Office of Environmental Management – Grand Junction

MOAB UTAH

UMTRA Project

Attachment 1
Disposal Cell Design and Engineering Specifications

June 2006

U.S. Department of Energy

Office of Environmental Management

Work Performed Under DOE Contract No. DE–AC01–02GJ79491
for the U.S. Department of Energy Office of Environmental Management.
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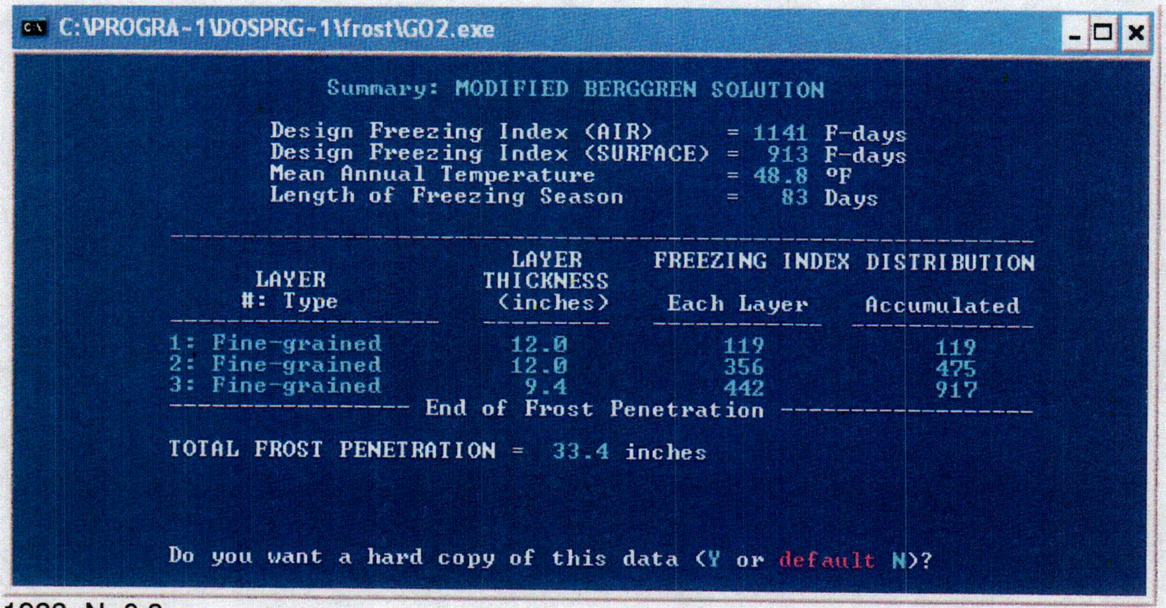
Contents



C:\PROGRA~1\DOSPRG~1\frost\GO2.exe

Summary: MODIFIED BERGGREN SOLUTION

Design Freezing Index (AIR) = 1141 F-days
Design Freezing Index (SURFACE) = 913 F-days
Mean Annual Temperature = 48.8 ºF
Length of Freezing Season = 83 Days

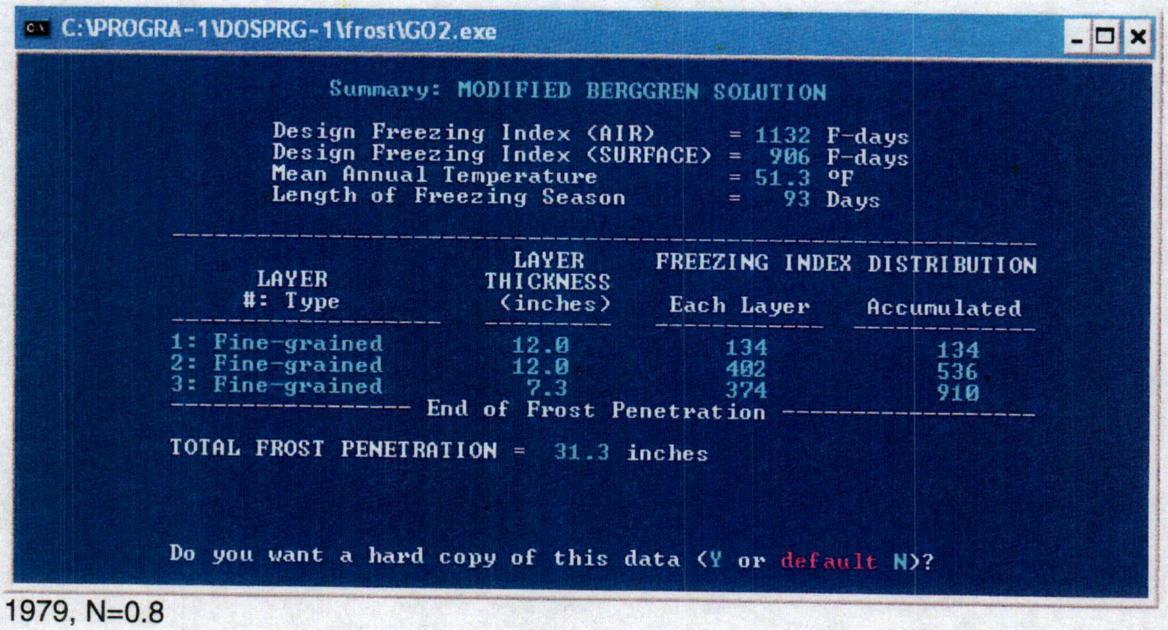
LAYER #: Type	LAYER THICKNESS (inches)	FREEZING INDEX DISTRIBUTION Each Layer	Accumulated
1: Fine-grained	12.0	119	119
2: Fine-grained	12.0	356	475
3: Fine-grained	9.4	442	917

End of Frost Penetration

TOTAL FROST PENETRATION = 33.4 inches

Do you want a hard copy of this data (Y or default N)?

1933, N=0.8



C:\PROGRA~1\DOSPRG~1\frost\GO2.exe

Summary: MODIFIED BERGGREN SOLUTION

Design Freezing Index (AIR) = 1132 F-days
Design Freezing Index (SURFACE) = 906 F-days
Mean Annual Temperature = 51.3 ºF
Length of Freezing Season = 93 Days

LAYER #: Type	LAYER THICKNESS (inches)	FREEZING INDEX DISTRIBUTION Each Layer	Accumulated
1: Fine-grained	12.0	134	134
2: Fine-grained	12.0	402	536
3: Fine-grained	7.3	374	910

End of Frost Penetration

TOTAL FROST PENETRATION = 31.3 inches

Do you want a hard copy of this data (Y or default N)?

1979, N=0.8

C01

C:\PROGRA~1\DOSPRG~1\frost\GO2.exe

Summary: MODIFIED BERGGREN SOLUTION

Design Freezing Index (AIR) = 970 F-days
Design Freezing Index (SURFACE) = 776 F-days
Mean Annual Temperature = 50.1 oF
Length of Freezing Season = 83 Days

LAYER #: Type	LAYER THICKNESS (inches)	FREEZING INDEX DISTRIBUTION Each Layer	Accumulated
1: Fine-grained	12.0	129	129
2: Fine-grained	12.0	386	515
3: Fine-grained	5.5	264	779

End of Frost Penetration

TOTAL FROST PENETRATION = 29.5 inches

Do you want a hard copy of this data (Y or default N)?

1937, N=0.8

C:\PROGRA~1\DOSPRG~1\frost\GO2.exe

Summary: MODIFIED BERGGREN SOLUTION

Design Freezing Index (AIR) = 1141 F-days
Design Freezing Index (SURFACE) = 1027 F-days
Mean Annual Temperature = 48.8 oF
Length of Freezing Season = 83 Days

LAYER #: Type	LAYER THICKNESS (inches)	FREEZING INDEX DISTRIBUTION Each Layer	Accumulated
1: Fine-grained	12.0	116	116
2: Fine-grained	12.0	349	465
3: Fine-grained	11.6	558	1023

End of Frost Penetration

TOTAL FROST PENETRATION = 35.6 inches

Do you want a hard copy of this data (Y or default N)?

1933, N=0.9

CO2

C:\PROGRA~1\DOSPRG~1\frost\GO2.exe

Summary: MODIFIED BERGGREN SOLUTION

```
Design Freezing Index (AIR)       = 1132 F-days
Design Freezing Index (SURFACE)   = 1019 F-days
Mean Annual Temperature           = 51.3 oF
Length of Freezing Season         =   93 Days
```

LAYER #: Type	LAYER THICKNESS (inches)	FREEZING INDEX DISTRIBUTION Each Layer	Accumulated
1: Fine-grained	12.0	131	131
2: Fine-grained	12.0	392	523
3: Fine-grained	9.6	500	1023

End of Frost Penetration

TOTAL FROST PENETRATION = 33.6 inches

Do you want a hard copy of this data (Y or default N)?

1979, N=0.9

C:\PROGRA~1\DOSPRG~1\frost\GO2.exe

Summary: MODIFIED BERGGREN SOLUTION

```
Design Freezing Index (AIR)       =  970 F-days
Design Freezing Index (SURFACE)   =  873 F-days
Mean Annual Temperature           = 50.1 oF
Length of Freezing Season         =   83 Days
```

LAYER #: Type	LAYER THICKNESS (inches)	FREEZING INDEX DISTRIBUTION Each Layer	Accumulated
1: Fine-grained	12.0	125	125
2: Fine-grained	12.0	376	501
3: Fine-grained	7.7	376	877

End of Frost Penetration

TOTAL FROST PENETRATION = 31.7 inches

Do you want a hard copy of this data (Y or default N)?

1937, N=0.9

C03

U.S. Department of Energy—Grand Junction, Colorado

Calculation Cover Sheet

Calc. No.: MOA-02-05-2006-5-19-00 **Discipline:** Engineering Design **No. of Sheets:** 4

Project: Moab UMTRA Project

Site: Crescent Junction Disposal Site

Feature: Freeze/Thaw Layer Design

Sources of Data:

Climate Data: Western Regional Climate Center
Desert Research Institute
University of Nevada, Reno, Nevada
Climate Data from Thompson, Utah
National Climate Data Center COOP Station # 428705
Latitude: 38°58'
Longitude: 109°43'
Elevation: 5150' AMS

Soil Data: Moab UMTRA Project: Attachment 5 - Field Investigations
Drilling at Crescent Junction: Field Test Documentation

Sources of Formulae and References:

See "Sources of Formulae and References" on page 2.

Preliminary Calc. ☐ Final Calc. ☐ Supersedes Calc. No.

Author: Morgan M. Smith 6/13/06 (Name, Date) Checked by: R. H. Bush 6/13/06 (Name, Date)

Approved by: John E. Elmer 6/13/06 (Name, Date) Name Date

Mark Kautsky for Greg Lord 6-9-06 (Name, Date)

Reviewed by: Frank B. Green 6-9-06 (Name, Date)

Problem Statement:

An important design parameter for the final cover of the Moab uranium mill tailings repository is the maximum depth to which frost can be expected to penetrate into the cover. When surficial soils freeze, the coupled processes of freeze-induced expansion and desiccation result in reduced soil density and the development of cracks and fissures in the cover soils. These occurrences lead to increases in hydraulic conductivity and gas permeability, which manifest as detrimental increases in the infiltration of meteoric water into the cover, and also to increased flux of soil gases (e.g. radon) from the cover. As it is a design imperative to reduce both the water infiltration into and the radon flux out of the repository, the upper surface of the radon barrier must be situated sufficiently below the effective ground surface that it is protected from seasonal freeze/thaw effects. The objective of this calculation set is to identify the design maximum frost penetration (design frost depth) at the repository site assuming a recurrence interval of 200 years for design of the freeze/thaw protective layer.

Method of Solution:

- Obtain climate data for the site.
- Obtain material properties for the in-situ borrow materials from the Field Test Documentation Calc set for the Crescent Junction Site.
- Use the method described in Smith and Rager (2002) to predict the maximum depth of frost penetration for the Crescent Junction Disposal Site.

Sources of Formulae and References:

Aldrich, H.P. and Paynter, H.M., 1953. "Analytical Studies of Freezing and Thawing of Soils," First Interim Report, U.S. Army Corps of Engineers, New England Division, Arctic Construction and Frost Effects Laboratory (ACFEL) Technical Report 42.

Kersten, M.S., 1949."Laboratory Research for the Determination of the Thermal Properties of Soils," Final Report, U.S. Army Corps of Engineers, New England Division, Arctic Construction and Frost Effects Laboratory (ACFEL) Technical Report 23.

NAVFAC, 1986. Naval Facilities Engineering Command. Soil Mechanics Design Manual 7.01. Alexandria, VA. pp 7.1-42.

Smith, G. E. and Rager, R. E., 2002. "Protective Layer Design in Landfill Covers Based on Frost Penetration." ASCE J. Geotechnical/Geoenvironmental Engineering, 128:9, pp. 794-799.

U. S. Army and Air Force, 1988. (Departments of the Army and the Air Force). "Arctic and Subarctic Construction Calculation Methods for Determination of Depths of Freeze and Thaw in Soils, First Intern Report." Army TM 5-852-6, Air Force AFR 88-19, Vol. 6.

Assumptions:

- No climate data is available for the Crescent Junction Disposal Site. Climate data from Thompson Springs, Utah, was available for 37 of 61 years from 1933 to 1994. Thompson Springs is located approximately 5 miles due east of the proposed disposal cell site. The elevation at the weather station (5,150 feet [ft]) is approximately 112 ft higher than the estimated highest top-of-cover elevation (5,038 ft) at the Crescent Junction Site. It is assumed that the climate at the Crescent Junction Disposal Site is the same as that of nearby Thompson Springs, Utah.
- Literature sources are reliable and representative sources of the physical phenomena.
- Regardless of the final cover configuration selected, the loosely compacted cover materials will act as either the protective layer over a typical compacted soil radon barrier or as the upper zone of a monolithic cover. The effects of rock mulch or other surface treatment were conservatively neglected. Frost penetration decreases with both increasing soil bulk density and increasing water content, due

to the insulating effect of ice that forms as water freezes. Although the loosely placed cover materials will initially have higher bulk density and water content than the in-situ borrow materials, the cover soil density and moisture conditions will eventually return to their in-situ state due to prolonged exposure to freezing and thawing cycles. Consequently, soil conditions for the frost prediction model were assumed to approximate those of the in-situ borrow soils, as indicated below.

Borrow Material Condition	Dry Density (pcf)	Water Content (gravimetric) %
Loosely placed cover (85% ASTM D 1557 max dry density @ 2% below optimum water content)	103.5	9.7
Average in-situ conditions	87.9	7.2
Conditions modeled	90.0	8.0

Calculation:

- Step 1. Determine Freeze-Index Parameters
  Climate data consisting of 37 years of maximum and minimum daily air temperatures were used to compute the air-freeze index (degree-days), duration of freeze, and mean annual temperature for each year. Plotted data are included as Appendix A.

- Step 2. Determine Surface Temperature Correction Data
  The daily temperature data used to determine the freeze-index parameters are typically measured 1.5 meters (m) above ground surface. However, measured ground temperatures can be greater than air temperatures due to the effects of snow cover, net solar radiation, thermal conduction from warmer soils below the surface, and convective heat transfer (Smith and Rager 2002). The ratio of the surface-freeze index to the air-freeze index is related through a factor, N. Because of the complexity and uncertainty between the freeze indices, a conservative estimate for N is recommended for practitioners (U.S. Army and Air Force 1998). The surface correction factor, N, was conservatively assumed to be 1.0 for analysis of the Crescent Junction Disposal Site. In addition, values for N of 0.8 and 0.9 are used to more realistic estimates for depth of frost penetration assuming a vegetative cover and a rock cover, respectively.

- Step 3. Determine Soil Thermal Properties
  Soil thermal properties—thermal conductivity, heat capacity, and latent heat of fusion—are products of empirical relationships between the dry unit weight (pcf) and gravimetric moisture content (%). These relationships are reproduced in Aitken and Berg (1968) originally published by Aldrich and Paynter (1953) and Kersten (1949).

- Step 4. Determine Annual Frost Depths
  Annual frost depths were determined for each of the subject years using the Modified Berggren Formula (MBF) as discussed in Smith and Rager (2002). The MBF was converted to PC software by the U. S. Army Corps of Engineers in 1997. Computer output for each year analyzed are presented as Appendix B, including design air freezing index, design surface freezing index, mean annual temperature, length of freezing season, and total frost penetration.

- Step 5. Determine Extreme Frost Depth
  Extreme-value frost depths for the 200-year recurrence interval are determined by extrapolating beyond the record of observed data using the cumulative probability distribution of the Gumbel function (Smith and Rager 2002). Frost depths are plotted in relation to the standard variate and recurrence interval, and linear regression is used to extrapolate and interpolate freezing depths. Graphical results of the extreme-frost-depth analysis are included in Appendix C, and indicate a

maximum frost penetration of 41 inches (104 centimeters [cm]) for a recurrence interval of 200 years with a surface factor of 1.0. Frost-depth predictions are also made with surface factors of 0.9, predicted depth of 41.5 inches; and with a surface factor of 0.8, a frost-penetration depth of 38.5 inches is determined.

Discussion:

Placing a 44-inch-thick frost-protection layer over the radon barrier layer is the maximum thickness of soil required to prevent freeze-thaw degradation of the barrier layer (N=1.0). Less thicknesses of 41.5 inches (N=0.9), down to 38.5 inches (N=0.8) are also predicted dependent on the ratio between the air temperature and surface temperature. Verification of the 41-inch predicted frost depth at proposed Crescent Junction Disposal Site compares well to other uranium mill tailings disposal cells in the general region as shown in the Table below.

Site	Design Dry Density (pcf)	Design Water Content (%)	Predicted Frost Depth (inches)
Monticello, UT	90	17	45
Cheney (Grand Junction, CO)[1]	104	12	38
Estes Gulch (Rifle, CO)[1]	106	9	69
Green River, UT	No frost protection layer included in the design		

[1]Three layers in protective cover: 12-inch coarse material (rock riprap), 6-inch coarse material (sand bedding), and fine material with these properties reported.

Green River, Utah, is the closest constructed disposal cell to the proposed Crescent Junction Site. No information was found to document that a frost-penetration analysis had been performed here. The cover at the Green River Site consists of a 12-inch-thick riprap layer underlain by a 6-inch-thick sand drainage layer. Discussions with designers of the disposal cell reveal that an analysis was performed and without a protective layer, the depth of frost penetration does extend into the radon barrier, but not completely through the layer. No performance data was discovered.

Given similar density and moisture conditions, the depth of frost penetration into coarse-grained soils, such as a sand layer, is slightly greater than for a fine-grained soil layer. Thus, inclusion of a sand drainage layer below a protective layer of soil would slightly increase the magnitude of frost penetration, if the sand were used to replace the fine-grained soil. However, the magnitude of the difference in thicknesses is not expected to be significant.

Conclusions and Recommendations:

- Based on results of the freeze/thaw analysis, a maximum frost penetration of 41.5 inches (1.05 m) should be assumed for design of the Moab uranium tailings cover at the Crescent Junction Disposal Site, using a rock cover, and 38.5 inches (0.98 m) if a vegetated cover is used
- The design depth of frost protections depends on the type of cover chosen in the final design.

Computer Source:

- MBF (Modified Berggren Formula). Coded for personal computer use by U.S. Army Corps of Engineers, Cold Regions Research and Engineering Laboratory in 1997.

Appendix A

Plotted Freeze-Index Data

Appendix B

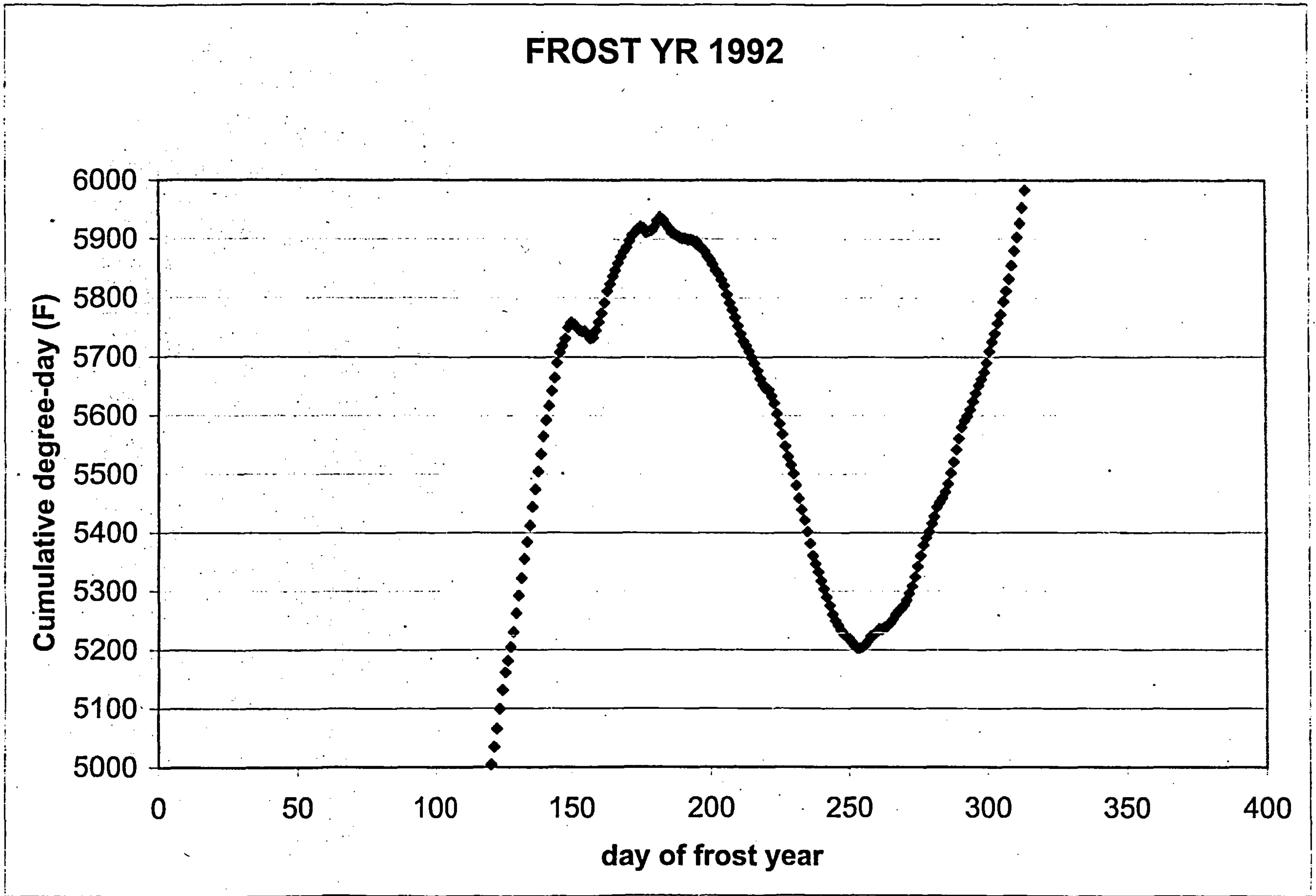
MBF Computer Output

Appendix C

Results of Extreme Frost Depth Analysis

APPENDIX A

PLOTTED FREEZE-INDEX DATA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Cumulative degree-day (F)
6000
5900
5800
5700
5600
5500
5400
5300
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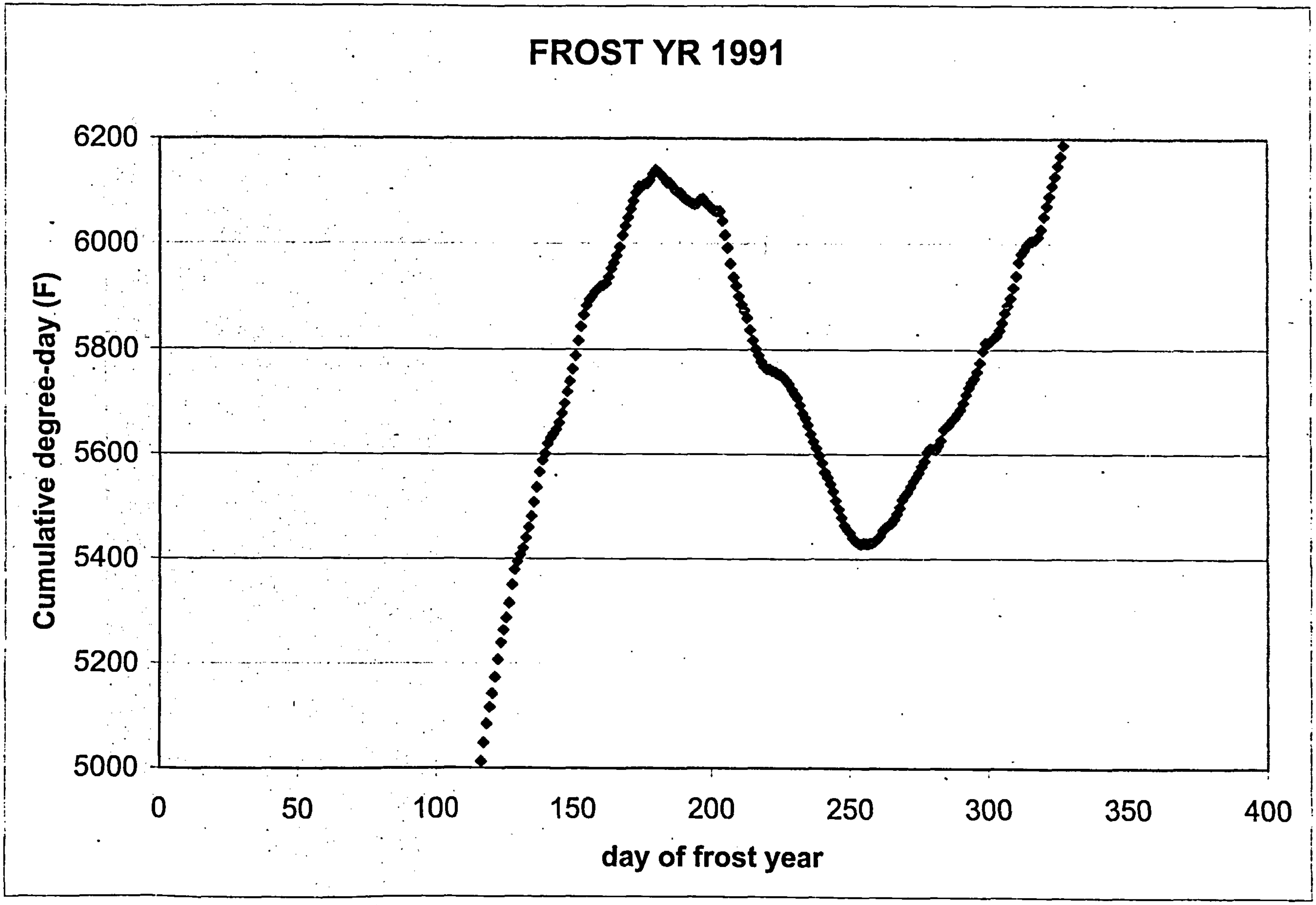
5100
5000
0
50
100
150
200
250
300
350
400
day of frost year



FROST YR 1991
Cumulative degree-day (F)
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5600
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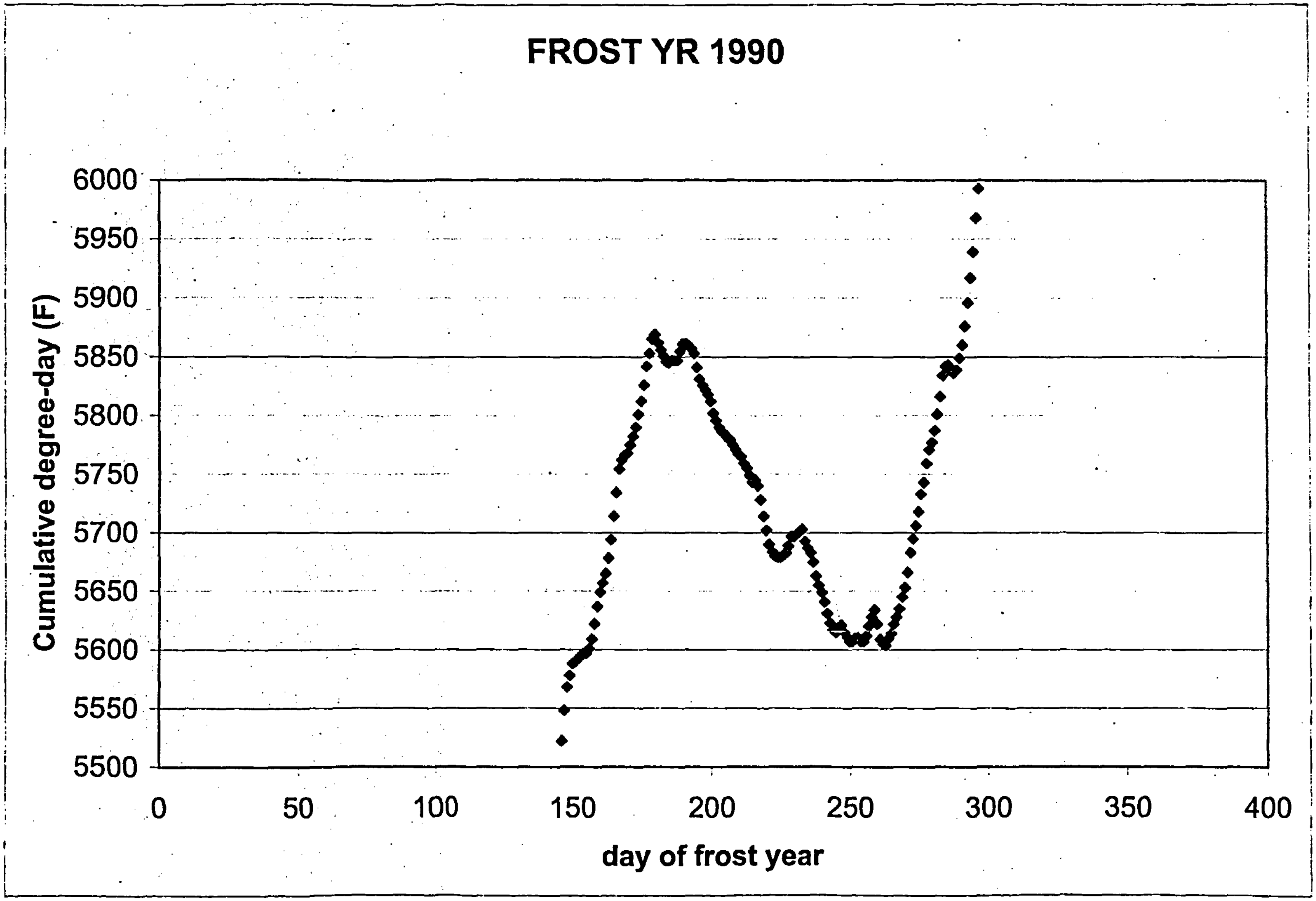
100
150
200
250
300
350
400
day of frost year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Cumulative degree-day (F)
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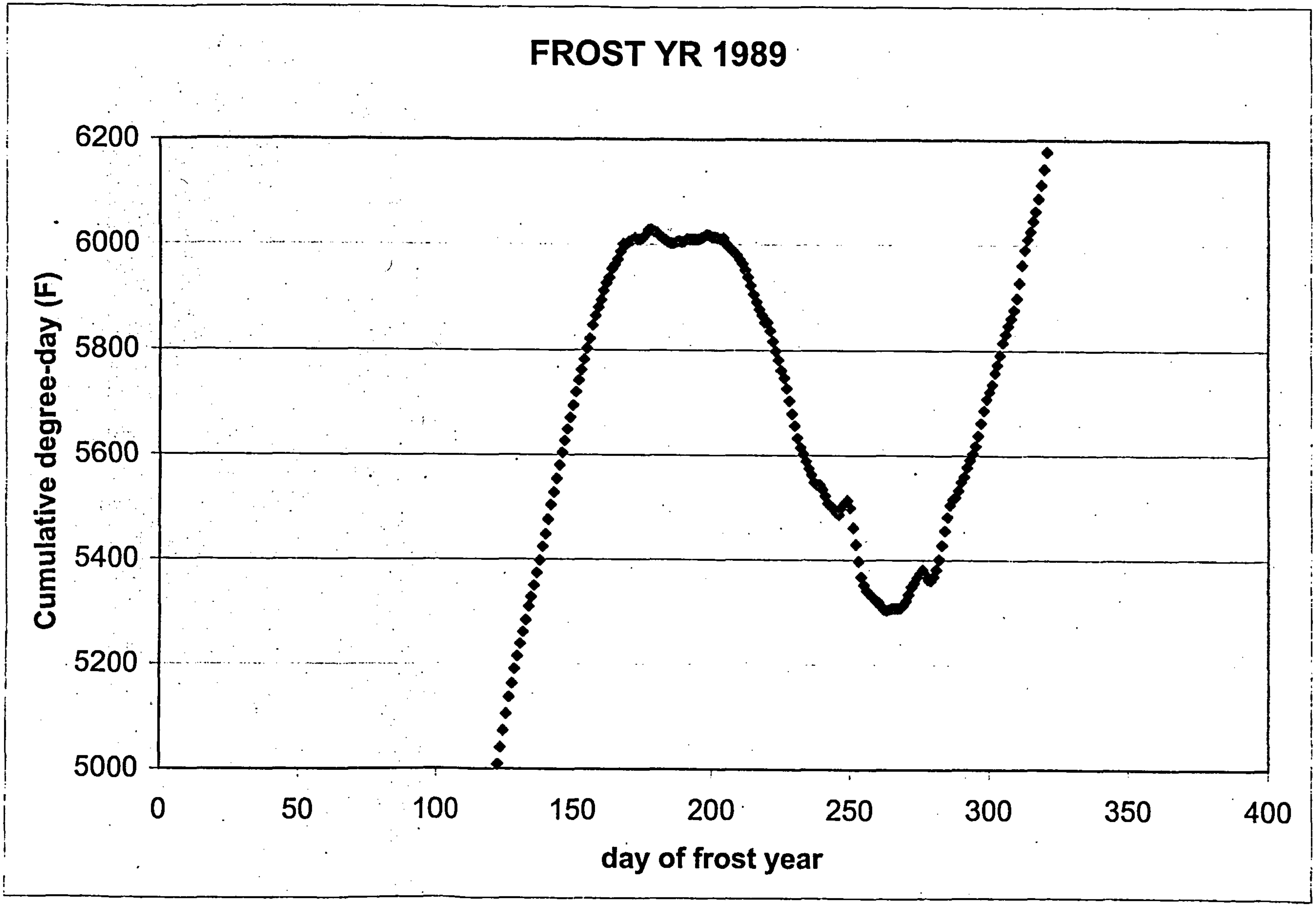
5950
5900
5850
5800
5750
5700
5650
5600
5550
5500
0
50
100
150
200
250
300
350
400
day of frost year



