1988

Technical Report EL-88-18: Reliability of the Federally Owned Water Main System

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ENVIRONMENTAL LABORATORY

TECHNICAL REPORT EL-88-18

RELIABILITY OF THE FEDERALLY OWNED WATER MAIN SYSTEM

by

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November 1988

Final Report

Approved For Public Release; Distribution Unlimited

Prepared for DEPARTMENT OF THE ARMY
US Army Engineer District, Baltimore
Washington Aqueduct Division
Washington, DC 20315-0220

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) Technical Report EL-88-18	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION USAEWES Environmental Laboratory 6b. OFFICE SYMBOL *(If applicable)*	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS *(City, State, and ZIP Code)* PO Box 631 Vicksburg, MS 39181-0631	7b. ADDRESS *(City, State, and ZIP Code)*
8a. NAME OF FUNDING/SPONSORING ORGANIZATION USAED, Baltimore 8b. OFFICE SYMBOL *(If applicable)*	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS *(City, State, and ZIP Code)* Washington Aqueduct Division Washington, DC 20315-0220	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO. / WORK UNIT ACCESSION NO.

11. TITLE *(Include Security Classification)*
Reliability of the Federally Owned Water Main System

12. PERSONAL AUTHOR(S)
Chase, Donald V.; Ormsbee, Lindell E.; Walski, Thomas M.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT *(Year, Month, Day)*	15. PAGE COUNT
Final report	FROM ______ TO ______	November 1988	173

16. SUPPLEMENTARY NOTATION Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

17. COSATI CODES			18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*
FIELD	GROUP	SUB-GROUP	Fire demand; Main break; Reliability; Water distribution; Water supply

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

This report assesses the reliability of the existing Federally Owned Water Main (FOWM) system with a special emphasis on possible long-term outages. A mathematical model of the system was created using information supplied by Washington Aqueduct Division and Arlington County officials. The model was calibrated using fire hydrant flow test results. The response of the system to different pipe outages under different loading conditions was then examined using the computer model.

Several alternatives for improving the reliability of the FOWM system were investigated. These alternatives include new river crossings between FOWM and Washington, DC, new pipeline construction within the FOWM system, a new storage tank, new interconnections between FOWM and an adjacent distribution system, and the use of existing interconnections between FOWM and Arlington County. Hydraulic, engineering, and economic analysis of each

(Continued)

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE *(Include Area Code)* / 22c. OFFICE SYMBOL

19. ABSTRACT (Continued).

alternative were performed. The impact of the new and existing interconnections on the extended performance of both systems was also investigated. Recommendations to improve FOWM system reliability based on the hydraulic, engineering, and economic analyses are given.

SUMMARY

The reliability of the Federally Owned Water Main (FOWM) system was examined, and recommendations to improve system reliability are made. The existing FOWM system is very dependent upon three different pipe links. The first and most important link is the Francis Scott Key Bridge river crossing. This link carries the entire FOWM supply, and if taken out of service, an alternate means of supply must be used. At present, the only alternate source of supply is through interconnections with the adjacent Arlington County, Virginia, system.

The second vital link is the 30-in. steel main which extends from the Key Bridge river crossing to the Pentagon. This line carries approximately 83 percent of the total delivery to the FOWM system. If taken out of service, all flow in the FOWM system would have to be routed through the 16-in. main along George Washington Parkway and Eisenhower Drive. During periods of high water use, flow in this 16-in. line would cause excessive friction losses. As a result, adequate system pressures cannot be maintained, and system demands cannot be fully met.

The final critical pipe link is the feed to National Airport. This link consists of a 24-in. pipe and a 16-in. pipe connected in series. At present, this is the only source of water for National Airport. If this line were taken out of service, an alternate source of supply must be found. Furthermore, the available fire flow to the airport through this line during maximum daily demands falls below Insurance Services Office requirements.

Several system improvements were evaluated to determine their contribution to the overall reliability of the FOWM system. System improvements consisted of operating existing and new interconnections, constructing new river crossings, installing a new storage tank, new line construction, and combinations of the above. System improvements were evaluated and ranked based on hydraulic performance, engineering impact, and total cost.

The tabulation on page 3 shows a ranking of the proposed system improvements. Although it is the most costly, the reliability of the FOWM system can be greatly increased by constructing a new river crossing across the 14th Street Bridge and installing a new line from the Pentagon to Washington National Airport. Implementing these improvements will double the redundancy of the system and allow the FOWM system to "stand alone" and not rely on

adjacent systems for proper operation during emergencies. Furthermore, if this combined alternative is connected to the Arlington County Third Gravity pressure zone, significant energy savings plus an increase in Arlington County reliability could be realized.

In addition to the recommendation made above, two other projects should be seriously considered. The 16-in. pipe loop around the Pentagon is disconnected around the eastern face of the building. This line should be repaired or replaced so that the loop around the Pentagon is complete. Also, an 8-in. National Airport interconnection should be repaired or replaced to provide the airport with at least two sources of supply.

Recommendations to Improve FOWM Reliability

Rank	Alternative	Hydraulic Performance*	Engineering Impact**	Total Capital Costs (thousands of dollars)
1	14th Street Bridge River Crossing and New Airport Feed	E	14	13,331
2	Booster Pump Off Low Service and New Airport Feed	VG	15	10,979†
3	14th Street Bridge River Crossing only	VG	8	10,990
4	New Airport Feed only	VG	6	2,341
5	Booster Pump Off Low Service only	G-VG	9	8,638†
6	Roosevelt Bridge River Crossing and paralleling 30-in. main	G-VG	14	11,191
7	Roosevelt Bridge River Crossing	G	8	9,750
8	Paralleling 30-in. Main	G	6	1,441
9	Subaqueous River Crossing	G	10	8,948
10	Existing Interconnections	P	10	0

* E = excellent
VG = very good
G = good
F = fair
P = poor
** See Table 10.
† Does not include O&M costs.

PREFACE

This report describes a study conducted by the US Army Engineer Waterways Experiment Station (WES) for the US Army Engineer District (USAED), Baltimore, Washington Aqueduct Division (WAD).

The work was conducted at the WES, and the University of Kentucky (UK) Civil Engineering Department. The report was written by Mr. Donald V. Chase, Water Resources Engineering Group (WREG), Environmental Engineering Division (EED), Environmental Laboratory (EL), WES; Dr. Lindell E. Ormsbee, Assistant Professor of civil engineering at UK working with WES under an Intergovernmental Personnel Act agreement; and Dr. Thomas M. Walski, Research Civil Engineer, WREG. At the time this study was performed, Mr. Chase was a graduate student at UK. Mr. Wayne W. Sharp of the WREG assisted in the field data collection. The report was edited by Mr. Bobby Odom, assigned to the Information Technology Laboratory under the Intergovernmental Personnel Act.

Work done for WAD of the USAED, Baltimore, was performed under the purview of Mr. Harry C. Ways, Chief, WAD; Mr. Perry Costas, Assistant Chief, WAD; and Mr. Pete Peterson, Chief, Engineering Branch, WAD. The report was reviewed by Drs. Paul Schroeder and Douglas Shields, WREG. The study was conducted under the supervision of Dr. Schroeder, Acting Chief, WREG; Dr. Raymond L. Montgomery, Chief, EED; and Dr. John Harrison, Chief, EL.

COL Dwayne G. Lee, EN, is Commander and Director of WES. Dr. Robert W. Whalin is Technical Director.

This report should be cited as follows:

Chase, Donald V., Ormsbee, Lindell E., and Walski, Thomas M. 1988. "Reliability of the Federally Owned Water Main System," Technical Report EL-88-18, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC)
UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
feet	0.3048	metres
gallons (US liquid)	3.785412	cubic decimetres
horsepower (550 foot-pounds (force) per second)	745.6999	watts
inches	2.54	centimetres
miles (US statute)	1.609347	kilometres
pounds (force) per square inch	6.894757	kilopascals

RELIABILITY FOR THE FEDERALLY OWNED WATER MAIN SYSTEM

PART I: INTRODUCTION

Background

1. The Federally Owned Water Main (FOWM) distribution system serves Federal facilities in the northern section of Arlington County, Virginia. Among the facilities served by the system are the Pentagon, Washington National Airport, the Navy Annex, Arlington National Cemetery, Fort Myer, and the Pentagon heating plant. The FOWM system is operated and maintained by the Washington Aqueduct Division (WAD) of the US Army Engineer District, Baltimore.

2. The FOWM system is supplied from the Washington, DC, water distribution system via two water mains. The two lines, a 30-in.* line and a 16-in. line, cross the Potomac River at Key Bridge. Failure of one of these mains recently raised concern for the reliability of the overall system. In case of an emergency, the FOWM system can be served through interconnections with the Arlington County, Virginia, water system. However, the operational impact of such an arrangement on the FOWM and Arlington County systems has not been fully investigated.

3. The condition of the FOWM system has been addressed in a previous study "Analysis of Federally Owned Water Main System" (Walski 1984). This study analyzed the system in terms of pipe outage and evaluated the pressures and flows in the FOWM system for several emergency conditions. Due to their condition, several lines were determined to be very susceptible to breakage. Furthermore, in the event of a failure of the 30-in. supply line, the fire-fighting capacity of the system could not be maintained without opening one or more connections with the Arlington County system. The impact of the operation of these interconnections on the extended performance of both systems was not investigated in the previous study.

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* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 7.

Purpose

4. The purpose of this report was to evaluate the reliability of the existing FOWM system with a special emphasis on possible long-term outages. Several alternatives for improving the system reliability were investigated. These alternatives include new pipeline construction within the FOWM system, new river crossings between FOWM and the Washington, DC, system, a new storage tank, new interconnections between FOWM and Arlington County, and the use of existing interconnections. Hydraulic, economic, and environmental analyses of each alternative were performed. The operational impact of the new and existing interconnections on the extended performance of both the FOWM and Arlington systems was also evaluated.

Overview

5. A mathematical model of the FOWM system and neighboring Arlington County system was constructed using information supplied by Washington Aqueduct and Arlington County officials. The model was calibrated using data gathered during fire hydrant flow tests on each of the systems. Calibration was accomplished by adjusting pipe roughness and water usage within prescribed boundaries until predicted heads matched those observed in the field.

6. The performance of the existing FOWM system was evaluated under a series of loading conditions. Loadings included average daily demand, maximum daily demand, peak hourly demand, and fire demands. The existing system was then evaluated under the same loading conditions for several pipe outages. This identified key mains which when placed out of service would adversely affect the performance of the FOWM system.

7. Several alternatives designed to improve the performance of the FOWM system were evaluated under the same loading conditions and pipe outages as the existing system. The evaluation consisted of a hydraulic and engineering assessment as well as an economic assessment. Recommendations designed to improve the reliability of the FOWM system were made based on the results of the hydraulic, engineering, and economic evaluations.

PART II: STUDY AREA

Washington, DC, System

8. The WAD of the Corps of Engineers (CE) has the responsibility of securing, treating, and supplying water to Washington, DC (hereafter referred to as DC). This is accomplished through the use of two water treatment plants (Dalecarlia and McMillan), both of which receive their raw water from the Potomac River. In addition to supplying water to DC, the Washington Aqueduct also supplies water to the FOWM system, Arlington County and Falls Church, Virginia.

9. Distribution of finished water to consumers in DC and areas east of the Anacostic River is the primary responsibility of the Water and Sewer Utility Administration (WSUA) of the DC Department of Public Works. Pumping of the finished water is the responsibility of both the WAD of the CE and WSUA. The major pumping stations of the system are the Dalecarlia Pump Station (CE) and the Bryant Street Pump Station (WSUA).

10. Ground elevations in DC and vicinity vary from <7 ft to 420 ft mean sea level (MSL). To provide average water pressure of about 50 psi over this altitude range, the city is divided into seven pressure zones: (a) Low, (b) First High, (c) Second High, (d) Third High, (e) Fourth High, (f) Anacostia First High, and (g) Anacostia Second High. Each pressure zone comprises a certain range of ground elevations. The pressure in each of these service areas is controlled to maintain a range of 40 to 80 psi, depending upon whether a given location is near the upper or lower boundary of the service area. A schematic of the DC service area is shown in Figure 1.

FOWM System

11. The FOWM system is supplied from the First High pressure zone of the DC distribution system. FOWM is connected to the DC system via a 30-in. and a 16-in. transmission main suspended beneath the Francis Scott Key Bridge (hereafter called Key Bridge). This is the only direct link between the FOWM system and the DC system. In the event of an emergency, FOWM must be supplied from the Arlington County distribution system through a series of emergency interconnections.

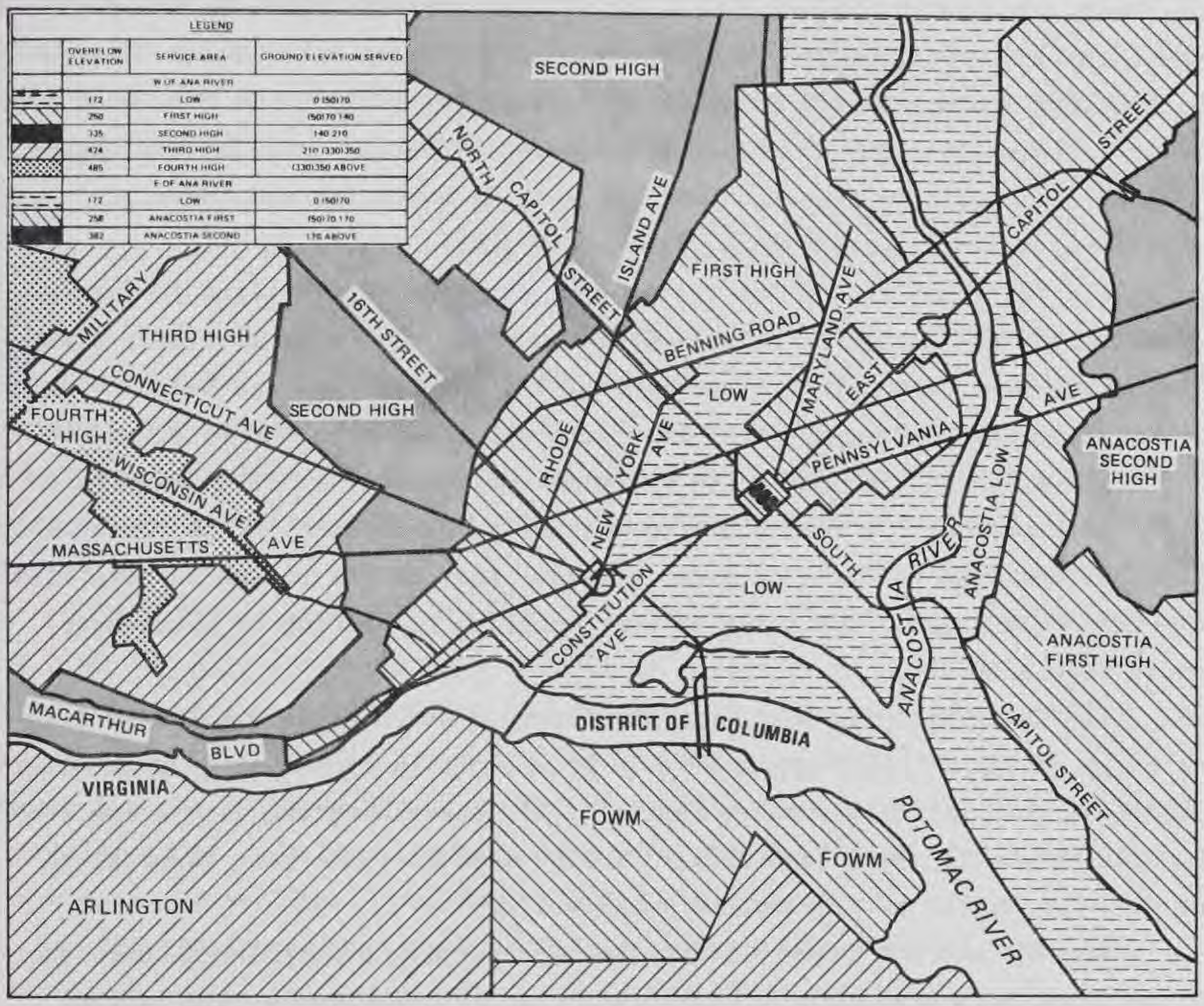


Figure 1. Map of Washington, DC, service area

12. The FOWM transmission and distribution system contains approximately 25 miles of water main. Pipe sizes range from 1.25 to 30 in. Nearly all of this length was laid in the late 1930's and early 1940's when the Pentagon and Washington National Airport were constructed. As a result, most of the lines in the FOWM system are unlined cast iron with an average age of 40 to 50 years.

13. As part of the previous study on the system (Walski 1984), most of the mains in the FOWM system were found to be in generally good condition. However, several mains were identified as having high breakage rates and requiring some type of corrective action. The first of these mains is the 16-in. Pentagon loop which runs from the 30-in. steel line in the Pentagon

north parking mall, along the north, east, and south faces of the Pentagon to the 24-in. pipe at the southwest corner of the building. Most of the problems with this line are corrosion-related. The area between the Potomac River and the Pentagon was originally marshland. Fill has been placed in this area to provide a foundation for buildings and roadways. Previous soils investigations in the area have revealed that the soil is corrosive and therefore aggressive to the uncoated 16-in. line (Page 1983).

14. The condition of the 16-in. line circling the Pentagon is further aggravated by the fact that a portion of this line is not in service. A section of the line along the eastern face of the Pentagon was crushed, and as a result, approximately 1,100 ft of this loop has been taken out of service.

15. A second pipeline found to be in questionable condition is the 24-in. main west of the Pentagon from the 30-in. steel main in the Pentagon north parking mall to 15th and Eads Streets. Most of the breaks in this line were lead joint leaks attributed to poor jointing or bedding or inadequate thrust restraint.

16. The 6-in. pipe supplying the Pentagon heating plant was also identified as having a large number of main breaks. This line runs from an interconnection with Arlington County east of I-95, underneath the interstate, to the heating plant. Road construction in the area may have been responsible for the high number of pipe breaks in this line.

17. The previous report identified a potential problem area where the 30-in. steel main lies close to the Metro tracks. Frequently such systems have stray d-c current which can cause serious corrosion problems. The 30-in. main is vital to normal operation of the FOWM system, and corrosion to the line could result in this link being placed out of service.

18. Storage for the FOWM system is provided by the Foxhall Reservoir, a 14.5-MG underground facility, and Soldiers Home Reservoir, a 15-MG storage facility. Since Foxhall Reservoir is three times closer to the FOWM system than the Soldiers Home facility, the Foxhall Reservoir is the controlling tank for the FOWM system. However, there is no storage south of the Potomac River within FOWM itself.

19. In the event of an emergency, FOWM can be fed from Arlington County, Virginia, through a series of emergency interconnections. There are seven existing interconnections between the FOWM and the Arlington County systems. These interconnections can be used to help supply water from one system

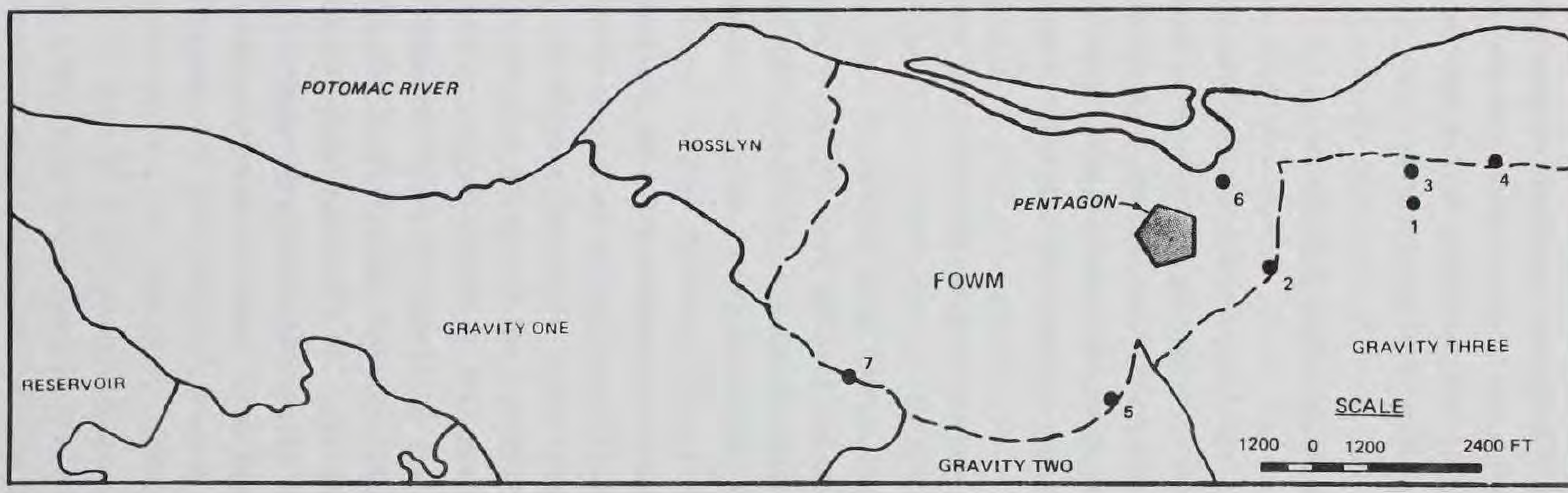
to the other in the event of a major line failure or large fire. The locations of the interconnections and the connecting pressure zones are shown in Figure 2. Note that the FOWM system and Gravity Three pressure zones have the same operating grades and elevations and therefore do not require pressure reducing values (PRV's) as part of the interconnections.

Arlington County System

20. Arlington County is served from the Dalecarlia Pump Station via a 24-in. and a 36-in. transmission main extending from the pump station to Chain Bridge. The bridge crossing consists of a manifold on both sides of the Potomac River with three 20-in. mains suspended from beneath the bridge. A 48-in. line in the immediate vicinity crosses underneath the river parallel to the bridge.

21. The Arlington County transmission and distribution system consists of over 430 miles of water main ranging in size from 4 to 36 in. Approximately 16 percent of the mileage is composed of 12-in. and larger mains. The majority of the lines in Arlington County have been installed since 1927 with major periods of expansion occurring during the 1940's and 1960's. Pipe material is either cast iron, ductile iron with cement lining, or concrete pressure pipe. Most lines laid prior to 1960 are cast iron.

22. At present Arlington County has seven separate pressure zones: (a) Gravity One, (b) Gravity Two, (c) Gravity Three, (d) Reservoir, (e) Lee-Minor Hill, (f) Rosslyn, and (g) Willston. A map of the county is provided in Figure 3. Since elevations in Reservoir and Lee-Minor Hill are greater than those in Gravity One, pumping is required from Gravity One to Reservoir and from Gravity One to Lee-Minor Hill. Water must flow through PRV's from Gravity One to Gravity Two, Rosslyn, and Gravity Three since Gravity One is at a higher elevation than the other zones. The PRV's have been placed in the major transmission lines in order to separate the system into various pressure zones. As shown in Figure 3, the Gravity One, Gravity Two, Gravity Three, and Rosslyn pressure zones provide a boundary between the Arlington County and FOWM water distribution systems.



FOWM/ARLINGTON COUNTY INTERCONNECTIONS

(1) 15th AND EADS INTERCONNECTION
(2) FERN STREET INTERCONNECTION
(3) CRYSTAL CITY INTERCONNECTION 1
(4) CRYSTAL CITY INTERCONNECTION 2
(5) NAVY ANNEX INTERCONNECTION
(6) PENTAGON HEATING PLANT INTERCONNECTION
(7) FORT MYER INTERCONNECTION

LEGEND

● EXISTING FOWM/ARLINGTON COUNTY INTERCONNECTION

– – FOWM AND ARLINGTON BOUNDARY

— ARLINGTON PRESSURE ZONE BOUNDARY

Figure 2. Location of existing FOWM/Arlington County interconnections

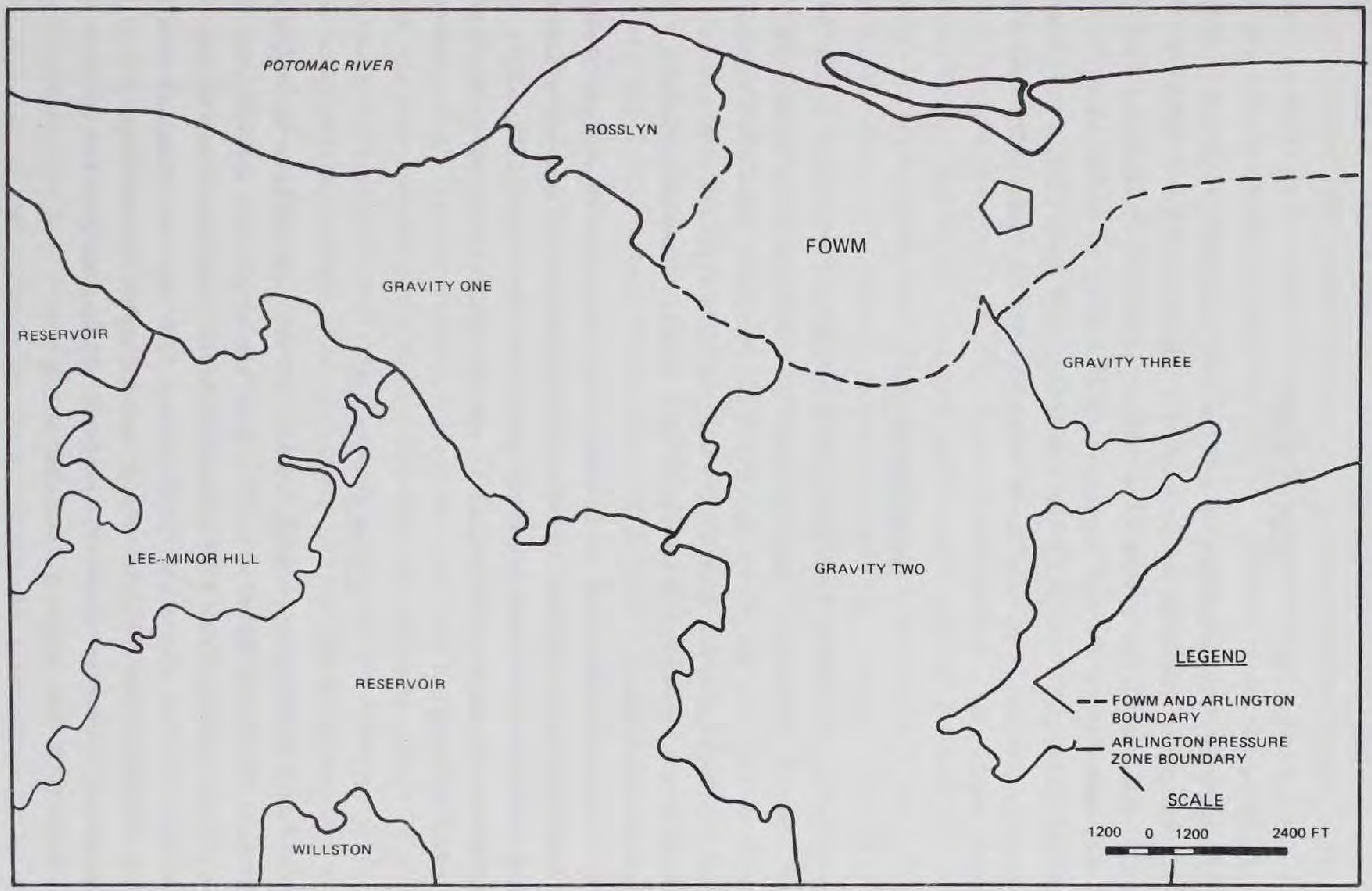


Figure 3. Map of Arlington County pressure zones

PART III: DEVELOPMENT OF THE COMPUTER MODEL

Computer Model

23. Analyzing the operation of a water distribution system under both normal and emergency operating conditions is a complex problem. Directly testing the response of the system to a component failure by shutting down part of the system would disrupt service. As a result, it is necessary to simulate such activities with a computer program. For this study, the FOWM water distribution system was evaluated using the KYPIPE (Wood 1980) computer simulation program.

System Schematic

24. Before the computer program can be applied, a schematic of the network must first be developed. The schematic is a diagram which illustrates the network through the use of circles and line segments. Each line segment corresponds to an individual pipe in the distribution system. Each circle corresponds to the intersection of two or more pipes. These intersection points are called nodes.

25. In computer modeling it is usually not necessary to include every pipe in the distribution system. Instead, it is possible to analyze a skeletal system which includes only the major mains but still produces accurate results because the mains not included in the skeletonized system do not carry a great deal of flow.

System Description

26. Before a computer program, such as KYPIPE, can be used to simulate a distribution system, a decision must be made concerning the scope of the modeling effort. Because the FOWM system is served from the DC system and since several existing interconnections between FOWM and the Arlington County system are available for use, both the DC and Arlington systems were included in the analysis. Descriptions of the skeletal systems derived for each of the major components of the study are provided below.

FOWM system

27. The FOWM system is supplied from the DC First High pressure zone. Water is delivered to users in the FOWM system through a 30-in. main and a 16-in. main suspended beneath Key Bridge. The two lines run parallel to each other from Key Bridge along the George Washington Memorial Parkway to the George Washington Parkway and US Highway 66 interchange. Here, the lines turn southwest a short distance to a point just north of Jefferson Davis Highway and Marshall Drive. At this location, the two lines diverge with the 30-in. steel line paralleling Jefferson Davis Highway to the Pentagon, and the 16-in. pipe paralleling Eisenhower Drive to the Navy Annex.

28. At the Pentagon, the 30-in. line branches into a 16-in. line and a 24-in. line. The 16-in. line runs north, east, and south around the Pentagon while the 24-in. pipe runs along the western face of the building. At the northwest corner of the Pentagon south parking lot, the two mains join to complete the loop around the Pentagon. At present, however, the loop is not closed since a segment of the 16-in. main along the eastern face of the building was crushed and taken out of service.

29. The 16-in. transmission main runs parallel to Eisenhower Drive up to a point between Patton Drive and Columbia Pike. At this location, the 16-in. line branches to a 10-in. pipe, which feeds the Navy Annex and Henderson Hall, and a 12-in. line. The 12-in. line runs parallel to I-95 a short distance to the southwest corner of the Pentagon south parking lot.

30. At this corner, an 18-in. pipeline connects the Pentagon loop and the 12-in. line from the Navy Annex. This line runs along the western boundary of the Pentagon south parking lot. At this point, the 12-in. line from the Navy Annex and the 18-in. line from the Pentagon join to a single 24-in. line which runs from the southwest corner of the Pentagon south parking lot to an interconnection with Arlington County at 15th and Eads Streets. A single 16-in. pipe runs from the 15th and Eads interconnection to Washington National Airport. At present the 24- and 16-in. lines form the only feed for the airport. A schematic of the FOWM system is shown in Figure 4.

Arlington system

31. Arlington County is supplied from the DC Third High pressure zone through the Chain Bridge river crossing. The river crossing consists of three 20-in. mains suspended beneath the bridge and a 48-in. subaqueous main crossing parallel to the bridge. The 48-in. subaqueous river crossing failed in

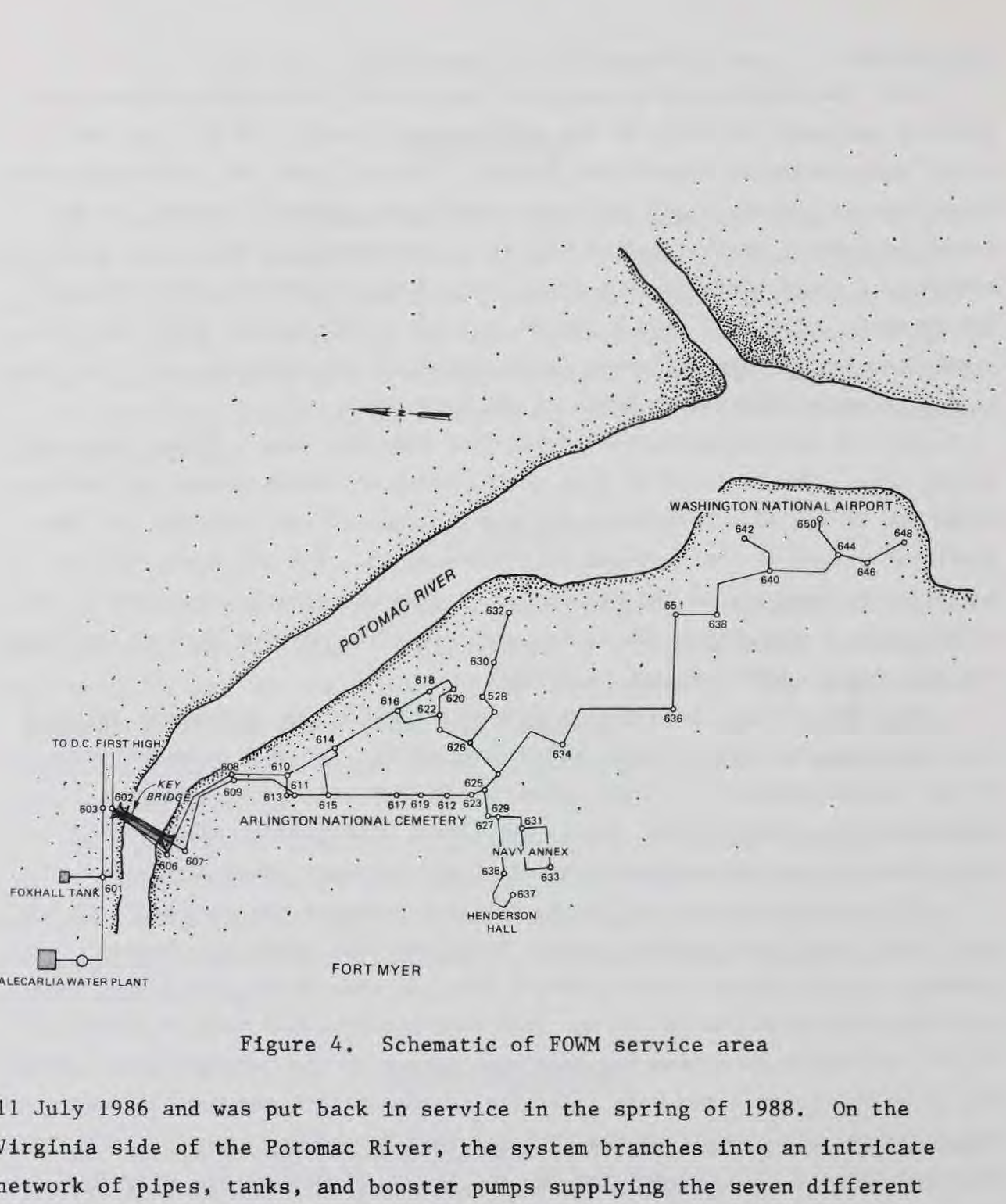


Figure 4. Schematic of FOWM service area

11 July 1986 and was put back in service in the spring of 1988. On the Virginia side of the Potomac River, the system branches into an intricate network of pipes, tanks, and booster pumps supplying the seven different pressure zones in Arlington County.

32. Because existing or potential interconnections with FOWM exist in four of the pressure zones, each of these zones was also included in the analysis. These zones include First Gravity, Second Gravity, Third Gravity, and Rosslyn. Since the Reservoir, Minor Hill, and Willston pressure zones do not directly impact the FOWM system, the demands for these systems were treated as

single demands in the First Gravity pressure zone. The schematic of the Arlington system is shown in Figure 5. Only the junction nodes of special interest are highlighted in the schematic.

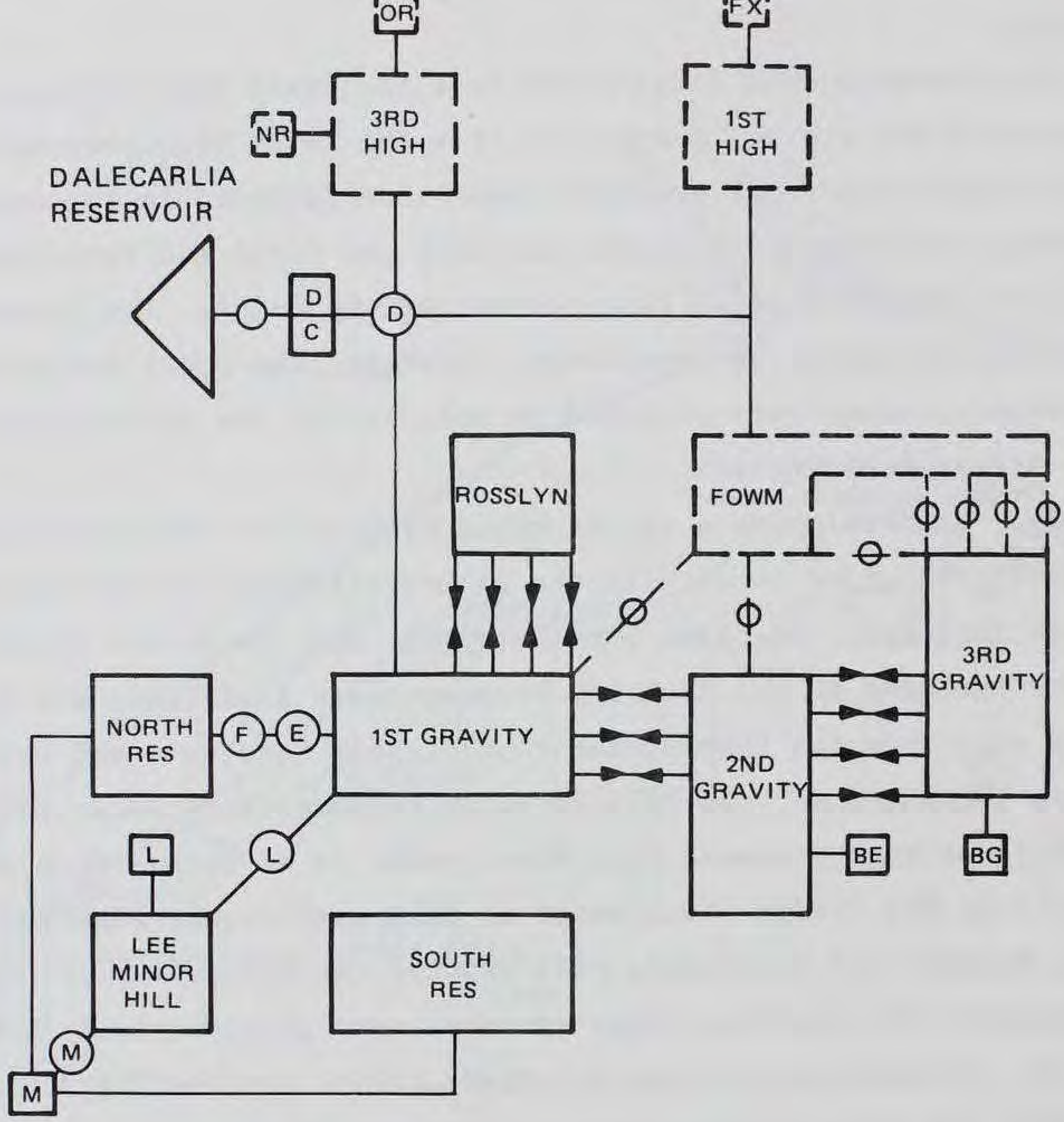
DC system

33. Because FOWM is supplied from the First High pressure zone and the Arlington County system is supplied from the Third High pressure zone, both the First and Third High pressure zones were included in the analysis. In developing skeletonized networks for both the First and Third High pressure zones, only the Dalecarlia Pump Station was included. The Bryant Street Pump Station was not directly considered. Instead, the total system demands for both pressure zones were adjusted to account for the contribution of the Bryant Street Pump Station.

34. In developing a skeletonized network for the First High pressure zone, only the pipes connecting the Dalecarlia Pump Station with the FOWM system were included. Soldiers Home Reservoir and the Bryant Street Pump Station were not included in the analysis because these facilities are three times further away from the FOWM system than Foxhall Reservoir and Dalecarlia Pump Station. Furthermore, the only location between the Dalecarlia Pump Station and the First High pressure zone where water is withdrawn from the First High system is at Key Bridge where water is delivered to the FOWM system. As a result, Foxhall and Dalecarlia will control the hydraulics of the FOWM system. The schematic for the First High pressure zone is shown in Figure 6.

35. In developing a skeletonized network for the Third High pressure zone, only the pipes influencing the Arlington County system were considered. This included the lines from the Dalecarlia Pump Station to the Arlington system and the lines from the Dalecarlia Pump Station to the Third High Reservoir. The schematic for the Third High pressure zone is shown in Figure 7.

36. One potential alternative to improve FOWM system reliability is to construct a booster pump station from the DC Low pressure zone to the FOWM system. Water would be carried from the Low service area, across the Potomac River, to the FOWM system. This requires that the DC Low pressure zone be included in the analysis as well. Unlike the First and Third High pressure zones, both the Dalecarlia and Bryant Street Pump Stations will be included in the skeletonalized network since the proposed booster pump station is located midway between the two pump stations. The schematic for the Low service pressure zone is shown in Figure 8.



LEGEND

PRESSURE REGULATING VALVE
○ – PUMP STATION
D – DALECARLIA
E – ETHAN ALLEN
F – LITTLE FALLS
M – MINOR HILL
L – LEE

– INTERCONNECTION
□ – RESERVOIR
OR – OLD RENO
NR – NEW RENO
L – LEE
M – MINOR HILL
BE – BARNARD ELEVATED
BG – BARNARD GROUND

Figure 5. Schematic of Arlington County system

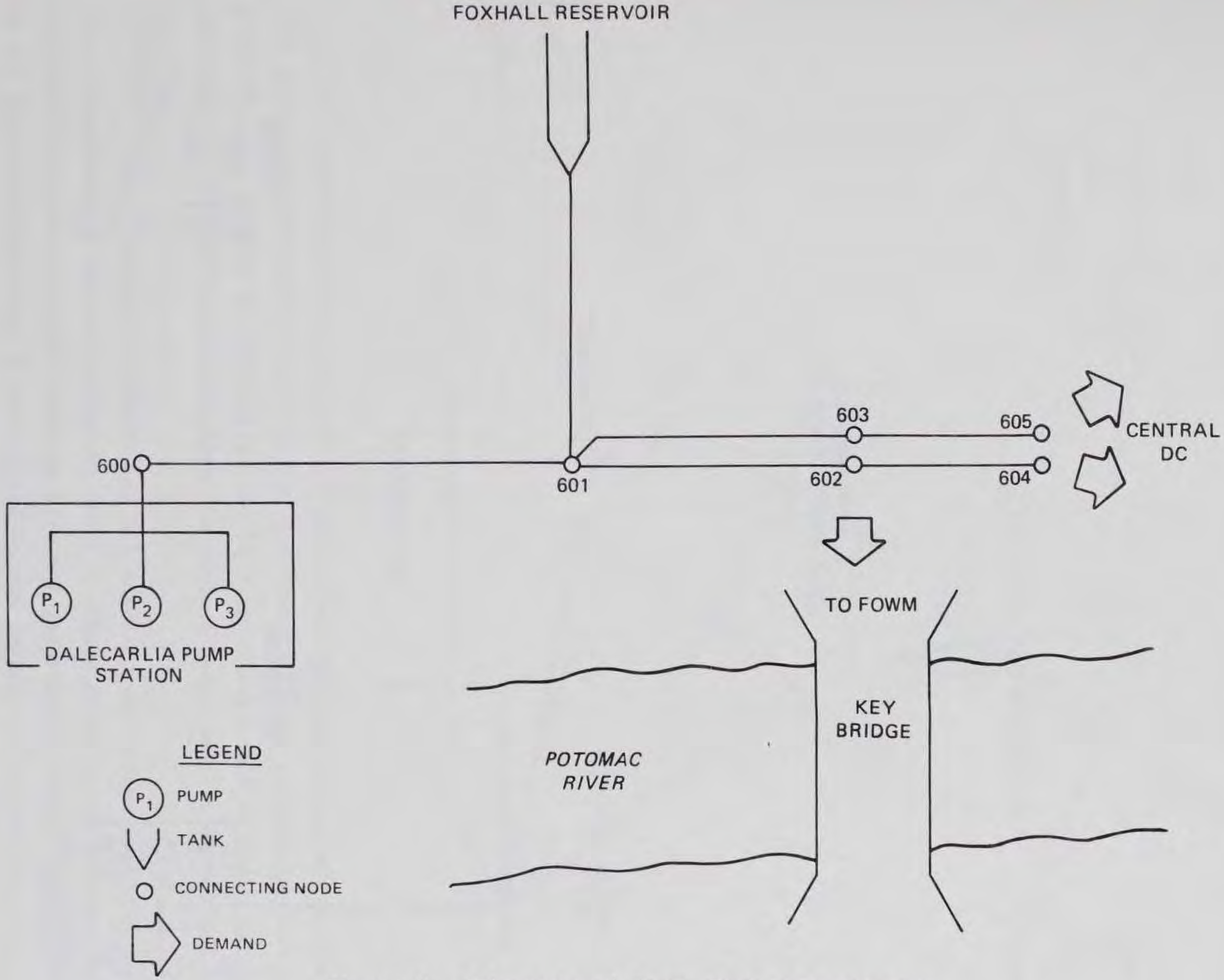


Figure 6. Schematic of First High pressure zone

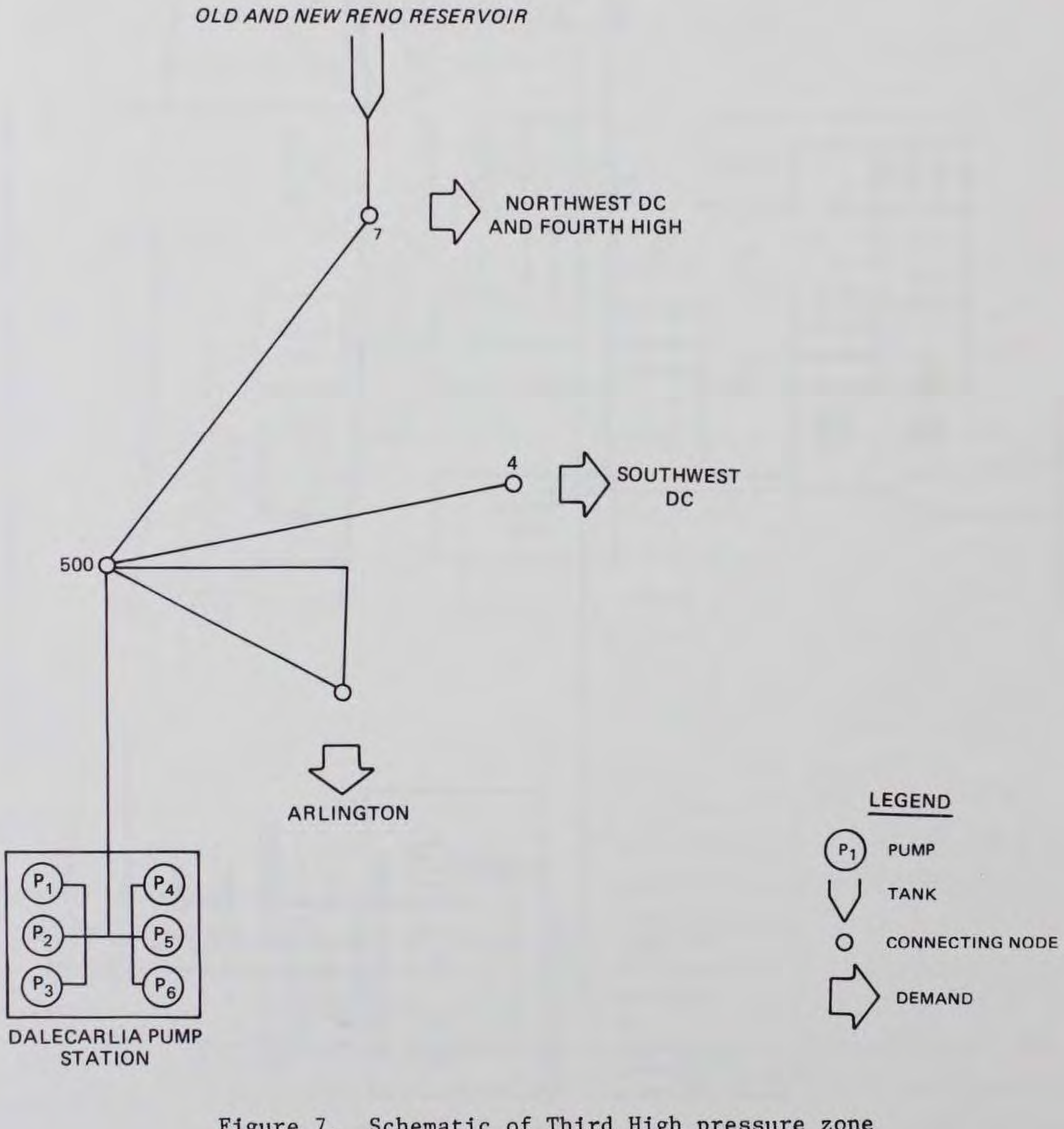


Figure 7. Schematic of Third High pressure zone

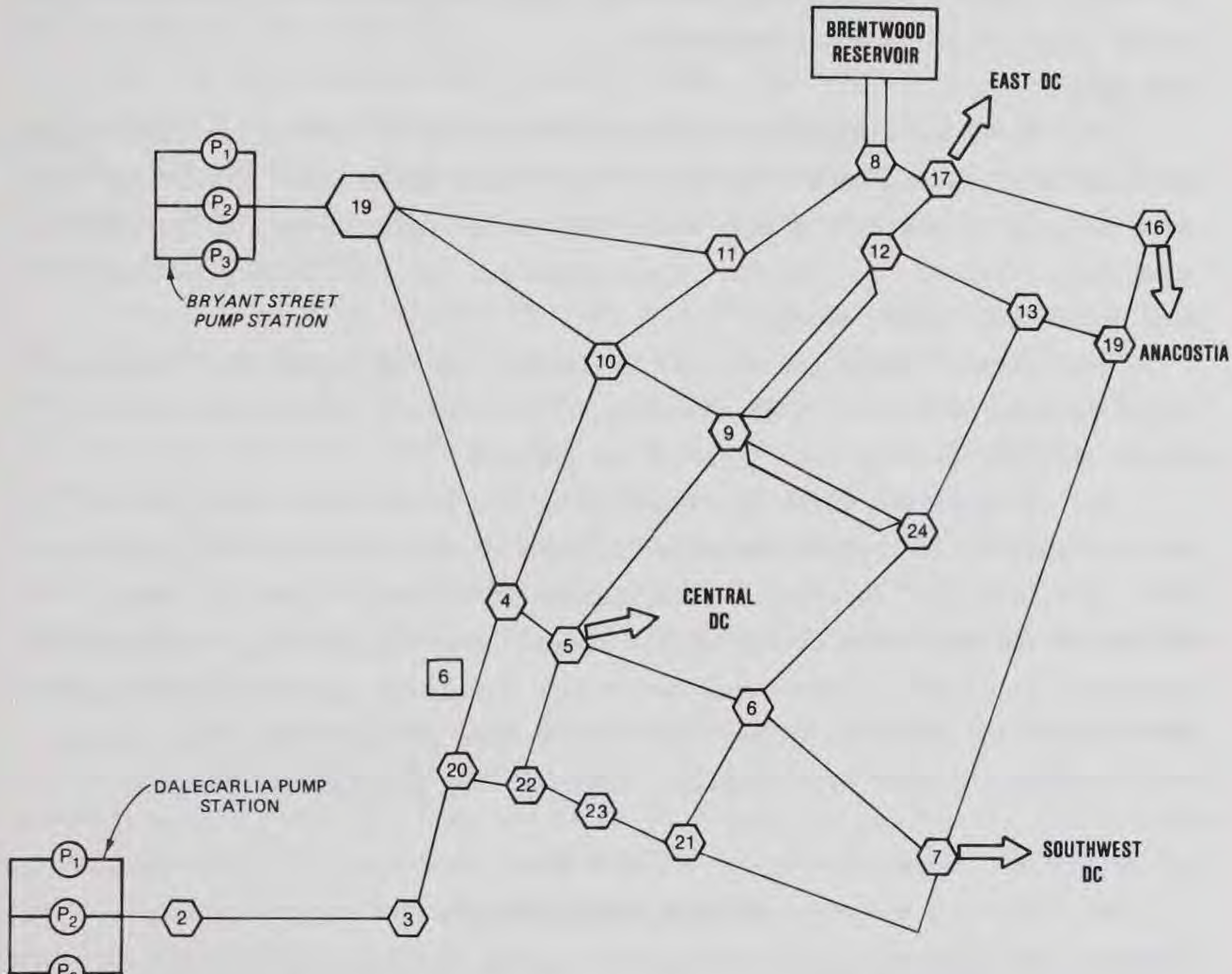


Figure 8. Schematic of Low service area

Network Data

37. Once a network schematic of the system has been developed, a data base must be established. The required data base includes information on each pipe and node as well as information on all pumps, tanks, and valves. In addition, the demands associated with the various nodes must be determined.

