OCEAN SYSTEMS RESEARCH REPORT 91-2

Rapid Thermal Ice Penetrator

Report on Test Results Using a Higher Energy Propellant

James K. Andersen
Ocean Systems Research, Inc.
580 Bellerive Drive, Suite 5C
Annapolis, MD 21401

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Prepared for:

Dr. Arthur Horbach
Naval Air Development Center
Code 5031
Warminster, PA 18974-5000

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Ocean Systems Research, Inc. has developed a Rapid Thermal Ice Penetrator with a demonstrated capability to penetrate thick ice at rates in excess of 6 feet per minute. Successful field testing was demonstrated at the APLIS 91 Arctic Ice Camp where 10 feet, 4 inches of ice was penetrated in 120 seconds. This report addresses the feasibility of increasing the energy density of the fuel (solid propellant) to reduce system size and weight. The testing proved that a higher energy propellant will allow significant reductions in system size and weight.

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TABLE OF CONTENTS

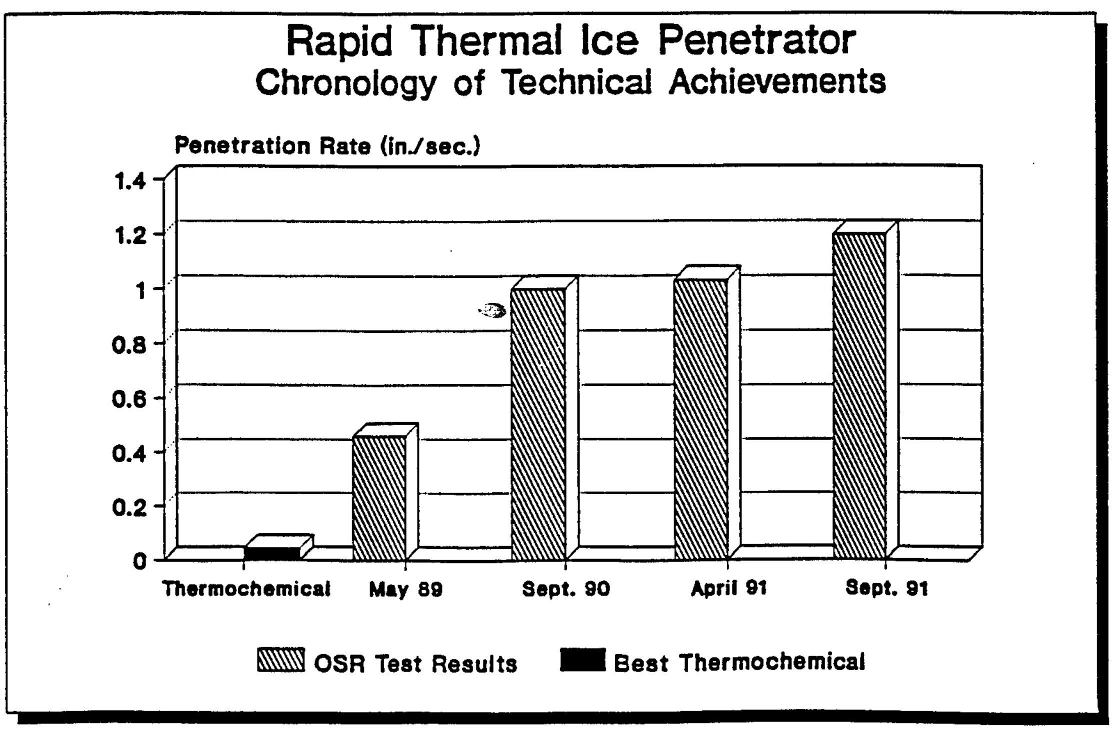
1.0 EXECUTIVE SUMMARY

Ocean Systems Research, Inc. under the sponsorship of the Naval Air Development Center and the Office of Naval Technology has recently completed testing modifications to their Rapid Thermal Ice Penetrator. The tests demonstrated that the use of higher energy propellants results in faster penetration, reduced propellant volume/weight, and a simplified design.

These tests, which were conducted through 10 foot thick columns of ice, clearly substantiated the performance advantages to be gained by increasing the energy content of the propellant. Using the same amount of propellant (21.3 pounds) as was used in our successful Arctic penetration test, the 10 foot ice column was penetrated in approximately 100 seconds. Since the total burn time was 141 seconds, this indicates that 30 percent of the propellant can be eliminated, while still achieving complete penetration through 10 feet of ice.

We predict that with additional increases in propellant energy content, and further refinements to the nozzle to increase melting efficiency, we can reduce propellant volume by more than 40 percent as compared to our Arctic tests.

The chart below highlights chronologically, the technological advancements made in the Rapid Thermal Ice Penetration program to date, along with a comparison with the competing thermochemical approach.



Although this contract dealt only with improvements to the ice penetrator itself, it should be noted that many significant technical hurdles have already been overcome in the development of the uprighting device. A necessary component of the autonomous ice penetrating sensor package, the uprighter raises the entire penetrator from horizontal to vertical once it has come to rest on the ice, and it provides guidance for the penetrator body during initial penetration into the ice. The prototype "A" size uprighter devices fabricated for Arctic testing, used a combination of high tension coil and leaf springs, and 6 legs that encircled the penetrator body, with a maximum thickness of .43 inches and a weight of less than 10 pounds. Successful operation of the device was demonstrated (with a 50 pound system weight) at APLIS 91.

The uprighter device also incorporated a revolutionary remote release device. No existing release mechanism could be found that could hold the 200 pound spring force, release it upon demand, and fit within our size constraints. OSR therefore designed, built, and tested a special release device that weighed less than an ounce, was capable of holding over 500 pounds, yet could be instantaneously released by a small 9.6 volt battery pack. The device, which was totally inert (i.e., contained no explosives or pyrotechnic devices), performed reliably in every Arctic test. This remote release technology has enormous potential for any application requiring extremely high release forces.

2.0 BACKGROUND

At the APLIS 91 ice camp, OSR, under the sponsorship of the Naval Air Development Center and the Office of Naval Technology, successfully demonstrated the ability to autonomously penetrate 10 feet of ice in under two minutes. This represented a major milestone towards the ultimate goal of this program, which is to develop an air deployable ice penetrating sensor package that fits within the standard "A" size configuration (i.e., 36 inches long by 4 7/8 O.D.). The units tested in the Arctic included a fully self-contained uprighting device (see Figures 1A and 1B) that uprighted the penetrator from horizontal to vertical and provided initial guidance to ensure vertical penetration.

In order to stay within the size constraints of the "A" size configuration, however, and still allow a sufficient volume for the sensor payload, the volume of propellent must be reduced. Based upon the size of the units tested at APLIS 91, this reduction in propellant volume must be on the order of 30-40 percent. The most straightforward method of achieving this reduction in propellant volume is by using a propellant with a higher energy density. Although our analytical model indicated that increasing the energy content of the propellant allows a reduction in propellant volume for the same depth of penetration, this had never been tested. All of the previous ice penetration testing performed by OSR had used the same basic propellant. This testing effort, therefore, was undertaken to determine if, in fact, use of higher energy propellants would lead to the significant reductions in propellant volume needed to meet the program requirements.

3.0 DESCRIPTION OF HARDWARE

The purpose of this testing effort was to prove that increasing the energy density of the propellant would singularly lead to decreased propellant volume requirements. Therefore, in order to keep costs low and to limit the introduction of new variables, the existing design and (where possible) hardware was used for this testing. Accordingly, two of the motor cases that had been used in the Arctic tests were refurbished. In addition, two nozzle closures used in the Arctic tests were also refurbished by burning out the nozzle inserts and insulator material, and by welding over the

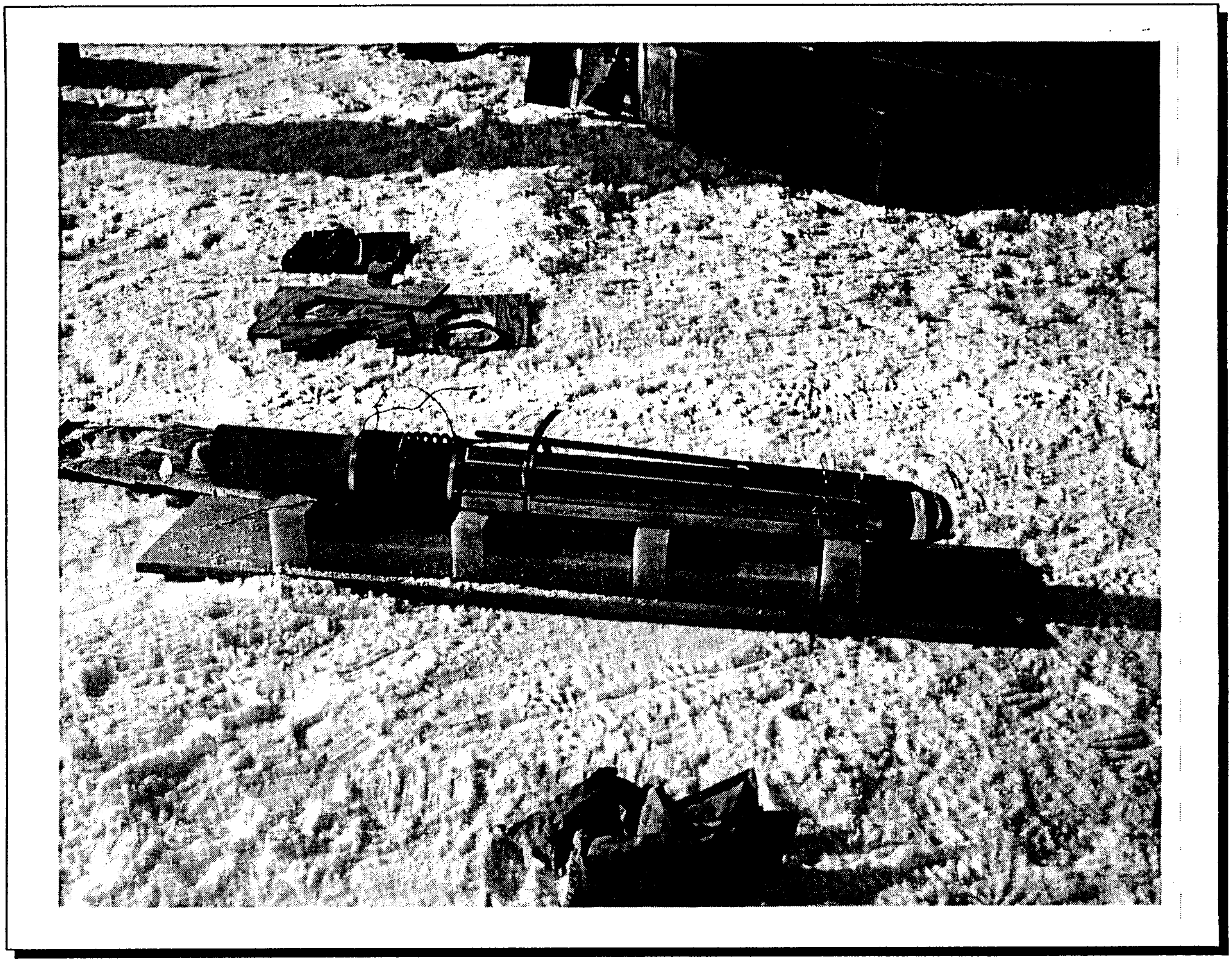


Figure 1A Uprighter Device in Closed Position
(Shown on pallet with ice penetrator inserted, prior to installation of release mechanism band clamp.)

