80
917.2	0.000882	2192.89	2.90
1206.1	0.000906	2550.55	3.00
1441.9	0.000759	3782.52	3.10
1640.5	0.000662	3943.41	3.20
1814.7	0.000531	4426.14	3.30
1975.4	0.000391	5689.97	3.40
2087.0	0.000303	6064.40	3.50
2171.0	0.000256	5882.65	3.60
2247.4	0.000219	5836.62	3.70
2318.0	0.000188	5912.60	3.80
2383.8	0.000162	6106.62	3.90
2446.0	0.000140	6422.78	4.00
2505.1	0.000121	6872.72	4.10

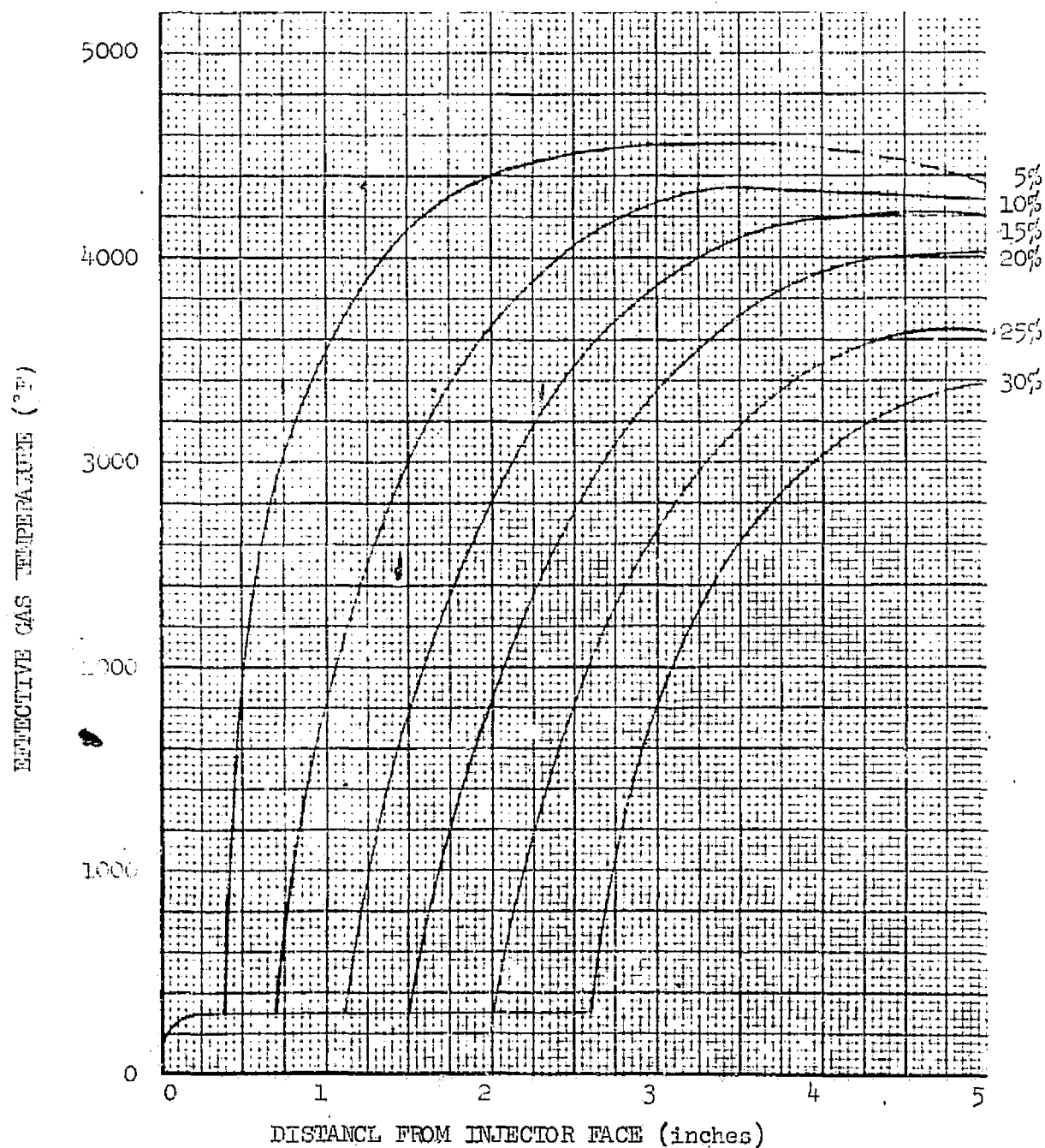
EFFECTIVE GAS TEMPERATURES

VS.

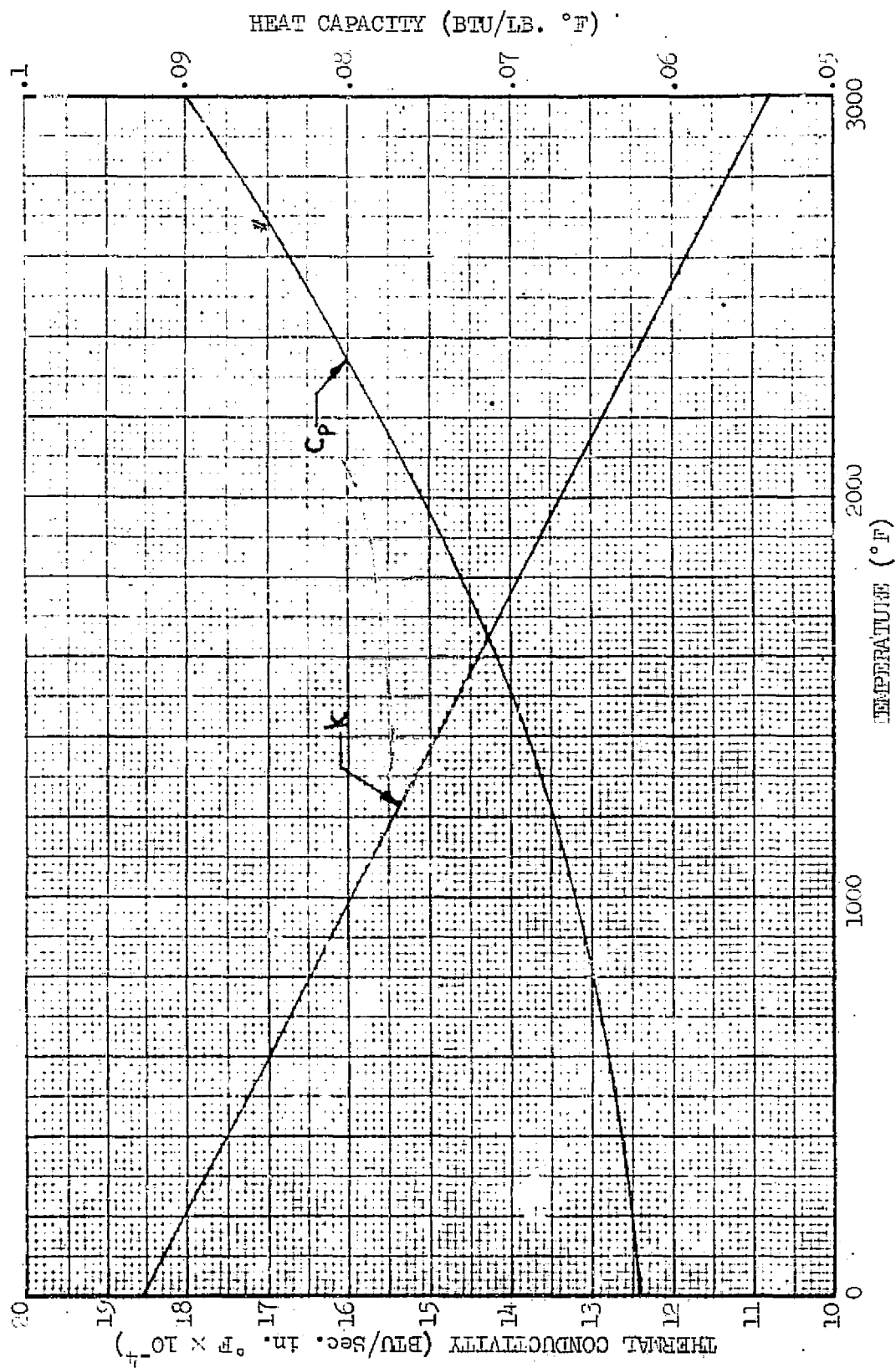
DISTANCE FROM INJECTOR FACE

R-4D Engine
O/F = 2.0
N₂O₂/MMH
C* = 95%

CHAMBER WALL
% OF TOTAL
FLOW



HEAT CAPACITY AND THERMAL CONDUCTIVITY OF MOLYBDENUM



For the fuel and oxidizer injector head passages, where the flow is laminar, transitional and turbulent, the heat transfer coefficients were found using Figure 19 which is reproduced from Reference 2. The heat transfer coefficients, the injector surface areas, and the calculated heat fluxes are shown in Figure 20.

The convective heat transfer coefficients inside the fuel and oxidizer valve passages were calculated using the standard correlation for turbulent flow which follows:

$$Nu = 0.023 Re^{.8} Pr^{.4} \quad (41)$$

Where:

Nu = Nusselt number
Pr = Prandtl number
Re = Reynolds number

The physical properties used in the calculations are shown below:

Oxidizer - N_2O_4 at 70°F

$C_p = 0.374$ Btu/lb°F
 $\mu = 0.00028$ lb/ft-sec.
 $k = 0.0755$ Btu/hr ft°F
 $\rho = 92.0$ lb/ft³

Fuel - MMH at 70°F

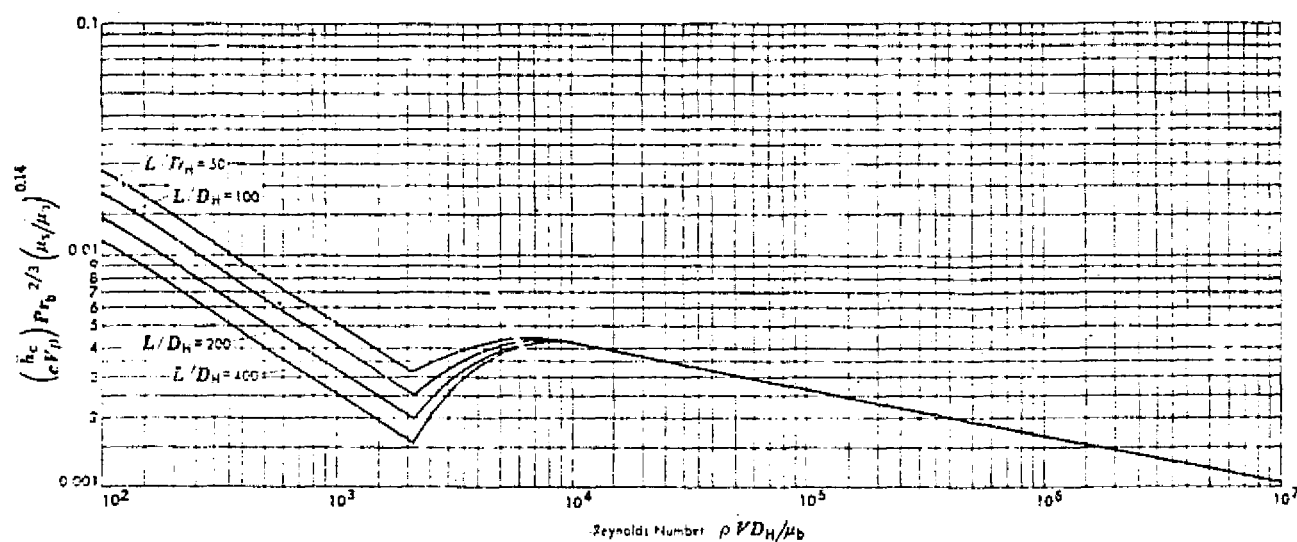
$C_p = 0.698$ Btu/lb°F
 $\mu = 0.000575$ lb/ft-sec.
 $k = 0.142$ Btu/hr ft°F
 $\rho = 54.86$ lb/ft³

Both steady state and transient thermal analyses were performed for varying amounts of film cooling. A tabular summary of the steady state results are shown in Figure 21 for 0, 5, 10, 15, 20, 25, and 30 percent chamber wall fuel cooling. The steady state throat and bell nut temperatures also are plotted in Figure 22. Figure 21 also shows maximum injector head and valve temperatures after a 100 second firing with 15 and 25 percent chamber wall fuel cooling. The 25 percent cooling represents essentially design point conditions for the R-4D engine. With only 15 percent cooling the biggest change is seen in the combustion chamber near the throat. The valve soakback temperatures are not appreciably different, but the injector soakback temperature is higher than desired. At less than 15 percent cooling, all temperatures become excessively high. With zero cooling, the throat temperature can be expected to exceed 3400°F.

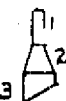
It has been shown that with no film cooling, it is possible that the combustion gas flow can be stratified by design to give a lower throat temperature than indicated with little or no loss in performance. A developmental engine with no film cooling and with optimized mixture ratio stratification has operated with high performance at a steady state throat temperature of 3000°F. A similar but non-optimized engine did operate with a throat temperature of 3400°F, in agreement with Figures 21 and 22.

During the conduct of the Task 2 testing with reduced cooling flow, the burn runs shall be restricted in time to avoid hardware damage.

RECOMMENDED CURVES
FOR
DETERMINING HEAT TRANSFER COEFFICIENT
IN THE
TRANSITION REGIME



CONVECTIVE HEAT TRANSFER COEFFICIENTS
FOR THE R-4D INJECTOR INSIDE PASSAGES

	Surface Area A-(in ²)	Reynolds No. *	Heat Transfer Coeff. h-(BTU/in ² -sec-°F)	hA BTU/sec-°F
Ox Standoff	0.680	13,200	1.98×10^{-3}	1.35×10^{-3}
Ox P.I. Tube Exit	0.0137	53,500	1.42×10^{-2}	1.95×10^{-4}
Ox Doublets	0.246	24,700	9.35×10^{-3}	2.30×10^{-3}
Fuel Doublets				
	(1) 0.0970	5,370	7.90×10^{-3}	7.66×10^{-4}
	(2) 0.0816	1,950	8.76×10^{-4}	7.15×10^{-5}
Fuel P.I. Tube				
	(1) 0.0141	14,100	1.78×10^{-2}	2.50×10^{-4}
	(2) 0.0289	7,000	1.22×10^{-2}	3.53×10^{-4}
	(3) 0.0300	443	6.65×10^{-3}	2.00×10^{-4}
Film Cooling Chamber				
	(1) 0.040	3,800	7.19×10^{-3}	2.87×10^{-4}
	(2) 0.368	1,575	1.39×10^{-3}	5.10×10^{-4}
Film Cooling P.I. Chamber				
	(1) 0.0125	4,400	1.57×10^{-2}	1.96×10^{-4}
	(1)**0.0032	8,800	3.91×10^{-3}	1.25×10^{-5}
	(2) 0.165	870	1.11×10^{-3}	1.83×10^{-4}
Fuel Manifold	1.0	9,330	6.21×10^{-3}	6.21×10^{-3}
Fuel Standoff	0.256	6,550	3.35×10^{-3}	8.55×10^{-4}
TOTAL OXIDIZER SURFACES				3.84×10^{-3}
TOTAL FUEL SURFACES				9.89×10^{-3}
TOTAL PROPELLANTS SURFACES				2.373×10^{-2}