Pipe data

38. Maps showing the location of all mains in the system were obtained from officials with WAD and Arlington County. Those pipes to be included in the model were then selected based on size and importance. Nodes were placed at all locations where two or more pipes joined together. Lengths between nodes were scaled off the maps and recorded. Roughness values were determined

by field tests and calibration analysis. The complete set of pipe data used in the analysis is shown in Appendix A.

Node data

39. Nodes were placed at locations where two or more mains join together. Junction data requirements included elevation and water use. Elevations for nodes located in the FOWM system were found from field surveys or determined using maps obtained from the CE. Elevations for nodes in Arlington County were found from field surveys.

40. Water consumption for the study area was estimated from historical operating records for the 1985 fiscal year. A summary of the average daily demand for each service area is shown in Table 1.

41. In reality, water is withdrawn from a particular water main at various service connections which are located along the entire length of the pipe. However, when modeling a distribution system on a computer, these demands are concentrated at individual nodes. The demands along the pipe are aggregated at certain nodes which are in the immediate vicinity of the water withdrawal. For example, water used at Fort Myer is withdrawn from various points within the Fort Myer complex. However, for purposes of computer

Table 1

Average Daily Demands

Service Area	Average Demand, mgd
Low (including Anacostia)	72.5
First High (including FOWM)	38.7
Second High (including Falls Church)	39.8
Third High (including Fourth High and Arlington)	64.6
Total	215.6
FOWM	3.2
Arlington	23.3
Falls Church	16.0
Remainder of Washington, DC	173.1
Total	215.6

analysis, the entire Fort Myer water demand is placed at one node located at the entrance of the facility.

42. In modeling the distribution system, the average daily demand for each service area was distributed among several nodes in each particular system. The selection of the demand nodes and the amount of water distributed to each node were based on an evaluation of the major users in each service area as described below.

43. For the FOWM system, demands were placed at nodes corresponding to the locations of the following major users: (a) the Pentagon, (b) the Pentagon heating plant, (c) the Navy Annex, (d) Henderson Hall, (e) Fort Myer, (f) Arlington National Cemetery, and (g) National Airport. The demands and nodes associated with each of these locations are shown in Appendix A.

44. Water use for the Arlington system was placed at nodes corresponding to the intersections of large mains or in areas of high building concentration such as Crystal City. The junction data for the Arlington system are shown in Appendix A.

45. For demands within the DC Low, First High, and Third High pressure zones, all water withdrawal was concentrated at several nodes in each network schematic. For the First High and Third High pressure zones, the distribution of demands within the pressure zones was not considered since FOWM and Arlington County are located between Dalecarlia Pump Station and the major water users in First High and Third High. As a result, only the magnitude of water used, not the distribution of water, in First High and Third High will affect the hydraulics of the system. On the other hand, the distribution of water usage in the Low service area is considered since the proposed FOWM load will be located on the boundary of the service area, midway between the two pump stations. The node data associated with each pressure zone are shown in Appendix A.

Pump data

46. For this study, only the Dalecarlia pumps supplying the DC First and Third High pressure zones were included in the analysis. For the Low service zone, both pump stations were included in the analysis. The remaining pressure zones, however, were not included since they do not supply either the FOWM or Arlington County systems or are not included as part of a reliability-improving alternative.

47. Three 500-hp pumps at the Dalecarlia Pump Station and three 325-hp

pumps at the Bryant Street Pump Station supply the DC Low service area. At the Dalecarlia facility, three 1,000-hp pumps supply the First High zone while six 1,590-hp pumps supply the Third High zone. Since all demands in FOWM and Arlington County are supplied by the Dalecarlia Pump Station, the First High and Third High pumps at the Bryant Street facility were not considered. The characteristic curves for the three sets of pumps are shown in Figures 9-11.

Tank data

48. Six different tanks were included in the computer analysis: Brentwood Reservoir in the Low service area, Foxhall tank in the First High pressure zone, the old and new Reno tanks in the Third High pressure zone, and the two tanks at Fort Barnard in Arlington. One of the tanks at Fort Barnard serves the Third Gravity pressure zone while the other tank serves the Second Gravity pressure zone. A description of each tank is provided in Table 2.

PRV data

49. The Arlington County system contains 11 PRV's. Three valves are used to separate First Gravity from Second Gravity and four valves are used to separate First Gravity from Rosslyn. The remaining four valves are used to

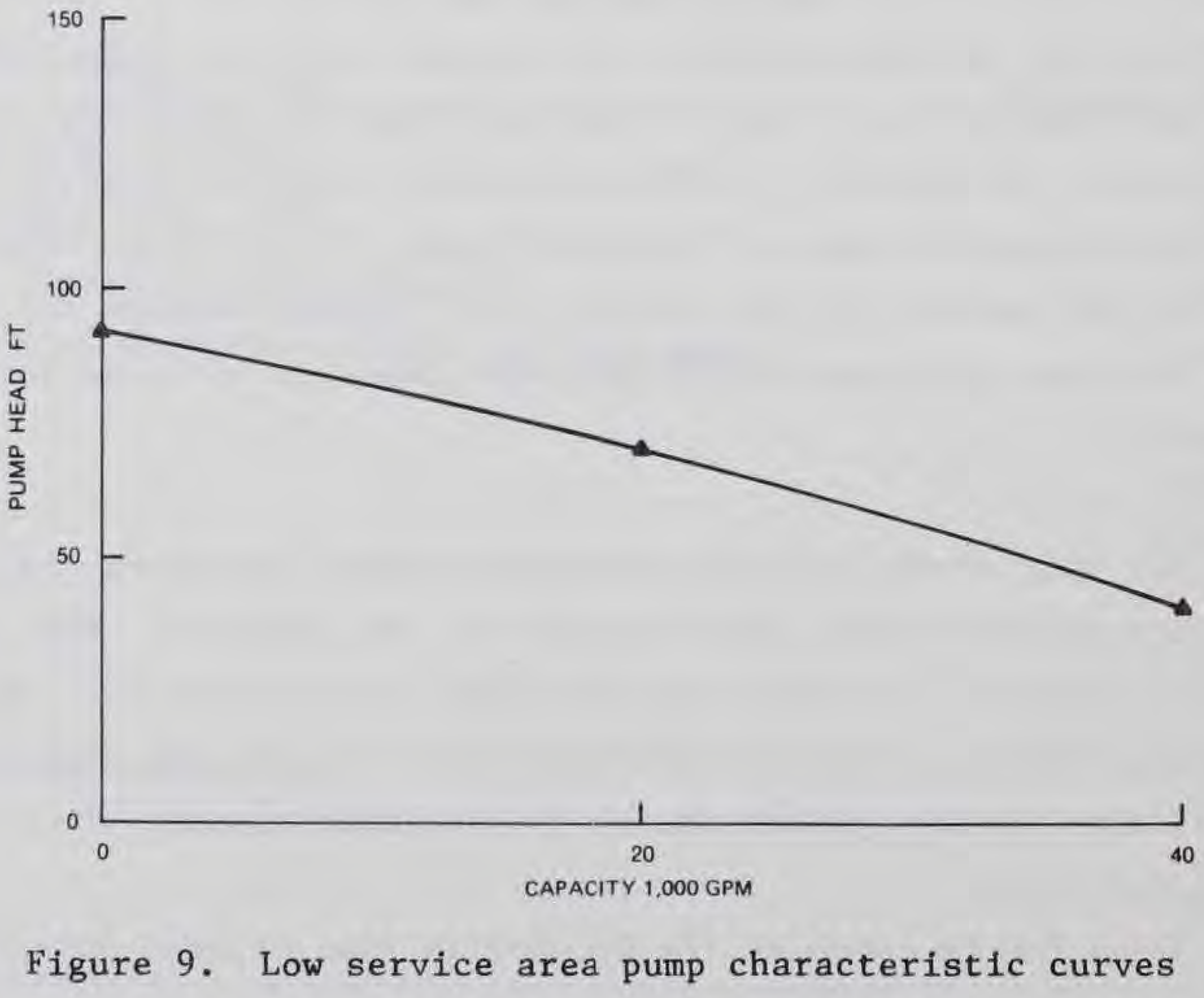


Figure 9. Low service area pump characteristic curves

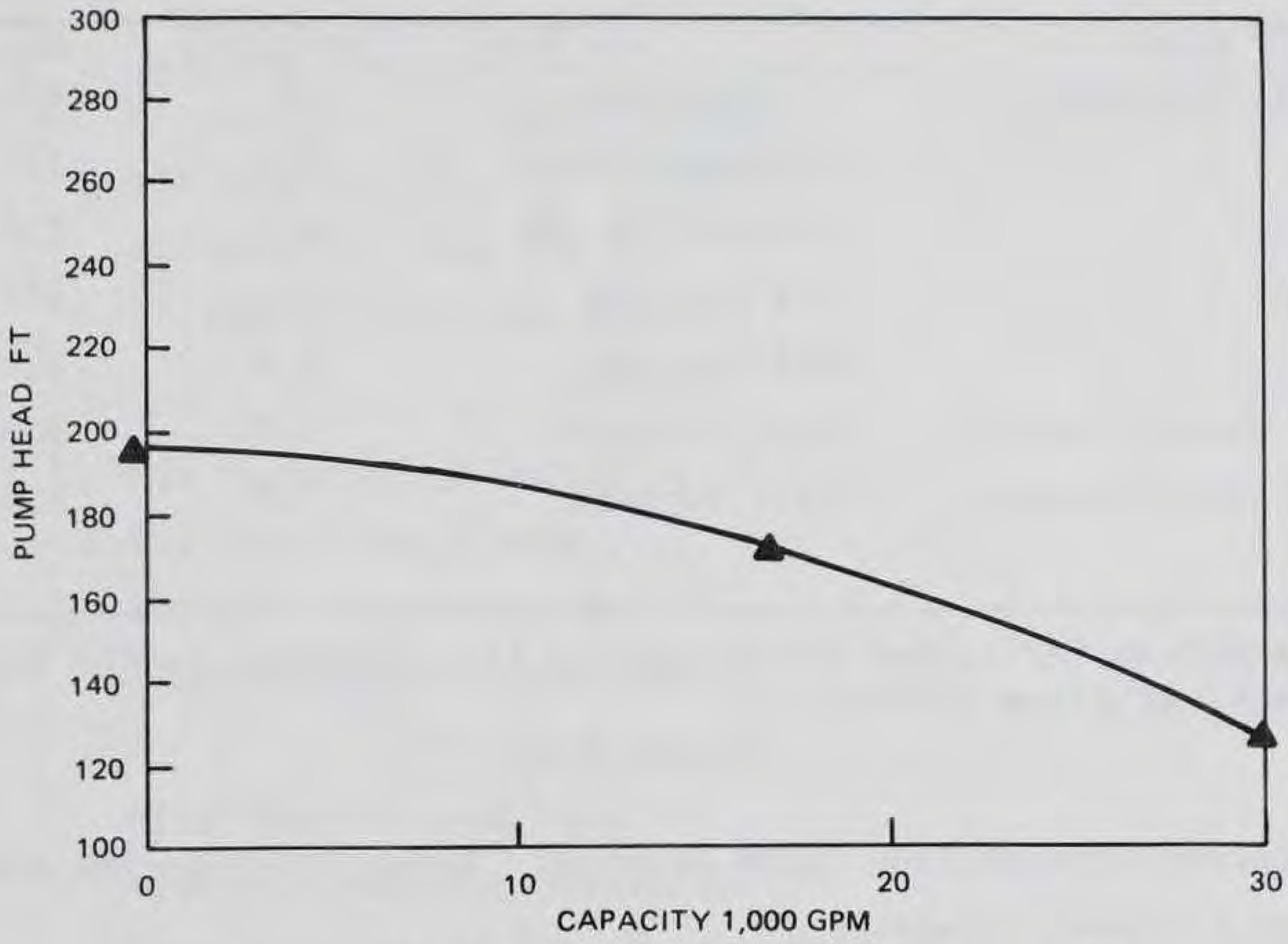


Figure 10. First high pressure zone pump characteristic curves

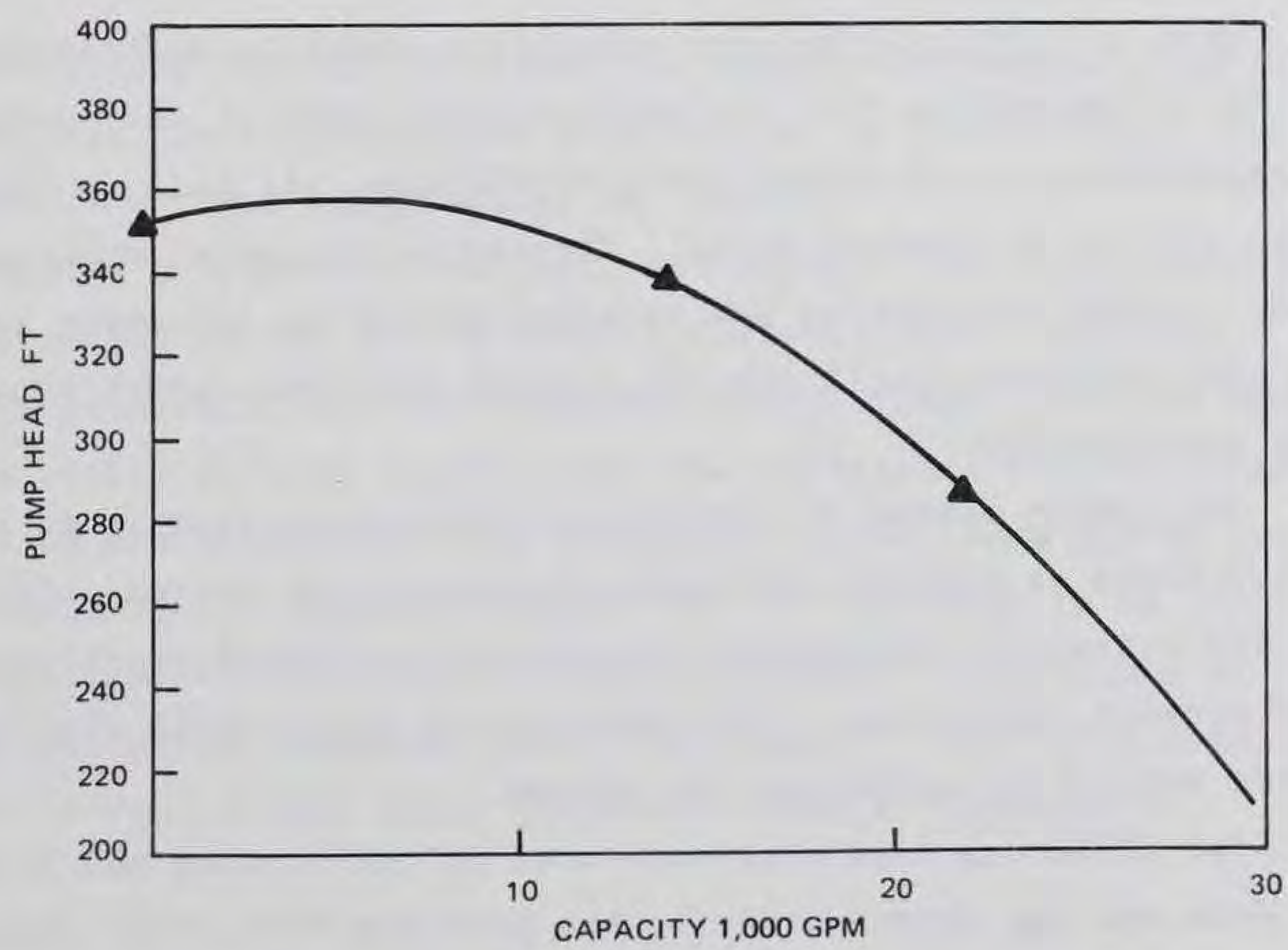


Figure 11. Third High pressure zone pump characteristic curves

Table 2

Tank Data

Service Area	Location	Capacity MG	Max el*	Min el
Low	Brentwood Park	25.0	172	135
First High	Foxhall Rd. NW	14.5	250	233
Third High	New Reno NW	20.0	424	406
	Old Reno NW	5.4	424	406
Arlington Second Gravity	Fort Barnard	0.5	300	275
Arlington Third Gravity	Fort Barnard	1.5	216	191

* All elevations (el) cited herein are in feet referred to the National Geodetic Vertical Datum (NGVD).

separate Second Gravity from Third Gravity. Table 3 delineates the location and setting of these valves.

System Calibration

50. When utilizing a computer simulation model in distribution system analysis, it is imperative that the mathematical model of the system be an accurate representation of actual field conditions. If this is not the case, the results will be of limited value. Therefore, the model must be calibrated. System calibration may be accomplished by adjusting both water usage and pipe roughness until predicted heads and flows match those observed from field measurements.

51. One common method for obtaining calibration data is to conduct fire hydrant flow tests at various locations throughout the system. Fire flow tests provide hydraulic information (pressures and flows) regarding both static and dynamic conditions. This information can be used with the computer model of the network to calibrate the system.

52. Two different data sets were used in calibrating the network model. The first data set was obtained during the previous FOWM study (Walski 1984). This data set includes the results from several fire flow tests conducted in the FOWM system. The results of these fire flow tests are provided in

Table 3

PRV Data

PRV Number	Location	Grade Setting, ft
	Second Gravity	
1	Washington Blvd. and Arlington Blvd.	346
2	Fillmore St. and 1st St.	348
3	Arlington Blvd. and Hudson St.	352
	Rosslyn	
4	Lee Highway and Veitch St.	320
5	Key Blvd. and N Troy St.	320
6	16th St. and N Troy St.	320
7	N Courthouse Rd. and 13th St.	320
	Third Gravity	
8	Army-Navy Dr. and Lynn St.	203
9	Lynn St. and 16th Street S	198
10	Four Mile Run Dr. and Walter Reed Dr.	195
11	31st St. and Randolph St.	202

Table 4. The second data set includes the results of several fire flow tests conducted in both the Arlington and FOWM systems in March 1987. The results of these fire flow tests are provided in Table 5.

53. System calibration was performed using a nonlinear optimization technique developed by two of the authors (Ormsbee and Chase 1988). This technique systematically adjusts roughness coefficients, junction demands, and PRV settings within defined limits until the difference between observed and predicted heads was minimized. The technique allows the adjusted parameters (roughness coefficient, junction demand, and PRV setting) to be constrained based on knowledge of the system. Table 6 provides a comparison of the observed and predicted pressures after calibration. The calibrated roughness coefficients (C-factor) and water usage are shown in Appendix A.

Table 4

Fire Test Results for FOWM System

Test Number	Location	Elevation ft	Pressure psi	Hydrant Discharge gpm	Hydrant Pressure psi
1	Meter vault below Key Bridge	9	100	--	--
2	Park Service hose bib	30	92	--	--
3	Along Metro	25	93	--	--
4	Pentagon north parking	48	83	1,300	78
5	South side Pentagon	34	92	1,140	85
6	Riverside parking lot	12	95	1,620	65
7	Pentagon heating plant	12	98	800	68
8	National Airport	20	95	1,140	80
9	National Airport South terminal	18	89	--	--
10	Navy Annex	150	62	650	45
11	H & S Headquarters	150	60-80	--	--
12	Arlington Cemetery Visitors Center	48	82	--	--
13	Lee Mansion	210	47	440	25

Table 5

Fire Test Results for Arlington System

Hydrant Test Number	Hydrant Location	Elevation ft	Pressure psi	Hydrant Discharge gpm	Hydrant Pressure psi
1*	15th and Fern St.	42	80	--	--
2*	15th and Fern St.	42	78	1,332	63
3**	15th and Fern St.	42	72	--	--
4**	15th and Fern St.	42	64	1,267	57
5	Washington Blvd. and Wayne St.	207	83	--	--
6	Washington Blvd. and Wayne St.	207	70	1,300	60
7	Columbia Pike at Navy Annex	142	85	--	--
8	Columbia Pike at Navy Annex	142	65	978	34

* 15th and Eads Interconnection open.
** 15th and Eads Interconnection closed.

Table 6

Calibration Results

Location	Observed Pressure psi	Predicted Pressure psi
	FOWM System	
Meter vault below Key Bridge	100	97
Along Metro	93	95
Riverside parking lot		
Hydrant discharge = 0 gpm	95	98
Hydrant discharge = 1,620 gpm	65	65
National Airport		
Hydrant discharge = 0 gpm	95	89
Hydrant discharge = 1,140 gpm	80	81
Arlington Cemetery Visitors Center	82	77
	Arlington County System	
15th and Fern St.*		
Hydrant discharge = 0 gpm	80	73
Hydrant discharge = 1,332 gpm	78	71
15th and Fern St.**		
Hydrant discharge = 0 gpm	72	69
Hydrant discharge = 1,268 gpm	64	67
Washington Blvd. and Wayne St.		
Hydrant discharge = 0 gpm	83	80
Hydrant discharge = 1,300 gpm	70	74
Columbia Pike at Navy Annex		
Hydrant discharge = 0 gpm	85	87
Hydrant discharge = 978 gpm	65	69

* 15th and Eads Interconnection open.

** 15th and Eads Interconnection closed.

PART IV: HYDRAULIC ASSESSMENT OF EXISTING SYSTEM

Evaluation Criteria

54. In order to properly analyze the effectiveness of an existing water system, certain evaluation criteria which are indicative of a properly sized and efficiently operated water system must be established. The design criteria selected for the FOWM system evaluation conform with generally recognized criteria for large community water systems in the United States. The standards selected for the FOWM system are based on criteria established by the Virginia State Health Department, criteria established by the Insurance Service Office (ISO), and generally accepted rules of thumb. The design criteria are summarized in the following paragraphs.

System pressure

55. During normal operation, system pressures should range from an allowable maximum of 100 psi to an allowable minimum of 40 psi. During emergency situations such as a fire flow, pressures should be maintained above 20 psi. Pressures much greater than 100 psi have a tendency to waste water and could damage existing residential and commercial plumbing systems. A pressure of 40 psi allows water to be supplied to the top floor of a four-story building. The 20-psi minimum has been set by the Virginia State Health Department and ensures adequate pressure for fighting fires.

Velocity and head loss

56. Using generally accepted rules of thumb, the maximum permissible velocity in mains with pipe diameter greater than or equal to 12 in. was set at 10 ft/sec. Velocities greater than this value may cause transient pressure problems or line scouring if they act over long periods of time. The maximum desirable head loss was set at 5 ft/1,000 ft of main.

Evaluation

57. In order to evaluate the performance of the existing FOWM system, the network was analyzed using the computer model for four different loading conditions. The four loading conditions were:

- a. Average daily demand.
- b. Maximum daily demand.

c. Peak hourly demand.

d. Fire demand.

58. Historical records for the Arlington County system indicate that the maximum daily demand is about 1.4 times the average daily day demand. Furthermore, the records indicate that the peak hourly demand is 1.8 times the maximum daily demand or 2.5 times the average daily demand. For the purpose of this study, the same factors were used for the FOWM system.

59. Fire demands were placed at the Pentagon, National Airport, and Fort Myer. All fire demands were superimposed on a maximum daily demand pattern. Using the 1980 Fire Suppression Rating Schedule (ISO 1980), the fire demand for the Pentagon and National Airport was placed at 7,500 gpm. The fire demand at Fort Myer was set at 2,400 gpm. Fire service for the Navy Annex is provided by Arlington County, thus a fire demand was not placed at the Navy Annex.

Average daily demands

60. For average daily demand loadings, the existing FOWM system performs well. Average system pressures, excluding those at the higher elevations by the Navy Annex and Henderson Hall, are about 85 psi. Pressures range from about 100 psi in the 30-in. main near Roosevelt Island to 64 psi near the entrance to the Navy Annex. Pressures at the Navy Annex and Henderson Hall are approximately 35 psi, which appears adequate for the booster pump at Henderson Hall and the hydropneumatic tank in the basement of the Navy Annex. Based on the results of the model, the hydraulic gradient for all lines is below 5 ft/1,000 ft. Pipe velocities range from 0.2 to 2.8 fps.

Maximum daily demands

61. The existing FOWM system also performs adequately under maximum day loading conditions. System pressures range from 97 to 61 psi with an average system-wide pressure of 82 psi. Pressures at the Navy Annex and Henderson Hall average about 30 psi. Although a bit higher than for average daily demand loadings, the line losses for the maximum day loading are still below the design standard (5 ft/1,000 ft) with the exception of an 8-in. pipe at the Navy Annex. The hydraulic gradient in this line is just over 8 ft/1,000 ft. Pipe velocities in the system range from 0.2 to 3.9 fps.

Peak hourly demands

62. Performance of the existing FOWM system under peak hourly demands is also adequate. System pressures average just over 70 psi with a range of

89 to 48 psi. Pressures at the suction side of the pressure control devices at the Navy Annex and Henderson Hall vary from 15 to 7 psi. During peak hourly demands, it is possible these low pressures may interfere with the normal operation of the booster pump and hydropneumatic tank at the Navy Annex and Henderson Hall. In several lines the head loss ratio exceeds 5 ft/1,000 ft; however, pipe velocities remain below the established criteria.

Fire demands

63. The existing FOWM system is capable of handling a fire demand of 7,500 gpm at the Pentagon during maximum daily demands. Under such a loading, the system pressures range from 89 to 43 psi. At the Navy Annex and Henderson Hall, the pressures dropped to 12 psi under these conditions. This may interfere with proper operation of the pressure control devices. For this loading the head loss ratios were generally below the design limit. The one exception was the 24-in. main on the west side of the Pentagon in the immediate vicinity of the fire demand. Head losses along this section of pipe were on the order of 16.5 ft/1,000 ft and velocities approached 6 fps. Elsewhere, velocities ranged from 0.2 to 4 fps. The fire flow available to the Pentagon at 20 psi during maximum daily demands is 14,000 gpm.

64. Although the existing system can handle a fire at the Pentagon, the system cannot provide adequate pressures for a fire demand of 7,500 gpm at National Airport. System pressures are adequate through most of the network; however, they are unacceptable (less than 20 psi) east of I-95. The decrease in pressure is due to the high head losses in the single 16-in. main serving the airport. Because of the high demand at National Airport, several lines around the Pentagon also experience high head losses since they provide the primary path of flow to the airport. (Note: All analysis for the existing system were made with the assumption that the 16-in. loop around the Pentagon was broken as is currently the case.) The fire flow available to National Airport through the existing system during maximum daily demands is 3,500 gpm. This does not meet the ISO fire flow requirements for a facility of this size.

65. The existing system is capable of supplying Fort Myer with adequate flows during a fire within the compound. This is based on the assumption that the Fort Myer booster pump station is withdrawing water at a rate of 2,400 gpm, which is the rated capacity of the pump. With a fire demand at Fort Myer during maximum daily demands, the average FOWM system pressure is 74 psi and falls no lower than 58 psi. Pressures at the Navy Annex and

Henderson Hall are about 27 psi but appear to be adequate for the booster pump and hydropneumatic tank.

Pipe Outage Analysis

66. In order to assess the reliability of the existing system, the system was evaluated for 10 different pipe outage scenarios. Each scenario is identified in Table 7 and Figure 12. Each pipe outage scenario was evaluated for the loading conditions listed below:

a. Average daily demand.

b. Maximum daily demand.

c. Peak hourly demand.

d. Fire demands.

Table 7

Pipe Outage Scenarios

30-in. main under Key Bridge
16-in. main under Key Bridge
30-in. main along Jefferson Davis Hwy. between Marshall Dr. and Memorial Dr.
30-in. main along Jefferson Davis Hwy. between Memorial Dr. and the Pentagon
16-in. main along Eisenhower Dr. between Marshall Dr. and Memorial Dr.
16-in. main along Eisenhower Dr. between Memorial Dr. and McMillan Dr.
12-in. main at Columbia Pike from the A.N.C Service building to southwest corner of the Pentagon south parking lot
18-in. main along the western boundary of the Pentagon south parking lot
24-in. main just west of I-95 from the southwest corner of the Pentagon parking lot to Fern St. and Army-Navy Dr.
16-in. main along 15th St. between Eads St. and Washington National Airport

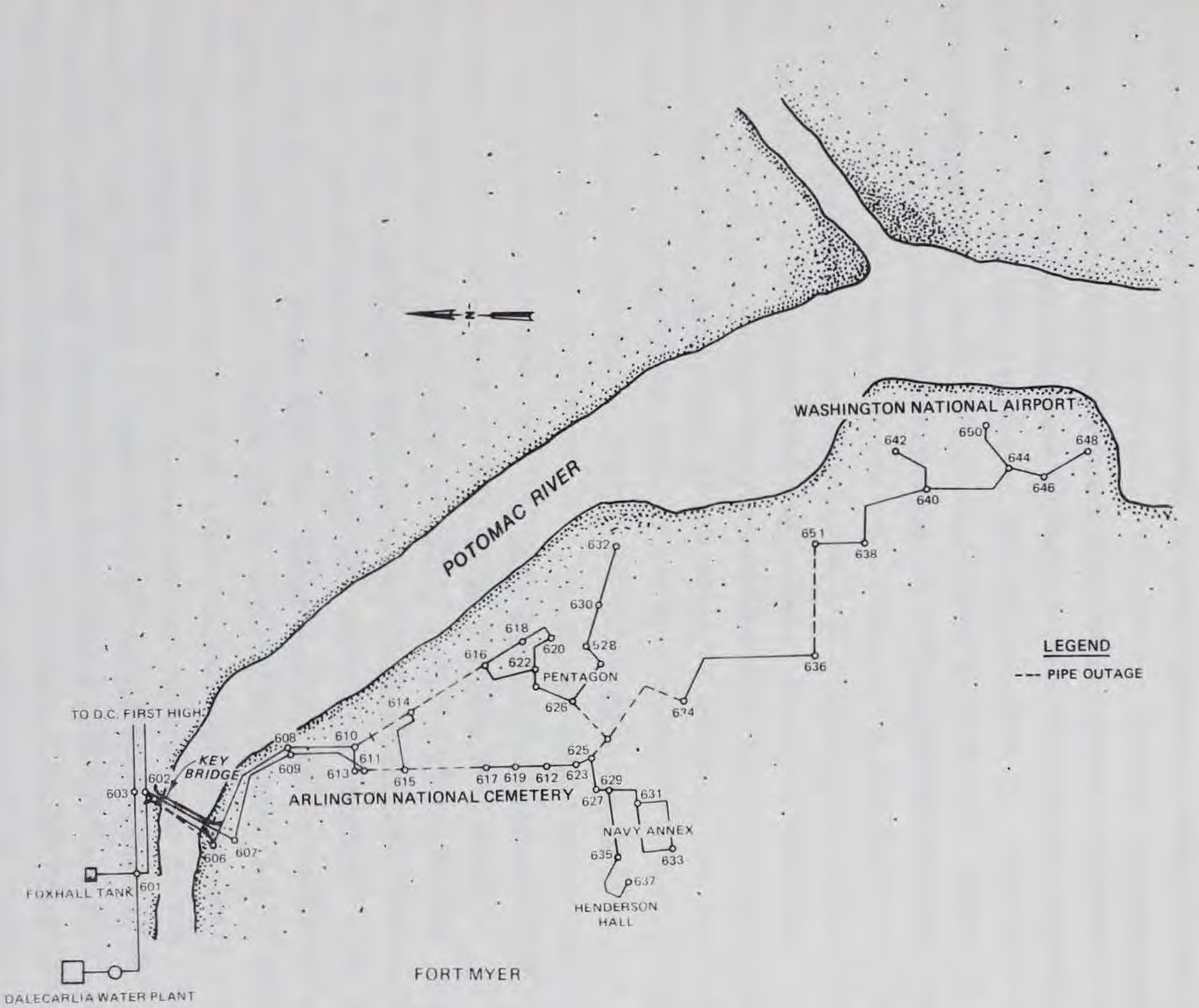


Figure 12. Location of pipe outage scenarios

(1) Fire demand at the Pentagon.

(2) Fire demand at Washington National Airport.

(3) Fire demand at Fort Myer.

For each of the pipe outage scenarios evaluated, all interconnections with Arlington County were assumed to be closed. This allows only the FOWM system to be analyzed with no external support from other distribution systems.

Pressure index

67. When analyzing a water distribution system for different pipe outage conditions, it is desirable to rank the scenarios to determine the most severe conditions. In order to rank the scenarios, some type of severity index is needed. The severity index used in this study is a pressure index based on pressure differences and is defined as follows:

$$PI = \frac{\sum_{i=1}^{N} (P_i - P_{min})}{N} \quad (1)$$

where

PI = pressure index

N = total number of nodes

P_i = pressure at junction node i

P_{min} = minimum allowable pressure

68. The advantage of using a severity index, such as the one above, is that it enables identification of those key mains which, when placed out of service, will adversely affect the performance of the FOWM system. The greater the value of the pressure index, the less impact a particular pipe outage has on the overall performance of the system. Consequently, one may tell at a glance which pipe outages result in an undesirable condition.

69. All 40 nodes within the FOWM system were included in the computation of the pressure index except for four nodes at the Navy Annex and Henderson Hall. Nodes at the Navy Annex and Henderson Hall were omitted because they are at much higher elevations than the remainder of the system and have pressure control devices to boost pressures to acceptable levels. Including these nodes in computation of the pressure indices would have skewed the results.

70. In addition to the pressure index, the number of nodes which fail to meet the minimum allowable pressure are determined. All the nodes in FOWM, including those at the Navy Annex and Henderson Hall, are included in this analysis.

71. For all scenarios except those involving fire demands, the minimum allowable pressure was set at 40 psi. For fire demand scenarios, the minimum allowable pressure was set at 20 psi. The pressure indices for each pipe outage under each loading condition for the existing system and the number of nodes which fail to meet minimum allowable pressure requirements are shown in Table 8.

Average daily loading

72. During average daily demands, the FOWM system performs adequately for all of the 10 pipe outage scenarios. Average system pressures do fluctuate a little depending upon the particular line placed out of service; however, for all cases the pressure was maintained above 40 psi minimum throughout most of the system. The lowest pressures are associated with the case where the 30-in. supply line is taken out of service. For this scenario, the lowest pressure, excluding those at the Navy Annex and Henderson Hall, was 50 psi. Pressure at the Navy Annex and Henderson Hall was 20 psi.

Maximum daily loading

73. For the most part, the FOWM system can also maintain adequate system pressures for all 10 pipe outages during maximum daily demands. The largest pressure drop occurs when the 30-in. supply line is removed from service. Even though adequate pressure is maintained throughout most of the FOWM system, up to 10 nodes fail to meet minimum pressure requirements when this vital link is placed out of service. When the 30-in. main is taken out of service, flow is rerouted through smaller lines thus resulting in higher head losses.

Peak hourly loading

74. Under peak hour loading conditions, average system pressures drop significantly if any segment of the 30-in. main is taken out of service. Pressures fall so low, in fact, that it is unlikely that demands in the FOWM system could be fully met even with the 16-in. river crossing in operation. This is due to the large head losses which occur in the 16-in. line. If the 30-in. line is in service, the FOWM can sustain the remaining set of pipe outages.

Table 8

Pressure Indices for Existing System*

Pipe Outage	ADD		MDD		PHD		F1		F2		F3	
	PI	FN	PI	FN	PI	FN	PI	FN	PI	FN	PI	FN
30 in. Key Bridge	30.10	4	14.43	6	-51.47	38	-181.09	39	-210.21	39	6.14	14
16 in. Key Bridge	44.62	4	41.51	4	28.95	4	45.11	12	15.22	12	61.22	0
30 in. Davis Hwy. #1	35.58	4	24.66	4	-21.09	30	-165.33	32	-190.39	32	53.01	0
30 in. Davis Hwy. #2	31.57	4	17.19	10	-43.28	29	-273.04	31	-295.59	31	48.30	0
16 in. Eisenhower Dr. #1	44.33	4	40.98	4	27.37	5	44.56	4	10.55	12	62.25	0
16 in. Eisenhower Dr. #2	44.21	4	40.76	4	26.71	6	44.05	4	8.96	14	62.09	0
12 in. Navy Annex	44.89	4	42.03	4	30.48	4	48.34	0	17.17	8	62.60	0
18 in. Pentagon	43.12	4	38.71	4	20.64	13	50.85	0	-126.13	21	60.42	0
24 in. Airport	++	13	++	13	++	13	++	12	++	9	++	9
16 in. Airport	++	11	++	11	++	11	++	10	++	7	++	7
No pipe outages	44.88	4	42.02	4	30.48	4	48.94	3	19.17	12	63.12	0

* ADD = average daily demands, MDD = maximum daily demand, PHD = peak hourly demands, F1 = Pentagon fire demand.
F2 = National Airport fire demand.
F3 = Fort Myer fire demand, PI = pressure index; and FN = failed nodes.
++ = indicates National Airport is without water.

Fire demands

75. The existing system was also analyzed for various main outages with fire demands of 7,500 gpm placed at the Pentagon and National Airport and 2,400 gpm at Fort Myer. Generally, the system can handle all fire demands if the 30-in. line remains in service. If any segment of the 30-in. main is taken out of service, then only the fire demand at Fort Myer can be satisfied. Furthermore, if the 18-in. main by the Pentagon is placed out of service, fire demands at National Airport cannot be met. (Note: Fort Myer, unlike the remainder of the FOWM system, has a storage facility at the military complex to augment supply.)

Summary

76. In general, with no pipe outages the existing FOWM system is adequate for most loading conditions. With the exception of a fire demand at Washington National Airport, pressures within most of the FOWM system are sufficient to allow for the proper delivery of water. The fire flow capacity of the 24- and 16-in. airport feed is 3,500 gpm during maximum daily demands. As a result, the ISO requirement of 7,500 gpm cannot be met. Also, during periods of high demand, pressures at the Navy Annex and Henderson Hall drop to levels which may affect proper operation of the pressure control devices at these locations. The performance of the existing FOWM system deteriorates dramatically when certain key mains fail or are taken out of service. These problem areas are itemized in the following paragraphs.

77. The existing FOWM system is served entirely from the 30- and 16-in. mains suspended beneath Key Bridge. This is the only independent source of supply for the system. If this link were to fail, demands in the existing FOWM system could not be met. In order for demands to be satisfied under this condition, an alternate means of supply, such as opening interconnections with the Arlington County system, must be found.

78. The existing FOWM system is almost entirely dependent upon the 30-in. main which extends from Key Bridge to the north face of the Pentagon. If any segment of this vital link were to be taken out of service, system pressures would be adversely affected. Moreover, if this pipe were taken out of service during periods of high demands, line losses in the paralleling 16-in. main would be so great that pressures and flows in the FOWM system

would be significantly reduced to the point where it is unlikely that system demands could be fully met.

79. Another area of major concern is the main which extends from the southwest corner of the Pentagon to Washington National Airport. This link is made up of a 16-in. line and a 24-in. line connected in series. This single main is the only source of water for National Airport. If this line were to fail, National Airport would be without water unless an interconnection with Arlington were opened. With this line in service and during periods of high flow to National Airport, excessive head loss in the 16-in. segment of this line produces pressures below the minimum acceptable level.

80. A third area of concern is the 10-in. line which feeds the Navy Annex and Henderson Hall. If this line were placed out of service, these facilities would be without water. Furthermore, the proper operation of both the booster pump at Henderson Hall and the hydropneumatic tank at the Navy Annex may be affected when the 16-in. main along Eisenhower Drive is disabled. This is especially true during periods of high demand regardless of which mains are out of service.

81. For those cases where installations would be without water during a pipe outage, it is apparent that with the existing system an interconnection must be opened between the outage and demand. In some cases existing system interconnections are available with the Arlington County system. However, it is possible that the operation of a particular interconnection could have a detrimental effect on the Arlington system. This possibility is investigated in the following parts.

PART V: SYSTEM IMPROVEMENTS

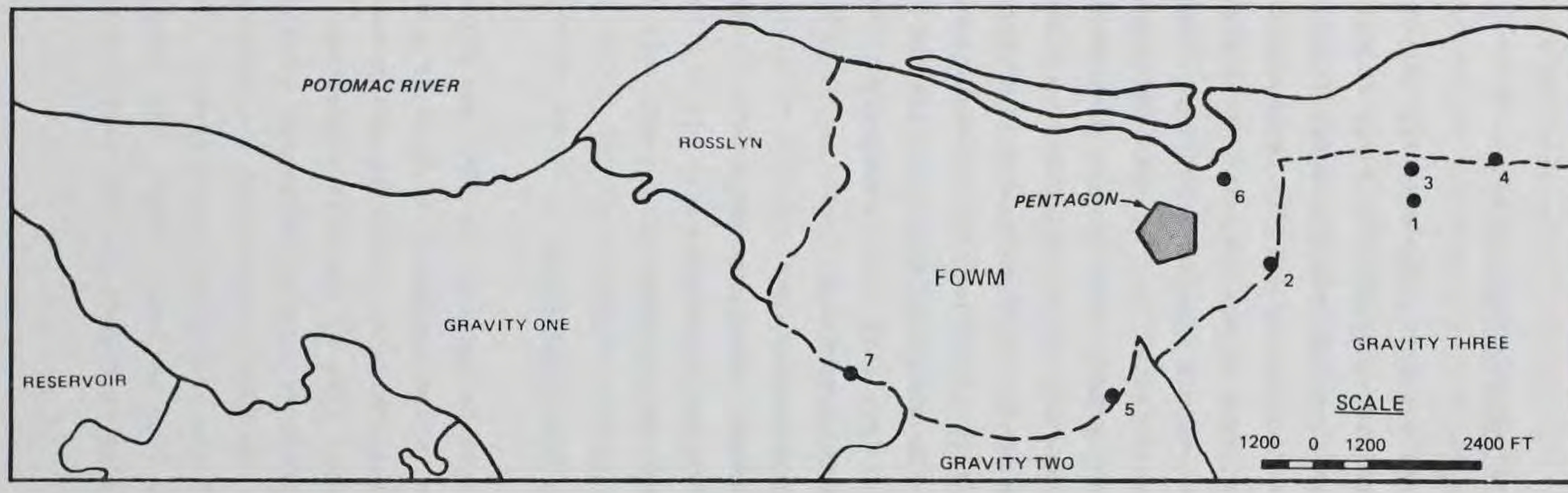
Identification of Supply Alternatives

82. As demonstrated in the previous part, the existing system is highly vulnerable to the loss of the supply lines suspended from Key Bridge and the 30-in. transmission main between Key Bridge and the Pentagon. National Airport is dependent upon a single line composed of a 24-in. main and a 16-in. main in series extending from the Pentagon to the airport. Both Henderson Hall and the Navy Annex are dependent upon a single 10-in. line along Columbia Pike. In order to increase the overall reliability of the FOWM system, several possible alternatives were investigated. The primary purpose of these alternatives is to provide an alternate source of supply to the FOWM system in the event of a failure of either the 30-in. transmission main or the entire Key Bridge river crossing. Other alternatives help to increase the amount of flow to a particular area or reduce the amount of head loss within the system. The various alternatives were grouped into five basic categories:

- a. Use of existing interconnections.
- b. Development of new interconnections.
- c. Construction of additional river crossings.
- d. Construction of new storage facilities.
- e. Construction of additional pipelines.