FROST YR 1989
Cumulative degree-day (F)
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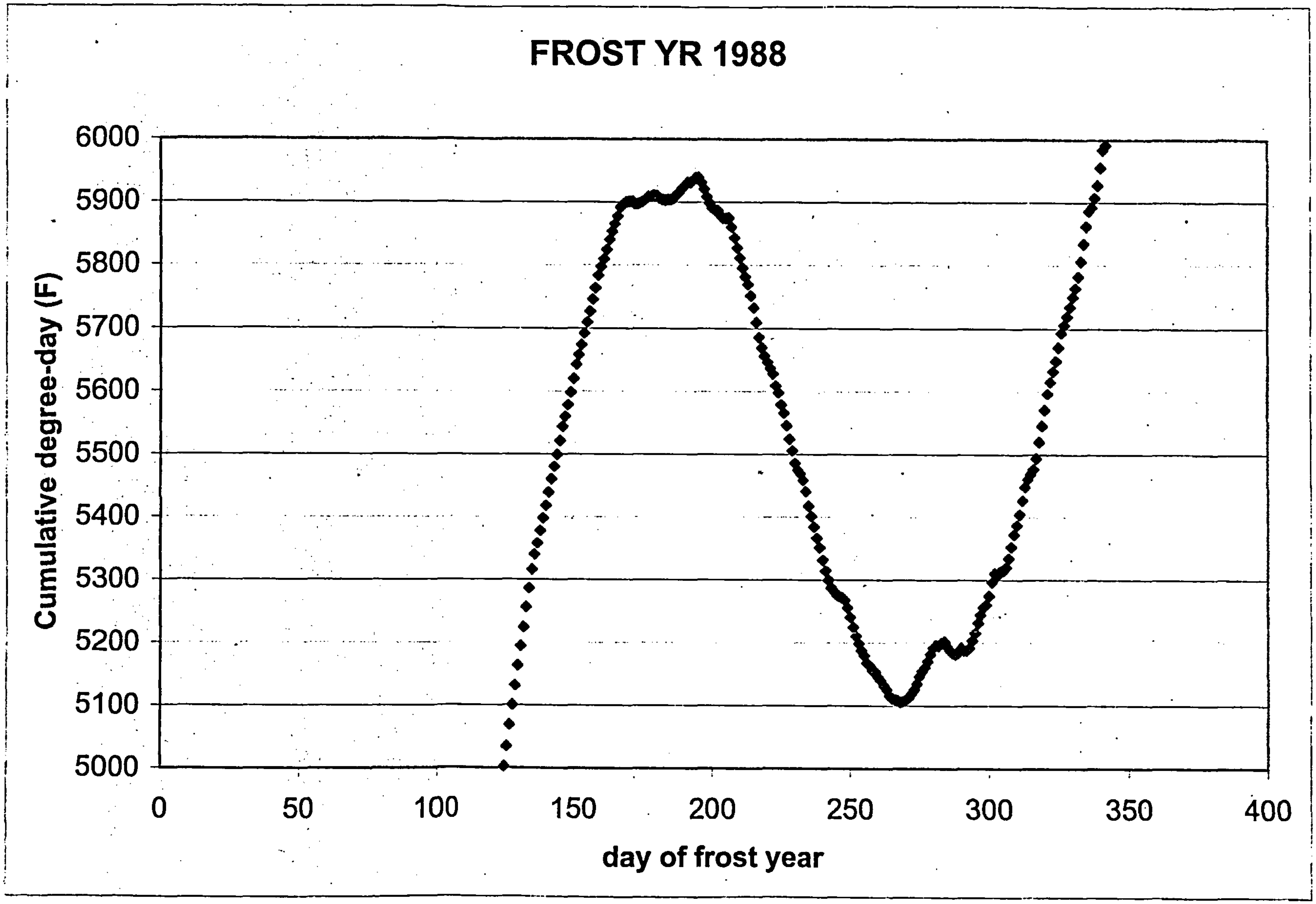
5800
5600
5400
5200
5000
0
50
100
150
200
250
300
350
400
day of frost year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Cumulative degree-day (F)
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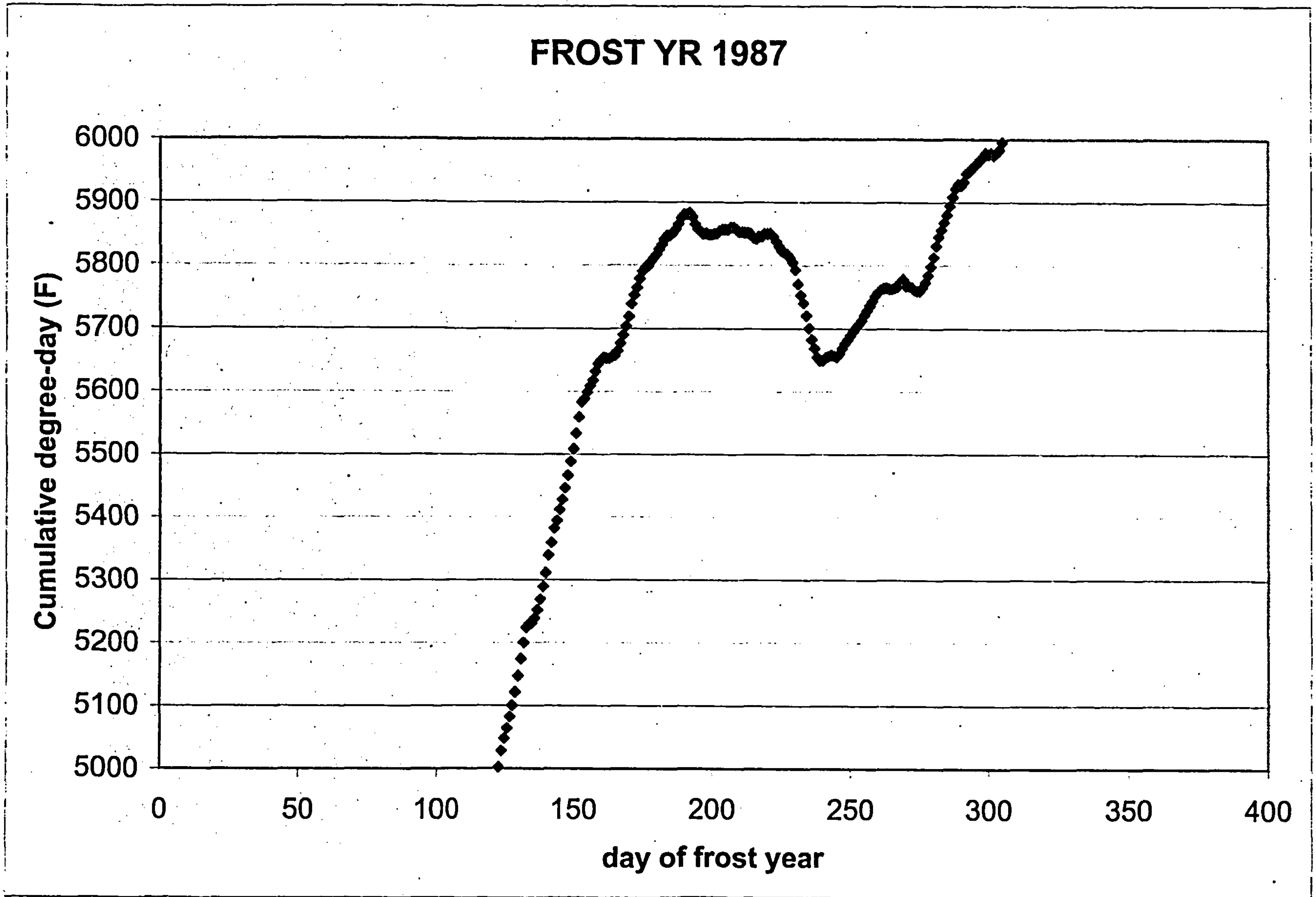
5800
5700
5600
5500
5400
5300
5200
5100
5000
0
50
100
150
200
250
300
350
400
day of frost year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Cumulative degree-day (F)
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5800
5700
5600
5500
5400
5300
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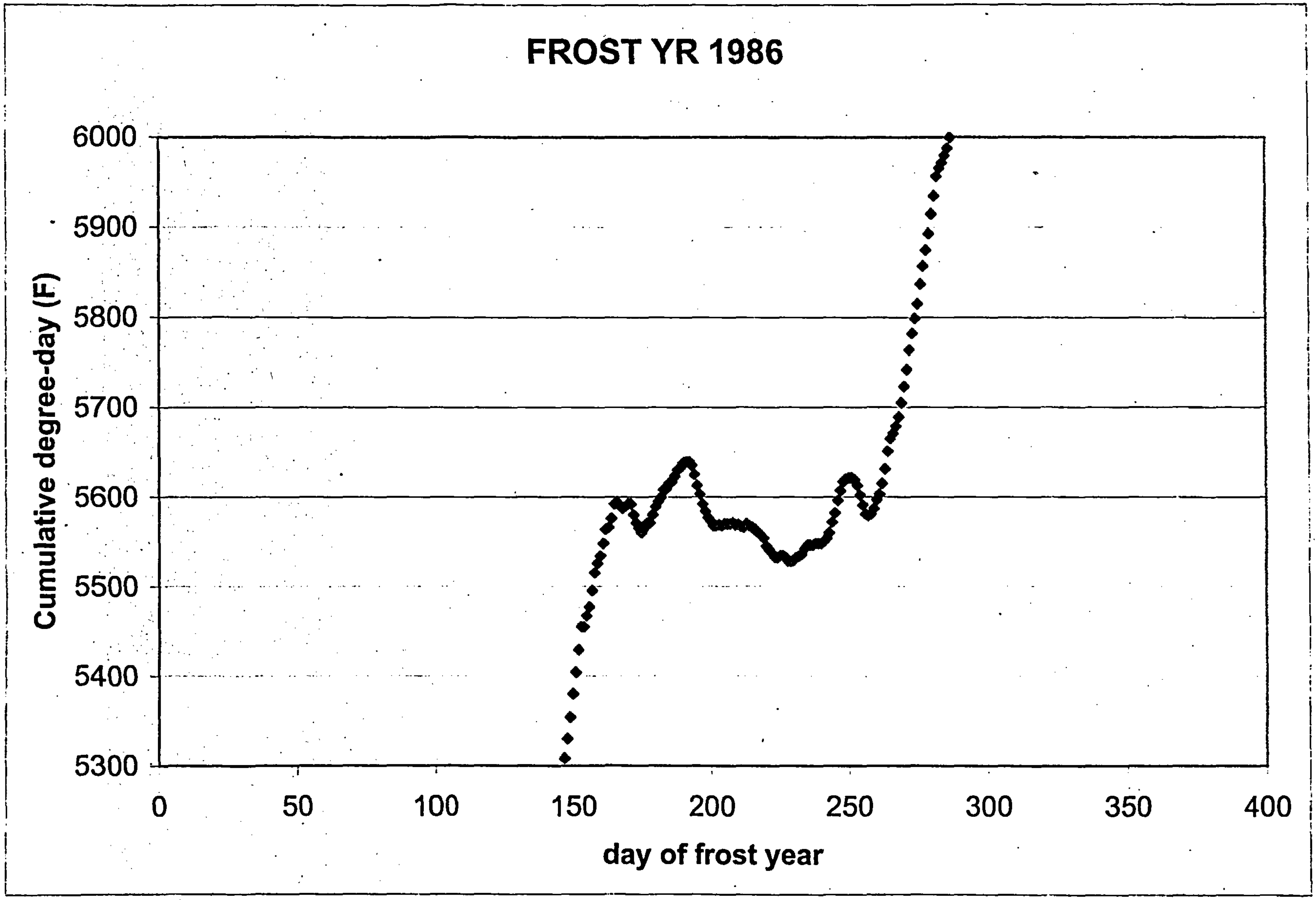
0
50
100
150
200
250
300
350
400
day of frost year



FROST YR 1986
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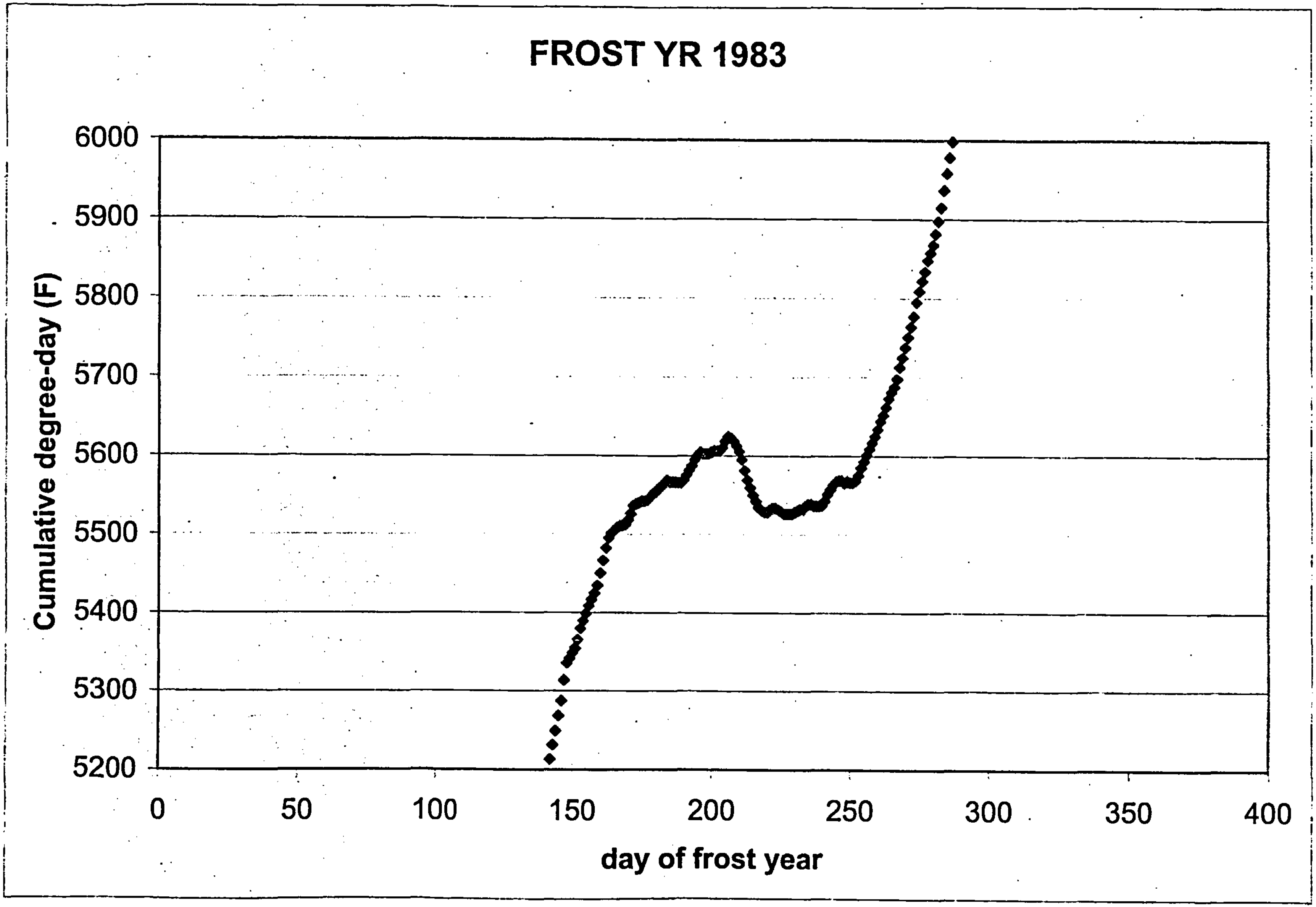
5800
5700
5600
5500
5400
5300
Cumulative degree-day (F)
0
50
100
150
200
250
300
350
400
day of frost year



FROST YR 1983
Cumulative degree-day (F)
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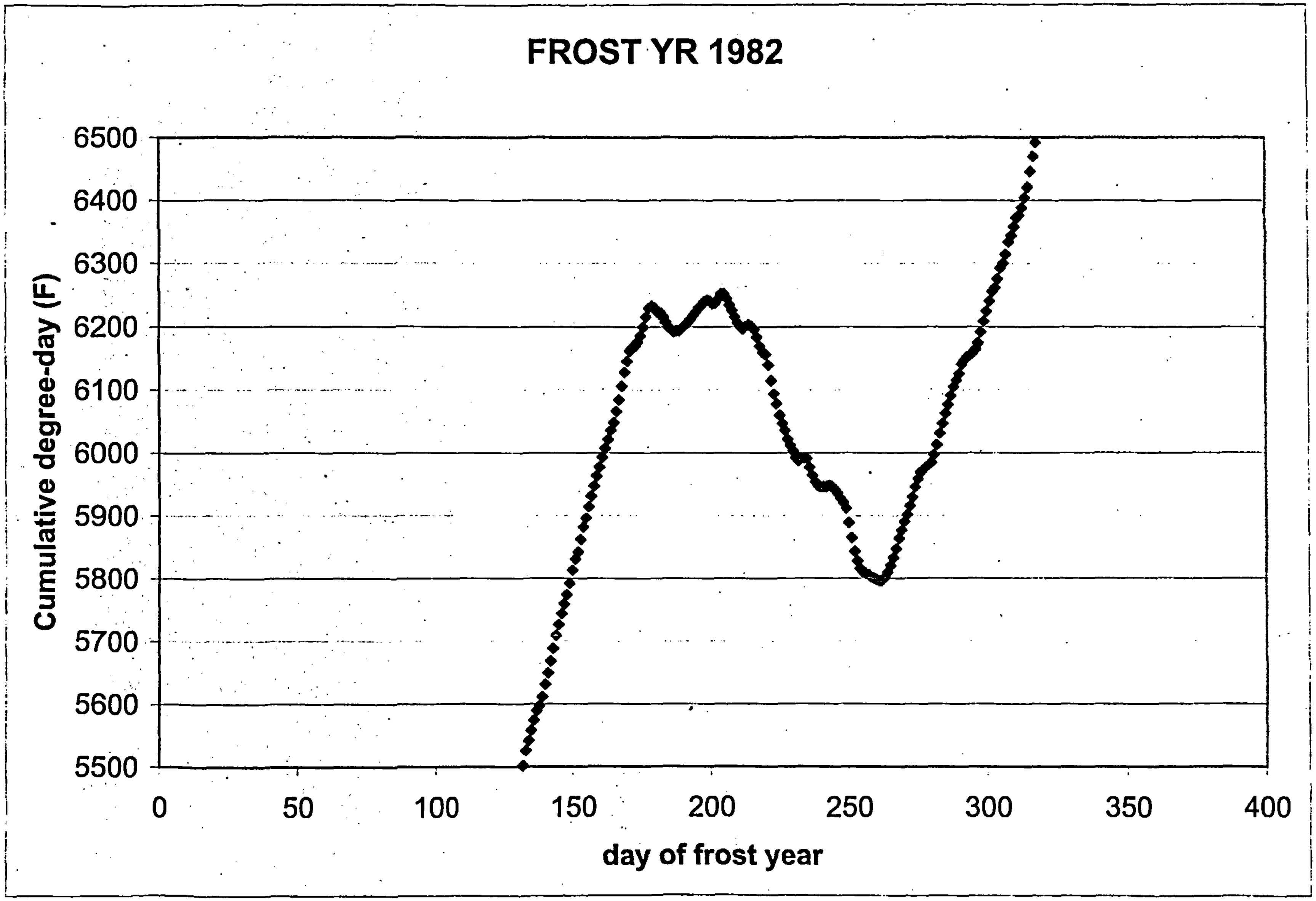
5600
5500
5400
5300
5200
0
50
100
150
200
250
300
350
400
day of frost year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Cumulative degree-day (F)
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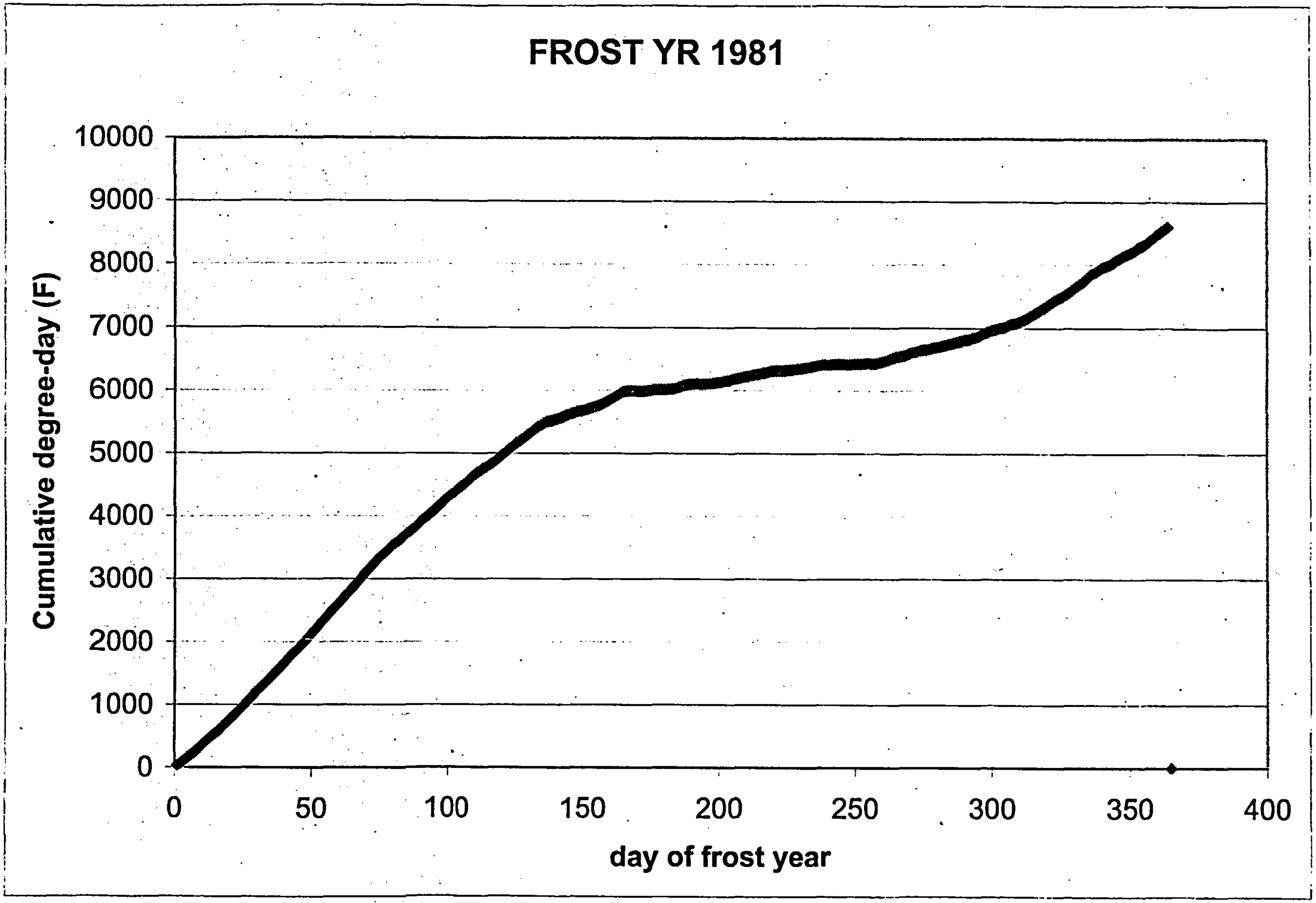
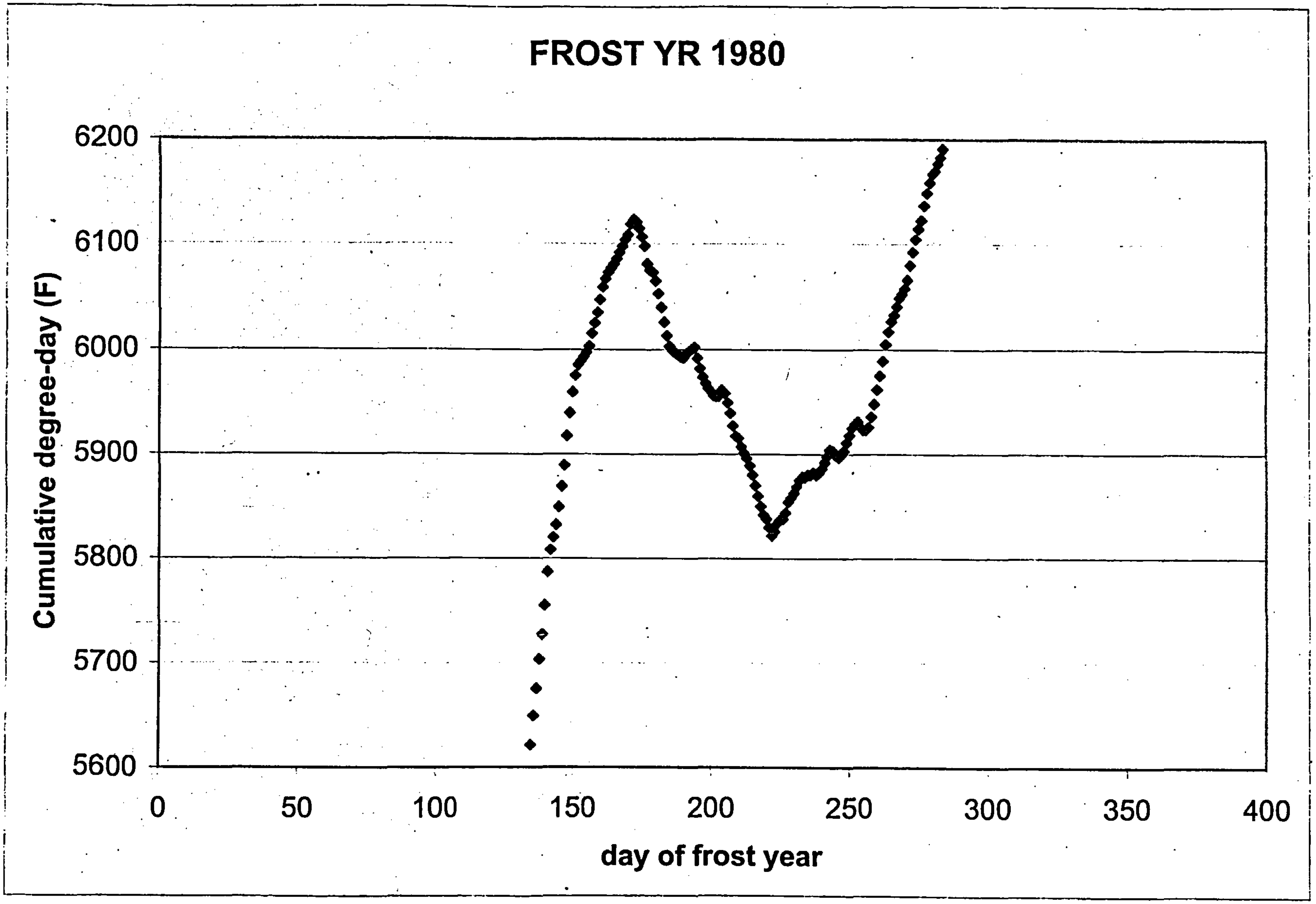
6400
6300
6200
6100
6000
5900
5800
5700
5600
5500
0
50
100
150
200
250
300
350
400
day of frost year


FROST YR 1981
Cumulative degree-day (F)
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0
50
100
150
200
250
300
350
400
day of frost year



FROST YR 1980
Cumulative degree-day (F)
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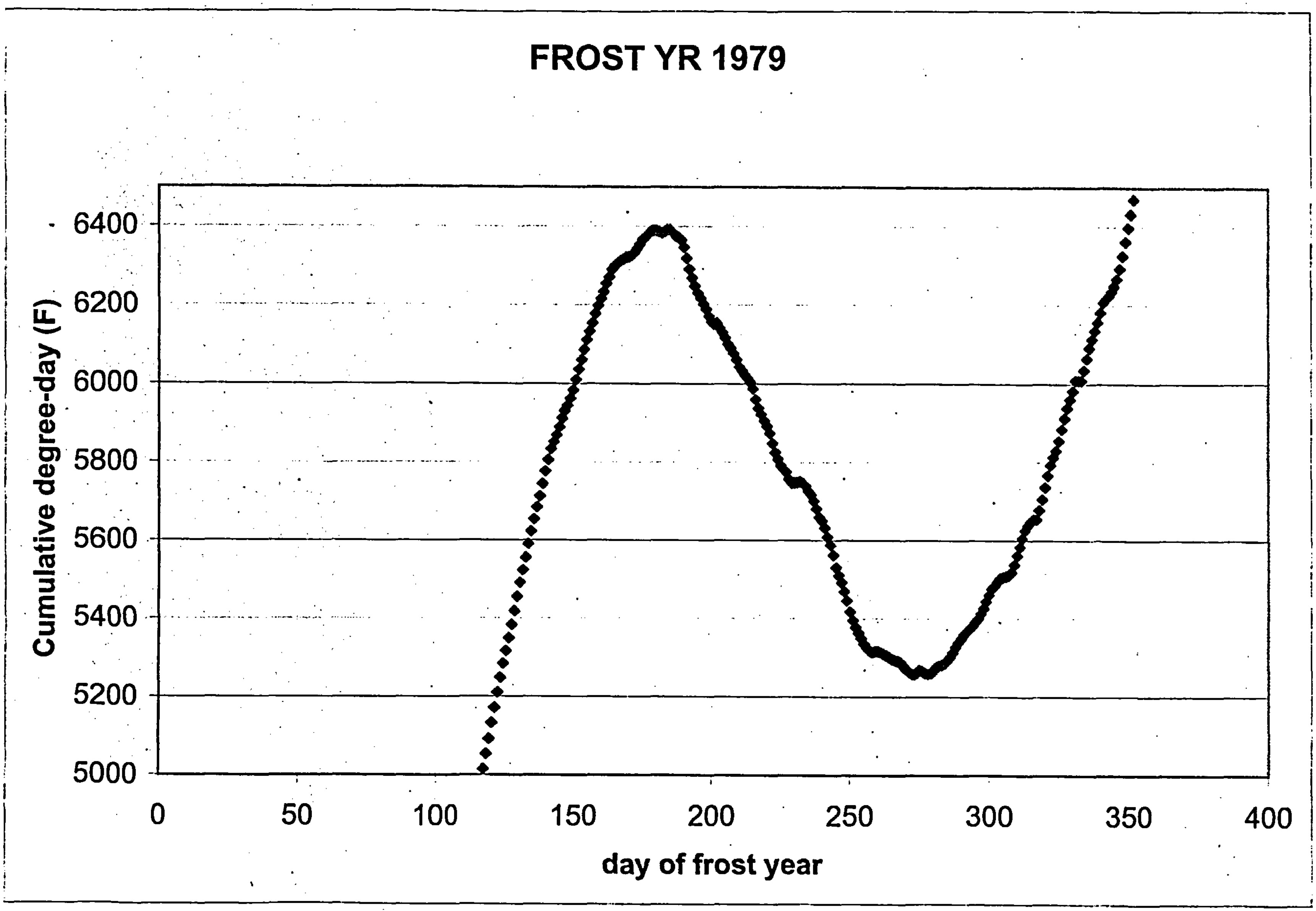
6100
6000
5900
5800
5700
5600
0
50
100
150
200
250
300
350
400
day of frost year



FROST YR 1979
Cumulative degree-day (F)
6400
6200
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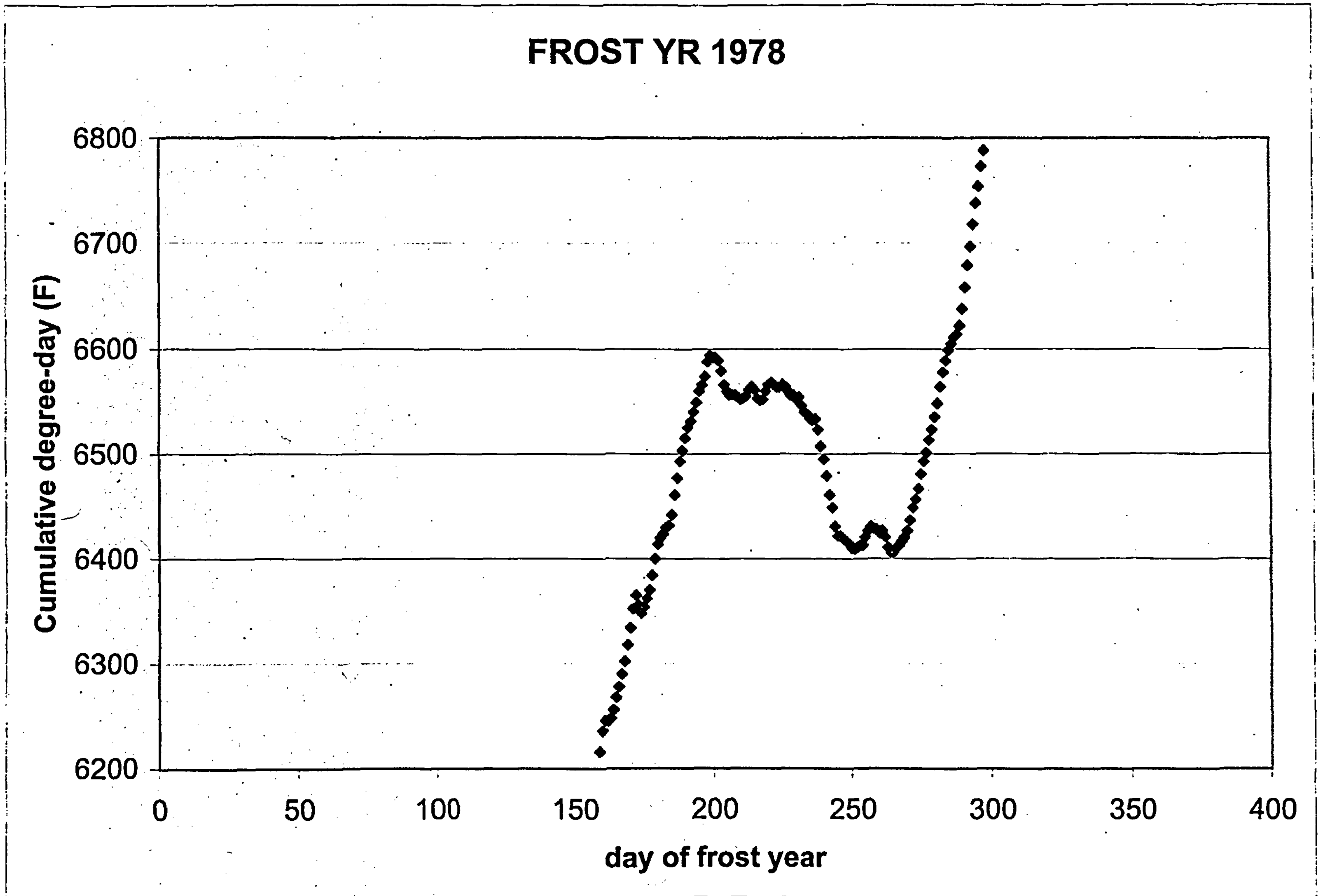
5800
5600
5400
5200
5000
0
50
100
150
200
250
300
350
400
day of frost year



FROST YR 1978
Cumulative degree-day (F)
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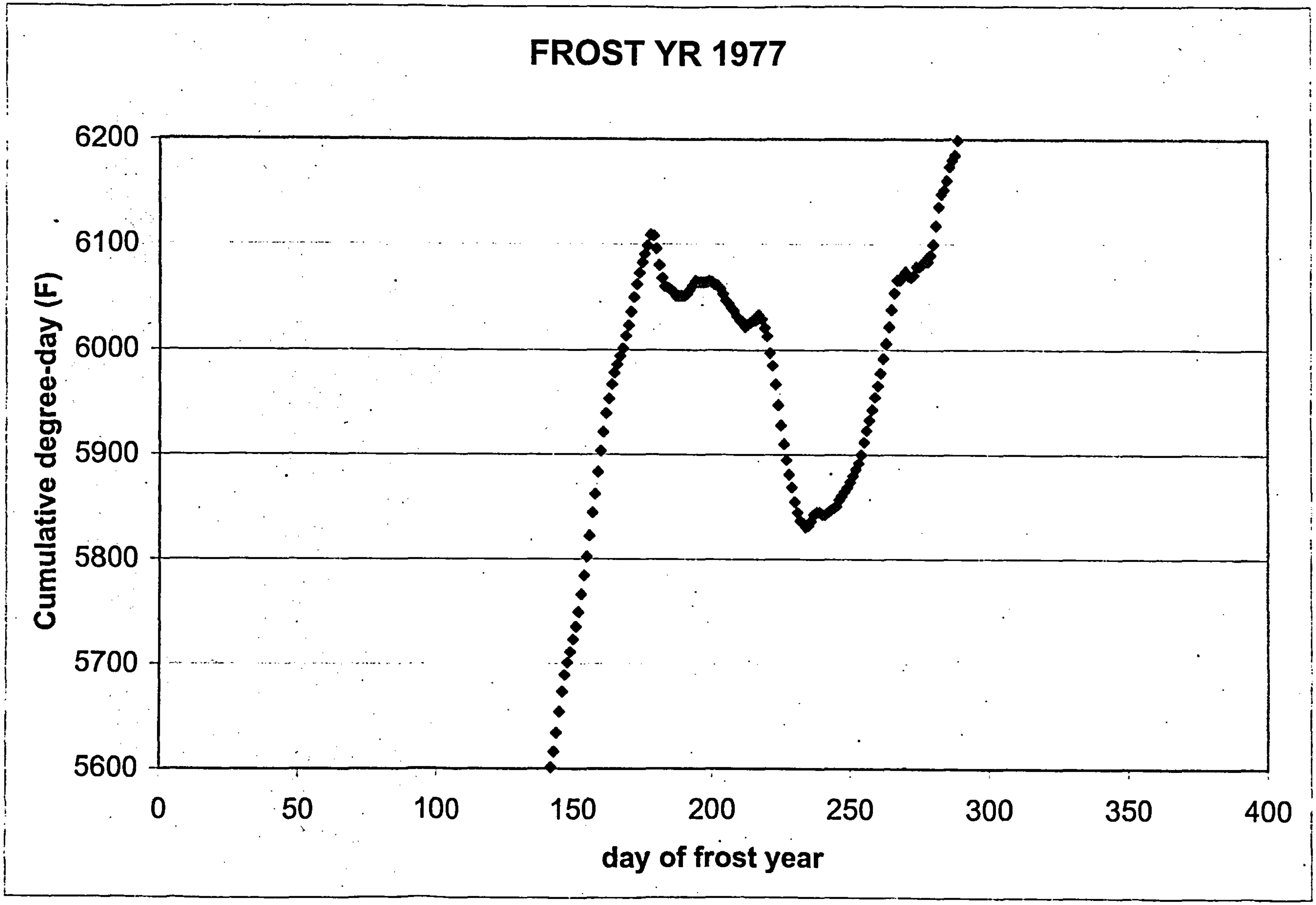
6700
6600
6500
6400
6300
6200
0
50
100
150
200
250
300
350
400
day of frost year