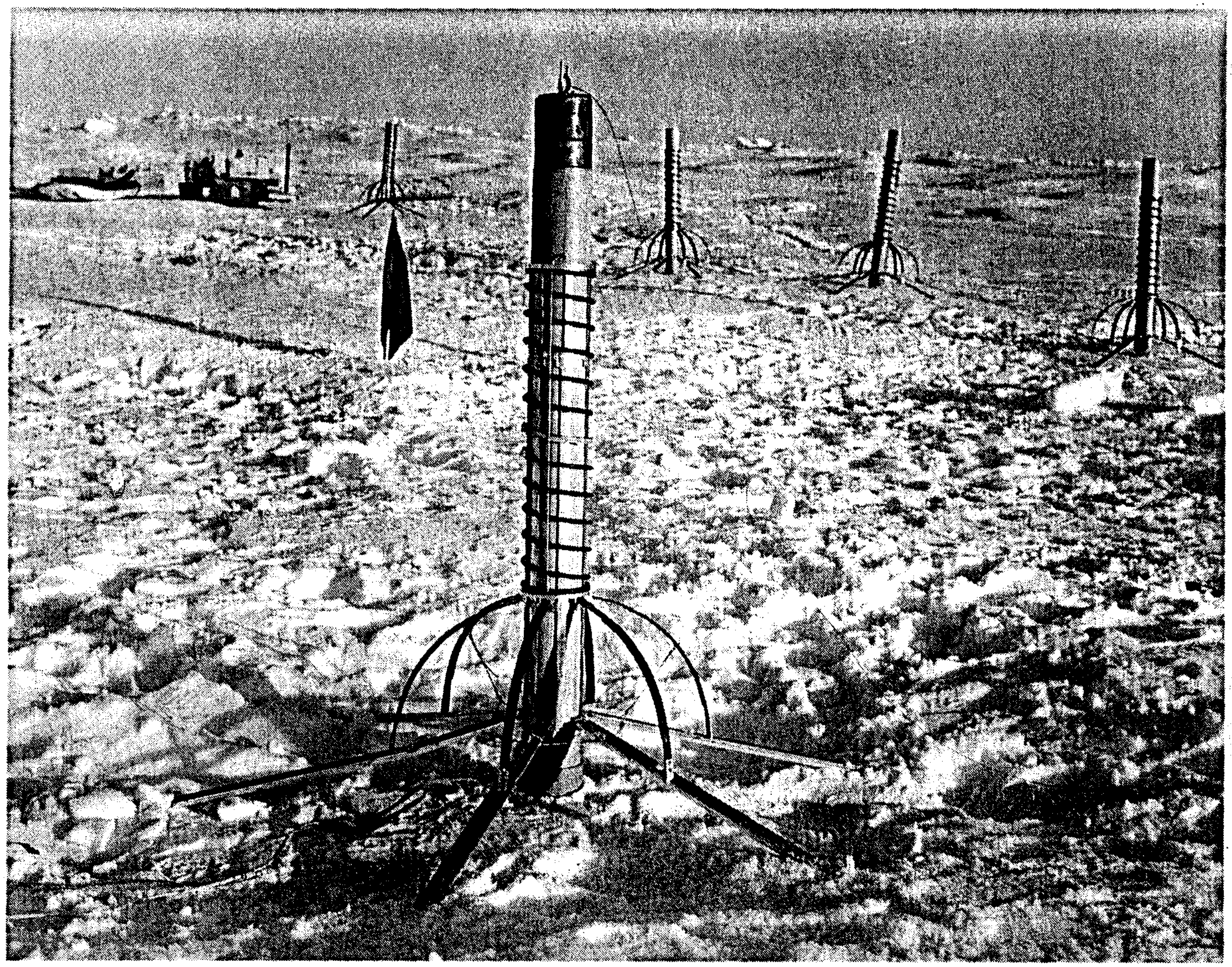


Figure 1B Uprighter Device In Open Position existing nozzle openings. Thus the external envelope, size, and configuration of these test units was identical to those tested in the Arctic.

To reduce the potential for clogging of the nozzles (as was experienced during the Arctic testing), several changes were made to the internal materials and configuration. Post test analysis of the Arctic units indicated that glass was the primary constituent of the substance clogging the nozzles. Since glass was a major component of the insulator used for the Arctic tests, an alternate insulator material was selected for these tests. The insulator selected was a Kevlar based EPDM with no appreciable glass content.

The internal nozzle configuration and materials were also changed. The erosion characteristics of the higher energy propellant are somewhat different than the propellants used in earlier testing. The Arctic units utilized a molybdenum nozzle insert whereas the new units used a 4-D carbon-carbon matrix insert. This change was required for several reasons. The higher energy propellant burns at a higher flame temperature, which is above the operating region for the molybdenum. In addition, the increased particulate content of the higher energy propellant exhaust tends to erode the molybdenum. Lastly, the increase in percentage of aluminum (fuel) decreases the free oxygen in the combustion products thereby reducing the reactivity of those gases with carbon. One added benefit from the switch to the carbon insert is that it is much easier to machine/fabricate.

Following the August 30 test, inspection revealed significant erosion occurred in the silica phenolic insulator used in the nozzle closure. To prevent the recurrence of this erosion, the silica phenolic insulator was burned out and replaced with a carbon phenolic for the second test (tested 16 September).

The configuration of the nozzle insert was also modified to eliminate any obstructions in the exhaust flowpath that could potentially lead to clogging of the nozzles. Figures 2A & B highlight these differences. Note that the Arctic units (Figure 2A) had several steps/ledges where material could coagulate. These steps/ledges were eliminated in the two latest unit tested. (See Figure 2B.)