* PROPERTIES at 70°F

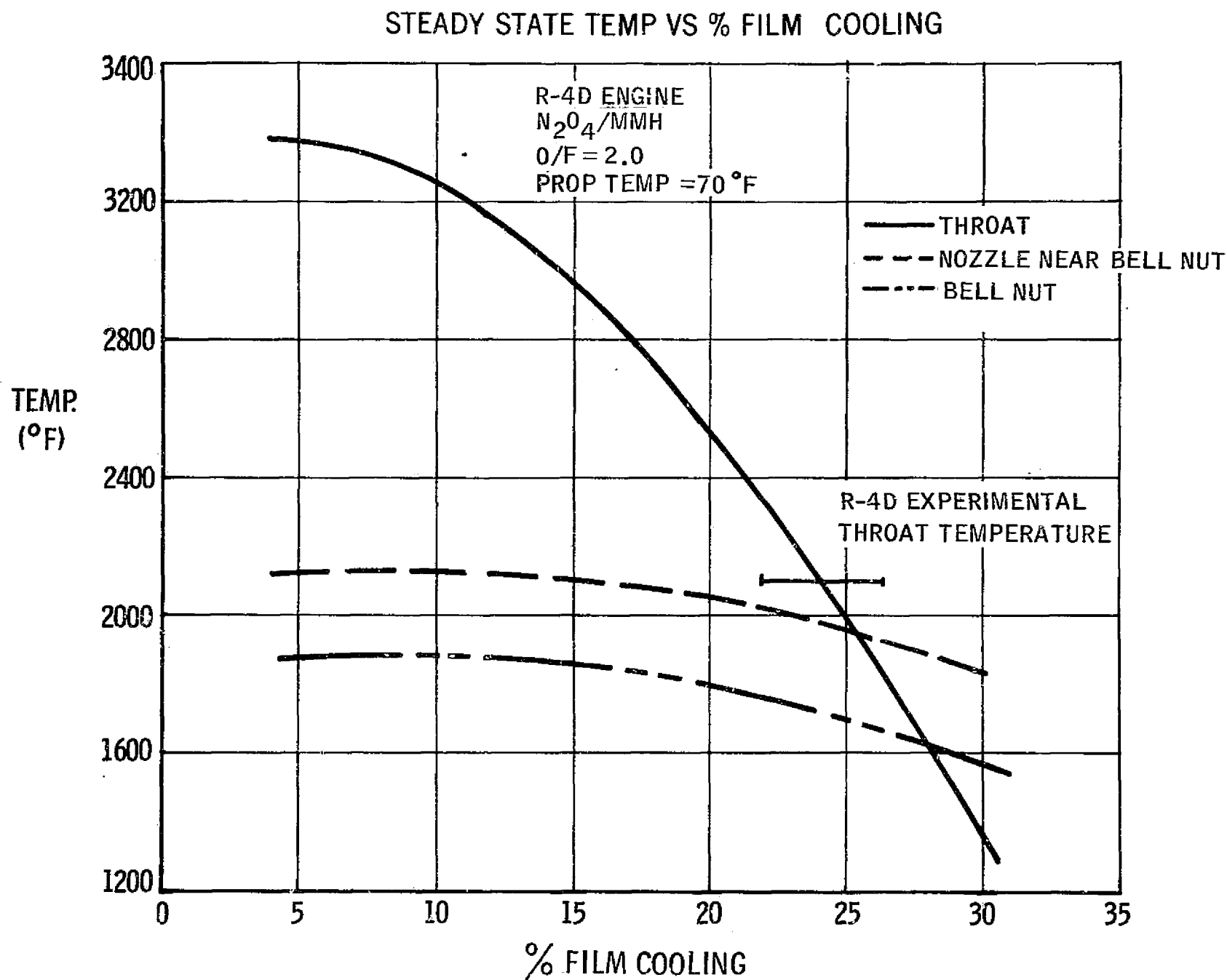
** ONE FILM COOLING HOLE FOR P.I. CHAMBER HAS LARGER DIAMETER.

SUMMARY OF R-4D TEMPERATURES
AS A FUNCTION OF CHAMBER WALL COOLING

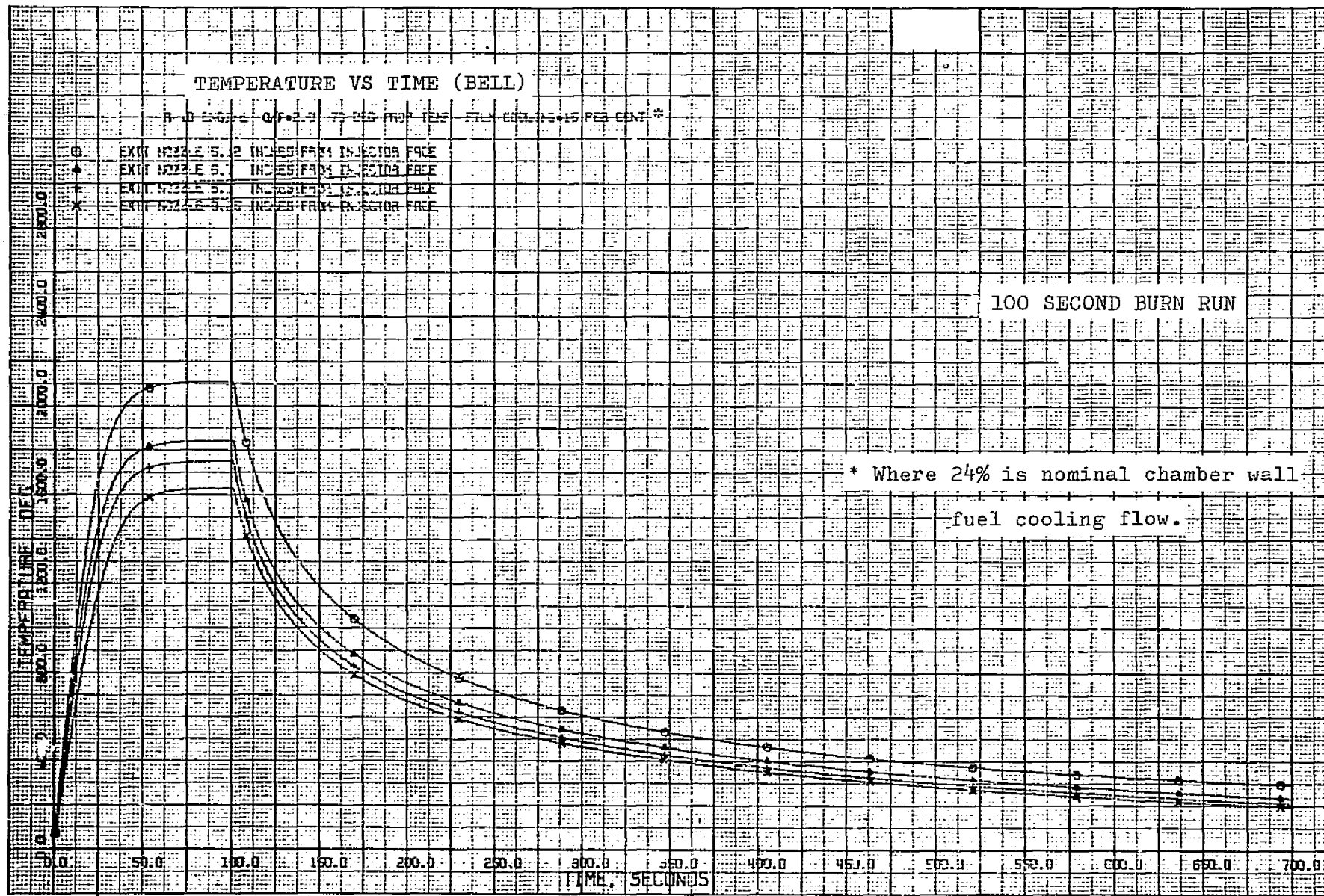
O/F = 2 Propellant Temperature = 70° Propellant N₂O₄/MMH
Temperatures are in °F

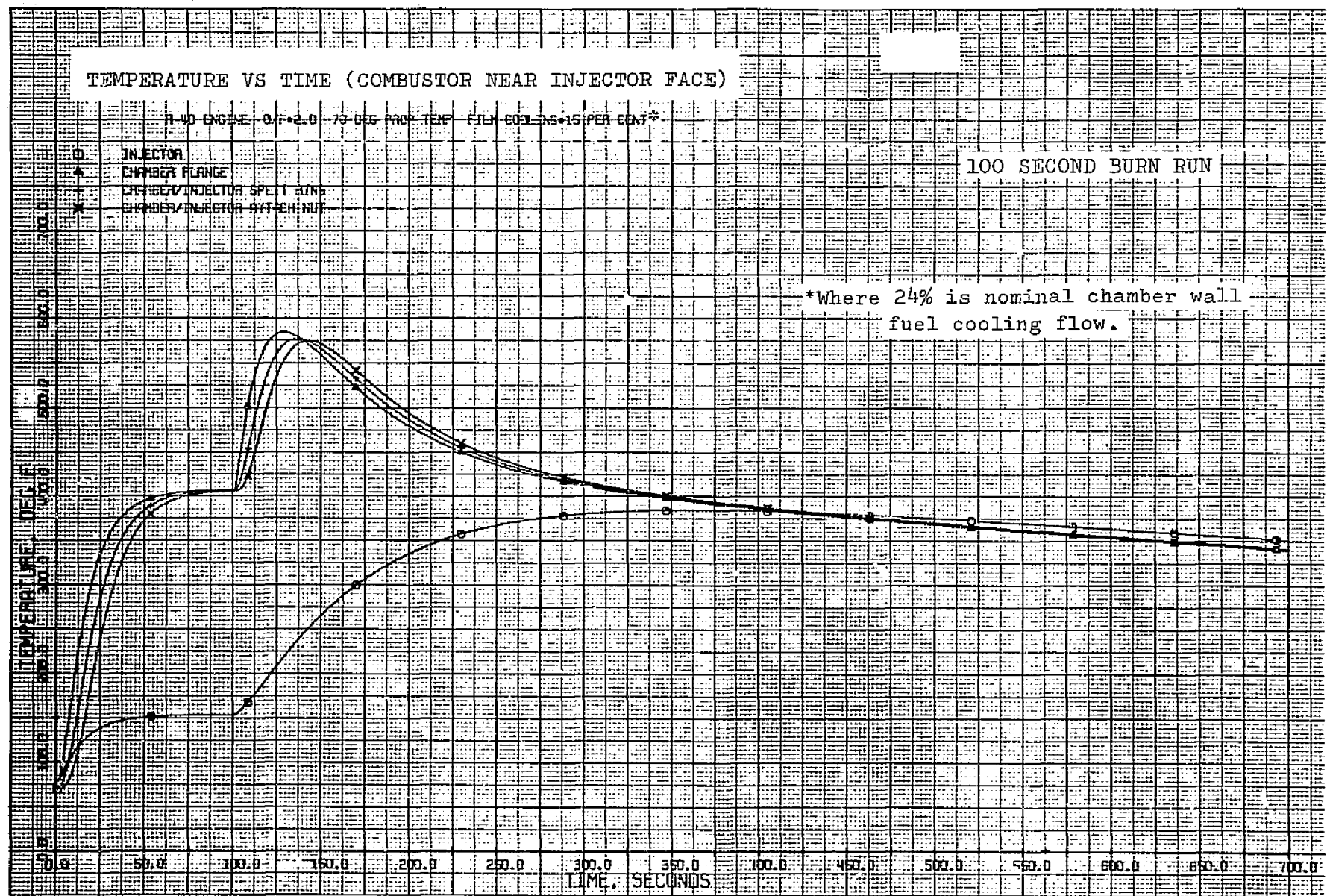
Percent Film Cooling*	0	5	10	15	20	25	30
<u>STEADY STATE</u>							
I. COMBUSTION CHAMBER							
A. 1.5 in. from injector face	3165	1901	1155	694	546	389	310
B. 1.3 in. from injector face	3320	3233	2917	2347	1856	1196	705
C. Throat	3450	3372	2244	2957	2555	1966	1358
D. Chamber Flange	2273	967	598	408	340	265	225
E. Chamber/Injector Split Ring	2273	967	598	408	340	265	225
F. Chamber/Injector Attach Nut	2273	967	598	408	340	265	225
II. INJECTOR	281	191	166	154	149	144	142
III. NOZZLE							
A. 4.3 in. from injector face	2385	2324	2310	2259	2163	1985	1729
B. 5.12 in. from injector face	2205	2135	2132	2110	2061	1972	1841
C. 5.7 in. from injector face	1910	1859	1856	1844	1811	1747	1659
D. 8.1 in. from injector face	1820	1762	1760	1750	1723	1669	1594
E. 9.25 in. from injector face	1692	1638	1636	1628	1606	1561	1498
<u>MAXIMUM SOAKBACK</u>							
I. INJECTOR	----	----	----	385	----	300	----
II. VALVES							
A. Oxidizer Valve Seat	----	----	----	160	----	130	----
B. Fuel Valve Seat	----	----	----	175	----	147	----
C. Oxidizer Valve	----	----	----	152	----	136	----
D. Fuel Valve	----	----	----	142	----	123	----

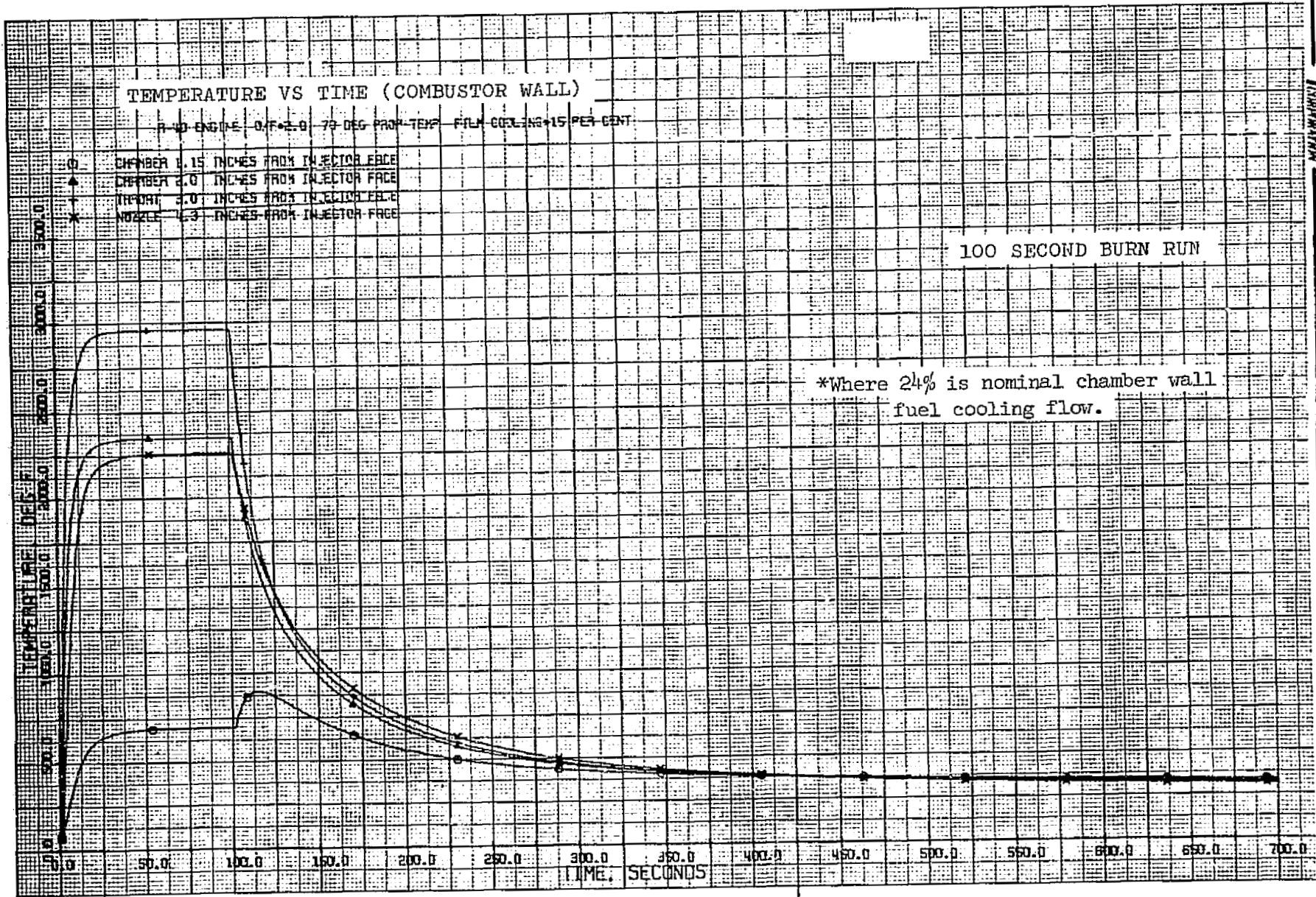
*Denotes percentage of total fuel flow utilized for chamber wall film cooling.
Nominal R-4D chamber wall fuel cooling flow is approximately 24% of total fuel flow.