FROST YR 1977
Cumulative degree-day (F)
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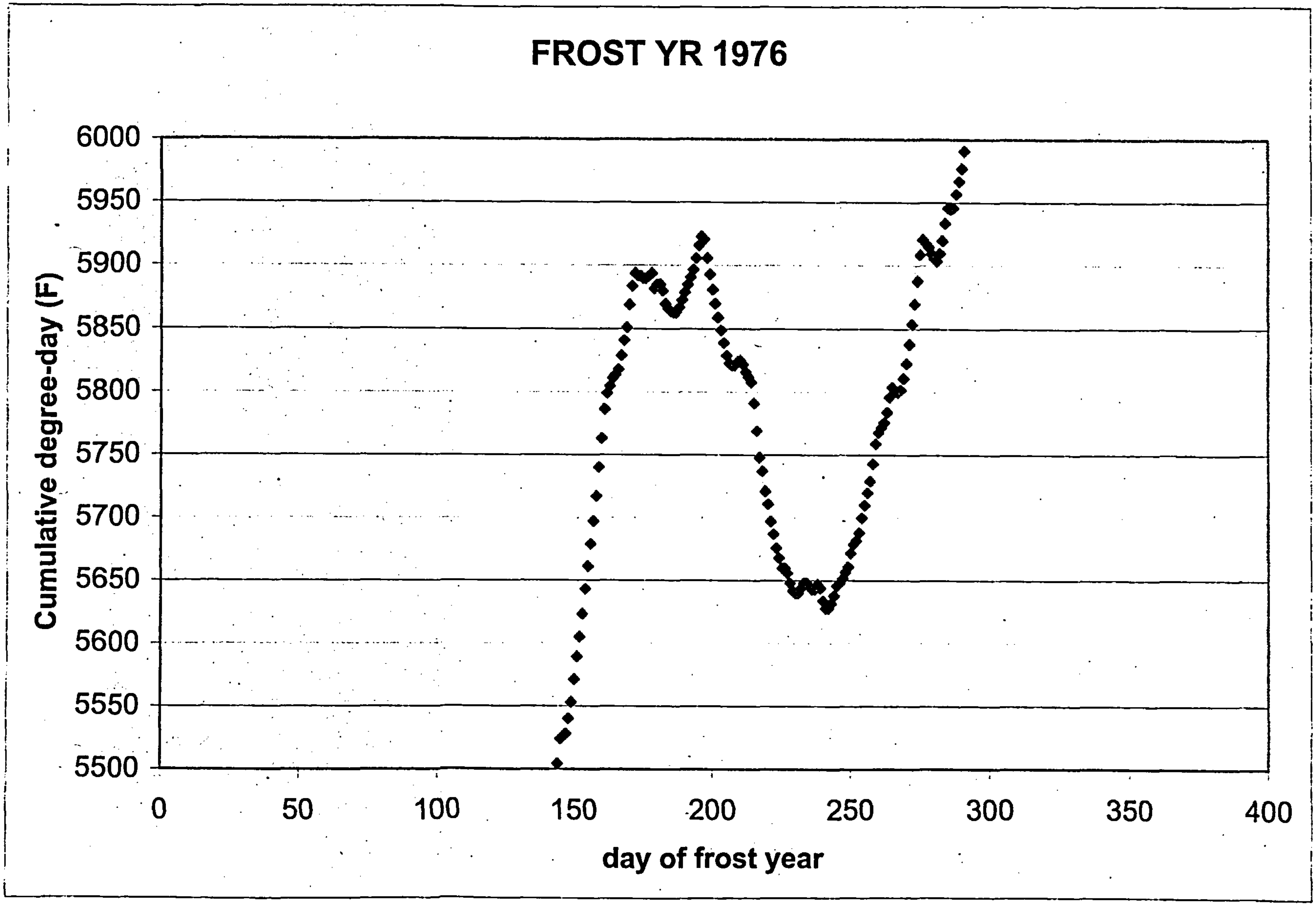
6000
5900
5800
5700
5600
0
50
100
150
200
250
300
350
400
day of frost year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Cumulative degree-day (F)
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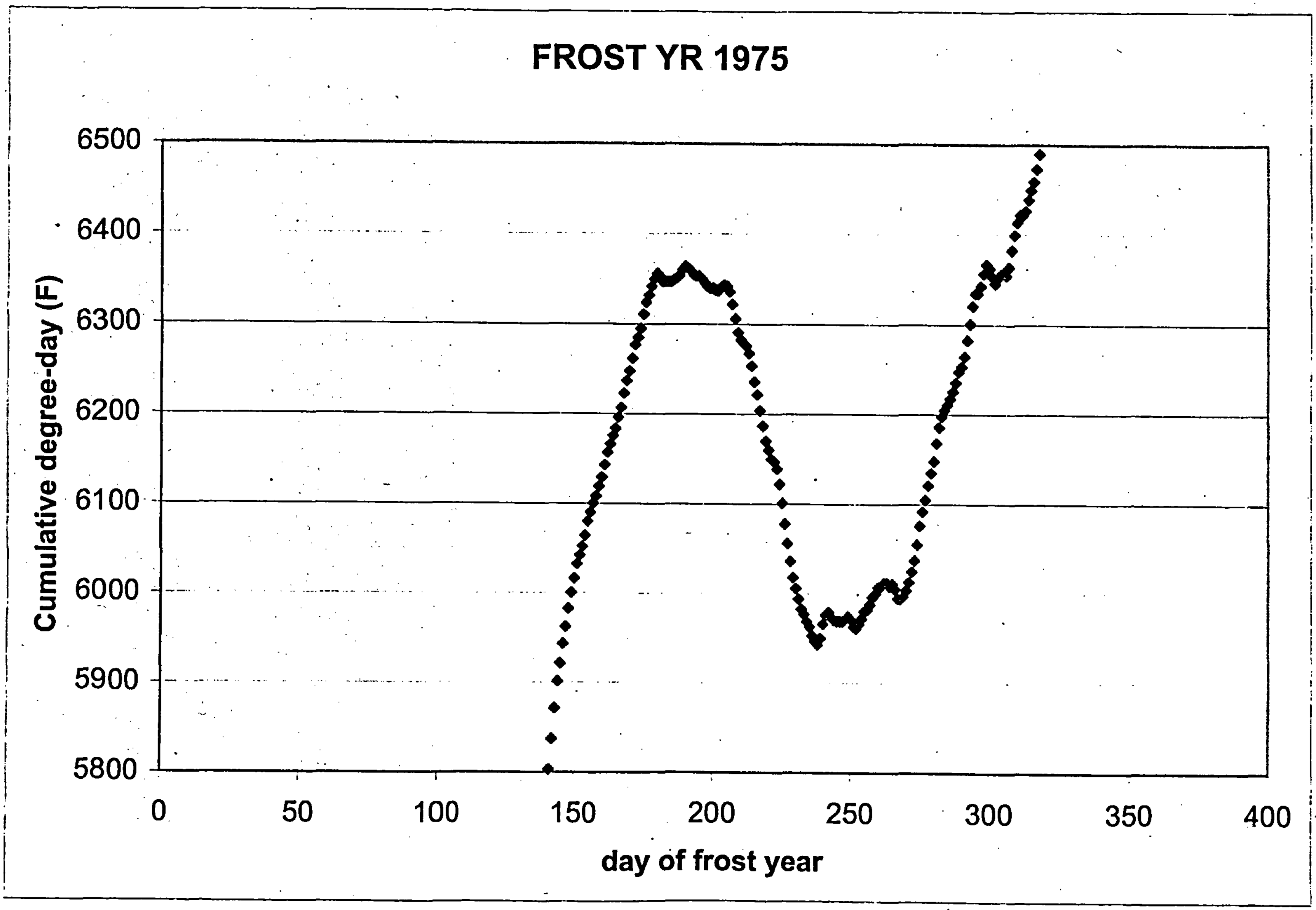
5950
5900
5850
5800
5750
5700
5650
5600
5550
5500
0
50
100
150
200
250
300
350
400
day of frost year



FROST YR 1975
Cumulative degree-day (F)
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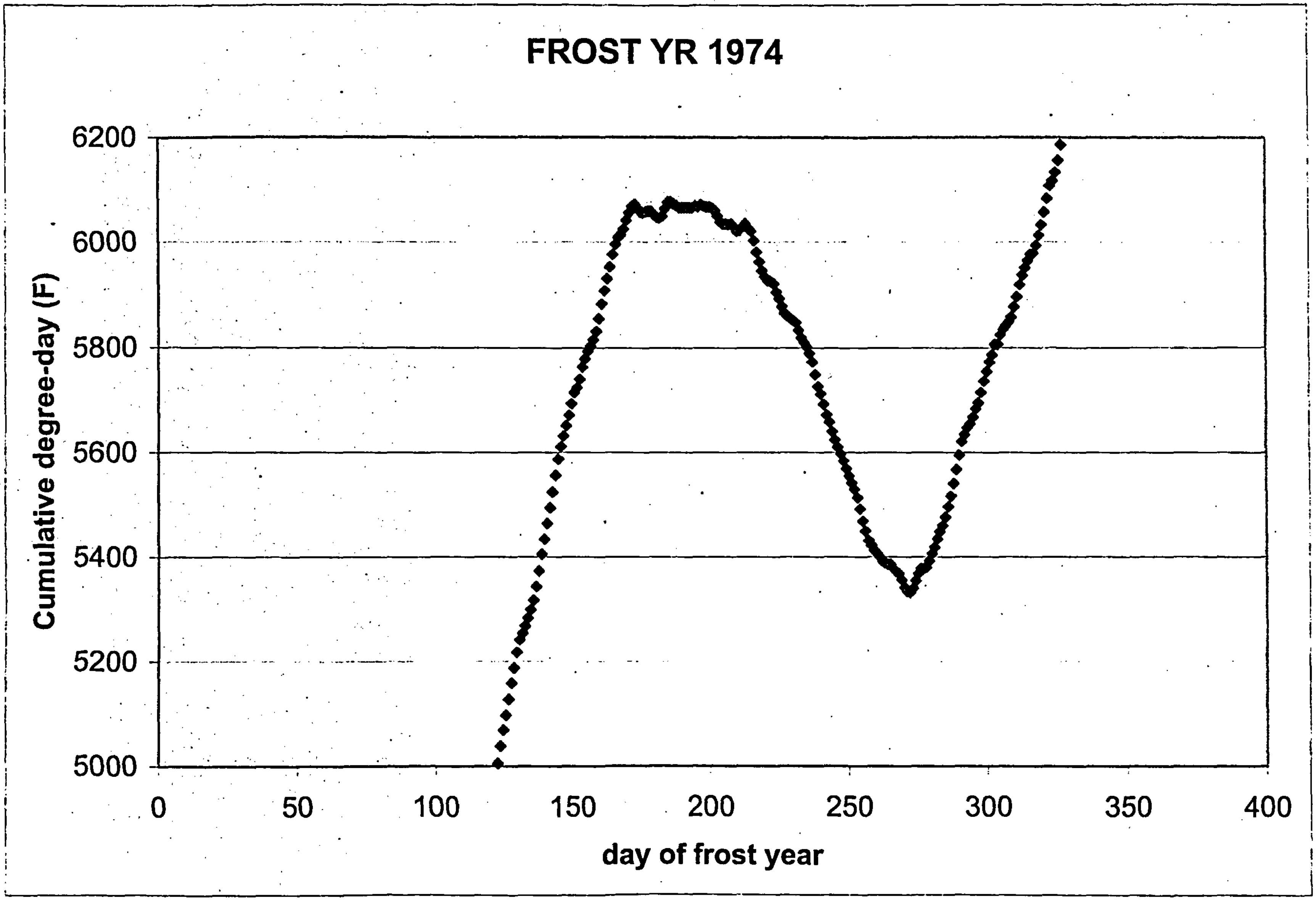
6400
6300
6200
6100
6000
5900
5800
0
50
100
150
200
250
300
350
400
day of frost year



FROST YR 1974
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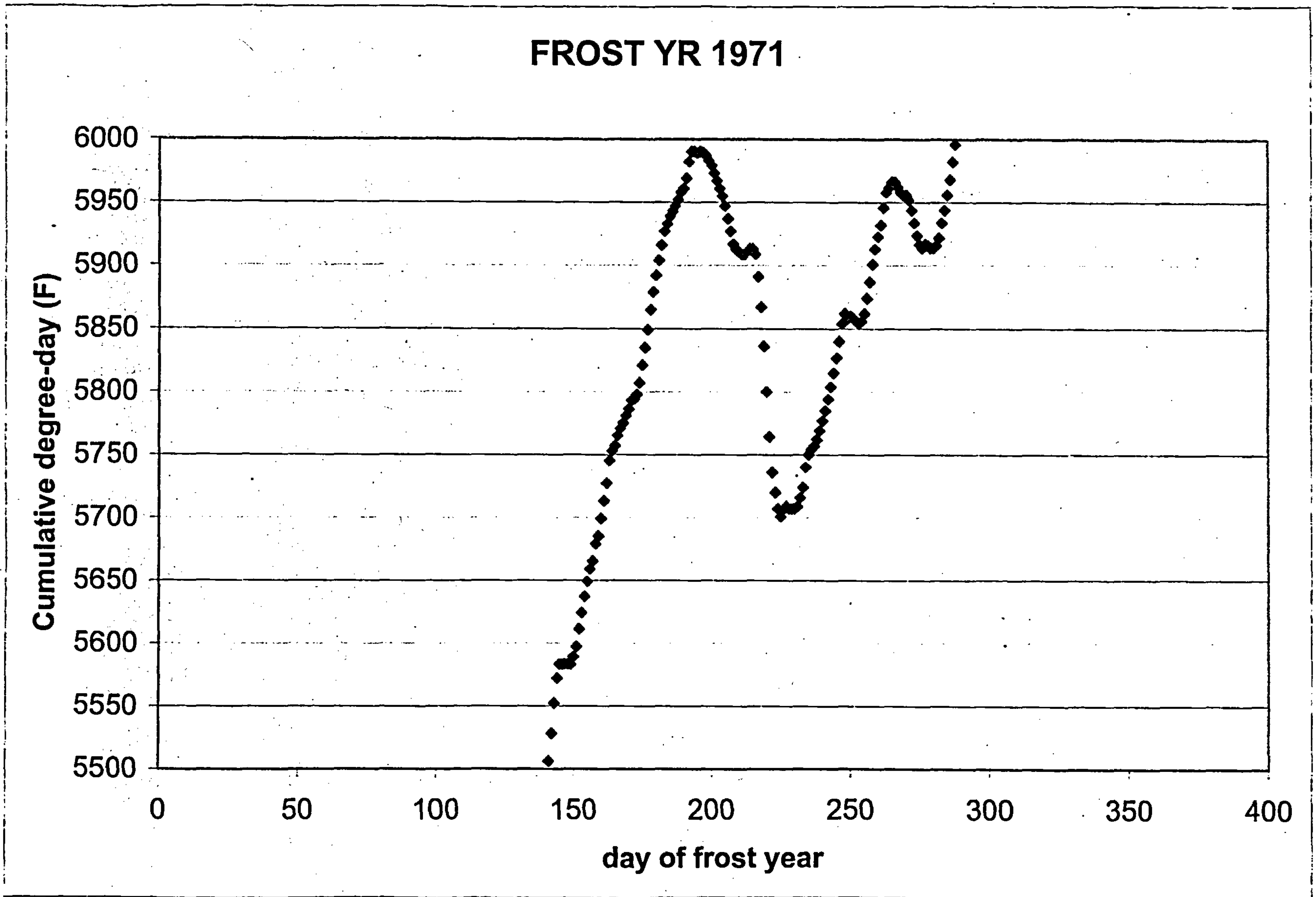
6000
5800
5600
5400
5200
5000
Cumulative degree-day (F)
0
50
100
150
200
250
300
350
400
day of frost year


FROST YR 1971
Cumulative degree-day (F)
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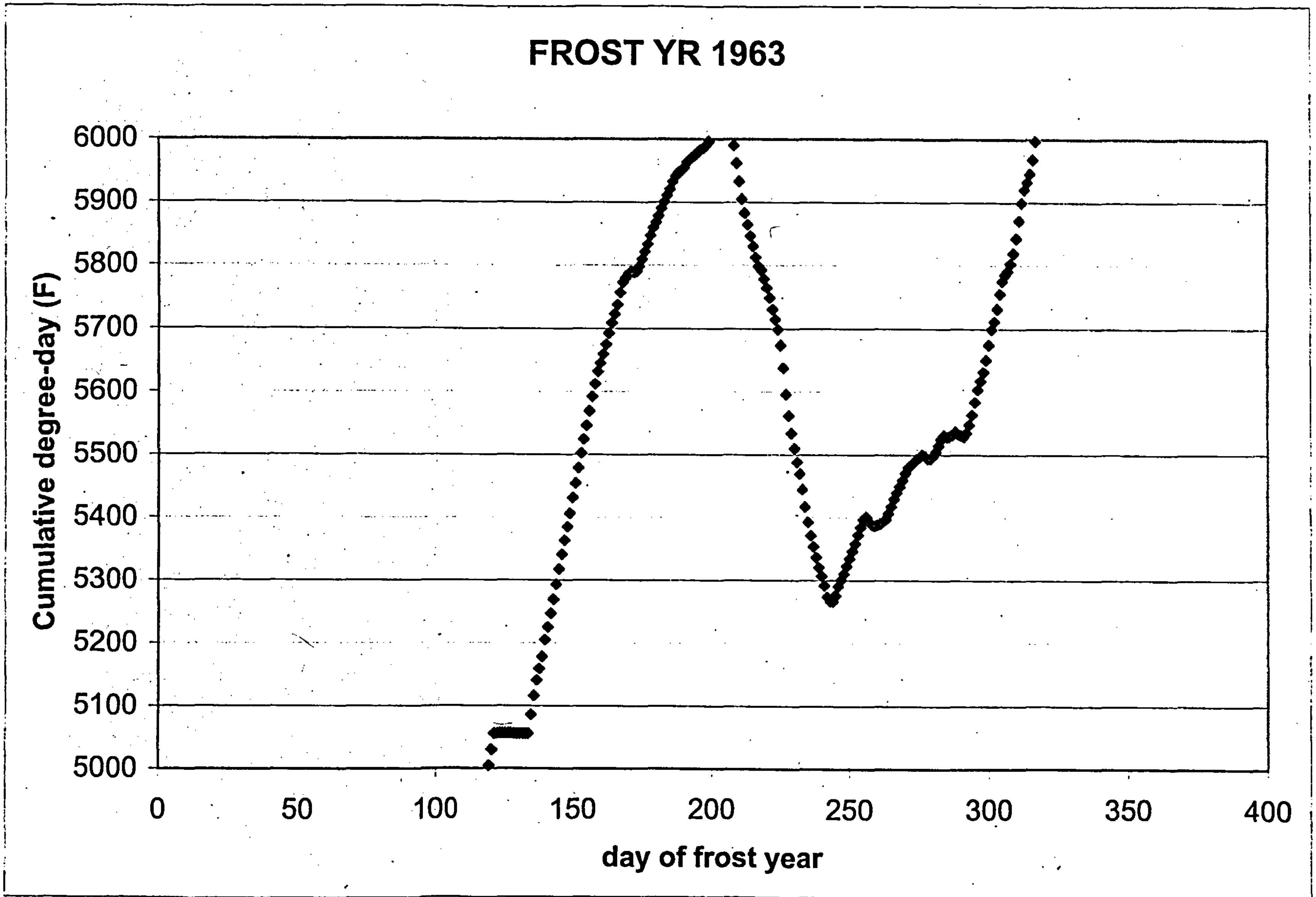
5950
5900
5850
5800
5750
5700
5650
5600
5550
5500
0
50
100
150
200
250
300
350
400
day of frost year



FROST YR 1963
Cumulative degree-day (F)
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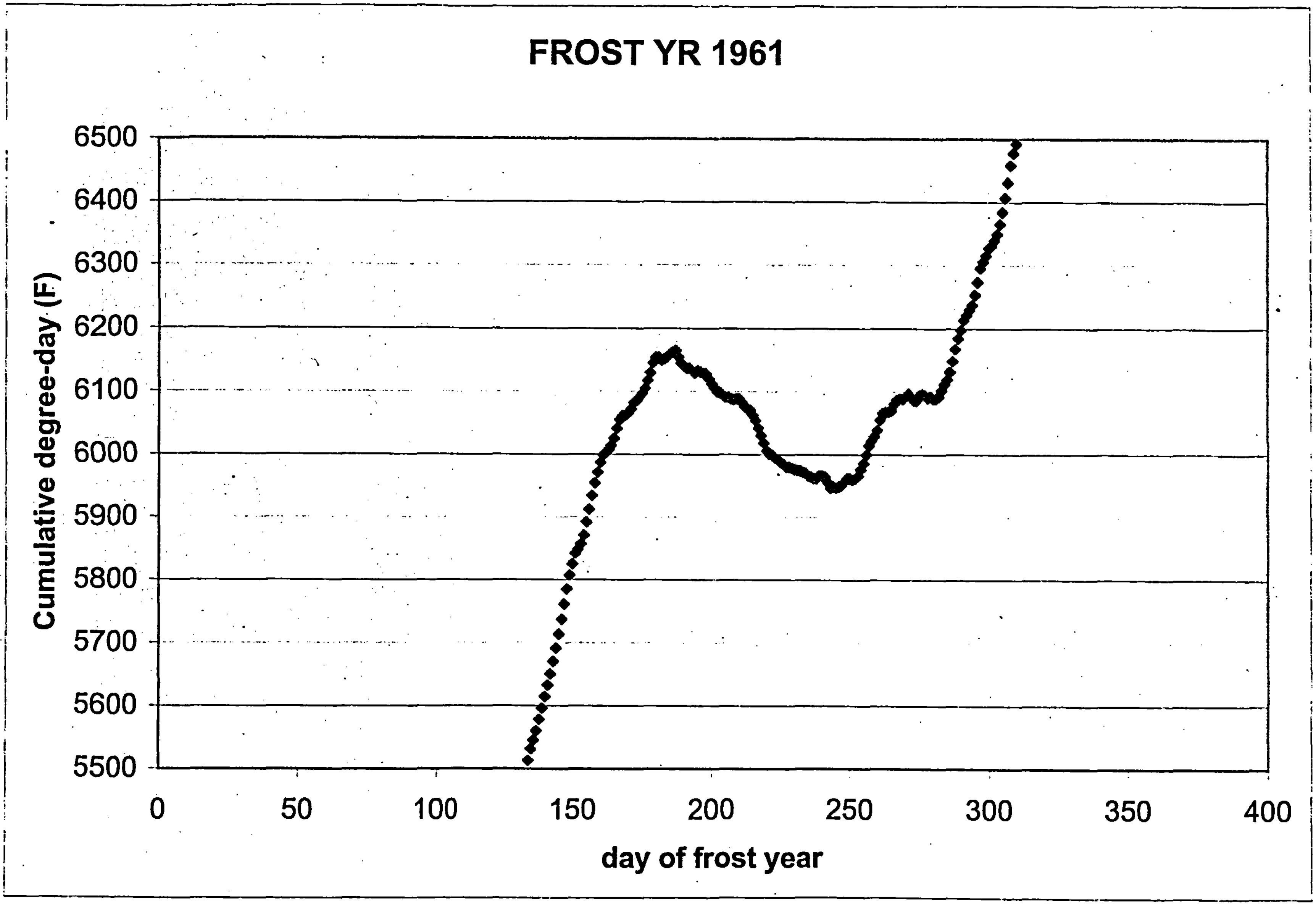
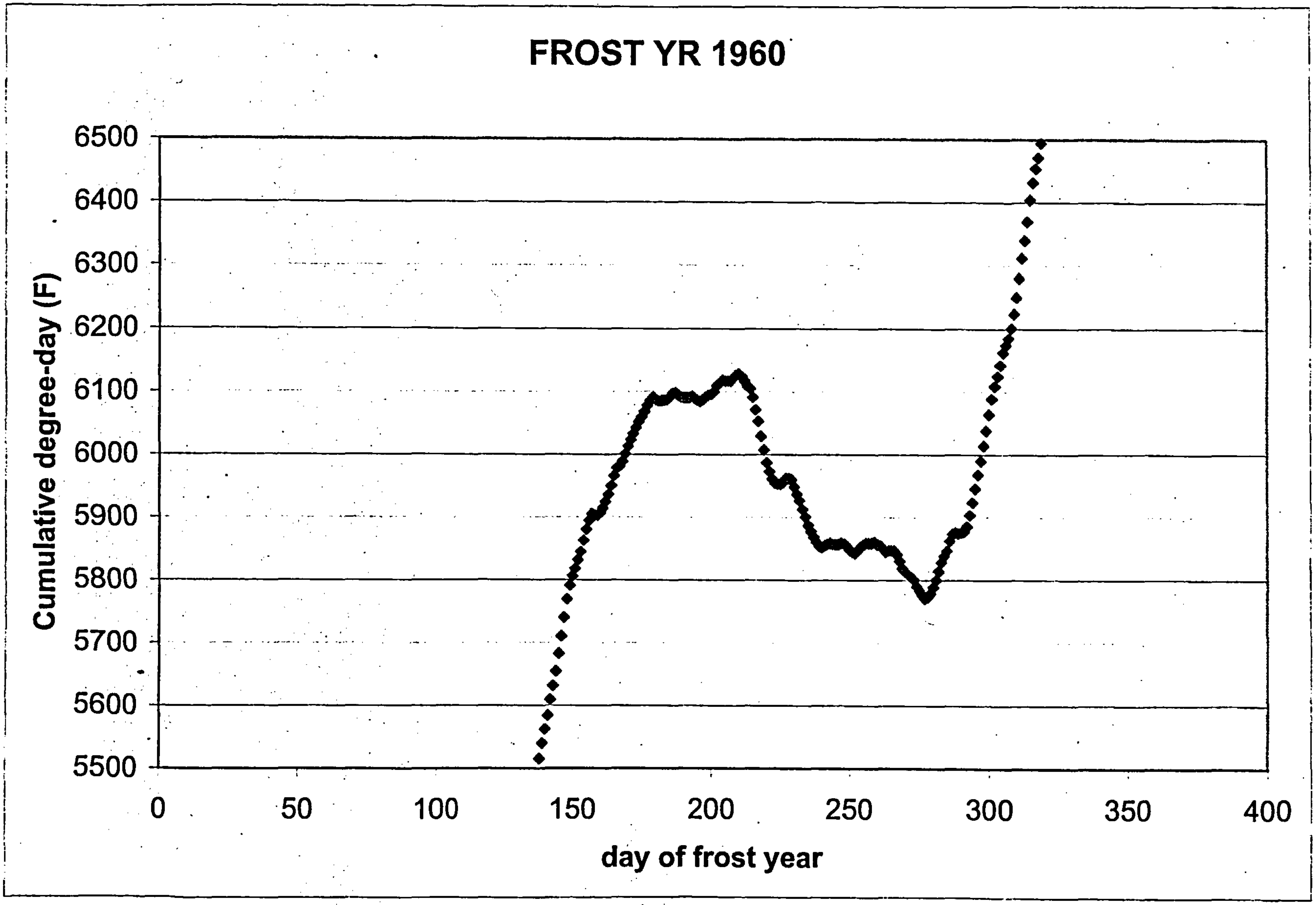
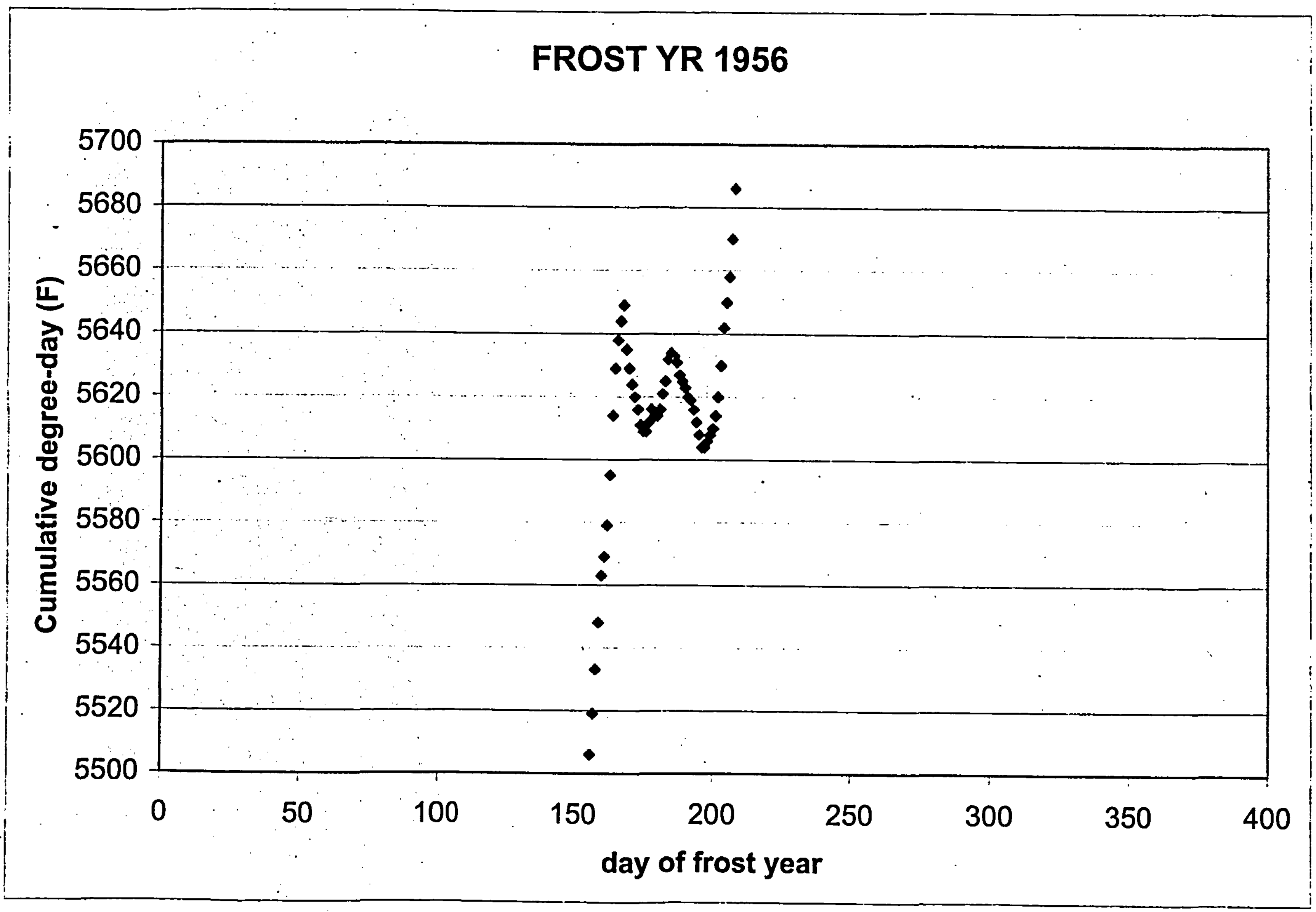
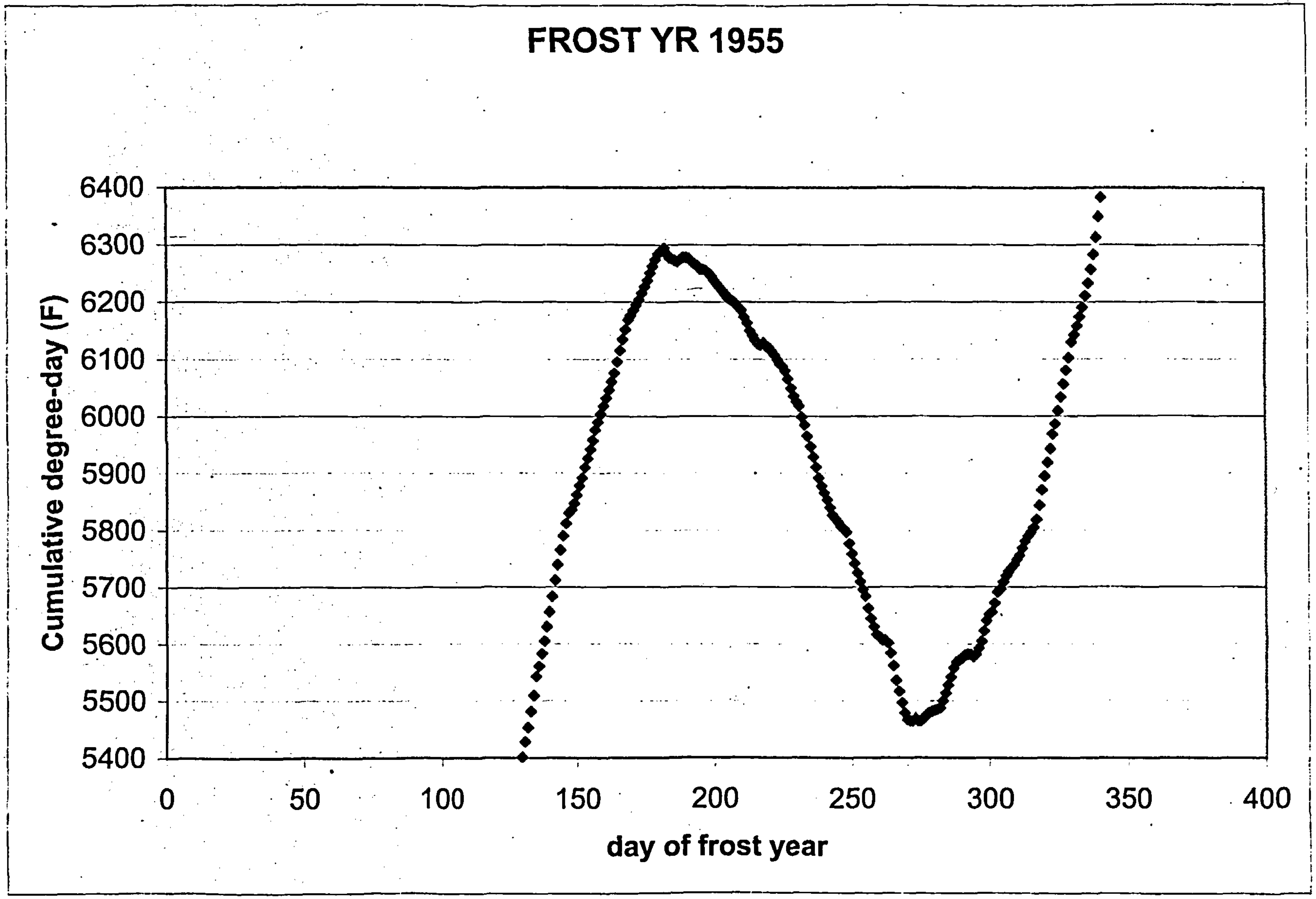
5800
5700
5600
5500
5400
5300
5200
5100
5000
0
50
100
150
200
250
300
350
400
day of frost year