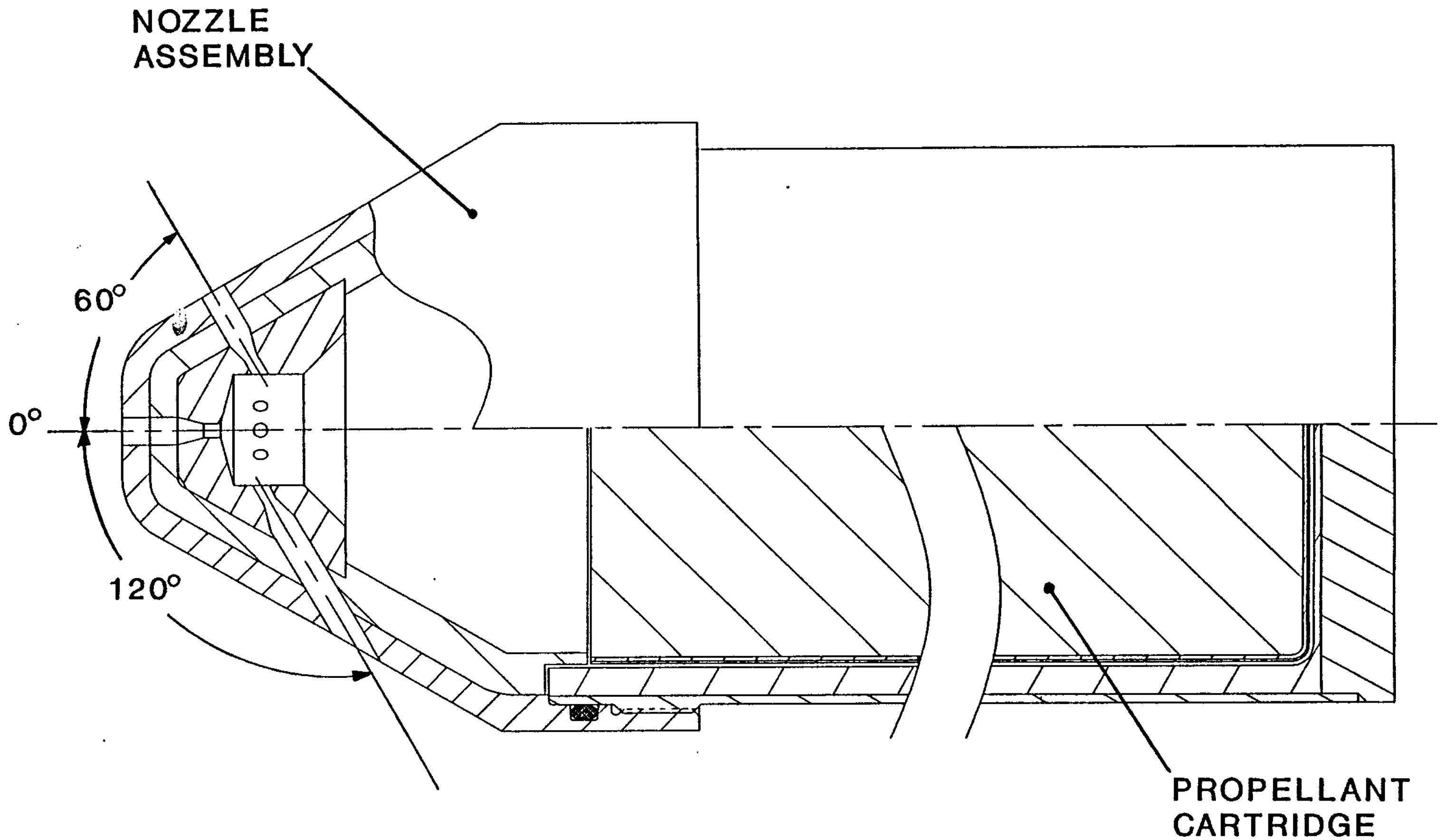


Figure 2A Nozzle Configuration - Arctic Units

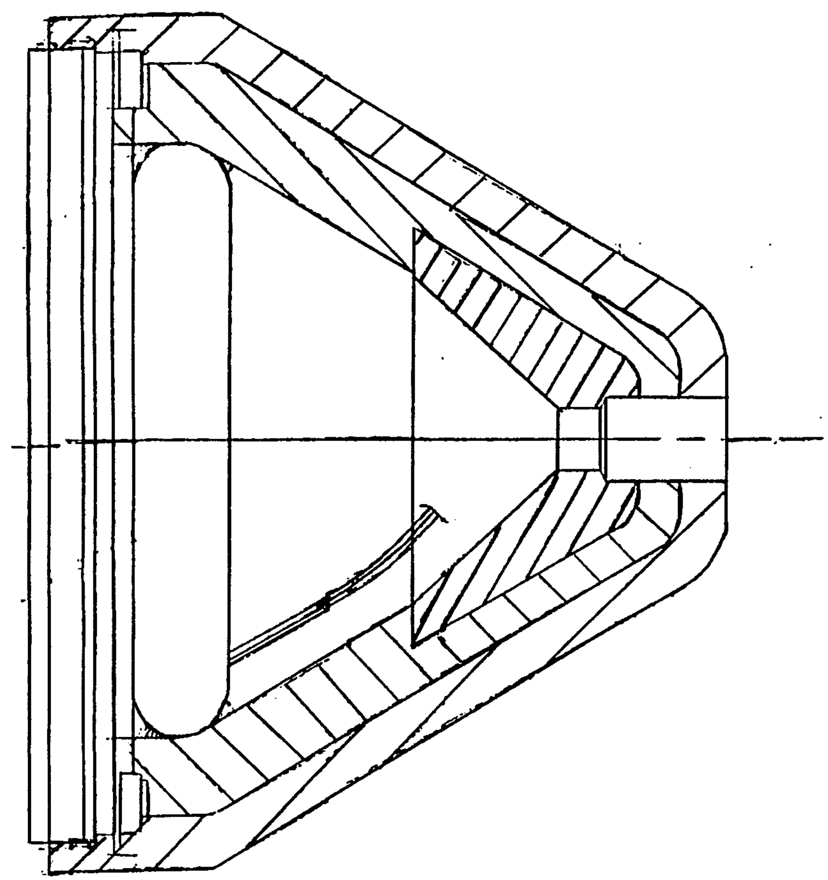


Figure 2B Nozzle Configuration - High Energy Units

3.1 Propellant Selection

The average energy content of the propellants tested prior to this effort was approximately 2300 Btu/Lbm. Our goal for this testing effort was to select a propellant with an energy content of over 3000 Btu/Lbm, however, due to other design and performance considerations a slightly lower energy propellant was selected. The propellant chosen for these tests had an energy content of approximately 2900 Btu/Lbm.

The following rationale was used in the propellant selection process. Figure 3 shows several possible propellant formulations suitable for this application. From Figure 3 it is readily apparent that flame temperature, as well as energy content (Btu/Lbm), increases almost linearly with increasing aluminum content in the propellant. Based upon this chart alone it would seem that propellant TP-3340 with 18 percent aluminum is a good choice. Among the other factors that had to be considered, however, are propellant mass flow rate and chamber pressure. All of our previous tests were designed to produce a mass flow rate of between 0.14 and 0.16 Lbm/sec (see Figure 4). This mass flow rate results in a approximate 2 to 2 1/2 minute burn time for the given propellant load. From Figure 4 one can see that in order to achieve a mass flow in the desired operational region using the TP-3340 propellant, a chamber pressure in excess of 1000 psia would be required.

Since the existing cases were designed for a 500 psia chamber pressure, a 1000 psia chamber pressure would require that new cases be fabricated. The higher pressure would also require a smaller nozzle diameter which is contrary to our desire to reduce the potential for nozzle clogging. Alternately, operating with the TP-3340 propellant at under 500 psia results in a mass flow rate of approximately 0.10 Lbm/sec, which translates into a burn time of approximately 3.5 minutes for the 21.0 lb propellant load. This burn time was deemed to be too far outside the 2.0 minute requirement. Propellant TP-3396 was therefore chosen because its mass flow rate (at 300 psia) provided us with the desired burn time, and its energy content of approximately 2900 Btu/Lbm was high enough above the previously tested propellants to provide us with appropriate performance characteristics.

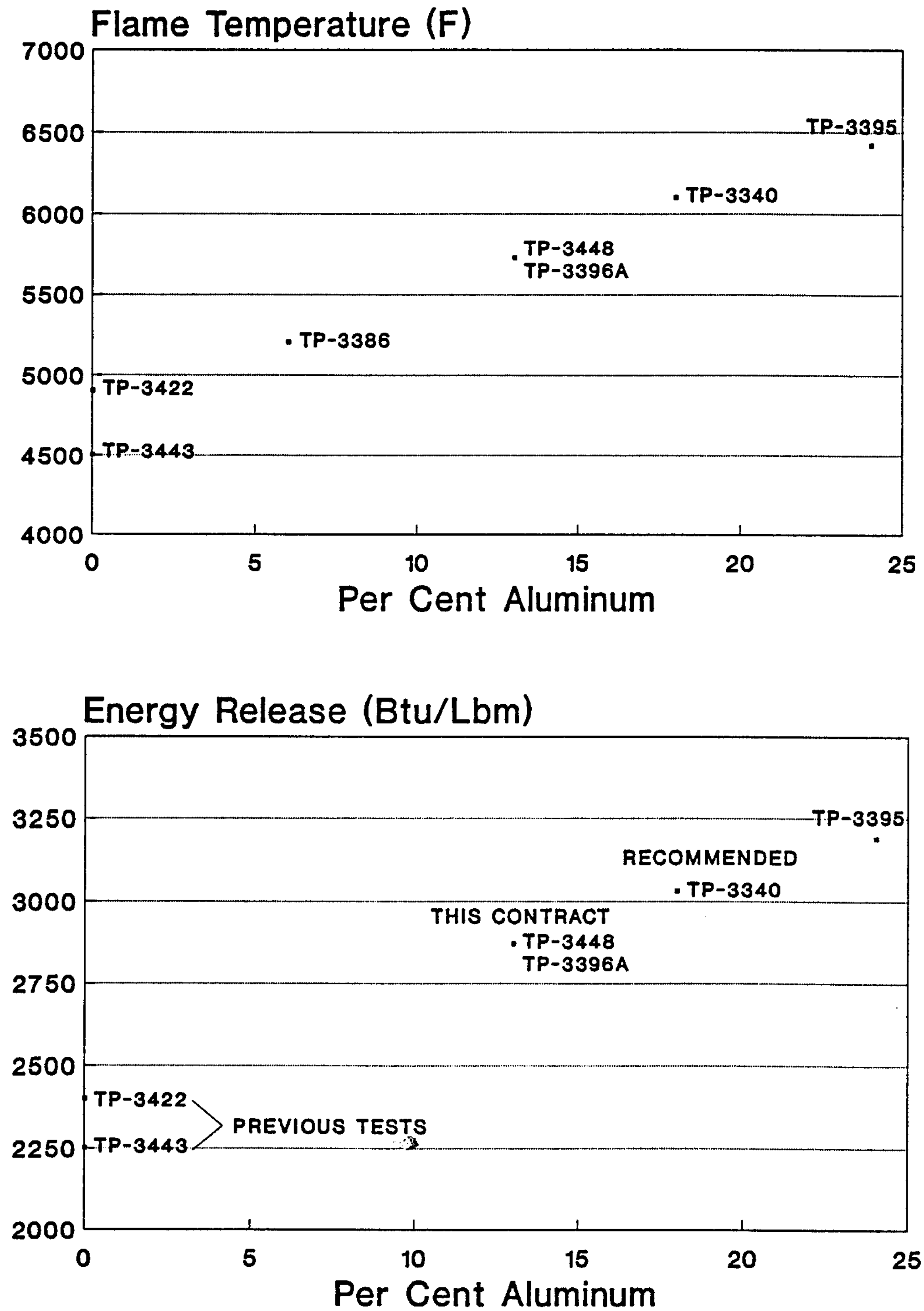


Figure 3 Propellant Characteristics

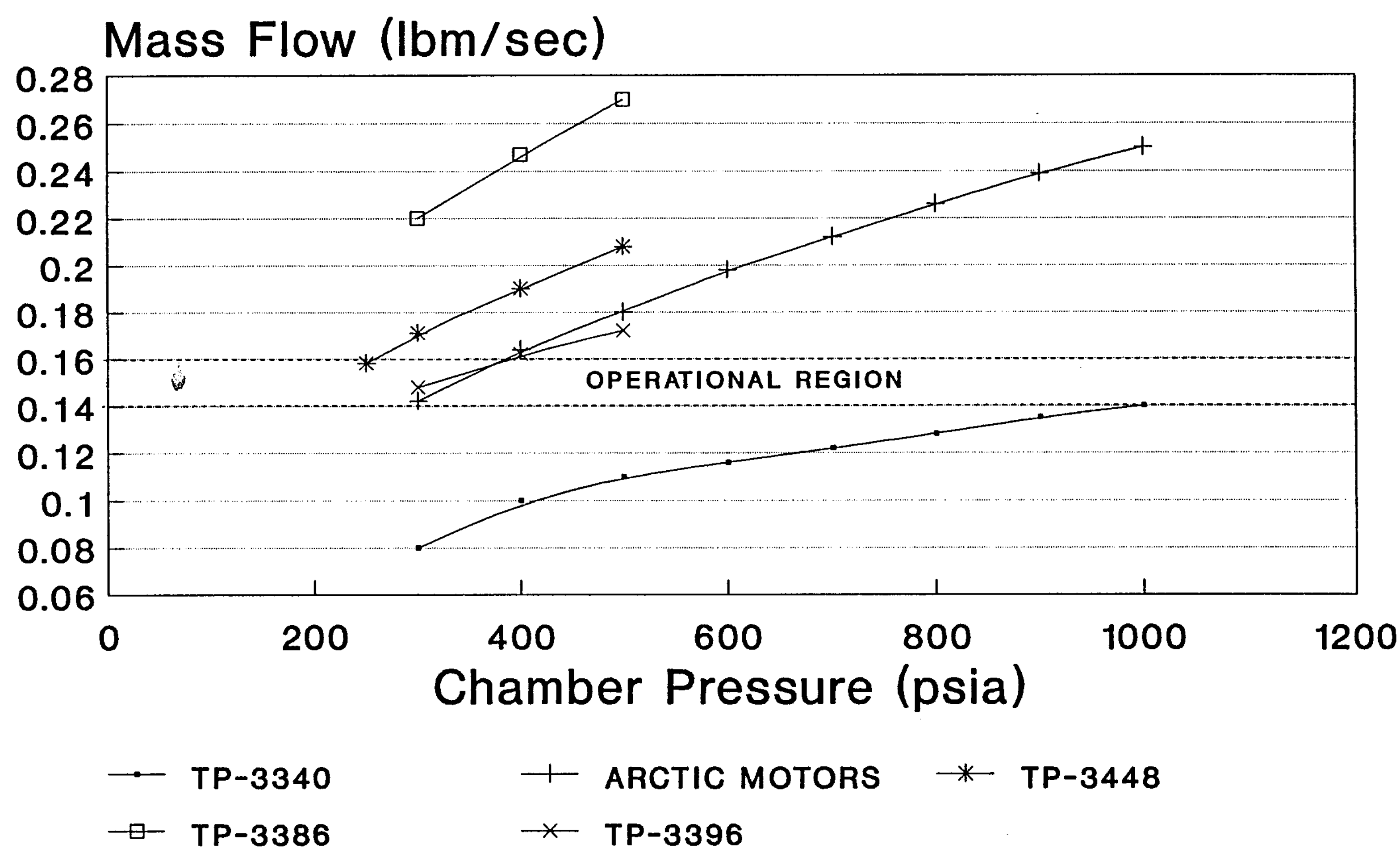


Figure 4 Propellant Mass Flow Comparison

4.0 TESTING

4.1 Test #1

The first of the two ice penetrator tests using a higher energy propellant was conducted on 30 August. The motor contained approximately 21.3 pounds of propellant with an energy content of about 2900 Btu/Lbm. It had one forward facing 0.313 diameter central nozzle, and two 0.85 diameter nozzles diametrically opposed at 120° for reverse thrust. The test setup was similar to previous tests (see Figure 5) in that the penetrator was mounted atop a 3 foot by 3 foot by 10 foot tall ice block. An absolute encoder was attached to the rear of the penetrator body for penetration distance vs. time measurements.