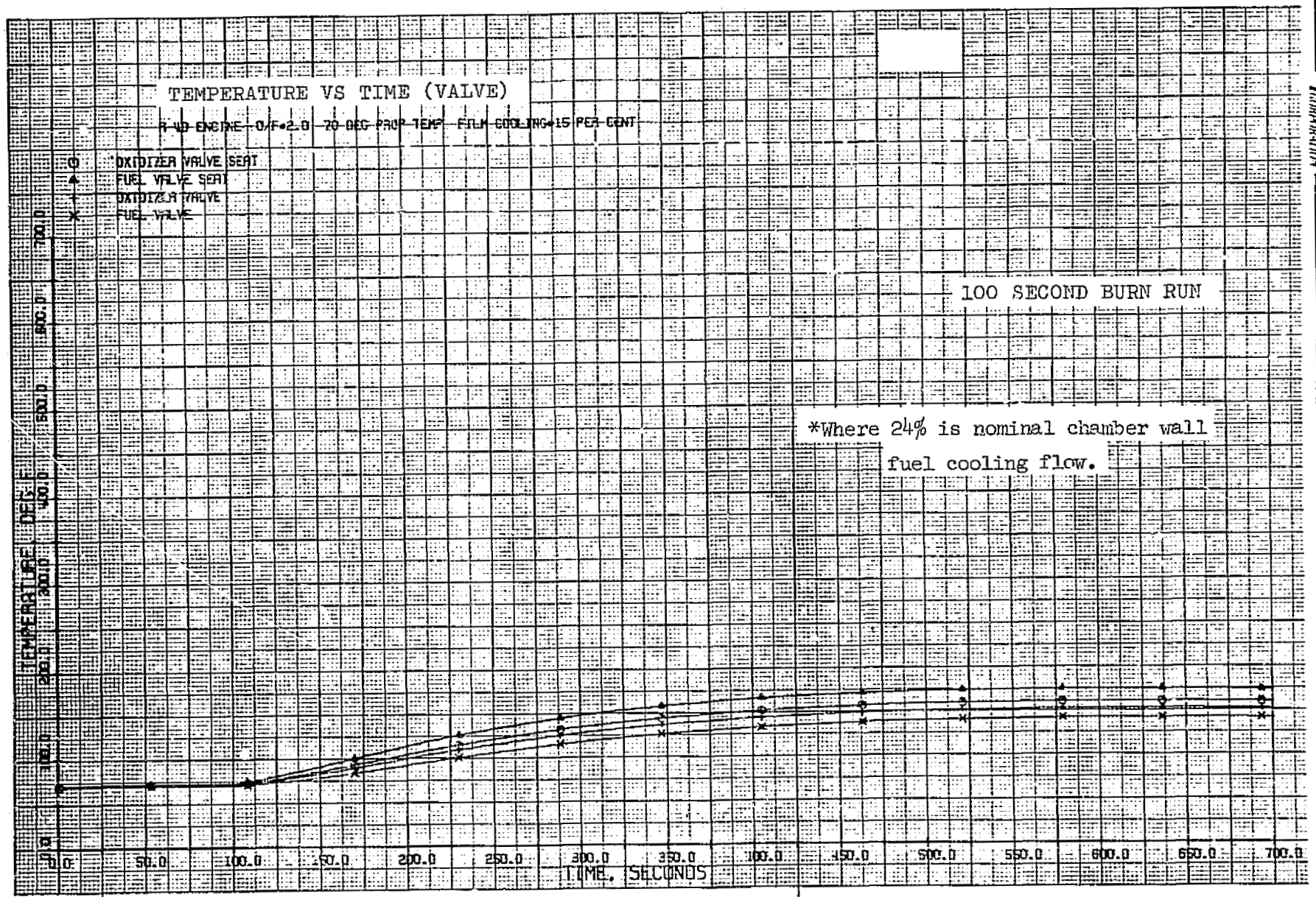


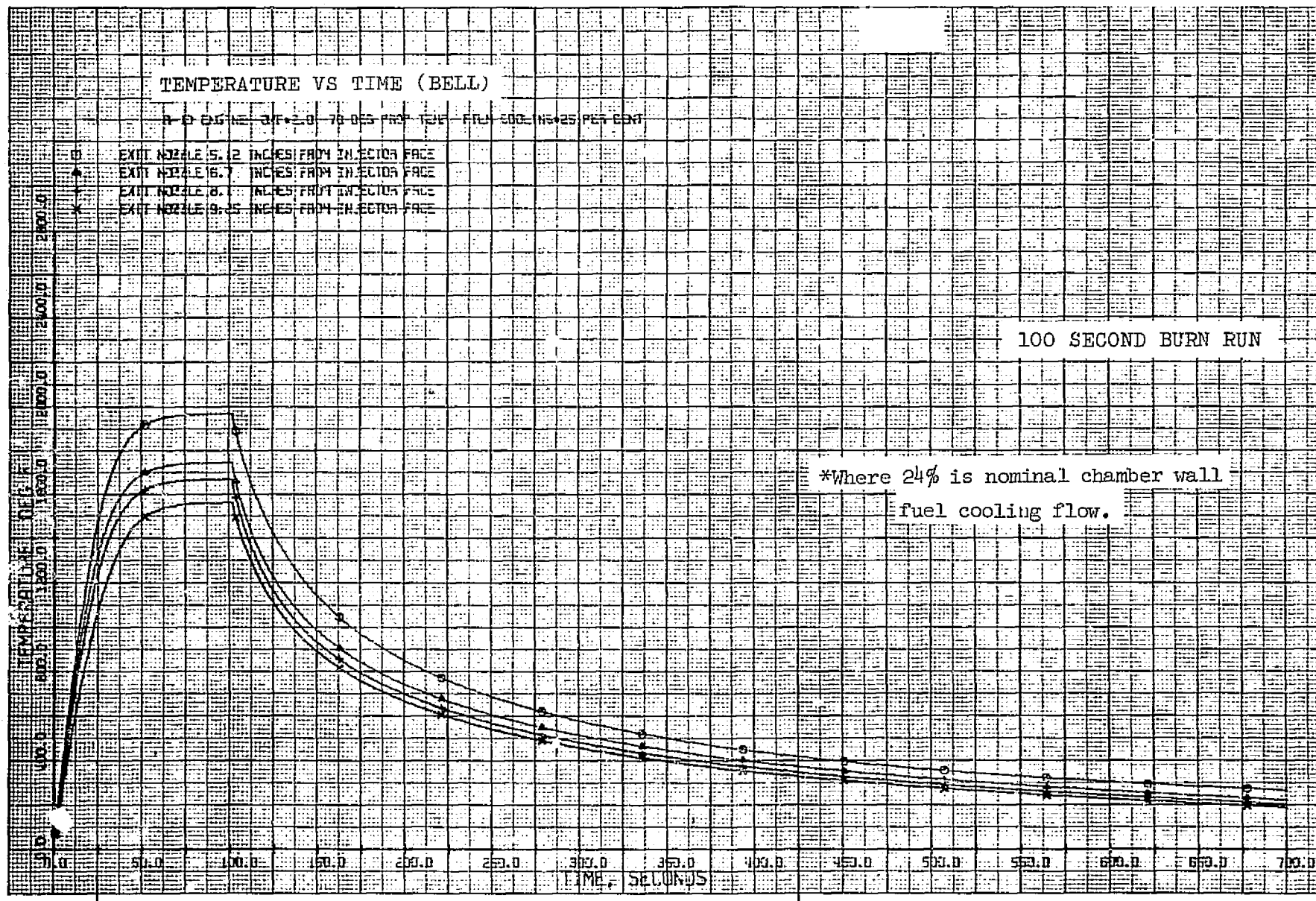
Figures 23 through 30 illustrate calculated transient temperatures for selected nodes for a 100 second burn run. Soakback temperatures after the run are shown also.