Existing Interconnections

83. Seven existing interconnections between the FOWM and Arlington County systems are available for use during emergencies, such as a main outage. The performance of each existing emergency interconnection was evaluated as part of the FOWM reliability study. Five of the interconnections join the FOWM system with the Third Gravity pressure zone of Arlington County. The remaining two interconnections join the FOWM network with the First Gravity and Second Gravity pressure zones of the Arlington County system. The interconnection between First Gravity and FOWM includes a PRV. The locations of the existing interconnections are shown in Figure 13, and each interconnection is described below.



FOWM/ARLINGTON COUNTY INTERCONNECTIONS

(1) 15th AND EADS INTERCONNECTION
(2) FERN STREET INTERCONNECTION
(3) CRYSTAL CITY INTERCONNECTION 1
(4) CRYSTAL CITY INTERCONNECTION 2
(5) NAVY ANNEX INTERCONNECTION
(6) PENTAGON HEATING PLANT INTERCONNECTION
(7) FORT MYER INTERCONNECTION

LEGEND

● EXISTING FOWM/ARLINGTON COUNTY INTERCONNECTION

– – FOWM AND ARLINGTON BOUNDARY

— ARLINGTON PRESSURE ZONE BOUNDARY

Figure 13. Location of existing interconnections

15th and Eads interconnection

84. The 15th and Eads interconnection is located at the intersection of 15th and Eads Streets in Crystal City and provides a connection between FOWM and the Arlington County Third Gravity pressure zone. This interconnection is perhaps the most important of the seven existing connections. The interconnection links a 24-in. main from the FOWM system with a 12-in. main from the Arlington County system. A flowmeter in the connection measures the amount of flow between the two systems. A detail of the interconnection is shown in Figure 14.

Fern Street interconnection

85. Another interconnection is located at the intersection of Fern Street and Army-Navy Drive. This interconnection provides a link between a 24-in. main in the FOWM system with a 12-in. main in the Arlington County Third Gravity system. A detail of this interconnection is provided in Figure 15.

Crystal City interconnections

86. Two additional interconnections which link FOWM and Arlington County Third Gravity pressure zone are located in Crystal City near National Airport. The first is located just east of the Jefferson Davis Highway on 15th Street. This interconnection joins the 16-in. main to National Airport with a 12-in. main from the Arlington County system.

87. The second Crystal City interconnection is closer to the airport. This interconnection is located at the intersection of 20th and Ball Streets and links the 16-in. FOWM airport feed with an additional 12-in. main from Arlington County. Details of these interconnections are shown in Figures 16 and 17.

Heating Plant interconnection

88. Another interconnection between FOWM and Arlington County Third Gravity is located near the Pentagon heating plant just east of the I-95 north-bound lane. This interconnection joins a 6-in. FOWM main with an 8-in. Arlington main. A detail of this interconnection is shown in Figure 18.

Navy Annex interconnection

89. An interconnection at the Navy Annex provides a link between the Second Gravity pressure zone of the Arlington system and the FOWM system. This interconnection is located within the Navy Annex compound at Columbia and Oak Streets. Normal water demands for the Navy Annex are supplied from the

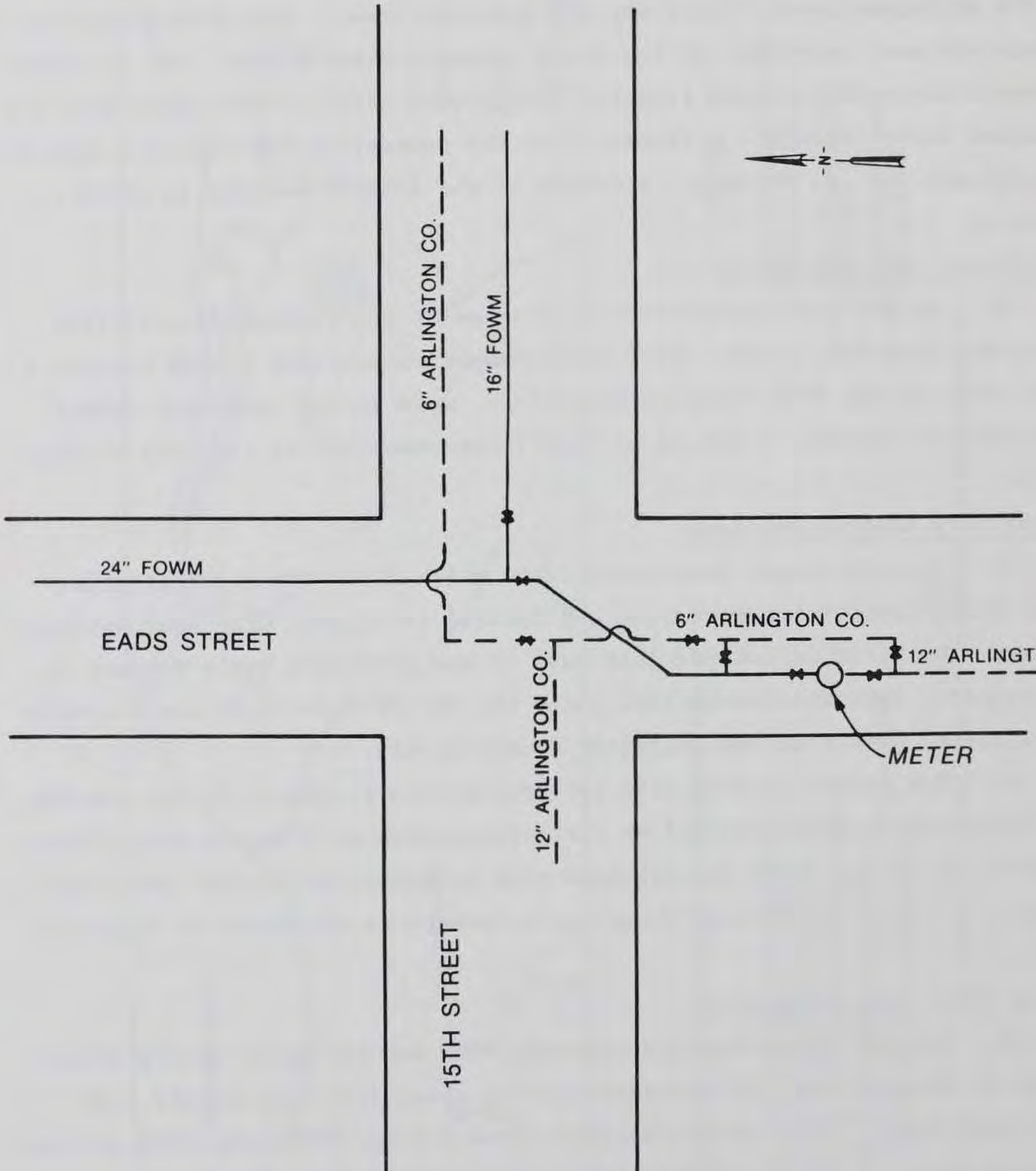


Figure 14. Detail of 15th and Eads interconnection

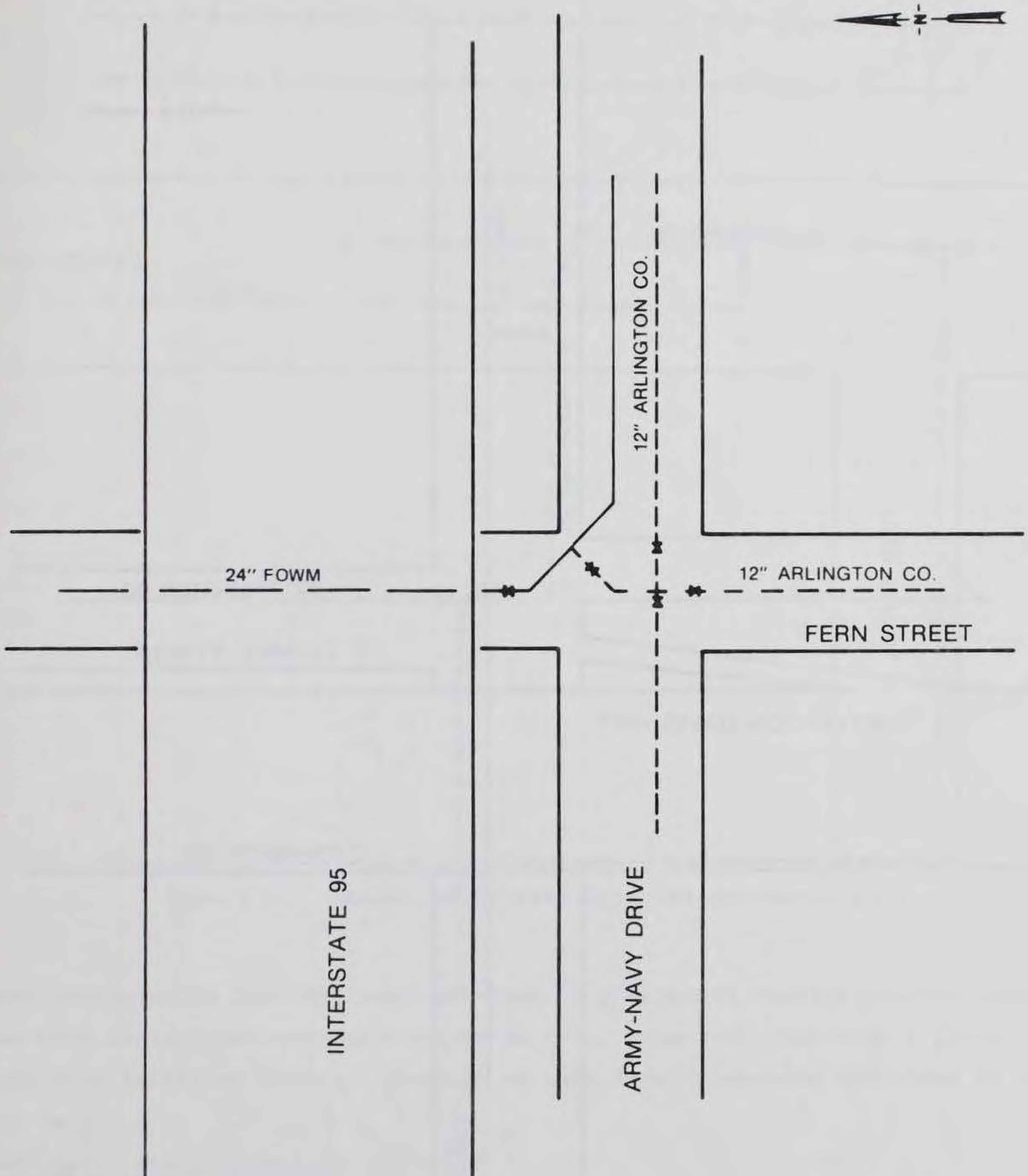


Figure 15. Detail of Fern Street interconnection

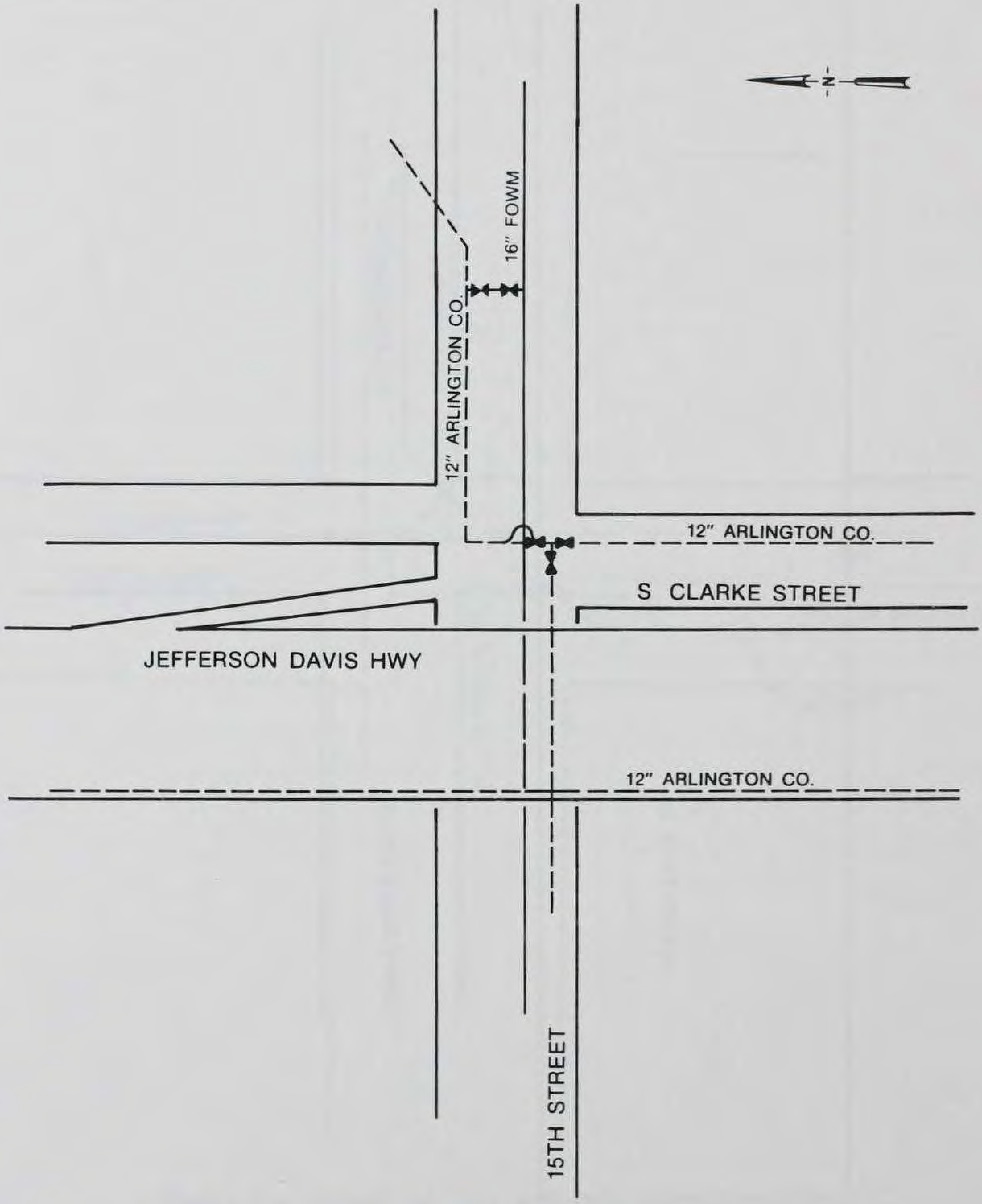


Figure 16. Detail of Crystal City interconnection #1

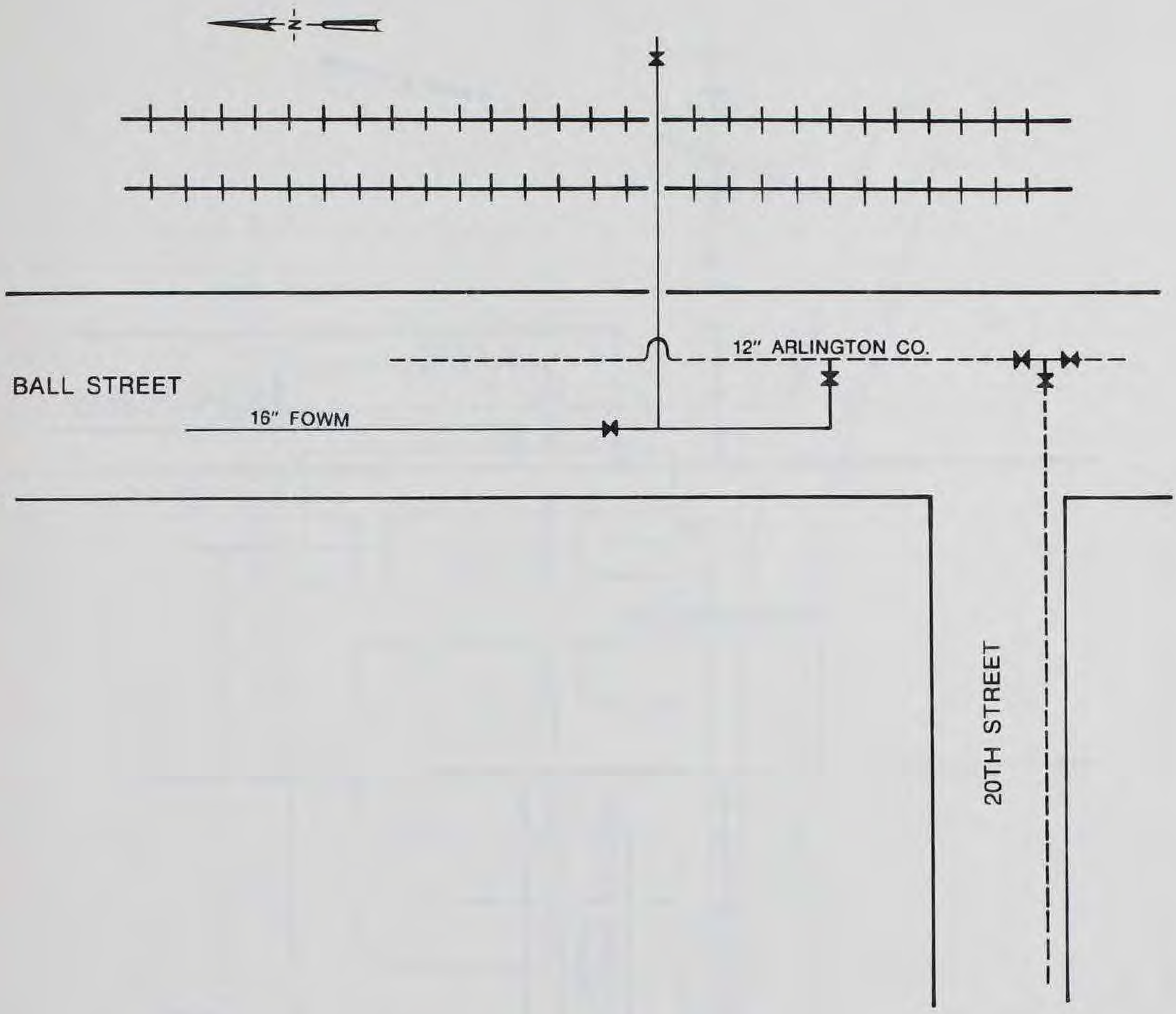


Figure 17. Detail of Crystal City interconnection #2

FOWM system while fire hydrants are tied to the Second Gravity pressure zone. The Navy Annex interconnection links an 8-in. pipe from FOWM with a 12-in. pipe from Arlington County. Details of this interconnection are shown in Figure 19.

Fort Myer interconnection

90. This interconnection is located near the intersection of Arlington and Washington Blvds., just south of Fort Myer. The interconnection serves Fort Myer during emergencies and is supplied from the First Gravity pressure zone of the Arlington County system. The interconnection consists of a 10-in. line from FOWM and a 16-in. line from Arlington. A PRV is located in the

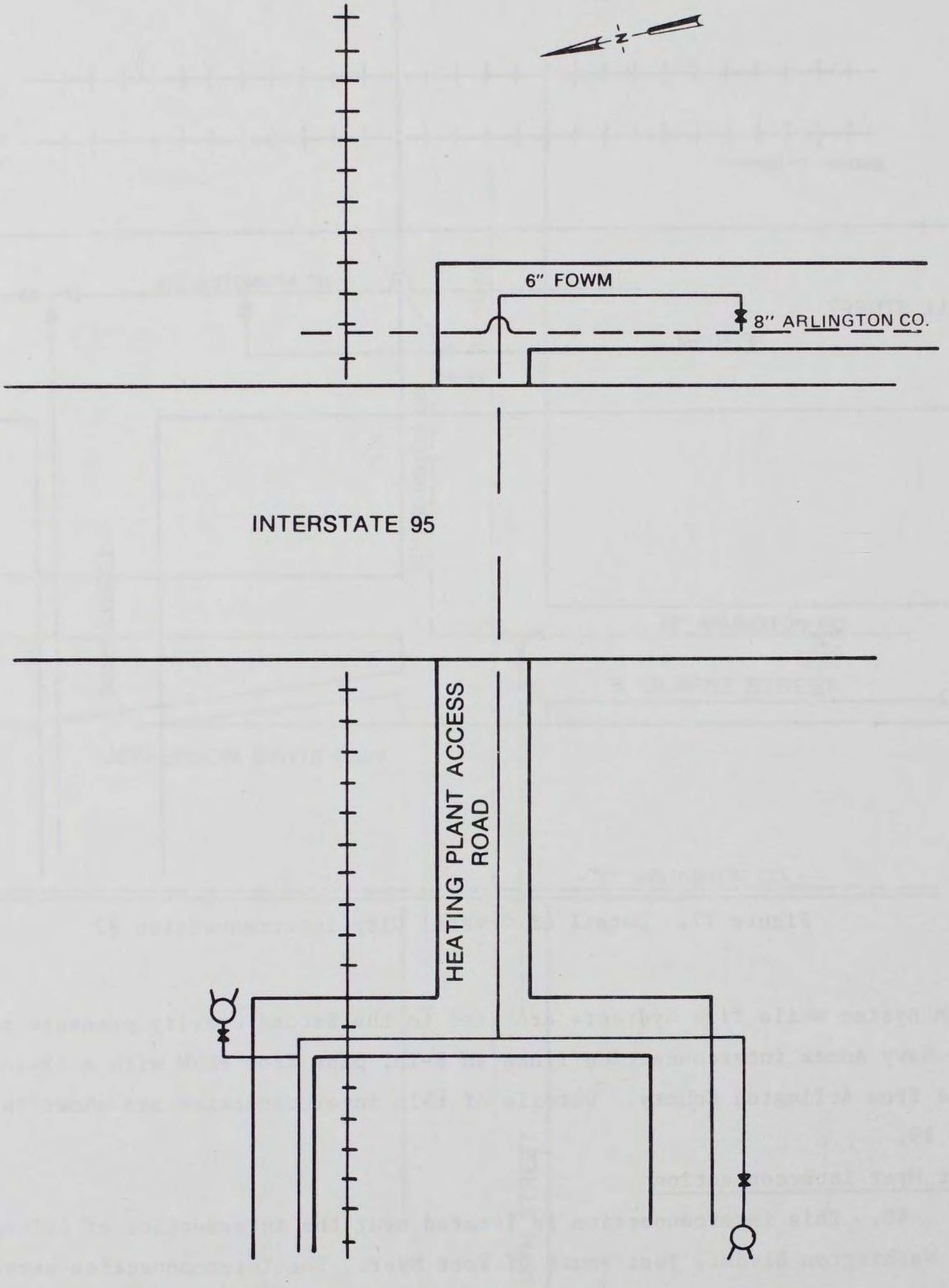


Figure 18. Detail of Pentagon heating plant interconnection

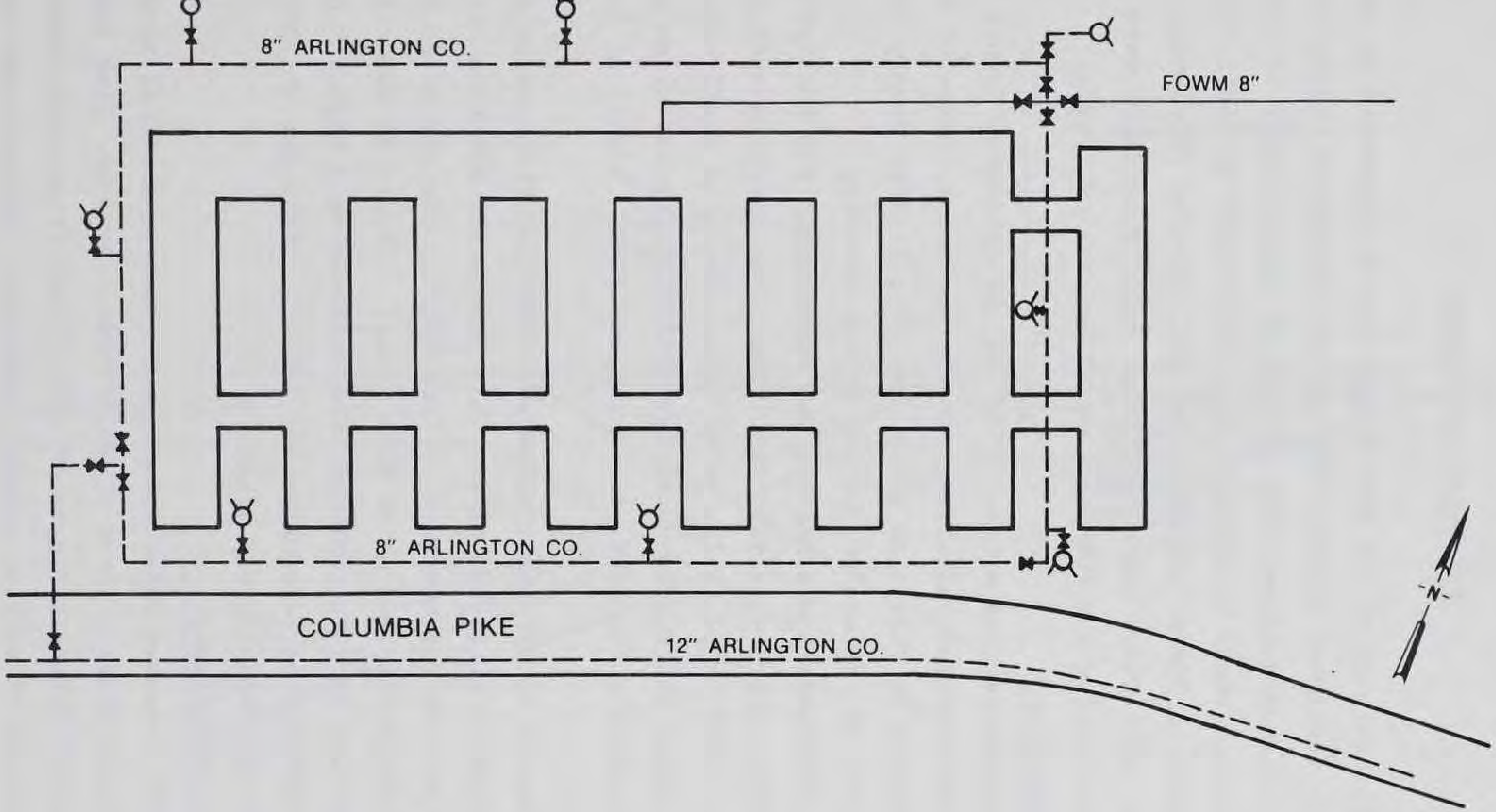


Figure 19. Detail of Navy Annex interconnection

10-in. line; however, the setting of the PRV is unknown. A detail of this interconnection is shown in Figure 20.

New Interconnections

91. The reliability of the FOWM system may be increased by constructing additional interconnections between FOWM and the Arlington County network. The additional interconnections would be used to supply water to areas within the FOWM system which would be without water if certain critical links (Key Bridge river crossing, 30-in. transmission main, airport feed) were placed out of service. For this study, three additional interconnections were considered, two between Rosslyn and FOWM and one at National Airport.

Rosslyn interconnections

92. An interconnection between FOWM and the Arlington County Rosslyn pressure zone would improve reliability in the northwest corner of the FOWM system. A connection in this area would provide a feed to supply the FOWM system in the event of failure of the Key Bridge crossing.

93. Two interconnections between the FOWM system and Rosslyn pressure zone are proposed to improve reliability. The first interconnection consists of approximately 2,000 ft of 16-in. water main. The line would extend from the FOWM 30-in. meter vault underneath Key Bridge to the end of an existing 16-in. line in Rosslyn's Key Blvd. at Fort Myer Drive. Figure 21 details this connection.

94. The second interconnection between FOWM and the Rosslyn pressure zone involves 1,500 ft of 12-in. pipe. This line would run from the end of the 16-in. FOWM main at the entrance of Fort Myer to the end of an existing 12-in. main at 12th Street and North Nash Street. Figure 22 shows this connection. Because the Rosslyn pressure zone operates at a higher hydraulic grade than the FOWM system (approximately 320 ft), PRV's set at 250 ft must be installed in each of the proposed lines.

National Airport interconnection

95. Another proposed interconnection is between National Airport and the Arlington County Gravity Three pressure zone. An 8-in. line linking the airport with Gravity Three at the south end of the airport was severely damaged and taken out of service several years ago. The proposed connection would replace this line to provide additional reliability for National

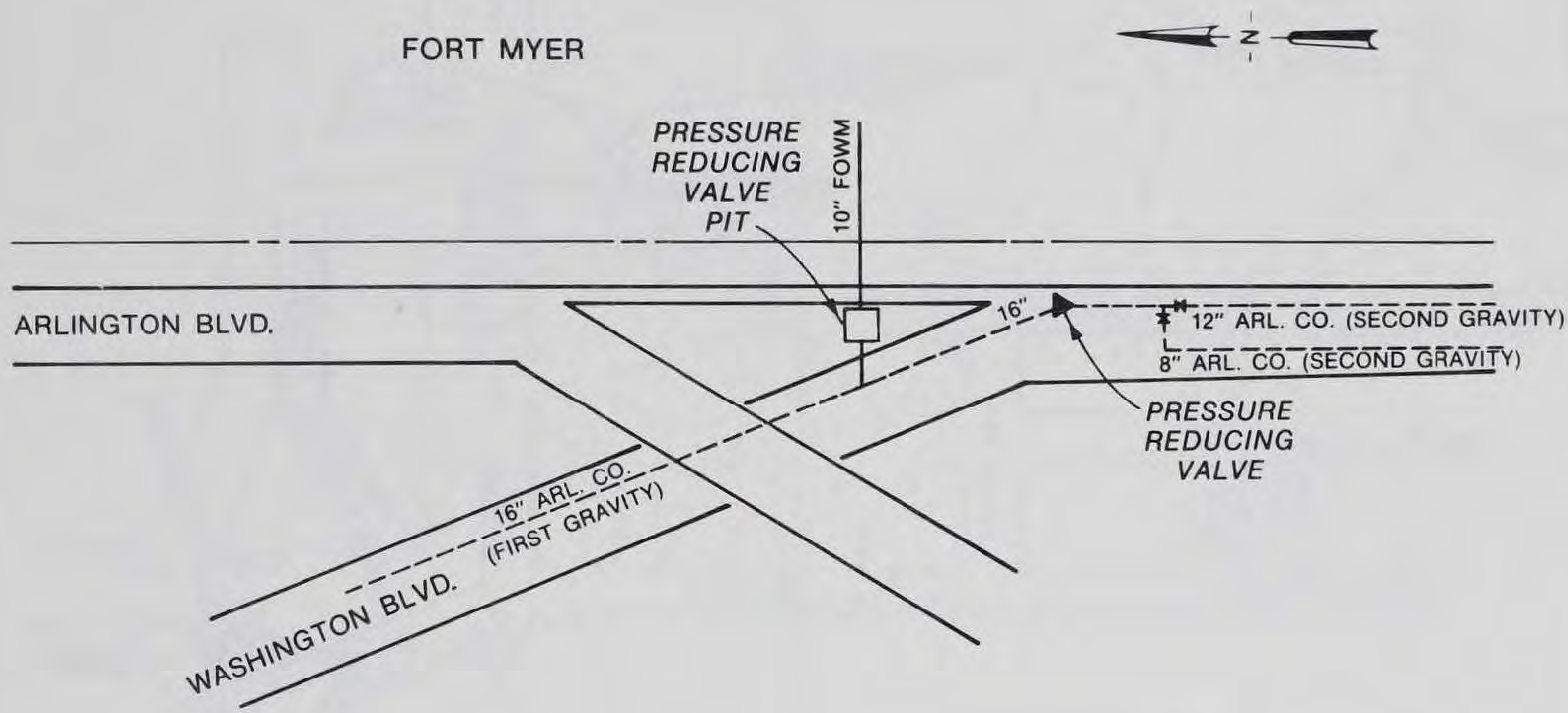


Figure 20. Detail of Fort Myer interconnection

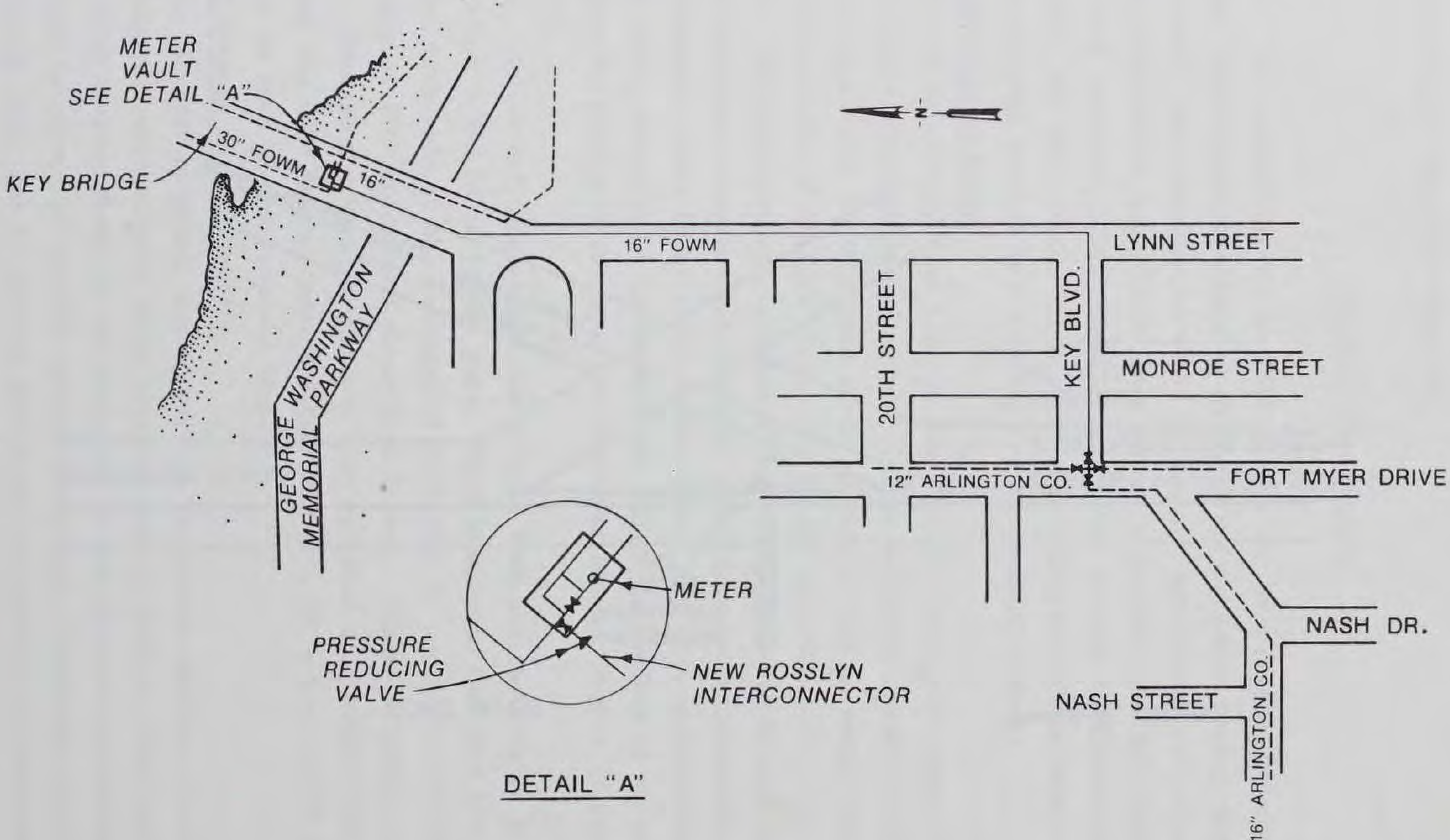


Figure 21. Detail of proposed Rosslyn interconnection #1

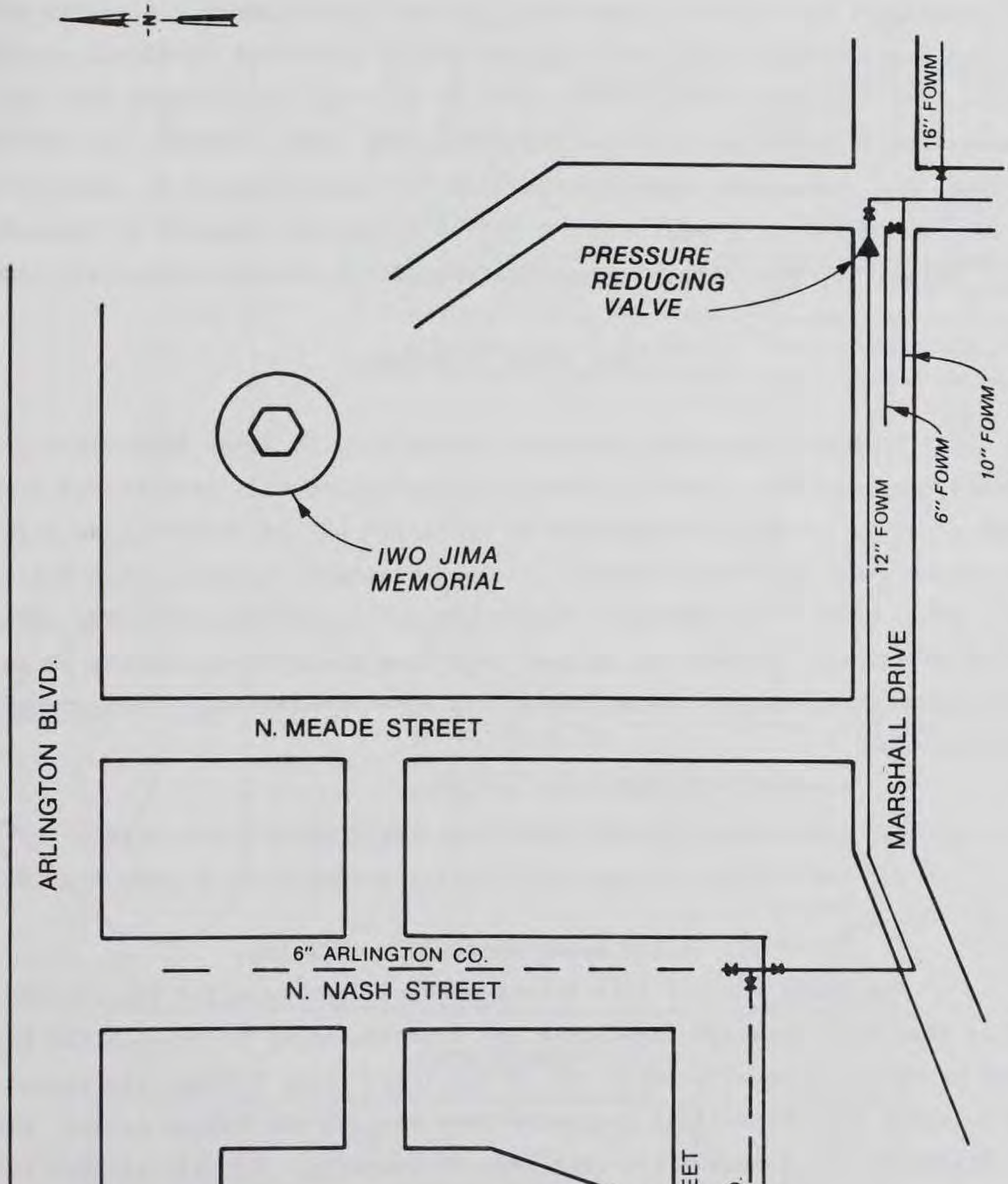


Figure 22. Detail of proposed Rosslyn interconnection #2

Airport. This line would also increase the fire flow capacity to the airport. The interconnection would consist of 1,950 ft of 12-in. line with a check valve and meter east of the connection with Arlington County. A tie-in with the FOWM system would be located adjacent to the southwest terminal, and connection with Arlington County would occur in a 12-in. county line near the intersection of Davis Hwy. and the airport access road. Details are provided in Figure 23. Depending upon the condition of the existing 8-in. line, it is possible to make this interconnection by replacing that segment of damaged line. This interconnection, if constructed, should remain open at all times.

New River Crossings

96. Presently the FOWM system is served from DC First High via a 30-in. transmission main and a 16-in. transmission main suspended beneath Key Bridge. If the existing bridge crossing were to be placed out of service, the existing FOWM system would be without water. Emergency interconnections with Arlington County would have to be opened to obtain water. A new river crossing would provide additional reliability against this scenario without relying on an external source of supply. Four variations of this alternative are proposed. These include:

a. Roosevelt Bridge river crossing.

b. 14th Street Bridge river crossing from DC First High.

c. 14th Street Bridge river crossing with booster pump from DC Low service.

d. Roosevelt Island subaqueous river crossing.

97. The Roosevelt and 14th Street bridges were selected for consideration as they would provide completely new crossing sites to replace the Key Bridge crossing if it were taken out of service. These bridges are structurally suitable for water lines suspended from beneath the bridge decks. Memorial Bridge is not suitable for this type of crossing. Details of each bridge crossing as well as the subaqueous crossing are given in the following sections.

Roosevelt Bridge crossing

98. The Roosevelt Bridge crossing involves a 30-in. line from Foxhall tank east along MacArthur Blvd. and Canal Road to Key Bridge. At this point the line turns southeast and parallel to the Potomac River up to Roosevelt

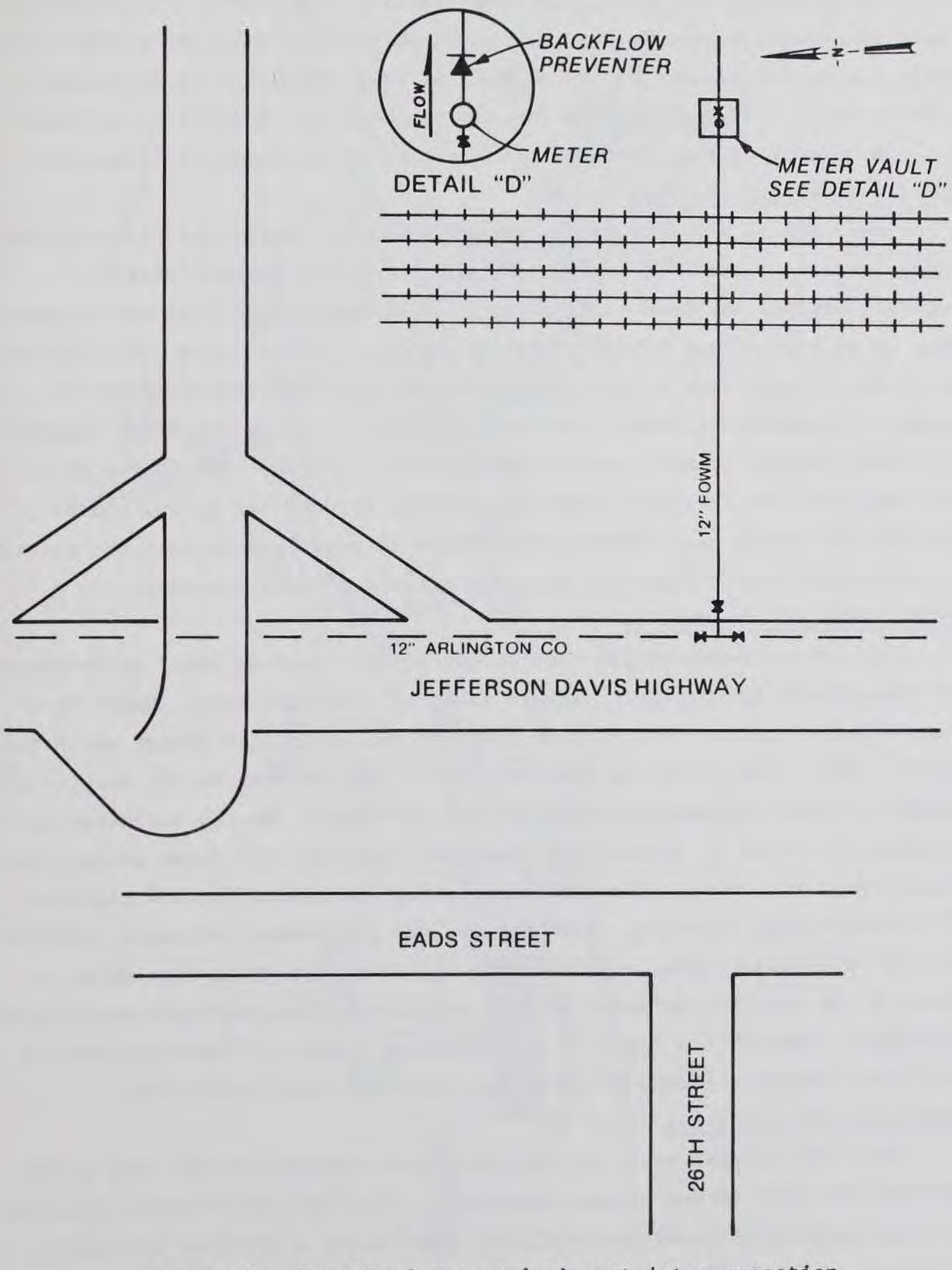


Figure 23. Detail of proposed airport interconnection

Bridge. This line would be approximately 14,150 ft long. The new line originates at Foxhall tank so that the hydraulics of the FOWM system will continue to be controlled by the Dalecarlia Pump Station. The 30-in. line would be suspended beneath Roosevelt Bridge across the Potomac River and through the George Washington Parkway and US Highway 66 interchange for an additional 4,000 ft until it intersects the FOWM 30-in. main at the junction of Davis Hwy. and Marshall Drive. Details of this project are shown in Figure 24.

14th Street Bridge crossing

99. The 14th Street Bridge crossing is very similar to the Roosevelt Bridge crossing in that it follows the same path from Foxhall tank to Roosevelt Bridge. At Roosevelt Bridge it continues to parallel the Potomac River up to 14th Street Bridge. Like the previous alternative, this line is also a 30-in. pipe with a total length of 21,700 ft from the tank to the bridge. An additional 30-in. line 2,500 ft long would be suspended beneath 14th Street Bridge to make up the actual river crossing. The 30-in. main would parallel the railroad tracks by National Airport for an additional 5,200 ft to a point east of Davis Hwy. where it would tie-in with the existing 16-in. airport feed. Figure 25 provides details of this crossing.