Following ignition, the motor penetrated approximately 2 feet of ice in just over 20 seconds, then appeared to stop moving. The motor went on to burn for approximately 3 minutes and 10 seconds, achieving a final penetration depth of about 4 feet. Post test inspection revealed that the forward nozzle, as well as one of the reverse facing nozzles, had become totally clogged. The one remaining nozzle opened up significantly, thus explaining the extended burn time. The material blocking the two nozzles was found to be aluminum (a constituent added to the propellant to increase flame temperature). A detailed review of the video tape recording of the test indicated that clogging of the forward nozzle began at about 5 seconds and it appeared fully clogged around 20 seconds.

4.2 Test #2

The second ice penetrator test using the high energy propellant was conducted on 16 September. The motor contained 21.32 pounds of propellant with an energy content of about 2900 Btu/Lbm. It had a single, forward facing central nozzle with a diameter of 0.325 inches. It was designed to operate at a chamber pressure of 282 psia with an average mass flow rate of 0.152 Lbm/sec. Total predicted burn time was 140 seconds. Approximately 30 pounds was added to the rear of the penetrator giving it a total weight of about 70 pounds. To prevent the motor from starting with the nozzle flush against the ice surface, an extender cup was welded to the front of the nozzle (see Figure 6).

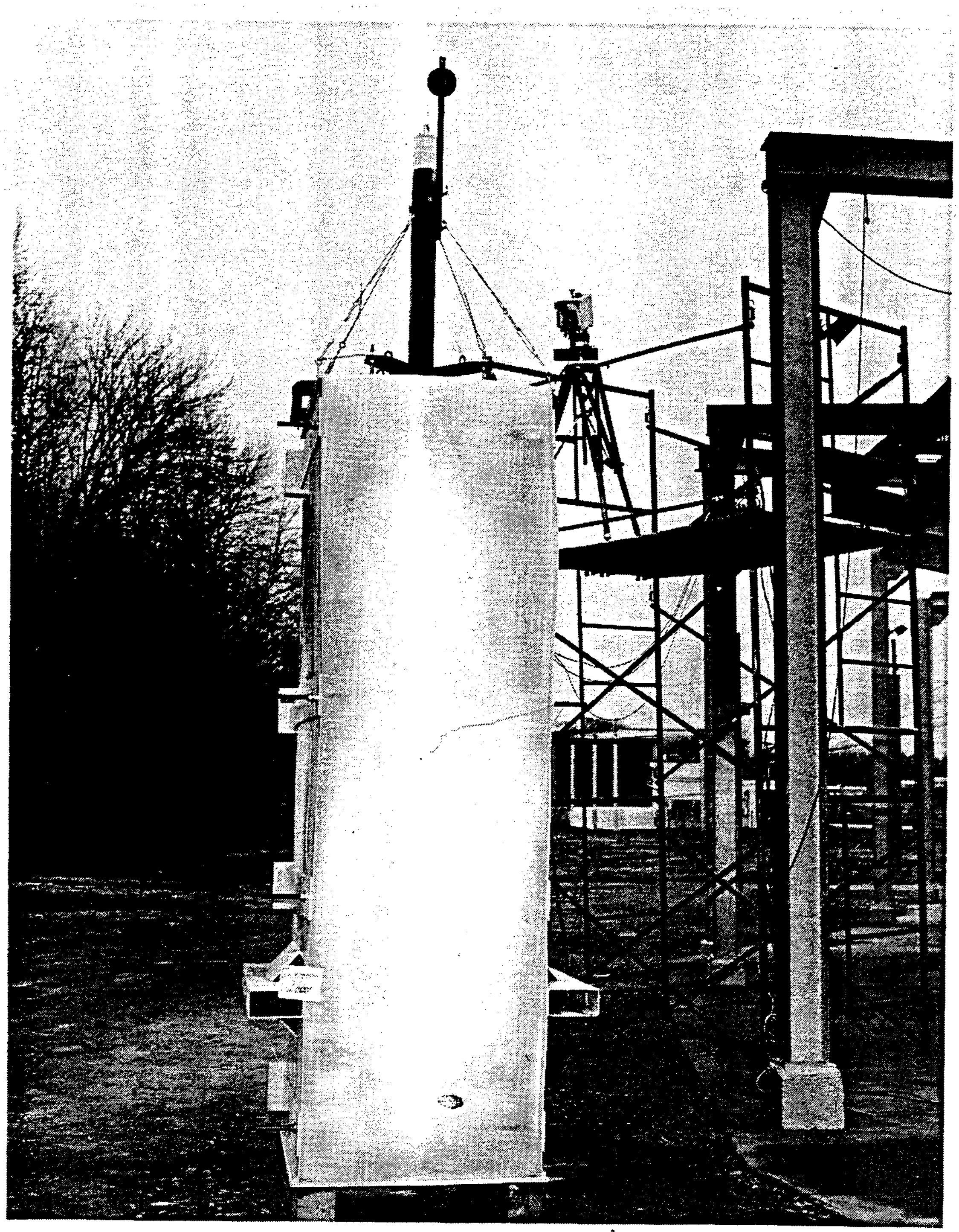


Figure 5 In-House Test Arrangement
(Ice Penetrator mounted in hollow tube atop 10 foot tall by 3 foot square ice block.)

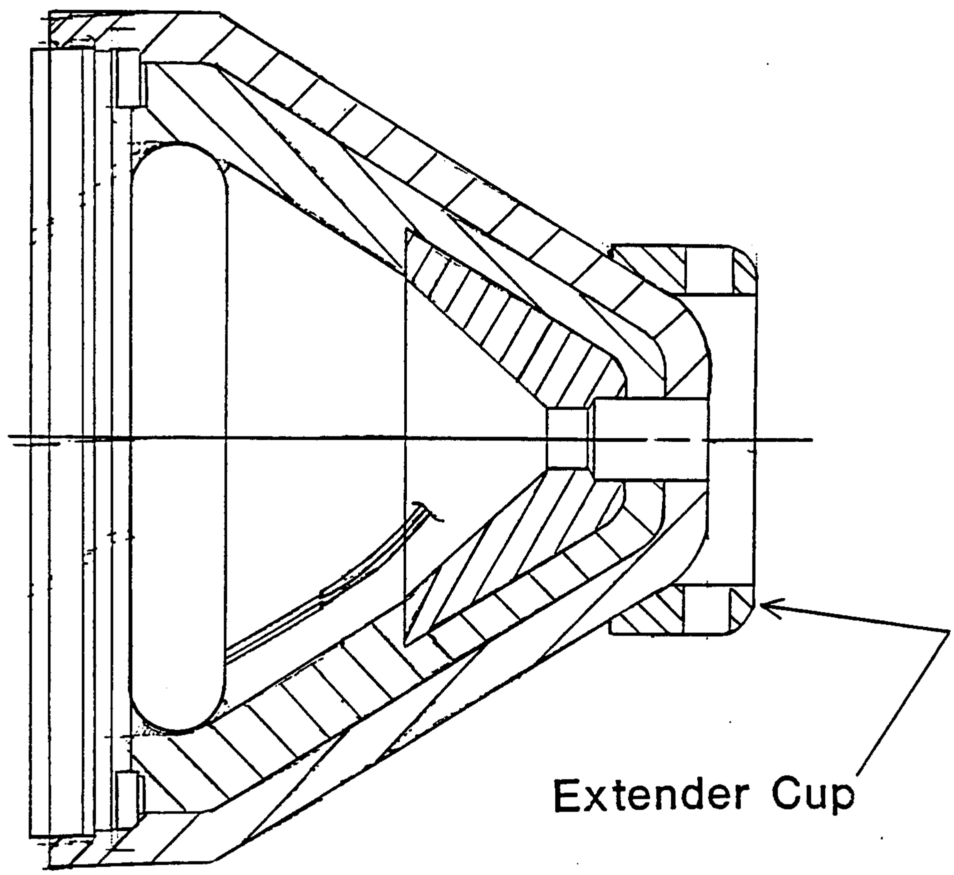


Figure 6 Penetrator Nozzle With Extender Cup

Prior to the test, two cracks were noted in the front surface of the ice, but their cause could not be determined as to the cause of the cracks. Two possible explanations are that they occurred during transport (via forklift) from the cold chamber to the test site, or that they were caused by thermal stresses due to the 90+ degree ambient temperature. Following ignition, the motor began penetrating the ice immediately. The average penetration rate was approximately 1.2 inches per second. Penetration occurred at about 1 minute 40 seconds, and the motor continued to burn for approximately 2 minutes, 21 seconds. The resultant hole was 6 to 6.5 inches in diameter and appeared perfectly vertical (see Figure 7).

5.0 ANALYTICAL MODELING

The analytical model developed by OSR under a previous NADC contract was used to help evaluate the various nozzle configurations prior to fabrication and testing. In addition, following each test, the actual results were used to improve the model's correlation.

As stated previously in this report, the penetrator used in test #1 had one central downward facing nozzle and two reverse acting nozzles. The predicted burn time was 131 seconds, and the predicted thrust was approximately 23 pounds. The model predicted penetration in approximately 95 seconds (see Figure 8A) unfortunately, the nozzle clogged during the test and successful penetration was not achieved.