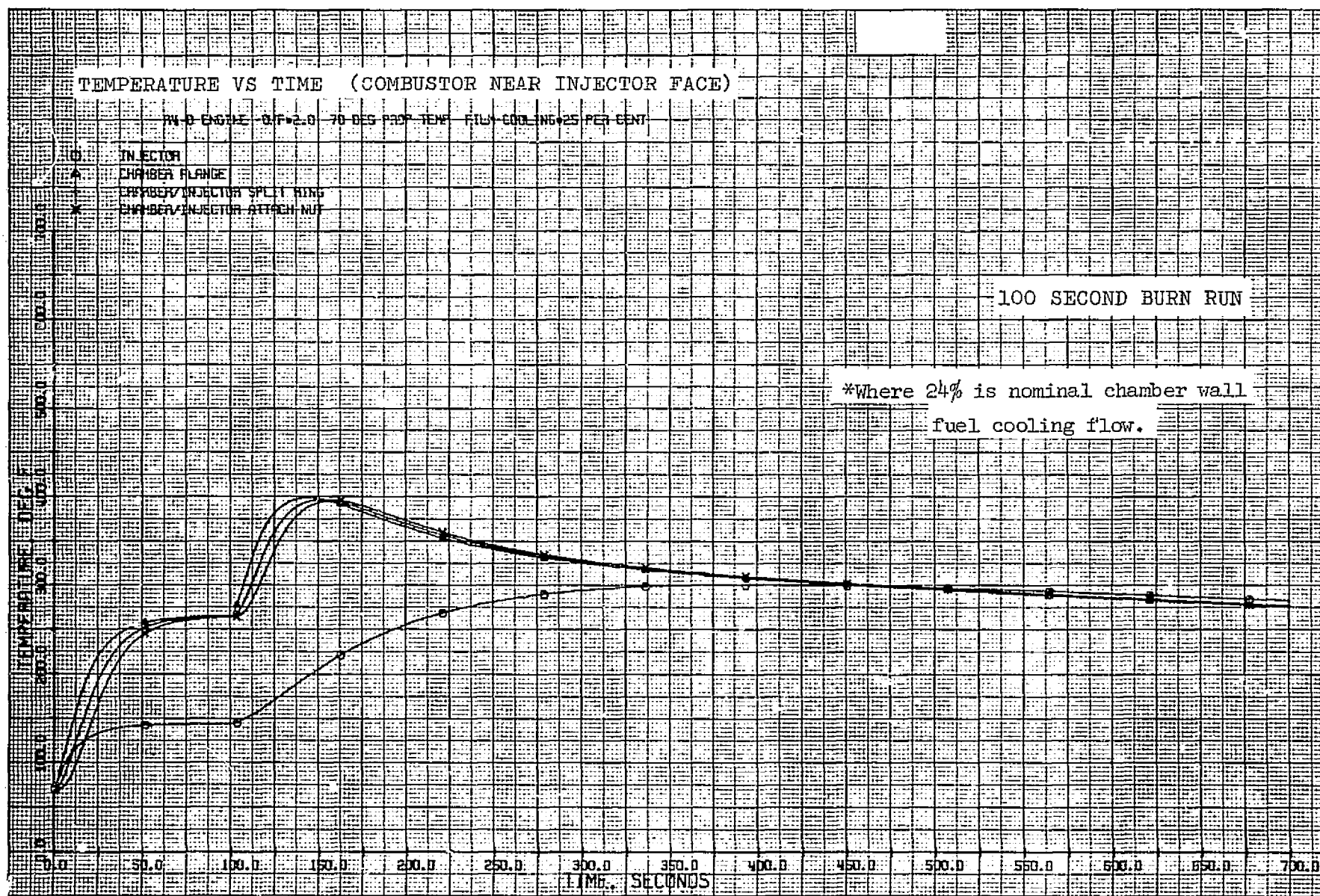


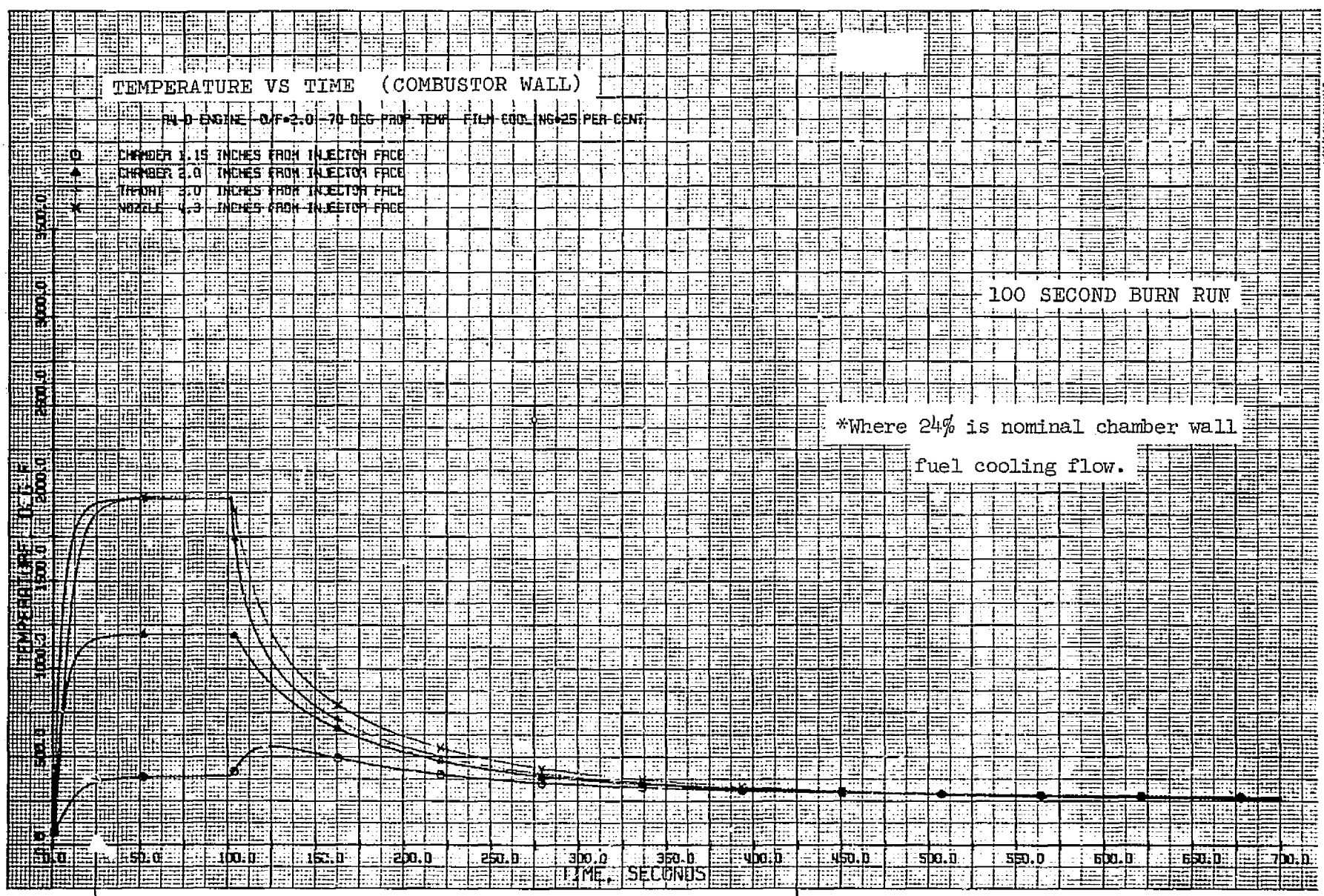


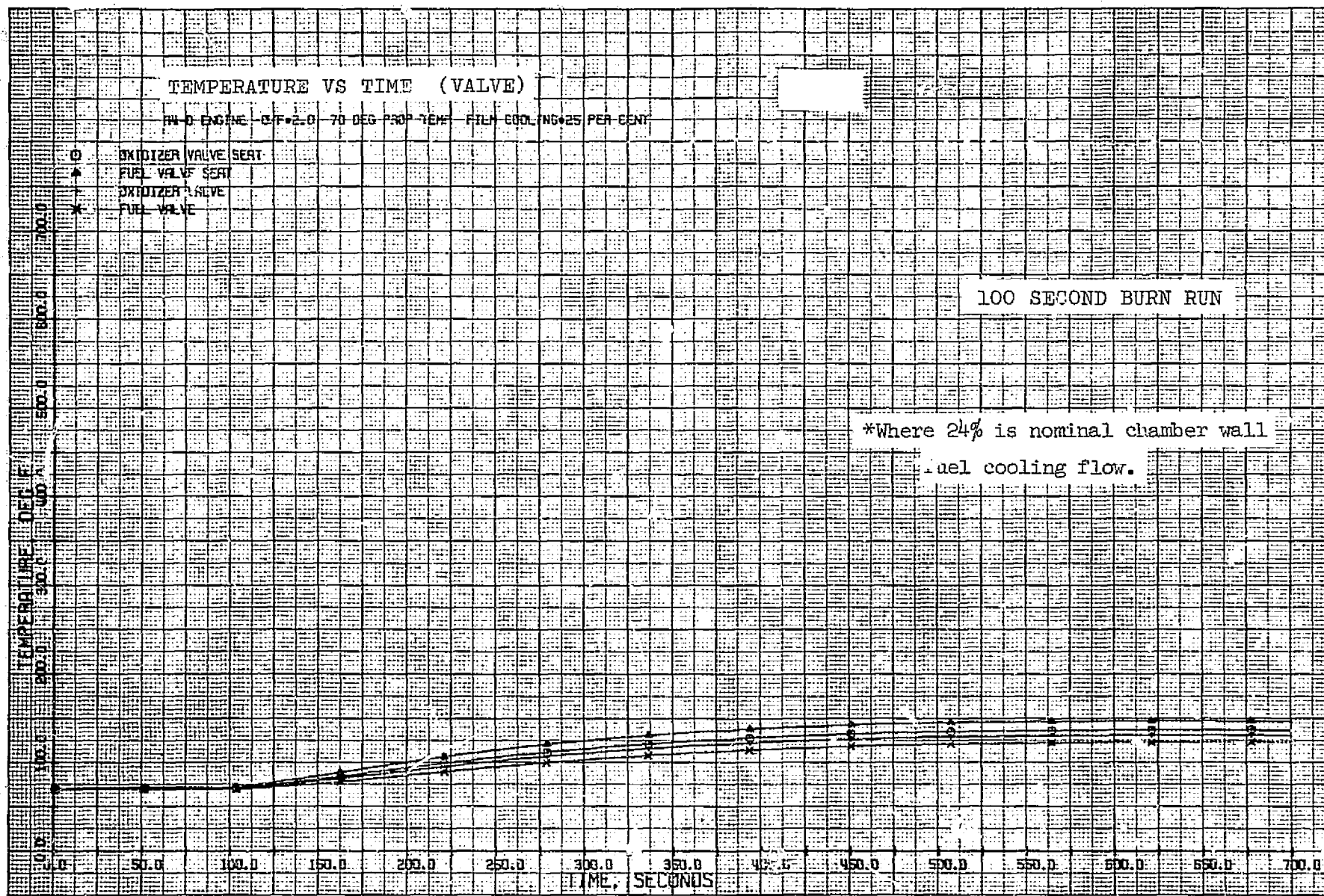












D. Pulse Performance

A TMC developed Quiktran Program was used to predict the effects of reduced film cooling on pulse performance.

A mathematical expression was used to describe the relation between pulse Isp and electrical pulse width. The existing data was found to be best represented by an expression of the form:

$$\eta = A_1 \sqrt{\text{epw}} + A_2 \text{epw} + A_3/\text{epw} + A_4 \quad (42)$$

Where:

(epw) is the electrical pulse width,

η is the ratio of pulse Isp to steady state Isp, and

A_1 , A_2 , A_3 , and A_4 are constants determined from the data.

Different values of the constants A_1 , A_2 , A_3 , A_4 were used for those pulse widths which were greater than 100 ms and less than 100 ms.

The pulse Isp is predicted by first predicting the steady state performance for the conditions of interest. The steady state performance Isp is then multiplied by the factor η to obtain the pulse Isp for a particular electrical pulse width.

Mixture ratio (O/F) is predicted by modifying the steady state value to consider the valve opening and closing times as functions of pressure and electrical pulse width. The expression used is:

$$(O/F)_p = (O/F)_{ss} \left(\frac{t_o}{t_f} \right), \text{ or} \quad (43)$$

$$(O/F)_p = (O/F)_{ss} \left\{ \frac{(\text{epw}) - (1.85 \times 10^{-2})(P_o) + (1.15) - \left(\frac{\alpha}{\text{epw}}\right)}{(\text{epw}) - (1.46 \times 10^{-2})(P_f) + (2.23)} \right\} \quad (44)$$

Where:

$(O/F)_p$ = pulse O/F

$(O/F)_{ss}$ = steady state O/F

t_o = oxidizer valve full open time (ms)

t_f = fuel valve full open time (ms)

P_o = oxidizer pressure (psia)

P_f = fuel pressure (psia)

α = an empirical constant determined from existing data.

Because all reduced fuel cooling configurations (Reference Figure 7) deliver the same chamber pressure, and hence the same steady state thrust, pulse impulse vs. pulse width will not vary from one configuration to another.

A tabulation of the specific impulse and mixture ratios for the five configurations under study are given in Figures 31 and 32. All calculations were made at propellant temperatures of 75°F.

FIGURE 31

PULSING Isp

Assumes the following Propellants - MMH/N₂O₄

Steady State Mixture Ratio - 2.03

Steady State Chamber Pressure - 97 psia.

Electrical Pulse Width ms	Configuration*				
	1	2	3	4	5
10	139.5	146.5	139.5	143.0	147.7
20	190.6	200.2	190.7	196.3	201.7
30	214.3	225.1	214.4	220.7	226.8
40	229.0	240.6	229.1	235.9	242.4
60	246.6	259.0	246.7	254.0	261.1
80	256.0	268.9	256.1	263.7	271.0
100	260.8	273.9	260.9	268.6	276.0
200	270.2	283.8	270.3	278.2	286.0
400	277.6	291.5	277.7	285.9	293.8
600	281.0	295.1	281.1	289.4	297.4
1,000	283.5	297.8	283.6	292.0	300.1

*NOTE: See Figure 7 for Configuration Description.

PULSING O/F

Assumes the following Propellants - MMH/N₂O₄

Steady State Mixture Ratio - 2.03

Steady State Chamber Pressure - 97 psia.

Electrical Pulse Width ms	Configuration*				
	1	2	3	4	5
10	1.30	1.32	1.30	1.30	1.32
20	1.76	1.77	1.76	1.76	1.77
30	1.87	1.88	1.87	1.87	1.88
40	1.92	1.93	1.92	1.92	1.92
60	1.96	1.97	1.96	1.96	1.96
80	1.98	1.98	1.98	1.98	1.98
100	1.99	1.99	1.99	1.99	1.99
200	2.01	2.01	2.01	2.01	2.01
400	2.02	2.02	2.02	2.02	2.02
600	2.02	2.02	2.02	2.02	2.02
1,000	2.03	2.03	2.03	2.03	2.03

*NOTE: See Figure 7 for Configuration Description.

E. Ignition Characteristics

During the early development of the preigniter configuration engine, a criterion for good preigniter and engine ignition was developed. For a given chamber configuration, characteristic length, and throat area, the total propellant flow rate must be above a certain value for ignition to take place. The development of the criterion is discussed in Marquardt report S-899, which is a discussion of the analysis effort accomplished as part of the Severe Off-Limit Evaluation task.

The ignition criterion was applied to the configurations of reduced fuel coolant flow rates. Tabulated in Figure 33 are the preigniter flow rates and preigniter O/F for Case 1 of the hydraulics program (Reference section IIIA). Case 1 is the case where the preigniter is not lit and the dribble volume is filling. The flow rates and O/F's correspond to the conditions prior to ignition in the preigniter. It can be seen from the tabulated flows that the percent flows do not vary from the present nominal so that the preigniter will light for all five configurations.

If satisfactory preigniter ignition is achieved, main chamber ignition will also be satisfactory. It is therefore concluded that good engine ignition will be obtained for all the planned reduced cooling flow configurations.

FIGURE 33

PREIGNITER CONDITIONS PRIOR TO IGNITION

Configuration	Percent of Nominal Film Cooling		Flow to Preigniter lbs/sec.	Preigniter O/F	% Flow
	Main Chamber	Preigniter			
1	100%	100%	0.1128	3.28	33.0%
2	0	100%	0.1136	3.19	33.2%
3	100%	0	0.1130	3.26	33.0%
4	50%	100%	0.1131	3.25	33.1%
5	0	0	0.1135	3.19	33.2%

$$\% \text{ Flow} = \frac{\text{Flow}}{0.342} \times 100$$

F. Short Pulse Width Thermal and Ignition Characteristics

During the past two years, since the original qualification of the Apollo SM-LM RCS engine, it has been found that under some environmental conditions with some pulsing duty cycles, combustion residues can form and remain for some period of time in the engine. These combustion residues can cause large ignition overpressures which can fail the engine combustion chamber.

A significant amount of testing has been accomplished with the R-4D engine at both the NASA's Manned Spacecraft Center and at Marquardt's multi-attitude space simulation facility. These tests were done with both monomethylhydrazine and Aerozine-50 fuels. The engine has been fired in vertical up, vertical down, and horizontal attitudes. Numerous duty cycles have been tested with varying ON times, OFF times, numbers of pulses, and propellant valve timing. The results of these tests indicate that combustion residue forms during or immediately after a firing pulse and slowly evaporates between pulses. Therefore, the time between pulses and the hardware temperature, play an important part in the accumulation of the residue from pulse to pulse.

The occurrence of an ignition overpressure, or spike, is the result of the rapid combustion of an accumulated quantity of combustion residue. The exact reason why the residue will react on some pulses and not on others is presently unknown; except it is known that longer than usual ignition delays (after the propellant valves are open) and oxidizer flow prior to fuel flow both tend to increase the probability of reaction or combustion of a quantity of residue.

Because the combustion residue accumulates on the combustor wall, the amount of fuel coolant sprayed onto the wall during a pulse must have some influence on the amount of residue formed. The objective of this analysis effort was to determine the relationship between amount of fuel coolant and amount of residue accumulation and the accompanying effect on engine temperatures.

Two existing TMC computer programs, the Evaporation Rate Program and the Pulse Operation Model Program were used in this analysis. The Evaporation Rate 360/40 Computer Program predicts the rate of evaporation of fuel from combustion chamber walls. This information constitutes a part of the input for the Marquardt Pulse Operation Model Computer Program. It plays a key role in determining the thermal characteristics of a pulsing engine. The Pulse Operation Model assumes that the fuel accumulates on the combustor walls during a pulse and evaporates during the off times between pulses. The program calculates the changing engine temperatures as a function of the engine firing and the fuel evaporating.

Throughout this analysis, the combustion residue has been assumed to be fuel. The formation of other compounds with different vapor pressure characteristics have not been included. The fuel evaporation times are such that all residual fuel should completely evaporate between the ends of most tests and the removal of the

engine from the test cell. However, some residue is usually found in the engine upon removal. This residue has been chemically analyzed several times and found to contain water, hydrazine, hydrazine nitrate, nitrate, and nitrite ions. Also the Bureau of Mines (Ref.3) has chemically analyzed residue from tests at the Manned Spacecraft Center with similar results. It is therefore apparent that the residue is not pure fuel and that the evaporation characteristics assumed in this analysis are not completely accurate. However, vapor pressures for the other compounds are not known and to some extent a meaningful analysis is possible assuming the residue to be fuel.

During each pulse, fuel is injected through the preigniter, through the preigniter cooling holes, through the main doublets, and through the main chamber cooling holes. Due to the short duration of most pulses, the fuel injected for cooling purposes is in excess of thermal requirements. This excess fuel is accumulated on the combustor walls. In addition, after each pulse, the injector passages empty, putting more fuel (and some oxidizer) on the walls.

After each pulse the chamber wall temperature adjusts to the net heat input from combustion, evaporation of propellants, and external heat losses or gains.

With the above background the following classifications have been made:

- Group 1. Pulse trains where the total heat input is positive, and evaporation of all accumulated propellants is accomplished prior to the next pulse. A qualitative diagram is shown in Figure 34a.
- Group 2. Pulse trains where the total heat input is positive, but evaporation of all accumulated propellants is not accomplished prior to the next pulse. This group is characterized by a rising wall temperature and initially by residue accumulation. This situation raises the evaporation rate of the accumulated residue. As long as the net heat input is positive, this situation will continue until the evaporation rate is fast enough to evaporate all the accumulated residue before the next pulse (the Group 1 situation), or until the pulsing is discontinued. A qualitative diagram is shown in Figure 34b.
- Group 3. Pulse trains where the total heat input is negative, and evaporation of all accumulated propellants is accomplished prior to the next pulse. This group is characterized initially by a lack of accumulation and a steady decrease in wall temperature. As the wall temperature decreases the evaporation rate decreases. If the net heat input continues to be negative, a point will be reached where accumulation will remain when the next pulse occurs. A qualitative diagram is shown in Figure 34c.
- Group 4. Pulse trains where the total heat input is negative, but evaporation of all accumulated propellants is not accomplished prior to the next pulse.