Booster pump off Low service

100. A variation of the 14th Street Bridge crossing would be to supply FOWM from the DC Low service pressure zone via a booster pump. Under this alternative, a booster pump station would be placed at 12th Street and Maine Avenue in DC. Water would be supplied from DC Low service to the booster pump through a 20-in. transmission main at 12th and Maine. On the discharge end of the pump, 11,270 ft of 30-in. line would run from 12th and Maine across 14th Street Bridge and would follow the same path as described for the previous 14th Street Bridge crossing. Although any one of a number of pumps could be used for this alternative, a 150-hp pump with the characteristics shown in Figure 26 was used for purposes of this analysis. This pump was used because it provides heads in the range of the operating grades at flows approaching peak hourly demand. Figure 27 shows the detail of this alternative.

Subaqueous river crossing

101. The initial route of the subaqueous crossing is the same as the Roosevelt and 14th Street Bridge crossings. This line would extend from Foxhall tank east along MacArthur Blvd. and Canal Road, a distance of about 1.5 miles, to Key Bridge. At this point the pipe will parallel the Potomac

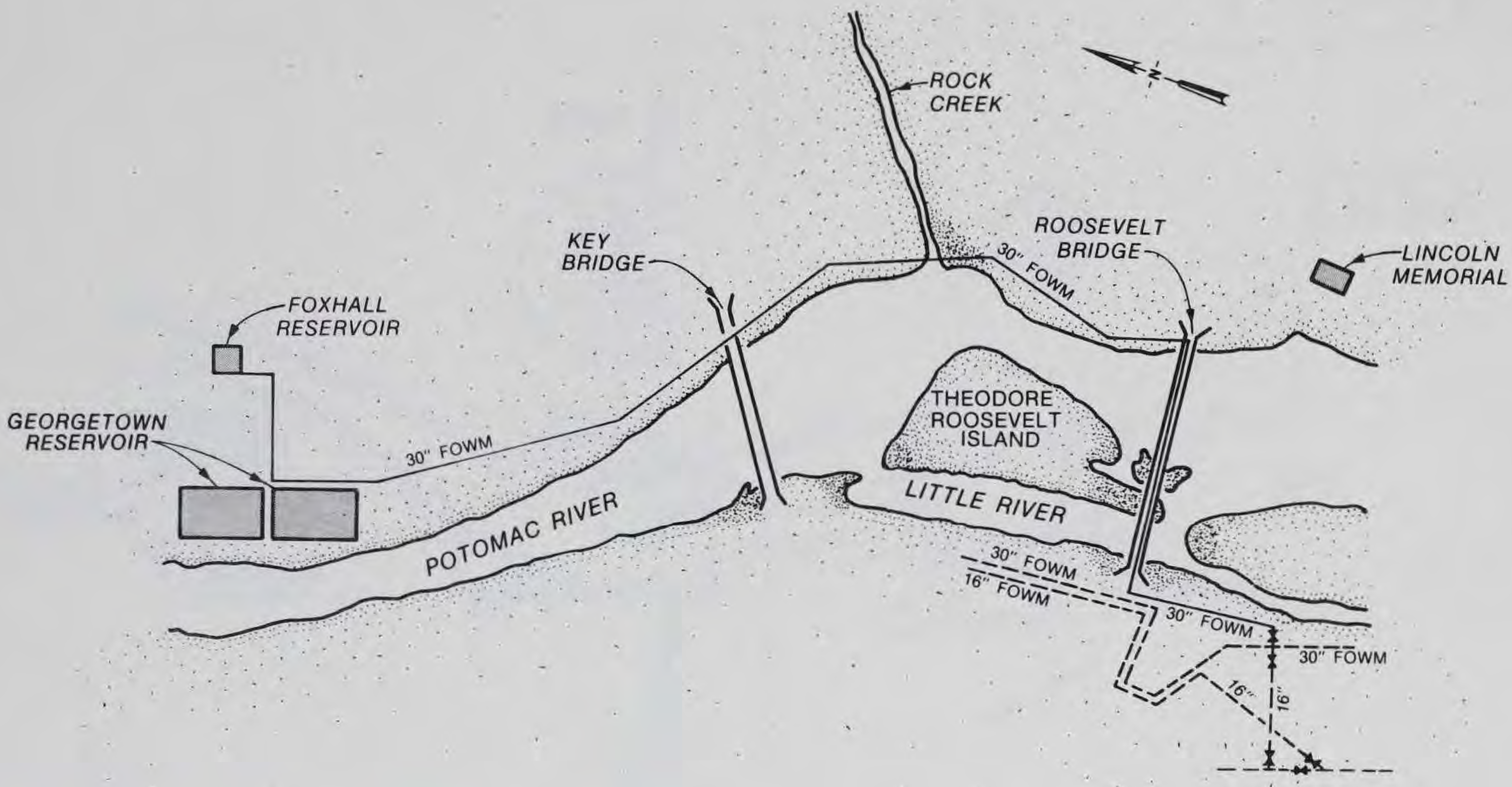


Figure 24. Detail of proposed Roosevelt Bridge river crossing

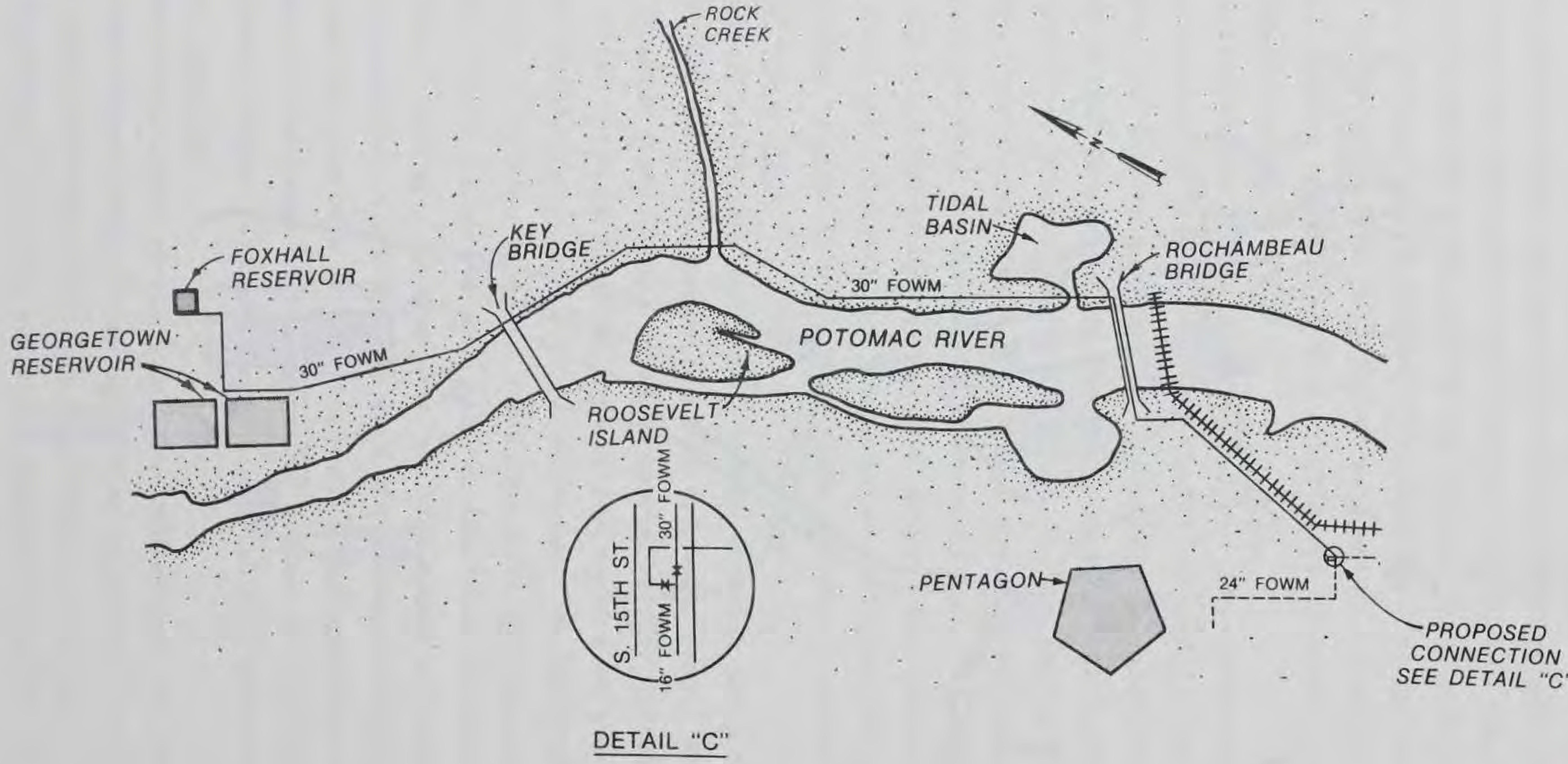


Figure 25. Detail of proposed 14th Street Bridge river crossing

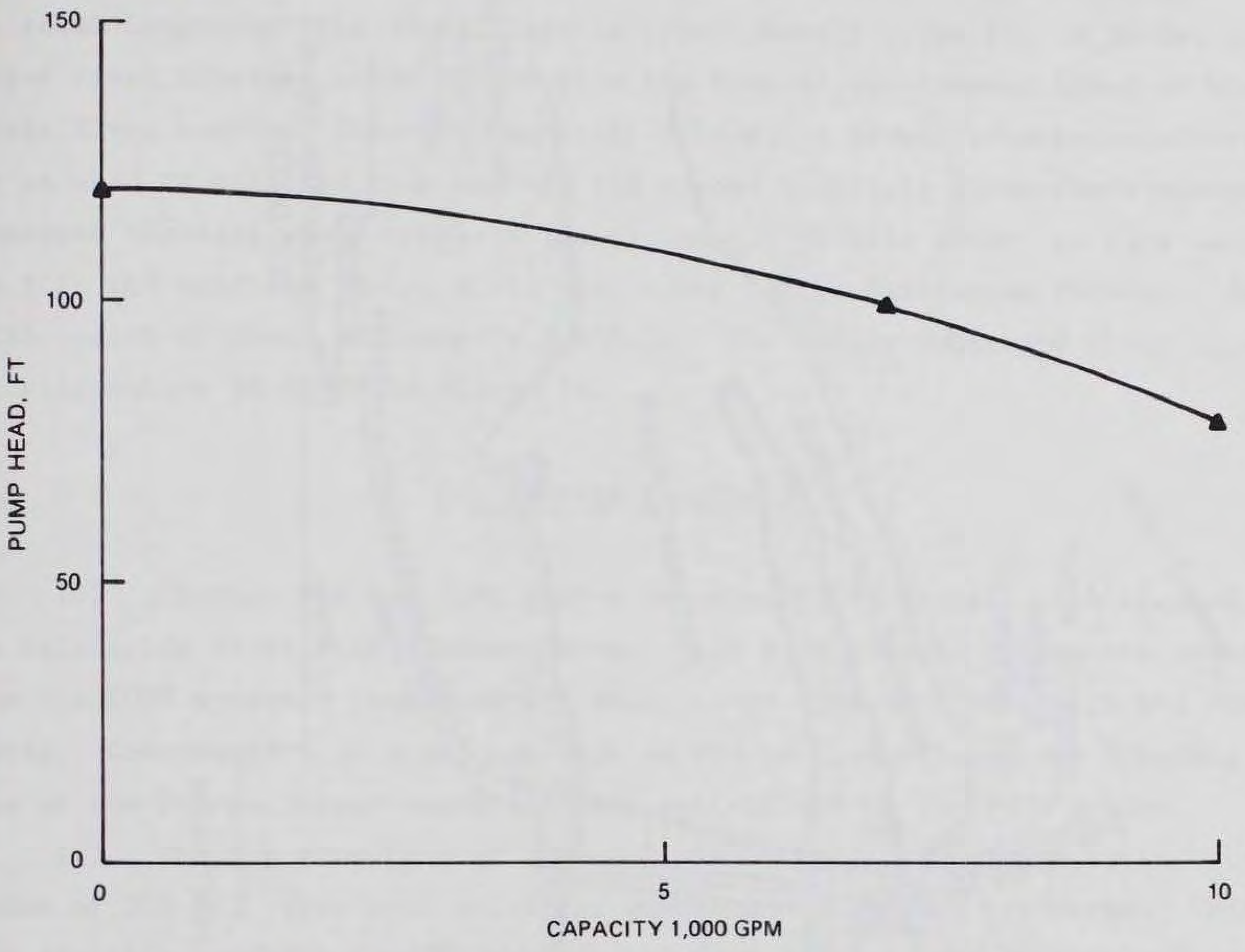


Figure 26. Proposed booster pump characteristic curves

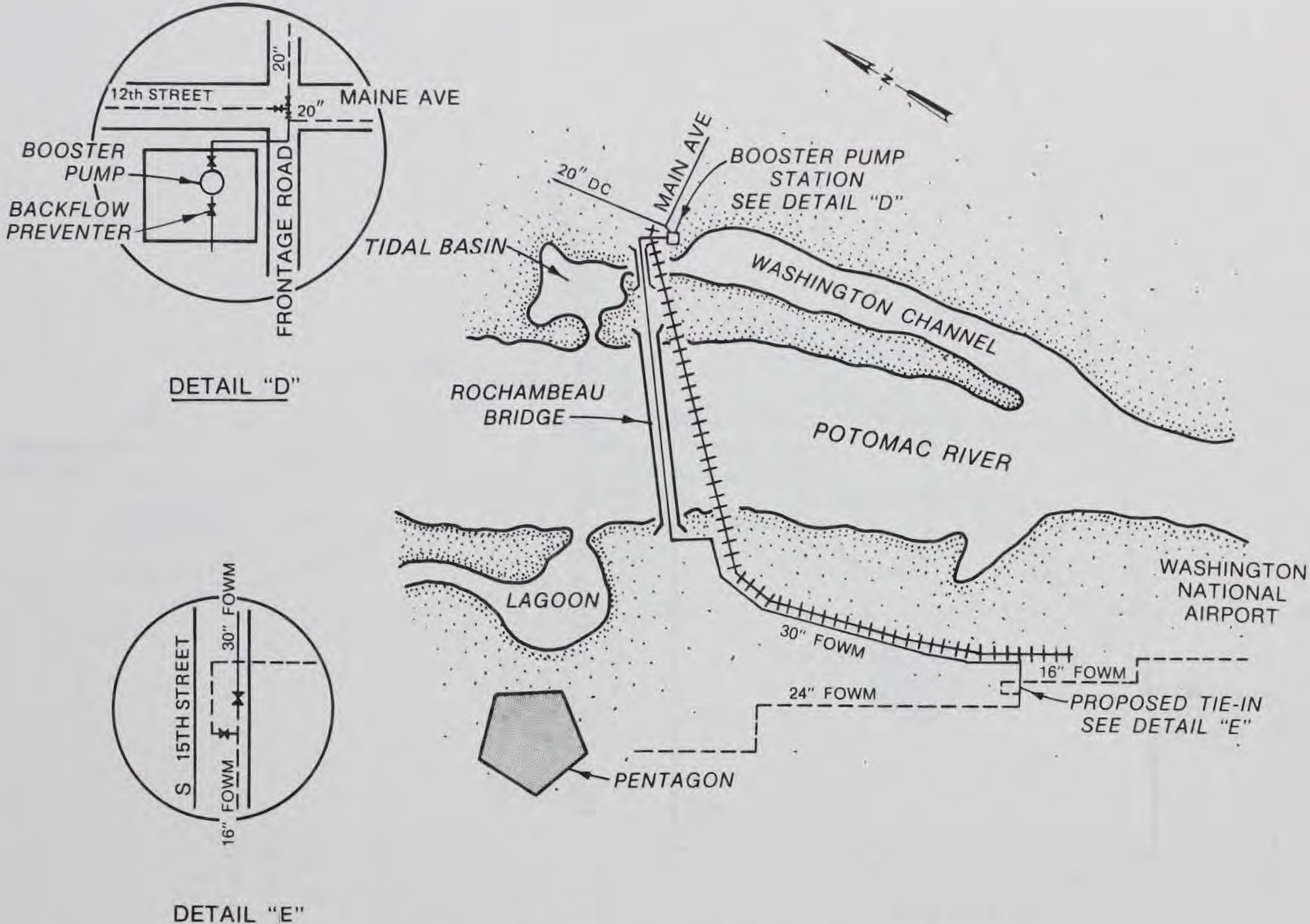


Figure 27. Detail of proposed booster pump off Low service

River and the B&O Railroad tracks up to a point south of Wisconsin Avenue. The total length of this 30-in. line is approximately 9,700 ft. A 30-in. submerged river crossing would extend from the bank of the Potomac River at Wisconsin Blvd. south to Theodore Roosevelt Island. A normal trench installation may be used to take the line through the island to Little River where another submerged crossing would complete the crossing. At this point the line would tie into the existing 30-in. steel main along George Washington Parkway. The total length of river crossing is 2,600 ft. The entire submerged river crossing alternative is shown in Figure 28.

New Storage Facilities

102. Storage for the FOWM system is provided by Foxhall tank located in the Dalecarlia First High pressure zone. This reservoir is across the river from the FOWM system. Consequently, there is no storage facility in the FOWM system. Construction of a storage tank on Federal property on the Virginia side of the Potomac River would increase reliability of the FOWM system.

103. The top elevation of the tank should be 250 ft with a bottom elevation of 225 ft. This will allow for adequate system-wide pressures. The most sensible location for the tank is the Navy Annex as the average elevation in this area is 150 ft. Locating the tank in a topographically high area reduces the height of the tank and thus the cost of the structure.

104. Tank diameter is a function of tank capacity which in turn depends upon the purpose of the storage facility. If the objective of storage is to help provide pressure and flow during periods of high demand, such as peak hourly loading, then a tank with a capacity in the low 100,000-gal range may be used. However, if the primary purpose of the tank is to provide flow during major fires, then a tank with much greater capacity should be used. Table 9 shows tank capacity required for various fire durations based on a fire demand of 7,500 gpm and a tank with top and bottom elevations of 250 and 225 ft, respectively.

105. For purposes of analysis, a diameter of 110 ft was used for the Navy Annex tank. This corresponds to a capacity of just under 1,800,000 gal. This will allow the ISO requirement of a 7,500-gpm fire demand for a duration of 4 hr to be met by this tank (ISO 1980).

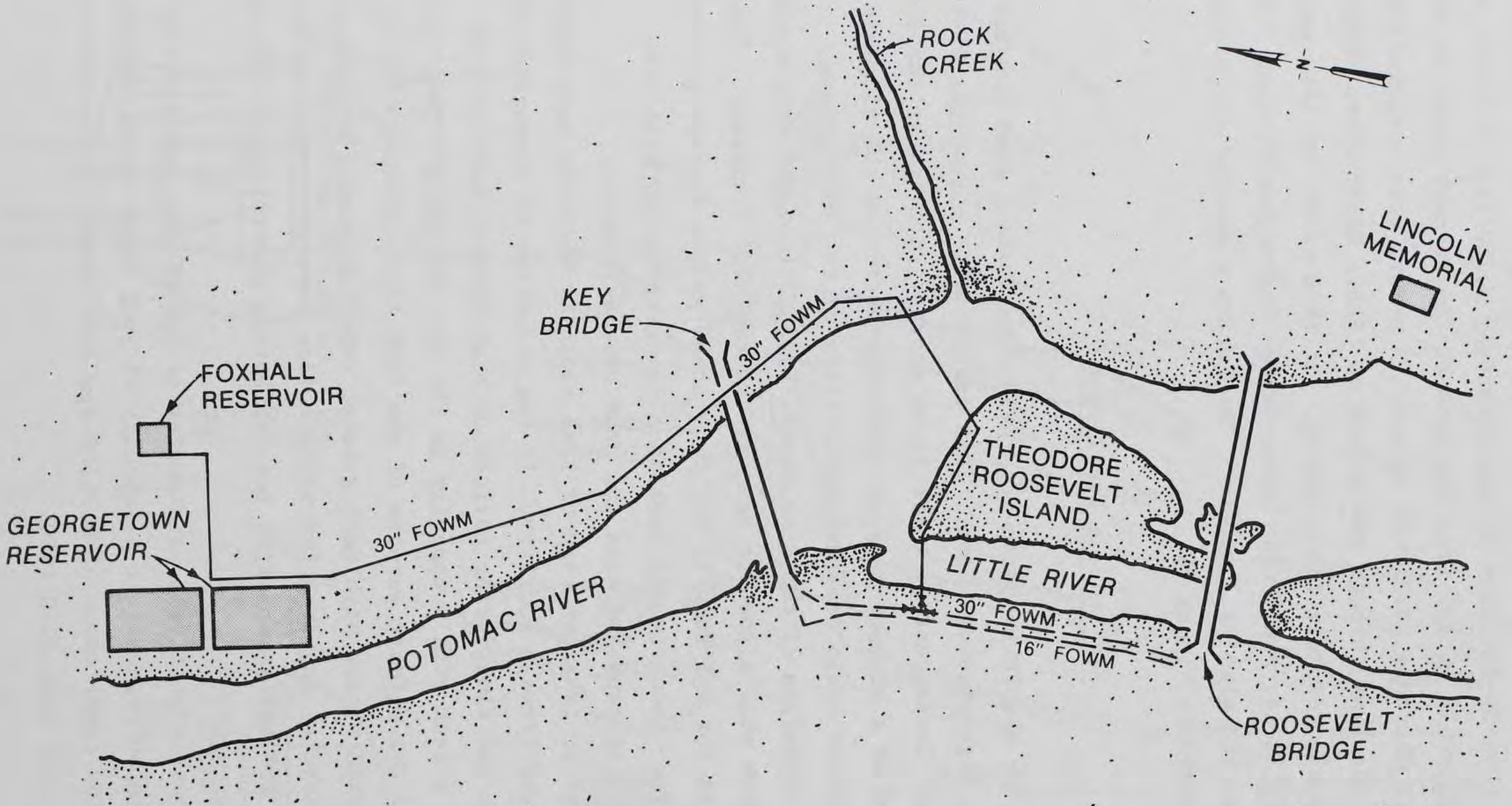


Figure 28. Detail of proposed subaqueous river crossing

Table 9

Tank Capacity Evaluation*

Tank Diameter, ft	Tank Capacity, MG	Fire Demand Duration, hr
10	0.01	0.03
20	0.06	0.13
30	0.13	0.29
40	0.24	0.52
50	0.37	0.82
60	0.53	1.17
70	0.72	1.60
80	0.94	2.09
90	1.19	2.64
100	1.47	3.26
110	1.78	3.95
120	2.11	4.70

* Top height = 250 ft, bottom width = 225 ft, fire demand = 7,500 gpm.

106. The tank would be placed on the east side of the Navy Annex compound. Approximately 1,500 ft of 16-in. pipe would connect the tank with the existing FOWM system at a point just west of the A.N.C. service building. Complete details of this proposal are shown in Figure 29.

New Pipeline Construction

107. Reliability of the FOWM system may also be improved by adding new lines in certain areas within the FOWM system. Not only is reliability increased, but adding new lines also has the net effect of improving overall system performance. Reliability is increased by introducing system redundancy and by creating loops when adding a new line. Performance is improved by reduction of head loss. For the purpose of this study, four new main construction projects were considered. Each project is summarized in the following sections.

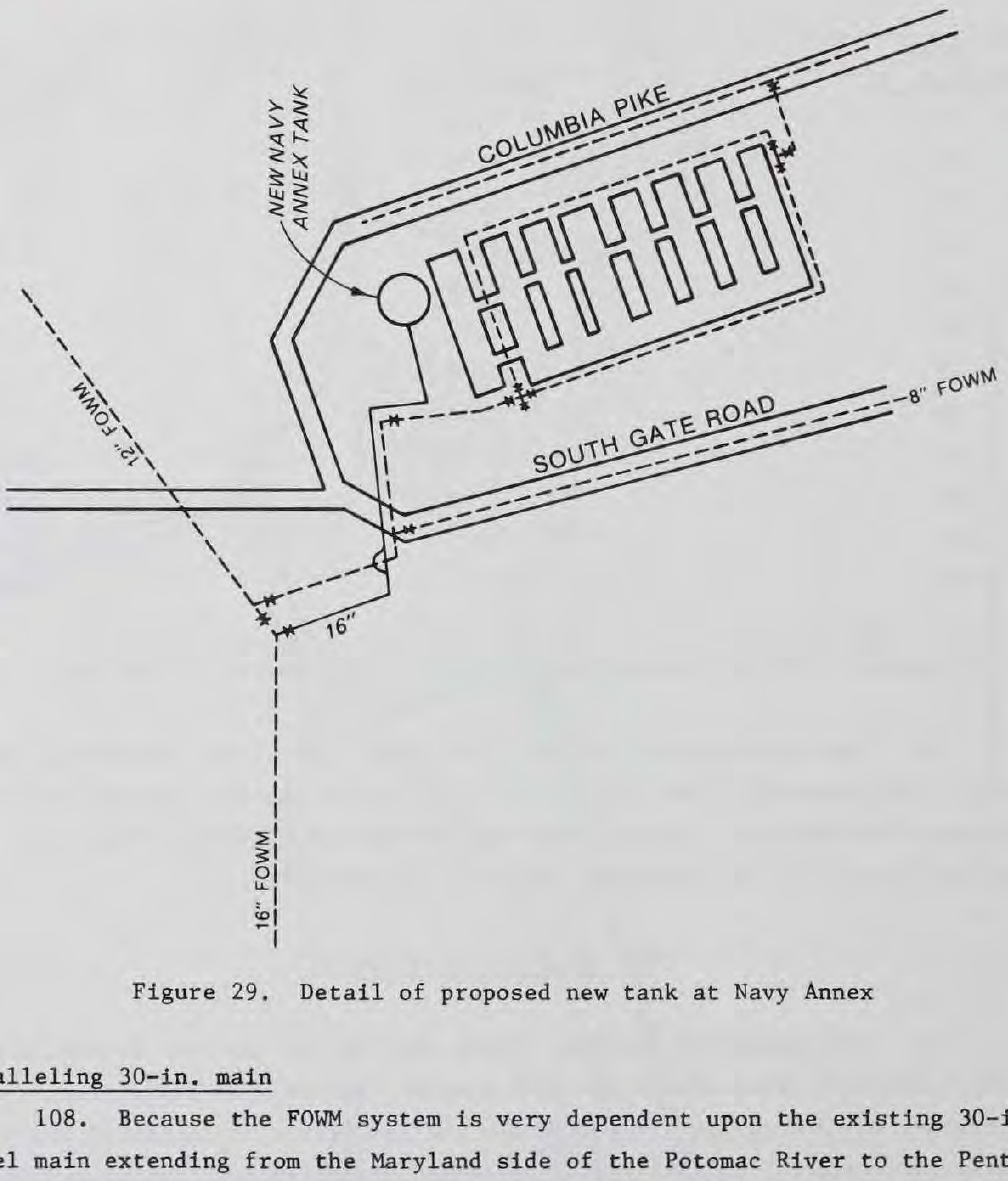


Figure 29. Detail of proposed new tank at Navy Annex

Paralleling 30-in. main

108. Because the FOWM system is very dependent upon the existing 30-in. steel main extending from the Maryland side of the Potomac River to the Pentagon, reliability may be improved by constructing new lines parallel to the 30-in. line. The total length of this line is a little over 13,500 ft, and it is paralleled along its entire length by an existing 16-in main. These lines follow generally the same path from the north side of Key Bridge to the intersection of Jefferson Davis Hwy. and Marshall Drive. At this point the lines diverge from one another with the 30-in. line running along George Washington

Parkway and the 16-in. main running along Eisenhower Drive.

109. Presently there is a connection between the existing 30- and 16-in. supply lines in the vicinity of the Roosevelt Bridge interchange. If the 30-in. line fails anywhere between the DC side of Key Bridge and this connection (approximately 7,000 ft of pipe), all FOWM supply would have to be routed through the parallel 16-in. main. A substantial amount of flow would induce significant head losses in this line. Installing new connections at various locations between the existing lines would improve reliability and reduce losses.

110. To further improve reliability, new lines could be installed adjacent to the existing 30-in. steel main from the intersection of Davis Hwy. and Marshall Drive to the end of the existing line at the north face of the Pentagon. This construction would involve 6,000 ft of 16-in. water line. Connections between the proposed and existing lines are placed approximately every 1,500 ft. Complete details are shown in Figure 30.

New airport feed

111. Constructing a new line from the Pentagon to Washington National Airport will also improve FOWM system reliability by creating another feed to the airport. This plan calls for installing approximately 4,700 ft of 24-in. pipe from a point near the eastern corner of the Pentagon southward parallel to Davis Hwy. to a point east of Davis Hwy. on 15th Street. Figure 31 provides the details for this line. This alternative reduces airport dependency on the single existing airport feed.

Closing Pentagon loop

112. Presently the loop consisting of the 24- and 16-in. pipe around the Pentagon is not connected. A 1,120-ft segment of 16-in. line on the eastern corner of the Pentagon is out of service and prevents the loop from being closed. Figure 32 shows the location of this line. There is no way of serving the heating plant if any portion of the 16-in. line on the southeast and southwest face of the Pentagon were to fail unless the heating plant interconnection were opened. Repairing or replacing the line currently out of service would allow for this contingency without opening the interconnection. Furthermore, this alternative would provide better fire flow to the Pentagon.

New Pentagon loop

113. There is a possibility that office space expansion at the Pentagon will increase floor space and presumably work force about 30 percent.

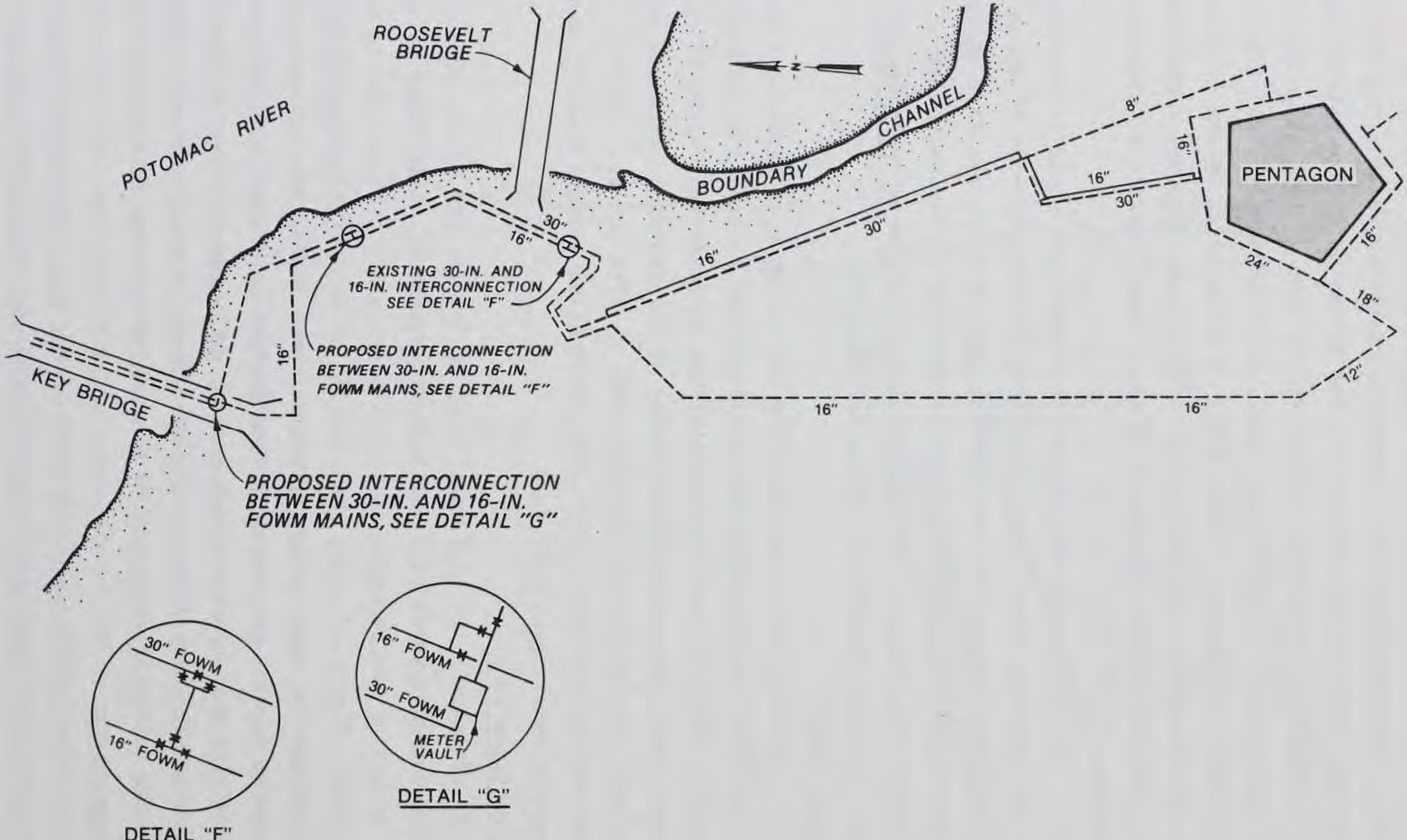


Figure 30. Detail of proposed paralleling 30-in. FOWM main

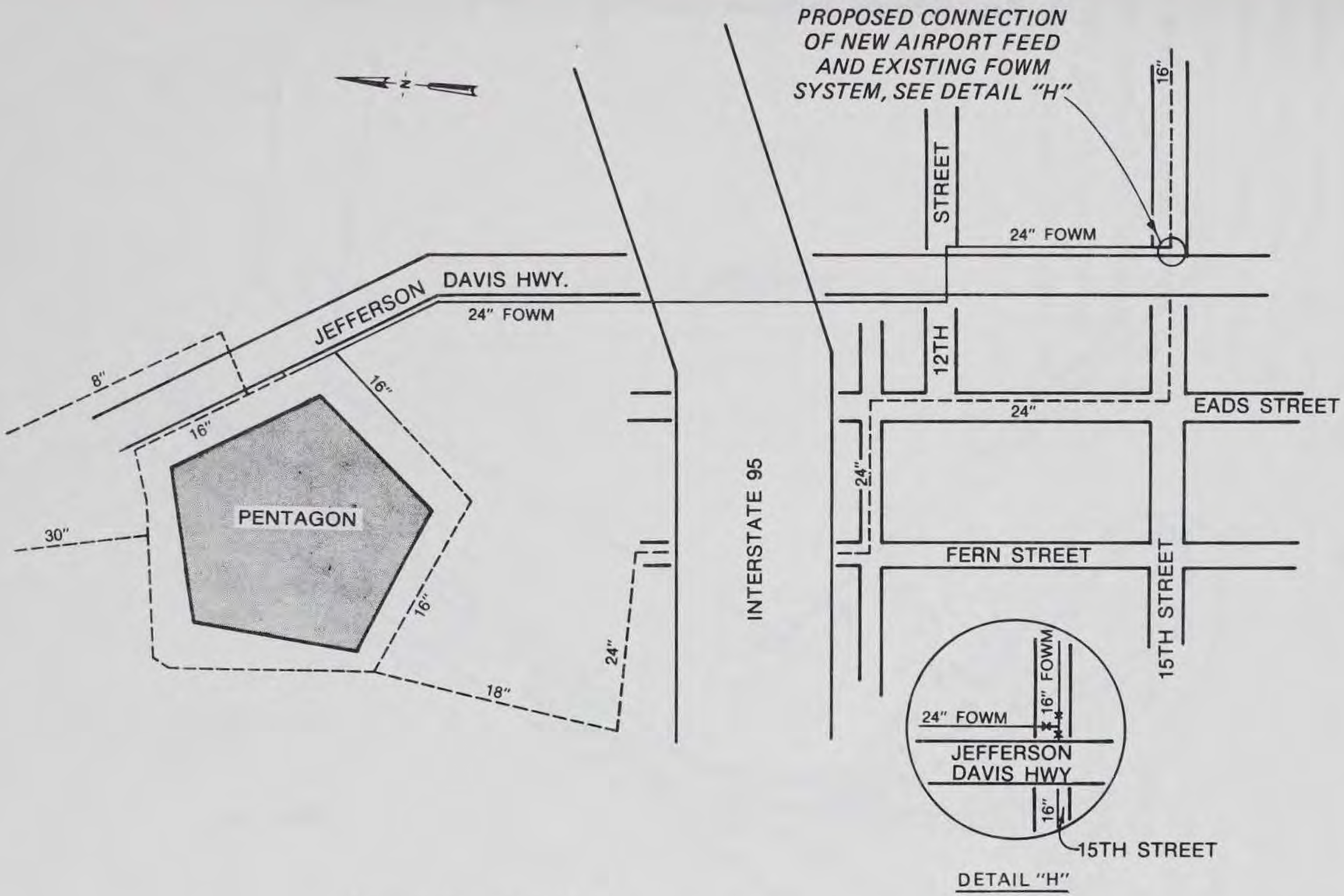


Figure 31. Detail of proposed new airport feed

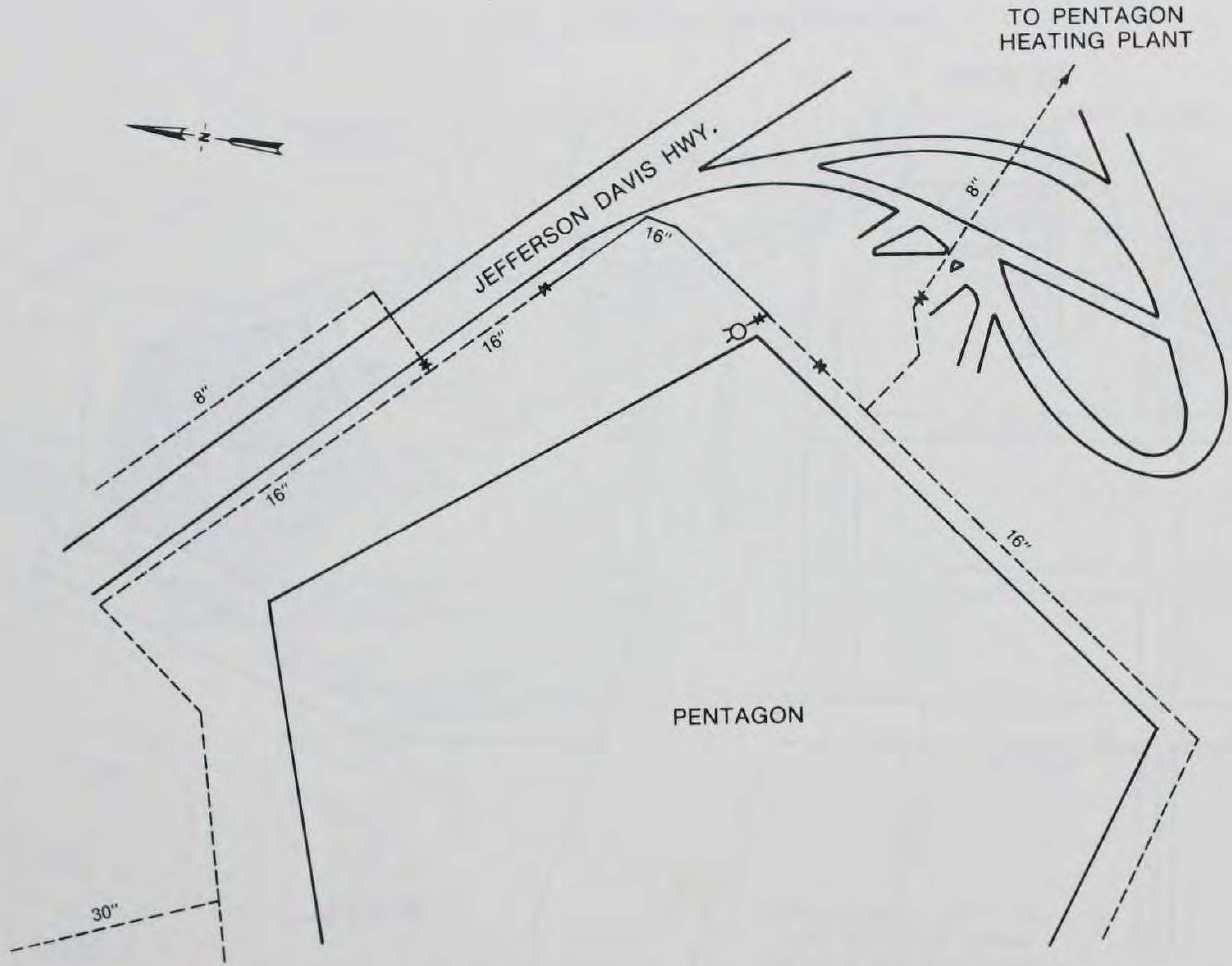


Figure 32. Detail of proposed closing of Pentagon loop

Preliminary indications are that the construction site will be located at a parking lot adjacent to the southwest building face. If construction does proceed, then it would be desirable to place a line on the eastern side of this parcel as shown in Figure 33. This pipe would be approximately 550 ft long with a diameter of 12 in. It would extend from the existing 16-in. main at the south corner of the Pentagon to the existing 24-in. line at the southeast corner of the potential construction site. This line would not only create another loop, thereby increasing reliability, but could also serve as a source of supply for future buildings.

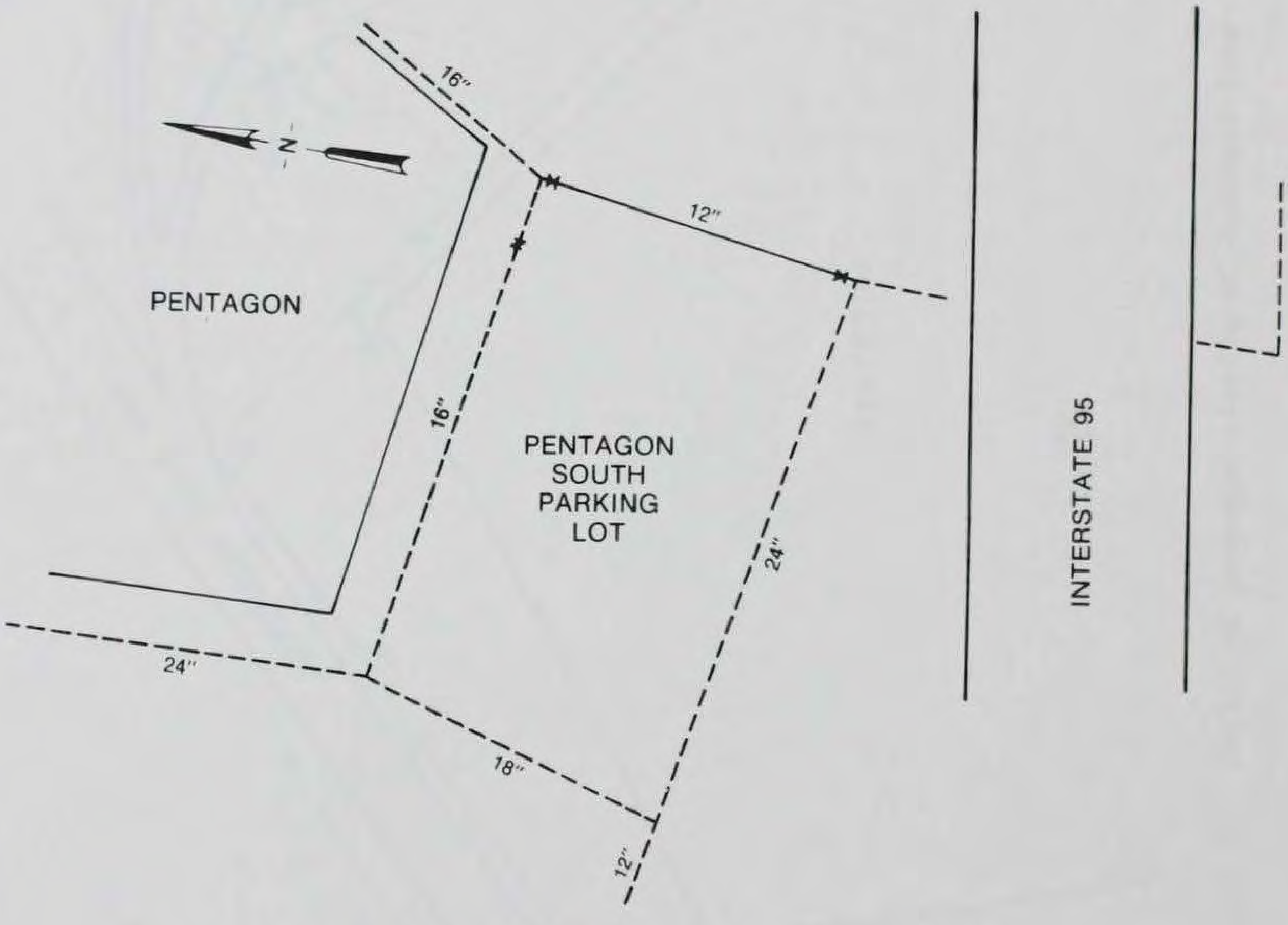


Figure 33. Detail of proposed new Pentagon loop

PART VI: STEADY-STATE ASSESSMENT OF SYSTEM IMPROVEMENTS

Breakdown of Alternatives

114. In the previous section, several alternatives designed to increase FOWM system reliability were identified. These alternatives included:

- a. Use of existing interconnections.
- b. Development of new interconnections.
- c. Construction of additional river crossings.
- d. Construction of new storage facilities.
- e. Construction of additional pipelines.

The first four alternatives can be thought of as supply alternatives since their primary purpose is to provide an alternate source of water to the FOWM system in the event of a supply disruption or major demand. The alternative involving construction of additional pipelines can be regarded as a main-strengthening alternative since construction of new pipes within the existing FOWM system creates additional loops to help offset the decreased hydraulic performance associated with key pipe outages. An alternative involving both a supply alternative and main-strengthening alternative can be regarded as a combined alternative.

Steady-State Evaluation of Supply Alternatives

115. In order to assess the impact of each supply alternative on the overall system reliability, each alternative was evaluated for the same 10 pipe outages used in evaluating the existing system. Furthermore, additional pipe outages which could affect the performance of the alternatives were included to determine the degree of dependency of an alternative upon a neighboring system. For example, analyses were made with pipe outages of critical mains in Arlington County for the interconnection alternatives to determine how dependent the interconnections are upon the Arlington County system. Finally, failure of the Key Bridge river crossing was simulated to determine the ability of an alternative to independently supply the FOWM system. The additional pipe outage scenerios include:

- a. Failure of the Key Bridge river crossing.
- b. Failure of the 36-in. Arlington County feed from Dalecarlia.

c. Failure of the 24-in. Arlington County feed from Dalecarlia.

d. Failure of the PRV at Army-Navy Drive and South Joyce Street.

e. Failure of the PRV at South 16th Street and Lynn Street.

f. Failure of the Arlington County Third Gravity storage tank.

Existing interconnections

116. 15th and Eads interconnection. The FOWM system can be supplied from the Arlington County system through the 15th and Eads interconnection for most pipe outages. However, with the Key Bridge river crossing out of service during periods of high demand, this alternative fails to meet established pressure criteria. Furthermore, in order for the 15th and Eads interconnection to satisfy all FOWM demands with the Key Bridge river crossing out of service, the 24-in. main between the Pentagon and National Airport must be open at all times regardless of loading condition.