Test #2 utilized the same propellant as test #1, however it had only one central nozzle. The predicted thrust was approximately 28 pounds. The model predicted penetration in approximately 110 seconds (see Figure 8B). The total system weight of the Test #2 unit was approximately 70 pounds. To depict the effect of thrust on penetration rate, Figure 8C shows that due to its higher thrust, the Test #2 unit would not penetrate 10 feet of ice if its weight were reduced to 50 pounds.

A copy of the computer code including the required model inputs is provided in Appendix A. The theoretical ice penetrator performance data for the Test #2 unit is provided in Appendix B.

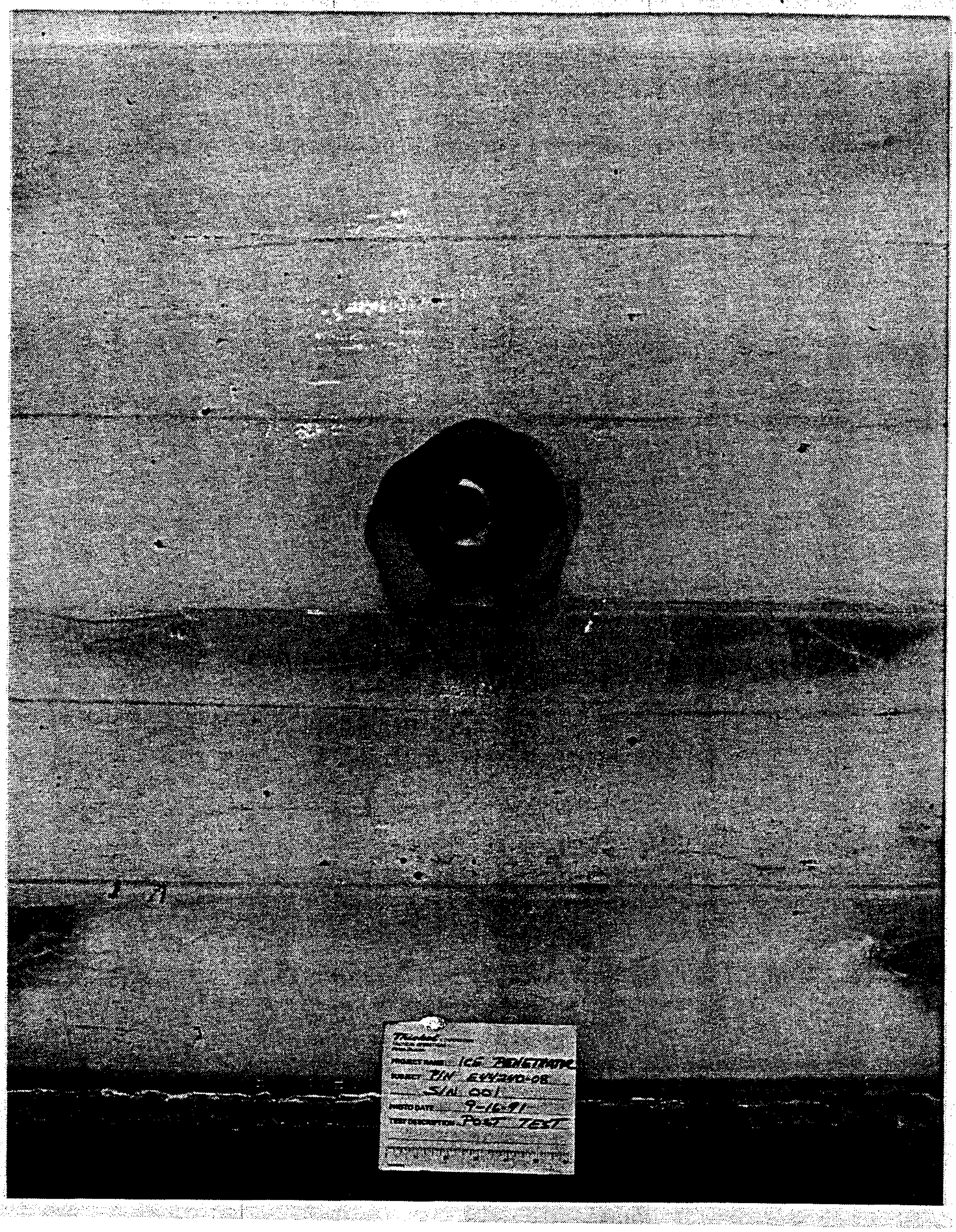


Figure 7 Test #2 Results
(Nearly vertical through the 10 foot thickness)