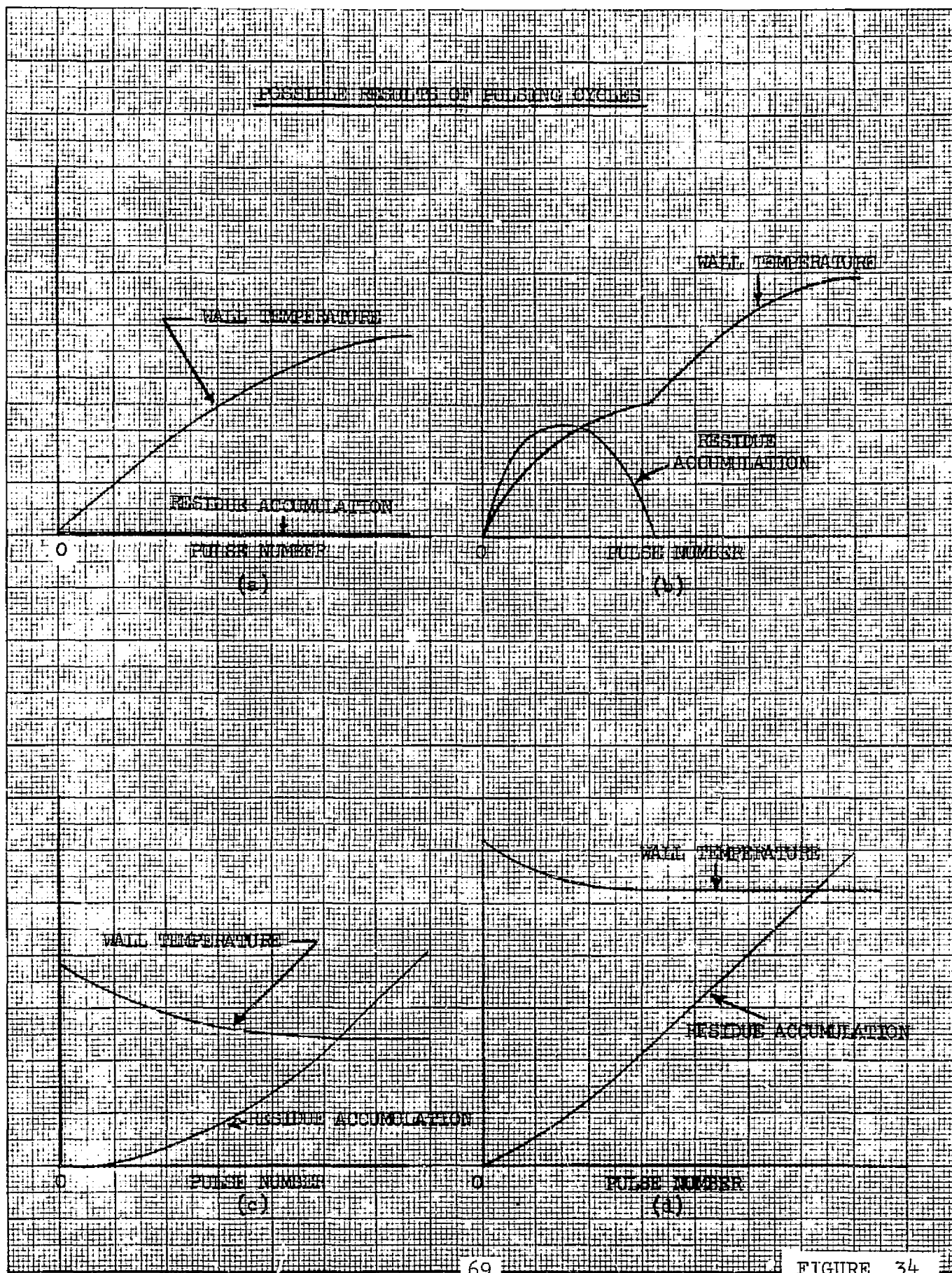


FIGURE 34

This group is characterized by fuel accumulation and a decreasing wall temperature. As the wall temperature decreases, the evaporation rate decreases, causing an increase in accumulation rate. The fuel accumulation increases with every pulse. A qualitative diagram is shown in Figure 34d.

The importance of adding enough heat to the engine so that only Group 1 cases are possible is obvious.

The Evaporation Rate Program determines fuel evaporation rates by simultaneous solution of expressions for the flow rate out the nozzle, the evaporation flow from the liquid surface, and the flow rate determined by the quantity of heat transferred through the liquid film. The evaporation rates are determined as functions of the film thickness, the wall temperature, the film area, and the properties of the fuel.

The evaporation rate determined by the heat transferred through the liquid layer is described by the following expression:

$$W = \frac{(T_w - T_s) (A_s k)}{h \lambda} \quad (45)$$

Where:

- W = evaporation rate
- T_w = wall temperature
- T_s = surface temperature
- h = film thickness
- A_s = surface area of film
- k = coefficient of thermal conductivity
- λ = heat of vaporization

Evaporation from the liquid surface is given by the following (Langmuir's Equation):

$$W = EA_s (P_s - P_c) \sqrt{\frac{M_g}{2\pi RT_s}} \quad (46)$$

Where:

- E = accommodation coefficient
- P_s = saturation pressure
- P_c = chamber pressure
- M = molecular weight of fuel
- g = acceleration of gravity
- R = gas constant

An appropriate expression for saturation pressure as a function of temperature is put into the program for the fuel being considered.

The expression for the rate of flow from a choked nozzle is as follows:

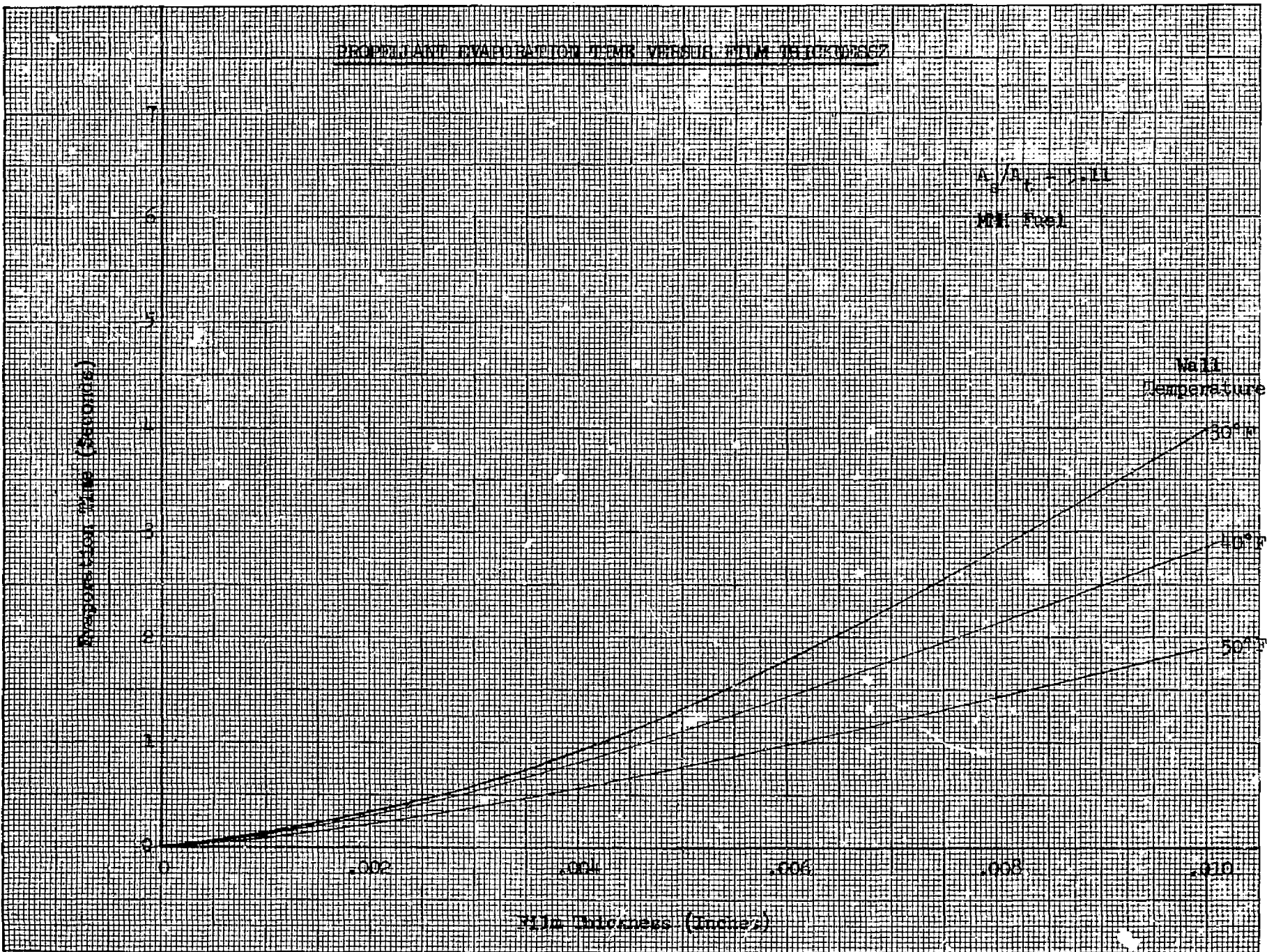
$$W = A_t P_c \sqrt{\frac{g\gamma}{RT_{og}}} \left(\frac{2}{\gamma+1} \right)^{\frac{\gamma+1}{2(\gamma-1)}} \quad (47)$$

Where: A_t = throat area
 γ = ratio of specific heats
 T_{og} = gas stagnation temperature

The program performs a simultaneous solution of the above equations. The output is an evaporation rate for given surface area, film thickness, and wall temperature. Figure 35 shows typical evaporation times for MMH at three different wall temperatures.

In the Pulse Operation Model, the phenomena of manifold filling dynamics, manifold emptying dynamics, combustion, heat transfer, and evaporation are accounted for. The fuel manifold fills at a prescribed rate which is greater than the steady state fuel flow rate. After the manifold is full, flow is reduced to the nominal or steady state flow rate. At this point, a prescribed percentage of the fuel is sprayed on the chamber wall. Flow continues into the fuel manifold at the nominal rate until the valve closes. Flow out of the manifold, with accompanying spray on the wall, continues at the nominal rates for the prescribed time (2 ms in present analysis) after valve closure. At this point in time flow out of the fuel manifold continues at a prescribed reduced rate until the manifold is empty. For this manifold emptying period, a different prescribed percentage of the fuel flow is allocated to the chamber wall. This simulates dribble volume emptying. If the manifold fails to completely empty on a particular pulse, this is taken into account on the next pulse. Ignition occurs when the fuel manifold is full and continues for a prescribed period of time based on actual test data. Heat transfer from the combustion gases to the chamber wall occurs only during this combustion period. Heat transfer between the chamber wall and the injector head (held at a constant temperature of 70°F) occurs at all times. Evaporation of fuel from the wall, with accompanying cooling of the wall, occurs whenever there is fuel on the wall. This evaporation is dependent on the chamber wall temperature and the thickness of the film of fuel on the wall as discussed above. If all the fuel does not evaporate from the chamber wall in a particular pulse, this is taken into account on the next pulse.

The significant outputs of the Pulse Operation Model are the changes in chamber wall temperature and the accumulation of fuel on the chamber wall as a function of pulse duty cycles, propellants, and temperatures. The results of the present analysis to predict the effects of reduced chamber cooling are presented in Figure 36



through 48.

Figure 36 shows the calculated change in chamber wall temperature for a series of 15 pulses of 0.012 seconds ON time. The fuel is MMH. The change in temperature is given as a function of OFF time between pulses. A comparison between the calculated values and actual test data shows that the model used is fairly representative. For pulse trains with OFF times longer than about 0.4 seconds, the resultant change in temperature is negative.

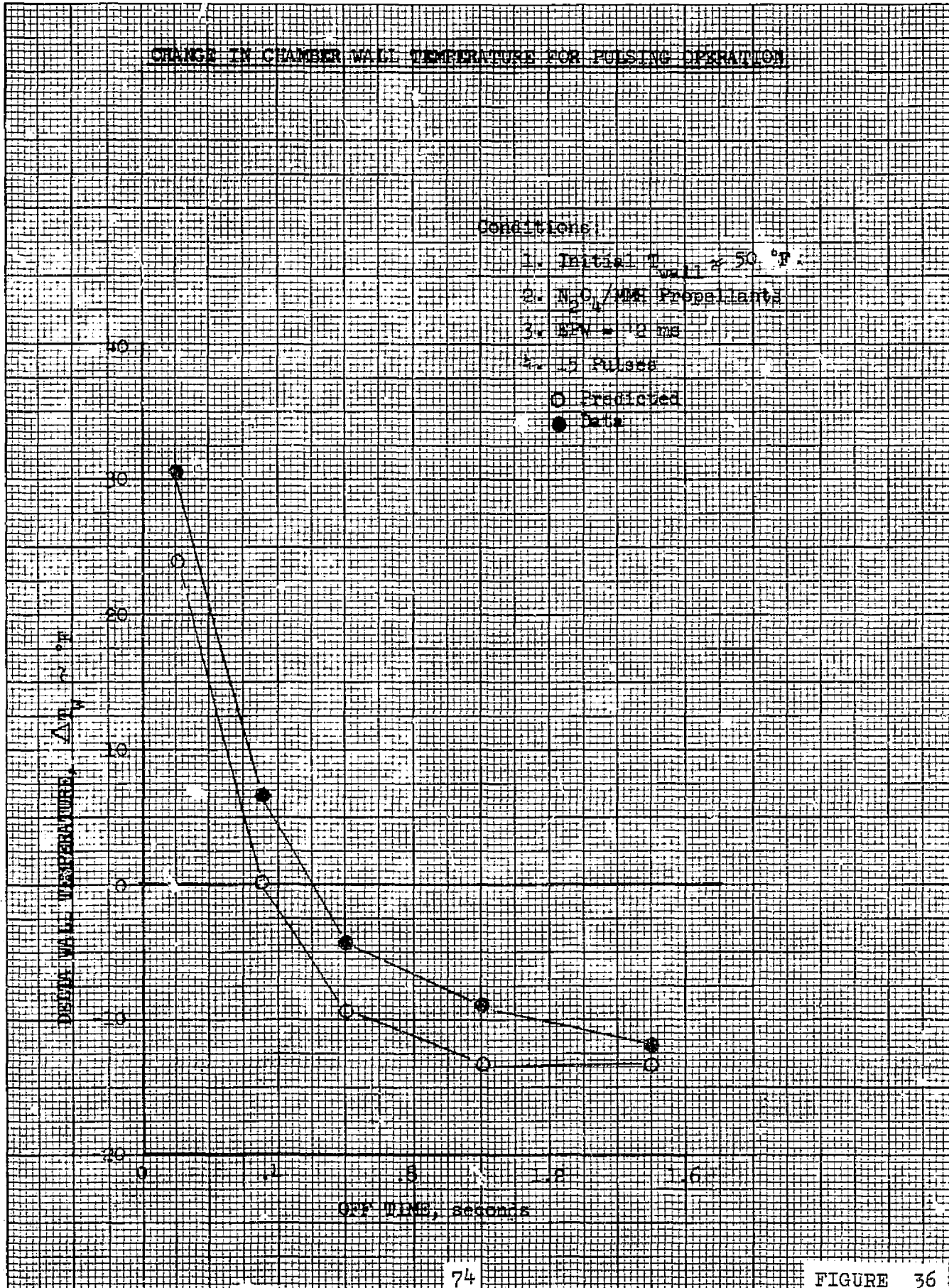
Figure 37, 38, and 39 show the expected changes in wall temperatures for the same propellant and duty cycle for three different initial wall temperatures. A prediction is made for normal fuel cooling and for zero and 50% fuel cooling. It can be seen that negative temperature changes are not expected for the reduced fuel cooling conditions. Figures 40, 41, and 42 illustrate the expected accumulation of fuel for the same conditions. Almost no fuel accumulation is expected with zero fuel cooling. Therefore, it may be reasonable to expect that ignition overpressures would not occur under these conditions. Also, it can be seen that 50% cooling accumulates a quantity of fuel at 30°F initial wall temperature that is about equivalent to the quantity accumulated by normal cooling at 50°F initial wall temperature. Therefore, comparable ignition overpressures may be expected for these two cases.