117. Fern Street interconnection. The FOWM system may also be supplied by the Fern Street interconnection. This interconnection operates much the same as the 15th and Eads interconnection. Like the 15th and Eads interconnection, this interconnection can supply FOWM for most pipe outages with the exception of a loss of the river crossing during a period of peak demand or a major fire demand. Moreover, with the river crossing out of service, the 24-in. airport feed must remain operational at all times in order for any FOWM system demands to be met by this alternative.

118. Crystal City interconnections. Both of the Crystal City interconnections, operating independently of one another, provide an impact similar to the two previous interconnections. Both interconnections can supply the FOWM system for all scenarios except during peak hourly demand or a major fire demand (for the case where the Key Bridge river crossing is out of service). If the 24-in. line or the 16-in. line between the Pentagon and National Airport were to fail with the Key Bridge river crossing out of service, neither of the Crystal City interconnections could supply demands at the Pentgaon, Navy Annex, Fort Myer, etc.

119. Heating plant interconnection. The interconnection at the Pentagon heating plant can, by itself, provide adequate flows to the FOWM system during average daily and maximum daily loading conditions for most of the pipe outage scenarios. In the event the river crossing is eliminated, system pressures drop well below acceptable levels. If the 30-in. main of the Key Bridge river crossing is removed, the interconnection is still unable to provide

adequate pressures during peak hourly demands and fire demands even with the 16-in. line in service. Furthermore, this interconnection is unable to meet airport demands if any portion of the 24- or 16-in. airport feed is out.

120. Navy Annex interconnection. This interconnection performs much the same as the heating plant interconnection. System pressures are adequately maintained during average and maximum daily loading condition for most of the pipe outage scenarios. During high demands such as peak hourly loading or fire demands, the average system pressure drops below the required minimum when any section of the 30-in. line is removed from service. In addition, this interconnection cannot supply National Airport in the event either the 24- or 16-in. airport supply line is closed.

121. Fort Myer interconnection. The Fort Myer interconnection makes use of a PRV to throttle flow into the Fort Myer system. The exact setting of this PRV is unknown, and as a result, a detailed hydraulic analysis of this interconnection was not possible.

122. Summary. In summary, it appears that the 15th and Eads, Fern Street, and Crystal City interconnections can supply the FOWM system during all loading conditions if the 30-in. supply main is taken out of service. However, if the 16-in. supply line is lost along with the 30-in. line (Key Bridge river crossing), the above interconnections can only handle average daily and maximum daily demands. System pressures would fall below acceptable limits during peak hourly loading, and fire demands at the Pentagon and Washington National Airport could not be met. Furthermore, with the Key Bridge river crossing placed out of service, the 24- and 16-in. line between the Pentagon and National Airport must remain in service at all times in order to supply demands in the FOWM system.

123. The Navy Annex and Pentagon heating plant interconnections also appear to be able to adequately sustain pressures in the FOWM system during periods of average demand. As demands increase, however, the 30-in. main becomes increasingly more important. During periods of high demand or fire demand, neither the Navy Annex nor Pentagon heating plant interconnection can properly supply the FOWM system without the 30-in. main in service. A summary of pressure indices for each of the existing interconnections is provided in Appendix B.

124. From this and previous analyses, it is apparent that the most critical link in the FOWM system is the 30-in. steel main extending from DC

First High to the Pentagon. During an extended outage of this line, operation of the 15th and Eads, Fern Street, or Crystal City interconnection is perhaps the best short-term remedy. However, if the Key Bridge river crossing (30- and 16-in. lines) is taken out of service, none of the existing interconnections could adequately supply the FOWM system for all loading conditions. Because of construction difficulty, failure of the Key Bridge river crossing would result in a long-term outage during which time it is highly likely that peak hourly demands would, at some time, exist. Preliminary analysis has indicated that use of multiple interconnections would still result in inadequate system performance. Because of its inability to adequately supply the FOWM system, the Naval Annex interconnection should be operated only to supply the Annex, not the remainder of the FOWM system. Likewise, the Pentagon heating plant interconnection should be used in the event the heating plant supply line fails.

New interconnections

125. Rosslyn interconnection. The hydraulic performance of the proposed Rosslyn interconnections, operating simultaneously, were evaluated for the same set of pipe outages and loading conditions as the previous alternatives. The primary objective of constructing the Rosslyn interconnections is to provide a source of supply in the event of failure of any portion of the Key Bridge river crossing. This system interconnection performs adequately during average daily and maximum daily loadings with various FOWM and Arlington mains out of service. However, during peak hourly loadings, system pressures cannot be maintained with any segment of the 30-in. FOWM transmission main out of service. This is due to the large head losses induced in the Rosslyn pressure zone during periods of high flow. Furthermore, this alternative is unable to provide a source of supply for National Airport in the event of failure of the airport feed (a 24-in. line and a 16-in. line connected in series). Unlike Second and Third Gravity, the Rosslyn pressure zone has no storage tank to help supply water and pressure during periods of high demand.

126. The Rosslyn interconnection fails to maintain adequate system pressures with fire demands placed at the Pentagon and National Airport during an outage of any section of the 30-in. main. This reiterates the importance of the existing 30-in. line. Fire demands at Fort Myer can be met with little detrimental effect. A summary of the resulting pressure indices for this interconnection is shown in Appendix B.

127. New airport interconnection. The purpose of this interconnection is not to supply the entire FOWM system in the event of failure within the network; rather it is intended to provide additional reliability for National Airport. At present, the airport is supplied by a single line composed of a 24-in. main and a 16-in. main connected in series. If this line were to fail, an existing Arlington County interconnection must be opened to deliver water to the airport. If failure occurred between the interconnection and the airport, no water could be delivered to the airport. The new airport interconnection, as proposed, would solve this problem.

New river crossings

128. Roosevelt Bridge crossing. During average daily and maximum daily demands, the Roosevelt Bridge crossing would provide adequate flows and pressures for each of the pipe outage scenarios. Also, under peak hourly loading conditions, this line could satisfy FOWM demands with the Key Bridge river crossing off line.

129. However, if the 30-in. FOWM transmission main were to be taken out of service anywhere along its length south of the new bridge tie-in during peak hour demands or fire loadings at the Pentagon and National Airport, average system pressures would fall below acceptable limits. Again, this is due to large volumes of water flowing through the existing 16-in. FOWM main, causing excessive head loss. Fire demands at Fort Myer can be met during any pipe outage with little adverse effect on the system.

130. Although this alternative allows FOWM to be supplied from DC First High in the event of Key Bridge river crossing failure, National Airport cannot be supplied if any part of the existing airport feed were closed. If this scenario were to occur, a system interconnection in the vicinity of the airport must be opened to supply National Airport.

131. 14th Street Bridge crossing. The 14th Street Bridge crossing provides adequate system pressures for all pipe outages under each loading condition with the exception of one case. The case in which the new crossing does not provide adequate pressure is for a fire demand at the Pentagon with the Key Bridge river crossing out of service. This is due to large line losses in the line between the proposed tie-in of this alternative with the FOWM system and the Pentagon.

132. Unlike the Roosevelt Bridge crossing, demands at National Airport can be met under this proposal if the existing airport feed were to fail

between the Pentagon and the tie-in with FOWM. This is possible because of the location of the tie-in with the FOWM system. However, without an interconnection between Arlington County and National Airport (as described in the previous section), the 14th Street Bridge alternative is unable to supply demands at National Airport if a segment of line between the proposed tie-in and the airport were to fail.

133. Booster pump off Low service. The performance of the booster pump alternative is very similar to the 14th Street Bridge river crossing from DC First High because of the location of the proposed tie-in with FOWM. Adequate system pressures can be maintained during all pipe scenarios with the exception of a fire demand at the Pentagon with the Key Bridge river crossing out of service. Again, this is due to the large head losses in the 24- and 16-in. lines between the proposed connection and the Pentagon.

134. Similarly, demands at National Airport can be met with this alternative if the existing airport feed were to fail between the Pentagon and the proposed tie-in with FOWM. However, without an interconnection between Arlington County and National Airport, this alternative is unable to supply demands at the airport if a segment of line between the proposed tie-in and the airport were to fail.

135. Subaqueous river crossing. Performance of the subaqueous river crossing is very much like that of the Roosevelt Bridge crossing. Average system pressure can be adequately maintained during all scenarios except during periods of high flow when the existing 30-in. FOWM main is out. Furthermore, demands at National Airport cannot be met with this crossing if any portion of the line feeding the airport were to fail. Pressure indices for all new river crossing alternatives are summarized in Appendix B.

New storage facilities

136. A tank placed at the Navy Annex with a top elevation of 250 ft, a bottom elevation of 225 ft, and capacity of 1,800,000 gal was evaluated to judge its contribution to FOWM reliability and performance. Operation of the facility was examined for the same pipe outages as the previous supply alternatives. For purposes of analysis, the tank was assumed to be full; however, steady-state simulations were made with the tank half-full and empty to evaluate the sensitivity of the FOWM system to tank level.

137. Adequate system pressures may be maintained with the Navy Annex storage tank during average daily, maximum daily, and peak hourly demands for

all pipe outages. Because of high head loss in existing FOWM lines, the tank cannot provide adequate system pressure for instances where the 30-in. FOWM main is out of service and fire demands are placed at the Pentagon or National Airport. Pressure indices for this alternative are summarized in Appendix B.

138. With the Key Bridge river crossing out of service, a storage facility at the Navy Annex can supply water to the entire FOWM system. However, this supply is limited and could not meet demands during long-term supply outages. This alternative is unable to meet airport demands if a segment of the existing airport feed were to fail. An interconnection in the vicinity of the airport must be opened in this case.

Summary

139. Several supply alternatives have been proposed in an effort to improve the reliability of the FOWM water distribution system. The primary purpose of the supply alternatives is to provide an alternate source of supply to FOWM in the event of a supply disruption, such as failure of the Key Bridge river crossing, or a major system load, such as a fire at the Pentagon. Each of the alternatives is able to supply the FOWM system with varying levels of performance.

140. Of the existing interconnections, the 15th and Eads, Fern Street, and Crystal City interconnections can supply the FOWM system during most pipe scenarios. The only case where these interconnections fail is when the Key Bridge crossing is out of service during periods of high demand. However, this assumes that the line between National Airport and the Pentagon is in service at all times. If any portion of this line between the Pentagon and the interconnection were to fail during a Key Bridge outage, demands at the Pentagon, Navy Annex, Henderson Hall, Fort Myer, and Arlington National Cemetery could not be met.

141. The Navy Annex and Pentagon heating plant connections are unable to adequately supply the FOWM system for several pipe scenarios. These interconnections are able to provide adequate supply to the facilities in the immediate vicinity of the connection (Navy Annex and Henderson Hall, Pentagon heating plant) and as a result should be used to supply these facilities during emergency conditions.

142. The Rosslyn interconnection is unable to provide adequate pressure and flow to the FOWM system during high flow periods if any portion of the 30-in. FOWM transmission main is out of service. This is due to large head

losses in lines located in the Rosslyn pressure zone. The National Airport interconnection is able to provide flow at adequate pressure to the airport under average daily, maximum daily, and peak hourly demands if the existing airport feed were to be closed. However, this alternative cannot, by itself, supply the required fire demand of 7,500 gpm to National Airport.

143. Each of the proposed river crossings is able to adequately supply the FOWM system during most pipe outage scenarios. Some of the river crossing alternatives perform better than others for certain scenarios. For example, neither the Roosevelt Bridge crossing nor the subaqueous crossing is able to supply demands at National Airport if a portion of the existing airport feed were to fail between the Pentagon and Crystal City. Both the 14th Street Bridge crossing and the Booster Pump Off Low Service alternatives, on the other hand, are able to supply National Airport during this scenario. Each of the river crossing alternatives is able to supply FOWM for an outage of Key Bridge assuming all remaining FOWM lines are in service.

144. The new storage tank at the Navy Annex alternative is similar to the Roosevelt Bridge and subaqueous river crossing proposals in that it is able to adequately supply FOWM system demands during most pipe outage scenarios. Like these river crossing alternatives, the proposed tank cannot deliver adequate pressure and flow for outages of the 30-in. transmission main during periods of high demand. Furthermore, this alternative is unable to supply enough volume of water to meet ISO fire fighting requirements (7,500 gpm for 4 hr) with the Key Bridge river crossing out of service.

Main-Strengthening Alternatives

145. Analysis of the existing system identified several critical lines or pairs of lines which, when placed out of service, would result in unacceptable hydraulic performance of the FOWM system. These lines include the 30- and 16-in. mains suspended beneath Key Bridge (Key Bridge river crossing), the 30-in. FOWM transmission main from Key Bridge to the Pentagon, the 24-in. main between the Pentagon and 15th and Eads Streets, and the 16-in. line between 15th and Eads Streets and National Airport. The last two lines comprise the only feed to National Airport.

146. Two alternatives were proposed; each was designed to reduce the effect of an outage of a critical line. These alternatives included

paralleling the 30-in. FOWM transmission main and installing a new airport feed. Two additional alternatives involving new pipeline construction were also proposed. Closing the Pentagon loop would make the FOWM system more hydaulically efficient by reducing head losses in the vicinity of the Pentagon. Constructing a new Pentagon loop is contingent upon proposed expansion of the Pentagon, but would also reduce head losses in this area. Each of the main-strengthening alternatives was evaluated for the same pipe outage scenarios as the existing system.

Paralleling the 30-in.
main and new airport feed

147. Paralleling the existing 30-in. FOWM transmission main with a 16-in. line and installing more interconnections between the existing 30- and 16-in. mains between Key Bridge and Marshall Drive helps to reduce the effect of an outage of the 30-in. line. Adequate system pressures can be maintained during most pipe outage scenarios. However, this alternative is unable to ensure adequate system-wide pressure during an outage of the 30-in. main under Key Bridge during fire demands at the Pengaton or National Airport. During these scenarios, high flows in the 16-in. line suspended beneath Key Bridge result in excessive head loss such that system pressures fall below minimum requirements. Furthermore, this alternative does not help to reduce large head losses generated in the existing airport feed during a fire at National Airport. Pressure indices for this alternative are shown in Appendix B.

148. Constructing a new feed to National Airport does not help to offset the reduced system performance caused by an outage of the 30-in. FOWM transmission main. However, this alternative does improve system reliability by creating another feed to National Airport. If any segment of the existing airport feed were to be placed out of service, demands at National Airport could still be met under this alternative without opening an interconnection with Arlington County. Furthermore, the new airport feed and the existing airport feed will deliver a fire flow of 7,750 gpm under maximum daily loading conditions, which exceeds ISO requirements. Pressure indices for this alternative are shown in Appendix B.

Closing the 16-in. Pentagon loop

149. Closing that portion of the 16-in. Pentagon loop which is currently out of service does not appreciably improve system performance over the existing FOWM system. System pressures fall well below acceptable limits if

any portion of the 30-in. FOWM transmission main is taken out of service. Also, demands at National Airport cannot be met under this alternative if a segment of the existing airport feed were to fail. Constructing this loop does increase reliability, however, by adding system redundancy. Pressure indices for this alternative are provided in Appendix B.

New Pentagon loop

150. Constructing a new Pentagon loop will not, by itself, reduce the effect of an outage of the 30-in. FOWM transmission main. System pressures fall below acceptable limits during peak hourly loading or fire demands at the Pentagon and National Airport under this alternative when a segment of 30-in. line is placed out of service. The only difference between existing system performance and performance under this alternative is the reduced effect of an outage of the 18-in. line by the Pentagon during a National Airport fire. This alternative will also ensure that demands at National Airport are met if a section of the 24-in. line along the Pentagon south parking lot were to fail. Pressure indices for the New Pentagon Loop alternative are shown in Appendix B.

Summary

151. None of the proposed main-strengthening alternatives, acting independently, will completely offset the reduction in system pressure and flow caused by outage of certain key lines. Paralleling the existing 30-in. line will result in adequate system-wide pressures if any portion of the 30-in. line on the Virginia side of the Potomac River were to fail. However, if the portion of this line suspended beneath Key Bridge were to fail, adequate pressure could not be maintained for fire demands at the Pentagon and National Airport. Constructing a new airport feed increases the available fire flow to the airport such that ISO requirements are met. Also, this alternative will ensure that demands are met at National Airport if a segment of the existing airport feed were to be placed out of service. Closing the Pentagon loop and constructing a new Pentagon loop does not drastically improve the performance of the FOWM system over the existing system. However, these alternatives do increase system reliability by adding new loops and thereby creating redundancy.

152. Although none of the main-strengthening alternatives can, by themselves, reduce the effect of an outage of a key FOWM main, combining a main-strengthening alternative with a supply alternative may result in a

system which can deliver adequate performance under all pipe outage scenarios.

Selection of Alternatives

153. Based on the results of the previous screening process, six separate measures to improve reliability were selected for further investigation. These include: (a) the 15th and Eads interconnection, (b) the Roosevelt Bridge river crossing, (c) the 14th Street Bridge river crossing, (d) the booster pump off Low service, (e) the subaqueous river crossing, and (f) the new tank at the Navy Annex.

15th and Eads interconnection

154. The 15th and Eads interconnection was selected for further examination because of its ability to supply the FOWM system in the event of an emergency. The Fern Street and Airport interconnections also appear capable of supplying flow at adequate pressures. All four interconnections are hydraulically similar. An assumption was made that the 15th and Eads interconnection would be operated during long-term outages, as opposed to the other interconnections, because a flowmeter that is part of this interconnection allows monitoring of flows between FOWM and Arlington County.

Roosevelt Bridge crossing

155. The Roosevelt Bridge crossing was chosen for further evaluation because of its ability to serve the FOWM system when the Key Bridge crossing is out of service. This alternative does not improve reliability or performance when the 30-in. main along George Washington Parkway is closed, yet it does meet the primary objective of providing another source of supply.

14th Street Bridge crossing

156. Like the previous alternatives, the 14th Street Bridge crossing was selected for further investigation because of its ability to supply FOWM during a Key Bridge outage. Unlike the Roosevelt Bridge crossing, it affords an added measure of reliability by being able to provide adequate system pressure during an outage of the 30-in. steel main along George Washington Parkway. Furthermore, it allows supply of National Airport during outages of the existing airport feed between the Pentagon and the proposed tie-in of this alternative.

Booster pump off Low service

157. The booster pump alternative was investigated further since it

also has the capability of supplying system demands during outages of critical FOWM lines. Demands at National Airport may be met by this alternative if a portion of the airport feed between the Pentagon and the proposed tie-in were to fail.

Subaqueous river crossing

158. The subaqueous river crossing is also able to supply the FOWM system during an outage of the Key Bridge crossing. However, because of the location of the tie-in with the existing system, it does not have the capability of providing adequate system pressures during an outage of the 30-in. steel main along George Washington Parkway.

New tank at Navy Annex

159. Similar to the previous alternatives, a storage tank at the Navy Annex has the ability to supply the FOWM system during an emergency such as the Key Bridge outage. Consequently, it was investigated further.

Remaining alternatives

160. The Navy Annex and Pentagon heating plant interconnections were not investigated further because of their inability to supply the FOWM system for an emergency event during periods of high flow. They do appear to be fully capable of supplying water to facilities immediately adjacent to the interconnection. As a result, they should be used for such applications and not for supply of the entire FOWM network.

161. The proposed Rosslyn interconnection has also been eliminated from further examination because of its inability to supply FOWM during periods of high flow. This alternative was to be used as a Key Bridge crossing backup; however, high head losses through the Arlington County system during high flow periods preclude its use as a viable alternative. The new airport interconnection was not selected for further examination because its primary use is only to supply National Airport, not the entire FOWM system.

PART VII: EXTENDED PERIOD EVALUATION OF SELECTED ALTERNATIVES

162. In addition to the steady-state evaluation performed in the previous part, each of the selected alternatives was evaluated for a series of extended period simulations. The purpose of the extended period analysis is to determine the impact of each proposed alternative on the supporting systems. The supporting system for the 15th and Eads interconnection is the Arlington County system, whereas the supporting system for the Roosevelt Bridge crossing, 14th Street Bridge crossing, the booster pump off Low service, and the subaqueous river crossing is the DC system. Such impacts could be a reduction of system pressures and an adverse effect on storage tank operation in the supporting network. Other detrimental effects to the supporting system are high pipe velocities and excessive hydraulic gradients.

163. Each alternative was analyzed for three extended period scenarios. For each scenario, the fluctuation of the water level in the controlling tank was observed as were supporting system pressures and FOWM system pressures.

Description of Extended Period Scenarios

First scenario

164. The first extended period scenario is a 48-hr simulation with average daily demands during the first 24 hr and maximum daily demands during the next 24 hr. Average daily demands are assumed to follow the pattern shown in Figure 34. Maximum daily demands are assumed to follow the same pattern, but are 40 percent greater. For this analysis, the Key Bridge river crossing is assumed to be out of service. Each simulation was begun at midnight, and all storage tanks were assumed to be half full at the start of the simulation.

Second scenario

165. The second simulation is similar to the first except that a main failure is assumed to occur along the existing 30-in. Key Bridge river crossing and to last for 1 hr at which time the main is shut down. During the hour before the main is valved off, water is assumed to discharge freely from the line. Once the main is valved off, it will remain out of service for the remainder of the simulation. The parallel 16-in. main remains in service for the entire duration of the analysis. Each simulation began at midnight, and all storage tanks were assumed to be half full at the start of the simulation.

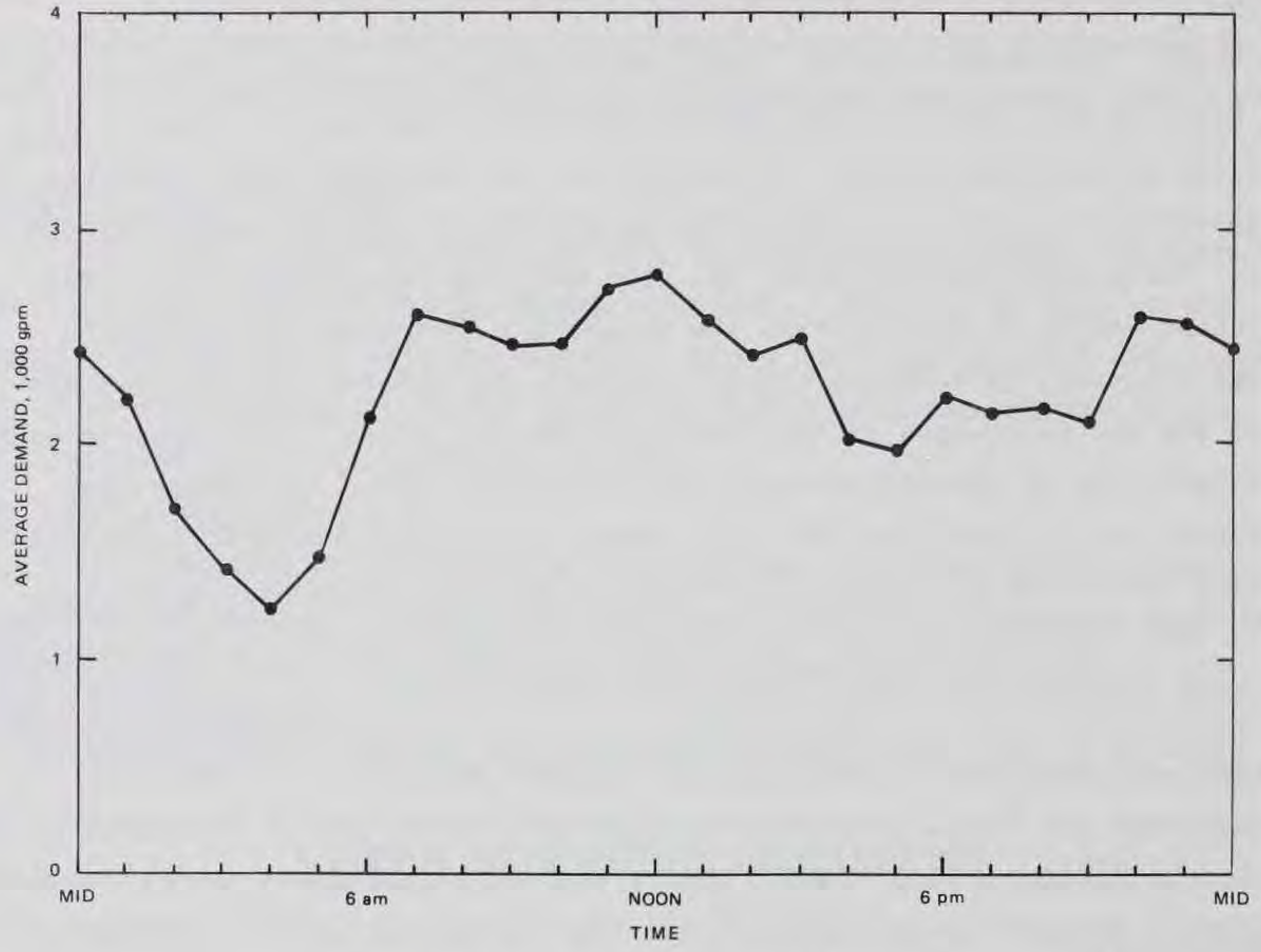


Figure 34. Variable demand pattern

Third scenario

166. The final scenario consisted of three 24-hr simulations with a fire demand superimposed over an average daily demand pattern. Fire demands were placed at the Pentagon, Washington National Airport, and Fort Myer. The variable demand pattern used is shown in Figure 34. A fire demand of 7,500 gpm for a duration of 4 hr, as specified by ISO requirements, was used for the Pentagon and National Airport. A 4-hr fire demand of 2,400 gpm, which is the rated capacity of the Fort Myer booster pumps, is also used for the military reservation. For this scenario, the 30-in. main under Key Bridge is assumed to be out of service.

167. Each simulation was begun at midnight, and fire demands were assumed to begin at noon. This corresponds to the peak demand for the demand pattern used. For the purposes of the study, all tanks were assumed to be half full at the start of the simulation. At the beginning of each simulation, one pump on each pressure zone was assumed to be operating. If a tank

reached a level corresponding to 25-percent full, another pump was placed on line. If a tank drained to 15 percent of its capacity, a third pump was placed on line. Once a tank regained 15 or 25 percent or its capacity, the additional pumps put on line were shut down. Also, if a tank filled to its capacity, all pumps at the pumping station were shut down, and the tank was allowed to feed the system.

15th and Eads Interconnection

First scenario

168. A 48-hr extended period simulation indicates that the operation of the 15th and Eads interconnection adversely affects the operation of the Third Gravity tank. With the tank initially half full, operation of the 15th and Eads interconnection drains the Third Gravity tank very rapidly. In fact, the tank is nearly empty 12 hr into the simulation. Tank levels recover somewhat during the next 20 hr, but the tank drains completely 32 hr into the analysis and remains empty for the remainder of the simulation. Figure 35 shows the variation in tank levels for this scenario.

169. With the Third Gravity tank empty, the 15th and Eads interconnection is able to satisfy FOWM system demands at adequate system pressures. However, when the tank is empty, average FOWM system pressure is a little greater than the 40-psi minimum. Furthermore, draining the Third Gravity tank is unacceptable since no emergency and fire storage for the Third Gravity system is available with an empty storage tank.

Second scenario

170. A second 48-hr simulation, identical to the previous scenario, was performed for the 15th and Eads interconnection alternative except the 30-in. line under Key Bridge was taken out of service 1 hr after failing. The 15th and Eads interconnection was opened at the same time the 30-in. line was closed. Tank levels for this case are shown in Figure 36.

171. During the 1-hr period before the 30-in. main is valved off, pressures in the FOWM system fall well below acceptable limits, and the Third Gravity tank drains a great deal. The 16-in. line augments the supply provided by the 15th and Eads interconnection once the 30-in. line is closed. Nonetheless, tank levels fall soon after the start of the simulation and drop to almost empty 37 hr into the analysis. For this scenario, tank levels are

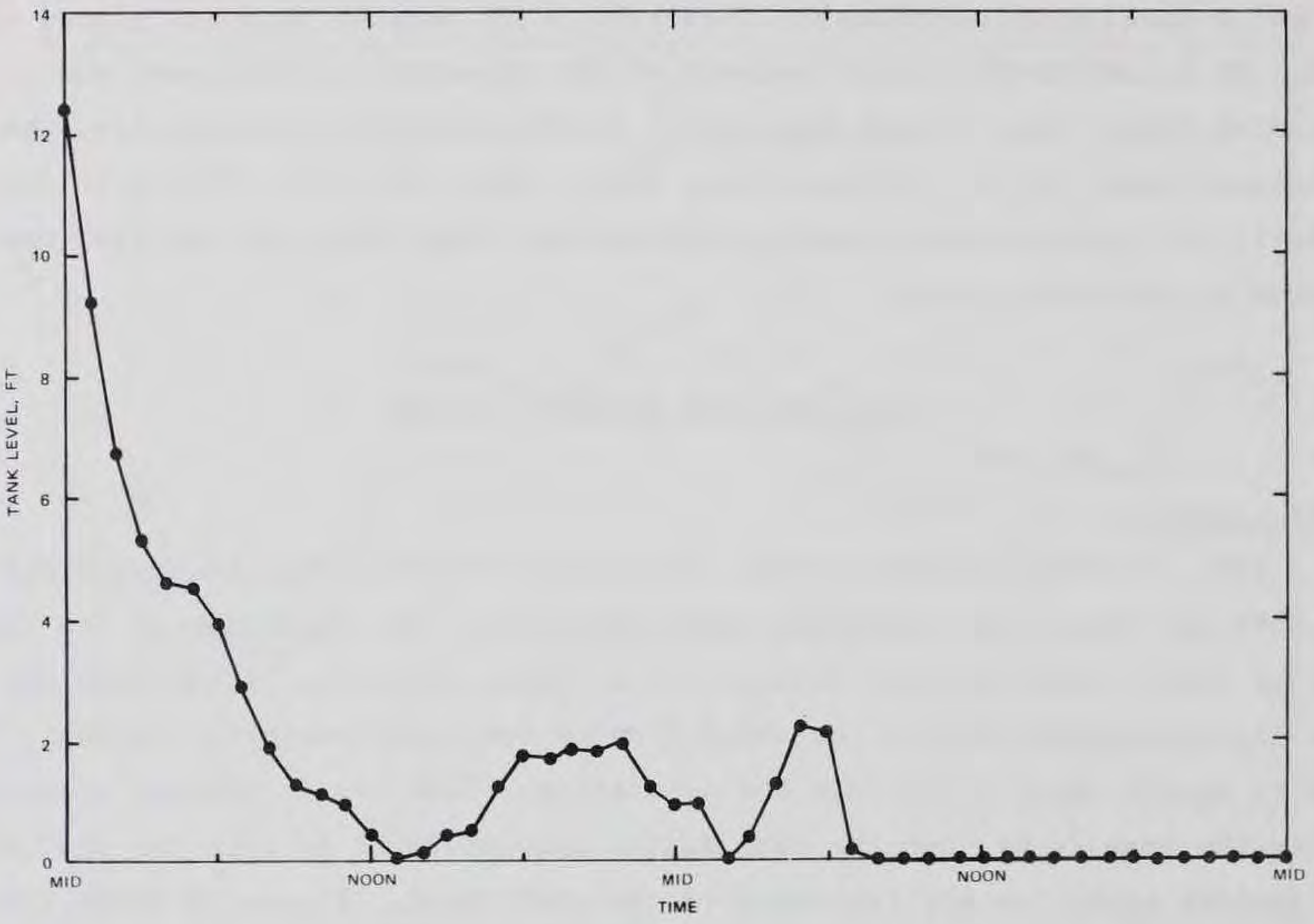


Figure 35. Third Gravity tank levels for first loading condition

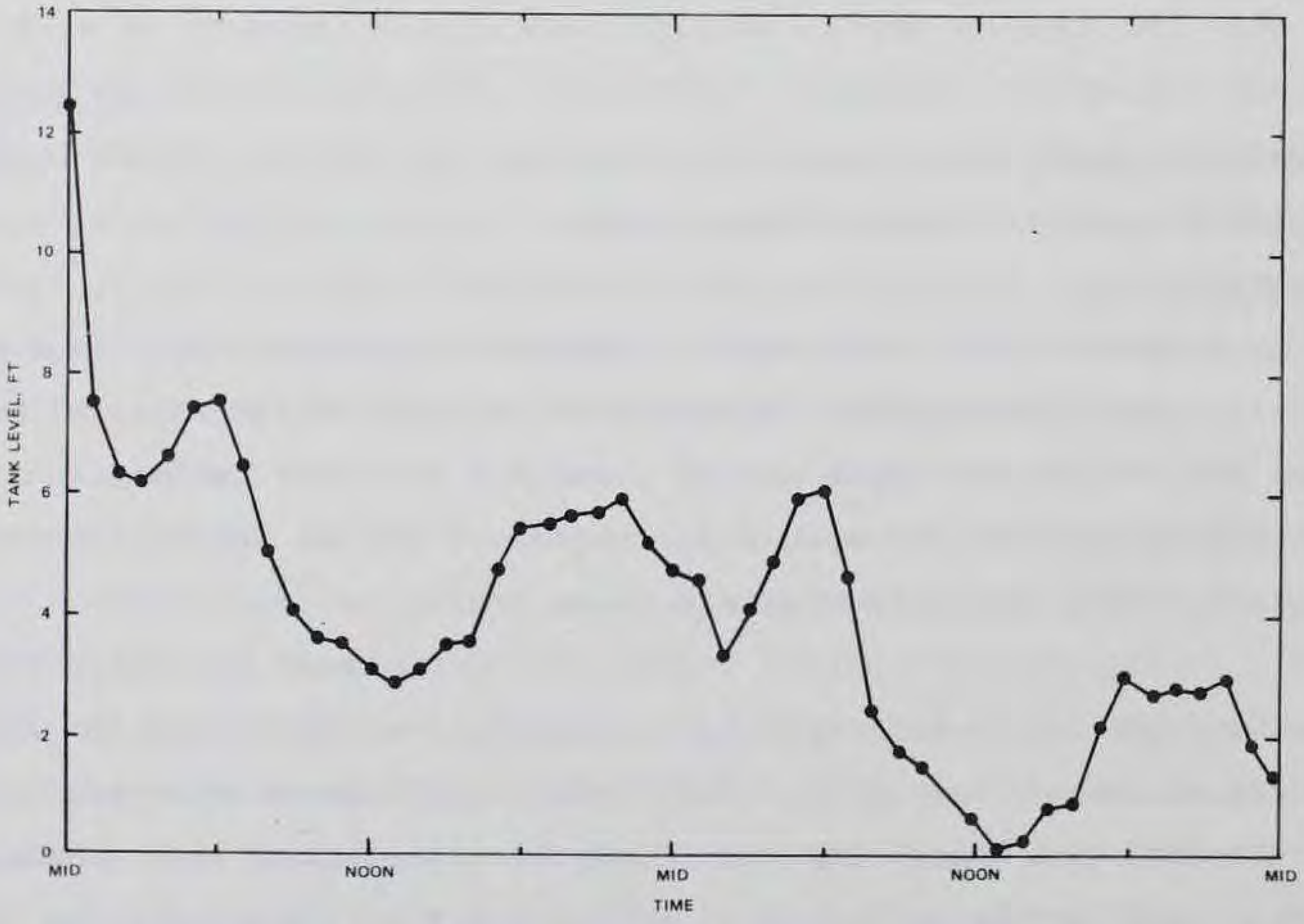


Figure 36. Third Gravity tank levels for second loading condition

unable to recover and never approach half full. Adequate system pressures can be maintained in both the FOWM and Third Gravity systems for the entire duration of the scenario once the 30-in. main is closed.

Third scenario

172. The impact of a fire in FOWM on the supporting Arlington County Third Gravity pressure zone was investigated for two cases: one with the 16-in. main under Key Bridge in service and one with the 16-in. main out of service. For both cases, the 30-in. main under Key Bridge was out of service. Fire loadings were placed at the Pentagon, National Airport, and Fort Myer. All fires were assumed to be 7,500 gpm for a duration of 4 hr except the Fort Myer fire which was rated at 2,400 gpm also for 4 hr.

173. Third Gravity tank levels are adversely affected by connecting the FOWM and Arlington County systems through the 15th and Eads interconnection. When a 7,500-gpm fire is placed at the Pentagon, the Third Gravity tank empties if the Key Bridge river crossing is in service. Tank levels are unable to reach half full even after the fire demand is removed. Figure 37 shows the Third Gravity tank levels for this scenario.

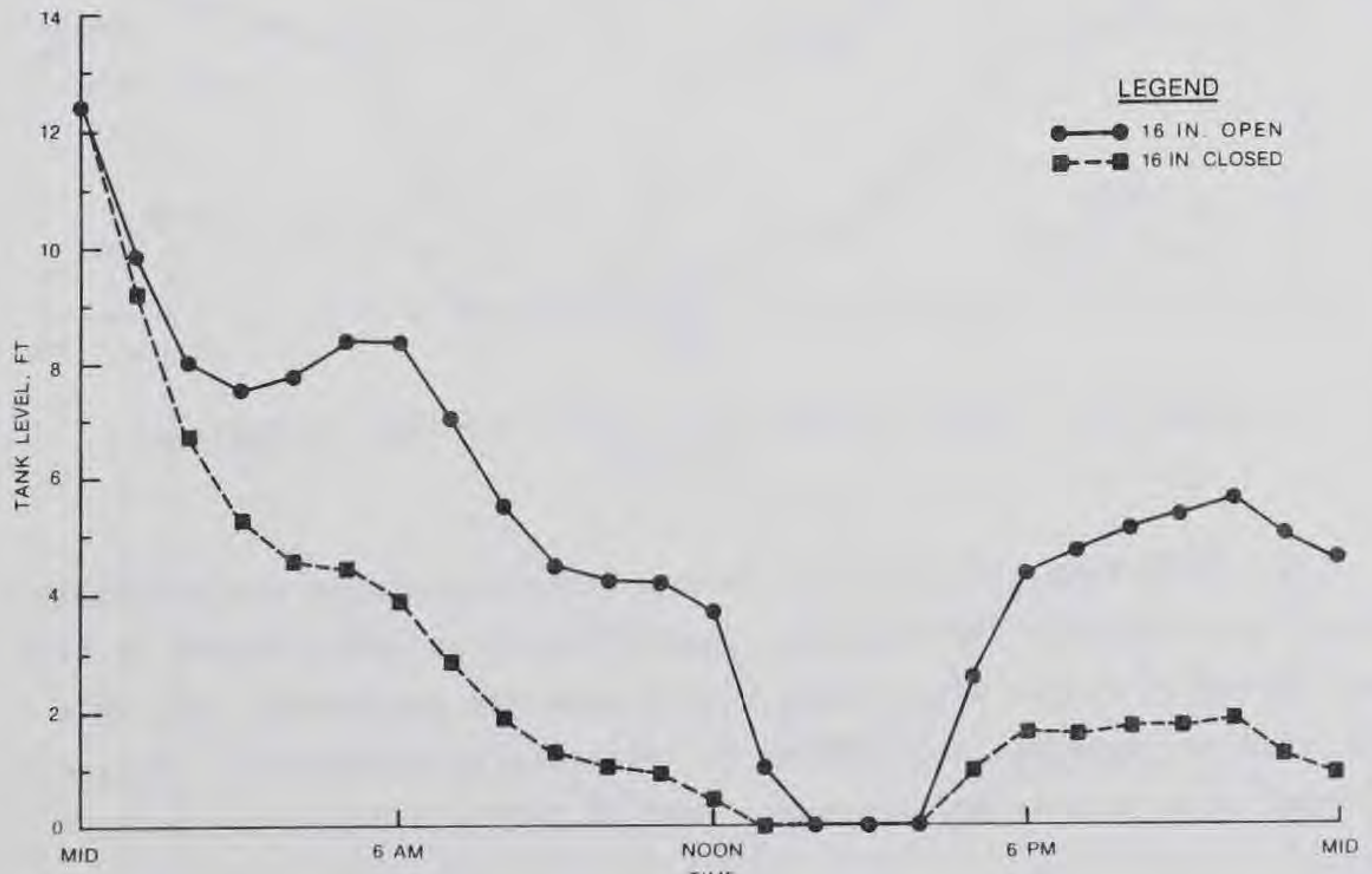


Figure 37. Third Gravity tank levels for fire at Pentagon

174. Not only are tank levels adversely affected by a fire at the Pentagon, but FOWM system pressures are also. Because the single 24- and 16-in. airport feed is the only flow route, high head losses are generated in this line. As a result, average system pressures are not acceptable. Pressures in the Third Gravity pressure zone are low, but generally they are above 40 psi.

175. Tank operation for a fire demand at National Airport is very similar to that of a fire at the Pentagon. Like the previous scenario, the Third Gravity tank empties with a 7,500-gpm fire demand placed at the airport. Figure 38 illustrates the tank operation for this case.

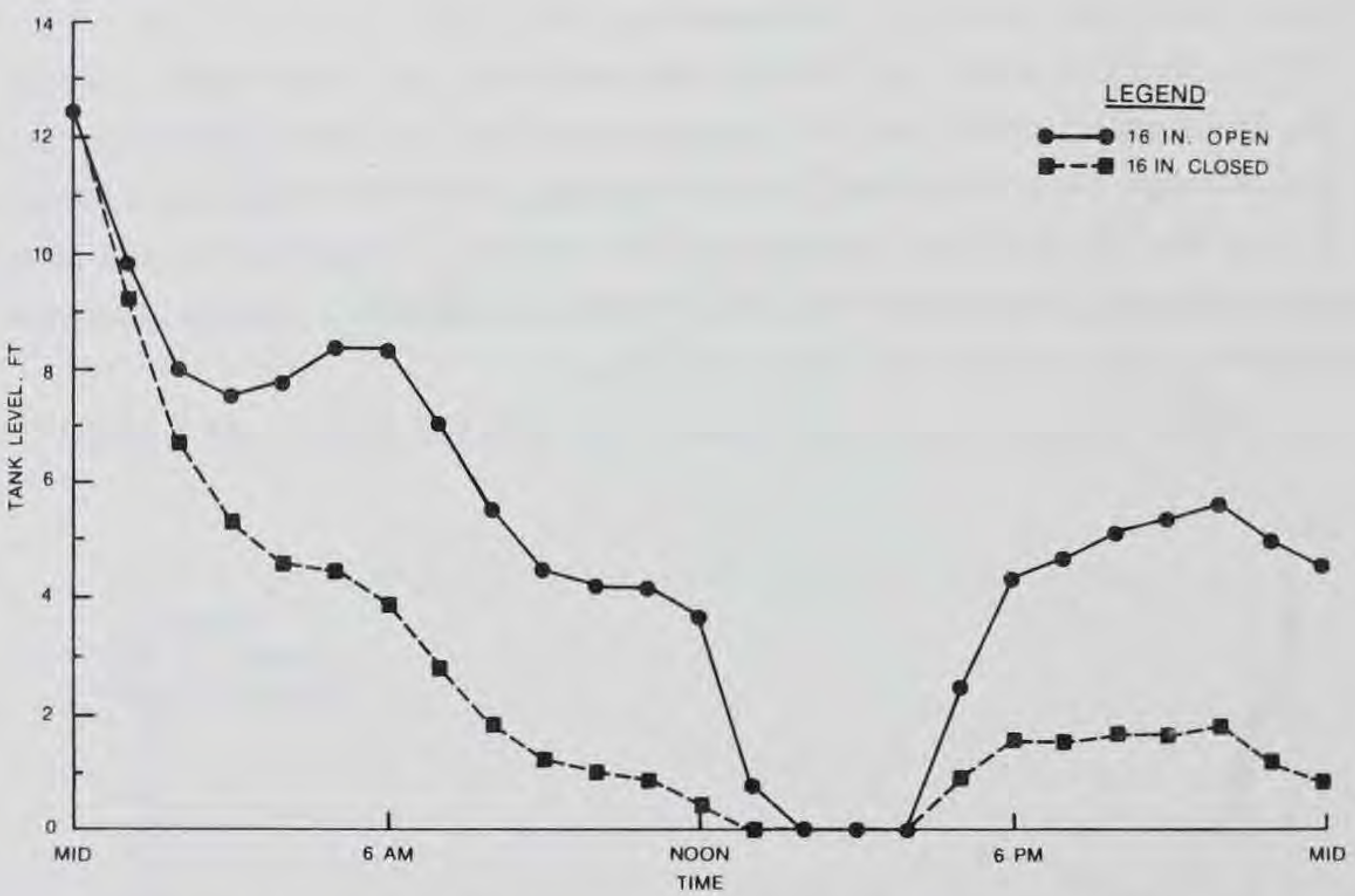


Figure 38. Third Gravity tank levels for fire at National Airport

176. Both FOWM and Arlington County system pressures are adversely affected by an airport fire demand. Again, because a large amount of flow is forced through a single pipe, large head losses are generated, and, as a result, system pressures are reduced to levels below acceptable. Even with the 16-in. line in service, pressures east of I-95 are below the design criteria.

177. Third Gravity tank levels are also influenced by a fire demand at Fort Myer. Even though the fire demand is of a lesser magnitude than the previous loadings, the Third Gravity tank still empties if no supply is offered from Dalecarlia First High. Tank operation is improved somewhat if the 16-in. line under Key Bridge contributes flow. Yet, tank levels are unable to reach the same levels as at the start of the simulation. Figure 39 shows tank fluctuations for this scenario.

178. Unlike the previous fire loadings, system pressures within the FOWM system can be maintained above standard for either case with the 16-in. Key Bridge crossing in or out of service with a fire demand at Fort Myer. Likewise, Arlington County Third Gravity pressures are kept above minimum.

New River Crossings

179. The Roosevelt Bridge, 14th Street Bridge, and Subaqueous River Crossing alternatives are very similar physically and hydraulically, and as a result, they provide nearly identical results. The three alternatives originate at the Foxhall Reservoir, consist of a length of 30-in. main, and connect with the existing FOWM system. The major differences between the alternatives are lengths of pipe associated with each alternative and the location of the tie-in with FOWM.