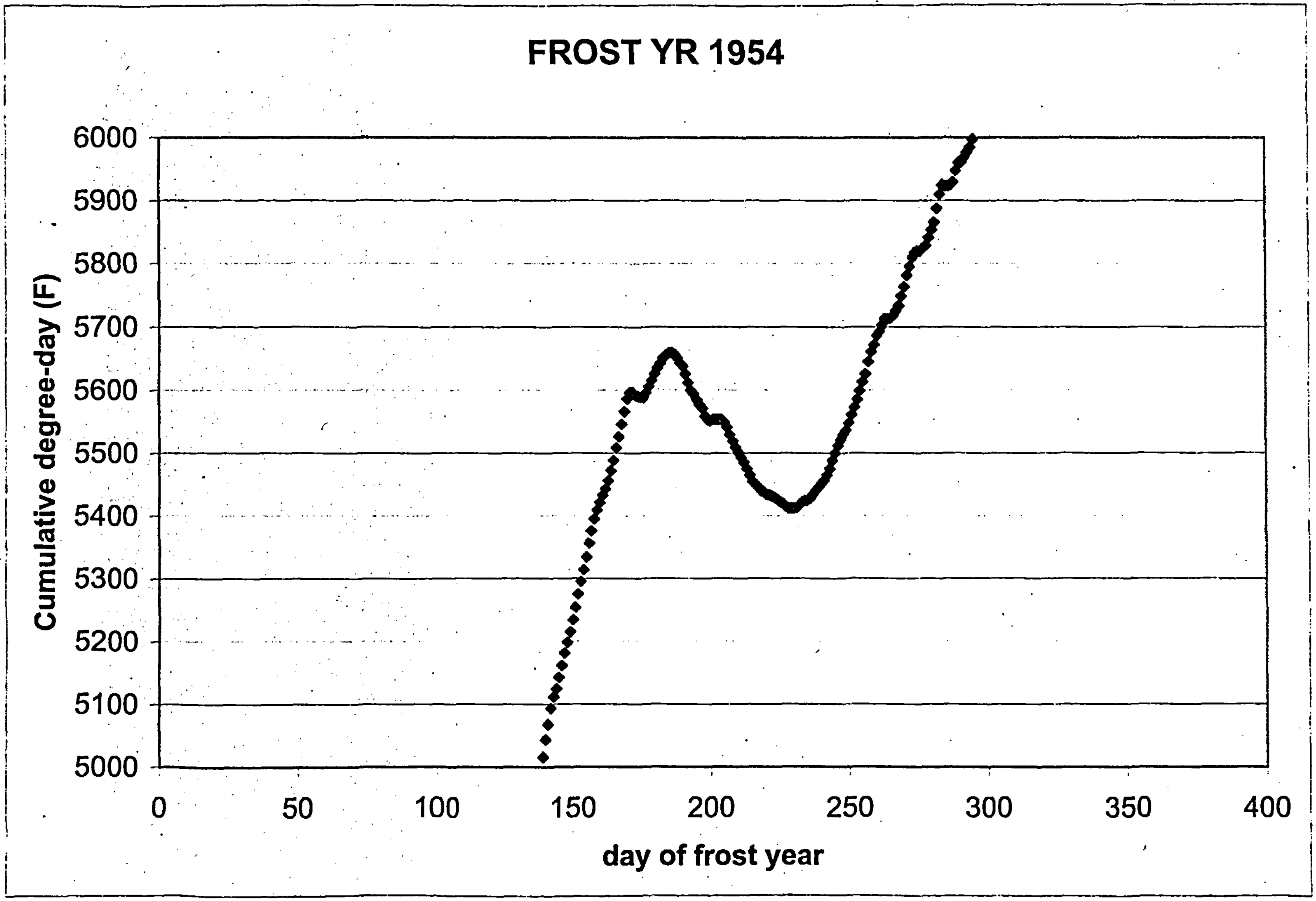

FROST YR 1961
Cumulative degree-day (F)
6500
6400
6300
6200
6100
6000
5900
5800
5700
5600
5500
0
50
100
150
200
250
300
350
400
day of frost year


FROST YR 1960
Cumulative degree-day (F)
6500
6400
6300
6200
6100
6000
5900
5800
5700
5600
5500
0
50
100
150
200
250
300
350
400
day of frost year

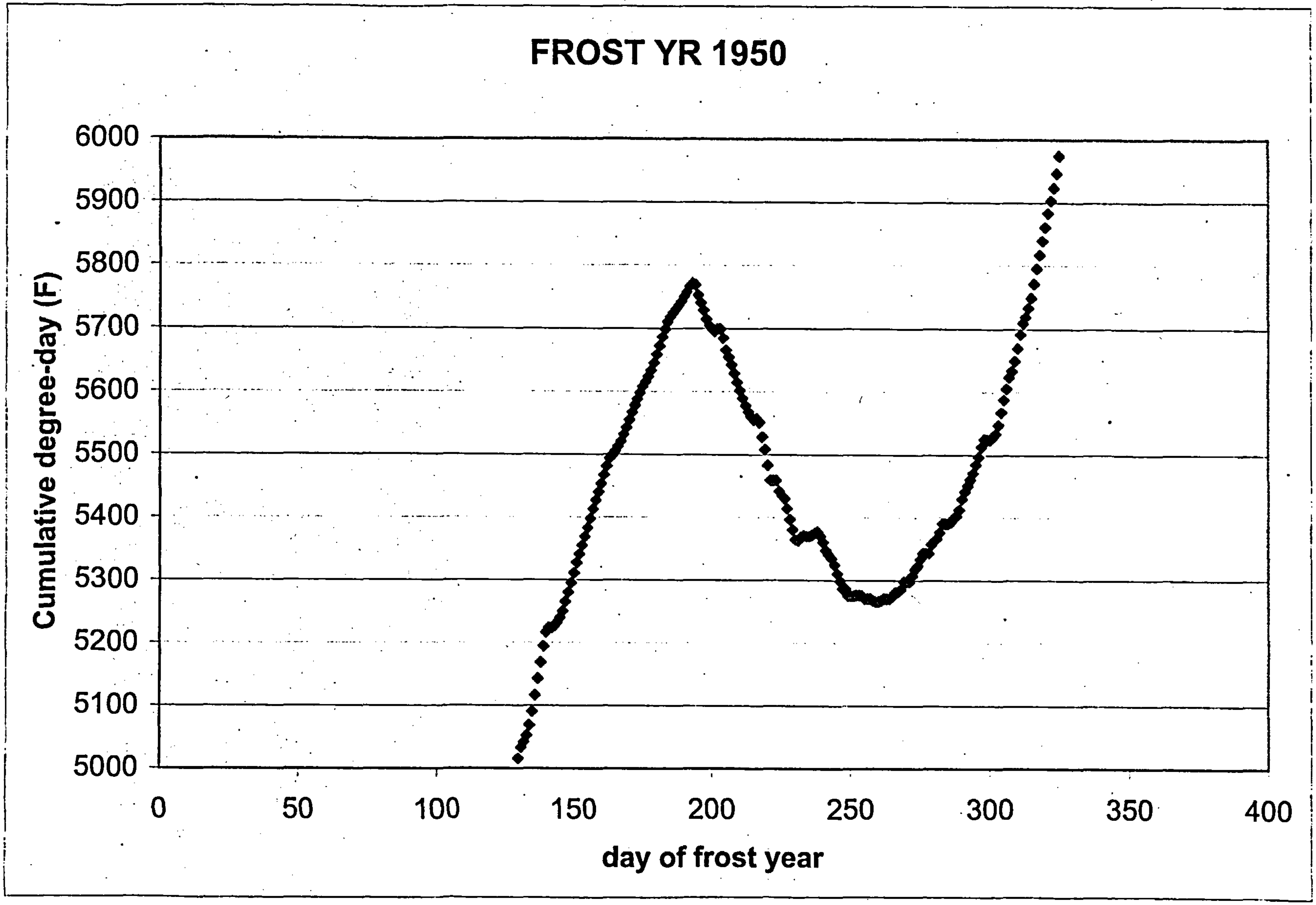


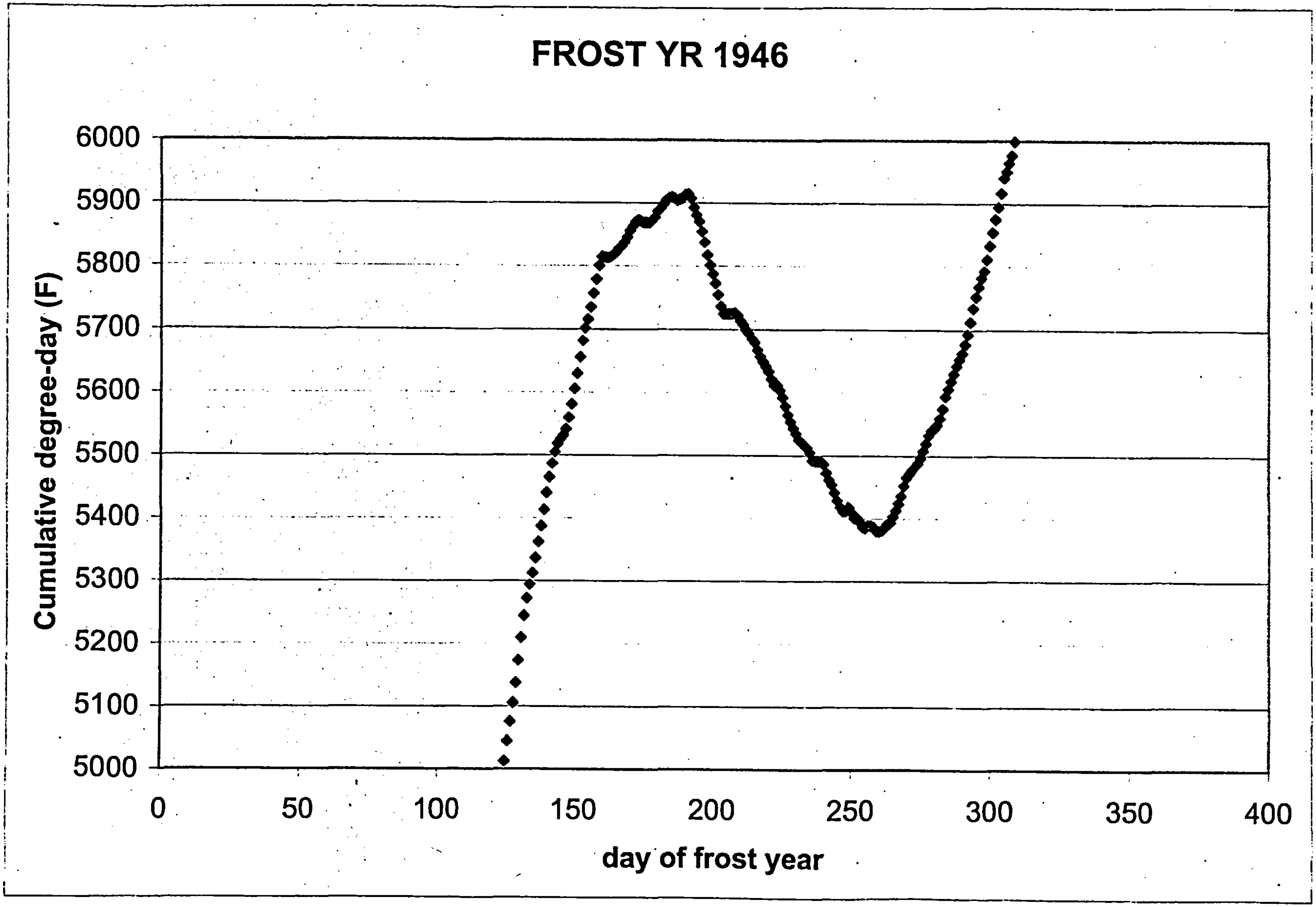
FROST YR 1956
Cumulative degree-day (F)
5700
5680
5660
5640
5620
5600
5580
5560
5540
5520
5500
0
50
100
150
200
250
300
350
400
day of frost year

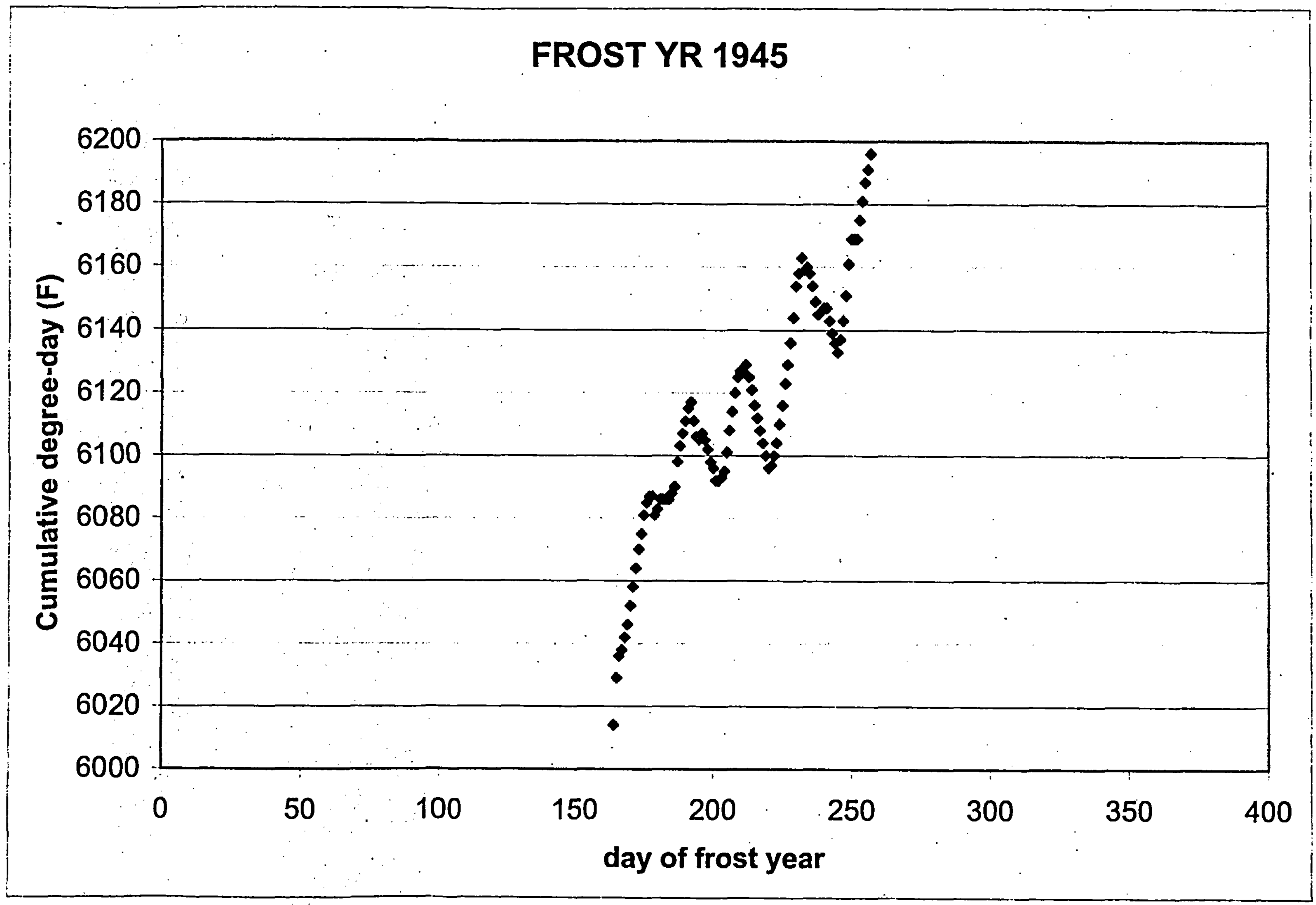

FROST YR 1955
Cumulative degree-day (F)
6400
6300
6200
6100
6000
5900
5800
5700
5600
5500
5400
0
50
100
150
200
250
300
350
400
day of frost year

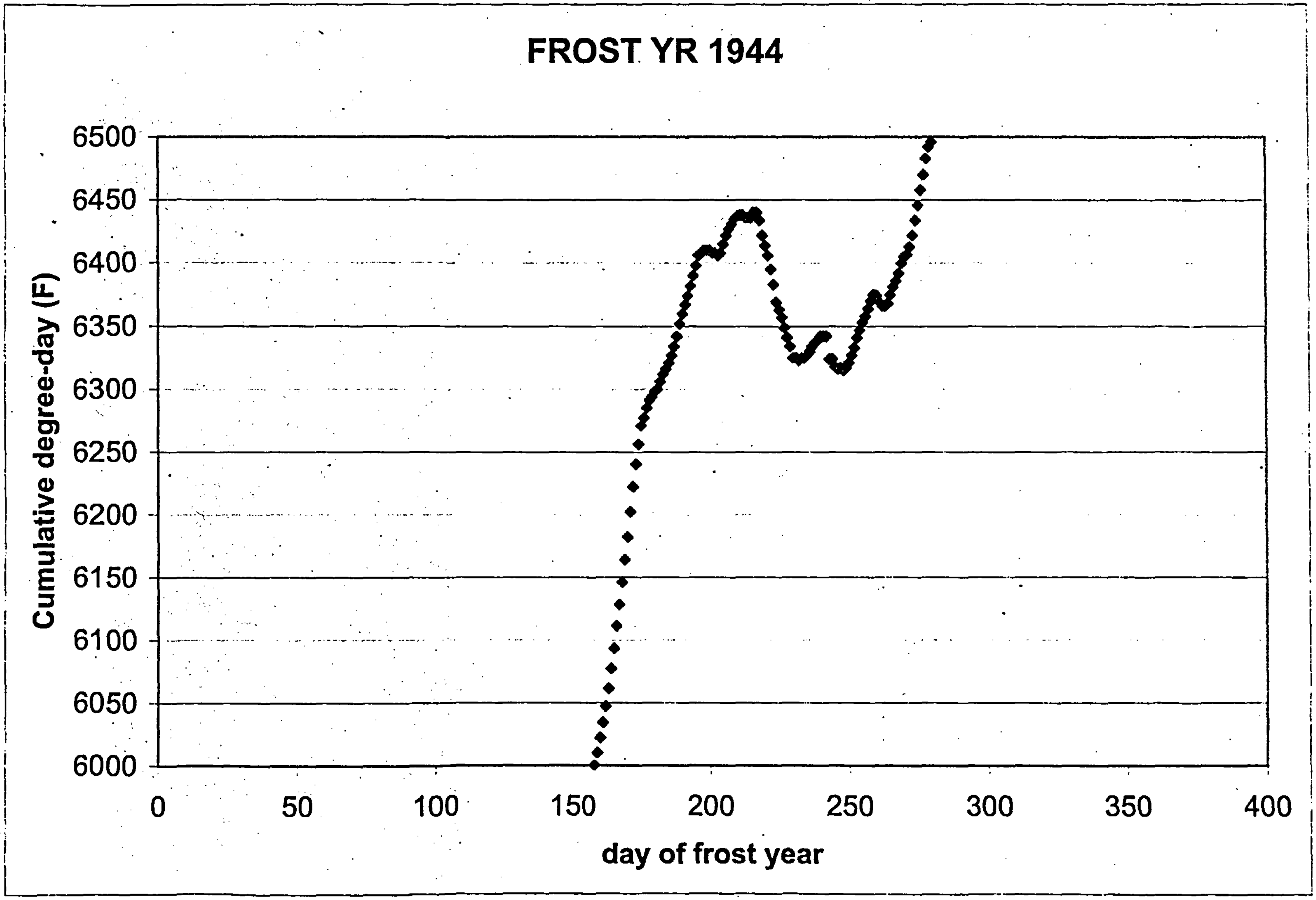


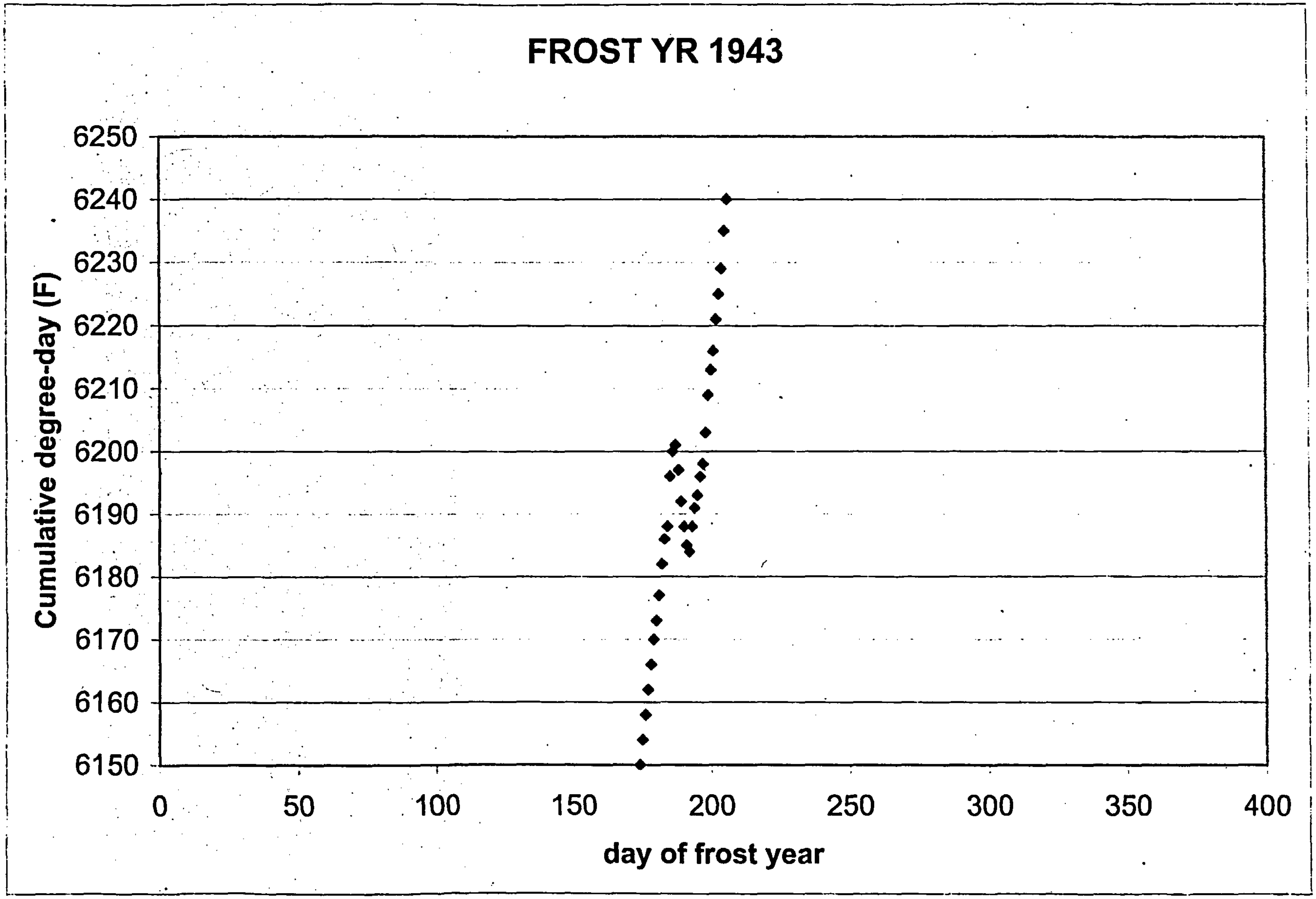
FROST YR 1954
Cumulative degree-day (F)
6000
5900
5800
5700
5600
5500
5400
5300
5200
5100
5000
0
50
100
150
200
250
300
350
400
day of frost year

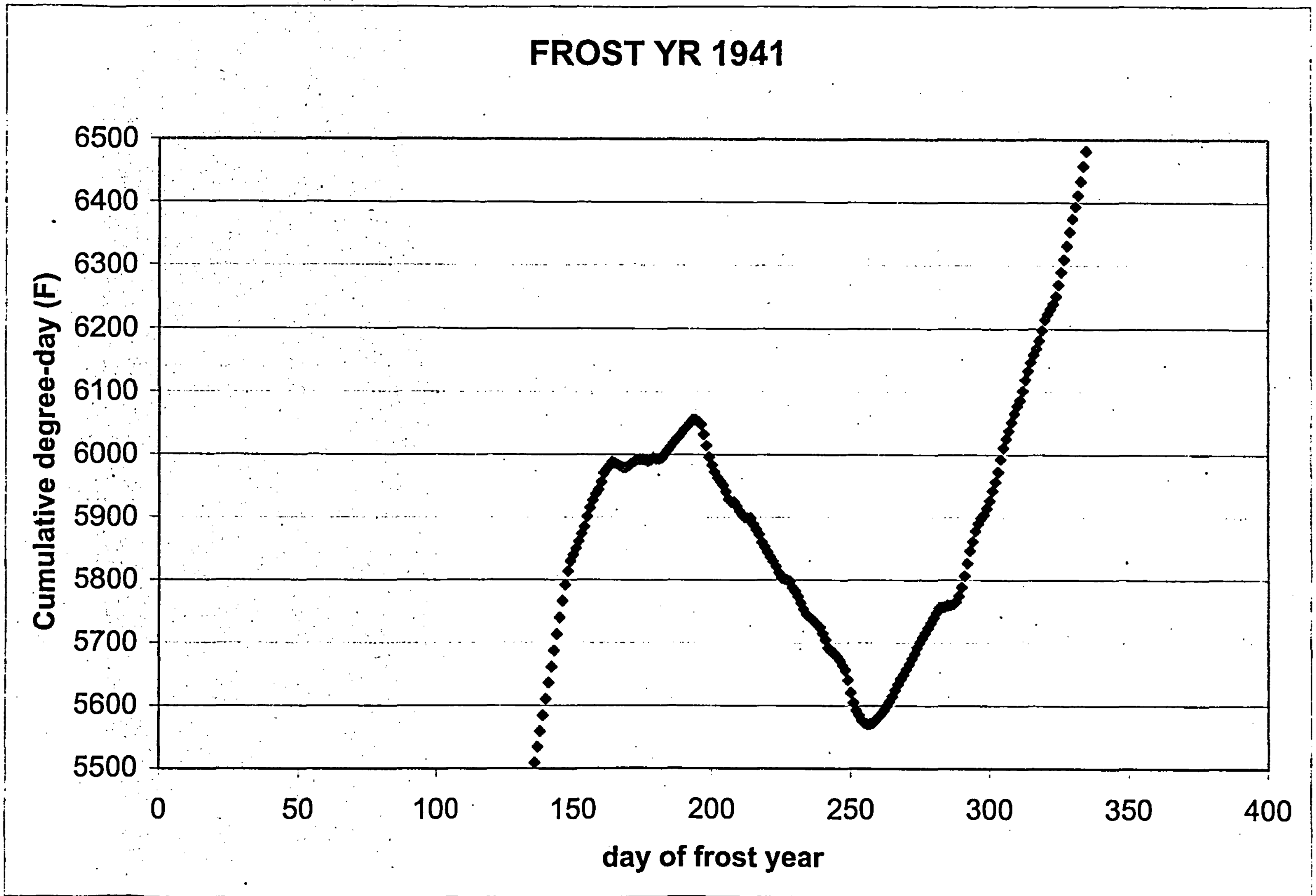

FROST YR 1950
Cumulative degree-day (F)
6000
5900
5800
5700
5600
5500
5400
5300
5200
5100
5000
0
50
100
150
200
250
300
350
400
day of frost year


FROST YR 1946
6000
5900
5800
5700
5600
5500
5400
5300
5200
5100
5000
Cumulative degree-day (F)
0
50
100
150
200
250
300
350
400
day of frost year

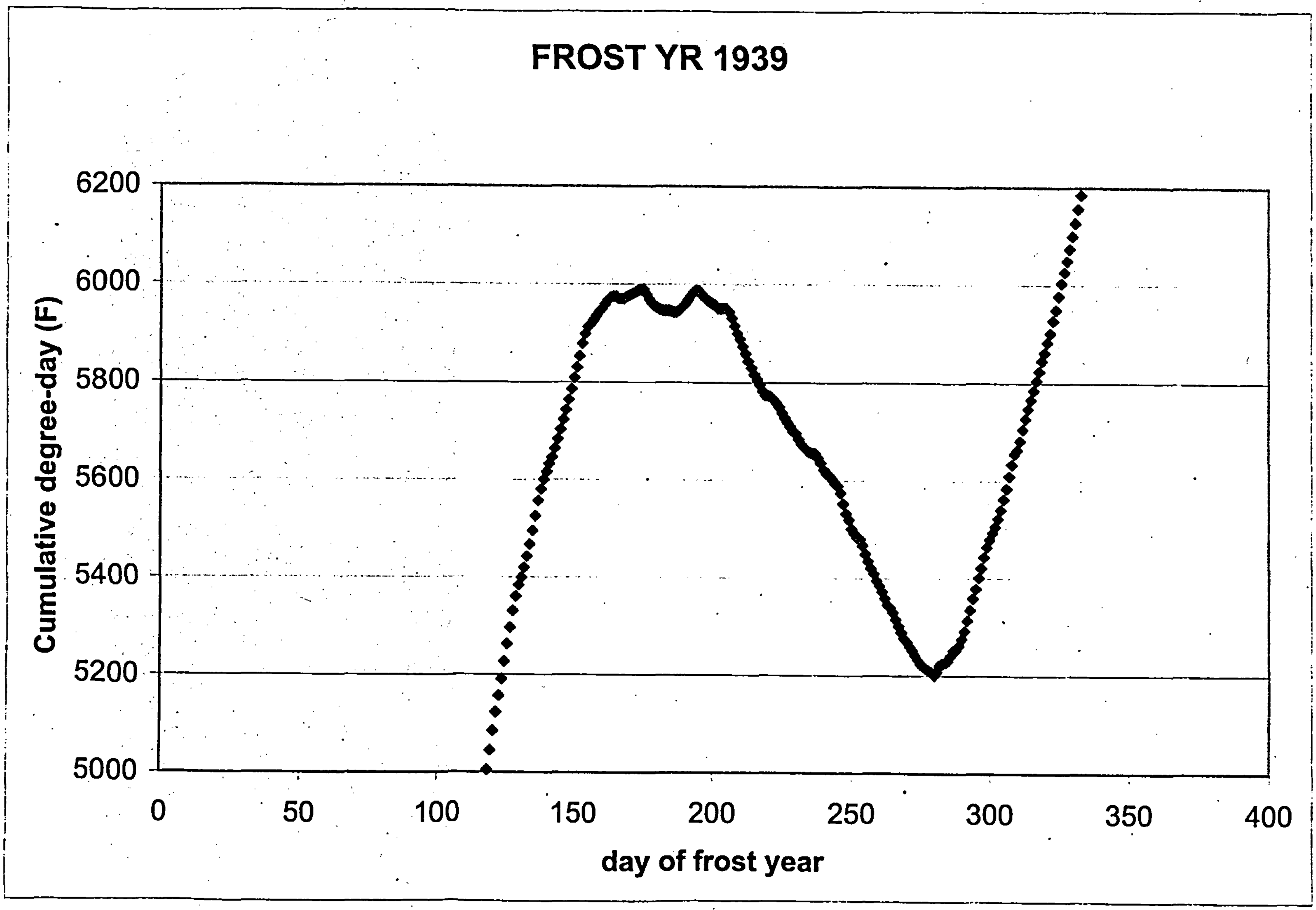

FROST YR 1945
Cumulative degree-day (F)
6200
6180
6160
6140
6120
6100
6080
6060
6040
6020
6000
0
50
100
150
200
250
300
350
400
day of frost year

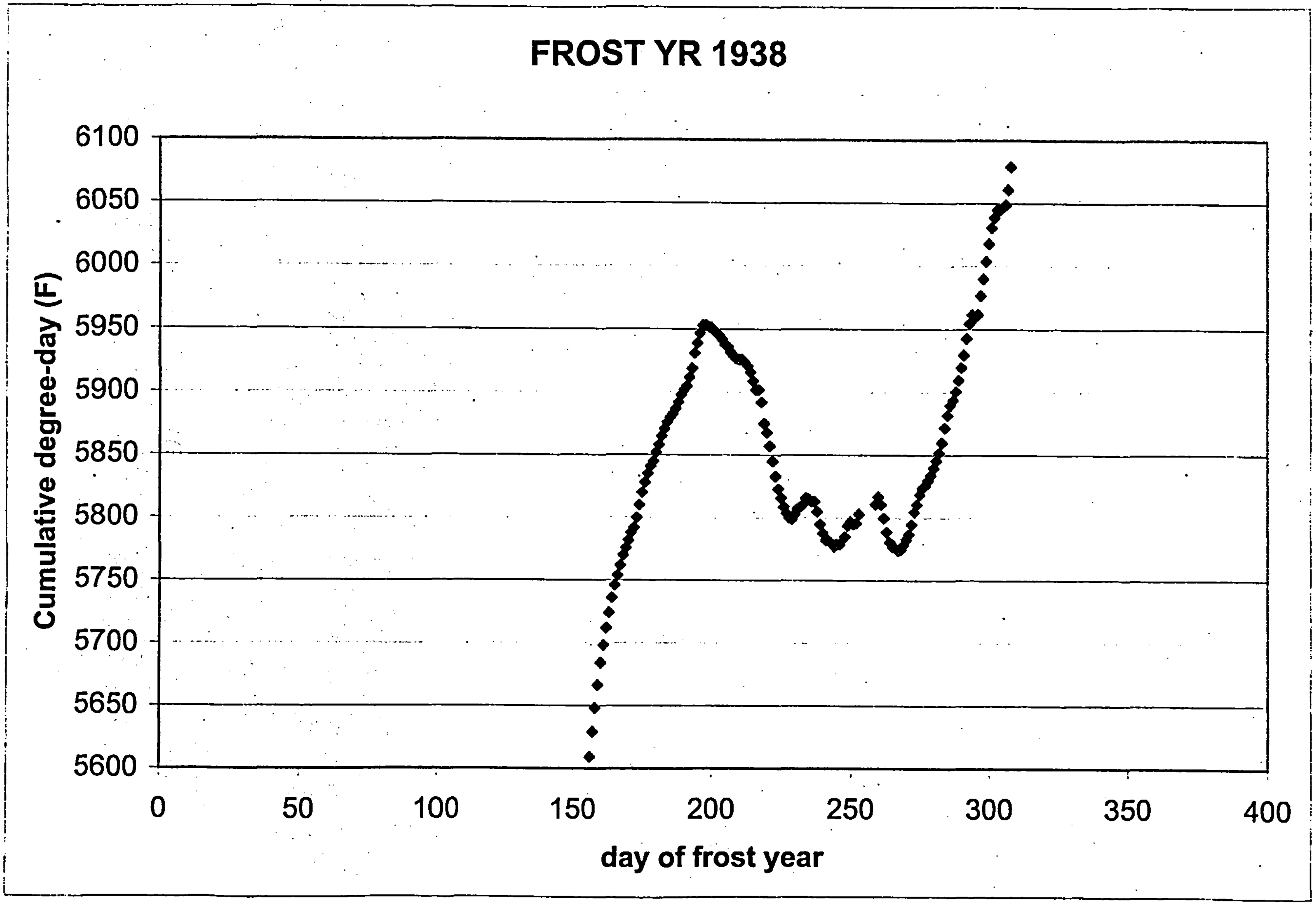

FROST YR 1944
Cumulative degree-day (F)
6500
6450
6400
6350
6300
6250
6200
6150
6100
6050
6000
0
50
100
150
200
250
300
350
400
day of frost year

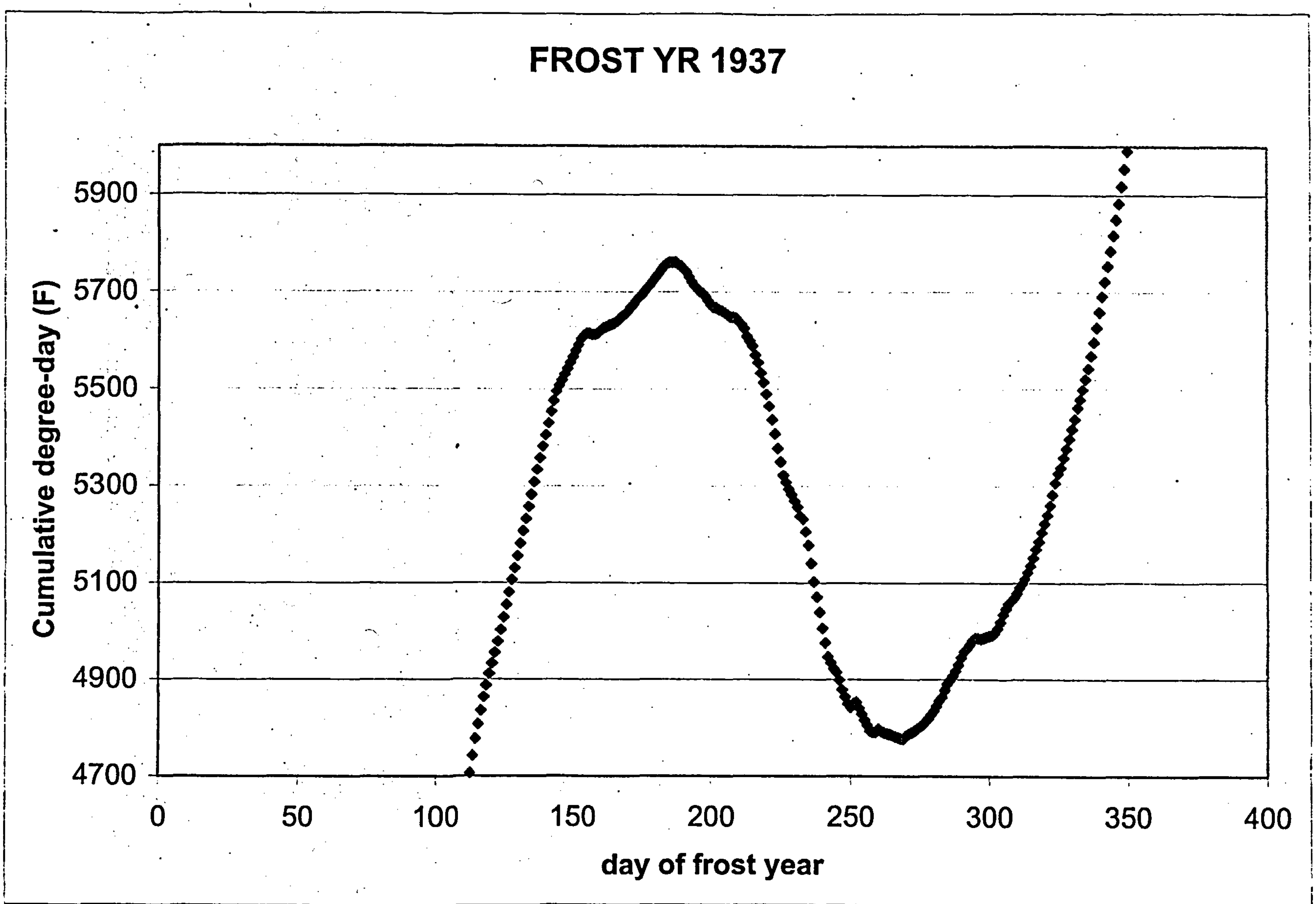

FROST YR 1943
Cumulative degree-day (F)
6250
6240
6230
6220
6210
6200
6190
6180
6170
6160
6150
0
50
100
150
200
250
300
350
400
day of frost year