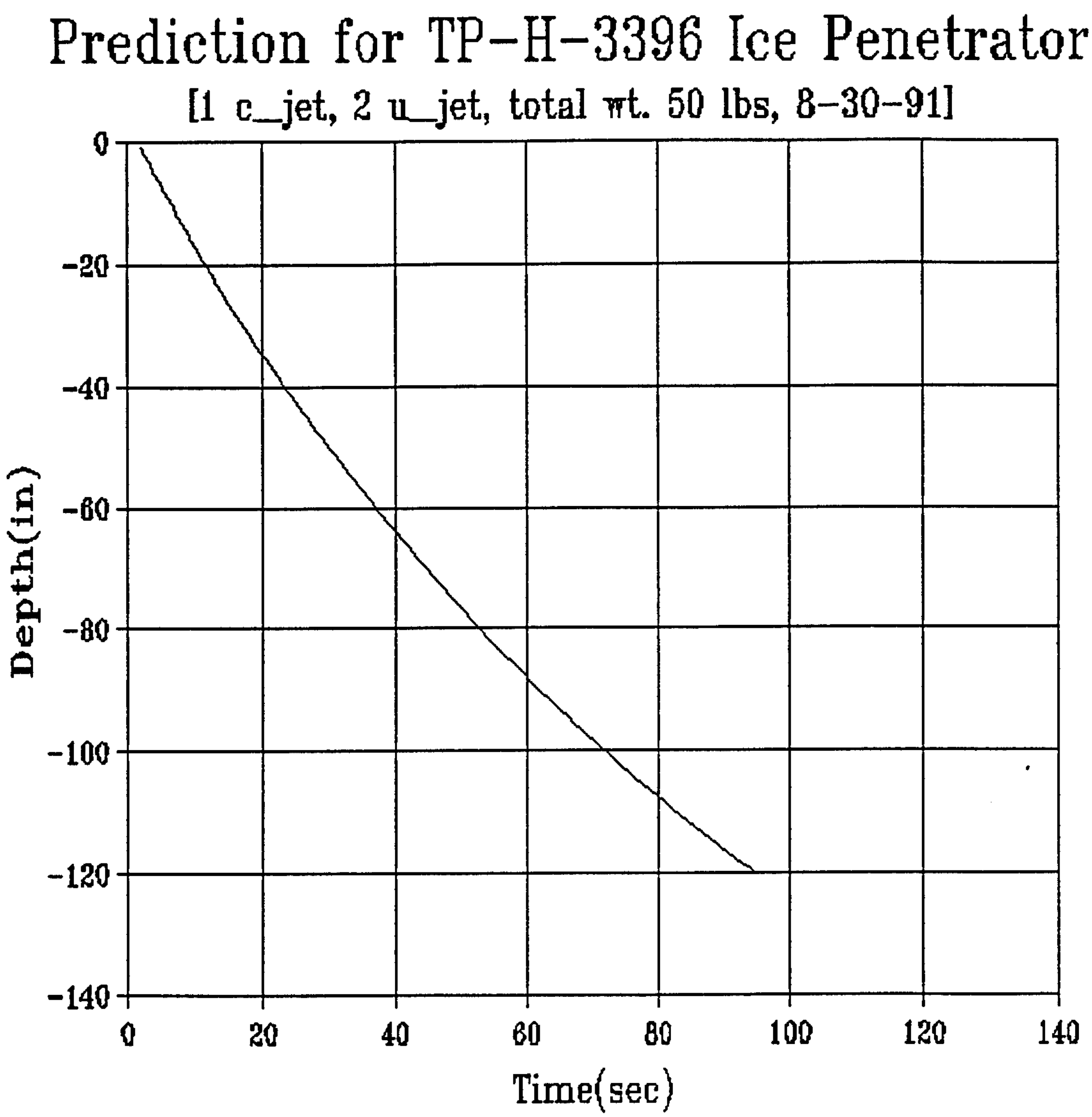


Figure 8A Model Prediction - Test #1

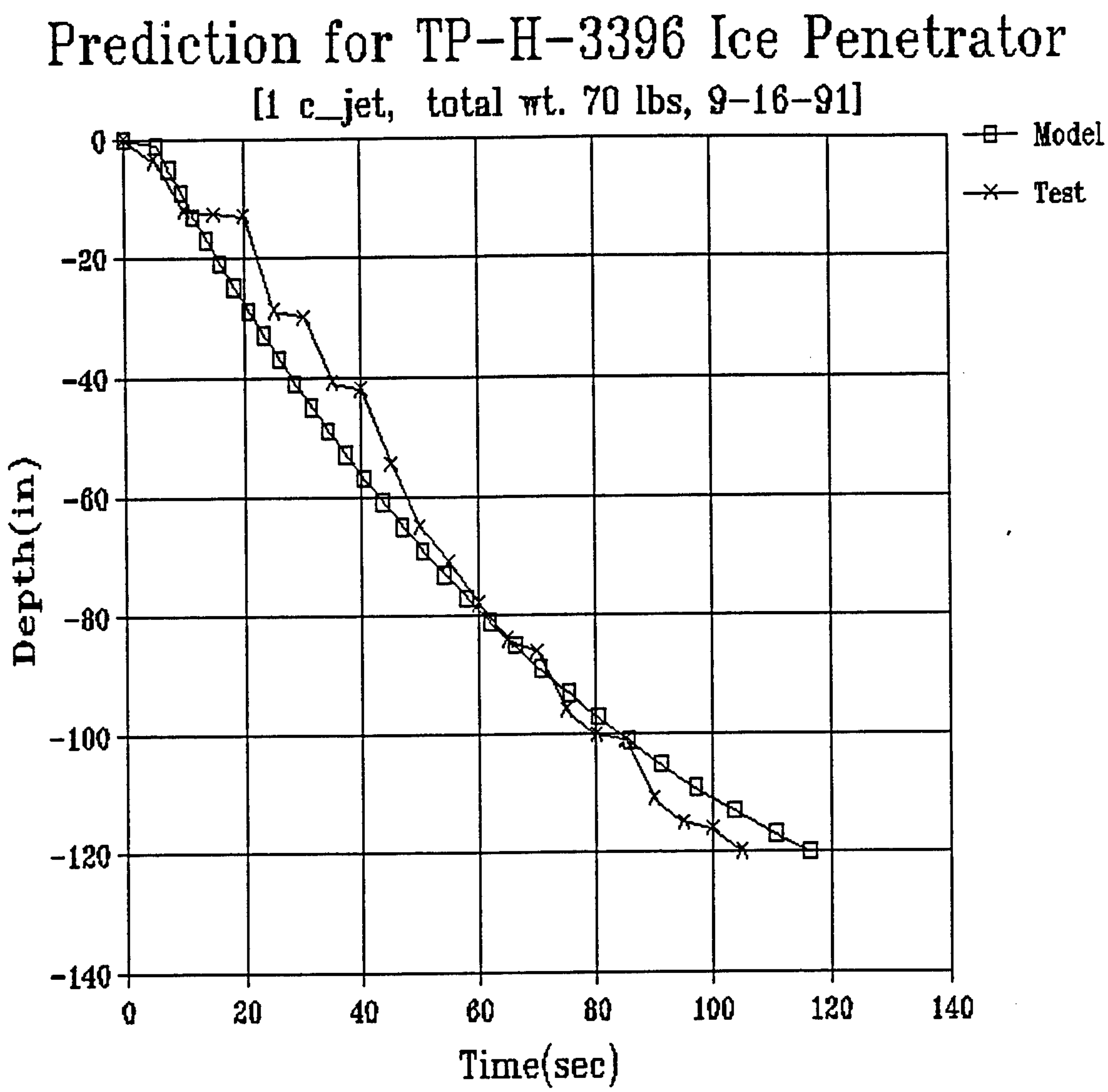


Figure 8B Model Prediction - Test #2

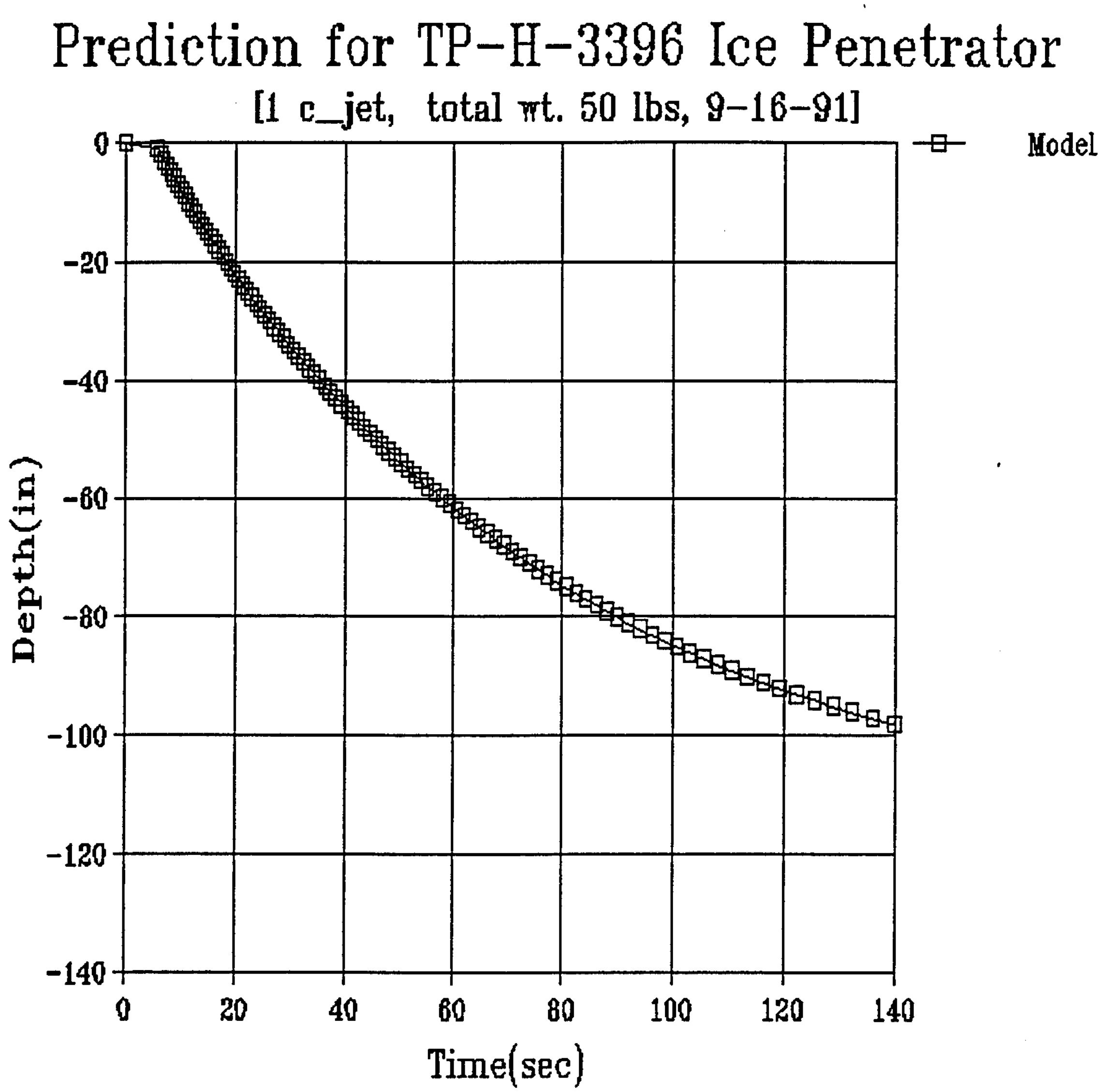


Figure 8C Model Prediction - Test #2 (Reduced Weight)

6.0 CONCLUSIONS/LESSONS LEARNED

Based upon this successful testing using a higher energy propellant, several conclusions were reached, i.e.,

- Use of the higher energy propellant makes an "A" size sensor package very feasible.
- A single central nozzle eliminates the nozzle clogging problem.
- Spinning is not required for vertical penetration over the 10 foot ice thickness.

The average penetration rate of 1.2 inches per second is our fastest to date. The single central nozzle also appears to be the most efficient design. It produced the smallest diameter (approximately 6 inches), and the smoothest and straightest hole to date.

Although the test program was a tremendous success there are still some areas requiring additional work. Since this was a propellant improvement program only, no improvements to the autonomous uprighting device were made. With regard to the ice penetrator motors, however, we feel very strongly that virtually every problem/risk area has been worked out, save one. The only remaining effort standing in the way of fully self contained "A" size ice penetrator/sensor package is a nozzle study/test program to reduce the thrust from over 20 pounds to approximately 5 pounds.

There are several options available for reducing the thrust including adjusting the propellant properties, varying the chamber pressure, adding a diffuser to the nozzle, etc. It is anticipated that the final low thrust design will incorporate some or all the these modifications. Based upon the outcome of these two tests, however, it is clear that increasing the energy density of the propellant increases the amount of ice melted per pound of propellant. The positive effect of this finding is that we can now use energy release rate (i.e., Btu/Lbm) rather than mass flow rate as a primary characteristic for propellant selection. Since this no longer locks us in to the 0.14 to 16 Lbm/sec mass flow rate, even higher energy, lower burn rate propellants now become excellent candidates. Of course, the lower burn rates mean lower mass flow rates which translates into reduced thrust. And fortunately, since the future propellant loads will be shorter, a reduced burn rate will be needed to achieve the total burn time required (i.e., 2 - 3 minutes).

APPENDIX A

```
-----Ocean Systems Research Ice Penetration Model (09-29-91)(K. Tzou)
*    user's information
-----------------------------------------------------------
      Input data
*
*     Ice(in) = Total Depth of Ice
      W_total(Lbs) = Initial total weight of the system
      W_propel(Lbs)= Initial total weight of the propellant
*     B_rate(Lbs/sec)  = Burning rate of the propellant
      N_cjet = No. of center jet
      N_dj1  = No. of down-ward jet type#1
*     N_dj2  = No. of down-ward jet type#2
      N_ujet = No. of up-ward jet
      d_cjet(in)= diameter of center jet
*     d_dj1 (in)= diameter of down-ward jet type#1
*     d_dj2 (in)= diameter of down-ward jet type#2
      d_ujet(in)= diameter of up-ward jet
*     ang_cjet(deg)= angle of center jet
*     ang_dj1 (deg)= angle of down-ward jet type#1
      ang_dj2 (deg)= angle of down-ward jet type#2
      ang_ujet(deg)= angle of up-ward jet
*     Dia(in)      = diameter of the ice penetrator
      Height (in)  = height of the ice penetrator
      son_vel(m/sec)= sonic velocity (from Thiokol)
*     Mach          = Mach number    (from Thiokol)
*     Rho(g/cc)     = exit gas density (from Thiokol)
      Vis(lbf-sec/ft**2) = exit gas viscosity (from Thiokol)
-     Spe. Heat(cal/gm-degK)= exit gas specif heat (from Thiokol)
*     Pr            = Exit gas mixture Prandtl number(from Thiokol)
      c_time, c_gwo, c_cro, t_start : correlation coefficients
-----------------------------------------------------------------
*     Output Results

      time (sec) : time in seconds
*     Depth(in)  : depth in inches
*     Weight(Lbs): total remaining weight
      v(in/sec)  : rate of penetration
*-----------------------------------------------
-----------------------------------------------
 1) prepare an input file called "sep_70.inp".

  TP-H-3396 Propellant - September 16, 1991
 *---------*---------*---------*---------*---------*
  Ice (in)   W_total  W_Propel   B_rate
  -120.0      70.0      21.32     0.152
*---------*---------*---------*---------*---------*
  N_cjet     N_dj1     N_dj2     N_ujet
    1.0       0.0       0.0       0.0
*---------*---------*---------*---------*---------*
  d_cjet     d_dj1     d_dj2     d_ujet
   0.465     0.000     0.000     0.00
*---------*---------*---------*---------*---------*
  ang_cjet  ang_dj1   ang_dj2   ang_ujet
    0.0       0.0       0.0       0.0
*---------*---------*---------*---------*---------*
   Dia(in)   Height    son_vel    Mach
    4.0       44.9      934.6     2.048
*---------*---------*---------*---------*---------*
    Rho        Vis     Spe.Heat       Pr
 3.0989e-4 0.1662e-5  0.48884     0.55906
```

```
---------*---------*---------*---------*---------*
  C_time     c_gwo     c_cro    t_start
   100.0      0.80      4.00     5.00
---------*---------*---------*---------*---------*
--------------------------------------------------
```

(2). prepare a run file called " go_ice.bat "

```
copy sep_70.inp ice.inp
osr_ice
opy ice.out sep_70.out
rase ice.out
print sep_70.out
```