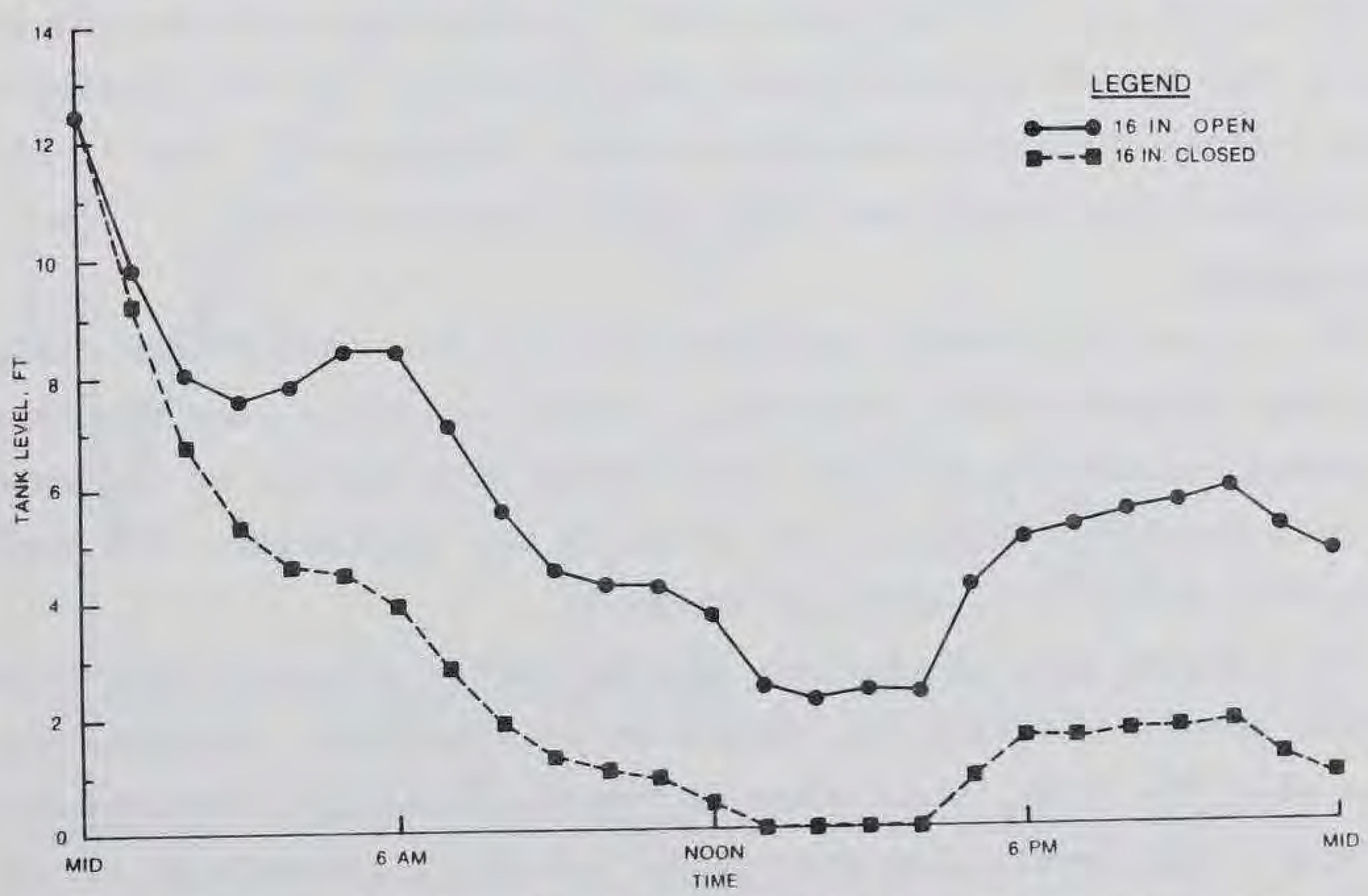


Figure 39. Third Gravity tank levels for fire at Fort Myer

Foxhall Tank

180. The Roosevelt Bridge, 14th Street, and Subaqueous River Crossing alternatives were analyzed for an extended period case consisting of an average daily demand pattern for 24 hr followed by a maximum daily demand pattern for the next 24 hr. The Key Bridge crossing was out of service for the entire duration of the simulation. Pumps were placed on-line if the Foxhall tank reached 25 percent of its capacity, and a third pump was placed on-line if the tank drained to 15 percent of its capacity. Once Foxhall tank regained 15 percent of its volume, a pump was taken off-line. Similarly, once the tank filled to 25 percent of its capacity, the other pump was shut down.

181. Hydraulic analysis indicates that proposed river crossings have no adverse impacts on the controlling Foxhall tank and DC First High system. Tank operation appears normal since Foxhall tank never completely drains or completely fills. However, this analysis was based on the assumption that pumps can be placed on-line or taken off-line at the Dalecarlia Pump Station as tanks near empty or full.

First scenario

182. For the average daily demand followed by maximum daily demand scenario, levels in Foxhall tank never fall below half full, which indicates adequate pumping capacity for average daily loadings. The tank trajectory for this case is the same for all three river crossing alternatives and is shown in Figure 40. System pressures also remain adequate for all alternatives although average pressures vary between each alternative. This is due to additional head loss associated with longer lengths of pipe.

Second scenario

183. A second scenario evaluated for the Roosevelt Bridge, 14th Street Bridge, and Subaqueous River Crossing alternatives was a case with average daily demand followed by maximum daily demand with failure of the existing 30-in. main under Key Bridge at the start of the simulation. The tank trajectory for this scenario is shown in Figure 41.

184. During this simulation, average system pressures fall below acceptable standards during the first hour of the event. This corresponds to the time when the 30-in. steel main is freely discharging approximately 70,000 gpm. Tank levels also drop about 5 ft until the main is valved off. Once the break is isolated, system pressures remain well above minimum. Also,

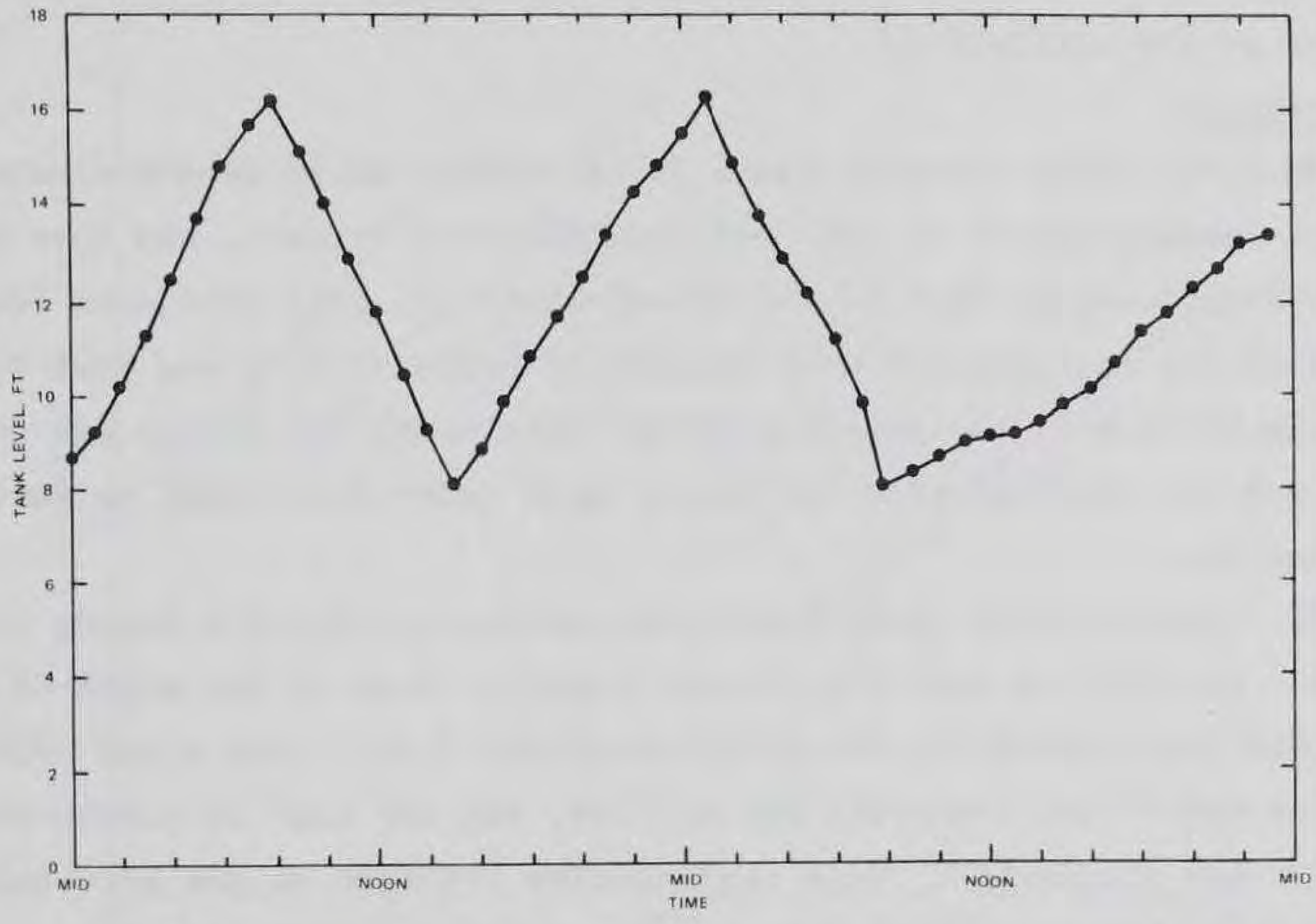


Figure 40. Foxhall tank levels for first loading condition

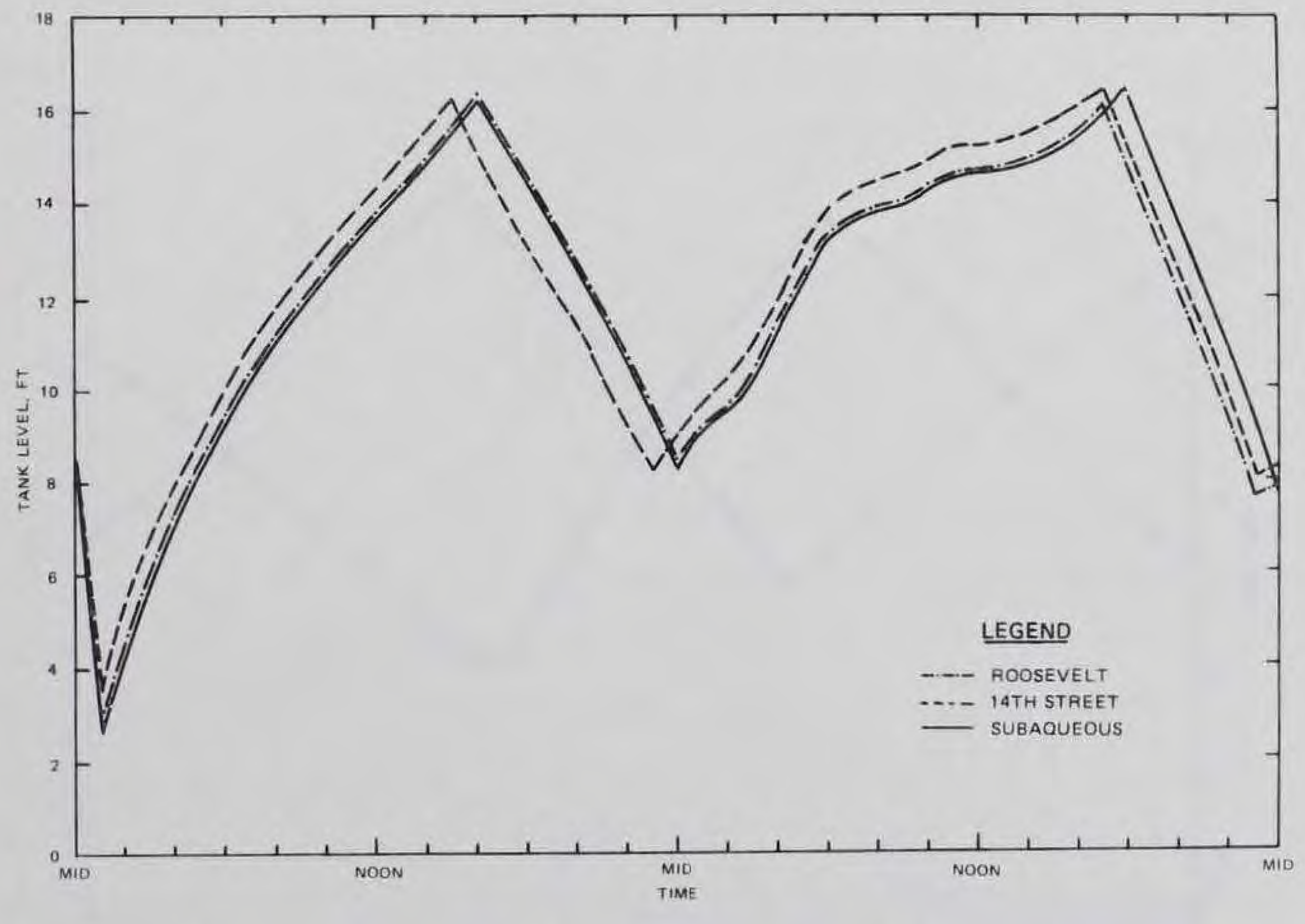


Figure 41. Foxhall tank levels for second loading condition

the Foxhall tank is able to recover, and levels remain above half full for the remainder of the simulation.

Third scenario

185. The final scenario was a 24-hr average daily demand simulation with fire demands placed at the Pentagon, National Airport, and Fort Myer. The same fire loadings used in the steady-state analysis were used for the extended period analysis and were assumed to begin at noon and last for 4 hr. This analysis assumed the existing 30-in. main under Key Bridge was out of service and was repeated with the 16-in. main under Key Bridge in service and out of service.

186. Foxhall tank operation is not adversely affected during this scenario. As would be expected, levels begin to drop at the start of the fire loading and drop throughout the duration of the fire. Levels are able to recover as additional pumps are put on line, and the tank is nearly full at the end of the simulation. Tank trajectories for each of the alternatives are the same with the 16-in. line open or closed for the fire demand scenario since tank level for this case is a function of demand and not path of flow. Trajectories for each fire loading condition are shown in Figures 42-44.

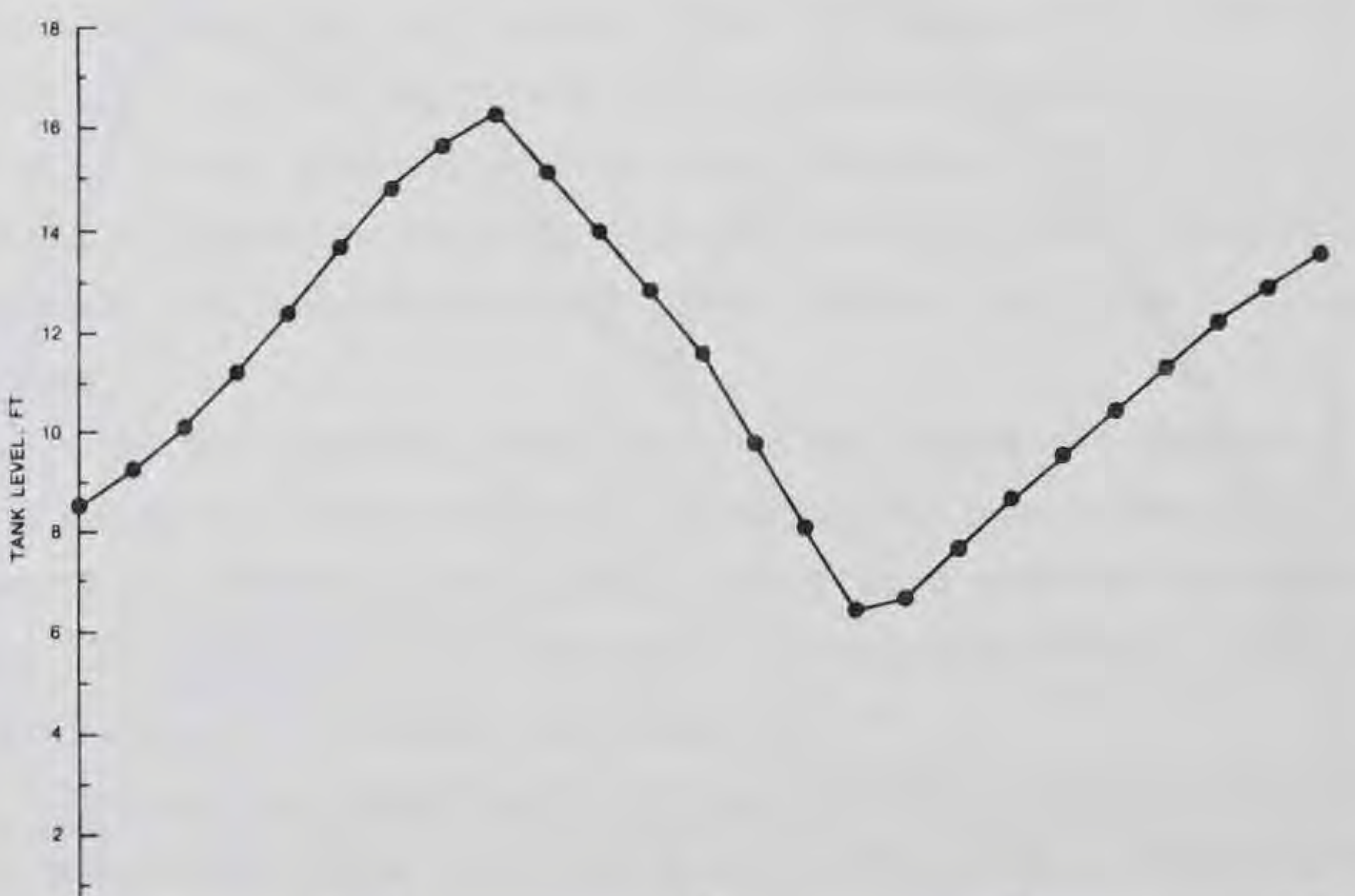


Figure 42. Foxhall tank levels for fire at Pentagon

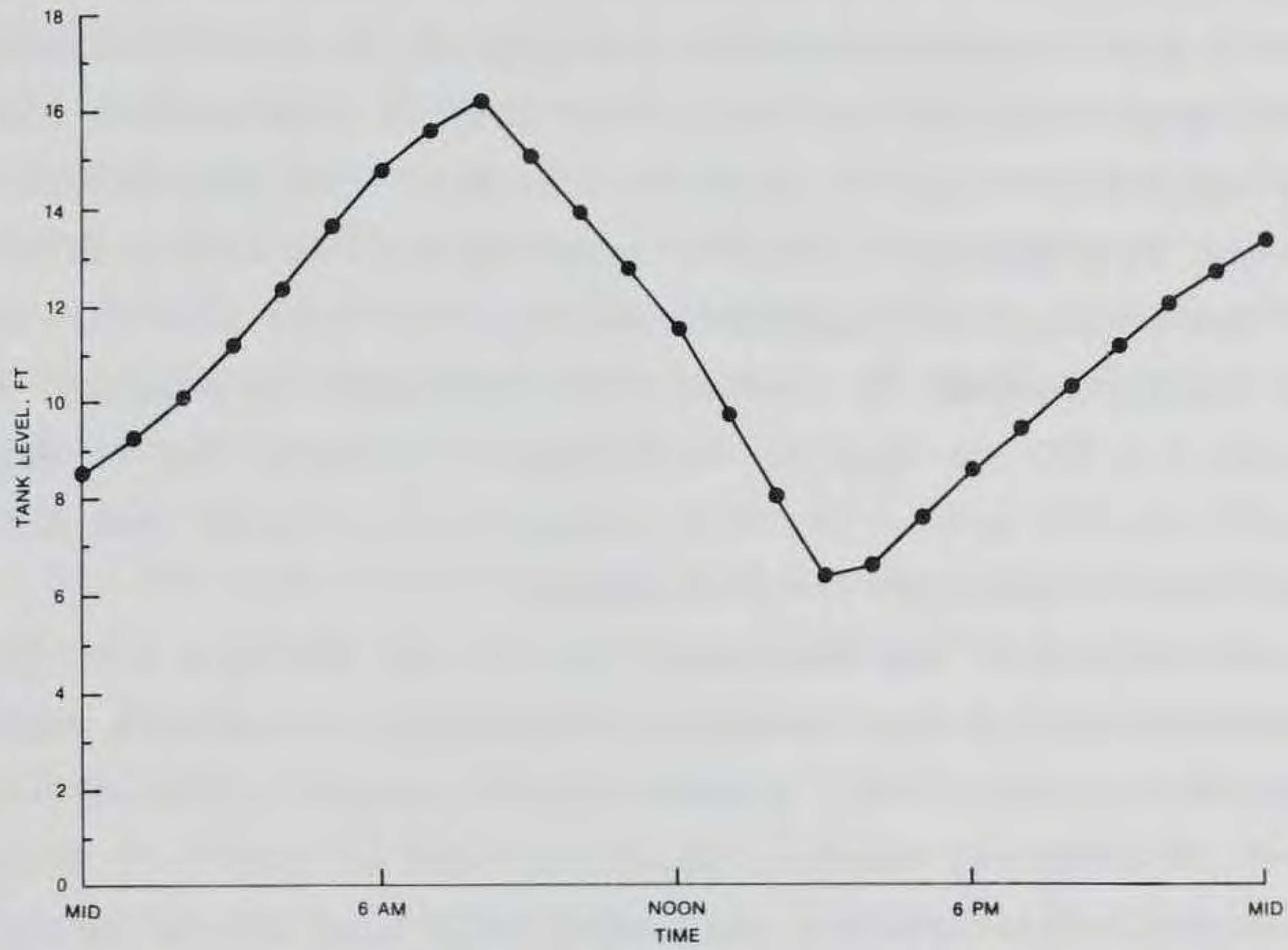


Figure 43. Foxhall tank levels for fire at National Airport

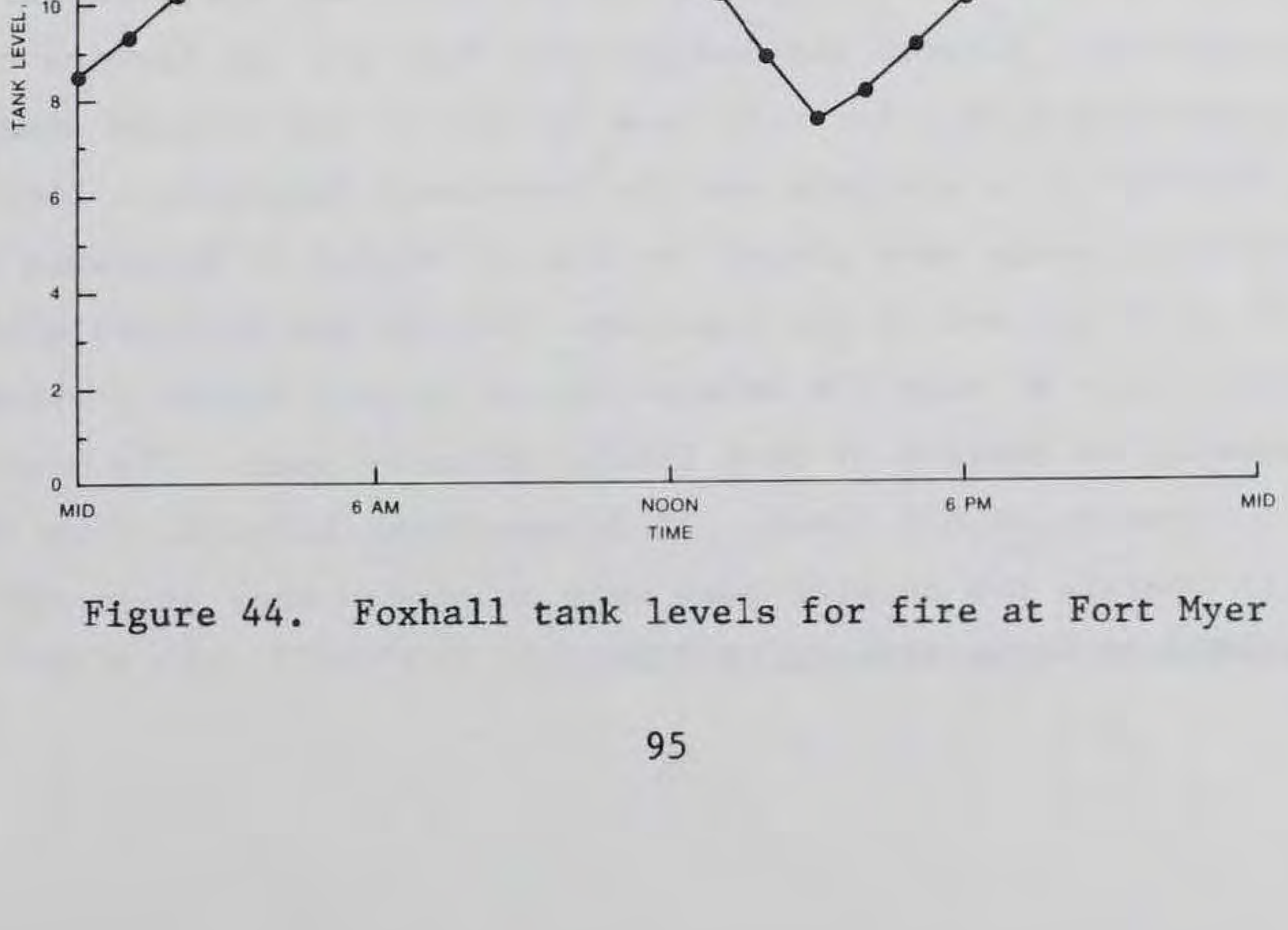


Figure 44. Foxhall tank levels for fire at Fort Myer

187. Average system pressures do appear to suffer during fire demand loading conditions. For a fire placed at the Pentagon, the Roosevelt Bridge and Subaqueous River Crossing alternatives provide adequate system-wide pressures for the entire duration of the fire. This is true whether the existing 16-in. main under Key Bridge is in service or not. The 14th Street Bridge alternative can also maintain adequate system pressures with a fire at the Pentagon if the 16-in. line remains in service. If this pipe were closed, the 14th Street river crossing, by itself, could not maintain adequate system pressures with a 7,500-gpm fire at the Pentagon. This is due to very large line losses in the 24- and 16-in. line between the proposed 14th Street tie-in with FOWM and the location of the fire demand.

188. For a fire of the same magnitude as the Pentagon fire located at National Airport, none of the three river crossing alternatives could provide adequate system-wide pressures. Pressures at locations north of I-95 can be maintained above standard; however, pressures east of I-95 fall drastically below the minimum. Pressures are reduced by high head losses in the single 24- and 16-in. airport feed. It is quite possible that a river crossing coupled with a main-strengthening alternative could adequately supply the FOWM system with acceptable pressures and flow during all loading conditions.

189. For a fire loading of 2,400 gpm for a duration of 4 hr located at Fort Myer, all river crossing alternatives can maintain adequate system-wide pressures.

Brentwood Tank

190. Another river crossing alternative which was analyzed for its effect on a supporting network was the Booster Pump Off Low Service alternative. The supporting system for this case is the DC Low service area. The controlling tank for this analysis was the Brentwood Reservoir. Like the previous alternatives, pumps were placed on-line as needed if Brentwood Reservoir drained to 25 or 15 percent of its capacity. Unlike the previous alternatives, however, pumps at both the Dalecarlia and Bryant Street pumping stations were assumed to operate if tank levels dictated such. The booster pump was assumed to operate at all times. It is possible, however, with this alternative to operate the booster pump only as needed when pressures within the FOWM system fall below acceptable limits.

First scenario

191. For the case with average daily demands followed by maximum daily demands, the Brentwood tank is somewhat adversely affected by a booster pump supplying the FOWM system. Tank levels do fall a bit below half full near the end of the average daily loading, but once an additional pump is placed on-line, tank levels quickly recover. However, tank levels do fall below half full near the end of the maximum daily loading pattern. System pressures are above acceptable limits for the entire duration of this analysis. Tank levels for this scenario are shown in Figure 45.

Second scenario

192. For the scenario with average daily demands followed by maximum daily demands and a 30-in. Key Bridge main break 1 hr into the simulation, Brentwood tank levels are affected to a greater degree than the first scenario. Tank levels do not drop any during the first hour of the simulation as is the case in the previous alternatives. However, tank levels do drain a great deal near the end of the maximum daily loading. Levels do recover to some extent once a pump is placed on-line. System pressures fall well below design standards immediately after the 30-in. line has failed. However, once the break is isolated, system pressures remain above acceptable levels. Tank levels for this scenario are shown in Figure 46.

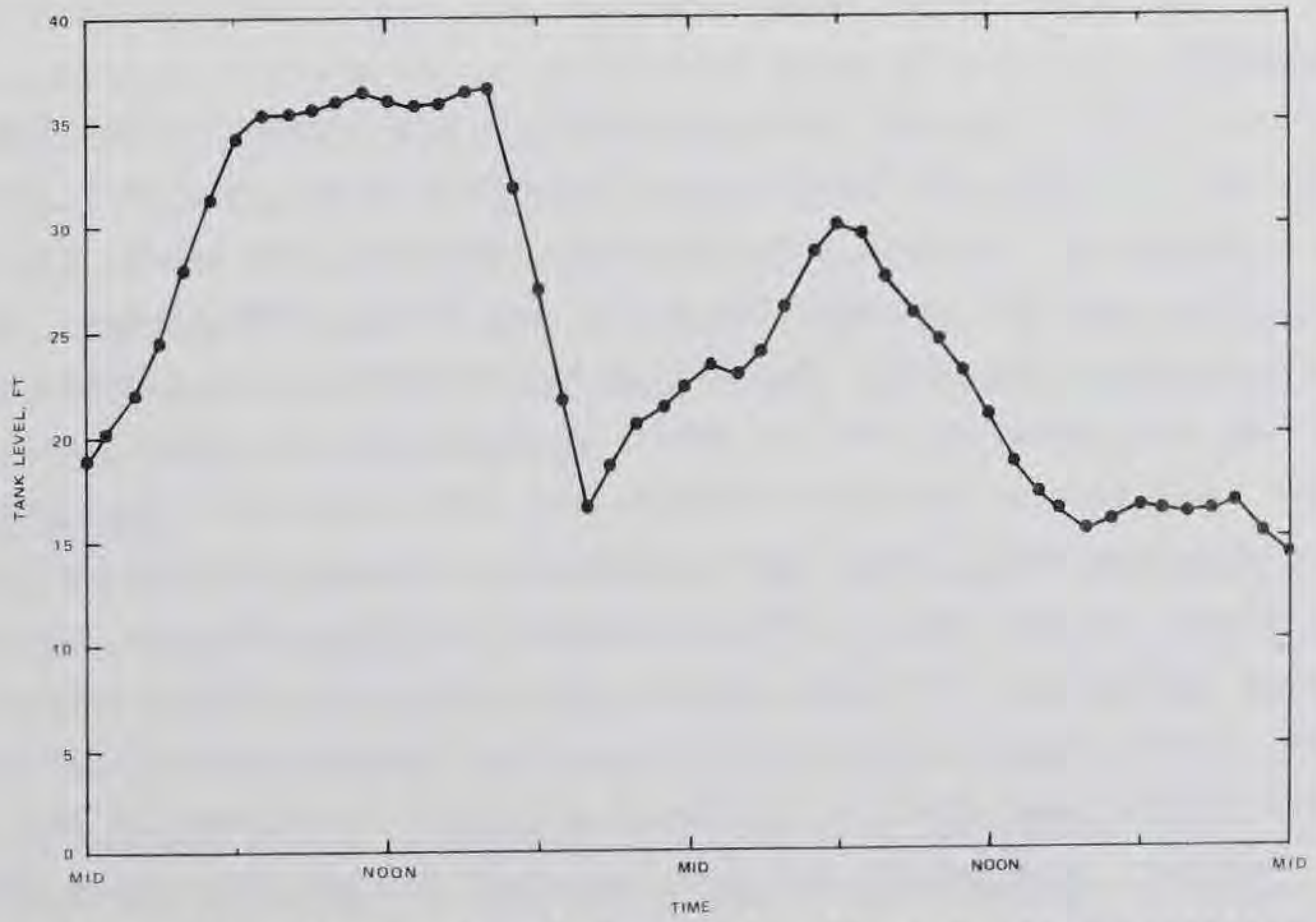


Figure 45. Brentwood tank levels for first loading condition

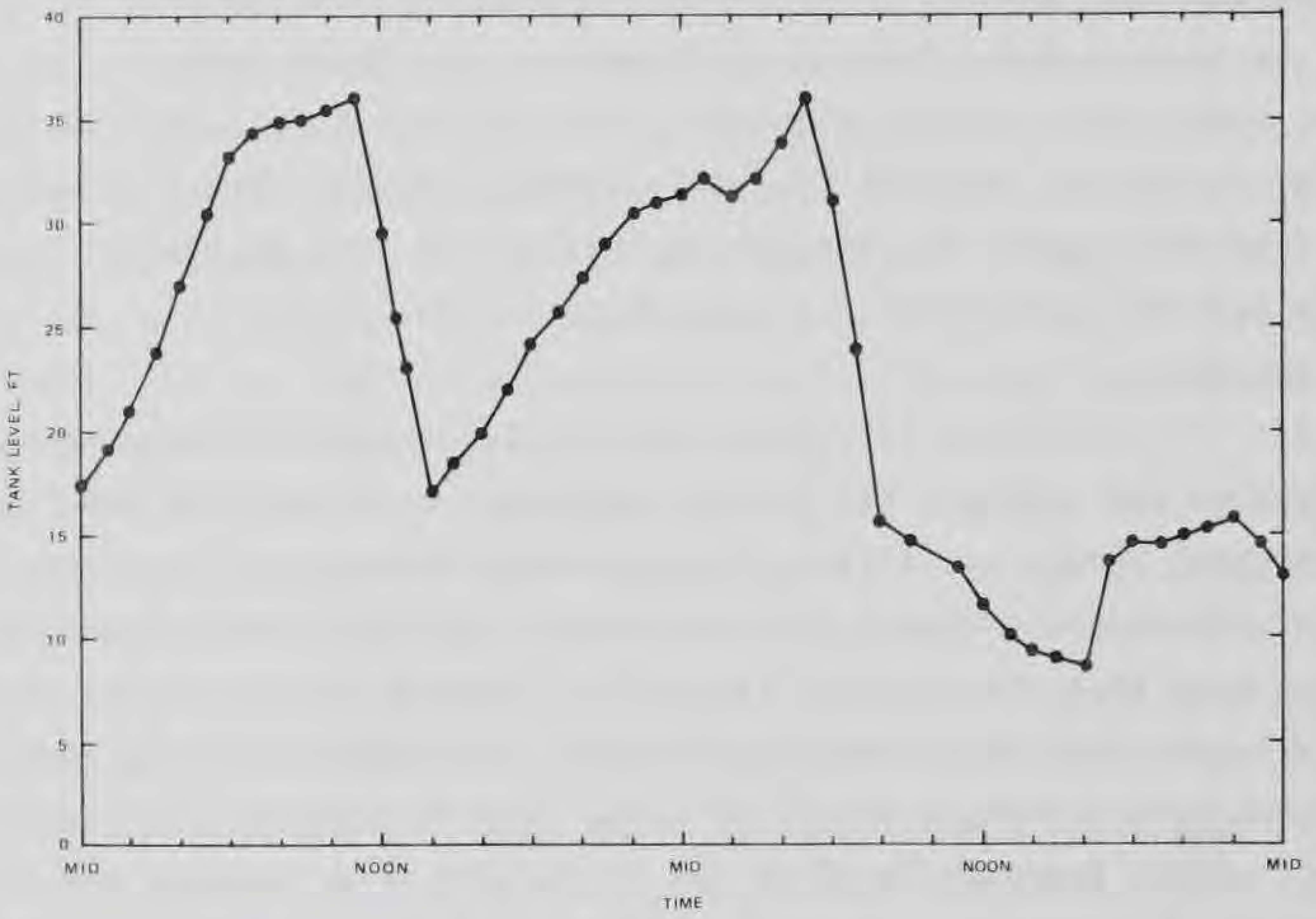


Figure 46. Brentwood tank levels for second loading condition

Third scenario

193. Operation of the Brentwood tank was evaluated for fire demands placed at the Pentagon, National Airport, and Fort Myer. For each fire demand, a simulation was made for two cases: one with the 16-in. Key Bridge river crossing open and one with the 16-in. Key Bridge line closed. For each of the simulations, the 30-in. Key Bridge river crossing was closed, and the booster pump was operating for the entire duration of the simulation.

194. For each of the fire demands, the Brentwood tank level trajectory is essentially the same. Tank levels gradually increase to near full at which time all pumps are shut down. Once all pumps are taken off-line, the tank level drops suddenly to half full whether the 16-in. Key Bridge main is open or closed. Tank levels are able to recover once another pump at Dalecarlia and Bryant Street pump stations is placed on-line. At the end of the simulation, however, tank levels are near half full for the case where all supply is provided from the booster pump. System pressures fall below acceptable

values during fire demands due to large line losses within FOWM. The tank trajectories for scenario are shown in Figures 47-49.

New Tank at Navy Annex

First scenario

195. The scenarios used to evaluate the performance of the proposed 1.8-MG tank at the Navy Annex were modified somewhat from the previous alternative. The water level in the tank was observed for three cases consisting of a 48-hr simulation with an average daily demand pattern followed by a maximum daily demand pattern and different conditions of the Key Bridge river crossing. Tank levels were observed for a case with the entire Key Bridge river crossing in service, the 30-in. main Key Bridge crossing out of service, and the entire Key Bridge out of service. The water level in the Navy Annex tank was initially set half full.

196. As Figure 50 indicates, the tank level fluctuates, but the tank never drains completely with the Key Bridge river crossing in service. This indicates proper operation of the tank as it is able to fill and drain. If the tank level were to remain constant for a significant amount of time (a few days), this would be undesirable as chlorine residuals would more than likely fall below acceptable limits. On the other hand, if the tank were to empty, this too would be undesirable as no storage could be provided. The tank at Navy Annex, as proposed, will retain at least 20 percent of its rated capacity at all times with the Key Bridge crossing on-line. However, if the 30-in. Key Bridge main or the entire Key Bridge crossing were lost, the proposed tank could not supply FOWM demands for very long. The tank empties about 14 hr into the simulation with the 30-in. line closed and drains completely in 8 hr if the entire bridge crossing is out.

Second scenario

197. A second scenario investigated the performance of the Navy Annex tank for fire demands placed at the Pentagon, National Airport, and Fort Myer. The magnitude and duration of the fire event were the same as the previous analyses. An assumption was made that DC First High pumps could be placed on-line or taken off-line as necessary if the tank approached empty or full. The analysis was repeated for the Key Bridge river crossing in service, the

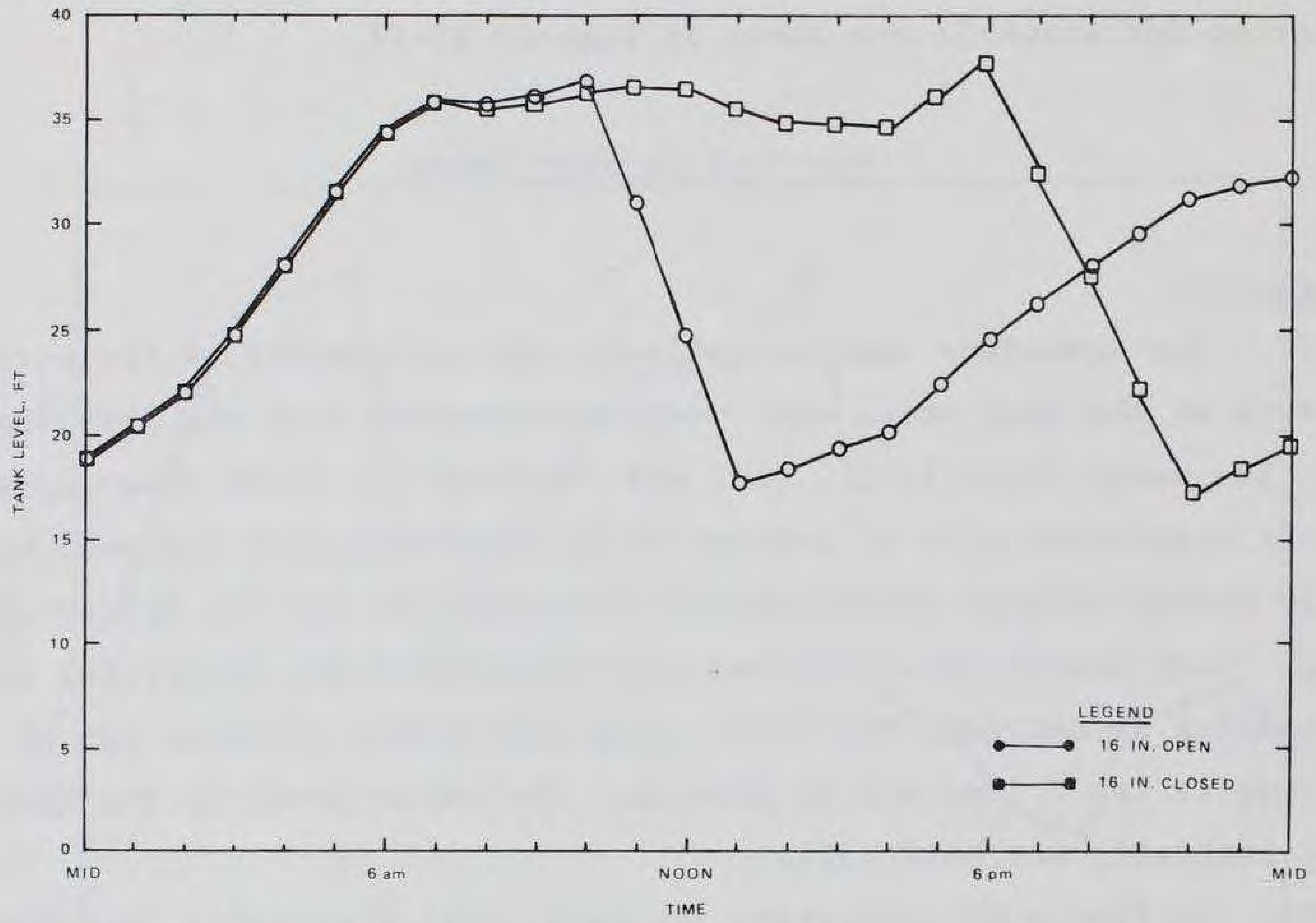


Figure 47. Brentwood tank levels for fire at Pentagon

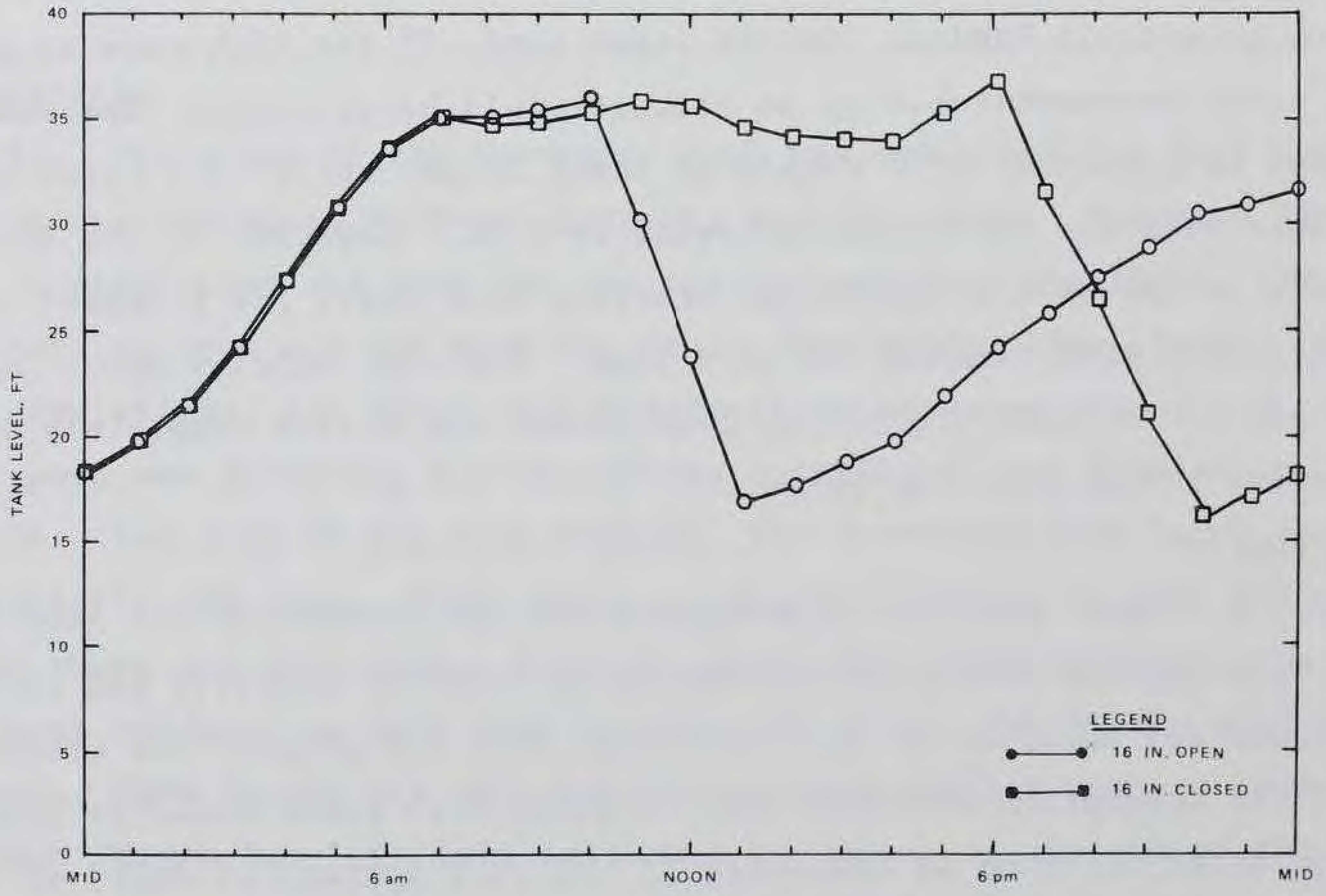


Figure 48. Brentwood tank levels for fire at National Airport

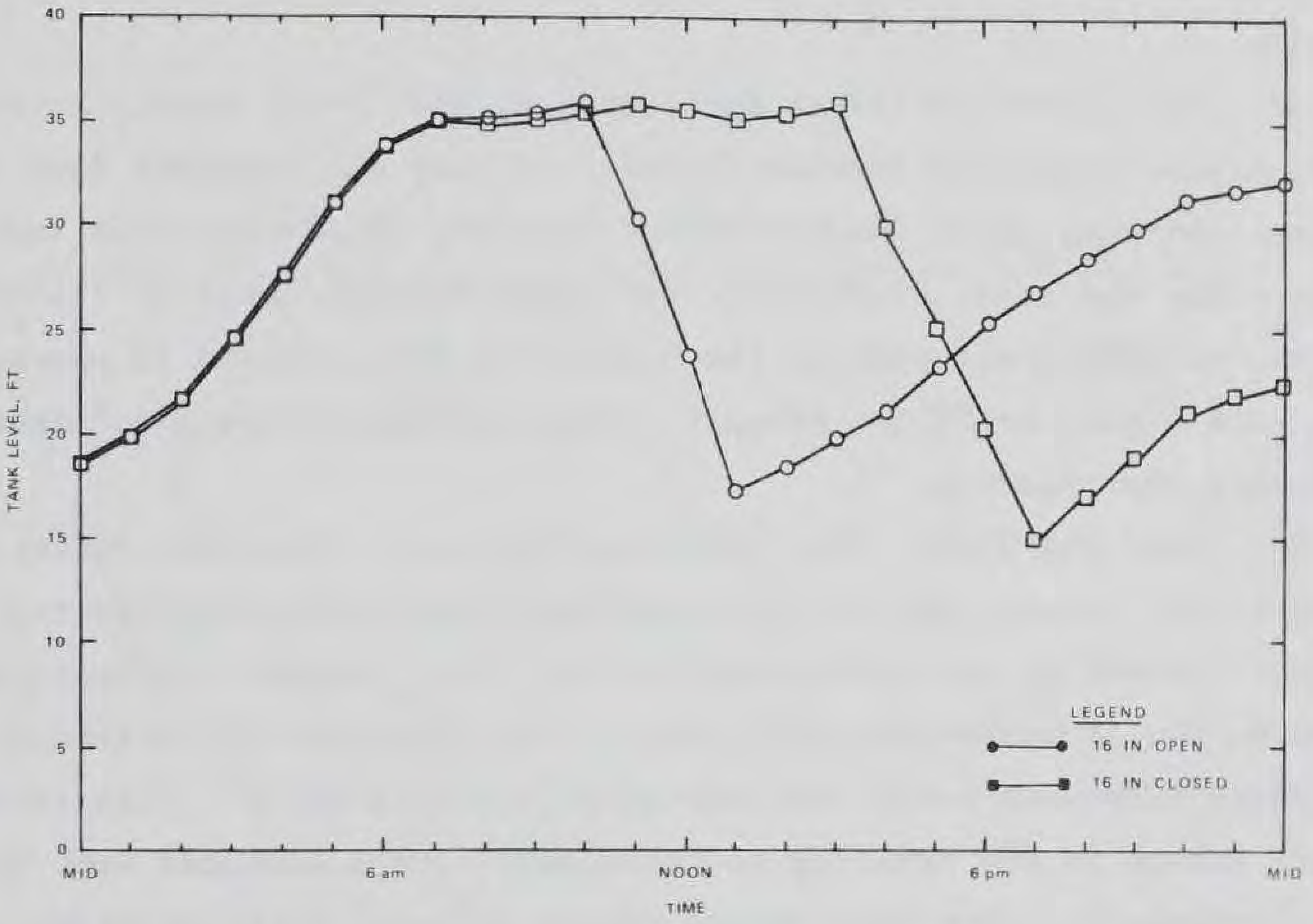


Figure 49. Brentwood tank levels for fire at Fort Myer

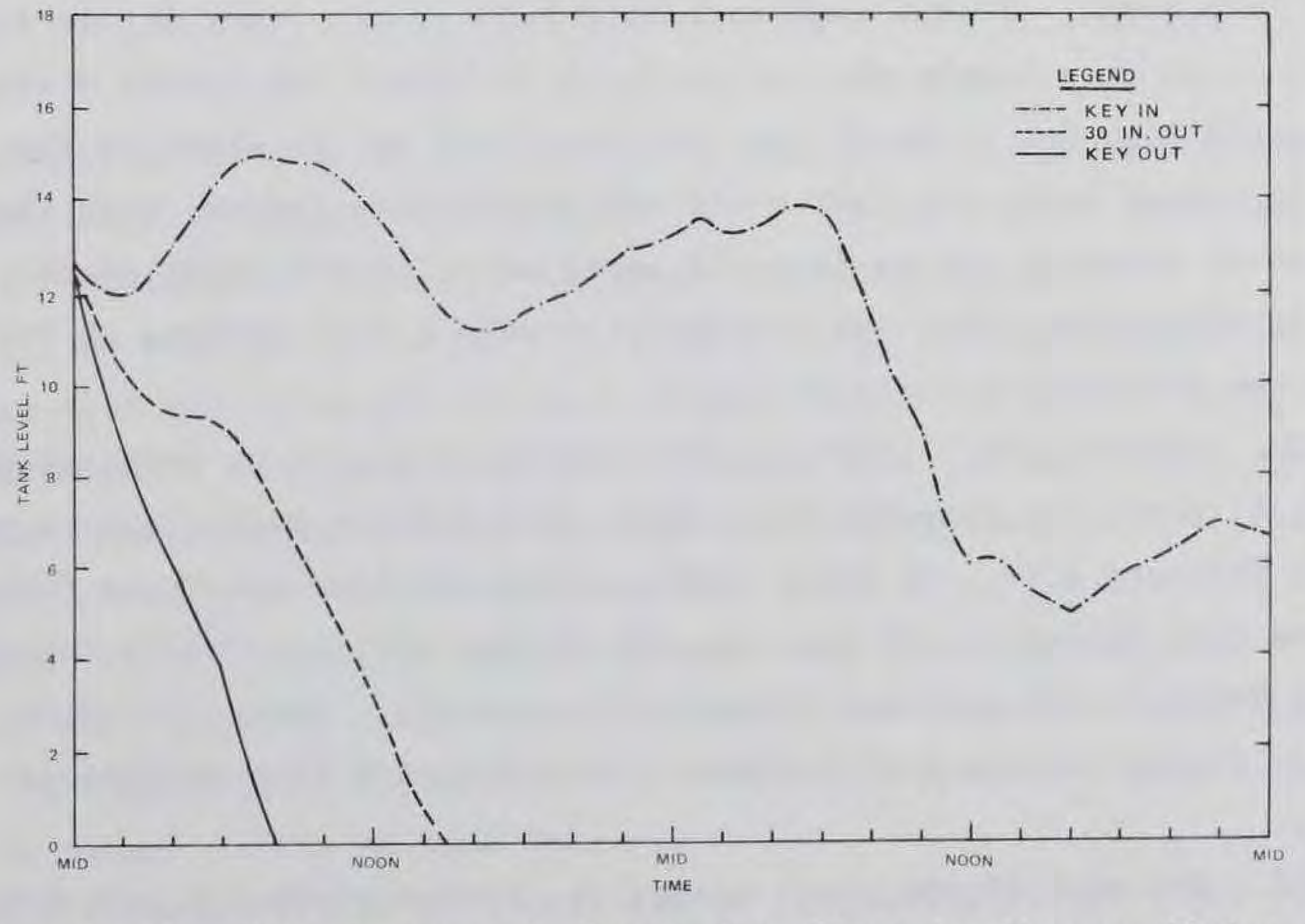


Figure 50. Navy Annex tank levels for first loading condition

30-in. line under Key Bridge out of service, and the entire river crossing out of service.