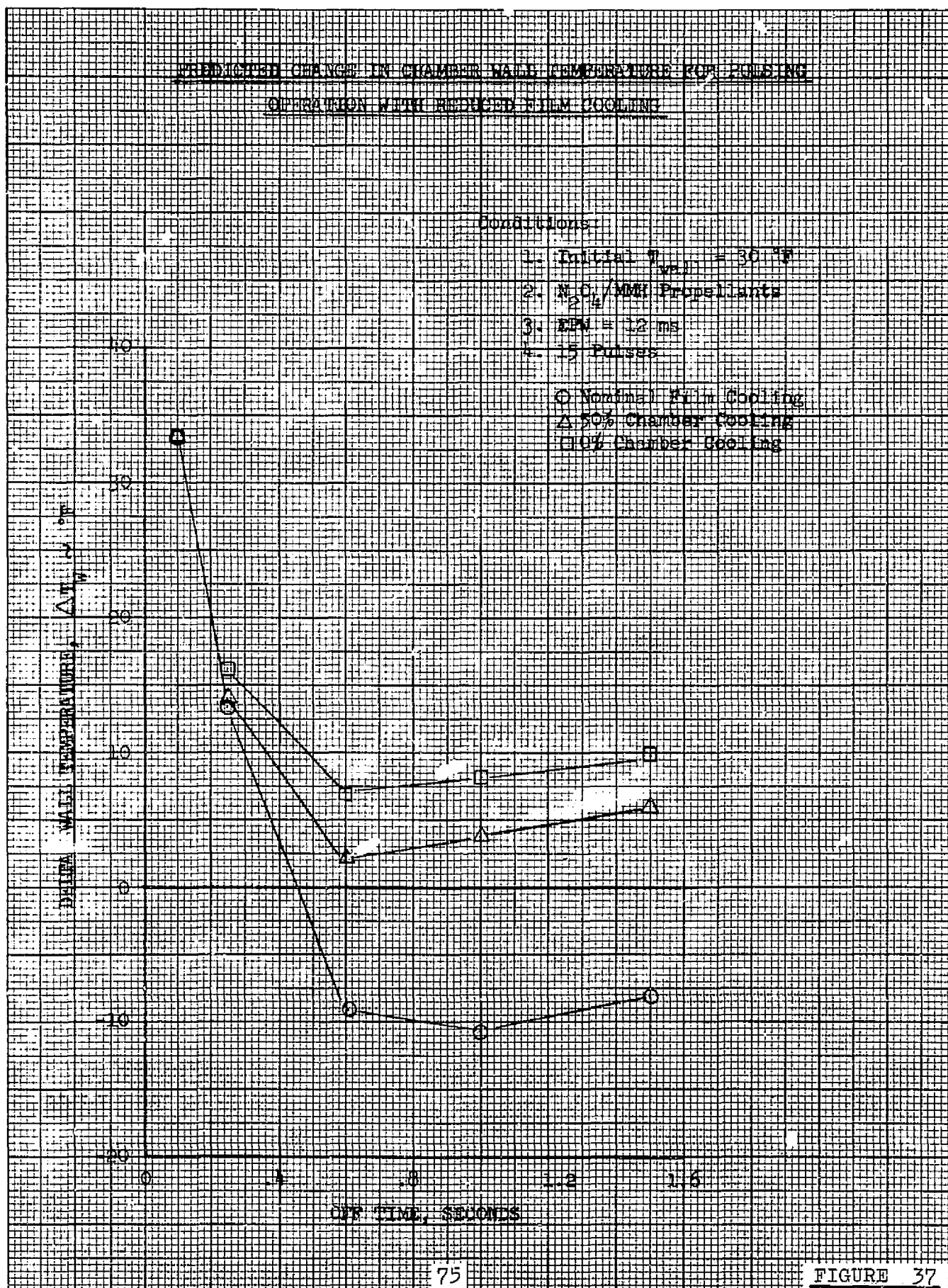
Figures 43 and 44 show the changes in wall temperature that are predicted for a series of 9 pulses with A-50 fuel with initial wall temperature of 70°F and 100°F. These predictions are for normal fuel cooling conditions and actual test data from previous testing is shown for comparison. The predictions are again reasonably close to the actual data.

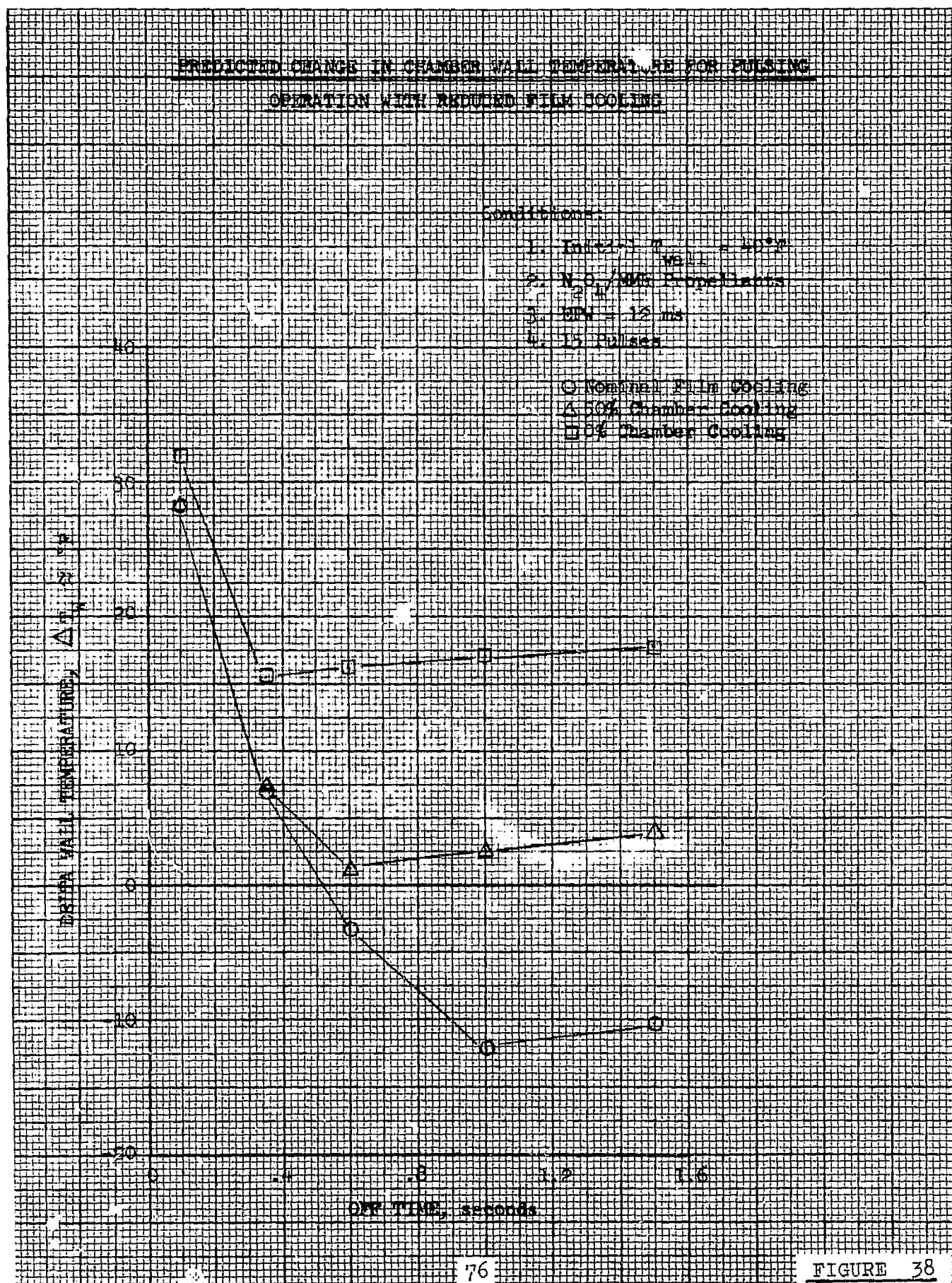
Figures 45 and 46 show the effects on expected changes in wall temperature of reducing the fuel cooling to 50% and zero. As with MMH discussed above, the changes in fuel cooling make a significant difference.

Figures 47 and 48 show the effects of film cooling upon fuel accumulation for the A-50 propellant. The changes in film cooling have about the same effect as with MMH above. The quantitative values of accumulated fuel are considerably different than with MMH; but this is caused by the change in the number of pulses used in the calculation, the initial temperatures assumed and the fact that only the hydrazine component of the A-50 fuel has a low enough vapor pressure to remain in the engine for any period of time.

The results of the temperature and fuel accumulation analysis discussed above lead to the conclusion that the effects of the changes in fuel cooling upon ignition overpressures should be significant with possibly no overpressures occurring with zero cooling flow.







PREDICTED CHANGE IN CHAMBER WALL TEMPERATURE FOR PULSING
OPERATION WITH REDUCED FILM COOLING

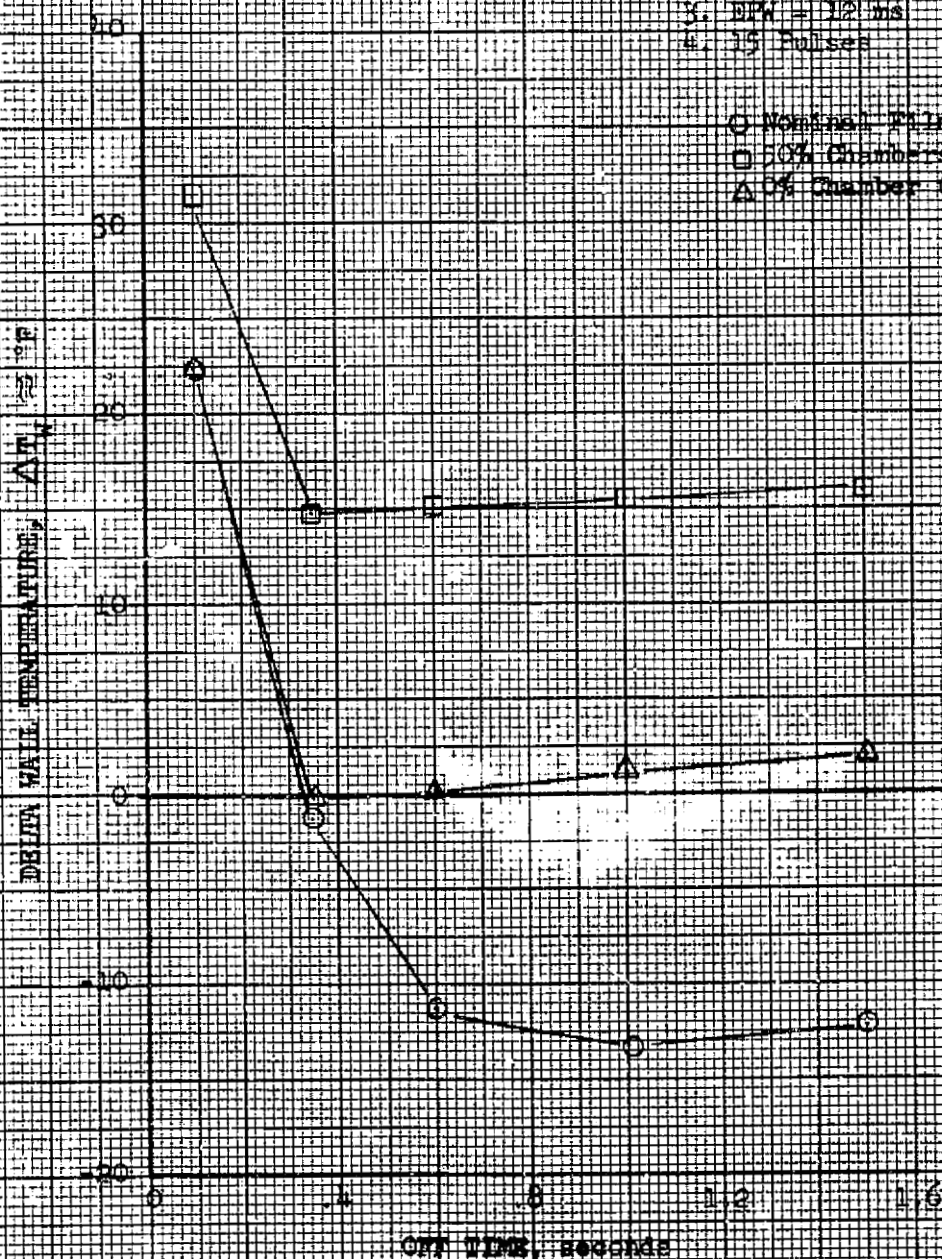
Conditions:

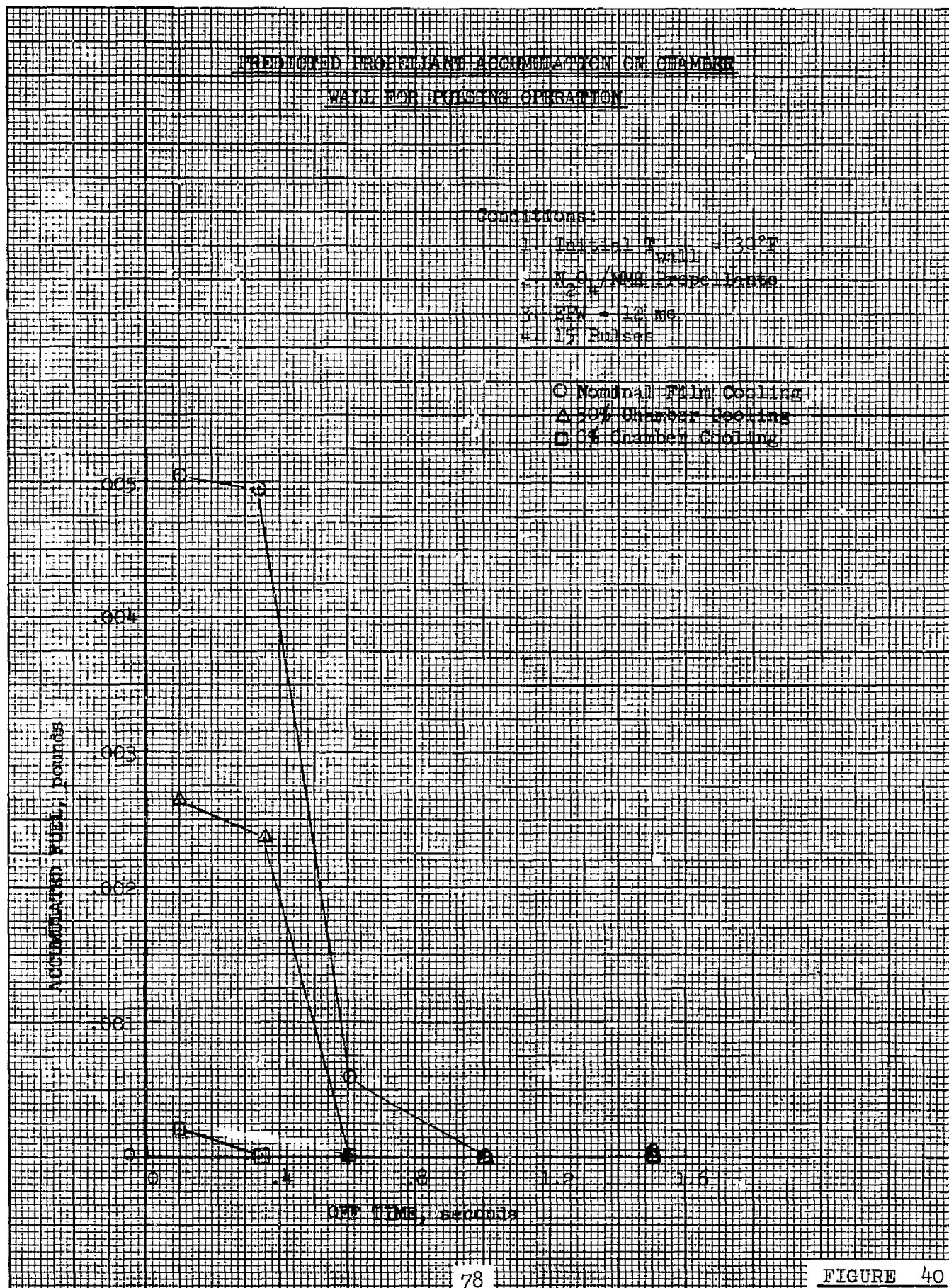
1. Initial $T_{\text{wall}} = 50^{\circ}\text{F}$
2. $\text{N}_2\text{O}_4/\text{MMH}$ Propellants
3. EPW = 12 ms
4. 15 Pulses