3). to run osr_ice program type

```
go_ice
```

---

4). an output file called " sep_70.out " will be printed out.

```
                TP-H-3396 Propellant - September 16, 1991

              *---------*---------*---------*---------*---------*
               Ice (in)    W_total  W_Propel   B_rate
                 -120.0      70.0     21.32      .152
              *---------*---------*---------*---------*---------*
               N_cjet      N_dj1     N_dj2     N_ujet
                  1.         0.        0.        0.
              *---------*---------*---------*---------*---------*
               d_cjet      d_dj1     d_dj2     d_ujet
                 .4650     .0000     .0000     .0000
              *---------*---------*---------*---------*---------*
               ang_cjet  ang_dj1   ang_dj2   ang_ujet
                  0.         0.        0.        0.
              *---------*---------*---------*---------*---------*
                Dia(in)    Height    son_vel     Mach
                   4.0       44.9    934.60     2.048
              *---------*---------*---------*---------*---------*
                  Rho        Vis     Spe.Heat       Pr
              .3099E-03 .1662E-05     .4888      .5591
              *---------*---------*---------*---------*---------*
                C_time      c_gwo     c_cro     t_start
                100.00       .800     4.000     5.000
              *---------*---------*---------*---------*---------*
```

time(sec)	Depth(in)	Weight(Lb)	V(in/sec)
5.48	-1.00	70.	2.0675
5.97	-2.00	70.	2.0521
6.46	-3.00	70.	2.0368
6.96	-4.00	70.	2.0215
7.46	-5.00	70.	2.0061
7.96	-6.00	70.	1.9908
8.46	-7.00	70.	1.9755
8.97	-8.00	69.	1.9602
9.49	-9.00	69.	1.9449
10.01	-10.00	69.	1.9296
10.53	-11.00	69.	1.9143
11.06	-12.00	69.	1.8991
11.59	-13.00	69.	1.8838
12.12	-14.00	69.	1.8686
12.66	-15.00	69.	1.8533
13.20	-16.00	69.	1.8381

```
*-----Ocean Systems Research Ice Penetration Model (09-29-91)(K. Tzou)
      Program  osr_ice
      real k_gas,N_jet,N_ujet,N_dj1,N_dj2,N_cjet,Nu_ave,k_ice,ice_Z,Mach
      character title*60, tit1*60, tit2*60
      dimension Z_total(150), T_total(150), t_sec(150)
      dimension h_gas(150), h_water(150), Weight(150)
      OPEN (UNIT=1, FILE='ice.inp', STATUS='OLD')
      OPEN (UNIT=2, FILE='ice.out', STATUS='NEW')
*---------------------------------------------------------------
*       Input data
*
*       Ice(in) = Total Depth of Ice
*       W_total(Lbs) = Initial total weight of the system
*       W_propel(Lbs)= Initial total weight of the propellant
*       B_rate(Lbs/sec)  = Burning rate of the propellant
*       N_cjet = No. of center jet
*       N_dj1  = No. of down-ward jet type#1
*       N_dj2  = No. of down-ward jet type#2
*       N_ujet = No. of up-ward jet
*       d_cjet(in)= diameter of center jet
*       d_dj1 (in)= diameter of down-ward jet type#1
*       d_dj2 (in)= diameter of down-ward jet type#2
*       d_ujet(in)= diameter of up-ward jet
*       ang_cjet(deg)= angle of center jet
*       ang_dj1 (deg)= angle of down-ward jet type#1
*       ang_dj2 (deg)= angle of down-ward jet type#2
*       ang_ujet(deg)= angle of up-ward jet
*       Dia(in)       = diameter of the ice penetrator
*       Height (in)   = height of the ice penetrator
*       son_vel(m/sec)= sonic velocity (from Thiokol)
*       Mach           = Mach number    (from Thiokol)
*       Rho(g/cc)      = exit gas density (from Thiokol)
*       Vis(lbf-sec/ft**2) = exit gas viscosity (from Thiokol)
*       Spe. Heat(cal/gm-degK)= exit gas specif heat (from Thiokol)
*       Pr             = Exit gas mixture Prandtl number(from Thiokol)
*       c_time, c_gwo, c_cro, t_start : correlation coefficients
*-------------------------------------------------------------------
*       Output Results
*       time (sec) : time in seconds
*       Depth(in)  : depth in inches
*       Weight(Lbs): total remaining weight
*       v(in/sec)  : rate of penetration
*----------------------------------------------------
*-------------- read input data
      read (1,100) title
      write(2,200) title
      print  100, title
 100  format(a60)
 200  format(/20x,a60/)
 201  format(20x,a60)
      read (1,102)tit1,tit2, ice_Z, W_total,  W_propel, B_rate
      write(2,202)tit1,tit2, ice_Z, W_total,  W_propel, B_rate
      read (1,102)tit1,tit2, N_cjet, N_dj1,  N_dj2,  N_ujet
      write(2,203)tit1,tit2, N_cjet, N_dj1,  N_dj2,  N_ujet
      read (1,102)tit1,tit2, d_cjet, d_dj1,  d_dj2,  d_ujet
      write(2,209)tit1,tit2, d_cjet, d_dj1,  d_dj2,  d_ujet
      read (1,102)tit1,tit2, ang_cjo,ang_dj1,ang_dj2,ang_ujet
      write(2,203)tit1,tit2, ang_cjo,ang_dj1,ang_dj2,ang_ujet
      read (1,102)tit1,tit2, Dia,   Height,  Son_vel, Mach
      write(2,204)tit1,tit2, Dia,   Height,  Son_vel, Mach
```

```
      read (1,106)tit1,tit2, Rho,   Vis,     Cp,      Pr
      write(2,206)tit1,tit2, Rho,   Vis,     Cp,      Pr
      read (1,102)tit1,tit2, C_time, c_gwo, c_cro, t_start
      write(2,208)tit1,tit2, C_time, c_gwo, c_cro, t_start
      read (1,100)tit1
      write(2,201)tit1
 102  format(a60/a60/5f10.0)
 202  format(20x,a60/20x,a60/20x,2f10.1, f10.2, f10.3)
 203  format(20x,a60/20x,a60/20x,4(f8.0,2x))
 204  format(20x,a60/20x,a60/20x,2f10.1,f10.2, f10.3)
 106  format(a60/a60/2e10.4,2f10.0)
 206  format(20x,a60/20x,a60/20x,2e10.4,2f10.4)
 208  format(20x,a60/20x,a60/20x,f10.2,3f10.3)
 209  format(20x,a60/20x,a60/20x,4f10.4)
 210  format(20x,a60/20x,a60/20x,2f10.4,3f10.2)
      write(2,220)
 220  format(/20x,'   time(sec)    Depth(in)   Weight(Lb)    V(in/sec)')
*------------------- assumption & initial conditions
      Z_total(1)=0.0
      T_total(1)=t_start
      t_sec(1)  =0.0
      Cm=0.85
      pi=3.1415927
      d_cjet=d_cjet/12.0
      d_dj1 =d_dj1 /12.0
      d_dj2 =d_dj2 /12.0
      d_ujet=d_ujet/12.0
      a_cjet=(pi/4.)*d_cjet**2
      a_dj1 =(pi/4.)*d_dj1**2
      a_dj2 =(pi/4.)*d_dj2**2
      a_ujet=(pi/4.)*d_ujet**2
      aN_cjet=N_cjet*a_cjet
      aN_dj1 =N_dj1 *a_dj1
      aN_dj2 =N_dj2 *a_dj2
      aN_ujet=N_ujet*a_ujet
      aN_jet=aN_cjet+aN_dj1+aN_dj2+aN_ujet
      c_d1=(90.-ang_dj1)*c_gwo/90.0
      c_d2=(90.-ang_dj2)*c_gwo/90.0
      C_gw=(aN_cjet*c_gwo+aN_dj1*c_d1+aN_dj2*c_d2)/aN_jet
:kt     print *, 'C_gw =',C_gw
      cr_d1=(90.0-ang_dj1)*c_cro/90.0
      cr_d2=(90.0-ang_dj2)*c_cro/90.0
      C_crack=(aN_cjet*c_cro+aN_dj1*cr_d1+aN_dj2*cr_d2)/aN_jet
:kt     print *, 'C_crack=',C_crack
      C_Nu=0.268
      C_Re=0.625
      C_u=6.630
      k_ice=1.25
      alpha=0.0450
      T=32.0
      Tf=212.0
      Ti=-15.0
      cu_ang=cos(pi*ang_ujet/180.0)
      cd1_ang=cos(pi*ang_dj1/180.0)
      cd2_ang=cos(pi*ang_dj2/180.0)
      Rho_steam=1.86
      Dia=Dia/12.0
*---------------------assume initial diameter of ice hole is 3" bigger
*                     than the diameter of the penetrator
      D_ice=Dia+3.0/12.0
```

```
360  format(/'  Time (sec) =',f6.1,5x,'Depth (in) =',f6.0)
     close (1)
     close (2)
     stop
     end
```

Following files are in this disk

```
 Volume in drive B has no label
 Directory of  B:\

FILE     DAT      598   9-29-91  12:39p -------> this file
SEP_70   OUT    10581   9-29-91  11:07a -------> sample output file
SEP_70   INP     1048   9-29-91  10:52a -------> sample input file
OSR_ICE  FOR     7621   9-29-91  12:27p -------> fortran program
OSR_ICE  EXE    36912   9-29-91  11:06a -------> compiled run file
READ     ME     13682   9-29-91  12:24p -------> user's information
GO_ICE   BAT      101   9-29-91  12:27p -------> batch run file
        7 File(s)   1141760 bytes free
```

APPENDIX B

THEORETICAL ROCKET PERFORMANCE ASSUMING EQUILIBRIUM COMPOSITION DURING EXPANSION

PC = 282.0 PSIA
CASE NO.= 1

	CHEMICAL FORMULA				WT FRACTION (SEE NOTE)	ENERGY CAL/MOL	STATE	TEMP DEG K	DENSITY G/CC	GFH
FUEL	C 7.27060	H 10.98200	N 0.07100	O 0.09440	0.097500	4000.000		0.0	0.9000	100.903
FUEL	CL 1.00000	H 4.00000	N 1.00000	O 4.00000	0.748000	-70690.000		0.0	1.9500	117.489
FUEL	C 14.00000	H 16.00000	N 2.00000	O 2.00000	0.003000	-58509.992		0.0	1.1310	244.296
FUEL	C 22.00000	H 42.00000	O 4.00000		0.020000	-311629.875		0.0	0.9275	370.577
FUEL	FE 2.00000	O 3.00000			0.001500	-197300.000		0.0	5.1200	159.692
FUEL	AL 1.00000				0.130000	0.0		0.0	2.7000	26.982

O/F= 0.0 PERCENT FUEL= 100.0000 EQUIVALENCE RATIO= 1.4925 PHI= 0.0 REACTANT DENSITY (GM/CC)= 1.7712
OCAL RATIO (MOLE FRACTIONS O/(C+1.5*AL))= 1.6543 REACTANT DENSITY (LB/IN3)= 0.06399