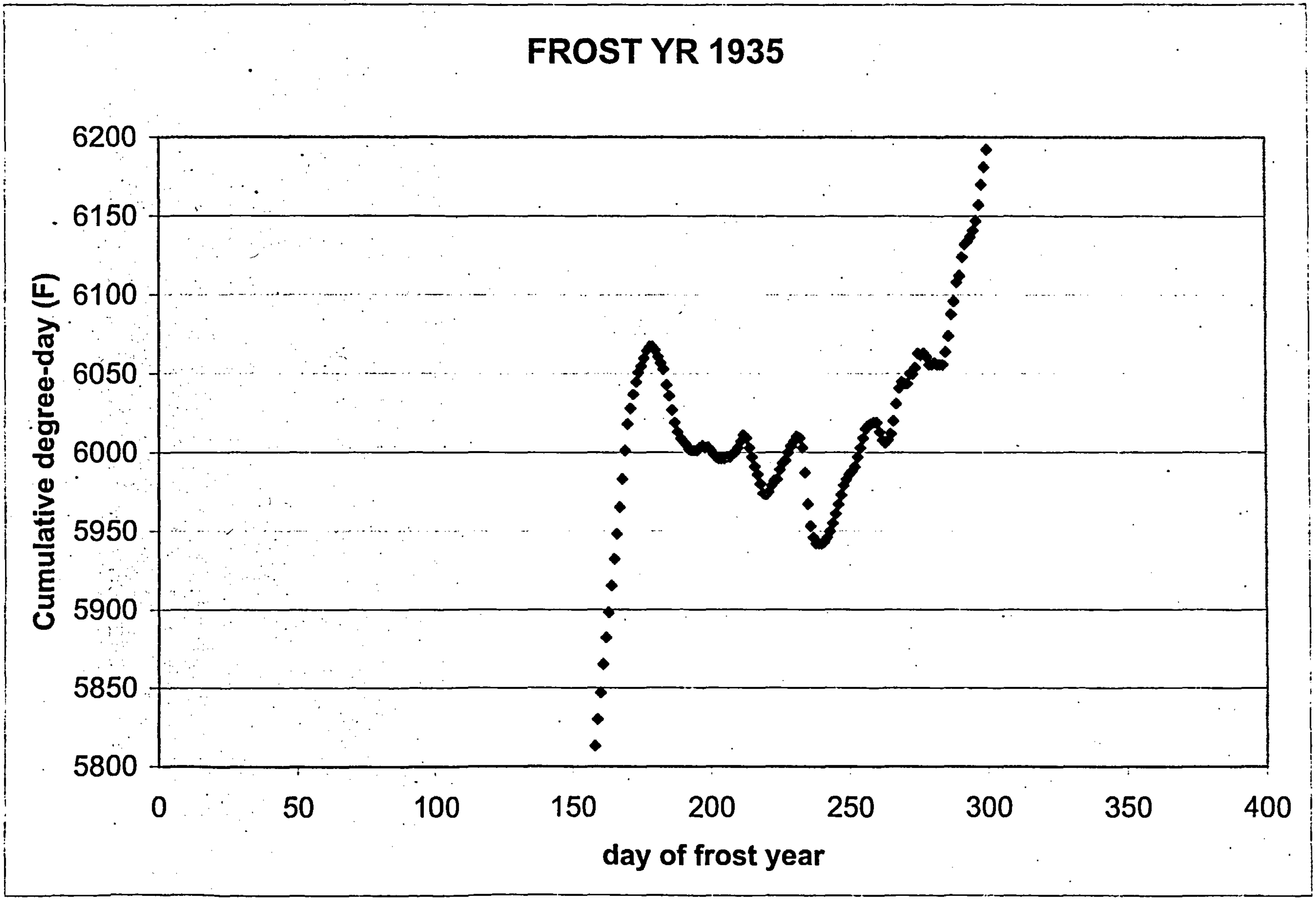


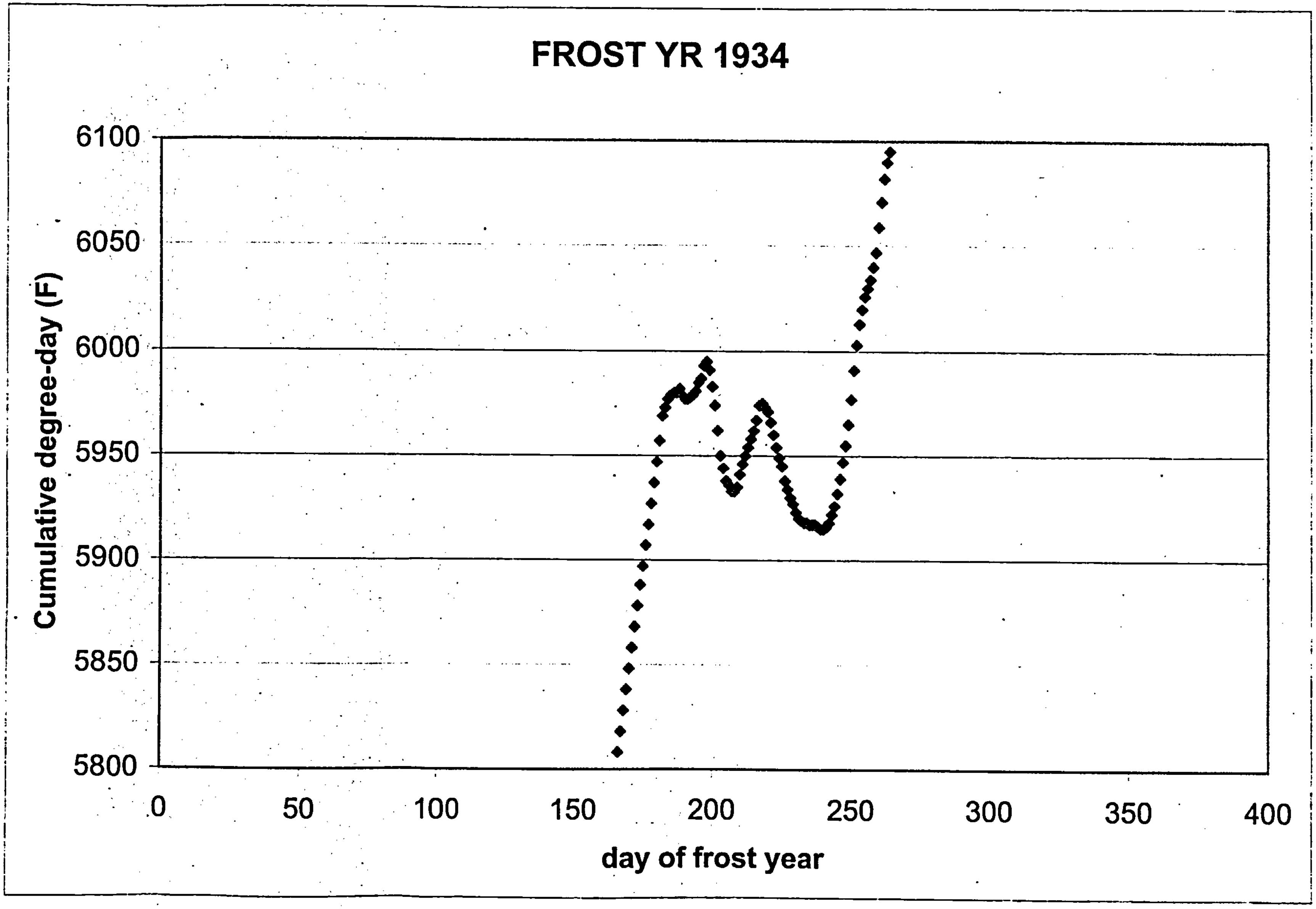
FROST YR 1941
6500
6400
6300
6200
6100
6000
5900
5800
5700
5600
5500
Cumulative degree-day (F)
0
50
100
150
200
250
300
350
400
day of frost year

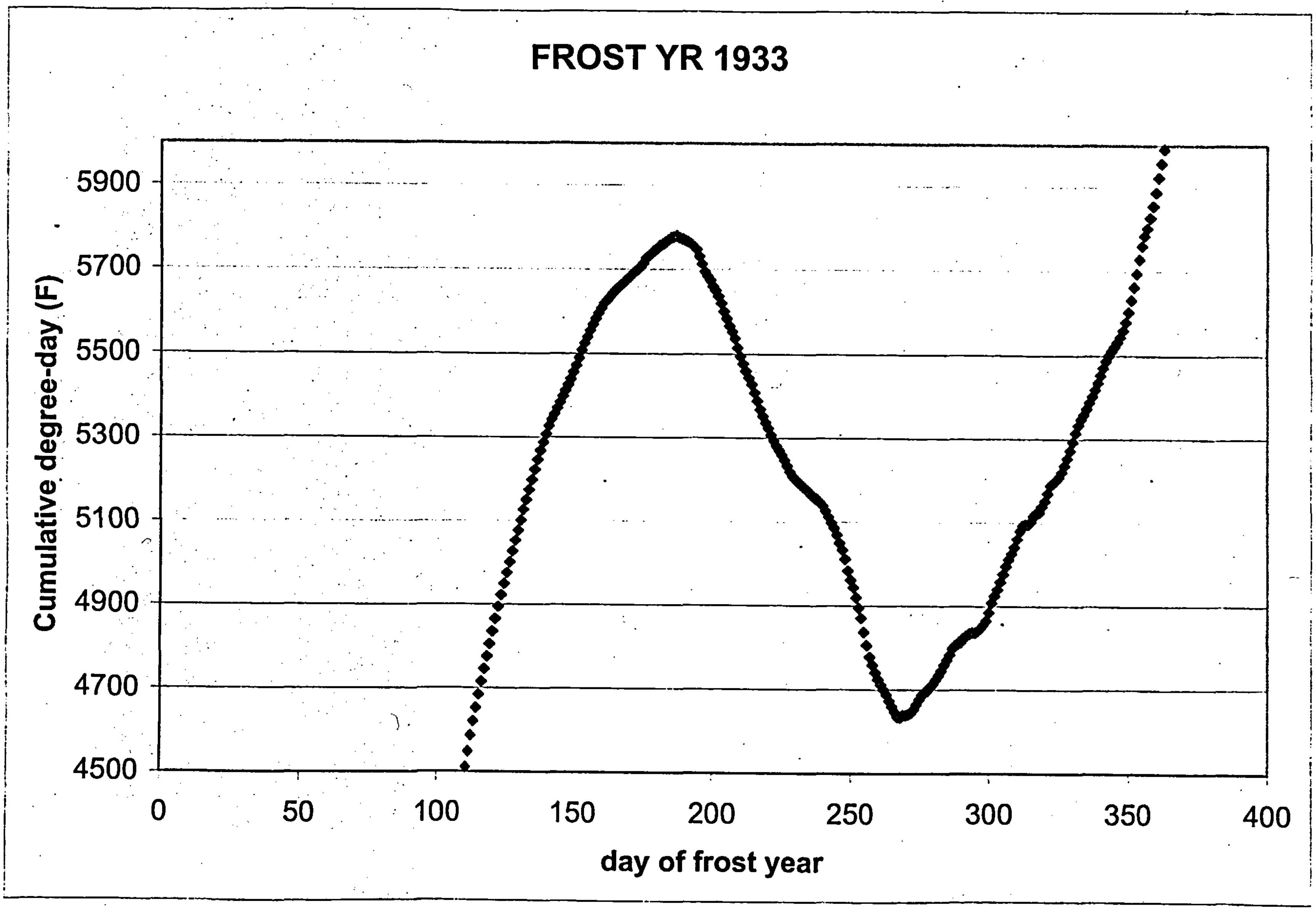

FROST YR 1939
Cumulative degree-day (F)
6200
6000
5800
5600
5400
5200
5000
0
50
100
150
200
250
300
350
400
day of frost year


FROST YR 1938
Cumulative degree-day (F)
6100
6050
6000
5950
5900
5850
5800
5750
5700
5650
5600
0
50
100
150
200
250
300
350
400
day of frost year

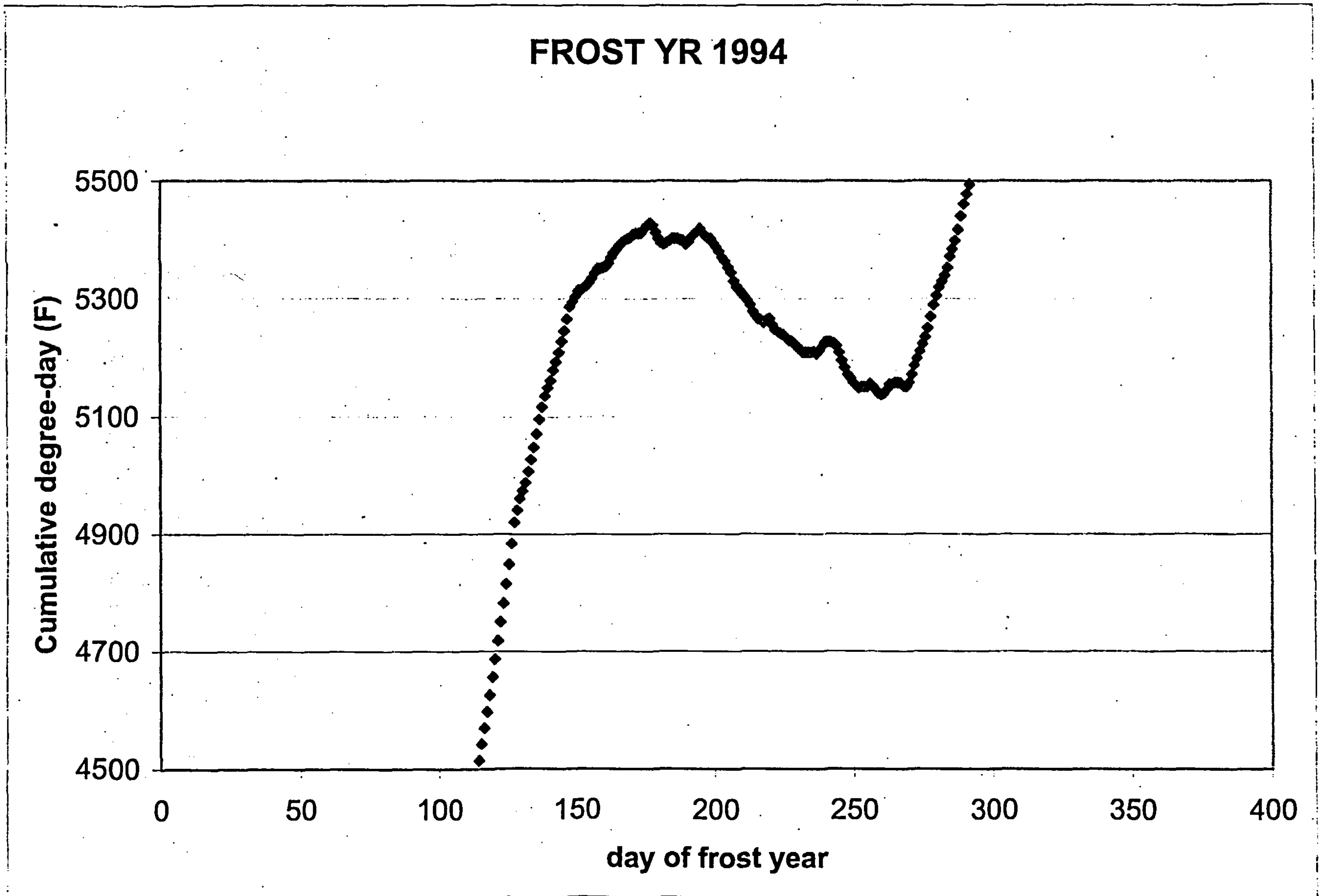

FROST YR 1937
Cumulative degree-day (F)
5900
5700
5500
5300
5100
4900
4700
0
50
100
150
200
250
300
350
400
day of frost year


FROST YR 1935
Cumulative degree-day (F)
6200
6150
6100
6050
6000
5950
5900
5850
5800
0
50
100
150
200
250
300
350
400
day of frost year


FROST YR 1934
Cumulative degree-day (F)
6100
6050
6000
5950
5900
5850
5800
0
50
100
150
200
250
300
350
400
day of frost year



FROST YR 1933
Cumulative degree-day (F)
5900
5700
5500
5300
5100
4900
4700
4500
0
50
100
150
200
250
300
350
400
day of frost year


FROST YR 1994
Cumulative degree-day (F)
5500
5300
5100
4900
4700
4500
0
50
100
150
200
250
300
350
400
day of frost year

APPENDIX B

MBF COMPUTER OUTPUT

1933

```
C:\PROGRA~1\DOSPRG~1\frost\GO2.exe

                 Summary: MODIFIED BERGGREN SOLUTION

        Design Freezing Index (AIR)     = 1141 F-days
        Design Freezing Index (SURFACE) = 1141 F-days
        Mean Annual Temperature         = 48.8 oF
        Length of Freezing Season       =   83 Days

 ----------------------------------------------------------------------
                          LAYER      FREEZING INDEX DISTRIBUTION
        LAYER           THICKNESS
       #: Type           (inches)     Each Layer     Accumulated
 ----------------      ----------   ------------   -------------
 1: Fine-grained          12.0          112             112
 2: Fine-grained          12.0          336             448
 3: Fine-grained          12.0          560            1008
 4: Fine-grained           2.3          134            1142
 ---------------- End of Frost Penetration ----------------------

 TOTAL FROST PENETRATION =  38.3 inches


 Do you want a hard copy of this data (Y or default N)?
```

1934

```
C:\PROGRA~1\DOSPRG~1\frost\GO2.exe

                 Summary: MODIFIED BERGGREN SOLUTION

        Design Freezing Index (AIR)     =   80 F-days
        Design Freezing Index (SURFACE) =   80 F-days
        Mean Annual Temperature         = 56.7 oF
        Length of Freezing Season       =   42 Days

 ----------------------------------------------------------------------
                          LAYER      FREEZING INDEX DISTRIBUTION
        LAYER           THICKNESS
       #: Type           (inches)     Each Layer     Accumulated
 ----------------      ----------   ------------   -------------
 1: Fine-grained           2.0           10             10
 2: Fine-grained           2.0           30          Berggren
 3: Fine-grained           1.0           22        Calculations
 4: Fine-grained         < 1.0           27      ←   could not
                                                     converge
                                                   Surface DFI
 ---------------- End of Frost Penetration ----------------------

 TOTAL FROST PENETRATION =   6.0 inches

 Do you want a hard copy of this data (Y or default N)?
```

C04

1935

C:\PROGRA~1\DOSPRG~1\frost\GO2.exe

Summary: MODIFIED BERGGREN SOLUTION

```
Design Freezing Index (AIR)      =  124 F-days
Design Freezing Index (SURFACE)  =  124 F-days
Mean Annual Temperature          = 53.3 ºF
Length of Freezing Season        =   62 Days
```

LAYER #: Type	LAYER THICKNESS (inches)	FREEZING INDEX DISTRIBUTION Each Layer	Accumulated
1: Fine-grained	6.0	71	71
2: Fine-grained	2.0	54	125

------------ End of Frost Penetration ------------

TOTAL FROST PENETRATION = 8.0 inches

Do you want a hard copy of this data (Y or default N)?

1937

C:\PROGRA~1\DOSPRG~1\frost\GO2.exe

Summary: MODIFIED BERGGREN SOLUTION

```
Design Freezing Index (AIR)      =  970 F-days
Design Freezing Index (SURFACE)  =  970 F-days
Mean Annual Temperature          = 50.1 ºF
Length of Freezing Season        =   83 Days
```

LAYER #: Type	LAYER THICKNESS (inches)	FREEZING INDEX DISTRIBUTION Each Layer	Accumulated
1: Fine-grained	12.0	122	122
2: Fine-grained	12.0	365	487
3: Fine-grained	9.9	486	973

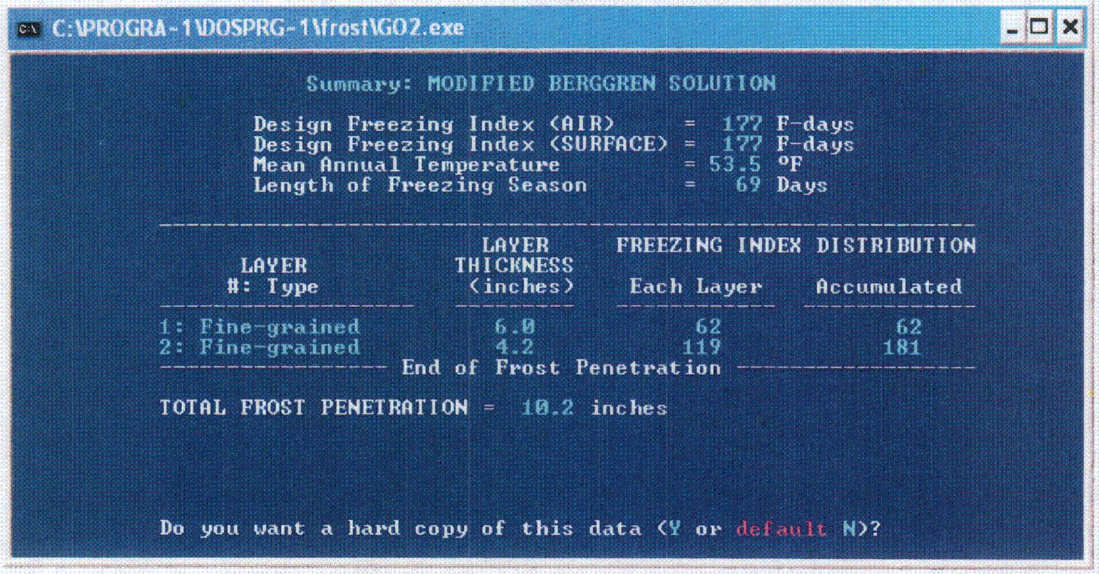
------------ End of Frost Penetration ------------

TOTAL FROST PENETRATION = 33.9 inches

Do you want a hard copy of this data (Y or default N)?

C05

1938



C:\PROGRA~1\DOSPRG~1\frost\GO2.exe

Summary: MODIFIED BERGGREN SOLUTION

Design Freezing Index (AIR) = 177 F-days
Design Freezing Index (SURFACE) = 177 F-days
Mean Annual Temperature = 53.5 °F
Length of Freezing Season = 69 Days

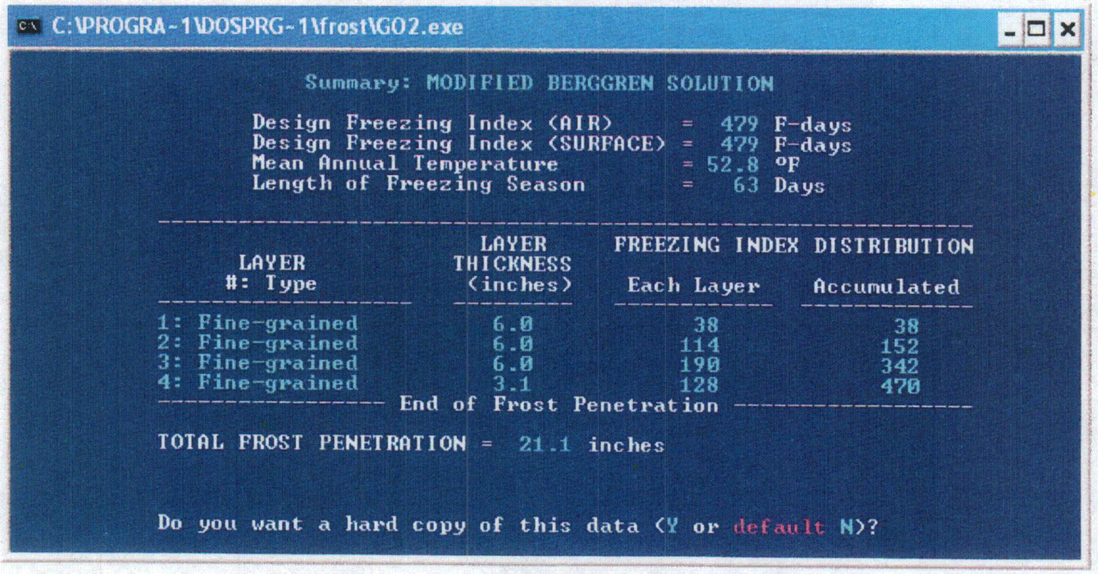
LAYER #: Type	LAYER THICKNESS (inches)	FREEZING INDEX DISTRIBUTION Each Layer	Accumulated
1: Fine-grained	6.0	62	62
2: Fine-grained	4.2	119	181

------ End of Frost Penetration ------

TOTAL FROST PENETRATION = 10.2 inches

Do you want a hard copy of this data (Y or default N)?

1941



C:\PROGRA~1\DOSPRG~1\frost\GO2.exe

Summary: MODIFIED BERGGREN SOLUTION

Design Freezing Index (AIR) = 479 F-days
Design Freezing Index (SURFACE) = 479 F-days
Mean Annual Temperature = 52.8 °F
Length of Freezing Season = 63 Days

LAYER #: Type	LAYER THICKNESS (inches)	FREEZING INDEX DISTRIBUTION Each Layer	Accumulated
1: Fine-grained	6.0	38	38
2: Fine-grained	6.0	114	152
3: Fine-grained	6.0	190	342
4: Fine-grained	3.1	128	470

------ End of Frost Penetration ------

TOTAL FROST PENETRATION = 21.1 inches

Do you want a hard copy of this data (Y or default N)?

C06

1943

C:\PROGRA~1\DOSPRG~1\frost\GO2.exe

Summary: MODIFIED BERGGREN SOLUTION

```
Design Freezing Index (AIR)      =   17 F-days
Design Freezing Index (SURFACE)  =   17 F-days
Mean Annual Temperature          = 55.8 oF
Length of Freezing Season        =    5 Days
```

LAYER #: Type	LAYER THICKNESS (inches)	FREEZING INDEX DISTRIBUTION Each Layer	Accumulated
1: Fine-grained	2.0	7	7

------------------ End of Frost Penetration ------------------

TOTAL FROST PENETRATION = 2.0 inches

Do you want a hard copy of this data (Y or default N)?

1944

C:\PROGRA~1\DOSPRG~1\frost\GO2.exe

Summary: MODIFIED BERGGREN SOLUTION

```
Design Freezing Index (AIR)      =  119 F-days
Design Freezing Index (SURFACE)  =  119 F-days
Mean Annual Temperature          = 55.2 oF
Length of Freezing Season        =   33 Days
```

LAYER #: Type	LAYER THICKNESS (inches)	FREEZING INDEX DISTRIBUTION Each Layer	Accumulated
1: Fine-grained	6.0	56	56
2: Fine-grained	2.8	65	121

------------------ End of Frost Penetration ------------------

TOTAL FROST PENETRATION = 8.8 inches

Do you want a hard copy of this data (Y or default N)?

C07

1945

C:\PROGRA~1\DOSPRG~1\frost\GO2.exe

Summary: MODIFIED BERGGREN SOLUTION

Design Freezing Index (AIR) = 32 F-days
Design Freezing Index (SURFACE) = 32 F-days
Mean Annual Temperature = 54.7 oF
Length of Freezing Season = 9 Days

LAYER #: Type	LAYER THICKNESS (inches)	FREEZING INDEX DISTRIBUTION Each Layer	Accumulated
1: Fine-grained	2.0	6	6
2: Fine-grained	1.0	8	14
3: Fine-grained	1.0	11	25

End of Frost Penetration

TOTAL FROST PENETRATION = 4.0 inches

Do you want a hard copy of this data (Y or default N)?

1946

C:\PROGRA~1\DOSPRG~1\frost\GO2.exe

Summary: MODIFIED BERGGREN SOLUTION

Design Freezing Index (AIR) = 520 F-days
Design Freezing Index (SURFACE) = 520 F-days
Mean Annual Temperature = 53.2 oF
Length of Freezing Season = 73 Days

LAYER #: Type	LAYER THICKNESS (inches)	FREEZING INDEX DISTRIBUTION Each Layer	Accumulated
1: Fine-grained	12.0	157	157
2: Fine-grained	10.0	371	528

End of Frost Penetration

TOTAL FROST PENETRATION = 22.0 inches

Do you want a hard copy of this data (Y or default N)?

C08

1950

C:\PROGRA~1\DOSPRG~1\frost\GO2.exe

Summary: MODIFIED BERGGREN SOLUTION

Design Freezing Index (AIR)	=	501 F-days
Design Freezing Index (SURFACE)	=	501 F-days
Mean Annual Temperature	=	52.5 °F
Length of Freezing Season	=	67 Days

LAYER #: Type	LAYER THICKNESS (inches)	FREEZING INDEX DISTRIBUTION Each Layer	Accumulated
1: Fine-grained	6.0	38	38
2: Fine-grained	6.0	114	152
3: Fine-grained	6.0	189	341
4: Fine-grained	3.6	151	492

End of Frost Penetration

TOTAL FROST PENETRATION = 21.6 inches

Do you want a hard copy of this data (Y or default N)?

1954

C:\PROGRA~1\DOSPRG~1\frost\GO2.exe

Summary: MODIFIED BERGGREN SOLUTION

Design Freezing Index (AIR)	=	240 F-days
Design Freezing Index (SURFACE)	=	240 F-days
Mean Annual Temperature	=	55.3 °F
Length of Freezing Season	=	45 Days

LAYER #: Type	LAYER THICKNESS (inches)	FREEZING INDEX DISTRIBUTION Each Layer	Accumulated
1: Fine-grained	6.0	48	48
2: Fine-grained	6.0	143	191
3: Fine-grained	1.4	46	237

End of Frost Penetration

TOTAL FROST PENETRATION = 13.4 inches

Do you want a hard copy of this data (Y or default N)?

1955

C:\PROGRA~1\DOSPRG~1\frost\GO2.exe

Summary: MODIFIED BERGGREN SOLUTION

Design Freezing Index (AIR) = 829 F-days
Design Freezing Index (SURFACE) = 829 F-days
Mean Annual Temperature = 51.4 °F
Length of Freezing Season = 93 Days

LAYER #: Type	LAYER THICKNESS (inches)	FREEZING INDEX DISTRIBUTION Each Layer	FREEZING INDEX DISTRIBUTION Accumulated
1: Fine-grained	12.0	136	136
2: Fine-grained	12.0	408	544
3: Fine-grained	5.7	289	833

End of Frost Penetration

TOTAL FROST PENETRATION = 29.7 inches

Do you want a hard copy of this data (Y or default N)?

1956

C:\PROGRA~1\DOSPRG~1\frost\GO2.exe

Summary: MODIFIED BERGGREN SOLUTION

Design Freezing Index (AIR) = 45 F-days
Design Freezing Index (SURFACE) = 45 F-days
Mean Annual Temperature = 55.3 °F
Length of Freezing Season = 29 Days

LAYER #: Type	LAYER THICKNESS (inches)	FREEZING INDEX DISTRIBUTION Each Layer	FREEZING INDEX DISTRIBUTION Accumulated
1: Fine-grained	12.0	13	13
2: Fine-grained	6.0	17	30
3: Fine-grained	6.0	24	54

End of Frost Penetration

TOTAL FROST PENETRATION = 24.0 inches

Do you want a hard copy of this data (Y or default N)?

c10

1960

C:\PROGRA~1\DOSPRG~1\frost\GO2.exe

Summary: MODIFIED BERGGREN SOLUTION

Design Freezing Index (AIR) = 338 F-days
Design Freezing Index (SURFACE) = 338 F-days
Mean Annual Temperature = 53.8 ºF
Length of Freezing Season = 67 Days

LAYER #: Type	LAYER THICKNESS (inches)	FREEZING INDEX DISTRIBUTION Each Layer	Accumulated
1: Fine-grained	6.0	46	46
2: Fine-grained	6.0	138	184
3: Fine-grained	4.0	144	328

End of Frost Penetration

TOTAL FROST PENETRATION = 16.0 inches

Do you want a hard copy of this data (Y or default N)?

1961

C:\PROGRA~1\DOSPRG~1\frost\GO2.exe

Summary: MODIFIED BERGGREN SOLUTION

Design Freezing Index (AIR) = 199 F-days
Design Freezing Index (SURFACE) = 199 F-days
Mean Annual Temperature = 54.0 ºF
Length of Freezing Season = 60 Days

LAYER #: Type	LAYER THICKNESS (inches)	FREEZING INDEX DISTRIBUTION Each Layer	Accumulated
1: Fine-grained	6.0	56	56
2: Fine-grained	5.1	136	192

End of Frost Penetration

TOTAL FROST PENETRATION = 11.1 inches

Do you want a hard copy of this data (Y or default N)?

1963

C:\PROGRA~1\DOSPRG~1\frost\GO2.exe

Summary: MODIFIED BERGGREN SOLUTION

Design Freezing Index (AIR)	=	735	F-days
Design Freezing Index (SURFACE)	=	735	F-days
Mean Annual Temperature	=	52.9	oF
Length of Freezing Season	=	44	Days

LAYER #: Type	LAYER THICKNESS (inches)	FREEZING INDEX DISTRIBUTION Each Layer	Accumulated
1: Fine-grained	12.0	126	126
2: Fine-grained	12.0	379	505
3: Fine-grained	4.9	225	730

---------------- End of Frost Penetration ----------------

TOTAL FROST PENETRATION = 28.9 inches

Do you want a hard copy of this data (Y or default N)?

1971

C:\PROGRA~1\DOSPRG~1\frost\GO2.exe

Summary: MODIFIED BERGGREN SOLUTION

Design Freezing Index (AIR)	=	289	F-days
Design Freezing Index (SURFACE)	=	289	F-days
Mean Annual Temperature	=	54.0	oF
Length of Freezing Season	=	29	Days

LAYER #: Type	LAYER THICKNESS (inches)	FREEZING INDEX DISTRIBUTION Each Layer	Accumulated
1: Fine-grained	6.0	37	37
2: Fine-grained	6.0	111	148
3: Fine-grained	4.6	135	283

---------------- End of Frost Penetration ----------------

TOTAL FROST PENETRATION = 16.6 inches

Do you want a hard copy of this data (Y or default N)?

1974

C:\PROGRA~1\DOSPRG~1\frost\GO2.exe

Summary: MODIFIED BERGGREN SOLUTION

```
Design Freezing Index (AIR)      =  734 F-days
Design Freezing Index (SURFACE)  =  734 F-days
Mean Annual Temperature          = 53.0 ºF
Length of Freezing Season        =   82 Days
```

LAYER #: Type	LAYER THICKNESS (inches)	FREEZING INDEX DISTRIBUTION Each Layer	Accumulated
1: Fine-grained	12.0	146	146
2: Fine-grained	12.0	437	583
3: Fine-grained	3.0	153	736

End of Frost Penetration

TOTAL FROST PENETRATION = 27.0 inches

Do you want a hard copy of this data (Y or default N)?

1975

C:\PROGRA~1\DOSPRG~1\frost\GO2.exe

Summary: MODIFIED BERGGREN SOLUTION

```
Design Freezing Index (AIR)      =  403 F-days
Design Freezing Index (SURFACE)  =  403 F-days
Mean Annual Temperature          = 53.3 ºF
Length of Freezing Season        =   44 Days
```

LAYER #: Type	LAYER THICKNESS (inches)	FREEZING INDEX DISTRIBUTION Each Layer	Accumulated
1: Fine-grained	12.0	146	146
2: Fine-grained	6.0	182	328
3: Fine-grained	1.8	68	396

End of Frost Penetration

TOTAL FROST PENETRATION = 19.8 inches

Do you want a hard copy of this data (Y or default N)?