198. For a fire placed at the Pentagon, the 30-in. supply main under Key Bridge must remain in service in order to keep the proposed Navy Annex tank from emptying. With the Key Bridge crossing in service, the tank begins to drain after the start of the fire and reaches a low level of 7.5 ft. At this time, an additional pump at the Dalecarlia Pump Station is placed on-line and the tank begins to fill. Adequate system pressures are maintained at all times during the scenario.

199. When the 30-in. line under Key Bridge is taken out of service, the existing 16-in. supply line and proposed Navy tank can satisfy system demands at adequate pressures up to the start of the fire loading. Without the 30-in. steel main, the proposed tank will empty 1 hr after the fire begins at which point system pressures cannot be maintained above standard. This is due to excessive losses in the existing 16-in. supply line associated with high flows. Consequently, the fire demand cannot be met. Tank levels do, however, begin to recover, and system pressures are acceptable once the fire load is removed.

200. If the entire Key Bridge river crossing were to be taken out of service, the only source of supply for the FOWM system would be the proposed tank at Navy Annex. If the tank were half full at the start of the simulation, it could only supply the system for 8 hr before completely draining. Supply would last for 14 hr if the tank were full at the start of the simulation. In either case, the tank could not supply fire demands with the Key Bridge river crossing out as it would empty prior to the start of the fire. Figure 51 illustrates the tank trajectories with a fire loading at the Pentagon for the three cases analyzed.

201. When a 7-hr, 7,500-gpm fire demand is placed at Washington National Airport, the proposed Navy Annex tank behaves much the same way as during a Pentagon fire. In fact, tank trajectories for the three fire loading scenarios (Key Bridge in, 30 in. out, Key Bridge out) are mostly the same for both the Pentagon and National Airport fire demands. Figure 52 shows the variation in tank levels for the three cases during a fire at National Airport.

202. For each of the three scenarios, system pressures fall below acceptable limits east of I-95 for an airport fire. The tank at the Navy

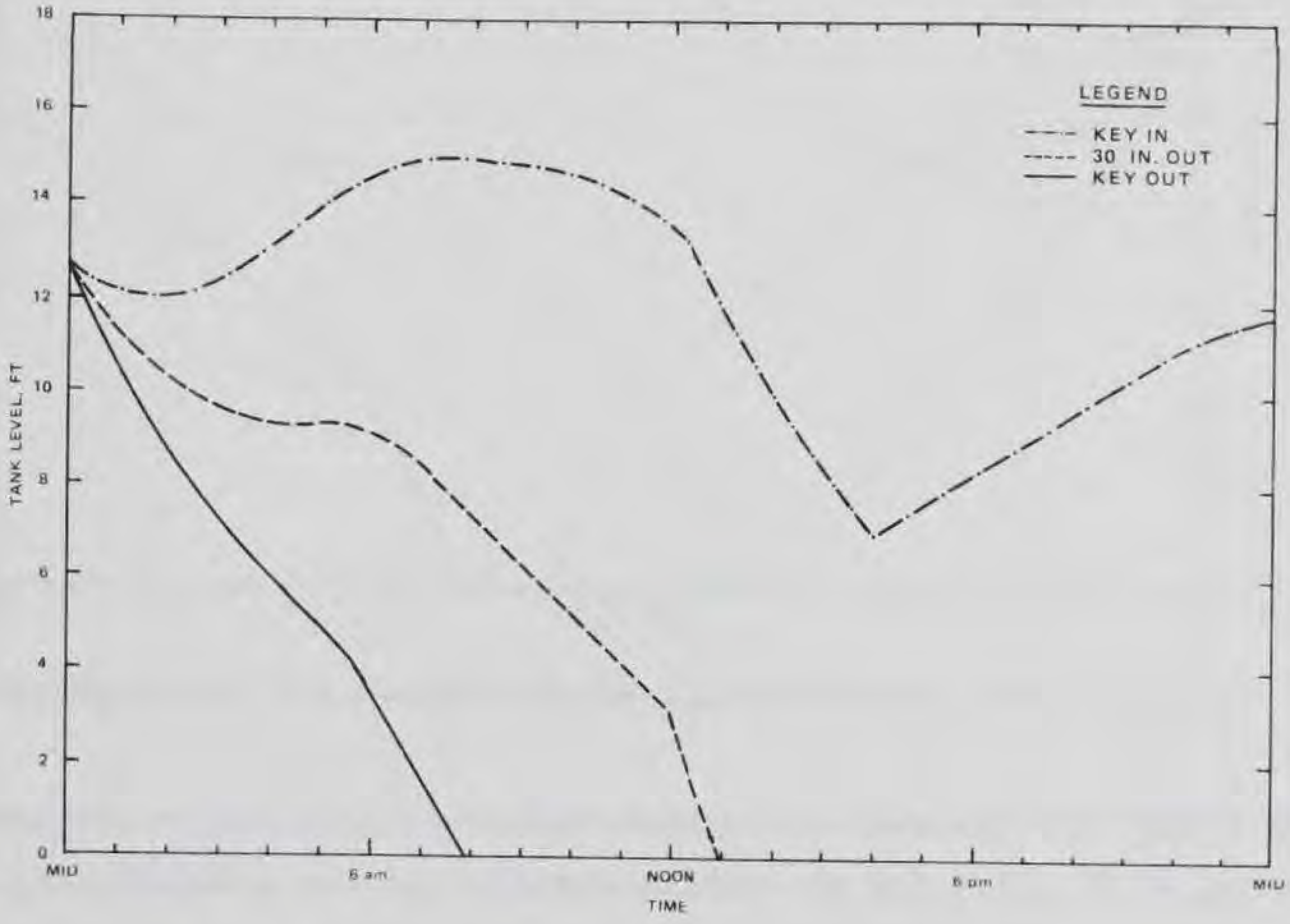


Figure 51. Navy Annex tank levels for fire at Pentagon

losses generated between the source (Key Bridge crossing, Navy Annex tank) and the demand (airport fire). The excessive line losses are due to a large amount of flow funneled through the single airport feed.

203. As with the previous fire loadings, the 30-in. supply main under Key Bridge must remain in service when a fire is located at Fort Myer; otherwise, the proposed Navy Annex tank will drain. With the Key Bridge crossing in service at all times, the tank level will never approach empty. With the 30-in. steel main off-line, the tank empties 14 hr after the start of the fire. When the Key Bridge is out of service, the tank will empty in 5 hr if Annex does not help to boost pressures in this area because of high head half full at the beginning of the simulation. Figure 53 shows the tank trajectory for a fire demand placed at Fort Myer.

204. Adequate system pressures can be maintained at all times with a fire at Fort Myer. Even when the Navy Annex tank is empty and the 30-in. line

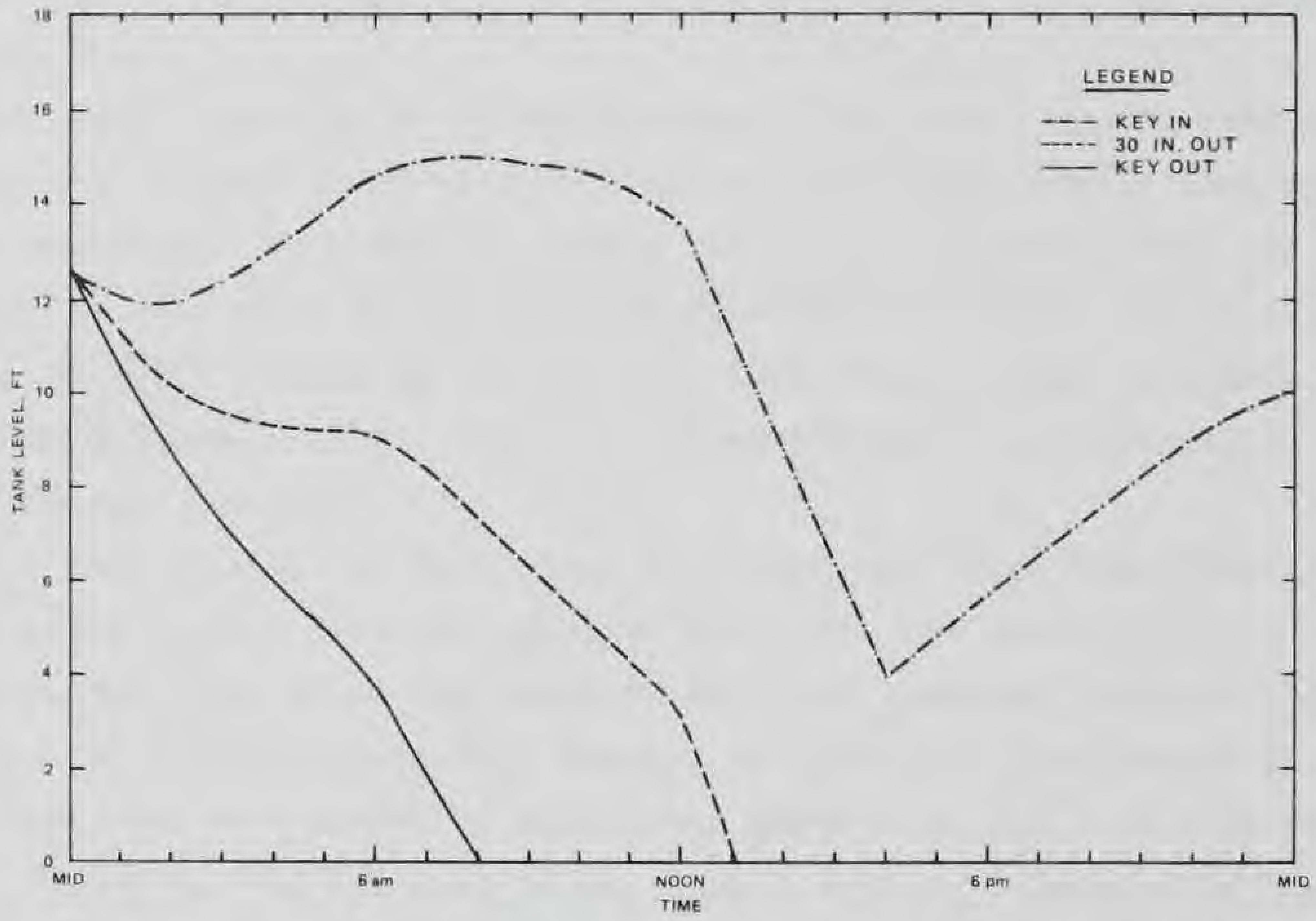


Figure 52. Navy Annex tank levels for fire at National Airport

under Key Bridge is out, adequate system-wide pressures can be supported by the existing 16-in. line for the entire duration of the simulation.

Summary

205. Several alternatives designed to improve the reliability of the FOWM system were evaluated for extended period simulations to determine the magnitude of impact each alternative has on the supporting network. Such impacts are an adverse effect on storage tank operation in the supporting system or unacceptable pressures in either the supporting network or the FOWM system. The alternatives examined include the 15th and Eads interconnection, the Roosevelt Bridge crossing, the 14th Street Bridge crossing, the Booster Pump Off Low service alternative, the subaqueous river crossing, and a new storage tank at the Navy Annex.

206. Extended operation of the 15th and Eads interconnection has a detrimental effect on the Third Gravity tank. For each scenario evaluated, the Third Gravity tank either drains completely or comes dangerously close to empty. An empty storage tank is unacceptable since no emergency storage or fire-fighting capacity is available. Minimum ISO requirements state that

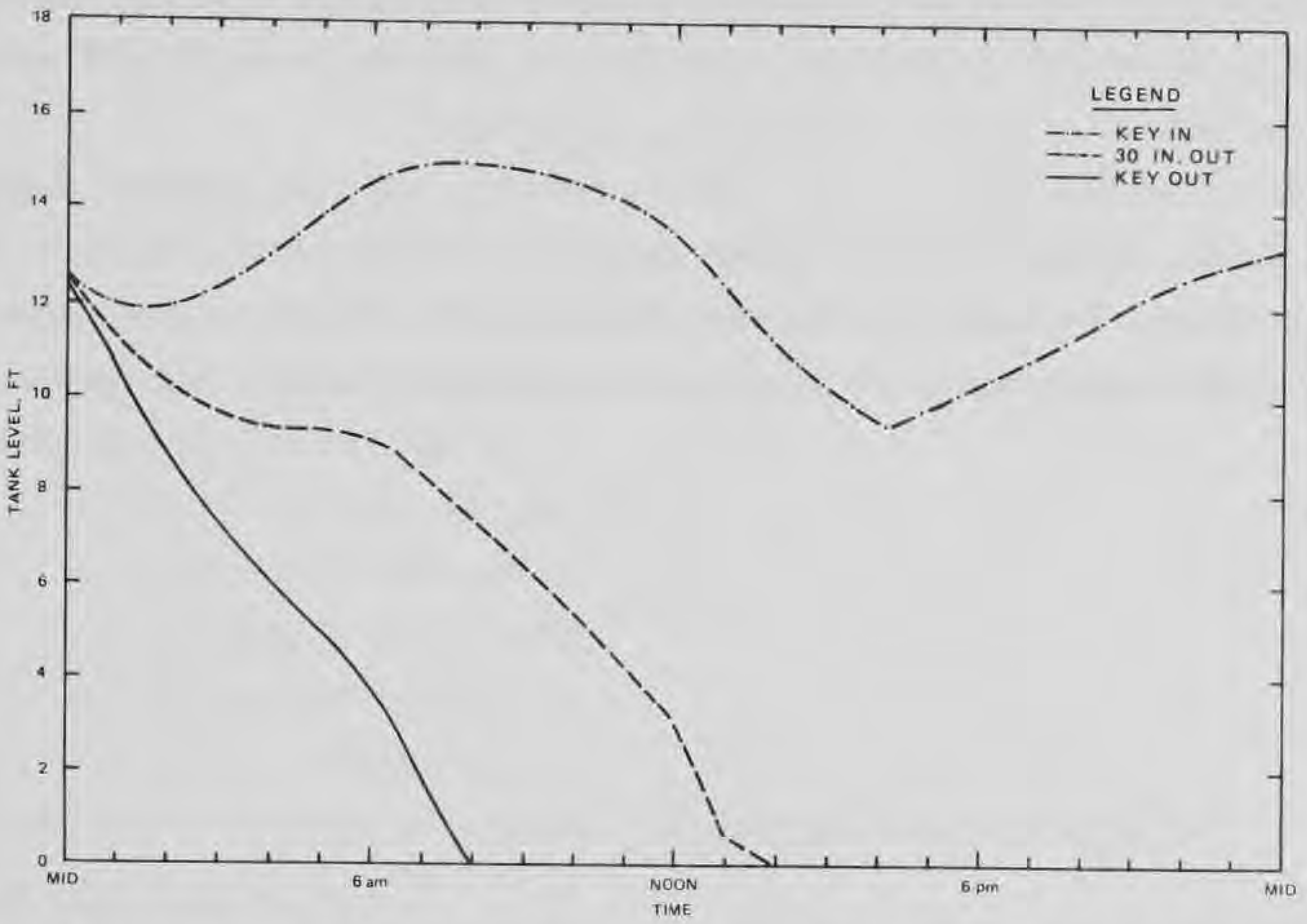


Figure 53. Navy Annex tank levels for fire at Fort Myer

storage tanks should contain a certain amount of water at all times, preferably a 24-hr supply for average daily demands. It is unlikely Arlington County would continue to allow FOWM to be supplied through the 15th and Eads interconnection if the Third Gravity tank drains close to empty. The Fern Street and Crystal City interconnections would have this same effect on the Third Gravity tank since all three interconnections are hydraulically similar.

207. Foxhall tank levels are not adversely affected by the Roosevelt Bridge, 14th Street, or Subaqueous River Crossing alternatives. Even though tank levels at times approach half full, putting another pump on-line quickly remedies the situation, and the tank is able to refill. Foxhall tank does drain a great deal if the 30-in. Key Bridge crossing breaks, but tank levels are able to recover once additional pumps are operated.

208. The Booster Pump Off Low Service alternative also appears to have a negative effect on the Brentwood Reservoir but not to the degree of the previous alternative. With average daily demands followed by maximum daily demands, tank levels fall below half full near the end of the maximum daily loading condition. Tank levels are able to recover once pumps at Dalecarlia and Bryant Street are placed on-line; however, tank levels remain less than

half full at the end of the simulation. With FOWM fire demands supplied entirely by Brentwood Reservoir, tank levels fall below half full near the end of the scenario.

209. The new tank at Navy Annex proposal can help augment supply from the Key Bridge river crossing during periods of peak demand or fire loading. The tank cannot, by itself, adequately supply the FOWM system without the 30-in. Key Bridge crossing or an alternate means of supply in service.

PART VIII: ENGINEERING ASSESSMENT OF SYSTEM IMPROVEMENTS

Assessment Criteria

210. In addition to evaluating the hydraulic performance of each alternative, an attempt was made to assess the engineering impacts of each scenario. Potential impacts have been grouped into five different categories. Each category is identified below:

- a. Difficulty of construction.
- b. Difficulty of access.
- c. Component reliability.
- d. System dependency.
- e. Energy efficiency.

A summary of each category is provided in the following paragraphs.

Difficulty of construction

211. Difficulty of construction describes the potential for encountering problems during installation of the alternative. Such difficulties could be drilling rock instead of blasting, deep trenching in poor soils, construction in swampy areas, presence of existing utilities, etc. These difficulties are considered as negative impacts which have the net effect of increasing the cost of the alternative.

212. One construction difficulty which is peculiar to the DC area is the presence of national park lands. Most of the alternatives involving new construction pass through national park land (areas) as a great deal of FOWM is itself national park land. Disturbance to the area must be kept at an absolute minimum, and any land which is disturbed must be returned to its exact original condition. The end result may be a cost several times higher than the estimated cost of other alternatives.

Difficulty of access

213. Difficulty of access refers to the difficulty of access to the construction site. Such constraints may be physical or regulatory. An example of such would be construction of the actual bridge crossing on the Roosevelt and 14th Street Bridge River crossing alternatives. Work in these areas must take place in limited space since traffic over the bridges would have to be maintained at all times. Alternatively, access to construction on Federal park lands may be limited by regulatory constraints. It is anticipated that

increased construction costs will be associated with those projects which have high degrees of difficulty of access. Difficulty of access and difficulty of construction are somewhat related.

Component reliability

214. Component reliability refers to the individual reliability of a proposed alternative. For example, a proposed river crossing may be more susceptible to failure than an existing or proposed interconnection on land. As a result, the interconnections may have a greater component reliability than a proposed river crossing.

System dependency

215. System dependency describes the extent to which a particular alternative is dependent upon another system. Some alternatives are more dependent than others for proper hydraulic performance. For instance, both the Roosevelt Bridge crossing and 15th and Eads interconnection could supply the FOWM system in most cases if the Key Bridge river crossing were placed out of service. The Roosevelt Bridge Crossing alternative relies on trouble-free operation of the Dalecarlia water plant and Foxhall tank to deliver flow at adequate pressures to the FOWM system.

216. The 15th and Eads interconnection, on the other hand, not only relies on problem-free operation of the Dalecarlia plant and Third High reservoir, but also on the Third Gravity tank and PRV's between First, Second, and Third Gravity pressure zones. Furthermore, the 15th and Eads interconnection is more sensitive to demand loadings in Third Gravity than the Roosevelt Bridge crossing is to loadings in DC First High.

Energy efficiency

217. Energy efficiency refers to the relative energy efficiency of each alternative. For example, use of water from the First High pressure zone via the new river crossings is much more efficient than the use of water from the Third High pressure zone via the 15th and Eads interconnection. If the FOWM system were to be supplied through the 15th and Eads interconnection, water must first be pumped to Arlington County First Gravity from the DC Third High pressure zone at a grade of approximately 420 ft. Water then flows to Second Gravity and to Third Gravity passing through PRV's between each Arlington County pressure zone at which point it reaches FOWM at a hydraulic grade of about 200 ft. This has the net effect of pumping water to a certain height and passing it through energy dissipators to get it to a lower height at

acceptable pressures. If, on the other hand, FOWM were to be supplied via a new river crossing connected to DC First High, then water would not have to be pumped to such a high grade to adequately supply the FOWM system.

Engineering Impacts Evaluation

218. For this analysis, all impacts are considered negative. The degree of engineering impact has been ranked on a numerical scale of 0 to 5 as shown in Table 10. The engineering impacts of each supply alternative are summarized in Table 11. The engineering impacts of each main-strengthening are shown in Table 12.

Supply Alternatives

15th and Eads interconnection

219. Since the 15th and Eads interconnection is an existing alternative, the engineering impacts of difficulty of construction and difficulty of access have been assigned a value of zero. This indicates that there are no negative impacts associated with the construction and access category.

220. The component reliability of this alternative is minimal since it consists of pipes, valves, and a meter. Although any of these appurtenances could fail, the number of parts (relative to the remaining alternatives) has been kept to a minimum.

Table 10

Assessment Scale

Numerical Ranking	Degree of Engineering Impact
0	None
1	Minimal
2	Slight
3	Moderate
4	Major
5	Extreme

Table 11

Engineering Impacts of Supply Alternatives*

Assessment Category	15th and Eads Interconnection	Roosevelt Bridge River Crossing	14th Street Bridge River Crossing	Booster Pump off Low Service	Subaqueous River Crossing	New Tank at Navy Annex
Difficulty of construction	0	3	3	2	4	1
Difficulty of access	0	3	3	3	4	5
Component reliability	1	1	1	2	1	1
System dependency	5	1	1	1	1	2
Energy efficiency	4	0	0	1	0	0
Total	10	8	8	9	10	9

* Numerical rankings are described in Table 10.

221. System dependency of the 15th and Eads Interconnection alternative is extreme since it relies entirely on proper operation of the Third Gravity pressure zone in Arlington County. In turn, proper operation of Third Gravity is dependent upon proper operation of Second Gravity, First Gravity, and DC Third High. Since it is located at the end of the Arlington County DC network, the 15th and Eads interconnection could be affected by an emergency in any of the previously mentioned pressure zones.

222. The 15th and Eads interconnection has been assigned a value of four for energy efficiency which corresponds to a major negative impact. Before water reaches FOWM through the 15th and Eads interconnection, it has been pumped to a grade of about 420 ft from DC Third High. In order to reach Third Gravity at acceptable pressures, water must flow through two sets of PRV's which reduce the amount of energy contained by the fluid. This is a waste of energy which could be avoided with other alternatives. The engineering impacts of the Fern Street and Crystal City interconnections are the same as the 15th and Eads Interconnection alternative.

Roosevelt Bridge river crossing

223. The Roosevelt Bridge River Crossing alternative, relative to the remaining alternatives, has been assigned a moderate engineering impact in the difficulty of construction category. Although it is difficult to estimate construction conditions without a detailed survey or rock soundings, this alternative does pass through national park lands. Park service officials may

Table 12

Engineering Impacts of Main-Strengthening Alternatives*

Assessment Category	Paralleling 30-in. FOWM Transmission Main	New Airport Feed	Closing Pentagon Loop	Constructing New Pentagon Loop
Difficulty of construction	2	3	3	1
Difficulty of access	3	2	2	1
Component reliability	1	1	1	1
System dependency	0	0	0	0
Energy efficiency	0	0	0	0
Total	6	6	6	3

* Numerical rankings are described in Table 10.

be reluctant to grant permission to install a pipe through these areas. If permission were granted, disturbance to these lands would have to be kept to a minimum, and any disturbed land would have to be restored to its exact original condition.

224. Difficulty of access of the Roosevelt Bridge crossing is also moderate relative to the other supply alternatives. With this proposal, approximately 4,000 ft of 30-in. main must be installed on the Roosevelt Bridge. Traffic over the structure is at times quite heavy and must be continuously maintained. This, in turn, acts to limit available space on the bridge which is initially at a premium. Also, since this alternative passes through Federal areas, permission to construct may be difficult to obtain.

225. Component reliability of this alternative is minimal since it is comprised of pipes and valves. Similar to the 15th and Eads Interconnection alternative, the Roosevelt Bridge crossing is not immune to failure; however, compared with the other alternatives, the probability of failure is minimal.

226. This alternative has minimal system dependency relative to the other supply alternatives. Under this proposal, the Roosevelt Bridge river crossing would extend from the Foxhall Reservoir across the Potomac River to FOWM. As a result, this alternative is dependent upon the DC First High system. However, the existing Key Bridge crossing is also dependent upon DC

First High. Consequently, this alternative has been assigned a value of one in the system dependency category.

227. The Roosevelt Bridge river crossing has no negative engineering impacts in the energy efficiency category. This crossing would be supplied from the DC First High pressure zone. The existing Key Bridge river crossing is also supplied from DC First High. Short of gravity flow, this is the most efficient method of supplying the FOWM system under existing conditions. Most of FOWM can be supplied by gravity from DC Low service which would result in a more efficient alternative; however, pressures at higher elevations are such that demands at these locations could not be met. As a result, gravity flow from DC Low service is an unsuitable alternative.

14th Street Bridge river crossing

228. The 14th Street Bridge river crossing has an engineering assessment very similar to that of the Roosevelt Bridge crossing. Difficulty of construction and difficulty of access have been assigned moderate engineering impacts for the same reasons. The 14th Street Bridge River Crossing alternative, however, does travel through more national park land than the Roosevelt Bridge River crossing alternative.

229. This alternative has the same degree of impact in the component reliability and system dependency categories as the previous alternative, again for the same reasons. In fact, the only difference between the two alternatives, besides location of the river crossing, is the length of pipe involved. This may contribute more of an impact to component reliability than the Roosevelt crossing. The energy efficiency of the 14th Street Bridge crossing has no negative engineering impacts as compared to the other supply alternatives.

Booster pump off Low service

230. The Booster Pump Off Low Service alternative has a lower degree of construction difficulty than the Roosevelt Bridge or 14th Street Bridge crossings because this proposal does not travel through national park lands to the same degree as the previous alternatives. Some park land is traversed, however, so a slight degree of impact has been assigned.

231. Difficulty of access is moderate since a pipe construction on 14th Street Bridge must be undertaken. Space is limited on the bridge, traffic over the bridge must be maintained, and construction must take place either on the bridge or from a barge in the Potomac River.

232. Component reliability with respect to the other alternatives is slight since this alternative primarily consists of pipes and valves. Unlike the other supply alternatives, this proposal involves a booster pump. The booster pump contributes another degree of negative impact since the pump adds more moving parts to the alternative, which in turn adds more components upon which the alternative relies.

233. The Booster Pump Off Low Service alternative depends upon proper operation of the Low service pressure zone. Like the Roosevelt Bridge and 14th Street Bridge River Crossing alternatives, the booster pump alternative is dependent upon another system and hence is assigned a minimal system dependency.

234. The energy efficiency impact of the booster pump alternative has been rated as minimal. Even though the combined head of the Low service pumps and the booster pump is equal to the head of the DC First High pumps, the First High pumps are in place and would not have to be operated any differently than they are now in order for the Roosevelt Bridge, 14th Street Bridge, and subaqueous river crossing to work. The booster pump alternative, on the other hand, would require operation of an additional pump. For this reason, the energy impact has been assigned a value of one.

Subaqueous river crossing

235. The subaqueous river crossing is much like the Roosevelt Bridge and 14th Street Bridge River Crossing alternatives from the perspective of negative engineering impacts. The difficulty of construction has been rated as major since this alternative not only traverses national park lands but also involves an underwater pipe installation. Subaqueous pipeline installation will require divers to accomplish some underwater construction. For this reason and the fact that park land is involved merits a major negative impact rating.

236. The difficulty of access is also aggravated by the underwater construction. Furthermore, a trench installation is proposed for a segment of this link crossing Roosevelt Island. Again, this involves national park land for which permission to construct may be difficult to obtain. As a result, moderate difficulty of access is anticipated.

237. The subaqueous river crossing is similar to the Roosevelt Bridge and 14th Street Bridge crossings in the remaining engineering impact categories. This alternative involves the use of pipes and valves; therefore,

component reliability is minimal. System dependency is also minimal since this alternative only depends upon proper operation of DC First High. Finally, there are no energy impacts since the crossing is supplied from DC First High.

New tank at Navy Annex

238. The New Navy Annex Tank alternative has been evaluated for the same negative engineering impacts at the other supply alternatives. The difficulty of construction of this alternative is minimal since only a very small amount of land will be disturbed. The proposed site of the tank is the Navy Annex, which appears to have the available land for such a structure.

239. Difficulty of access for the proposed Navy Annex tank is rated at extreme. Washington Aqueduct officials have indicated that opposition to storage tanks in the area surrounding the Navy Annex is very strong, and it is highly unlikely such a tank would obtain public approval. For this reason, the engineering impact has been assigned a value of five.

240. The component reliability of a Navy Annex tank is minimal with respect to the other supply alternatives since this alternative, like many of the previous alternatives, only involves pipes and valves. The system dependency, on the other hand, has been assigned a value of two. Not only is the tank dependent upon proper operation of the DC First High system but also upon proper operation of the FOWM network. If either of the systems experiences a serious emergency, proper operation may be affected. The energy efficiency of the tank experiences no negative impacts since it is hydraulically connected to DC First High.

Main-Strengthening Alternatives

Paralleling 30-in. main

241. Difficulty of construction for paralleling the 30-in. FOWM transmission main has been rated slight with respect to the other main-strengthening alternatives. Construction will either be in or along the Jefferson Davis Highway for most of its length, plus construction must take place in national park land areas. Although construction may not be that difficult, these facts contribute to slightly negative engineering impacts.

242. Access to a suitable pipeline route may also be difficult to obtain since the alternative is located in park areas for a substantial

portion of its length. Compared with the remaining pipeline alternatives, this alternative has been assigned a value of three for difficulty of access.

243. The component reliability of the Paralleling 30-in. Main alternative is minimal since this proposal only involves pipes and valves. The number of moving parts is kept to a minimum. The system dependency and energy efficiency of this alternative, with respect to the remaining main-strengthening alternatives, are nonexistent.

New airport feed

244. The negative engineering impacts for the New Airport Feed alternative are in most respects very similar to the previous alternative. Difficulty of construction is moderate since this alternative involves construction, not in park lands but in a congested urban area. A good deal of construction must take place in Crystal City, which is an urban setting. Presence of existing utilities may contribute to construction difficulty.

245. Unlike the previous alternative, access to this alternative may not be as difficult to obtain since only a small amount of national park land is involved. As a result, compared with the other main construction alternatives, only slight engineering impacts are expected.

246. This alternative is identical to the previous alternative in the component reliability, system dependency, and energy efficiency categories. As a result, the same impacts have been assigned to both alternatives.

Closing Pentagon loop

247. This alternative has been rated as moderately difficult to construct compared with the other alternatives. Presently, a segment of main circling the Pentagon is crushed and placed out of service; therefore, the loop is broken. This line is buried very deeply adjacent to the Pentagon. Repairing or replacing this segment of main merits a moderate rating.

248. Access to this alternative should not be as difficult to obtain as the paralleling alternative since little or no national park land is involved. However, construction will take place very close to the Pentagon. Construction may, to some degree, affect normal operation of the facility. As a result, a slightly negative impact has been given.

249. This alternative, like the previous main-strengthening alternatives, does not involve any negative system dependency or energy efficiency impacts. Component reliability impacts are minimal since only pipes and valves are involved.

Constructing new Pentagon loop

250. Installing a new loop near the Pentagon will result in only minimal construction difficulty since the area is not in national park areas nor adjacent to any roadways. Construction would occur in a parking lot which would present minor construction and access difficulty. This project also presents minimal component reliability since it only involves pipes and valves. Like the previous main-strengthening alternatives, no system dependency or energy efficiency impacts are expected.

PART IX: ECONOMIC EVALUATION OF SYSTEM IMPROVEMENTS

Evaluation Procedure

251. Another criterion for evaluating each alternative was cost. A four-step process was used to calculate construction costs for the proposed alternatives. The steps consisted of selecting the construction categories, developing unit costs for the categories chosen, determining the quantity of each type of construction within each route, and adding the products of the unit costs and the quantities assigned to each route to ascertain the construction cost.

Construction Categories

252. Based on a 1979 study for the Baltimore District by Hayes, Seay, Mattern and Mattern Engineers, seven different construction categories were chosen to reflect the various degrees of difficulty and types of construction to be encountered. The construction categories selected for finished water pipeline construction are as follows:

- a. Open area. The construction category for open areas refers to construction in open space or undeveloped land with ample room for materials and equipment. Trench construction is used for all lines with proper bedding, graveling, and at least 4 ft of cover placed over all pipes. Limited use of trench sheeting may be used in open area construction.
- b. Open area road. This category refers to construction in roads which contain few existing utilities and are not heavily traveled. Roadway repaving, traffic maintenance, traffic control devices, and trench sheeting for 36-in. and larger pipelines may be required for construction falling into this category.
- c. Urban area. Urban area construction occurs in built-up urban areas which contain many existing utilities and structures. Deeper than normal excavation with the use of trench sheeting and relocation of existing utilities may be required.
- d. Urban area street. Urban area street construction is similar to urban area construction in that activity may take place in urban streets which contain many existing utilities and require deeper than normal excavation, trench sheeting, and/or relocation of existing utilities. Unlike urban area construction, urban area street construction also involves roadway repaving and traffic control.

e. Highway (primary/interstate) and railroad crossings. This category involves construction of pipeline crossings of major transportation routes, assuming that a casing pipe will be required. For 24-in. and smaller pipelines, a steel casing pipe would be jacked under the road or railroad and filled with grout. For pipelines larger than 24 in., a linear plate tunnel would be constructed.

f. Bridge crossing. The bridge crossing construction category encompasses all pipeline construction occurring on a bridge structure. Pipe may either be secured to the side of the structure or suspended beneath the bridge. Maintenance of traffic is required at all times during bridge construction.

g. Subaqueous river crossing. This construction category involves construction in the banks and bed of the Potomac River. This category is only applicable to a subaqueous river crossing and involves underwater trenching and/or concrete placement. Ball and socket pipe is used for the river crossing, whereas other suitable pipe materials may be used for land construction.

Unit Costs

253. Unit costs for all six construction categories are summarized in Table 13 for a range of pipe diameters. These costs were based on estimates developed in two recent studies: "Arlington County Water System Study" by Montgomery Engineers of Virginia (1980) and "Development of Engineering and Cost Data for Finished and Raw Water Interconnections" by Hayes, Seay, Mattern and Mattern Engineers (1979). All costs were updated to the present using a December 1987 *Engineering News Record* Construction Cost Index of 4464.

Capital Construction Costs

254. The capital construction costs for the six supply alternatives and the four main-strengthening alternatives are shown in Appendix C. Each alternative was analyzed to determine how much of the alternative would fall into a given construction category. The costs were computed by multiplying the unit cost of a given construction category and the length of pipe which could be expected to be installed under the conditions of the category. Overhead and profit amounting to 15 percent of the capital cost were added to find the estimated cost of the alternative. The estimated cost of each alternative is provided in Table 14.

Table 13

Unit Costs

Construction Category	Summary of Unit Costs for Indicated Pipe Diameter, $/lin ft					
	12 in.	16 in.	20 in.	24 in.	30 in.	36 in.
Open area	49	54	70	78	104	129
Open area road	68	76	98	109	140	170
Urban area	114	126	163	181	218	254
Urban area street	133	148	191	212	253	294
Highway and railroad crossing	300	334	431	478	724	969
Bridge crossing	421	465	603	705	1,065	1,427
Subaqueous river crossing	450	500	750	1,000	1,540	2,000

Energy Costs

255. Water supplied through the 15th and Eads interconnection will cost significantly more than water supplied through the existing and alternative river crossings in terms of increased energy costs. Water for the interconnections is supplied from the Third High pressure zone while the water for the river crossings is supplied from the First High pressure zone. The relative cost of water from each pressure zone may be estimated on a unit flow basis using the following equation:

$$\text{Unit Cost } \frac{\$}{\text{kgal}} = 0.00314 \text{ R } \frac{h}{e} \qquad (2)$$

where

kgal = 1,000 gal

R = electric rate, $/kwhr

h = pump head, ft

e = average wire-to-water pump efficiency

Table 14

Capital Cost Estimates for Proposed Alternatives

Alternative	Capital Cost (Thousands of Dollars)
Supply alternative	
15th and Eads Interconnection	0
Roosevelt Bridge River Crossing	9,750
14th Street Bridge River Crossing	10,990
Booster Pump Off Low Service	8,638
Subaqueous River Crossing	8,948
New Tank at Navy Annex	2,033
Main-strengthening alternative	
Paralleling 30-in. main	1,441
New airport feed	2,341
Closing Pentagon loop	239
Constructing new Pentagon loop	54

256. Based on a previous study conducted by the US Army Corps of Engineers on the condition of the DC pumps (Ormsbee et al. 1987), the average efficiency of the First High and Third High pumping units was found to be 80 percent. The study also identified the seasonal and hourly electrical rate structure charged to the WAD. An average electrical cost of $0.0438/kwhr was found based on an analysis of the distribution of the rate schedule. Pumping heads were found by conducting a steady-state analysis on the First High and Third High systems assuming an average daily demand loading. The pump head for First High was found to be 140 ft while the Third High pump head was 330 ft.

257. Unit costs of energy costs were computed using Equation 2. The unit cost of pumping for DC First High, including the FOWM system, is $0.024/1,000 gal. For the Third High pressure zone which also includes Arlington County, a unit pumping cost of $0.057/1,000 gal was found. As can

be seen from these values, water supplied through the existing and proposed interconnections is approximately 2.5 times as expensive as water supplied through the existing and alternative river crossings.

PART X: RECOMMENDATIONS

258. Based on the hydraulic, engineering, and economic analyses, certain recommendations are made which will result in a more reliable FOWM water distribution system. The recommendations were made with an emphasis on possible long-term pipe outages. In other words, if a critical FOWM link, such as the Key Bridge river crossing or the 30-in. FOWM transmission main were placed out of service for an extended period of time, which recommended alternatives proposed could adequately supply the FOWM system under all loading conditions with no adverse effects? Such alternatives should allow the FOWM system to "stand alone" without having to rely on another distribution system.

259. Constructing a new river crossing from Foxhall Reservoir across the Potomac River to FOWM would essentially replicate the existing Key Bridge crossing, thereby greatly increasing FOWM reliability. The river crossing should be able to supply the FOWM system if a segment of the 30-in. transmission main in FOWM were to fail. The 14th Street Bridge River Crossing alternative can independently supply the FOWM network under such conditions. In fact, the 14th Street Bridge river crossing can adequately supply the FOWM system for outages of all critical FOWM lines during most loading conditions. The only case where the 14th Street Bridge crossing is unable to provide adequate flow to FOWM is during a Pentagon fire with the Key Bridge river crossing out of service.

260. With the Key Bridge river crossing out of service, a fire demand at the Pentagon cannot be satisfied by the 14th Street Bridge crossing because of high head losses in the existing 24- and 16-in. lines between the Pentagon and National Airport. If the New Airport Feed alternative were constructed along with the 14th Street Bridge river crossing, the head loss would be significantly reduced, plus water would be allowed to reach the fire from a different direction. As a result, a Pentagon fire demand could be met with the Key Bridge crossing out of service. Furthermore, installing the new airport feed results in a second supply source for National Airport. This also greatly increases the reliability of the FOWM system. With the 14th Street Bridge crossing and new airport feed in service, the fire flow to the airport is nearly 20,000 gpm during maximum daily demands. This easily exceeds ISO fire-fighting requirements.

261. With the combined 14th Street Bridge crossing and new airport feed alternative, the FOWM system can be supplied with adequate flows and pressures during FOWM pipe outage under any loading condition. Table 15 lists the pressure indices and number of failed nodes for the combined alternative during average daily demands, maximum daily demands, peak hourly demands, a 7,500-gpm fire demand at the Pentagon, a 7,500-gpm fire demand at National Airport, and a 2,400-gpm fire demand at Fort Myer.

262. The loop around the Pentagon and the National Airport interconnection from Arlington County should be repaired. Although these alternatives provide a marginal increase in hydraulic performance, reliability is increased by adding these lines as additional loops are created. Closing the Pentagon loop is part of the New Airport Feed alternative, and installing a new airport feed eliminates the need for an airport interconnection. Therefore, constructing the new airport feed will have the same effect as repairing the crushed Pentagon loop and airport interconnection. In fact, performance will be improved since the fire flow to National Airport is increased with the new airport feed.

263. A potential benefit identified during the course of the study is supplying Arlington County Third Gravity directly from DC First High. The elevations and hydraulic grades in FOWM and Arlington County Third Gravity are approximately the same. Currently, however, water is passed through PRV's in the Arlington County system before it reaches Third High in order to bring the pressure down to acceptable values. Since the operating grades in FOWM and Third Gravity are the same, and water supplied from DC First High is less expensive in terms of energy use than water from DC Third High, significant savings could be realized by supplying Third Gravity through FOWM.