EQUIV FORM= C 0.83847 H 3.85411 N 0.64597 O 2.58260 CL 0.63665 FE 0.00188 AL 0.48181

MOLE FRACT= C 0.09274 H 0.42627 N 0.07145 O 0.28564 CL 0.07041 FE 0.00021 AL 0.05329

MIX PROPS	CHAMBER	THROAT	EXIT	EXIT	
PC/P	1.0000	1.7301	6.4788	8.2028	
P, ATM	19.189	11.091	2.9618	2.3393	
T, DEG K	3312.4	3137.9	2732.7	2661.3	
RHO, G/CC	1.9790-3	1.2193-3	3.8109-4	3.0989-4	← Rho
H, CAL/G	-465.58	-590.29	-859.60	-903.36	
S, CAL/(G)(K)	2.3763	2.3763	2.3763	2.3763	
M, MOL WT	28.032	28.3[illegible]5	28.851	28.928	
(DLV/DLP)T	-1.02350	-1.01850	-1.00870	-1.00735	
(DLV/DLT)P	1.4302	1.3536	1.1854	1.1598	
CP, CAL/(G)(K)	1.0385	0.9506	0.7369	0.7016	
GAMMA (S)	1.1314	1.1323	1.1398	1.1420	
SON VEL,M/SEC	1054.3	1021.6	947.4	934.6	← Son_vel
MACH NUMBER	0.0	1.000	1.917	2.048	← Mach

AE/AT		1.0000	1.8000	2.1000
CSTAR, FT/SEC		5121.3	5121.3	5121.3
CF		0.6545	1.1633	1.2262
IVAC LB-SEC/LB		196.18	229.39	235.92
IMAT LB-SEC/LB		104.17	185.16	195.17

THIS COLUMN FOR 9/14/91 TEST

MASS FRACTIONS (IF GE 5.E-06)

AL1(G)	0.00004	0.00002	0.00000	0.00000
AL1CL1(G)	0.00393	0.00245	0.00054	0.00039
AL1CL101(G)	0.00405	0.00272	0.00074	0.00054
AL1CL2(G)	0.00174	0.00111	0.00028	0.00021
AL1CL3(G)	0.00027	0.00020	0.00009	0.00007
AL1H101(G)	0.00036	0.00021	0.00004	0.00003
AL1H102(G)	0.00173	0.00106	0.00022	0.00016
AL101(G)	0.00023	0.00010	0.00001	0.00000
AL102(G)	0.00012	0.00006	0.00000	0.00000
AL201(G)	0.00002	0.00001	0.00000	0.00000
AL202(G)	0.00001	0.00000	0.00000	0.00000
AL203(L)	0.23640	0.23985	0.24428	0.24465
C1CL101(G)	0.00001	0.00001	0.00000	0.00000
C1H101(G)	0.00001	0.00000	0.00000	0.00000
C101(G)	0.20407	0.20260	0.19878	0.19804
C102(G)	0.04835	0.05068	0.05668	0.05785
CL1(G)	0.02488	0.02125	0.01196	0.01038
CL1FE1(G)	0.00006	0.00005	0.00002	0.00002
CL1H1(G)	0.19995	0.20566	0.21777	0.21960

```
FROZEN TRANSPORT PROPERTIES CALCULATED FROM EQUILIBRIUM CONCENTRATIONS (A LA SPP) ...

     AT MOST,  20 SPECIES ARE CONSIDERED IN THIS CALCULATION.
     FOR REFERENCE, THEIR CHAMBER PROPERTIES ARE ...
```

SPECIES	VISCOSITY	CONDUCTIVITY	SIGMA	EPS/K	TSTAR	OMEGA	CP/R
CL1H1(G)	0.20929E-05	0.18309E-01	3.339	344.7	9.6095	0.8295	4.5190
H2O1(G)	0.20210E-05	0.52666E-01	2.641	809.1	4.0939	0.9652	6.8121
H2(G)	0.88828E-06	0.14128E+00	2.827	59.7	55.4840	0.6411	4.5446
N2(G)	0.17872E-05	0.20171E-01	3.798	71.4	46.3921	0.6581	4.4764
C1O1(G)	0.18245E-05	0.20683E-01	3.690	91.7	36.1221	0.6829	4.4973
C1O2(G)	0.17834E-05	0.20922E-01	3.941	195.2	16.9692	0.7677	7.5259
AL1CL1(G	0.19859E-05	0.10506E-01	3.578	932.0	3.5541	0.9963	4.6917
AL1CL3(G	0.16142E-05	0.82042E-02	5.127	472.0	7.0178	0.8724	9.9849
AL1O1(G)	0.22908E-05	0.20969E-01	3.204	542.0	6.1114	0.8937	5.6536
H1O1(G)	0.19966E-05	0.37072E-01	3.147	79.8	41.5087	0.6686	4.4707
CL1(G)	0.20295E-05	0.10780E-01	3.613	130.8	25.3241	0.7205	2.5284
H1(G)	0.73415E-06	0.13582E+00	2.708	37.0	89.5242	0.5978	2.5003
CL2(G)	0.18504E-05	0.87443E-02	4.217	316.0	10.4823	0.8203	4.7644
N1O1(G)	0.20356E-05	0.21662E-01	3.492	116.7	28.3838	0.7074	4.5244
O2(G)	0.21628E-05	0.23067E-01	3.467	106.7	31.0440	0.6975	4.8591
C1(G)	0.16484E-05	0.26759E-01	3.385	30.6	100.0000	0.5882	2.6300
N1(G)	0.16760E-05	0.22644E-01	3.298	71.4	46.3921	0.6581	2.5426
O1(G)	0.19761E-05	0.23270E-01	3.050	106.7	31.0440	0.6975	2.5297
AL1(G)	0.16297E-05	0.11274E-01	2.655	2750.0	1.2045	1.4495	2.5030
C1H4(G)	0.12396E-05	0.64231E-01	3.758	148.6	22.2907	0.7334	12.3250

```
     CHAMBER   ...GAS TEMPERATURE (K) =     3312.4
        MIXTURE VISCOSITY    (LBF-SEC/FT2 ) = 0.19223E-05
        MIXTURE CONDUCTIVITY (LBF/SEC-DEGR) = 0.44221E-01
        GAS FROZ SPECIF HEAT (CAL/GM -DEGK) =     0.49530
        MIXTURE PRANDTL NUMBER              =     0.53874

     EXIT      ...GAS TEMPERATURE (K) =     2661.3
        MIXTURE VISCOSITY    (LBF-SEC/FT2 ) = 0.16622E-05  ←  Vis
        MIXTURE CONDUCTIVITY (LBF/SEC-DEGR) = 0.36367E-01
        GAS FROZ SPECIF HEAT (CAL/GM -DEGK) =     0.48884  ←  Spe. Heat
        MIXTURE PRANDTL NUMBER              =     0.55906  ←  Pr

     SCALING OF VISCOSITY TO OTHER TEMPERATURES ... VISC = 0.19223E-05 (T/ 3312.4)** 0.66424

     AL1CL1O1(G)     WAS NOT CONSIDERED BUT HAS SIGNIFICANT MOLE FRACTION (GT 0.001) =  0.001358

        IF ANY OF THESE  1 SPECIES ARE OF CONCERN, SEE MARK SALITA (X2163)
```

```
      Height=Height/12.0
*---------------- assume crack area = C_crack times circular area
      area_ice =(pi/4.)* D_ice**2
      area_cro =C_crack* area_ice
      area_pen =(pi/4.)* Dia**2
      Weight(1)=W_total
      B_time=W_propel/B_rate
      N_jet=N_cjet+N_dj1+N_dj2
      s_jet=sqrt(pi*Dia**2/(4.*N_jet))
      u_exit=Cm*Son_vel*Mach*3.2808
 kt      print *,'u_exit', u_exit
      k_gas=Cp*Vis*32.2*3600./Pr
 kt      print *,'k_gas',k_gas
      z_del=1.0/12.0
      Rho=Rho*62.43
----------------------------assume 50% gas 50% water at 212 deg F
      Rho_mix=0.5*Rho+0.5*Rho_steam*32.2
ckt      print *,'Rho_mix',Rho_mix
      B_force=0.0
----------------------------------------- do
      do 300 k=2,140
      Z_total(k)=Z_total(k-1) - z_del
      Z_inch=Z_total(k)*12.0
      if(-Z_total(k).LE.Height) B_force=-Z_total(k)*area_pen*Rho_mix
      if(-Z_total(k).GT.Height) B_force=Height*area_pen*Rho_mix
 kt      if (k.EQ.2) print *,'B_force', B_force
      Weight(k)=Weight(k-1) -t_sec(k-1)*B_rate
      T_Weight=Weight(k)-B_force
      F_ujet=N_ujet*Rho*a_ujet*u_exit*C_u*u_exit*d_ujet*cu_ang
      F_dj1 =N_dj1 *Rho*a_dj1 *u_exit*C_u*u_exit*d_dj1*cd1_ang
      F_dj2 =N_dj2 *Rho*a_dj2 *u_exit*C_u*u_exit*d_dj2*cd2_ang
      F_cjet=N_cjet*Rho*a_cjet*u_exit*C_u*u_exit*d_cjet
      z_jet=(F_cjet-F_ujet+F_dj1+F_dj2)/T_weight
      Re_ave=C_u*(u_exit*d_cjet/z_jet)*s_jet*Rho/Vis
      Nu_ave=C_Nu*Re_ave**C_Re
      h_gas(k)=(C_Nu*k_gas/s_jet)*Re_ave**C_Re
 kt      if (k.EQ.2) print *,'h_gas',h_gas(k)
*--------------------------------assume h_water=C_gw*h_gas
      h_water(k)=C_gw*h_gas(k)
--------------------------------assume h_water vary with time..C_time
      time_sec=T_total(k-1)
      h_water(k)=h_water(k)*exp(-time_sec/C_time)
      ratio_h =h_water(k)/h_water(2)
--------------------
      area_cra = area_cro * 1.0
      c11=Log((T-Tf)/(Ti-Tf))
      time=-k_ice*z_del*area_ice*c11/(alpha*h_water(k)* area_cra)
      t_sec(k)=time*3600.0
      Vel_pen=z_del/t_sec(k)
      Vel_ips=Vel_pen*12.0
      T_total(k)=T_total(k-1)+t_sec(k)
      zin=z_jet*12.0
 kt      if(k.EQ.2) print *,'z_jet(in)=',zin
      if(T_total(k).GT.B_time) go to 320
      if (Z_inch.LT.ice_Z) go to 320
      write(2,260)T_total(k),Z_inch,Weight(k),Vel_ips
 261  format(2f10.2)
 260  format(20x,f10.2,4x,f10.2,4x,f8.0,7x,f8.4)
 300  continue
 320  print 360 , T_total(k-1), Z_inch+1.0
```