1976

C:\PROGRA~1\DOSPRG~1\frost\GO2.exe

Summary: MODIFIED BERGGREN SOLUTION

```
Design Freezing Index (AIR)      =  293 F-days
Design Freezing Index (SURFACE)  =  293 F-days
Mean Annual Temperature          = 53.7 oF
Length of Freezing Season        =   45 Days
```

LAYER #: Type	LAYER THICKNESS (inches)	FREEZING INDEX DISTRIBUTION Each Layer	Accumulated
1: Fine-grained	12.0	164	164
2: Fine-grained	3.8	119	283

End of Frost Penetration

TOTAL FROST PENETRATION = 15.8 inches

Do you want a hard copy of this data (Y or default N)?

1977

C:\PROGRA~1\DOSPRG~1\frost\GO2.exe

Summary: MODIFIED BERGGREN SOLUTION

```
Design Freezing Index (AIR)      =  264 F-days
Design Freezing Index (SURFACE)  =  264 F-days
Mean Annual Temperature          = 54.8 oF
Length of Freezing Season        =   55 Days
```

LAYER #: Type	LAYER THICKNESS (inches)	FREEZING INDEX DISTRIBUTION Each Layer	Accumulated
1: Fine-grained	12.0	197	197
2: Fine-grained	1.6	57	254

End of Frost Penetration

TOTAL FROST PENETRATION = 13.6 inches

Do you want a hard copy of this data (Y or default N)?

1978

C:\PROGRA~1\DOSPRG~1\frost\GO2.exe

Summary: MODIFIED BERGGREN SOLUTION

Design Freezing Index (AIR) = 179 F-days
Design Freezing Index (SURFACE) = 179 F-days
Mean Annual Temperature = 55.0 ºF
Length of Freezing Season = 6 Days

LAYER #: Type	LAYER THICKNESS (inches)	FREEZING INDEX DISTRIBUTION Each Layer	Accumulated
1: Fine-grained	6.0	30	Berggren Calculations could not converge Surface DFI
2: Fine-grained	6.0	90	
3: Fine-grained	< 2.4	52	

End of Frost Penetration

TOTAL FROST PENETRATION = 14.4 inches

Do you want a hard copy of this data (Y or default N)?

1979

C:\PROGRA~1\DOSPRG~1\frost\GO2.exe

Summary: MODIFIED BERGGREN SOLUTION

Design Freezing Index (AIR) = 1132 F-days
Design Freezing Index (SURFACE) = 1132 F-days
Mean Annual Temperature = 51.3 ºF
Length of Freezing Season = 93 Days

LAYER #: Type	LAYER THICKNESS (inches)	FREEZING INDEX DISTRIBUTION Each Layer	Accumulated
1: Fine-grained	12.0	127	127
2: Fine-grained	12.0	380	507
3: Fine-grained	12.0	634	1141

End of Frost Penetration

TOTAL FROST PENETRATION = 36.0 inches

Do you want a hard copy of this data (Y or default N)?

1980

C:\PROGRA~1\DOSPRG~1\frost\GO2.exe

Summary: MODIFIED BERGGREN SOLUTION

```
Design Freezing Index (AIR)      =  293  F-days
Design Freezing Index (SURFACE)  =  293  F-days
Mean Annual Temperature          = 53.5  °F
Length of Freezing Season        =   48  Days
```

LAYER #: Type	LAYER THICKNESS (inches)	FREEZING INDEX DISTRIBUTION Each Layer	Accumulated
1: Fine-grained	6.0	42	42
2: Fine-grained	6.0	125	167
3: Fine-grained	3.6	116	283

---------- End of Frost Penetration ----------

TOTAL FROST PENETRATION = 15.6 inches

Do you want a hard copy of this data (Y or default N)?

1982

C:\PROGRA~1\DOSPRG~1\frost\GO2.exe

Summary: MODIFIED BERGGREN SOLUTION

```
Design Freezing Index (AIR)      =  448  F-days
Design Freezing Index (SURFACE)  =  448  F-days
Mean Annual Temperature          = 53.4  °F
Length of Freezing Season        =   56  Days
```

LAYER #: Type	LAYER THICKNESS (inches)	FREEZING INDEX DISTRIBUTION Each Layer	Accumulated
1: Fine-grained	6.0	38	38
2: Fine-grained	6.0	114	152
3: Fine-grained	6.0	191	343
4: Fine-grained	2.4	96	439

---------- End of Frost Penetration ----------

TOTAL FROST PENETRATION = 20.4 inches

Do you want a hard copy of this data (Y or default N)?

1983

C:\PROGRA~1\DOSPRG~1\frost\GO2.exe

Summary: MODIFIED BERGGREN SOLUTION

Design Freezing Index (AIR) = 92 F-days
Design Freezing Index (SURFACE) = 92 F-days
Mean Annual Temperature = 53.3 °F
Length of Freezing Season = 21 Days

LAYER #: Type	LAYER THICKNESS (inches)	FREEZING INDEX DISTRIBUTION Each Layer	Accumulated
1: Fine-grained	6.0	47	47
2: Fine-grained	2.3	43	90

End of Frost Penetration

TOTAL FROST PENETRATION = 8.3 inches

Do you want a hard copy of this data (Y or default N)?

1986

C:\PROGRA~1\DOSPRG~1\frost\GO2.exe

Summary: MODIFIED BERGGREN SOLUTION

Design Freezing Index (AIR) = 106 F-days
Design Freezing Index (SURFACE) = 106 F-days
Mean Annual Temperature = 54.2 °F
Length of Freezing Season = 37 Days

LAYER #: Type	LAYER THICKNESS (inches)	FREEZING INDEX DISTRIBUTION Each Layer	Accumulated
1: Fine-grained	6.0	61	61
2: Fine-grained	2.0	46	107

End of Frost Penetration

TOTAL FROST PENETRATION = 8.0 inches

Do you want a hard copy of this data (Y or default N)?

1987

C:\PROGRA~1\DOSPRG~1\frost\GO2.exe

Summary: MODIFIED BERGGREN SOLUTION

Design Freezing Index (AIR) = 225 F-days
Design Freezing Index (SURFACE) = 225 F-days
Mean Annual Temperature = 53.7 ºF
Length of Freezing Season = 51 Days

LAYER #: Type	LAYER THICKNESS (inches)	FREEZING INDEX DISTRIBUTION Each Layer	Accumulated
1: Fine-grained	6.0	48	48
2: Fine-grained	6.0	145	193
3: Fine-grained	0.8	26	219

End of Frost Penetration

TOTAL FROST PENETRATION = 12.8 inches

Do you want a hard copy of this data (Y or default N)?

1988

C:\PROGRA~1\DOSPRG~1\frost\GO2.exe

Summary: MODIFIED BERGGREN SOLUTION

Design Freezing Index (AIR) = 832 F-days
Design Freezing Index (SURFACE) = 832 F-days
Mean Annual Temperature = 50.8 ºF
Length of Freezing Season = 74 Days

LAYER #: Type	LAYER THICKNESS (inches)	FREEZING INDEX DISTRIBUTION Each Layer	Accumulated
1: Fine-grained	6.0	32	32
2: Fine-grained	6.0	95	127
3: Fine-grained	6.0	159	286
4: Fine-grained	6.0	222	508
5: Fine-grained	6.0	285	793
6: Fine-grained	0.7	36	829

End of Frost Penetration

TOTAL FROST PENETRATION = 30.7 inches

Do you want a hard copy of this data (Y or default N)?

C18

1989

C:\PROGRA~1\DOSPRG~1\frost\GO2.exe

Summary: MODIFIED BERGGREN SOLUTION

Design Freezing Index (AIR) = 714 F-days
Design Freezing Index (SURFACE) = 714 F-days
Mean Annual Temperature = 53.1 ºF
Length of Freezing Season = 88 Days

LAYER #: Type	LAYER THICKNESS (inches)	FREEZING INDEX DISTRIBUTION Each Layer	Accumulated
1: Fine-grained	12.0	151	151
2: Fine-grained	6.0	189	340
3: Fine-grained	6.0	264	604
4: Fine-grained	1.9	102	706

--- End of Frost Penetration ---

TOTAL FROST PENETRATION = 25.9 inches

Do you want a hard copy of this data (Y or default N)?

1990

C:\PROGRA~1\DOSPRG~1\frost\GO2.exe

Summary: MODIFIED BERGGREN SOLUTION

Design Freezing Index (AIR) = 255 F-days
Design Freezing Index (SURFACE) = 255 F-days
Mean Annual Temperature = 53.6 ºF
Length of Freezing Season = 85 Days

LAYER #: Type	LAYER THICKNESS (inches)	FREEZING INDEX DISTRIBUTION Each Layer	Accumulated
1: Fine-grained	6.0	57	57
2: Fine-grained	6.0	172	229
3: Fine-grained	0.5	21	250

--- End of Frost Penetration ---

TOTAL FROST PENETRATION = 12.5 inches

Do you want a hard copy of this data (Y or default N)?

1991

C:\PROGRA~1\DOSPRG~1\frost\GO2.exe

Summary: MODIFIED BERGGREN SOLUTION

Design Freezing Index (AIR) = 696 F-days
Design Freezing Index (SURFACE) = 696 F-days
Mean Annual Temperature = 52.0 °F
Length of Freezing Season = 77 Days

LAYER #: Type	LAYER THICKNESS (inches)	FREEZING INDEX DISTRIBUTION Each Layer	Accumulated
1: Fine-grained	6.0	34	34
2: Fine-grained	6.0	103	137
3: Fine-grained	6.0	172	309
4: Fine-grained	6.0	241	550
5: Fine-grained	2.8	138	688

End of Frost Penetration

TOTAL FROST PENETRATION = 26.8 inches

Do you want a hard copy of this data (Y or default N)?

1992

C:\PROGRA~1\DOSPRG~1\frost\GO2.exe

Summary: MODIFIED BERGGREN SOLUTION

Design Freezing Index (AIR) = 718 F-days
Design Freezing Index (SURFACE) = 718 F-days
Mean Annual Temperature = 52.0 °F
Length of Freezing Season = 74 Days

LAYER #: Type	LAYER THICKNESS (inches)	FREEZING INDEX DISTRIBUTION Each Layer	Accumulated
1: Fine-grained	12.0	138	138
2: Fine-grained	12.0	413	551
3: Fine-grained	3.4	168	719

End of Frost Penetration

TOTAL FROST PENETRATION = 27.4 inches

Do you want a hard copy of this data (Y or default N)?

1994

C:\PROGRA~1\DOSPRG~1\frost\GO2.exe

Summary: MODIFIED BERGGREN SOLUTION

```
Design Freezing Index (AIR)      =  284 F-days
Design Freezing Index (SURFACE)  =  284 F-days
Mean Annual Temperature          = 52.3 ºF
Length of Freezing Season        =   83 Days
```

LAYER #: Type	LAYER THICKNESS (inches)	FREEZING INDEX DISTRIBUTION Each Layer	Accumulated
1: Fine-grained	6.0	50	50
2: Fine-grained	6.0	150	200
3: Fine-grained	2.3	85	285

End of Frost Penetration

TOTAL FROST PENETRATION = 14.3 inches

Do you want a hard copy of this data (Y or default N)?

1939

C:\PROGRA~1\DOSPRG~1\frost\GO2.exe

Summary: MODIFIED BERGGREN SOLUTION

```
Design Freezing Index (AIR)      =  765 F-days
Design Freezing Index (SURFACE)  =  765 F-days
Mean Annual Temperature          = 52.1 ºF
Length of Freezing Season        =   87 Days
```

LAYER #: Type	LAYER THICKNESS (inches)	FREEZING INDEX DISTRIBUTION Each Layer	Accumulated
1: Fine-grained	12.0	142	142
2: Fine-grained	12.0	425	567
3: Fine-grained	3.7	189	756

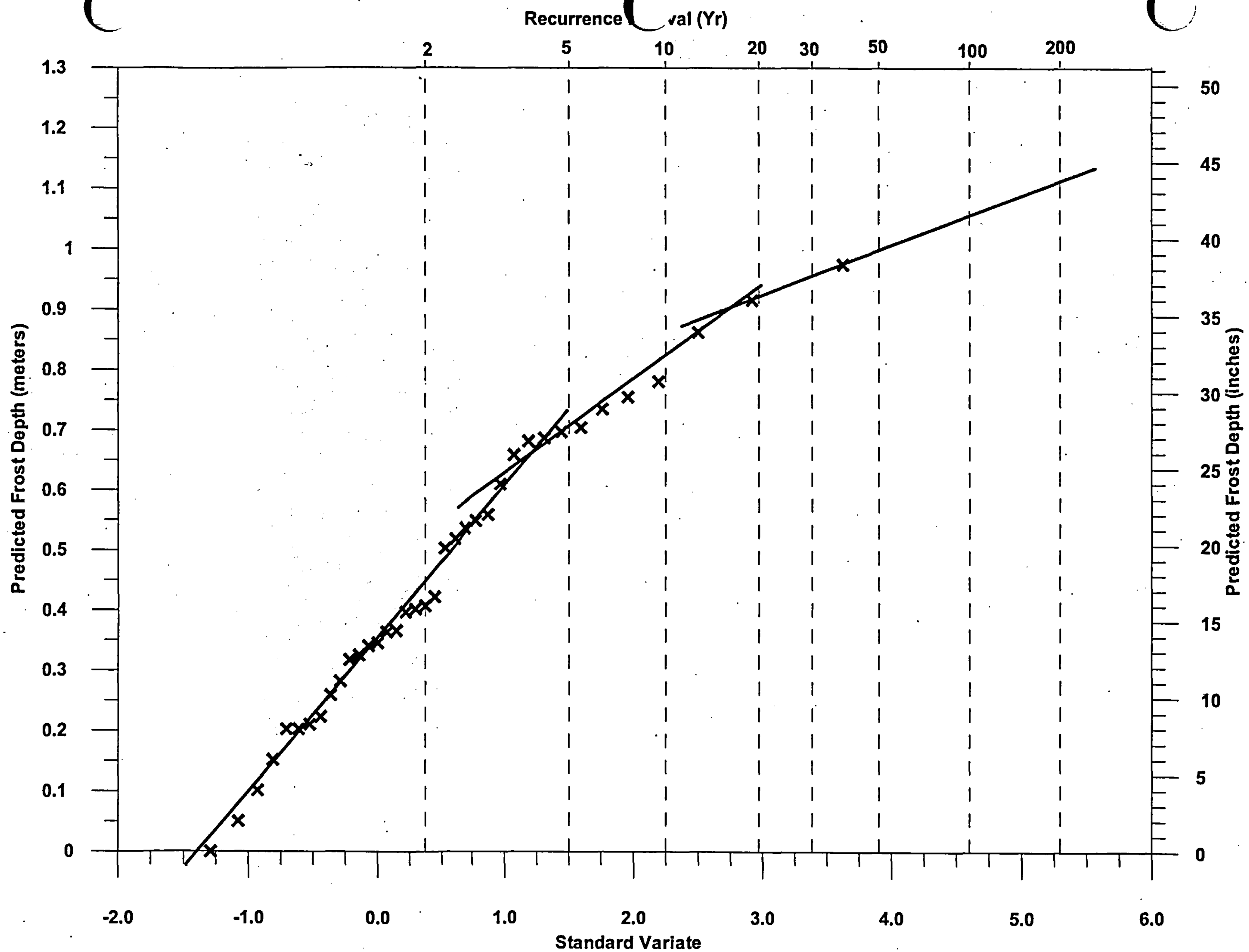
End of Frost Penetration

TOTAL FROST PENETRATION = 27.7 inches

Do you want a hard copy of this data (Y or default N)?

APPENDIX C

RESULTS OF EXTREME FROST DEPTH ANALYSIS



Recurrence Interval (Yr)
2
5
10
20
30
50
100
200
Predicted Frost Depth (meters)
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Predicted Frost Depth (inches)
50
45
40
35
30
25
20
15
10
5
0
-2.0
-1.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
Standard Variate

U.S. Department of Energy—Grand Junction, Colorado

Calculation Cover Sheet

Calc. No.: MOA-02-05-2006-3-13-00 **Discipline:** Geology **No. of Sheets:** 16

Project: Moab UMTRA Project

Site: Crescent Junction Disposal Site

Feature:
Radon Barrier Design Remedial Action Plan Calculation

Sources of Data:

See below.

Sources of Formulae and References:

Golder Associates, 2006a. *Bench Scale Testing Program on Uranium Mill Tailings*, April.

—— 2006b. Draft Tech Memo, April 3.

Nuclear Regulatory Commission (NRC), 1989. "Calculation of Radon Flux Attenuation by Earthen Uranium Mill Tailings Covers," Regulatory Guide 3.64.

Rogers, V.C., K.K. Nielson, and D.R. Kalkwarf, 1984. "Radon Attenuation Handbook for Uranium Mill Tailings Cover Design," NUREG/CR-3533, prepared for U.S. Nuclear Regulatory Commission (NRC), April.

United States Department of Energy (DOE), 1989. "Technical Approach Document, Revision II," UMTRA-DOE/AL 050425.0002.

——, 2006a. Calculation Set MOA-02-03-2006-4-01-00, *Geotechnical Properties of Native Materials*. Prepared by S.M. Stoller Corporation, March.

——, 2006b. Calculation Set MOA-02-05-2006-03-21-00, *Infiltration Modeling for Alternative Cover Design*. Prepared by S.M. Stoller Corporation, June.

——, 2006c. Calculation Set MOA-02-05-2006-5-08-00, *Site Hydrology Report*. Prepared by S.M. Stoller Corporation, June.

——, 2006d. Calculation Set MOA-02-05-2006-5-02-00, *Volume Calculation for the Moab Tailings*. Prepared by S.M. Stoller Corporation, June.

——; 2006e. Calculation Set MOA-01-05-2006-4-08-00, *Geotechnical Laboratory Testing Results, Moab Processing Site*, in production. Prepared by S.M. Stoller Corporation..

——; 2006f. MOA 02-03-2006-4-01-00 Geotechnical Laboratory Testing Results-Vol 1. Prepared by S.M. Stoller Corporation, March.

——; 2006g. MOA-02-05-2006-4-08-00 Geotechnical Laboratory Testing Results-Vol 2. Prepared by S.M. Stoller Corporation, May.

Preliminary Calc. ☐ **Final Calc.** ☐ **Supersedes Calc. No.**

Author: [signature] 6/13/06 **Checked by:** [signature] for [signature] 6-13-06
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Approved by: [signature] 6/13/06 [signature] 6-13-06
Name Date Name Date

Name Date

Name Date

Problem Statement:

- Part 40 of the *Code of Federal Regulations*, section 192.02 (40 CFR 192.02) requires that control of radioactive materials and their listed constituents shall be designed to provide reasonable assurance that release of radon-222 from residual radioactive material (RRM) to the atmosphere will not exceed an average of 20 picocuries per square meter per second ($pCi/m^2/sec$), averaged over the entire cover top slope.
- The cover of the Crescent Junction Disposal Cell must be sufficient to provide isolation of tailings and control of radon emanation for the period of up to one thousand years, to the extent reasonably achievable, and, in any case, for at least 200 years.
- This calculation establishes the dimensions and input parameters for design of the Crescent Junction Disposal Cell radon barrier that will provide the requisite reasonable assurance of performance.

Method of Solution:

- Site-specific data for the RRM, which includes tailings, contaminated soils, mill debris, and other contaminated materials, and for the native cover materials were developed through thorough field investigations and laboratory testing programs (DOE 2006a; Golder 2006a). These site-specific data are presented in summary tables presented in Appendix B.
- Two conceptual design configurations were evaluated. One using a compacted-clay radon barrier (Uranium Mill Tailings Remedial Action [UMTRA] checklist cover) and one using a monolithic soil cover (Alternative cover).
- The Nuclear Regulatory Commission (NRC) computer code RAECOM (Rogers et al. 1984) was used to calculate the optimum radon-barrier thickness, given the specific input parameters for each model run.
- In order to evaluate the impact of the uncertainty for the input parameter values on the calculated radon-barrier thickness, model runs were performed using the mean value of the key input parameters and using the mean value plus the standard error of the mean (SEM). A ratio of the calculated radon-barrier thickness, using these two ranges of input values of greater than 1.4, indicates that additional characterization of the input materials may be required to decrease the design uncertainty (DOE 1989).

Assumptions:

- Tailings activity will be relatively homogeneous as placed; no layers of different radium-226 activity were modeled. This is conservative, as placement of contaminated soils of lower activity may be placed in the upper portions of the pile. It is anticipated that the cover design will be re-evaluated during construction using actual as-placed source material activities and properties to ensure the cover is optimized for as-built conditions.
- Bottom-boundary radon flux is equal to zero, as per the Technical Approach Document (TAD) (DOE 1989).
- Ambient air radon concentrations were assumed to equal the conservative default value of zero, no local ambient air radon concentration data were available. Should these data become available prior to construction, these measured values should be considered in evaluation of the final cover design.
- The tailing side slopes will be constructed of dikes made from clean fill to thicknesses far in excess of the cover and with properties comparable to the cover material; therefore, radon flux through the side slopes was not modeled.
- Following UMTRA precedence, materials above the radon barrier (e.g., freeze/thaw protection layers, riprap, or rock mulch erosion-protection layers) were not modeled. These overlying materials provide additional radon attenuation. This conservative assumption enhances the reasonable assurance that the barrier as designed will provide the requisite protection and long-term performance.

- A clean-fill interim cover 1 foot (ft) thick will be placed over the tailings as a best management practice.
- Physical properties of the cover materials are adequately represented by the characterization data. This is supported by analysis of parameter uncertainty using the SEM in cover calculations. These show that the calculated radon-barrier thickness when using the mean parameter values plus the SEM is less than 40 percent greater than the calculated radon-barrier thickness when using the mean parameter values.
- RAECOM model default values for radon-emanation coefficient (0.35) are assumed conservative and appropriate.
- Capillary breaks and biointrusion layers were assumed to have insignificant impact on radon attenuation, given their large pore size and low long-term moisture content. Therefore, these layers have conservatively been omitted form the RAECOM model runs.

Calculation:

- The mean value (x_{mean}) of any parameter is calculated by the equation:

$$x_{mean} = \sum x_i / n$$

where: x_i = the i[th] value, and
n = the total number of values.

- The standard deviation (s) of a set of values is calculated by the equation:

$$s = sqrt((\sum(x_i - x_{mean})^2 / [n-1]))$$

where: sqrt = the square root of the value.

- The SEM is calculated by the equation:

$$SEM = s / sqrt(n)$$

- Porosity (η) of a sample is calculated from the equation:

$$(\eta = (1 - [\text{dry bulk density} \div (\text{specific gravity} \times \text{unit weight of water})])$$

where the unit weight of water is 62.4 pounds per cubic foot (pcf), or 1 gram per cubic centimeter (g/cc).

- The density of a sample in g/cc is converted to pcf by multiplying the unit weight of water (62.4 pcf).

- The Rawls & Brakensiek equation referenced in the NRC Regulatory Guide 3.64 (NRC 1989a) can be used to estimate the 15 bar moisture content as a reasonable lower bound of long-term moisture content. The equation is:

$$\text{15 bar moisture content} = 0.026 + 0.005z + 0.0158y$$

where: z = percent clay in the soil
y = percent organic matter in the soil

For example, the calculated 15 bar moisture content of the alluvial site materials, which have a mean clay content of 18.63 percent and a mean organic matter content of 0.28 percent is:

15 bar moisture content = 0.026 + 0.005(18.23) +0.0158(0.28)
15 bar moisture content = 0.075, or 7.5 percent

The individual RAECOM model output files, which include the input parameter values for each model layer, are included in Appendix A. Appendix B provides additional calculations and data supporting development of the input parameters.

Discussion:

Two general cover configurations were considered: 1) a "typical" UMTRA-style cover consisting of a compacted, native-clay radon barrier (see Figure 1); and 2) an alternative cover design using a monolithic cover of loosely compacted native materials (see Figure 2). It has been assumed as a best management practice that a 1-ft-thick interim cover of clean native materials will be placed on the RRM to control wind transport of fine material and to provide for a relatively clean and uniform work surface on which the radon barrier will be constructed.

The radon barrier layers have been optimized by the RAECOM model to limit the radon flux to 20 pCi/m^2/sec under long-term moisture content conditions. As with previous UMTRA Title I cover designs, the attenuation of radon by the freeze/thaw or erosion protection layers are not considered in these analyses, though these layers will further reduce the radon flux rate at the Disposal Cell surface.

Because the Disposal Cell design calls for clean-fill dikes, only flux through the top cover is modeled.

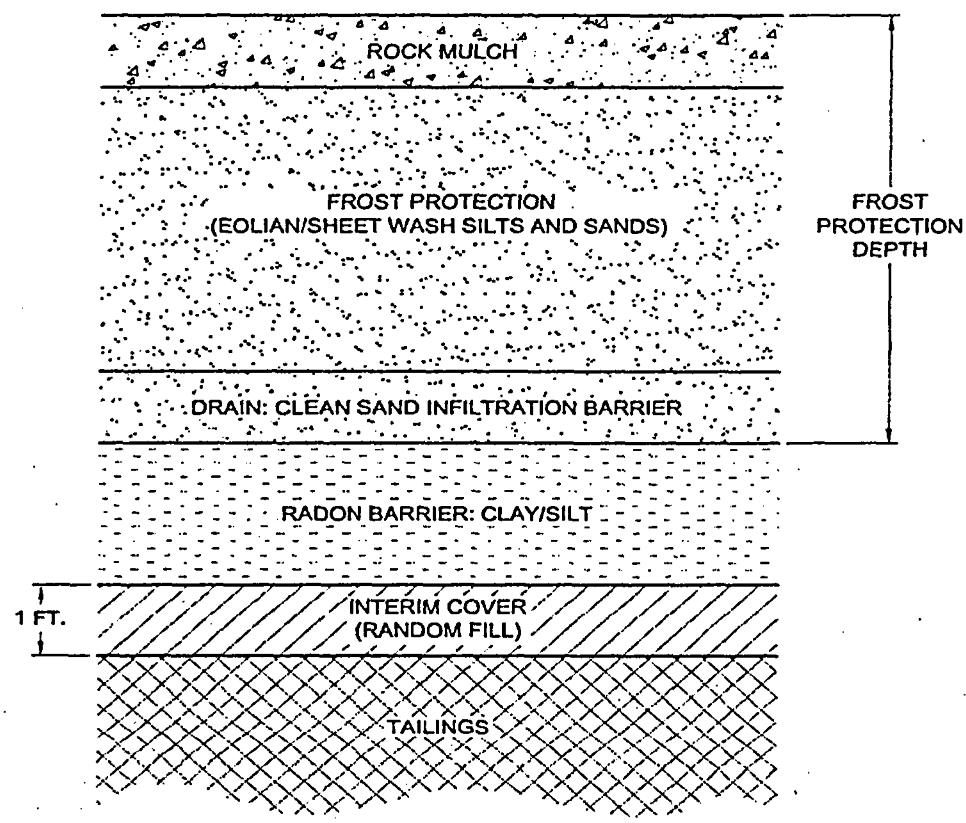
Description of Model and Input Values

Radon emanation calculations from a multilayered cover system were made with the RAECOM model (Rogers et al. 1984; NRC 1989), a one-dimensional model that calculates radon flux from decay of a radium-226 (Ra-226) source (such as the tailings). The key input parameters to the model include:

- Layer thickness.
- Porosity.
- Mass density.
- Ra-226 activity concentration.
- Emanation coefficient.
- Weight percent moisture.
- Coefficient of radon diffusion.

Only those material layers including the radon barrier and below are modeled. This ensures that the radon barrier alone can meet the long-term average radon flux requirement of 20 pCi/m^2/s, without the additional attenuation provided by overlying layers such as freeze/thaw protection layers or rock mulch layers. The input parameters and values used in the model are outlined below. Table 1 summarizes the individual input parameters used for all of the models run and their bases.

As per the TAD (DOE 1989), the uncertainty regarding model parameters has been evaluated. Input parameter uncertainty is evaluated by comparing the calculated radon barrier thickness using mean input parameters to the calculated radon barrier thickness using mean +/– SEM input parameters. If the ratio of the radon barrier calculated using mean +/– SEM input parameters to the calculated radon barrier thickness using mean input parameters is greater than 1.4, then the uncertainty regarding the variability of the input parameters is considered too large and additional input parameter characterization is recommended. Table 1 summarizes the input parameters for each model run and the calculated radon barrier thickness. Appendix B provides additional calculations of the mean input values and related statistics, including the SEM.



MFG, Inc. *consulting scientists and engineers*	FIGURE 1 UMTRA CHECKLIST TOP COVER	Date: MAY 2006 Project: 181268 File: TOPCOVER.DWG

Figure 1. UMTRA Checklist Top Cover

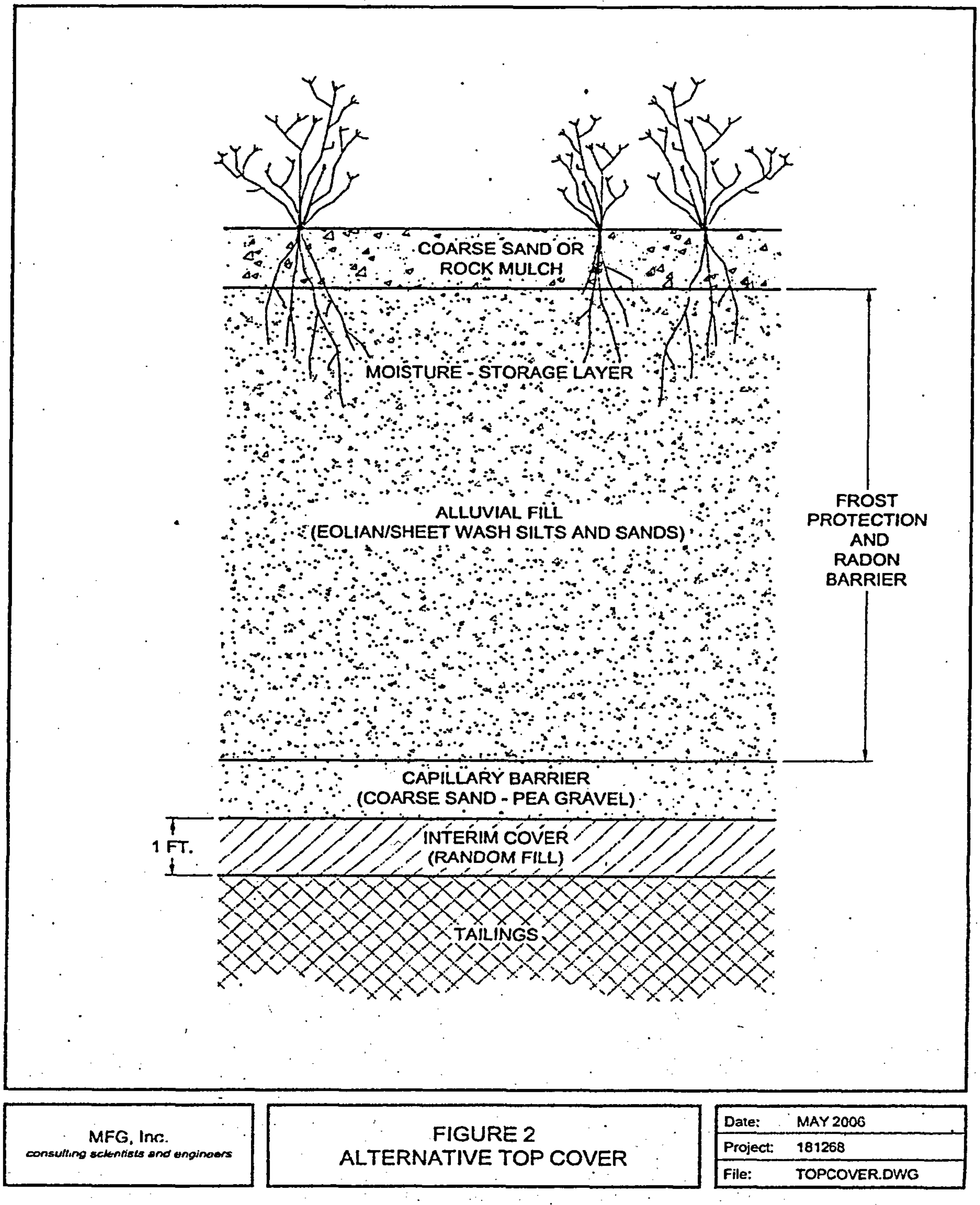


Figure 2. Alternative Top Cover

Table 1. Crescent Junction Disposal Cell Radon Barrier Design, RAECOM Model Runs Summary, UMTRA Cover

	Output File Name UMTRA 1		Output File Name UMTRA 2		Output File Name UMTRA 3	
Parameters						
Run Purpose	UMTRA Cover, Mean input values		UMTRA Cover, Mean +/- SEM input values		UMTRA Cover, Mean input values, Radon Barrier moisture content @ Mean – SEM value	
		Source for Input Parameters		**Source for Input Parameters**		**Source for Input Parameters**
Tailings						
Specific Gravity	2.8	Average value for tailings from Shaw Lab Data (DOE 2006e) for all tailings samples	2.8	Average value for tailings from Shaw Lab Data (DOE 2006e) for all tailings samples	2.8	Average value for tailings from Shaw Lab Data (DOE 2006e) for all tailings samples
Porosity	0.44	Calculated	0.44	Calculated	0.44	Calculated
Dry Density (g/cc)	1.57	Calculated	1.57	Calculated	1.57	Calculated
Dry Density (pcf)	98	90% of average standard proctor max dry density of transition tailings from Golder bench scale test (2006a)	98	90% of average standard proctor max dry density of transition tailings from Golder bench scale test (2006a)	98	90% of average standard proctor max dry density of transition tailings from Golder bench scale test (2006a)
Moisture Content (%)	15	Based on calculated long-term moisture content from *Infiltration modeling*	15	Based on calculated long-term moisture content from *Infiltration modeling*	15	Based on calculated long-term moisture content from Infiltration modeling
Degree of Saturation (%)	53.5	Calculated	53.5	Calculated	53.5	Calculated
Radium Activity (pCi/g)	868	Mean of 27 values from November 2005 OCS analysis of tailings	954	Mean plus SEM from November 2005 OCS analysis of tailings	868	Mean of 27 values from November 2005 OCS analysis of tailings
Diffusion Coef (cm^2/sec)	1.045 x 10^-2	Calculated by RAECOM	1.045 x 10^-2	Calculated by RAECOM	1.045 x 10^-2	Calculated by RAECOM
Thickness (cm)	500	Model not sensitive to depths greater than 500 cm	500	Model not sensitive to depths greater than 500 cm	500	Model not sensitive to depths greater than 500 cm
Thickness (ft)	16.4	Calculated	16.4		16.4	
Interim Cover						
Specific Gravity	2.67	Average value for sheet wash, fluvial, and eolian soils from GEG lab data (DOE 2006f)	2.7	Average plus SEM for sheet wash, fluvial, and eolian soils from GEG lab data (DOE 2006f)	2.67	Average value for sheet wash, fluvial, and eolian soils from GEG lab data (DOE 2006f)
Porosity	0.38	Calculated	0.39	Calculated	0.38	Calculated
Density (g/cc)	1.65	Calculated	1.65	Calculated	1.65	Calculated
Density (pcf)	103	85% of average modified proctor max dry density of	103	85% of average modified proctor max dry density of	103	85% of average modified proctor max dry density of sheet wash,

	Output File Name UMTRA 1		Output File Name UMTRA 2		Output File Name UMTRA 3	
Parameters						
Run Purpose	UMTRA Cover, Mean input values		UMTRA Cover, Mean +/- SEM input values		UMTRA Cover, Mean input values, Radon Barrier moisture content @ Mean – SEM value	
		Source for Input Parameters		**Source for Input Parameters**		**Source for Input Parameters**
		sheet wash, fluvial, and eolian soils from GEG lab data (DOE 2006f)		sheet wash, fluvial, and eolian soils from GEG lab data (DOE 2006f)		fluvial, and eolian soils from GEG lab data (DOE 2006f)
Moisture Content (%)	8	Mean gravimetric moisture content value estimated form in-situ soils analysis, Rawls & Brakensiek Equation, and average measured 15 bar moisture content for sheet wash and fluvial/eolian materials by ASTM D3152	7	Mean minus SEM gravimetric moisture content value estimated form in-situ soils analysis, Rawls & Brakensiek Eqn, and average measured 15 bar moisture content for sheet wash and fluvial/eolian materials by ASTM D3152	8	Mean gravimetric moisture content value estimated form in-situ soils analysis, Rawls & Brakensiek Eqn, and average measured 15 bar moisture content for sheet wash and fluvial/eolian materials by ASTM D3152
Degree of Saturation (%)	34.7	Calculated	29.6	Calculated	34.7	Calculated
Radium Activity (pCi/g)	1.86	Mean from February 2006 OCS sheet wash and eolian data	2.02	Mean plus 1 SEM from February 2006 OCS sheet wash and eolian data	1.86	Mean from February 2006 OCS sheet wash and eolian data
Diffusion Coef (cm^2/sec)	2.089 x 10^-2	Calculated by RAECOM	2.541 x 10^-2	Calculated by RAECOM	2.089 x 10^-2	Calculated by RAECOM
Thickness (cm)	**30.5**		**30.5**		**30.5**	
Thickness (ft)	**1**		**1**		**1**	
Radon Barrier						
Specific Gravity	2.65	Mean value for weathered Mancos soils from GEG lab data (DOE 2006f)	2.73	Mean plus SEM value for weathered Mancos soils from GEG lab data (DOE 2006f)	2.65	Mean value for weathered Mancos soils from GEG lab data (DOE 2006f)
Porosity	0.33	Calculated	0.35	Calculated	0.33	Calculated
Density (g/cc)	1.78	Calculated	1.78	Calculated	1.78	Calculated
Density (pcf)	111	90% of average modified proctor max dry density of weathered Mancos soils from GEG lab data (DOE 2006f)	111	90% of average modified proctor max dry density of weathered Mancos soils from GEG lab data (DOE 2006f)	111	90% of average modified proctor max dry density of weathered Mancos soils from GEG lab data (DOE 2006f)
Moisture Content (%)	12	Mean gravimetric moisture content value estimated form in-situ soils analysis, Rawls & Brakensiek Eqn, and average	10	Value is mean observed insitu value, lower than mean plus SEM Gravimetric moisture content value estimated from in-situ soils analysis, Rawls &	10	Value is mean observed insitu value, lower than mean plus SEM Gravimetric moisture content value estimated from in-situ soils

	Output File Name UMTRA 1		Output File Name UMTRA 2		Output File Name UMTRA 3	
Parameters						
Run Purpose	UMTRA Cover, Mean input values		UMTRA Cover, Mean +/- SEM input values		UMTRA Cover, Mean input values, Radon Barrier moisture content @ Mean – SEM value	
		Source for Input Parameters		**Source for Input Parameters**		**Source for Input Parameters**
		measured 15 bar moisture content for weathered Mancos Shale by ASTM D3152		Brakensiek Eqn, and average measured 15 bar moisture content for weathered Mancos Shale by ASTM D3152		analysis, Rawls & Brakensiek Eqn, and average measured 15 bar moisture content for weathered Mancos Shale by ASTM D3152
Degree of Saturation (%)	64.7	*Calculated*	50.9	*Calculated*	53.9	*Calculated*
Radium Activity (pCi/g)	2.3	Mean from February 2006 OCS weathered Mancos	3	Mean plus 1 SEM from February 2006 OCS weathered Mancos	2.3	Mean from February 2006 OCS weathered Mancos
Diffusion Coef (cm^2/sec)	4.423 x 10^-3	Calculated by RADON	1. X 10^-2	Calculated by RADON	1.025 x 10^-2	Calculated by RADON
Thickness (cm)	**126.1**	Calculated	**235.3**	Calculated	**197.7**	Calculated
Thickness (ft)	**4.1**	Calculated	**7.7**	Calculated	**6.5**	Calculated
Note: RADON uses gravimetric water contents.						
		Ratio of calculated radon barrier thickness: 1.2.				