- Nominal Film Cooling
- 50% Chamber Cooling
- △ 0% Chamber Cooling

DELTA WALL TEMPERATURE, ΔT_w , $^{\circ}\text{F}$

OFF TIME, seconds



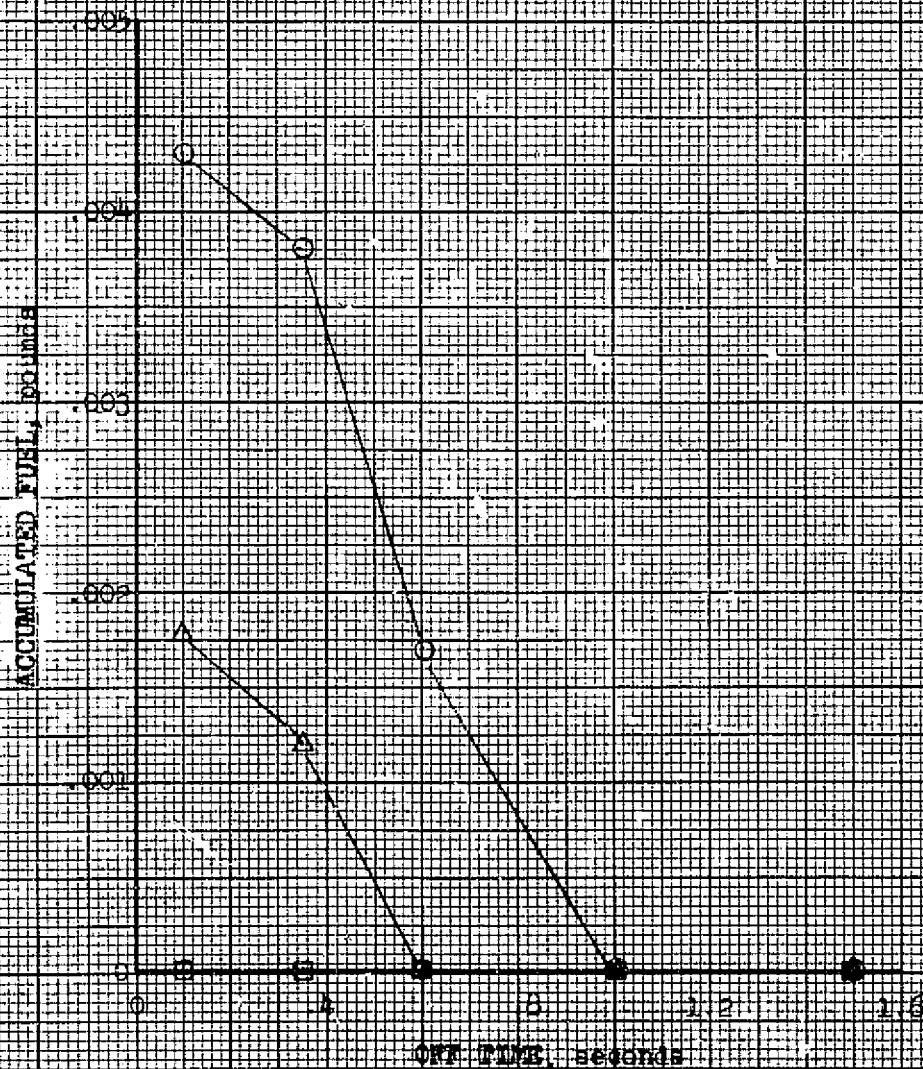


PREDICTED PROPELLANT ACCUMULATION ON CHAMBER
WALL FOR PULSED OPERATION

Conditions:

1. Initial Temp. = 40°F
2. N_2O_4 /MMR Propellants
3. PPW = 12 ms
4. 15 Pulses

○ Nominal Film Cooling
△ 50% Chamber Cooling
□ 10% Chamber Cooling

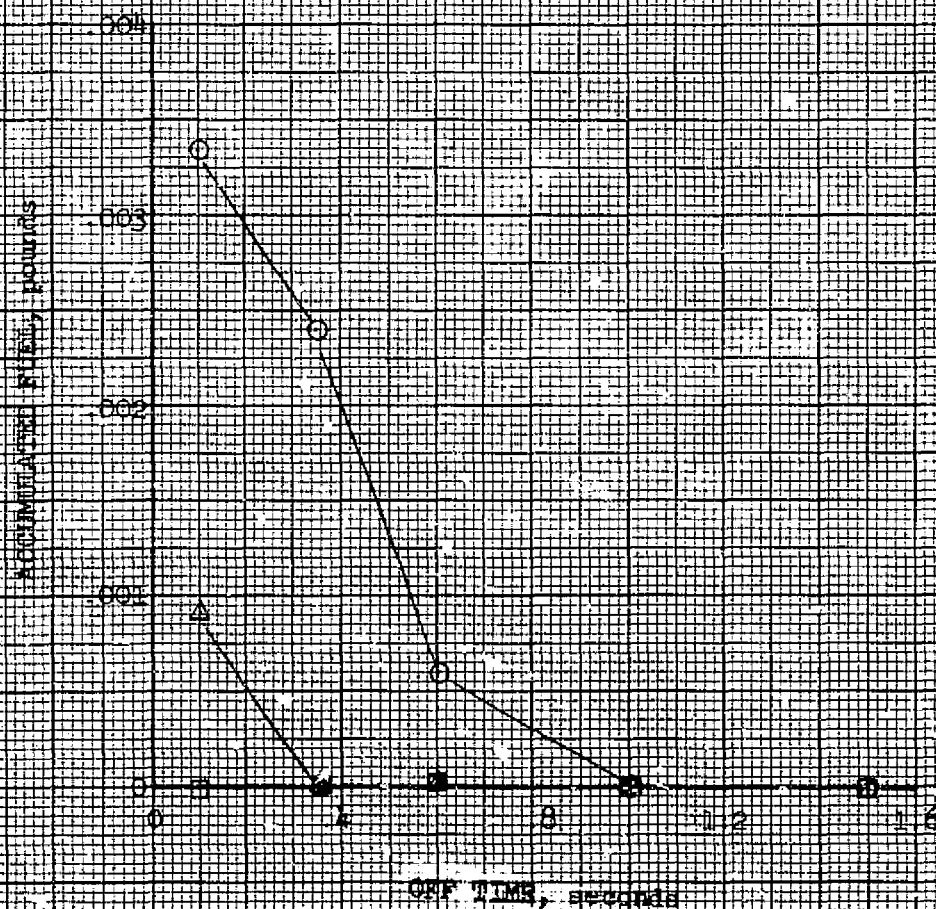


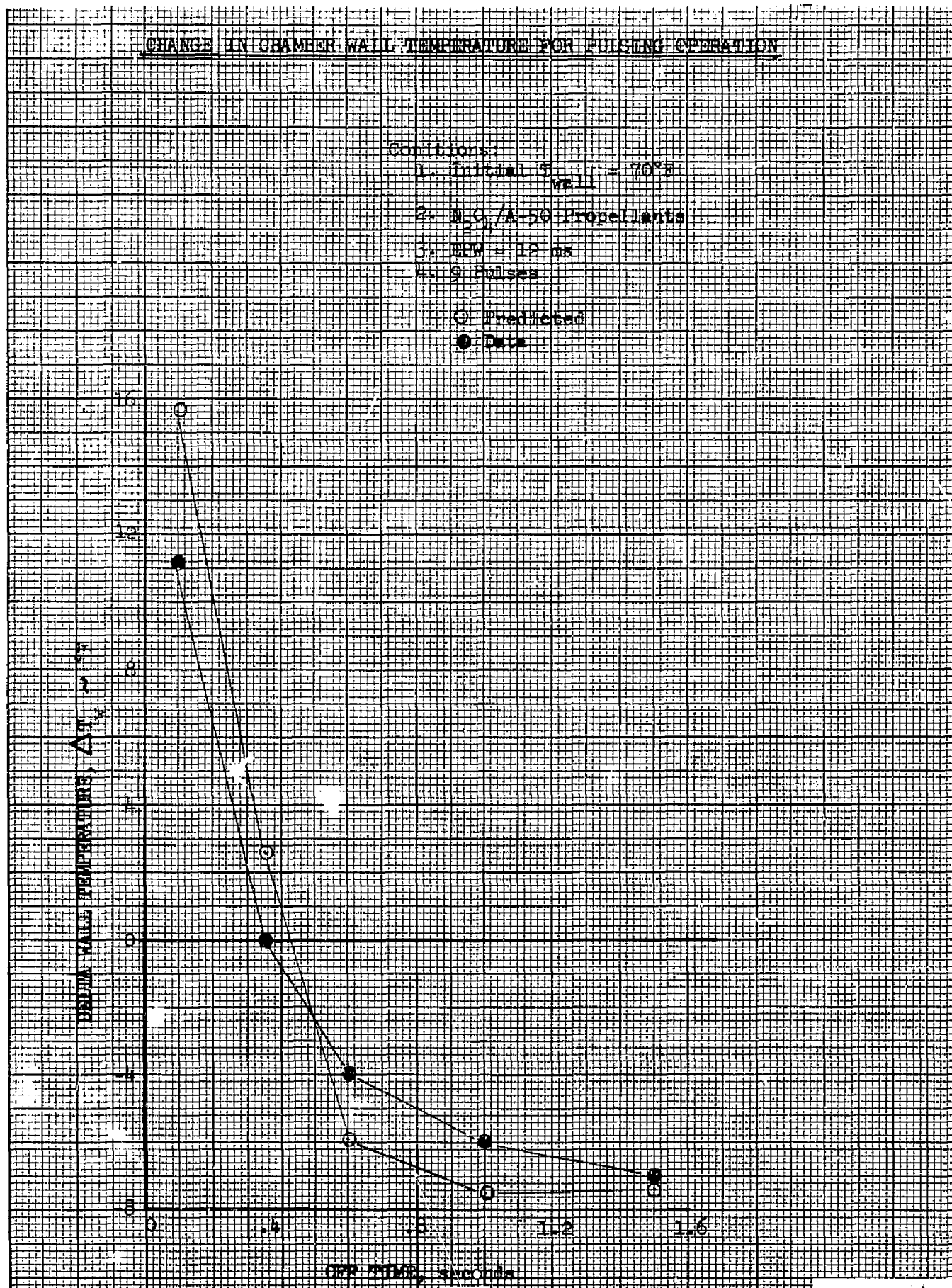
PREDICTED PROPELLANT ACCUMULATION ON CHAMBER
WALL FOR PULSED OPERATION

Conditions:

1. Initial $T_{wall} = -50^{\circ}\text{K}$
2. $\text{N}_2\text{O}_4/\text{MMH}$ Propellant
3. $\text{CPW} = 12 \text{ ms}$
4. 15 Pulses

○ Nominal Film Cooling
△ 50% Chamber Cooling
□ 0% Chamber Cooling





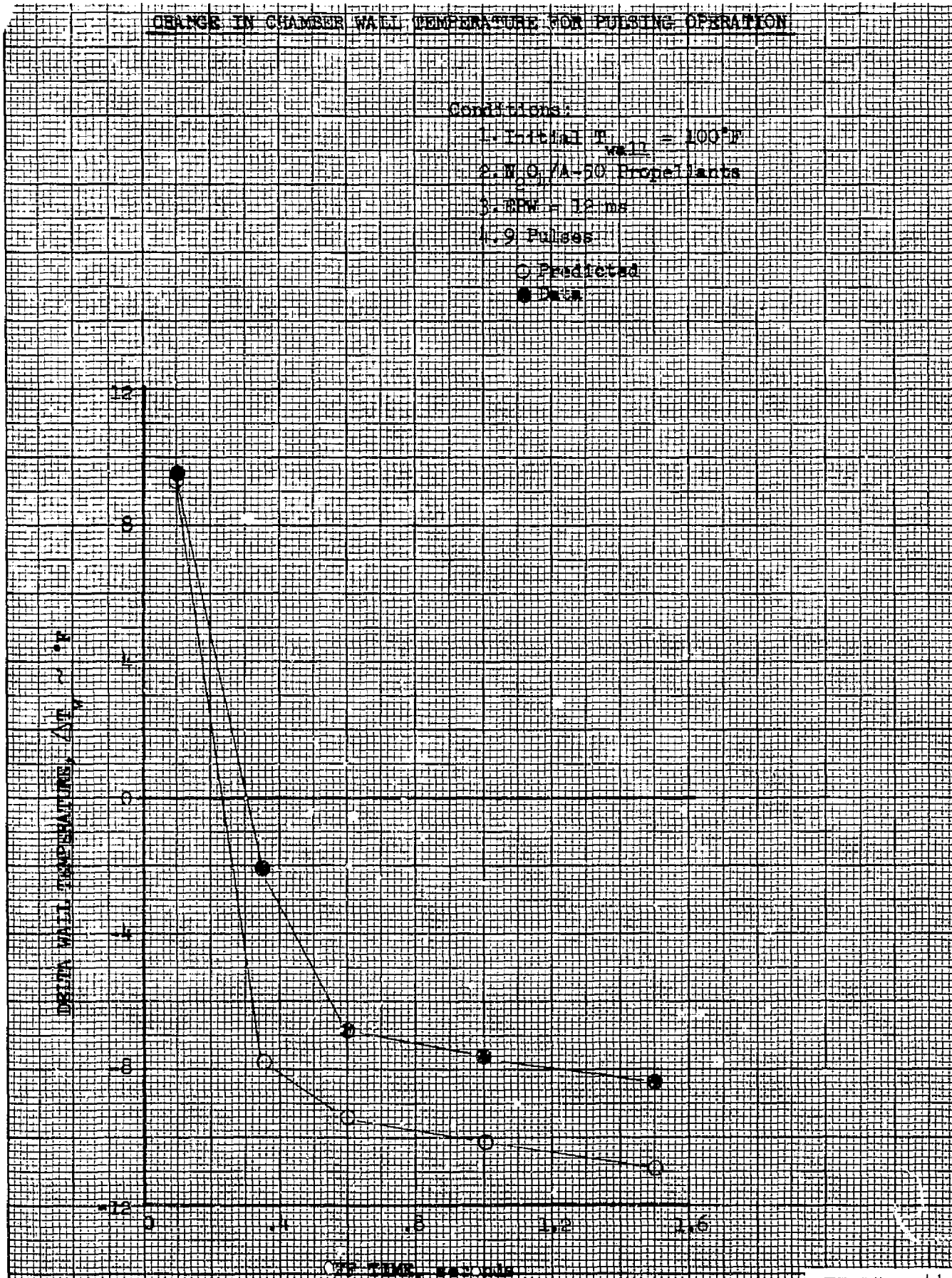
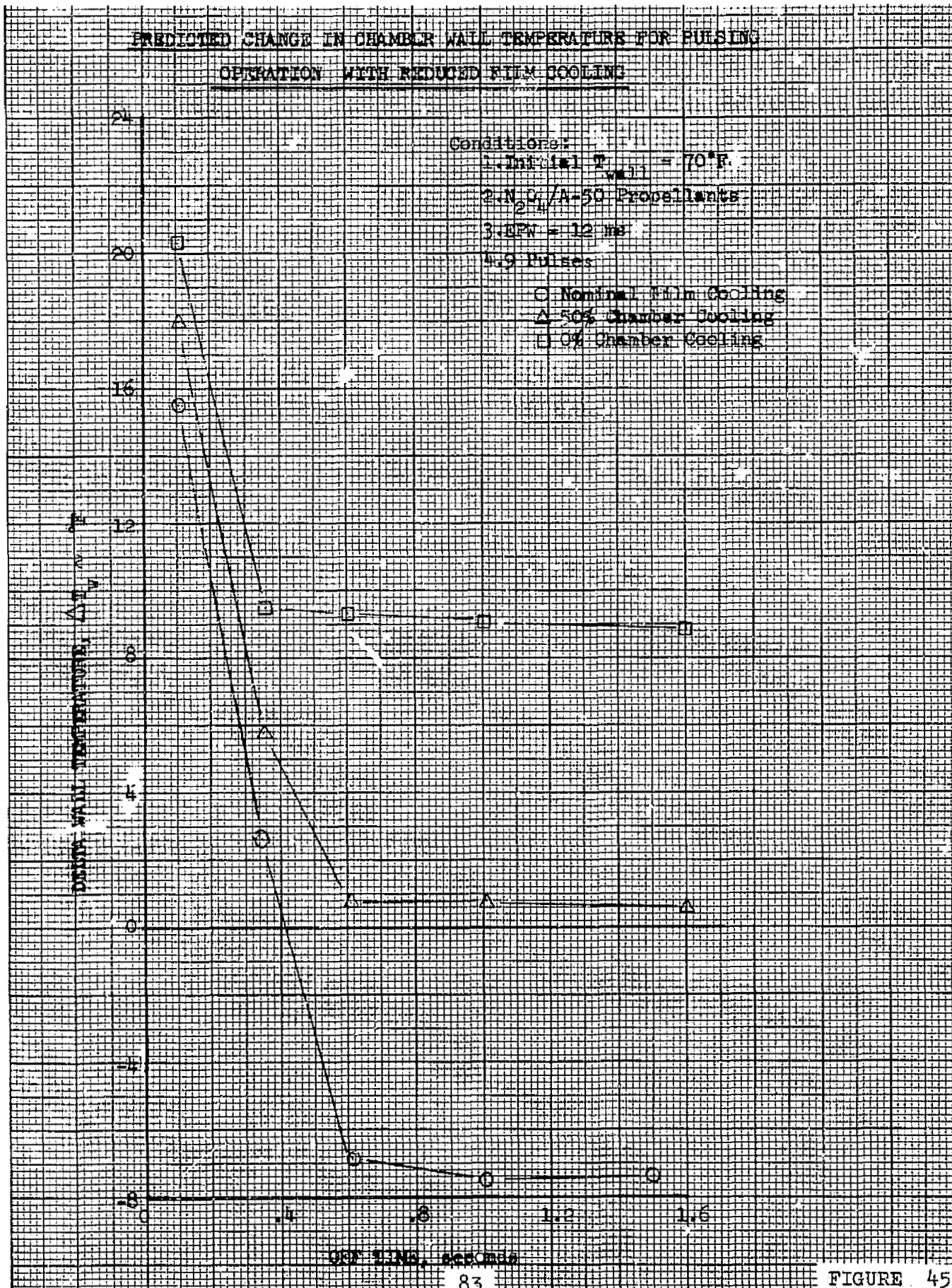