The model output file names and the purpose of the model runs are summarized below.

- Model Run UMTRA 1 uses mean input values for the UMTRA style cover.
- Model Run UMTRA 2 uses mean +/– SEM input values for the UMTRA style cover.
- Model Run UMTRA 3 uses mean input values for the UMTRA style cover except it uses the mean minus SEM long-term moisture content for the radon barrier to evaluate the sensitivity of the model to this parameter.
- Model Run ALT 1 uses mean input values for the Alternative cover.
- Model Run ALT 2 uses mean +/– SEM input values for the Alternative cover.

Layer Thickness

The layers and sequences are illustrated in Figure 1 and Figure 2 and represent the geometries of the tailings and of each cover-layer component. For all model runs, a tailings thickness of 500 centimeters (cm) is used; the model output is insensitive to source term thicknesses greater than 500 cm.

UMTRA-Style Cover

The current conceptual design of the UMTRA cover system consists of 1 ft of interim cover below the compacted-clay radon barrier. A 1-ft-thick interim cover of clean, native materials will be placed on the surface of the tailings as a best management proaction to control wind transport of fine material and to provide for a relatively clean, uniform work surface upon which to construct the radon barrier. The model is used to optimize the layer thickness of the compacted-clay radon barrier.

Alternative Cover

The current conceptual design of the alternative cover system consists of one foot of interim cover, a 9-inch-thick capillary break/biointrusion layer and a monolithic moisture-storage/radon-barrier layer. However, because the capillary barrier is very coarse grained and will have very low long-term moisture content, experience has shown that its influence on radon attenuation is minimal. Therefore, it has conservatively been omitted from the model runs.

The Alternative cover uses a monolithic soil layer placed at a density similar to existing native soils conditions and is modeled under conservative long-term soil moisture conditions. Therefore, a freeze/thaw protection layer is not needed to protect it from changes due to seasonal freeze/thaw cycles. This monolithic soil layer will also be covered by a rock mulch designed to resist wind and surface water runoff erosional forces under the Probable Maximum Flow (PMF) event, ensuring that the layer endures as an integral unit for the design life of the disposal cell.

Porosity (n)

The porosity of the layer materials have been calculated based on the dry density and the specific gravity of the specific materials according to the following equation:

$$n = 1 - (\text{dry density} \div [\text{specific gravity} \times \text{unit weight of water}])$$

for example, tailings porosity is:

$$n = 1 - (1.57 \text{ g/cc} \div [2.8 \times 1 \text{ g/cc}])$$
$$n = 0.44$$

The porosity of the tailings was modeled as 0.44, given a mean specific gravity of 2.8 for the tailings based on the data in the Shaw Labs Calculation set (DOE 2006e), and a designed placement density of 1.57 g/cc (98 pcf).

The porosity of the interim cover and the monolithic layer of the alternative cover, to be developed from the alluvial silty sands and sheet wash deposits overlying the in-situ weathered Mancos Shale, was modeled as 0.38, given a mean specific gravity of 2.67—based on nine samples presented in Calculation Set MOA-02-03-2006-4-01-00 (DOE 2006a) and Appendix B—and a designed placement density of 1.65 g/cc (103 pcf). These two layers will be constructed of the same on-site materials from the Crescent Junction Site and will be placed in the same conditions.

The porosity of the compacted Mancos Shale was modeled as 0.33, given a mean specific gravity for the Mancos of 2.65—based on the data in Calculation Set MOA-02-03-2006-4-01-00 (DOE 2006a) and Appendix B—and a designed placement density of 1.78 g/cc (111 pcf).

Mass Density

The dry density of the tailings as placed has been modeled as 1.57 g/cc (98 pcf), which is 90 percent of the mean standard Proctor maximum dry density of transition tailings materials as reported in the Golder Draft Tech Memo (2006b).

The density of the interim cover materials and the alternative cover monolithic layer, as placed, has been modeled as 1.65 g/cc (103 pcf), which is 85 percent of the mean modified Proctor dry density value (121.6 pcf) for these materials as developed in Calculation Set MOA-02-03-2006-4-01-00 (DOE 2006a).

The density of the compacted clay materials and the UMTRA-style cover, as placed, has been modeled as 1.78 g/cc (111 pcf), which is 90 percent of the mean modified Proctor dry density value (123 pcf) for these materials as developed in Calculation Set MOA-02-03-2006-4-01-00 (2006).

Radium Activity Concentration

The radium-226 activity concentration values used in the model for each specific material are outlined below.

<u>Tailings</u>

The Ra-226 activity values for the tailings are based on 27 tailings samples collected in November 2005, and range in depth from the tailings surface to 75 ft below the surface. The collection and analysis of the samples is discussed in the Calculation Set MOA-02-05-2006-5-02-00 (DOE 2006a). The samples were analyzed using the opposed crystal system (OCS) at the Moab Site. Measured Ra-226 activity values range from 186 picocuries per gram (pCi/g) to 1,670 pCi/g, with a mean value of 868 pCi/g (see Appendix B). To evaluate the impact of uncertainty of the tailings activity as an input parameter for the radon-barrier design, the tailings' Ra-226 activity have been modeled using the mean activity and the mean-plus-one SEM as per the TAD (DOE 1989). Appendix B provides supporting documentation regarding Ra-226 activity measurements.

The current conceptual plan for tailings removal and placement would entail a significant amount of blending of lower-activity beach sands and higher-activity slimes. Therefore, no layering of the tailings source term has been modeled, and a single activity value has been used. However, it is highly likely that lower-activity contaminated sub-pile soils and contaminated soils from the mill site and clean up of peripheral and vicinity properties will be placed above the higher activity tailings, which would serve to further reduce Ra-226 activity at the base of the cover. However, the source term activity and properties as well as the actual properties of the cover materials once delivered to the site should be reevaluated to ensure that the cover design is optimized for the actual as-built conditions of the cell contents.

<u>Interim Cover and Alternative Cover Monolithic Layer</u>

The monolithic layer Ra-226 activity for the interim and alternative covers is based on eight samples of native materials collected from the Crescent Junction Site that will be used to construct the cover and clean-fill perimeter dikes (see Appendix B). Samples were collected from alluvial materials with depth ranging from 4 to 15 ft below the surface. The samples were analyzed using the OCS at the Moab Site.

The Ra-226 activity of the alluvial material ranged from 1.4 to 2.3 pCi/g with a mean value of 1.86 pCi/g. To evaluate the impact of uncertainty of the cover materials activity as an input parameter for the radon barrier design, the cover materials Ra-226 activity have been modeled using the mean activity and the mean plus one SEM as per the TAD (DOE, 1989).

Compacted Clay Layer

The Ra-226 activity value for the compacted clay layer is based on two samples of Mancos Shale collected from the Crescent Junction Site that will be used to construct the compacted-clay radon barrier and clean-fill perimeter dikes (see Appendix B). Samples were collected from weathered Mancos Shale samples with depths of approximately 20 to 22 ft below the surface. The Ra-226 activity of the weathered Mancos Shale ranged from 1.6 to 3.0 pCi/g, with a mean value of 2.3 pCi/g. The samples were analyzed using the OCS at the Moab Site. To evaluate the impact of uncertainty of the cover materials activity as an input parameter for the radon-barrier design, the Ra-226 activity of the cover materials has been modeled using the mean activity and the mean-plus-one SEM as per the TAD (DOE 1989).

Radon Emanation Coefficient

A radon-emanation coefficient of 0.35 was used for all of the tailings, random fill, and cover materials. This is the conservative default value used in the RADON model.

Weight Percent Moisture

The mean weight percent moisture of the tailings has been modeled as 15 percent based on the modeled long-term moisture content from the calculation set MOA-02-05-2006-03-21-00 (*Infiltration Modeling for Alternative Cover Design*).

The mean long-term gravimetric moisture content of the interim cover and alternative cover monolithic layer is modeled as 8 percent. This value is based on a review of the measured in-situ moisture content for the alluvial materials (6.8 percent), the mean measured 15 bar moisture content (9.0 percent) as determined by ASTM Method D3152 and presented in the GEG calculation set (DOE 2006g), and a calculated 15 bar moisture content based on the Rawls and Brakenseik equation (7.5 percent) as presented in the NRC Regulatory Guide 3.64 (NRC 1989). These data are summarized in Appendix B.

The mean long-term moisture content of the compacted clay derived form the on-site weathered Mancos Shale is modeled as 10 percent. This value is based on a review of the measured in-situ moisture content for the weathered Mancos Shale (10.2 percent), the mean measured 15-bar moisture content for the weathered Mancos Shale (12.1 percent) as determined by ASTM Method D3152 and presented in the GEG calculation set (DOE 2006g), and a calculated 15-bar moisture content based on the Rawls and Brakensiek equation (11.9 percent) as presented in the NRC Regulatory Guide 3.64 (NRC 1989). Table 2 summarizes these data. The lower value of 10 percent was selected because it was the observed in-situ condition and, though these materials will be remolded during the cover construction process, it represents a conservative lower bound on future performance as per NRC guidance.

Radon-Diffusion Coefficient

The radon-diffusion coefficient used in the RAECOM model can either be calculated within the model (based on an empirical relationship with degree of saturation) or input directly into the model using values measured from laboratory testing. For this evaluation, the RAECOM model was used to calculate the values in the model runs. The lower the diffusion coefficient value, the lower the resulting rate of radon emanation. The values that were calculated by the model are summarized in Appendix A.

Radon in Ambient Air

The ambient air radon concentrations above the radon-barrier layer are assumed to zero in absence of site-specific data.

Conclusion and Recommendations

- The alternative cover design showed less than 40 percent difference in modeled radon-barrier thickness (actual ratio is 1.2) when modeled using mean input parameter values and mean values plus the SEM input values. This indicates three things: 1) that the current characterization data for the input parameters are adequate for this design; 2) that uncertainty related to the variability of input parameter data is sufficiently low; and 3) that further characterization to reduce this uncertainty is not required for this level of design.
- The UMTRA-style cover showed greater than 40 percent difference in modeled radon-barrier thickness (actual ratio is 1.9) when modeled using mean input parameter values and mean values plus the SEM input values. This indicates that: 1) the current characterization data for the input parameters is not adequate for this design; 2) uncertainty related to the variability of input parameter data is large; and 3) further characterization to reduce this uncertainty is required for this level of design. The difference is likely related to the differences in long-term moisture content of the compacted-clay radon barrier and the increased Ra-226 activity of the tailings. Model Run UMTRA 3 uses mean input values for all input parameters except the long-term moisture content, which is set at 10 percent rather than the mean value of 12 percent. This single-input change accounts for approximately one third of the difference between the two scenarios.

Table 2. Crescent Junction Disposal Cell Radon Barrier Design, RAECOM Model Runs Summary, Alternative Cover

	ALT 1		ALT 2	
Parameters	**Output File Name**	**Source for Input Parameters**	**Output File Name**	**Source for Input Parameters**
Tailings				
	Mean Input Parameter Values		Mean Plus SEM Input Parameter Values	
Specific Gravity	2.8	Average value for tailings from Shaw Lab Data (DOE 2006e) for all tailings samples	2.8	Average value for tailings from Shaw Lab Data (DOE 2006e) for all tailings samples
Porosity	0.44	Calculated	0.44	Calculated
Dry Density (g/cc)	1.57	Calculated	1.57	Calculated
Dry Density (pcf)	98	90% of average standard proctor max dry density of transition tailings from Golder bench scale test, 2006	98	90% of average standard proctor max dry density of transition tailings from Golder bench scale test, 2006
Moisture Content (%)	15	Based on calculated long-term moisture content from Infiltration modeling	15	Based on calculated long-term moisture content from Infiltration modeling
Degree of Saturation (%)	53.5	Calculated	53.5	Calculated
Radium Activity (pCi/g)	868	Mean of 27 values from November 2005 OCS analysis of tailings	954	Mean plus 1 SEM from November 2005 OCS analysis of tailings
Diffusion Coef (cm^2/sec)	1.045 x 10^-2	Calculated by RAECOM	1.045 x 10^-2	Calculated by RAECOM
Thickness (cm)	500	Model not sensitive to depths greater than 500 cm	500	Model not sensitive to depths greater than 500 cm
Thickness (ft)	16.4	Calculated	16.4	Calculated
Interim Cover				
Specific Gravity	2.67	Average value for sheet wash, fluvial, and eolian soils from GEG lab data (DOE 2006f)	2.7	Average plus SEM for sheet wash, fluvial, and eolian soils from GEG lab data (DOE 2006f)
Porosity	0.38	Calculated	0.39	Calculated
Density (g/cc)	1.65	Calculated	1.65	Calculated

	ALT 1		ALT 2	
Parameters	**Output File Name**	**Source for Input Parameters**	**Output File Name**	**Source for Input Parameters**
Density (pcf)	103	85% of average modified proctor max dry density of sheet wash, fluvial, and eolian soils from GEG lab data (DOE 2006f)	103	85% of average modified proctor max dry density of sheet wash, fluvial, and eolian soils from GEG lab data (DOE 2006f)
Moisture Content (%)	8	Mean gravimetric moisture content value estimated form in-situ soils analysis, Rawls & Rakenseik Eqn, and average measured 15 bar moisture content for sheet wash and fluvial/eolian materials by ASTM D3152	7	Mean plus SEM gravimetric moisture content value estimated form in-situ soils analysis, Rawls & Rakenseik Eqn, and average measured 15 bar moisture content for sheet wash and fluvial/eolian materials by ASTM D3152
Degree of Saturation (%)	34.7	Calculated	29.6	Calculated
Radium Activity (pCi/g)	1.86	Mean plus 1 SEM from February 2006 OCS sheet wash and eolian data	2.02	Mean plus 1 SEM from February 2006 OCS sheet wash and eolian data
Diffusion Coef (cm^2/sec)	2.089 x 10^-2	Calculated by RAECOM	2.541 x 10^-2	Calculated by RAECOM
Thickness (cm)	**30.5**		**30.5**	
Thickness (ft)	**1**		**1**	
Radon Barrier				
Specific Gravity	2.67	Average value for sheet wash, fluvial, and eolian soils from GEG lab data (DOE 2006f)	2.7	Average plus SEM for sheet wash, fluvial, and eolian soils from GEG lab data (DOE 2006f)
Porosity	0.38	Calculated	0.39	Calculated
Density (g/cc)	1.65	Calculated	1.65	Calculated
Density (pcf)	103	85% of average modified proctor max dry density of sheet wash, fluvial, and eolian soils from GEG lab data (DOE 2006f)	103	85% of average modified proctor max dry density of sheet wash, fluvial, and eolian soils from GEG lab data (DOE 2006f)

	ALT 1		ALT 2	
Parameters	**Output File Name**	**Source for Input Parameters**	**Output File Name**	**Source for Input Parameters**
Moisture Content (%)	8	Mean gravimetric moisture content value estimated form in-situ soils analysis, Rawls & Rakenseik Eqn, and average measured 15 bar moisture content for sheet wash and fluvial/eolian materials by ASTM D3152	7	Mean plus SEM grávimetric moisture content value estimated form in-situ soils analysis, Rawls & Rakenseik Eqn, and average measured 15 bar moisture content for sheet wash and fluvial/eolian materials by ASTM D3152
Degree of Saturation (%)	34.7	Calculated	29.6	Calculated
Radium Activity (pCi/g)	1.86	Mean plus 1 SEM from February 2006 OCS sheet wash and eolian data	2.02	Mean plus 1 SEM from February 2006 OCS sheet wash and eolian data
Diffusion Coef (cm^2/sec)	2.089 x 10^-2	Calculated by RAECOM	2.541 x 10^-2	Calculated by RAECOM
Thickness (cm)	**355**	Calculated by RAECOM	**415.1**	Calculated by RAECOM
Thickness (ft)	**11.6**	Calculated by RAECOM	**13.6**	Calculated by RAECOM
Note: RADON uses gravimetric water contents.				
		Ratio of Calculated Radon Barrier Thicknesses:	**1.2**	

- The compacted-clay radon barrier of the UMTRA checklist-type cover under the modeled conditions, using the mean plus SEM input values, is 7.7 ft thick.
- The alternative cover design, under the modeled conditions, using the mean plus SEM input values, is 13.6 ft thick.
- Based on these results, either design is capable of meeting the requisite reasonable assurance of providing long-term control of radon flux to the specific average of 20 $pCi/m^2/sec$.
- It is recommended that the model be run again once the laboratory Ra-226 data for the tailings source term are available.
- It is recommended that three actions occur during construction and prior to placement of the radon barrier:
    1. Additional testing of Ra-226 activity for the contaminated materials placed in the upper 10 ft of the cell.
    2. Additional testing of long-term moisture content of materials stockpiled for construction of the radon barrier.
    3. Another run of the model to refine the required cover thickness.

Computer Source:

Rogers, V.C., K.K. Nielson, and D.R. Kalkwarf, 1984. "Radon Attenuation Handbook for Uranium Mill Tailings Cover Design," NUREG/CR-3533, prepared for U.S. Nuclear Regulatory Commission, April.

Appendix A

RAECOM Model Output Files

-----*****! RADON !**********-----

Version 1.2 - MAY 22, 1989 - G.F. Birchard tel.# (301)492-7000
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RADON FLUX, CONCENTRATION AND TAILINGS COVER THICKNESS ARE CALCULATED FOR MULTIPLE LAYERS

OUTPUT FILE: Alt 1

DESCRIPTION: Alternative Cover, Mean Input Values

CONSTANTS

RADON DECAY CONSTANT	.0000021	s^-1
RADON WATER/AIR PARTITION COEFFICIENT	.26	
DEFAULT SPECIFIC GRAVITY OF COVER & TAILINGS		2.65

GENERAL INPUT PARAMETERS

LAYERS OF COVER AND TAILINGS	3	
DEFAULT RADON FLUX LIMIT	20	pCi m^-2 s^-1
NO. OF THE LAYER TO BE OPTIMIZED	3	
DEFAULT SURFACE RADON CONCENTRATION	0	pCi l^-1
SURFACE FLUX PRECISION	.001	pCi m^-2 s^-1

LAYER INPUT PARAMETERS

LAYER 1 Tailings

THICKNESS	500	cm
POROSITY	.44	
MEASURED MASS DENSITY	1.57	g cm^-3
MEASURED RADIUM ACTIVITY	868	pCi/g^-1
DEFAULT LAYER EMANATION COEFFICIENT	.35	
CALCULATED SOURCE TERM CONCENTRATION	2.276D-03	pCi cm^-3 s^-1
WEIGHT % MOISTURE	15	%
MOISTURE SATURATION FRACTION	.535	
CALCULATED DIFFUSION COEFFICIENT	1.045D-02	cm^2 s^-1

LAYER 2 Interim Cover

THICKNESS	30.5	cm
POROSITY	.38	
MEASURED MASS DENSITY	1.65	g cm^-3
MEASURED RADIUM ACTIVITY	1.86	pCi/g^-1
DEFAULT LAYER EMANATION COEFFICIENT	.35	
CALCULATED SOURCE TERM CONCENTRATION	5.936D-06	pCi cm^-3 s^-1
WEIGHT % MOISTURE	8	%
MOISTURE SATURATION FRACTION	.347	
CALCULATED DIFFUSION COEFFICIENT	2.089D-02	cm^2 s^-1

LAYER 3 Radon Barrier

THICKNESS	30	cm
POROSITY	.38	
MEASURED MASS DENSITY	1.65	g cm^-3
MEASURED RADIUM ACTIVITY	1.86	pCi/g^-1
DEFAULT LAYER EMANATION COEFFICIENT	.35	
CALCULATED SOURCE TERM CONCENTRATION	5.936D-06	pCi cm^-3 s^-1
WEIGHT % MOISTURE	8	%
MOISTURE SATURATION FRACTION	.347	
CALCULATED DIFFUSION COEFFICIENT	2.089D-02	cm^2 s^-1

DATA SENT TO THE FILE 'RNDATA' ON DRIVE A:

N	F01	CN1	ICOST	CRITJ	ACC
3	-1.000D+00	0.000D+00	3	2.000D+01	1.000D-03

LAYER	DX	D	P	Q	XMS	RHO
1	5.000D+02	1.045D-02	4.400D-01	2.276D-03	5.352D-01	1.570
2	3.050D+01	2.089D-02	3.800D-01	5.936D-06	3.474D-01	1.650
3	3.000D+01	2.089D-02	3.800D-01	5.936D-06	3.474D-01	1.650

BARE SOURCE FLUX FROM LAYER 1: 7.059D+02 pCi m^-2 s^-1

RESULTS OF THE RADON DIFFUSION CALCULATIONS

LAYER	THICKNESS (cm)	EXIT FLUX (pCi m^-2 s^-1)	EXIT CONC. (pCi l^-1)
1	5.000D+02	4.234D+02	4.342D+05
2	3.050D+01	3.120D+02	3.940D+05
3	3.550D+02	2.000D+01	0.000D+00

-----*****! RADON !*********-----

Version 1.2 - MAY 22, 1989 - G.F. Birchard tel.# (301)492-7000
U.S. Nuclear Regulatory Commission Office of Research

RADON FLUX, CONCENTRATION AND TAILINGS COVER THICKNESS ARE CALCULATED FOR MULTIPLE LAYERS

OUTPUT FILE: Alt 2

DESCRIPTION: Alternative Cover, Mean Plus Standard Error of the Mean Input Values

CONSTANTS

RADON DECAY CONSTANT	.0000021	s^-1
RADON WATER/AIR PARTITION COEFFICIENT	.26	
DEFAULT SPECIFIC GRAVITY OF COVER & TAILINGS		2.65

GENERAL INPUT PARAMETERS

LAYERS OF COVER AND TAILINGS	3	
DEFAULT RADON FLUX LIMIT	20	pCi m^-2 s^-1
NO. OF THE LAYER TO BE OPTIMIZED	3	
DEFAULT SURFACE RADON CONCENTRATION	0	pCi l^-1
SURFACE FLUX PRECISION	.001	pCi m^-2 s^-1

LAYER INPUT PARAMETERS

LAYER 1 Tailings

THICKNESS	500	cm
POROSITY	.44	
MEASURED MASS DENSITY	1.57	g cm^-3
MEASURED RADIUM ACTIVITY	954	pCi/g^-1
DEFAULT LAYER EMANATION COEFFICIENT	.35	
CALCULATED SOURCE TERM CONCENTRATION	2.502D-03	pCi cm^-3 s^-1
WEIGHT % MOISTURE	15	%
MOISTURE SATURATION FRACTION	.535	
CALCULATED DIFFUSION COEFFICIENT	1.045D-02	cm^2 s^-1

LAYER 2 Interim Cover

THICKNESS	30.5	cm
POROSITY	.39	
MEASURED MASS DENSITY	1.65	g cm^-3
MEASURED RADIUM ACTIVITY	2.02	pCi/g^-1
DEFAULT LAYER EMANATION COEFFICIENT	.35	
CALCULATED SOURCE TERM CONCENTRATION	6.281D-06	pCi cm^-3 s^-1
WEIGHT % MOISTURE	7	%
MOISTURE SATURATION FRACTION	.296	
CALCULATED DIFFUSION COEFFICIENT	2.541D-02	cm^2 s^-1

LAYER 3 Radon Barrier

THICKNESS	30	cm
POROSITY	.39	
MEASURED MASS DENSITY	1.65	g cm^-3
MEASURED RADIUM ACTIVITY	2.02	pCi/g^-1
DEFAULT LAYER EMANATION COEFFICIENT	.35	
CALCULATED SOURCE TERM CONCENTRATION	6.281D-06	pCi cm^-3 s^-1
WEIGHT % MOISTURE	7	%
MOISTURE SATURATION FRACTION	.296	
CALCULATED DIFFUSION COEFFICIENT	2.541D-02	cm^2 s^-1

DATA SENT TO THE FILE 'RNDATA' ON DRIVE A:

N	F01	CN1	ICOST	CRITJ	ACC
3	-1.000D+00	0.000D+00	3	2.000D+01	1.000D-03

LAYER	DX	D	P	Q	XMS	RHO
1	5.000D+02	1.045D-02	4.400D-01	2.502D-03	5.352D-01	1.570
2	3.050D+01	2.541D-02	3.900D-01	6.281D-06	2.962D-01	1.650
3	3.000D+01	2.541D-02	3.900D-01	6.281D-06	2.962D-01	1.650

BARE SOURCE FLUX FROM LAYER 1: 7.758D+02 pCi m^-2 s^-1

RESULTS OF THE RADON DIFFUSION CALCULATIONS

LAYER	THICKNESS (cm)	EXIT FLUX (pCi m^-2 s^-1)	EXIT CONC. (pCi l^-1)
1	5.000D+02	4.970D+02	4.287D+05
2	3.050D+01	3.767D+02	4.206D+05
3	4.151D+02	1.999D+01	0.000D+00

-----*****! RADON !*********-----

Version 1.2 - MAY 22, 1989 - G.F. Birchard tel.# (301)492-7000
U.S. Nuclear Regulatory Commission Office of Research

RADON FLUX, CONCENTRATION AND TAILINGS COVER THICKNESS ARE CALCULATED FOR MULTIPLE LAYERS

OUTPUT FILE: UMTRA 1

DESCRIPTION: Mean Input Values

CONSTANTS

RADON DECAY CONSTANT	.0000021	s^-1
RADON WATER/AIR PARTITION COEFFICIENT	.26	
DEFAULT SPECIFIC GRAVITY OF COVER & TAILINGS		2.65

GENERAL INPUT PARAMETERS

LAYERS OF COVER AND TAILINGS	3	
DEFAULT RADON FLUX LIMIT	20	pCi m^-2 s^-1
NO. OF THE LAYER TO BE OPTIMIZED	3	
DEFAULT SURFACE RADON CONCENTRATION	0	pCi l^-1
SURFACE FLUX PRECISION	.001	pCi m^-2 s^-1

LAYER INPUT PARAMETERS

LAYER 1 Tailings

THICKNESS	500	cm
POROSITY	.44	
MEASURED MASS DENSITY	1.57	g cm^-3
MEASURED RADIUM ACTIVITY	868	pCi/g^-1
DEFAULT LAYER EMANATION COEFFICIENT	.35	
CALCULATED SOURCE TERM CONCENTRATION	2.276D-03	pCi cm^-3 s^-1
WEIGHT % MOISTURE	15	%
MOISTURE SATURATION FRACTION	.535	
CALCULATED DIFFUSION COEFFICIENT	1.045D-02	cm^2 s^-1

LAYER 2 Interim Cover

THICKNESS	30.5	cm
POROSITY	.38	
MEASURED MASS DENSITY	1.65	g cm^-3
MEASURED RADIUM ACTIVITY	1.86	pCi/g^-1
DEFAULT LAYER EMANATION COEFFICIENT	.35	
CALCULATED SOURCE TERM CONCENTRATION	5.936D-06	pCi cm^-3 s^-1
WEIGHT % MOISTURE	8	%
MOISTURE SATURATION FRACTION	.347	
CALCULATED DIFFUSION COEFFICIENT	2.089D-02	cm^2 s^-1

LAYER 3 Radon Barrier

THICKNESS	30	cm
POROSITY	.33	
MEASURED MASS DENSITY	1.78	g cm^-3
MEASURED RADIUM ACTIVITY	2.3	pCi/g^-1
DEFAULT LAYER EMANATION COEFFICIENT	.35	
CALCULATED SOURCE TERM CONCENTRATION	9.118D-06	pCi cm^-3 s^-1
WEIGHT % MOISTURE	12	%
MOISTURE SATURATION FRACTION	.647	
CALCULATED DIFFUSION COEFFICIENT	4.423D-03	cm^2 s^-1

DATA SENT TO THE FILE 'RNDATA' ON DRIVE A:

N	F01	CN1	ICOST	CRITJ	ACC
3	-1.000D+00	0.000D+00	3	2.000D+01	1.000D-03

LAYER	DX	D	P	Q	XMS	RHO
1	5.000D+02	1.045D-02	4.400D-01	2.276D-03	5.352D-01	1.570
2	3.050D+01	2.089D-02	3.800D-01	5.936D-06	3.474D-01	1.650
3	3.000D+01	4.423D-03	3.300D-01	9.118D-06	6.473D-01	1.780

BARE SOURCE FLUX FROM LAYER 1: 7.059D+02 pCi m^-2 s^-1

RESULTS OF THE RADON DIFFUSION CALCULATIONS

LAYER	THICKNESS (cm)	EXIT FLUX (pCi m^-2 s^-1)	EXIT CONC. (pCi l^-1)
1	5.000D+02	3.136D+02	6.027D+05
2	3.050D+01	1.458D+02	6.539D+05
3	1.261D+02	1.998D+01	0.000D+00

-----*****! RADON !*****-----

Version 1.2 - MAY 22, 1989 - G.F. Birchard tel.# (301)492-7000
U.S. Nuclear Regulatory Commission Office of Research

RADON FLUX, CONCENTRATION AND TAILINGS COVER THICKNESS ARE CALCULATED FOR MULTIPLE LAYERS

OUTPUT FILE: UMTRA 2

DESCRIPTION: Mean plus standard error of the mean input values.

CONSTANTS

RADON DECAY CONSTANT	.0000021	s^-1
RADON WATER/AIR PARTITION COEFFICIENT	.26	
DEFAULT SPECIFIC GRAVITY OF COVER & TAILINGS	2.65	

GENERAL INPUT PARAMETERS

LAYERS OF COVER AND TAILINGS	3	
DEFAULT RADON FLUX LIMIT	20	pCi m^-2 s^-1
NO. OF THE LAYER TO BE OPTIMIZED	3	
DEFAULT SURFACE RADON CONCENTRATION	0	pCi l^-1
SURFACE FLUX PRECISION	.001	pCi m^-2 s^-1

LAYER INPUT PARAMETERS

LAYER 1 Tailings

THICKNESS	500	cm
POROSITY	.44	
MEASURED MASS DENSITY	1.57	g cm^-3
MEASURED RADIUM ACTIVITY	954	pCi/g^-1
DEFAULT LAYER EMANATION COEFFICIENT	.35	
CALCULATED SOURCE TERM CONCENTRATION	2.502D-03	pCi cm^-3 s^-1
WEIGHT % MOISTURE	15	%
MOISTURE SATURATION FRACTION	.535	
CALCULATED DIFFUSION COEFFICIENT	1.045D-02	cm^2 s^-1

LAYER 2 Interim Cover

THICKNESS	30.5	cm
POROSITY	.39	
MEASURED MASS DENSITY	1.65	g cm^-3
MEASURED RADIUM ACTIVITY	2.02	pCi/g^-1
DEFAULT LAYER EMANATION COEFFICIENT	.35	
CALCULATED SOURCE TERM CONCENTRATION	6.281D-06	pCi cm^-3 s^-1
WEIGHT % MOISTURE	7	%
MOISTURE SATURATION FRACTION	.296	
CALCULATED DIFFUSION COEFFICIENT	2.541D-02	cm^2 s^-1

LAYER 3 Radon Barrier

THICKNESS	30	cm
POROSITY	.35	
MEASURED MASS DENSITY	1.78	g cm^-3
MEASURED RADIUM ACTIVITY	3	pCi/g^-1
DEFAULT LAYER EMANATION COEFFICIENT	.35	
CALCULATED SOURCE TERM CONCENTRATION	1.121D-05	pCi cm^-3 s^-1
WEIGHT % MOISTURE	10	%
MOISTURE SATURATION FRACTION	.509	
CALCULATED DIFFUSION COEFFICIENT	1.025D-02	cm^2 s^-1

DATA SENT TO THE FILE `RNDATA' ON DRIVE A:

N	F01	CN1	ICOST	CRITJ	ACC
3	-1.000D+00	0.000D+00	3	2.000D+01	1.000D-03

LAYER	DX	D	P	Q	XMS	RHO
1	5.000D+02	1.045D-02	4.400D-01	2.502D-03	5.352D-01	1.570
2	3.050D+01	2.541D-02	3.900D-01	6.281D-06	2.962D-01	1.650
3	3.000D+01	1.025D-02	3.500D-01	1.121D-05	5.086D-01	1.780

BARE SOURCE FLUX FROM LAYER 1: 7.758D+02 pCi m^-2 s^-1

RESULTS OF THE RADON DIFFUSION CALCULATIONS

LAYER	THICKNESS (cm)	EXIT FLUX (pCi m^-2 s^-1)	EXIT CONC. (pCi l^-1)
1	5.000D+02	4.150D+02	5.546D+05
2	3.050D+01	2.504D+02	6.153D+05
3	2.353D+02	1.998D+01	0.000D+00

Appendix B

Supporting Calculations and Data

Summary of Geotechnical Testing Data From Calculation Set X0156200 (Geotechnical Prope

Sample	Number	Field Description	Tested Depth (ft)	Natural Moisture (%)	Dry Density (pcf)	Liquid Limit (%)	Plasticity Index (%)	Passing No. 200 (%)	Specific Gravity	γ_{max} (Modified Proctor)	W_{opt} (Modified Proctor)
TP	156	eolian	12			19	2	64	2.64	124.5	11.0
TP liner	154	eolian	13	5.7	82.0	20	2	69			
TP liner	156	eolian	12.25	7.9	88.0	0	0	50			
TP	152	fluvial/eolian	15			21	3	84	2.63	127.5	10.0
TP	153	fluvial/eolian	8.5			0	0	67	2.65	118.0	11.0
TP	154	fluvial/eolian	12			20	3	63	2.65	122.0	12.0
BH	005	sandy silt	2	4.2	91.0	21	4	69			
BH	007	sandy silt									
BH	009	sandy silt	4	6.6	83.0	24	9	74			
BH	011	sandy silt	2	6.1	83.0	22	9	78			
BH	013	sandy silt	7	8.3	113.4	0	0	43			
BH	013	sandy silt	2.5	5.8	89.0	24	9	70			
BH	023	sandy silt	3.5	6.0		25	8	72			
BH	025	sandy silt	16.5	7.3	106.0	21	6	66			
BH	025	sandy silt	6	4.9	89.0	24	9	59			
BH	027	sandy silt	16.5	8.4	108.0	24	11	87			
BH	027	sandy silt	4	5.9		24	3	44			
BH	029	sandy silt	7	13.4	77.0	23	6	77			
BH	031	sandy silt	12	8.2	96.0	24	4	50			
BH	031	sandy silt	5.5	7.0	87.0	25	9	85			
BH	043	sandy silt	3.5	6.1	90.0	25	8	53			
BH	045	sandy silt	1.5	4.6	84.0	19	7	57			
BH	045	sandy silt	6.5	8.6	98.0	32	9	78			
BH	049	sandy silt	6.5	6.0	83.0	20	6	62			
BH	049	sandy silt	12	5.4	102.0	19	5	80			
BH	051	sandy silt	3.5	3.8	85.0	20	6	57			
BH	062	sandy silt	4	7.6	103.0	29	10	69			
BH	062	sandy silt									
BH	064	sandy silt	2	12.4	95.0	34	5	74			
BH	066	sandy silt	3.5	4.7	90.0	21	5	53			
BH	068	sandy silt	2	4.2	94.0	21	6	36			
BH	078	sandy silt	7	5.7	85.0	23	7	70			
BH	080	sandy silt	3	2.8	95.0	19	5	53			

Summary of Geotechnical Testing Data From Calculation Set X0156200 (Geotechnical Prope

Sample	Number	Field Description	Tested Depth (ft)	Natural Moisture (%)	Dry Density (pcf)	Liquid Limit (%)	Plasticity Index (%)	Passing No. 200 (%)	Specific Gravity	γ_{max} (Modified Proctor)	w_{opt} (Modified Proctor)
BH	080	sandy silt	7	6.0	89.0	24	7	65			
BH	082	sandy silt	12	4.7	91.0	21	8	79			
BH	092	sandy silt	2	5.7	87.0	22	9	63			
BH	094	sandy silt	4	12.2	89.0	31	10	61			
BH	094	sandy silt	17	7.1	102.0	20	5	37			
BH	095	sandy silt	7	6.5	85.0	23	7	46			
BH	099	sandy silt	2.5	4.8	87.0	18	3	47			
BH	100	sandy silt	4	8.0		25	5	69			
TP	151	sheet wash	4.5			24	5	66		118.5	13.0
TP	152	sheet wash	7.5			26	9	74	2.64	120.5	13.0
TP	153	sheet wash	3.5			23	5	72	2.68	120.5	12.5
TP	154	sheet wash	4			22	4	83		123.0	12.0
TP	156	sheet wash	5			24	7	69	2.82	120.0	11.5
TP liner	154	sheet wash	4	9.5	81.0	22	5	81			
TP liner	156	sheet wash	3.5	9.5	89.0	0	0	79			
TP liner	156	sheet wash	7.25	6.0	91.0			63			
BH	011	silty gravel	11.5	2.6		21	4	19			
BH	005	weathered shale	11	6.0	118.0	25	10	79			
BH	009	weathered shale	6.5	6.6	107.2	28	9	84			
BH	026	weathered shale	15.5	5.7		24	10	71			
BH	029	weathered shale	27	6.4	81.0	29	10	81			
BH	033	weathered shale	10.75	6.7	117.0	34	18	82			
BH	043	weathered shale	6	5.0	93.0	24	16	47			
BH	046	weathered shale									
BH	064	weathered shale	3.5	10.0	109.0	31	19	86			
BH	066	weathered shale	7	12.3	112.0	31	10	90			
BH	079	weathered shale	10.5			25	10	78			
BH	082	weathered shale	17	7.1	118.0	34	14	93			
BH	090	weathered shale	12	8.2	99.0	22	5	55			
BH	092	weathered shale	12	7.7	71.0	26	6	71			
BH	094	weathered shale	21.5	6.8	112.0	21	4	33			
TP	152	weathered shale	23			33	12	97		121.0	12.0
TP	154	weathered shale	20			38	20	95	2.73	120.5	13.0
TP	156	weathered shale	22			25	7	84	2.56	127.5	11.0

Summary of Geotechnical Testing Data From Calculation Set X0156200 (Geotechnical Prope

Sample	Number	Field Description	Tested Depth (ft)	Natural Moisture (%)	Dry Density (pcf)	Liquid Limit (%)	Plasticity Index (%)	Passing No. 200 (%)	Specific Gravity	γ_{max} (Modified Proctor)	w_{opt} (Modified Proctor)
		All Data	Max	13.4	118.0	38	20	97	2.82	127.5	13.0
			Min	2.6	71.0	0	0	19	2.56	118.0	10.0
			Avg.	6.8	94.0	23	7	67	2.67	122.0	11.8
			Median	6.4	90.5	24	7	69	2.65	120.8	12.0
			count	51.0	46.0	63	63	64	9.00	12.0	12.0
		Standard Deviation		2.3	11.6	7.4	4.2	16.1	0.1	3.1	1.0
		Standard Error of the Mean (SEM)		0.3	1.7	0.9	0.5	2.0	0.0	0.9	0.3
		Average - SEM		6.5	92.3	21.9	6.6	65.4	2.6	121.1	11.6
		Weathered Mancos	Max	12.3	118.0	38	20	97	2.73	127.5	13.0
			Min	5.0	71.0	21	4	33	2.56	120.5	11.0
			Avg.	7.4	103.4	28	11	77	2.65	123.0	12.0
			Median	6.8	109.0	27	10	82	2.65	121.0	12.0
			count	12	11	16	16	16	2	3	3
		Standard Deviation		2.0	15.8	4.9	4.9	17.8	0.1	3.9	1.0
		Standard Error of the Mean (SEM)		0.6	4.8	1.2	1.2	4.5	0.1	2.3	0.6
		Average - SEM		6.8	98.6	26.9	10.0	72.2	2.6	120.7	11.4
		All Data without Weathered Mancos	Max	13.4	113.4	34.0	11.0	87.0	2.8	127.5	13.0
			Min	2.8	77.0	0.0	0.0	36.0	2.6	118.0	10.0
			Avg.	6.8	91.1	21.0	5.8	65.2	2.7	121.6	11.8
			Median	6.1	89.0	22.0	6.0	67.0	2.7	120.5	12.0
			count	38	35	46	46	47	7	9	9
		Standard Deviation		2.3	8.3	7.4	2.9	12.9	0.1	3.0	1.0
		Standard Error of the Mean (SEM)		0.4	1.4	1.1	0.4	1.9	0.0	1.0	0.3
		Average - SEM		6.4	89.7	20.0	5.3	63.4	2.6	120.6	11.4

Summary of Geotechnicalərties of Native Materials

Sample	Number	Field Description	Sieve % Gravel	% Sand	% Fines	Hydrometer % silt	% clay	Double Hydrometer
TP	156	eolian	0	35	65	39	26	83
TP liner	154	eolian						
TP liner	156	eolian						
TP	152	fluvial/eolian	49	22	29	15	14	
TP	153	fluvial/eolian	1	32	67	52	15	
TP	154	fluvial/eolian	0	33	67	40	27	62
BH	005	sandy silt						
BH	007	sandy silt						
BH	009	sandy silt						
BH	011	sandy silt						
BH	013	sandy silt						
BH	013	sandy silt						
BH	023	sandy silt						
BH	025	sandy silt						
BH	025	sandy silt						
BH	027	sandy silt						
BH	027	sandy silt						
BH	029	sandy silt						
BH	031	sandy silt						
BH	031	sandy silt						
BH	043	sandy silt						
BH	045	sandy silt						
BH	045	sandy silt						
BH	049	sandy silt						
BH	049	sandy silt						
BH	051	sandy silt						
BH	062	sandy silt						
BH	062	sandy silt						
BH	064	sandy silt						
BH	066	sandy silt						
BH	068	sandy silt						
BH	078	sandy silt						
BH	080	sandy silt						

Summary of Geotechnicalerties of Native Materials

Sample	Number	Field Description	Sieve % Gravel	Sieve % Sand	Sieve % Fines	Hydrometer % silt	Hydrometer % clay	Double Hydrometer
BH	080	sandy silt						
BH	082	sandy silt						
BH	092	sandy silt						
BH	094	sandy silt						
BH	094	sandy silt						
BH	095	sandy silt						
BH	099	sandy silt						
BH	100	sandy silt						
TP	151	sheet wash	4	30	66			
TP	152	sheet wash	0	25	75	59	16	
TP	153	sheet wash	0	27	73	60	13	
TP	154	sheet wash	0	16	84	62	22	79
TP	156	sheet wash	1	29	70	54	16	61
TP liner	154	sheet wash						
TP liner	156	sheet wash						
TP liner	156	sheet wash						
BH	011	silty gravel						
BH	005	weathered shale						
BH	009	weathered shale						
BH	026	weathered shale						
BH	029	weathered shale						
BH	033	weathered shale						
BH	043	weathered shale						
BH	046	weathered shale						
BH	064	weathered shale						
BH	066	weathered shale						
BH	079	weathered shale						
BH	082	weathered shale						
BH	090	weathered shale						
BH	092	weathered shale						
BH	094	weathered shale						
TP	152	weathered shale	0	3	97	55	42	
TP	154	weathered shale	0	5	95	55	40	62
TP	156	weathered shale	2	14	84	53	31	86

Summary of Geotechnicalerties of Native Materials

Sample	Number	Field Description	Sieve % Gravel	Sieve % Sand	Sieve % Fines	Hydrometer % silt	Hydrometer % clay	Double Hydrometer
		All Data	49	35	97	62	42	86
			0	3	29	15	13	61
			5	23	73	49	24	72
			0	26	72	54	22	71
			12	12	12	11	11	6
		Standard	14.0	10.8	17.7	13.6	10.4	11.7
		Standard Error of the Me	4.0	3.1	5.1	4.1	3.1	4.8
		Avera	0.7	19.5	67.6	45.4	20.7	67.4
		Weathered Mancos	2	14	97	55	42	86
			0	3	84	53	31	62
			1	7	92	54	38	74
			0	5	95	55	40	74
			3	3	3	3	3	2
		Standard	1.2	5.9	7.0	1.2	5.9	17.0
		Standard Error of the Me	0.7	3.4	4.0	0.7	3.4	12.0
		Avera	0.0	4.0	88.0	53.7	34.3	62.0
		All Data without Weathered Mancos	49.0	35.0	84.0	62.0	27.0	83.0
			0.0	16.0	29.0	15.0	13.0	61.0
			6.1	27.7	66.2	47.6	18.6	71.3
			0.0	29.0	67.0	53.0	16.0	70.5
			9	9	9	8	8	4
		Standard	16.1	6.0	15.2	15.8	5.6	11.4
		Standard Error of the Mc	5.4	2.0	5.1	5.6	2.0	5.7
		Avera	0.7	25.7	97	42.0	16.7	65.6

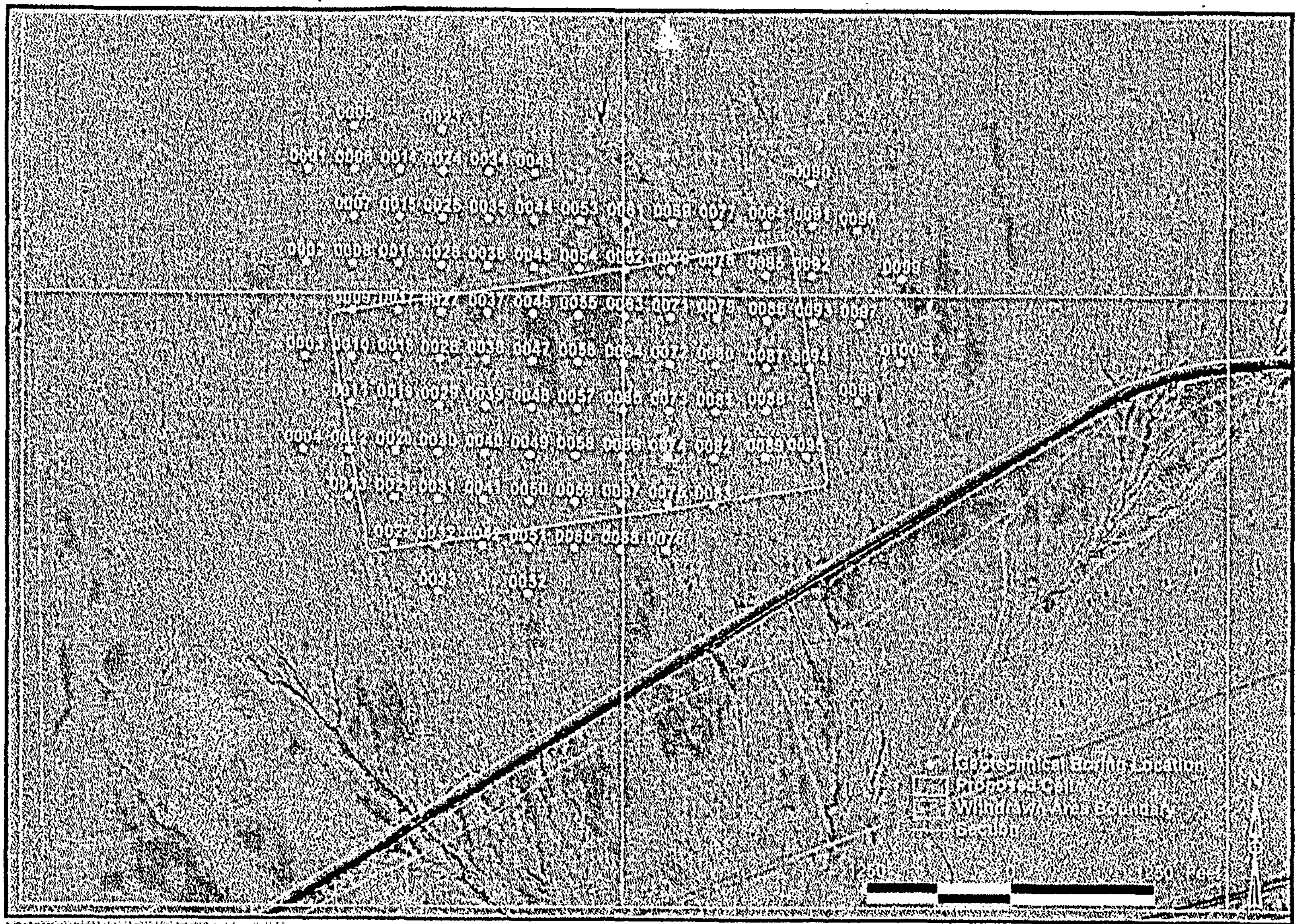

Figure 1. Map Depicting the Locations of the 100 Geotechnical Boreholes at the Crescent Junction Site

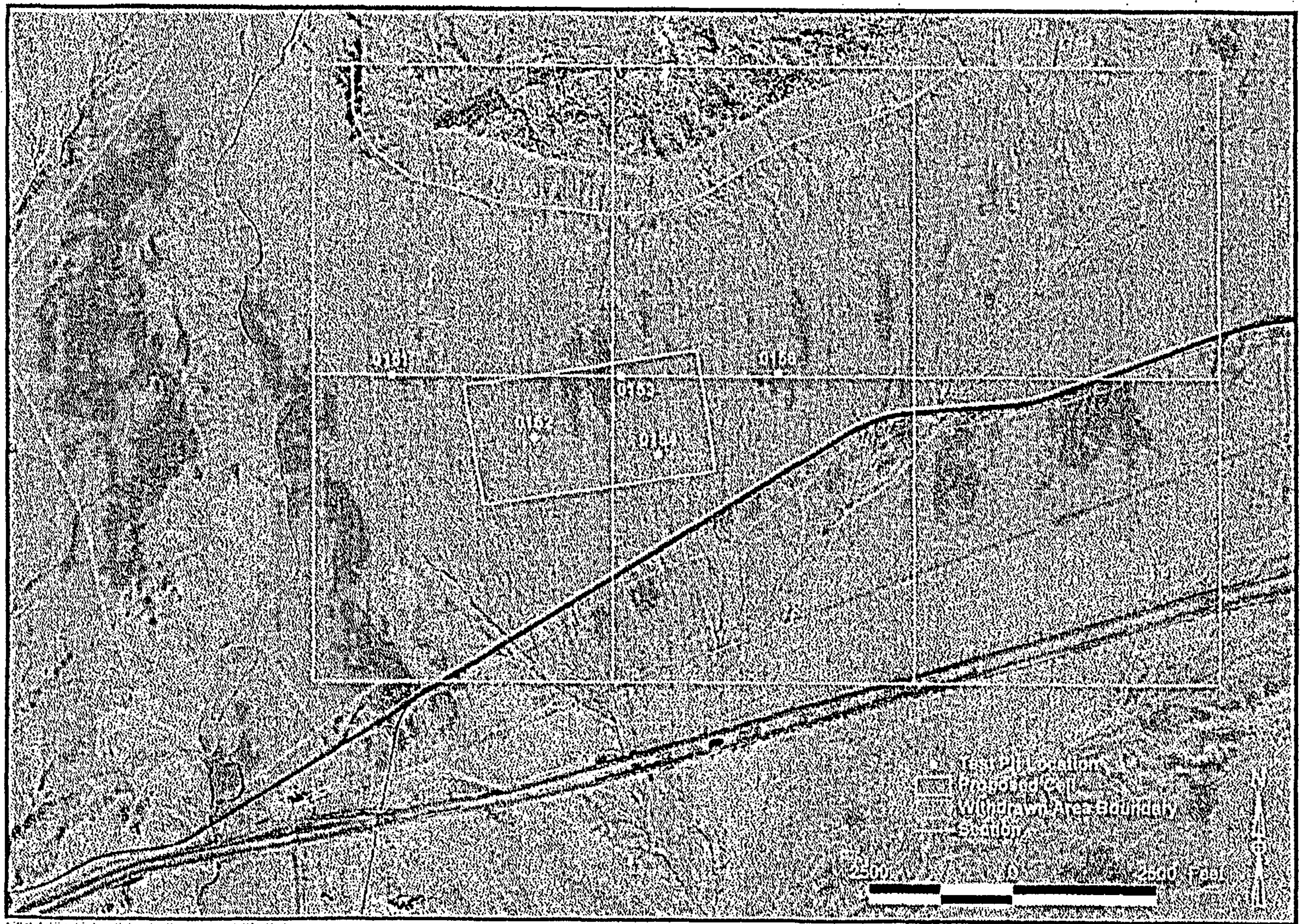

Figure 2. Map Depicting the Location of the Five Test Pits at the Crescent Junction Site

Moab Project, Crescent Junction Disposal Cell
Radon Barrier Design, RAECOM Model Runs
Summary of Mean and Standard Error of the Mean (SEM) Calculations for Key Parameters

Porosity f (G_s)	No. of Samples	G_s	γd	n	G_s+SEM	γd	n
Alluvium	9	2.67	1.65	0.38	2.7	1.65	0.39
Weathered Mancos	3	2.65	1.78	0.33	2.73	1.78	0.35
Tailings	?	2.8	1.57	0.44	?	1.57	?

Long-term Gravimetric Moisture Content (%)	No. of Samples	In Situ	Rawls & Breckensic	ASTM D3151 15 bar tests	n	mean	St Dev	Mean - SEM	Used
			Avg	Avg					
Alluvium	38	6.8	7.5	9	3	7.8	1.12	7.1	7
Weathered Mancos	12	7.4	13.4	12.1	3	11	3.16	7.8	8
Tailings		NA	15						

Ra-226 Activity (pCi/g)	No. of Samples	Mean	SEM	Mean+SEM
Alluvium	5	1.86	0.16	2.02
Weathered Mancos	2	2.3	0.7	3
Tailings	27	868	86.2	954

Moab Project, Crescent Junction Disposal Cell

Native Materials for Cover Construction

Sample	Number	Tested Depth (ft)	Field Description	Specific Gravity[1]	% Organic Matter[1]	% Clay[1]	Ra-226[2] (pCi/g)
TP	156	12	eolian	2.64	0.10	26	2.1
TP	156	15	fluvial/eolian		0.20		
TP	152	15	fluvial/eolian	2.63		14	1.4
TP	153	8.5	fluvial/eolian	2.65		15	
TP	154	12	fluvial/eolian	2.65	0.20	27	1.6
TP	152	7.5	sheet wash	2.64		16	1.9
TP	153	3.5	sheet wash	2.68		13	
TP	154	4	sheet wash		0.50	22	2.3
TP	155	4-5	sheet wash		0.40		2.4
TP	156	5	sheet wash	2.82		16	
TP liner	156	3.5	sheet wash				
TP liner	156	7.25	sheet wash		0.30		
TP	152	23	weathered shale			42	
TP	154	20	weathered shale	2.73		40	1.6
TP	156	23	weathered shale		0.40		
TP	156	22	weathered shale	2.56		31	3.0

		Specific Gravity	% Organic Matter	% Clay	Ra-226
All data	Max	2.82	0.50	42.00	3.00
	Min	2.56	0.10	13.00	1.40
	Avg.	**2.67**	**0.30**	**23.82**	**2.04**
	Median	2.65	0.30	22.00	2.00
	count	9	7	11	8
	Standard Deviation	0.07	0.14	10.37	0.53
	Standard Error of the Mean (SEM)	0.02	0.05	3.13	0.19
	Average + SEM	**2.69**	**0.25**	**20.69**	**2.22**
All Data w/out Weathered Shale	Max	2.82	0.50	27.00	2.40
	Min	2.63	0.10	13.00	1.40
	Avg.	**2.67**	**0.28**	**18.63**	**1.95**
	Median	2.65	0.25	16.00	2.00
	count	7	6	8	6
	Standard Deviation	0.07	0.15	5.55	0.39
	Standard Error of the Mean (SEM)	0.03	0.06	1.96	0.16
	Average + SEM	**2.70**	**0.22**	**16.66**	**2.11**
Weathered Shale Only	Max	2.73	0.40	42.00	3.00
	Min.	2.56	0.40	31.00	1.60
	Avg.	2.65	0.40	37.67	2.30
	Median	2.65	0.40	40.00	2.30
	count	2	1	3	2
	Standard Deviation	0.12	NA	5.86	0.99
	Standard Error of the Mean (SEM)	0.08	NA	3.38	0.70
	Average + SEM	**2.73**	**NA**	**34.28**	**3.00**

Note: For % organic matter and % clay, Agerage minus SEM is used.

[1] Geotechnical data are from calculation set X0156200 (Geotechnical Properties of Native Materials)

[2] OCS system analyses of native materials from Crescent Junction

Moab Project , Moab Tailings ,
OCS system analyses of tailings samples
Nov-05

Sample Location Number	Depth in Feet	Date Sampled	Ra-226 pCi/g
BH 700	30-60	11-07 to 11-09-05	466.5
BH 713	20-36.5	11-07 to 11-09-05	631.1
BH 701	0-20	11-07 to 11-09-05	400.9
BH 701	20-40	11-07 to 11-09-05	480.8
BH 701	40-60	11-07 to 11-09-05	758.9
BH 709	0-20	11-07 to 11-09-05	289.9
BH 709	20-40	11-07 to 11-09-05	546.6
BH 709	40-60	11-07 to 11-09-05	1195.3
BH 709	60-65,75	11-07 to 11-09-05	1205.8
BH 701	60-80	11-07 to 11-09-05	1215.8
BH 703	0-20	11-07 to 11-09-05	457.6
BH 703	20-40	11-07 to 11-09-05	610.1
BH 703	40-60	11-07 to 11-09-05	1396.3
BH 703	65-73	11-07 to 11-09-05	1333
BH 715	0-20	11-10 to 11-13-05	1000.5
BH 715	20-40	11-10 to 11-13-05	278.9
BH 715	40-60	11-10 to 11-13-05	1225.9
BH 715	60+	11-10 to 11-13-05	1518.6
BH 719	0-20	Nov-05	357.4
BH7 19	20-40	Nov-05	1117.7
BH 719	40-51.5	Nov-05	1669.7
BH 705	0-20	Dec-05	186.2
BH 705	20-40	Dec-05	616.9
BH 705	40-60	Dec-05	1232.8
BH 718	0-20	Dec-05	717.8
BH 718	20-40	Dec-05	917.3
BH 718	40-43	Dec-05	1601.7
		MAX	1669.7
		MIN	186.2
		Average	868
		Median	759
		Count(n)	27
		Std. Dev.	447.8
		Standard Error of the Mean (SEM)	86.2
		Average + SEM	954.0

Golder Associates Inc.

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DRAFT TECHNICAL MEMORANDUM

TO:	Greg Lord, S.M. Stoller	**DATE:**	April 3, 2006
FR:	James M. Johnson, Golder Associates Inc. Luis A. Quirindongo, Golder Associates Inc. Ron DiDonato, Golder Associates Inc.	**OUR REF:**	053-2269.2050

RE: RESULTS OF THE BENCH SCALE TESTING PROGRAM ON COVER SOILS AND URANIUM MILL TAILINGS FROM THE MOAB TAILINGS IMPOUNDMENT, GRAND COUNTY, UTAH

INTRODUCTION

As part of our approved work program on the Moab Project, personnel from Golder Associates Inc. (Golder) completed an onsite bench scale testing program during the period of March 15 through March 23, 2006.

The objective of the bench scale testing program was to advance the tailings characterization efforts started during the August 2005 preliminary tailings test program, adjusted to meet the evolving needs and goals of the tailings relocation materials handling evaluation and design.

During this period Golder completed the following tests:

- As sampled moisture content testing of the cover soils and tailings materials after compositing (ASTM D2216) – 14 tests;
- Standard Proctor compaction testing (ASTM D698) – 14 tests;
- Loose density testing (no ASTM standard) – 14 tests; and
- Settled density tests (no ASTM standard) – 14 tests.

Each of the 14 samples was created by mixing either bulk samples obtained from the ten backhoe test pits completed in early December 2005, or selected Shelby tube and/or split spoon samples from the November/December 2005 geotechnical drilling and sampling program.

TESTING PROGRAM DESCRIPTION

Sample Preparation

The bench scale testing program was designed to make use of cover soils and tailings samples remaining onsite, exclusive of the samples already selected and shipped for offsite geotechnical laboratory testing. The samples pre-selected for use in this program are listed in the March 14, 2006 Golder letter describing the proposed bench scale testing program. At the start of the sample preparation phase of the work, Golder personnel noted that some of the pre-selected samples were no longer available onsite or were different material types than originally classified. Therefore, the list of samples to be used in this testing program was modified based on review of the available samples and material types. The final sample list is presented in Table 1.

From March 15 through March 17, Messrs. Luis Quirindongo and Jeff Robison of Golder visited the site to begin the preparation of the samples for the testing program. Each group of samples was mixed to create a composite sample, with splits set aside for Proctor compaction and loose/settled density testing. The sample for Proctor compaction testing was set out to air dry (over the weekend of March 18-19, 2006). The samples for loose and settled density testing were placed either in buckets or bags to preserve the as-sampled moisture content.

Sample Testing

During the sample preparation period, moisture content samples were obtained and tested to determine the initial, or as-sampled moisture content. During the period of March 20 through 23, Messrs. Luis Quirindongo and Ron DiDonato were present on site to perform the standard Proctor compaction and loose/settled density testing. During the course of the week, sample processing, moisture conditioning, and testing were performed. All testing was completed by March 23.

Natural Moisture Content Testing

- Fourteen moisture content tests were performed following ASTM D2216 procedures.

Standard Proctor Compaction Testing

- Fourteen compaction tests were performed following ASTM D698, Method A procedures.

Loose Settled Density Testing

- Fourteen loose settled density tests were performed. These are non-standard tests designed to collect data which we expect to be useful indicators of material characteristics following excavation and during and after transport. ASTM D4253 - Standard Method for Maximum Index Density and Unit Weight of Soil Using Vibratory Table and ASTM D4254 Standard Method for Maximum Index Density and Unit Weight of Soil and Calculation of Relative Density were used as guidelines. The procedures developed by Golder for these tests are as follows:

  - For loose density testing, a standard Proctor mold with a known volume was used. Material at its natural moisture content was placed in the mold as loosely as possible, struck off at the top of the mold, and the weight of the mold plus wet soil was recorded.

  - For the settled density test, the same mold and material was used. To prevent any loss of mass and obtain a smoother recording surface, a cap weighing 1.34 pounds was placed on top of the sample before proceeding with testing. To settle the sample, the mold with the sample was dropped on a concrete floor from a height of 1 to 3 inches, 100 times. After every 25 drops, the side of the mold was tapped with a hammer approximately 16 to 20 times. After shaking the sample, height changes and moisture content were measured and recorded.

TEST RESULTS

During sample preparation and testing, materials were mixed to represent four typical types found at the site: cover soils, sand tailings, transition tailings, and slimes tailings. Golder recommends that leftover sample materials be tested for classification properties in an offsite laboratory to either confirm the visual classification presented in this technical memorandum or provide a basis for modifying the classification. The range of measurements obtained for the four primary material types are presented below.

Natural Moisture Content:
- Cover Soil – 6.5%
- Sand Tailings – 1.1 to 9.4%
- Transition Tailings – 16.5 to 37.0%
- Slimes Tailings – 37.5 to 52.3%

Proctor Maximum Dry Density:
- Cover Soil – 109.2 to 117.7 pcf
- Sand Tailings – 103.9 to 107.3 pcf
- Transition Tailings – 102.0 to 113.3 pcf
- Slimes Tailings – 95.0 to 101.6 pcf

Proctor Optimum Moisture Content:
- Cover Soil – 11.9 to 13.8%
- Sand Tailings – 12.7 to 15.6%
- Transition Tailings – 13.1 to 21.1%
- Slimes Tailings – 20.9 to 28.7%

Loose Wet Density:
- Cover Soil – 71.5 to 78.7 pcf
- Sand Tailings – 63.7 to 66.8 pcf
- Transition Tailings – 71.6 to 103.1 pcf
- Slimes Tailings – 49.0 to 93.8 pcf

Loose Dry Density:
- Cover Soil – 66.9 to 73.1 pcf
- Sand Tailings – 57.7 to 61.7 pcf
- Transition Tailings – 53.2 to 83.9 pcf
- Slimes Tailings – 33.2 to 64.3 pcf

Settled Wet Density:
- Cover Soil – 100.9 to 103.3 pcf
- Sand Tailings – 93.1 to 95.9 pcf
- Transition Tailings – 107.3 to 126.4 pcf
- Slimes Tailings – 58.9 to 114.2 pcf

Settled Dry Density:
- Cover Soil – 93.7 to 96.6 pcf
- Sand Tailings – 84.3 to 88.6 pcf
- Transition Tailings – 84.6 to 102.9 pcf
- Slimes Tailings – 39.9 to 80.7 pcf

Percent Vertical Compression (under dynamic loading):
- Cover Soil – 22.0 to 30.8%
- Sand Tailings – 30.3 to 31.5%
- Transition Tailings – 18.4 to 39%
- Slimes Tailings – 16.9 to 39.6%

Percent Compaction (Settled Dry Density as a percentage of the standard Proctor maximum dry density):
- Cover Soil – 82.0 to 85.8%
- Sand Tailings – 79.3 to 82.6%
- Transition Tailings – 78.8 to 94.6%
- Slimes Tailings – 39.3 to 84.9%

All test results are summarized on Table 2. The bench scale test data sheets are included in Attachment 1.

TABLES

TABLE 1
SAMPLE SELECTION MIX SUMMARY

Bench Test Sample No.	Borehole or Test Pit	Depth or Interval	Mixed Description
GABT-01	GATP-05	0-5'	SAND (SP), little silt, trace gravel, fine grained, reddish brown, cover soil
	GATP-11	0-5'	
GABT-02	GATP-08	0-5'	SAND (SP), some silt, poorly graded, yellowish brown, cover soil
	GATP-09	0-5'	
GABT-03	GATP-04	5-10'	SAND (SP), some silt, poorly graded, moist, yellowish brown, sand tailings
		10-15'	
		15-20'	
GABT-04	GATP-08	5-10'	SAND (SP), trace to little silt, trace clay, poorly graded, moist, light brown, sand tailings
		10-15'	
		15-20	
GABT-05	GATP-06	5-10'	Clayey SAND (SC), poorly graded, saturated, reddish brown, transition tailings
		10-15'	
		15-20'	
GABT-06	GATP-09	5-10'	SAND (SP), little to some silt, saturated, reddish brown, sand tailings
		10-15'	
		15-20'	
GABT-07	GATP-05	10-15'	Sandy SILT (ML), moist, reddish brown, transition tailings
	GATP-07	10-15'	
GABT-08	GATP-10	10-15'	Sandy SILT (ML), moist, little to some clay, reddish brown, transition tailings
	GATP-11	10-15'	
GABT-09	700	12-14'	Sandy CLAY (CL), some silt, medium plasticity, grayish brown, moist, transition tailings
		24-26'	
		40-42'	
		42-44'	
		44-46'	
GABT-10	707	6-8'	Sandy CLAY (CL), some silt, medium plasticity, dark gray, wet, transition tailings
		8-10'	
		10-12'	
		12-14'	
		18-20'	
		20-22'	
	713	13.5-15.5'	
GABT-11	703	18-20'	SILT (ML), low plasticity, moist, dark brown, slimes tailings
		33-35'	
		38-40'	
		43-45'	
		58-60'	
		63-65'	
		68-70'	
GABT-12	709	13-15'	Silty CLAY (CL), medium plasticity, moist, grayish brown, slimes tailings
		23-25'	
		28-30'	
		48-50'	
		53-55'	
		63-65'	
GABT-13	700	64-66'	CLAY (CL), low to medium plasticity, moist, grayish brown, slimes tailings
		70-72'	
		78-80'	
		80-82'	
	707	34-36'	
		50-52'	
		52-54'	
GABT-14	708	20-22'	CLAY (CH), high plasticity, moist, dark gray, slimes tailings
		30-32'	
		38-40'	
		44-46'	
		59-60'	
		60-62'	

TABLE 2
BENCH TESTING RESULTS SUMMARY

Bench Test Sample No.	Initial Moisture Content (Taken March 17, 2006)	Maximum Dry Density (pcf)	Optimum Moisture Content	Loose Wet Density (pcf)	Loose Dry Density (pcf)	Settled Wet Density (pcf)	Settled Dry Density (pcf)	Vertical Percent Settlement	Settled Percent Compaction	Comments
GABT-01	6.5%	117.7	11.9%	71.5	66.9	103.3	96.6	30.8%	82.0%	Cover Soil
GABT-02	6.5%	109.2	13.8%	78.7	73.1	100.9	93.7	22.0%	85.8%	Cover Soil
GABT-03	9.4%	106.3	12.7%	63.7	57.7	93.1	84.3	31.5%	79.3%	Sand Tailings
GABT-04	1.1%	103.9	15.6%	66.1	59.3	95.1	85.4	30.5%	82.2%	Sand Tailings
GABT-05	19.9%	113.3	13.1%	103.1	83.9	126.4	102.9	18.4%	90.9%	Transition Tailings
GABT-06	5.9%	107.3	14.6%	66.8	61.7	95.9	88.6	30.3%	82.6%	Sand Tailings
GABT-07	35.4%	107.3	18.4%	72.7	53.2	115.7	84.6	37.1%	78.8%	Transition Tailings
GABT-08	16.5%	112.8	16.0%	71.6	62.7	107.3	93.9	33.3%	83.3%	Transition Tailings
GABT-09	37.0%	102.0	21.1%	71.8	54.7	117.6	89.7	39.0%	87.9%	Transition Tailings
GABT-10	30.7%	107.8	18.7%	82.5	66.2	127.0	102.0	35.1%	94.6%	Transition Tailings
GABT-11	49.4%	96.0	27.8%	58.3	40.6	94.5	65.7	38.3%	68.5%	Slimes Tailings
GABT-12	40.8%	101.6	22.5%	49.0	33.2	58.9	39.9	16.9%	39.3%	Slimes Tailings
GABT-13	37.5%	95.0	28.7%	68.9	48.7	114.2	80.7	39.6%	84.9%	Slimes Tailings
GABT-14	52.3%	101.5	20.9%	93.8	64.3	113.4	77.7	17.3%	76.6%	Slimes Tailings