FIGURE 44



PREDICTED CHANGE IN CHAMBER WALL TEMPERATURE FOR PULSING
OPERATION WITH REDUCED FILM COOLING

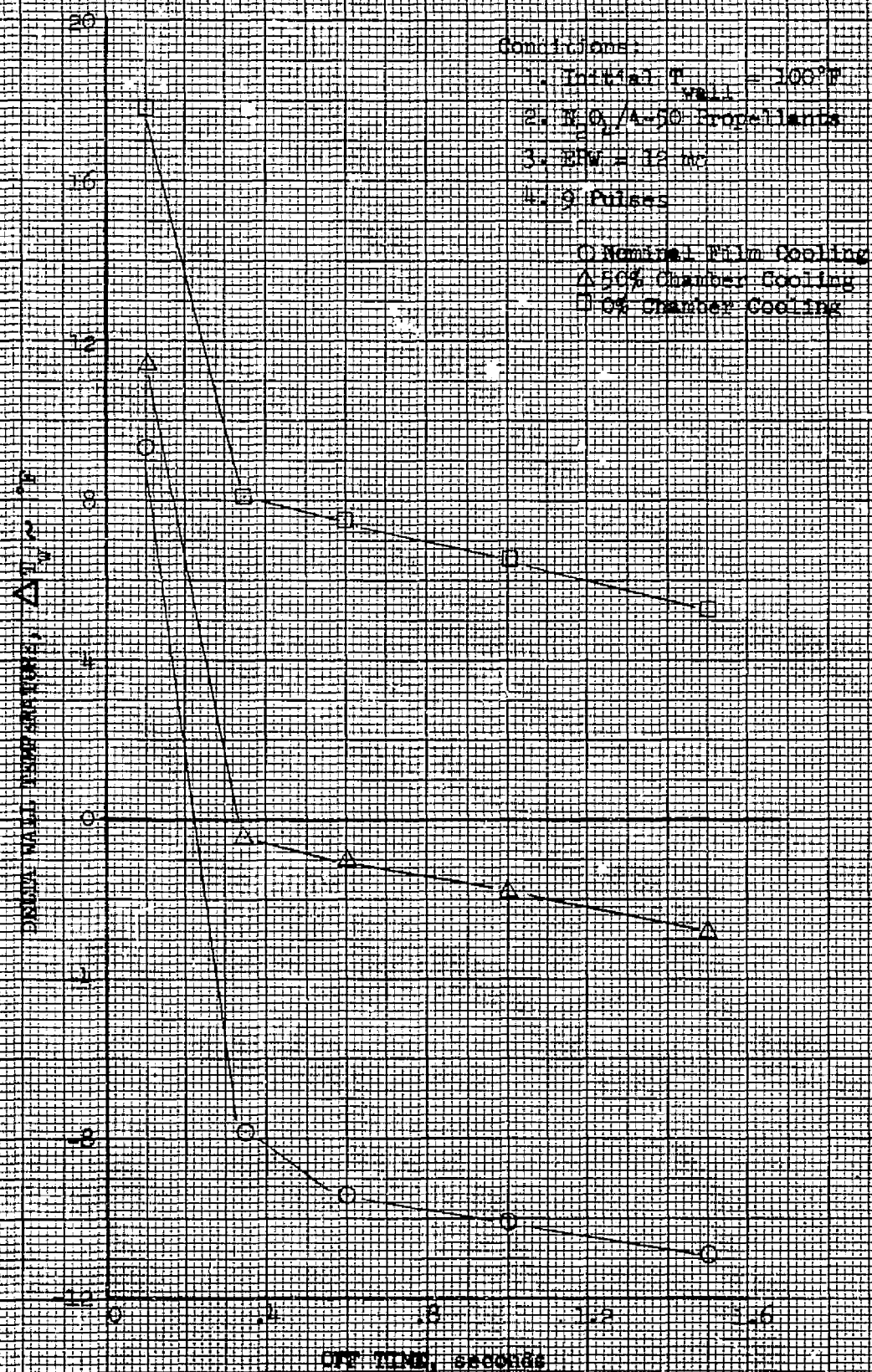


FIGURE 46

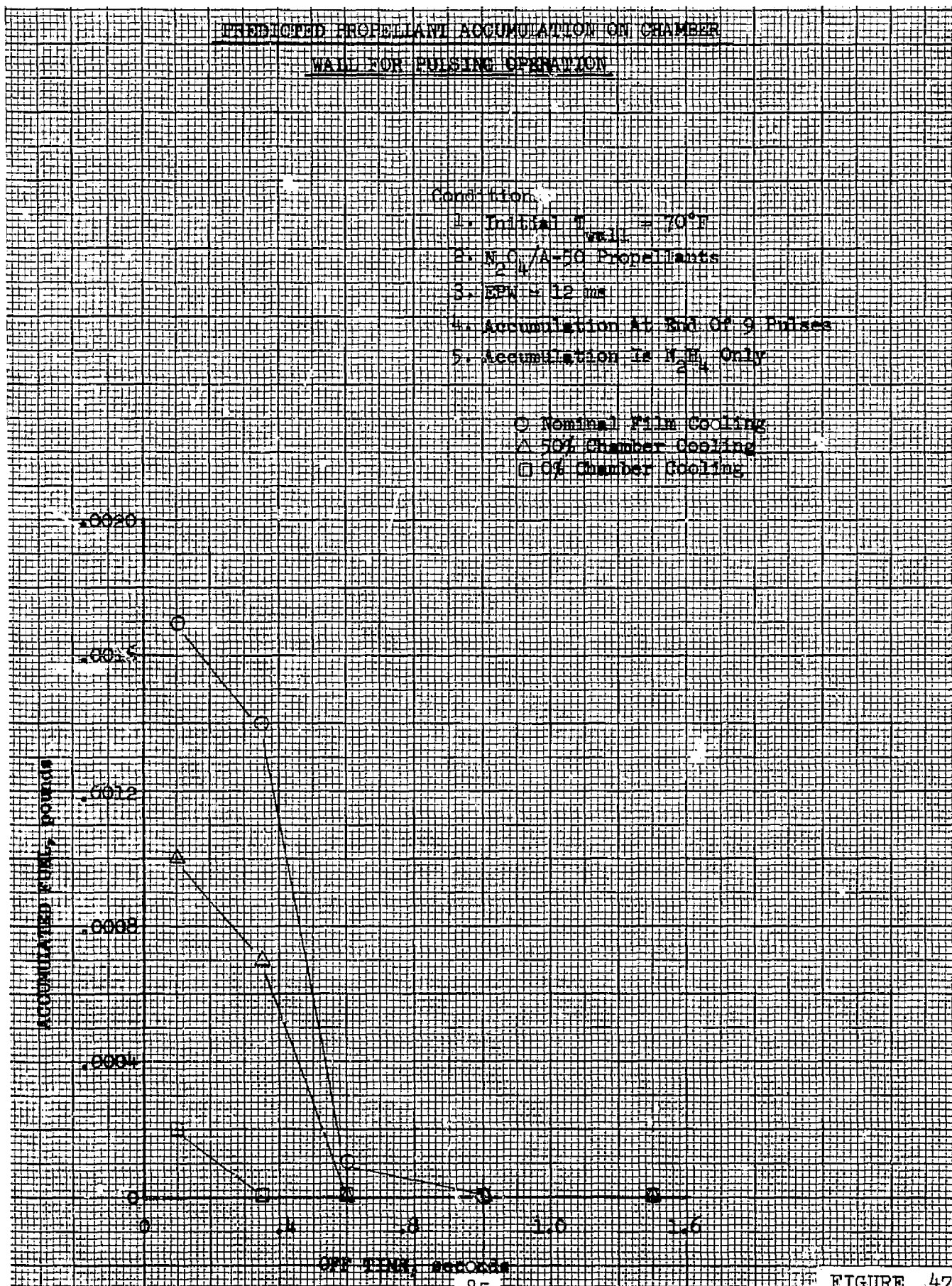


FIGURE 47

PREDICTED PROPELLANT ACCUMULATION ON CHAMBER
WALL FOR PULSED OPERATION

Conditions:

1. Initial $T_{wall} = 100^\circ F$
2. H₂O/A-50 propellant
3. EPW = 12 ms
4. Accumulation At End of 9 Pulses
5. Accumulation Is N₂H₄ only

○ Nominal Film Cooling
△ 50% Chamber Cooling
□ 0% Chamber Cooling

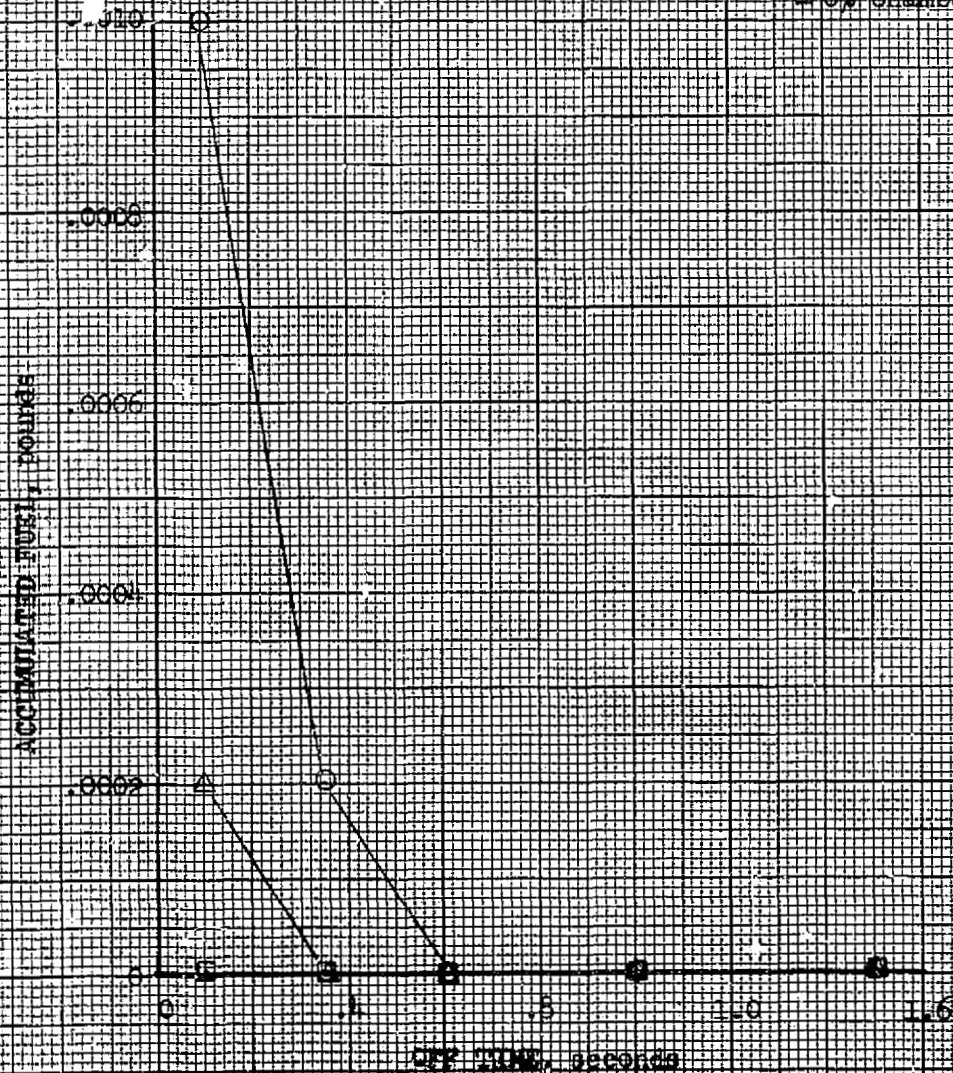


FIGURE 48

IV. CONCLUSIONS

From the pretest analysis conducted in support of The Reduced Fuel Cooling Effects Program, the following summarizing conclusions may be drawn:

1. Computer programs now exist which can determine the injector face hole diameters and inlet pressures necessary for engines similar to the R-4D.
2. The reduced fuel cooling configurations will equal or exceed the steady state and pulse mode specific impulse achieved with the nominal R-4D engine.
3. Steady state temperatures for some reduced fuel cooling engine configurations will be in excess of the safe limits, and therefore must be monitored continuously during test.
4. All reduced fuel cooling configurations will exhibit satisfactory ignition characteristics.
5. Residue accumulation studies indicate that the effect of reduced fuel cooling should be significant with possibly no overpressures occurring with zero cooling flow.

V.

LIST OF REFERENCES

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3. Christos, Theodore, et al, Exploratory Study of Hypergolic Ignition Spike Phenomena, United State Department of Interior, Bureau of Mines, Pittsburgh, Pennsylvania, Phase II, Part II, July 1 to September 30, 1966.