264. From a previous energy analysis for the 15th and Eads interconnection, it was found that water supplied by DC Third High has a unit cost 2.5 times greater than water supplied by DC First High. Assuming an average daily demand of 3,900 gpm for Arlington County Third Gravity, an annual savings of approximately $70,000 may be realized by supplying Arlington County Third Gravity from DC First High through the FOWM system. Even more savings may be realized with increased Crystal City growth and water demand. The implementation of such an operation policy would be dependent upon the hydraulic capacity of the Dalecarlia First High Pump Station, the hydraulic characteristics of FOWM, and the coordination of the various utilities. The existing FOWM

Table 15

Pressure Indices for Combined 14th Street Bridge River Crossing and New Airport Feed Alternative*

	ADD		MDD		PHD		F1		F2		F3	
Pipe Outage	PI	FN	PI	FN	PI	FN	PI	FN	PI	FN	PI	FN
30 in. under Key Bridge	45.77	4	43.67	4	35.36	4	42.42	4	42.34	4	61.12	0
16 in. under Key Bridge	46.28	4	44.82	4	38.19	4	59.18	0	56.38	0	64.56	0
30 in. along Davis Hwy. #1	46.22	4	44.50	4	37.83	4	49.64	0	48.47	0	65.08	0
30 in. along Davis Hwy. #2	46.23	4	44.52	4	37.90	4	49.41	0	48.33	0	65.16	0
16 in. along Eisenhower Dr. #1	46.12	4	44.31	4	37.26	4	59.14	0	56.29	0	65.07	0
16 in. along Eisenhower Dr. #2	46.08	4	44.24	4	37.05	4	59.05	0	56.17	0	65.01	0
12 in. by Navy Annex	46.26	4	44.57	4	38.05	4	60.32	0	57.35	0	64.94	0
18 in. by Pentagon	46.34	4	44.72	4	38.49	4	60.43	0	56.96	0	65.10	0
24 in. to Airport	46.33	4	44.71	4	38.45	4	60.01	0	57.17	0	65.09	0
16 in. to Airport	46.31	4	44.67	4	38.35	4	59.72	0	57.44	0	65.05	0
30 in. and 16 in. under Key Bridge	44.67	4	41.62	4	29.26	4	16.37	6	23.10	5	54.34	0

* ADD = average daily demand, MDD = maximum daily demand, PHD = peak hourly demand, F1 = Pentagon fire demand, F2 = National Airport fire demand, F3 = Fort Myer fire demand, PI = pressure index, and FN = number of failed nodes.

system may not be able to handle the added strain associated with the increase in demand from Arlington County Third High. However, constructing the 14th Street Bridge river crossing would most likely avert any problems of this nature. Furthermore, supplying Arlington Third Gravity from the 14th Street Bridge not only results in energy savings but also increases the reliability of the Third High pressure zone since an additional source of supply is provided.

PART XI: SUMMARY AND RECOMMENDATIONS

Existing System Summary

265. The reliability of the existing FOWM system is highly dependent upon three different pipe links. The first and most important segment is the Key Bridge river crossing which carries the entire FOWM supply. If the two mains which make up this crossing are taken out of service, an alternate means of supply must be employed. At the present time, the only alternate means of supply are several interconnections with the Arlington County, Virginia, distribution system.

266. A second vital link in the FOWM system is the 30-in. steel main extending from Key Bridge to the Pentagon. This line carries close to 83 percent of the total delivery to the FOWM system. If this line were to be placed out of service, all flow would have to be routed through the 16-in. line along Eisenhower Drive. During periods of high consumption or fire demand, flow in the 16-in. line would cause excessive head loss. As a result, system pressures would be reduced below acceptable levels, and system demands could not be fully met.

267. A final area of concern is the feed to National Airport. This link consists of a 24-in. pipe and a 16-in. pipe connected in series. This is the only source of supply for National Airport. If this line were out of service, an alternate means of supply would have to be provided in order for the airport to continue its normal operations. Furthermore, the available fire flow to the airport through this line is 3,500 gpm during maximum daily demands. Consequently, ISO fire fighting requirements of 7,500 gpm cannot be met by this line.

System Improvements Summary

268. Several system improvements were evaluated to determine their contribution to the overall reliability of the FOWM system. System improvements may be categorized as supply alternatives or main-strengthening alternatives. Supply alternatives consist of both existing and proposed interconnections, proposed river crossings, and a proposed storage tank. Main-strengthening

alternatives include paralleling existing lines, repairing damaged lines, and laying new pipe.

Existing interconnections

269. The 15th and Eads, Fern Street, and Crystal City interconnections can supply the FOWM system during normal flow periods in the event of supply disruption through the existing Key Bridge river crossing. As system demands increase, however, the performance of existing interconnections deteriorates to such a point that FOWM system pressures cannot be kept above the 40-psi standard for extended periods of time.

270. Performance of the Arlington Third Gravity storage tank is adversely affected with operation of the 15th and Eads, Fern Street, and Crystal City interconnections. Opening these connections to supply FOWM will cause the tank to ultimately drain completely. This is unacceptable since no emergency storage or fire storage is available in the tank. In fact, it is unlikely Arlington County will allow continued supply of the FOWM system if the Third Gravity tank drains to a dangerously low level.

271. The Navy Annex and Pentagon heating plant interconnections cannot adequately supply the FOWM system. These connections may, however, be used to supply the adjacent Federal areas. The Fort Myer interconnection is very similar to the Navy Annex interconnection and, as a result, should be used to help supply Fort Myer in the event of an emergency.

Proposed interconnections

272. The proposed Rosslyn interconnections cannot adequately supply the FOWM system particularly during a period of high flow because of large head losses induced in the Rosslyn pressure zone. The Rosslyn pressure zone, unlike Second and Third Gravity, does not have a storage tank to help augment supply during peak loadings. The National Airport interconnection is to be used as an alternate feed to the airport only. Although it can supply the airport during most loading conditions, the interconnection cannot, by itself, supply the necessary 7,500-gpm fire flow.

New river crossings

273. The proposed river crossing alternatives may also be used to supply the FOWM network in the event of an outage of the Key Bridge river crossing. It is assumed that these new supply lines will be operated at all times and not just in times of emergency. Coupled with certain main-strengthening alternatives, the proposed new river crossings can supply FOWM

at adequate pressures during each of the outage scenarios analyzed as part of this study.

274. The proposed river crossing alternatives have no adverse effect on the controlling Foxhall tank. Because of the large capacity of Foxhall tank and the rated capacity of the Dalecarlia First High pumps, Foxhall tank can be filled as necessary to provide ample storage. The proposed river crossing alternatives merely act to replace the existing river crossing and as a result drain the tank no differently than the existing crossing.

New tank at Navy Annex

275. A proposed storage tank at the Navy Annex may also be used to supply the FOWM system during a Key Bridge outage, but only for a limited period of time. With the existing Key Bridge river crossing in service, the proposed tank is able to fill and drain thereby providing proper turnover of water. If both pipes comprising the existing river crossing were taken off-line and the existing interconnections not opened, the proposed tank would drain in a matter of hours depending upon the initial tank level. A more practical use for the storage tank would be to help augment supply during short duration peak loading conditions or during periods of fire demand.

Main-Strengthening Alternatives

Paralleling 30-in. main

276. In addition to the Key Bridge river crossing, outage of certain other critical lines will also cause below par performance of the existing system, specifically, outage of the 30-in. line from Key Bridge to the Pentagon and the compound 24- and 16-in. airport feed. Installing connections between the existing 30- and 16-in. supply lines and paralleling the existing 30-in. line with a 16-in. main would help to relieve stress on the 16-in. line during a 30-in. main outage. This main-strengthening alternative acts to keep as much of the 30-in. line as possible in service at all times. Employing this strategy would enable system pressures to remain above the 40-psi limit during outage of a segment of the existing 30-in. line. However, this alternative does not provide adequate pressures during an outage of the 30- and 16-in. supply lines under Key Bridge during period of high flow.

New airport feed

277. Another main-strengthening alternative is construction of the

proposed new airport feed. Presently the available fire flow to National Airport through this line is approximately 3,500 gpm. As a result, ISO firefighting requirements of 7,500 gpm cannot be met. Installation of the new airport feed would allow ISO requirements at the airport to be met and would provide another source of flow to the airport.

Closing Pentagon loop and constructing new Pentagon loop

278. Other reliability-improving measures involving new pipeline construction are closing the Pentagon loop and creating a new Pentagon loop. Although the improvement in system performance with these alternatives is marginal, reliability is increased since adding these lines creates additional loops.

Recommendations

279. The reliability of the FOWM system can be greatly increased by constructing a new river crossing extending from the Foxhall Reservoir across the 14th Street Bridge and connecting to the FOWM system in Crystal City. Along with the 14th Street Bridge crossing, the new airport feed from the Pentagon along Jefferson Davis Highway to Washington National Airport should also be constructed to provide even more reliability. The two alternatives, working in tandem, provide a hydraulically equivalent backup to the Key Bridge river crossing, the 30-in. FOWM transmission main, and the existing airport feed. This combined alternative provides adequate flows and pressures during outages of critical FOWM lines during any loading condition. Furthermore, if this combined alternative is connected to the Arlington County Third Gravity pressure zone, significant energy savings plus an increase in Arlington County reliability could be realized.

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APPENDIX A: HYDRAULIC NETWORK DATA

Table A1

Pipe Data for First High Pressure Zone

Connecting Nodes		Length ft	Diameter in.	Hazen-Williams C-Factor
600	601	11,900	48	90
601	0	1,200	48	90
601	602	7,320	30	90
601	603	7,420	48	90
603	602	2	30	90
603	605	10	30	90
602	604	10	48	90

Table A2

Pipe Data for Third High Pressure Zone

Connecting Nodes		Length ft	Diameter in.	Hazen-Williams C-Factor
500	101	4,150	24	91
500	101	4,530	36	117
500	7	12,480	48	150
500	4	7,200	36	100
7	0	500	36	150

Table A3

Pipe Data for Arlington System

Connecting Nodes		Length ft	Diameter in.	Hazen-Williams C-Factor
101	102	700	20	91
101	102	700	20	91
101	102	700	20	91
101	102	700	48	117
102	103	1,800	36	117
103	104	1,460	36	117
103	112	4,900	36	117
104	105	1,000	8	108
105	107	1,225	8	108
105	106	1,450	8	108
106	107	1,730	8	108
107	109	1,230	8	108
109	111	1,060	8	108
104	108	3,680	20	91
112	111	650	8	108
112	115	1,920	36	117
115	114	280	30	117
108	110	1,535	20	91
111	110	760	8	108
109	108	375	8	108
111	114	2,265	8	108
110	114	800	20	91
110	162	2,450	8	108
162	113	1,150	8	108
113	164	1,135	30	117
114	113	2,680	30	117
113	116	3,970	6	108
114	116	2,050	20	91
116	117	1,760	20	91
115	118	3,475	36	117
118	119	2,455	36	117
117	119	1,825	16	105
117	120	2,000	20	91
120	121	1,360	12	117
119	121	2,300	36	117
119	126	5,810	16	105
121	125	1,860	12	117
125	126	2,855	12	117
126	159	625	12	117
121	124	2,670	36	117
124	134	3,850	20	91
134	135	550	20	91
126	135	900	16	105

(Continued)

(Sheet 1 of 7)

Table A3 (Continued)

Connecting Nodes		Length ft	Diameter in.	Hazen-Williams C-Factor
135	157	1,150	16	105
134	136	730	12	117
136	156	1,600	16	105
136	135	450	16	105
136	137	650	16	105
124	129	1,650	36	117
120	122	2,170	12	117
122	123	1,000	16	105
123	127	850	12	117
127	129	2,285	12	117
129	133	915	12	117
133	137	2,855	8	108
137	138	1,085	8	108
138	163	460	12	117
163	173	1,500	6	108
159	174	3,245	12	117
157	175	1,850	16	105
156	176	675	16	105
137	139	515	16	105
139	141	450	16	105
139	140	935	12	117
140	138	500	12	117
140	142	750	6	108
142	141	1,035	12	117
141	150	1,840	16	105
129	131	460	36	117
131	132	350	36	117
131	133	950	16	105
132	158	915	8	108
158	160	475	12	117
160	149	1,675	12	117
133	160	500	16	105
160	149	1,565	16	105
149	148	710	12	117
149	150	1,225	16	105
148	147	400	12	117
148	152	600	8	108
152	161	900	8	108
150	161	850	16	105
172	152	1,200	12	117
161	151	1,330	16	105
155	170	650	16	105
155	177	550	16	105
147	146	1,300	12	117

(Continued)

(Sheet 2 of 7)

Table A3 (Continued)

Connecting Nodes		Length ft	Diameter in.	Hazen-Williams C-Factor
146	154	425	12	117
132	144	2,500	36	117
144	147	1,735	8	108
144	145	1,425	30	117
145	146	1,235	8	108
145	153	1,100	30	117
131	128	2,530	16	105
132	130	2,600	8	108
144	143	1,160	8	108
143	130	3,235	6	108
128	127	1,330	8	108
130	128	1,300	8	108
154	178	1,900	12	117
153	179	1,260	30	117
102	104	2,715	24	91
104	501	550	24	91
170	151	230	16	105
151	171	300	12	117
171	172	300	12	117
149	165	230	12	117
243	244	2,570	8	117
244	237	4,300	12	96
237	236	2,240	12	96
261	235	1,530	12	96
235	270	760	12	116
239	243	3,090	12	116
239	238	900	12	116
238	237	875	12	116
242	243	1,040	8	116
242	224	3,185	30	71
223	224	1,050	12	116
224	239	480	12	116
224	225	660	24	71
225	226	2,920	20	71
248	242	1,850	8	116
223	240	2,200	8	116
240	248	1,200	8	116
238	226	2,165	12	116
226	227	1,610	20	71
227	228	2,380	20	71
227	228	2,200	12	116
228	229	1,700	20	71
229	235	1,730	8	116
229	273	1,300	20	71

(Continued)

(Sheet 3 of 7)

Table A3 (Continued)

Connecting Nodes		Length ft	Diameter in.	Hazen-Williams C-Factor
229	231	3,075	8	116
229	230	3,690	6	116
230	231	1,525	6	116
231	232	1,100	8	116
232	233	1,500	8	116
233	234	1,650	8	116
241	240	4,430	6	116
222	223	1,150	6	116
222	241	1,360	6	116
241	202	1,900	8	116
202	780	2,650	12	116
202	201	1,635	8	116
219	226	2,980	12	116
219	225	1,825	20	116
219	223	2,350	8	116
221	222	3,820	6	116
219	221	2,480	8	116
203	221	2,080	8	116
202	203	2,165	12	116
203	217	2,930	20	71
221	218	2,050	6	116
219	220	2,270	8	116
220	246	2,300	8	116
219	247	2,290	12	71
219	247	2,370	16	71
218	247	860	12	116
217	247	1,915	16	116
218	246	775	6	116
217	218	920	12	116
216	215	3,880	16	116
201	204	1,500	20	116
204	203	1,530	20	116
207	206	825	6	116
204	207	2,060	8	116
205	204	2,230	12	116
205	206	1,440	12	116
208	216	2,075	12	116
206	208	2,565	12	116
208	209	5,130	8	116
209	215	2,200	8	116
209	210	1,000	12	116
212	214	2,290	8	116
213	214	1,360	16	116
214	215	500	16	116
213	212	350	16	116

(Continued)

(Sheet 4 of 7)

Table A3 (Continued)

Connecting Nodes		Length ft	Diameter in.	Hazen-Williams C-Factor
210	213	1,655	8	116
210	211	3,145	8	116
211	212	1,985	8	116
215	271	2,180	6	116
216	217	775	16	116
217	272	500	12	116
236	260	1,100	12	116
260	261	630	12	116
303	302	565	8	113
301	302	2,600	12	113
302	305	2,775	12	113
305	304	1,400	12	113
304	316	5,500	24	101
305	306	1,650	12	113
306	307	1,375	12	113
307	310	4,345	12	113
305	308	4,020	8	113
308	309	1,865	8	113
309	310	950	8	113
332	333	1,855	12	113
333	334	1,200	12	110
329	334	2,100	12	113
334	335	550	12	110
335	336	760	12	110
335	337	2,000	12	113
336	337	1,500	24	101
338	331	875	20	77
301	339	1,830	16	113
304	339	4,540	24	101
331	332	950	12	113
331	330	500	20	77
330	329	840	12	77
329	332	1,520	12	113
330	317	550	16	77
317	318	525	16	77
318	329	800	8	113
318	319	550	16	77
329	328	1,400	12	77
328	327	800	12	113
327	325	1,050	12	113
327	326	460	12	113
326	337	1,010	12	113
326	325	980	12	113
325	324	975	12	113
320	336	2,790	24	101

(Continued)

(Sheet 5 of 7)

Table A3 (Continued)

Connecting Nodes		Length ft	Diameter in.	Hazen-Williams C-Factor
325	321	1,475	12	113
325	321	1,475	12	113
325	321	1,475	12	113
324	323	1,550	12	113
323	321	825	12	113
321	311	1,000	12	113
323	322	1,115	12	113
322	311	850	12	113
321	311	720	12	113
321	311	1,020	12	113
319	316	2,420	24	101
316	314	1,650	8	113
314	319	865	16	113
313	314	1,000	16	113
314	315	1,200	8	113
319	320	1,125	24	101
312	313	1,200	16	113
320	315	865	16	113
315	312	1,000	16	113
315	321	830	8	113
312	311	1,040	16	113
325	326	980	12	113
310	311	3,840	12	113
328	340	475	12	110
340	341	475	12	113
341	342	230		113
342	343	150	8	113
342	336	80	12	113
415	411	1,015	12	100
415	414	2,200	12	100
414	413	1,360	12	100
411	412	1,260	16	100
412	413	500	16	100
404	405	2,535	12	100
405	412	615	12	100
405	406	470	12	100
406	413	600	12	100
403	404	665	12	100
402	403	570	12	100
401	402	1,150	6	100
402	410	1,665	12	100
410	408	2,075	8	100
410	409	950	12	100
409	408	1,400	6	100
403	407	2,800	12	100

(Continued)

Table A3 (Concluded)

Connecting Nodes		Length ft	Diameter in.	Hazen-Williams C-Factor
408	407	630	8	100
407	406	500	12	100
159	411	3,245	12	100
157	411	1,850	16	100
156	404	675	16	100
163	401	1,500	6	100
155	244	550	16	117
154	243	1,900	12	117
153	242	1,260	30	117
235	333	760	12	116
229	338	1,300	20	71
217	301	500	12	116
215	303	2,180	6	116
247	0	100	12	88
339	0	100	16	107
636	327	1	24	100
638	324	1	16	120
651	326	1	16	120
632	351	1	8	120
351	350	1,330	8	111
350	337	1,000	12	111
634	335	1	24	120
633	670	1	8	120

(Sheet 7 of 7)

Table A4

Pipe Data for FOWM System

Connecting Nodes		Length ft	Diameter in.	Hazen-Williams C-Factor
602	606	1,580	30	93
602	607	1,820	16	103
606	608	2,590	30	93
607	609	2,360	16	96
608	610	3,340	30	93
609	611	3,450	16	96
610	612	340	30	93
610	613	530	16	93
611	613	63	16	96
612	614	1,890	30	93
611	615	1,900	16	96
614	615	1,590	8	60
614	616	1,960	30	93
615	617	1,390	16	96
616	618	1,210	8	60
618	620	1,600	8	60
620	674	990	16	84
674	622	240	16	84
674	675	65	10	60
675	676	375	8	60
616	622	1,830	30	93
617	619	1,260	16	96
619	621	880	16	96
621	623	670	16	96
623	625	240	16	96
625	627	420	10	90
627	629	66	8	70
629	631	720	8	70
631	633	1,400	8	70
629	635	1,460	8	70
635	637	1,150	8	70
625	624	1,610	12	66
664	626	285	24	65
626	624	700	18	86
620	628	1,120	16	84
626	628	1,940	16	84
628	630	1,120	8	60
630	677	325	6	60
677	632	845	6	60
624	634	1,860	24	60
634	636	2,800	24	60
636	651	1,070	16	90
638	640	1,540	16	90
640	642	1,250	8	60
640	644	1,650	16	90

(Continued)

Table A4 (Concluded)

Connecting Nodes		Length ft	Diameter in.	Hazen-Williams C-Factor
644	646	570	16	90
646	648	1,330	8	60
644	650	1,100	8	60
622	660	265	24	65
660	661	300	8	111
660	662	360	24	65
662	663	440	24	65
663	664	350	24	65
260	670	180	8	96
670	671	900	8	116
671	672	230	8	116
672	673	300	8	116
651	638	660	16	90

Table A5

Junction Data for First High Pressure Zone

Node	Demand gpm
604	6,163
605	6,163

Table A6

Junction Data for Third High Pressure Zone

Node	Demand gpm
4	7,100
7	7,100

Table A7

Junction Data for Arlington System

Node	Demand gpm
114	530
131	998
135	1,004
164	950
217	768
219	1,420
234	813
237	403
304	1,102
313	1,444
325	753
330	605
403	559
406	559
409	559
411	559
501	3,145

Table A8

Junction Data for FOWM System

Node	Demand gpm
613	249
615	62
617	62
626	479
628	249
630	124
631	124
633	124
637	124
642	124
644	124
646	124
648	124
650	124

APPENDIX B: PRESSURE INDICES

1. A steady-state hydraulic analysis was conducted for each supply and main-strengthening alternative for a given pipe outage under a particular loading condition to determine its contribution to Federally Owned Water Main (FOWM) system reliability and hydraulic performance. For a given alternative and for each pipe scenario (pipe outage under a particular loading condition), a pressure index or severity index was computed (Tables B1-B15).

2. The severity index used in this study is a pressure index based on pressure differences from an absolute minimum and is defined below:

$$PI = \frac{\sum_{i=1}^{N} (P_i - P_{min})}{N} \qquad \text{(B1)}$$

where

PI = pressure index

N = total number of nodes

P_i = pressure at junction node i

P_{min} = minimum allowable pressure

3. The advantage of using a severity index is that it enables quick identification of those key mains which, when placed out of service, will adversely affect the performance of the system. The minimum allowable pressure was set at 40 psi for all scenarios except those which involved fire demands. For fire demand situations, the minimum allowable pressure was set at 20 psi.

Table B1

Pressure Indices for 15th and Eads Interconnection*

Pipe Scenario	ADD	MDD	PHD	F1	F2	F3	F4
30 in. under Key Bridge	30.02	27.45	13.02	24.74	18.90	45.74	40.65
16 in. under Key Bridge	38.41	35.99	27.49	50.61	36.52	55.65	55.60
30 in. along Davis Hwy. #1	34.74	32.42	21.22	35.99	27.29	53.55	47.96
30 in. along Davis Hwy. #2	35.23	32.99	21.44	35.54	27.08	54.10	47.79
16 in. along Eisenhower Dr. #1	37.98	35.53	26.62	50.58	35.69	56.41	54.90
16 in. along Eisenhower Dr. #2	37.88	35.36	26.26	50.60	35.52	56.30	54.75
12 in. by Navy Annex	39.44	37.16	28.88	23.00	38.00	57.47	56.93
18 in. by Pentagon	39.53	37.31	28.71	50.90	36.50	57.88	55.85
24 in. to airport	41.25	39.19	30.30	51.56	38.50	59.71	57.80
16 in. to airport	N/A	N/A	N/A	N/A	N/A	N/A	N/A
30 in. and 16" under Key Bridge	24.16	19.07	-12.71	-22.56	0.03	30.25	25.96
24 in. from Dalecarlia	39.10	36.81	28.56	52.18	37.61	57.16	56.55
36 in. from Dalecarlia	39.10	36.81	23.86	52.18	37.61	57.16	56.55
PRV at Army-Navy Dr.	39.10	36.81	28.61	52.18	37.61	57.16	56.55
PRV at S 16th and Lynn St.	39.10	36.81	28.61	52.18	37.61	57.16	56.55
Gravity Three tank riser	38.82	36.11	26.82	51.94	37.04	56.71	55.97

* ADD = average daily demand, MDD = maximum daily demand, PHD = peak hourly demand, F1 = Pentagon fire demand, F2 = National Airport fire demand, F3 = Fort Myer fire demand, F4 = Crystal City fire demand.

Table B2

Pressure Indices for Fern Street Interconnection*

Pipe Scenario	ADD	MDD	PHD	F1	F2	F3	F4
30 in. under Key Bridge	30.10	27.96	14.78	31.66	16.39	46.93	44.56
16 in. under Key Bridge	37.78	35.31	27.54	51.02	31.31	54.91	56.01
30 in. along Davis Hwy. #1	34.79	32.69	22.24	40.58	24.25	53.64	50.83
30 in. along Davis Hwy. #2	35.34	33.33	22.53	41.02	24.62	54.24	51.58
16 in. along Eisenhower Dr. #1	37.27	34.95	26.73	51.03	30.49	55.64	55.41
16 in. along Eisenhower Dr. #2	37.19	34.83	26.40	51.10	30.43	55.57	55.34
12 in. by Navy Annex	39.01	36.70	28.92	53.33	33.14	56.97	57.51
18 in. by Pentagon	39.52	37.35	28.97	50.94	32.28	57.88	57.41
24 in. to airport	41.30	39.29	30.53	51.62	34.66	59.77	59.40
16 in. to airport	N/A	N/A	N/A	N/A	N/A	N/A	N/A
30 in. and 16" under Key Bridge	25.91	22.36	-5.09	2.17	0.49	36.80	34.93
24 in. from Dalecarlia	38.60	36.14	28.54	52.43	32.47	56.57	56.93
36 in. from Dalecarlia	38.60	36.14	23.23	52.43	32.47	56.57	56.93
PRV at Army-Navy Dr.	38.60	36.14	28.62	52.43	32.47	56.57	56.93
PRV at S 16th and Lynn St.	38.60	36.14	28.62	52.43	32.47	56.57	56.93
Gravity Three tank riser	37.99	35.74	26.85	52.19	31.94	56.02	56.54

* ADD = average daily demand, MDD = maximum daily demand, PHD = peak hourly demand, F1 = Pentagon fire demand, F2 = National Airport fire demand, F3 = Fort Myer fire demand, F4 = Crystal City fire demand.

Table B3

Pressure Indices for Airport Interconnections*

Pipe Scenario	ADD	MDD	PHD	F1	F2	F3	F4
30 in. under Key Bridge	30.27	27.26	10.89	10.45	19.81	43.83	38.73
16 in. under Key Bridge	39.87	37.29	28.31	50.18	44.69	56.90	56.06
30 in. along Davis Hwy. #1	34.96	32.44	20.39	25.33	29.83	53.68	46.44
30 in. along Davis Hwy. #2	35.31	32.87	20.32	22.98	29.09	54.13	46.30
16 in. along Eisenhower Dr. #1	39.45	26.78	27.34	50.07	43.79	57.70	55.39
16 in. along Eisenhower Dr. #2	39.31	26.57	26.96	50.04	43.52	57.54	55.19
12 in. by Navy Annex	40.59	38.19	29.60	52.66	45.90	58.52	57.11
18 in. by Pentagon	39.78	37.55	29.00	51.01	41.69	58.08	55.05
24 in.to airport	41.26	39.21	30.38	51.58	42.18	59.73	56.34
16 in. to airport	42.25	40.16	31.36	51.48	45.41	60.60	58.42
30 in. and 16" under Key Bridge	20.47	12.18	-32.76	-95.07	-21.01	13.31	13.65
24 in. from Dalecarlia	40.44	38.01	29.38	52.00	45.75	58.38	56.91
36 in. from Dalecarlia	40.44	38.01	25.31	52.00	45.75	58.38	56.91
PRV at Army-Navy Dr.	40.44	38.01	29.43	52.00	45.75	58.38	56.91
PRV at S 16th and Lynn St.	40.44	38.01	29.43	52.00	45.75	58.38	56.91
Gravity Three tank riser	40.01	37.46	27.68	51.80	45.29	57.83	56.34

* ADD = average daily demand, MDD = maximum daily demand, PHD = peak hourly demand, F1 = Pentagon fire demand, F2 = National Airport fire demand, F3 = Fort Myer fire demand, F4 = Crystal City fire demand.

Table B4

Pressure Indices for Heating Plant Interconnection*

Pipe Scenario	ADD	MDD	PHD	F1	F2	F3	F4
30 in. under Key Bridge	30.38	18.65	-33.74	-130.73	-159.45	16.53	47.69
16 in. under Key Bridge	43.84	40.79	29.02	46.15	16.50	60.49	63.49
30 in. along Davis Hwy. #1	35.38	27.75	-7.34	-106.67	-132.51	52.96	53.33
30 in. along Davis Hwy. #2	33.56	23.54	-19.78	-169.56	-193.89	51.05	51.34
16 in. along Eisenhower Dr. #1	43.55	40.26	27.54	45.66	12.06	61.49	53.20
16 in. along Eisenhower Dr. #2	43.42	40.03	26.93	45.24	10.63	61.33	53.07
12 in. by Navy Annex	44.15	41.34	30.42	49.27	18.51	61.88	53.82
18 in. by Pentagon	42.42	38.05	20.37	51.47	-126.55	59.75	52.11
24 in. to airport	N/A	N/A	N/A	N/A	N/A	N/A	N/A
16 in. to airport	N/A	N/A	N/A	N/A	N/A	N/A	N/A
30 in. and 16 in. under Key Bridge	-857.85	-1,625.66	-4,898.08	-13780	-13808	-3425.79	-849.98
24 in. from Dalecarlia	44.15	41.33	30.39	49.63	20.08	61.88	63.82
36 in. from Dalecarlia	44.15	41.33	29.40	49.63	20.08	61.88	63.79
PRV at Army-Navy Dr.	44.15	41.33	30.39	49.63	20.08	61.88	63.82
PRV at S 16th and Lynn St.	44.15	41.33	30.39	49.63	20.08	61.88	63.82
Gravity Three tank riser	44.07	41.29	29.88	49.49	19.97	61.80	63.70

* ADD = average daily demand, MDD = maximum daily demand, PHD = peak hourly demand, F1 = Pentagon fire demand, F2 = National Airport fire demand, F3 = Fort Myer fire demand, F4 = Crystal City fire demand.

Table B5

Pressure Indices for Navy Annex Interconnection*

Pipe Scenario	ADD	MDD	PHD	F1	F2	F3	F4
30 in. under Key Bridge	39.94	28.93	-17.52	-98.57	-126.77	31.22	56.13
16 in. under Key Bridge	45.62	42.83	30.72	48.81	19.45	62.91	65.01
30 in. along Davis Hwy. #1	40.01	30.92	-8.30	-129.67	-154.61	57.24	57.92
30 in. along Davis Hwy. #2	36.87	24.67	-27.30	-226.02	-248.56	24.30	54.46
16 in. along Davis Hwy	45.76	42.82	30.25	49.53	17.85	64.01	64.93
16 in. along Eisenhower Dr.	45.86	42.84	30.21	49.20	16.50	64.12	64.92
12 in. by Navy Annex	45.67	42.96	31.70	50.37	19.19	63.18	65.18
18 in. by Pentagon	45.09	41.50	25.34	54.20	-98.83	62.93	64.05
24 in. to airport	N/A	N/A	N/A	N/A	N/A	N/A	N/A
16 in. to airport	N/A	N/A	N/A	N/A	N/A	N/A	N/A
30 in. and 16 in. under Key Bridge	-173.39	-390.55	-1,255.39	-3,857.41	-3,883.15	-887.25	-174.65
24 in. from Dalecarlia	45.72	43.09	31.81	51.82	22.51	63.82	65.19
36 in. from Dalecarlia	45.51	42.64	30.27	51.24	21.88	63.47	64.80
PRV at Army-Navy Dr.	45.72	43.12	31.90	51.82	22.51	63.82	65.22
PRV at S 16th and Lynn St.	45.72	43.12	31.90	51.82	22.51	63.82	65.22
Gravity Three tank riser	45.63	43.01	31.44	51.53	22.18	53.65	65.08

* ADD = average daily demand, MDD = maximum daily demand, PHD = peak hourly demand, F1 = Pentagon fire demand, F2 = National Airport fire demand, F3 = Fort Myer fire demand, F4 = Crystal City fire demand.

Table B6

Pressure Indices for Rosslyn Interconnections*

Pipe Scenario	ADD	MDD	PHD	F1	F2	F3	F4
30 in. under Key Bridge	48.06	45.91	0.07	46.28	16.57	65.76	68.06
16 in. under Key Bridge	46.50	44.09	27.42	52.96	23.16	64.96	66.50
30 in. along Davis Hwy. #1	37.57	27.44	-22.43	-156.33	-181.36	55.79	57.58
30 in. along Davis Hwy. #2	33.34	19.80	-44.65	-265.05	-287.57	51.82	53.45
16 in. along Eisenhower Dr. #1	45.84	43.05	26.00	49.87	15.86	64.73	65.84
16 in. along Eisenhower Dr. #2	45.72	42.86	25.34	49.48	14.34	64.60	65.74
12 in. by Navy Annex	46.45	44.19	29.11	54.02	22.85	65.28	66.45
18 in. by Pentagon	44.75	40.98	19.20	56.74	-119.04	63.44	64.74
24 in. to airport	N/A	N/A	N/A	N/A	N/A	N/A	N/A
16 in. to airport	N/A	N/A	N/A	N/A	N/A	N/A	N/A
30 in. and 16 in. under Key Bridge	49.07	47.13	-48.76	20.53	-9.25	65.10	69.07
24 in. from Dalecarlia	46.45	44.07	28.16	54.55	24.77	65.28	66.38
36 in. from Dalecarlia	45.27	39.62	12.84	50.68	20.91	63.33	62.25
PRV at Army-Navy Dr.	46.45	44.19	29.11	54.63	24.87	65.28	66.45
PRV at S 16th and Lynn St.	46.45	44.19	29.11	54.63	24.87	65.28	66.45
Gravity Three tank riser	46.45	44.19	29.11	54.63	24.87	65.28	66.45

* ADD = average daily demand, MDD = maximum daily demand, PHD = peak hourly demand, F1 = Pentagon fire demand, F2 = National Airport fire demand, F3 = Fort Myer fire demand, F4 = Crystal City fire demand.

Table B7

Pressure Indices for Roosevelt Bridge Crossing*

Pipe Scenario	ADD	MDD	PHD	F1	F2	F3
30 in. under Key Bridge	45.68	43.50	34.86	44.79	15.03	62.68
16 in. under Key Bridge	45.74	43.61	35.19	54.25	24.35	64.11
30 in. along Davis Hwy. #1	36.33	26.05	-16.97	-160.44	-185.50	53.73
30 in. along Davis Hwy. #2	32.34	18.62	-39.03	-267.90	-290.45	50.08
16 in. along Eisenhower Dr. #1	45.23	42.66	32.35	50.93	16.92	64.32
16 in. along Eisenhower Dr. #2	45.11	42.43	31.68	50.41	15.29	64.16
12 in. by Navy Annex	45.78	43.67	35.37	54.66	23.49	64.61
18 in. by Pentagon	43.98	40.26	25.24	57.14	-120.67	62.32
24 in. to airport	N/A	N/A	N/A	N/A	N/A	N/A
16 in. to airport	N/A	N/A	N/A	N/A	N/A	N/A
30 in. and 16" under Key Bridge	45.37	42.91	33.10	34.28	4.58	59.84

* ADD = average daily demand, MDD = maximum daily demand, PHD = peak hourly demand, F1 = Pentagon fire demand, F2 = National Airport fire demand, F3 = Fort Myer fire demand, F4 = Crystal City fire demand.

Table B8

Pressure Indices for 14th Street Bridge Crossing*

Pipe Scenario	ADD	MDD	PHD	F1	F2	F3
30 in. under Key Bridge	45.12	42.44	31.72	28.18	32.36	58.02
16 in. under Key Bridge	46.16	44.39	37.49	57.88	47.03	64.29
30 in. along Davis Hwy. #1	45.85	43.81	35.79	38.64	38.54	64.52
30 in. along Davis Hwy. #2	45.86	43.82	35.81	36.87	38.15	64.63
16 in. along Eisenhower Dr. #1	45.99	44.08	36.57	58.00	46.50	64.88
16 in. along Eisenhower Dr. #2	45.95	44.00	36.35	57.89	46.32	64.82
12 in. by Navy Annex	46.15	44.38	37.47	59.41	47.80	64.76
18 in. by Pentagon	46.26	44.57	38.04	58.32	45.48	64.91
24 in. to airport	46.11	44.30	37.24	56.37	45.71	64.55
16 in. to airport	46.01	44.10	36.65	55.19	47.35	64.34
30 in. and 16" under Key Bridge	42.01	36.65	14.52	-46.28	8.14	40.43

* ADD = average daily demand, MDD = maximum daily demand, PHD = peak hourly demand, F1 = Pentagon fire demand, F2 = National Airport fire demand, F3 = Fort Myer fire demand, F4 = Crystal City fire demand.

Table B9

Pressure Indices for Booster Pump Off Low Service*

Pipe Outage	ADD	MDD	PHD	F1	F2	F3
30 in. under Key Bridge	50.17	46.58	29.87	37.42	42.96	65.33
16 in. under Key Bridge	48.85	46.49	36.62	62.14	50.85	67.57
30 in. along Davis Hwy. #1	50.66	47.33	34.40	45.85	46.50	69.90
30 in. along Davis Hwy. #2	50.96	47.59	34.27	43.96	46.25	70.20
16 in. along Eisenhower Dr. #1	48.90	46.25	35.51	62.03	50.43	68.21
16 in. along Eisenhower Dr. #2	48.86	46.17	35.41	62.20	50.40	68.12
12 in. by Navy Annex	48.82	46.40	36.70	63.22	51.26	67.82
18 in. by Pentagon	49.82	47.26	37.10	62.49	50.24	68.79
24 in. to airport	49.22	46.69	36.47	59.54	50.32	67.68
16 in. to airport	48.43	45.97	36.06	57.65	43.32	66.78
30 in.and 16" under Key Bridge	54.50	46.48	11.83	-26.45	27.97	54.27

* ADD = average daily demand, MDD = maximum daily demand, PHD = peak hourly demand, F1 = Pentagon fire demand, F2 = National Airport fire demand, F3 = Fort Myer fire demand, F4 = Crystal City fire demand.

Table B10

Pressure Indices for Subaqueous River Crossing*

Pipe Scenario	ADD	MDD	PHD	F1	F2	F3
30 in. under Key Bridge	45.73	43.58	35.09	45.37	15.60	62.82
16 in. under Key Bridge	45.35	42.89	33.03	49.11	19.21	62.74
30 in. along Davis Hwy. #1	36.18	25.78	-17.78	-162.85	-187.91	53.07
30 in. along Davis Hwy. #2	32.18	18.32	-39.93	-270.47	-293.02	49.39
16 in. along Eisenhower Dr. #1	44.97	42.17	30.90	47.49	13.48	63.43
16 in. along Eisenhower Dr. #2	44.85	41.94	30.23	46.98	11.90	63.27
12 in. by Navy Annex	45.53	43.21	33.99	51.26	20.08	63.76
18 in. by Pentagon	43.73	39.87	24.06	53.76	-123.46	61.55
24 in. to airport	N/A	N/A	N/A	N/A	N/A	N/A
16 in. to airport	N/A	N/A	N/A	N/A	N/A	N/A
30 in. and 16 in. under Key Bridge	45.44	43.04	33.50	35.58	5.68	60.12

* ADD = average daily demand, MDD = maximum daily demand, PHD = peak hourly demand, F1 = Pentagon fire demand, F2 = National Airport fire demand, F3 = Fort Myer fire demand, F4 = Crystal City fire demand.

Table B11

Pressure Indices for New Tank at the Navy Annex*

Pipe Scenario	ADD	MDD	PHD	F1	F2	F3
30 in. under Key Bridge	46.59	44.05	32.99	28.91	1.91	60.76
16 in. under Key Bridge	46.78	44.92	37.47	56.31	27.38	65.53
30 in. along Davis Hwy. #1	43.37	32.94	15.58	-64.98	-89.71	62.65
30 in. along Davis Hwy. #2	40.82	33.09	1.05	-139.43	-161.94	60.24
16 in. along Eisenhower Dr. #1	46.94	45.12	37.88	57.43	28.93	65.86
16 in. along Eisenhower Dr. #2	46.82	44.96	37.54	56.93	58.54	65.61
12 in. by Navy Annex	46.84	44.43	36.23	53.94	22.77	65.35
18 in. by Pentagon	46.88	44.67	35.79	60.64	-49.65	66.11
24 in. to airport	N/A	N/A	N/A	N/A	N/A	N/A
16 in. to airport	N/A	N/A	N/A	N/A	N/A	N/A
30 in. and 16 in. under Key Bridge	46.01	41.42	21.94	-21.04	-46.78	49.56

* ADD = average daily demand, MDD = maximum daily demand, PHD = peak hourly demand, F1 = Pentagon fire demand, F2 = National Airport fire demand, F3 = Fort Myer fire demand, F4 = Crystal City fire demand.

Table B12

Pressure Indices for Paralleling 30-in. FOWM Transmission Main*

Pipe Outage	ADD	MDD	PHD	F1	F2	F3
30 in. under Key Bridge	41.50	35.69	11.68	-2.94	-32.85	24.06
16 in. under Key Bridge	44.89	42.02	30.46	49.21	19.30	53.37
30 in. along Davis Hwy. #1	44.25	40.82	26.89	34.58	5.86	50.20
30 in. along Davis Hwy. #2	44.24	40.82	26.89	34.58	5.86	50.20
16 in. along Eisenhower Dr. #1	44.43	41.16	27.90	46.37	12.29	52.07
16 in. along Eisenhower Dr. #2	44.30	40.92	27.21	45.90	10.76	51.60
12 in. by Navy Annex	44.94	42.12	30.76	49.58	18.41	53.63
18 in. by Pentagon	34.81	38.74	20.7±	51.40	-125.73	26.95
24 in. to airport	++	++	++	++	++	++
16 in. to airport	++	++	++	++	++	++

* ADD = average daily demand, MDD = maximum daily demand, PHD = peak hourly demand, F1 = Pentagon fire demand, F2 = National Airport fire demand, F3 = Fort Myer fire demand, F4 = Crystal City fire demand, ++ = indicates National Airport is without water.

Table B13

Pressure Indices for New Airport Feed*

Pipe Outage	ADD	MDD	PHD	F1	F2	F3
30 in. under Key Bridge	30.38	14.96	-49.91	-180.03	-186.17	6.41
16 in. under Key Bridge	44.94	42.11	30.72	46.42	40.16	61.58
30 in. along Davis Hwy. #1	35.73	24.94	-20.28	-165.71	-170.95	52.15
30 in. along Davis Hwy. #2	31.70	17.42	-42.58	-273.13	-277.69	48.41
16 in. along Eisenhower Dr. #1	44.79	41.84	29.94	46.89	39.96	62.70
16 in. along Eisenhower Dr. #2	44.72	41.70	29.53	46.69	39.58	62.60
12 in. by Navy Annex	45.20	42.60	32.20	49.97	43.57	62.90
18 in. by Pentagon	45.15	42.50	31.91	50.67	41.35	62.85
24 in. to airport	45.16	42.52	31.99	50.33	39.56	62.89
16 in. to airport	45.18	42.56	32.07	50.29	41.06	62.91

* ADD = average daily demand, MDD = maximum daily demand, PHD = peak hourly demand, F1 = Pentagon fire demand, F2 = National Airport fire demand, F3 = Fort Myer fire demand, F4 = Crystal City fire demand.

Table B14

Pressure Indices for Closing 16-in. Pentagon Loop*

Pipe Outage	ADD	MDD	PHD	F1	F2	F3
30 in. under Key Bridge	30.18	14.58	-51.02	-180.37	-208.87	6.21
16 in. under Key Bridge	44.72	41.70	29.51	46.01	16.80	61.34
30 in. along Davis Hwy. #1	35.59	24.68	-21.03	-165.37	-190.38	52.01
30 in. along Davis Hwy. #2	31.59	17.22	43.18	-273.18	-295.59	48.21
16 in. along Eisenhower Dr. #1	44.51	41.32	28.39	46.26	13.54	62.42
16 in. along Eisenhower Dr. #2	44.41	41.13	27.83	45.97	12.42	62.29
12 in. by Navy Annex	44.99	42.21	31.03	49.52	19.38	62.69
18 in. by Pentagon	43.13	38.74	20.74	51.20	-126.07	60.44
24 in. to airport	++	++	++	++	++	++
16 in. to airport	++	++	++	++	++	++

* ADD = average daily demand, MDD = maximum daily demand, PHD = peak hourly demand, F1 = Pentagon fire demand, F2 = National Airport fire demand, F3 = Fort Myer fire demand, F4 = Crystal City fire demand, ++ = indicates National Airport is without water.

Table B15

Pressure Indices for New Pentagon Loop*

Pipe Outage	ADD	MDD	PHD	F1	F2	F3
30 in. under Key Bridge	30.10	14.45	-51.45	181.00	-208.60	6.14
16 in. under Key Bridge	44.62	42.51	28.97	45.11	17.04	61.23
30 in. along Davis Hwy. #1	35.58	24.66	-21.09	-165.13	-189.84	52.01
30 in. along Davis Hwy. #2	31.59	17.22	-43.18	272.09	-295.28	48.31
16 in. along Eisenhower Dr. #1	44.33	40.97	27.36	44.53	13.23	62.23
16 in. along Eisenhower Dr. #2	44.23	40.80	26.84	44.09	12.50	62.11
12 in. by Navy Annex	44.90	42.04	30.53	48.34	19.45	62.60
18 in. by Pentagon	44.68	41.64	29.34	49.01	9.66	62.32
24 in. to airport	++	++	++	++	++	++
16 in. to airport	++	++	++	++	++	++

* ADD = average daily demand, MDD = maximum daily demand, PHD = peak hourly demand, F1 = Pentagon fire demand, F2 = National Airport fire demand, F3 = Fort Myer fire demand, F4 = Crystal City fire demand, ++ = indicates National Airport is without water.

APPENDIX C: COST ESTIMATES FOR PROPOSED ALTERNATIVES

Table C1

Cost Estimates for Roosevelt Bridge River Crossing

Construction Category	Total Length ft	Diameter in.	Unit Cost $	Total Cost Thousands of Dollars
1	0	--	--	0
2	6,650	30	140	931
3	0	--	--	0
4	7,500	30	253	1,898
5	900	30	724	652
6	3,100	30	1,065	3,302
7	0	--	--	0
		Additional Items: None		0
			Subtotal	6,783
			15% Overhead and Profit	1,017
			Total Construction Cost	7,800
			25% Engineering, Design, and Administration	1,950
			Total Cost	9,750

Table C2

Cost Estimates for 14th Street Bridge River Crossing

Construction Category	Total Length ft	Diameter in.	Unit Cost $	Total Cost Thousands of Dollars
1	4,270	30	104	444
2	14,200	30	140	1,988
3	0	--	--	0
4	7,500	30	253	1,898
5	900	30	724	652
6	2,500	30	1,065	2,663
7	0	--	--	0
		Additional Items: None		0
			Subtotal	7,645
			15% Overhead and Profit	1,147
			Total Construction Cost	8,792
			25% Engineering, Design, and Administration	2,198
			Total Cost	10,990

Table C3

Cost Estimates for Booster Pump Off Low Service

Construction Category	Total Length ft	Diameter in.	Unit Cost $	Total Cost Thousands of Dollars
1	4,270	30	104	444
2	2,500	30	140	350
3	0	--	--	0
4	1,000	30	253	253
5	1,000	30	724	724
6	2,500	30	1,065	2,663
7	0	--	--	0
Additional Items:	150-hp Booster Pumping Station			75
			1 acre land	1,500
			Subtotal	6,009
			15% Overhead and Profit	901
			Total Construction Cost	6,910
			25% Engineering, Design, and Administration	1,728
			Total Cost	8,638

Table C4

Cost Estimates for Subaqueous River Crossing

Construction Category	Total Length ft	Diameter in.	Unit Cost $	Total Cost Thousands of Dollars
1	0	--	--	0
2	2,300	30	140	322
3	0	--	--	0
4	7,500	30	253	1,898
5	0	--	--	0
6	0	--	--	0
7	2,600	30	1,540	4,004
		Additional Items: None		0
			Subtotal	6,224
			15% Overhead and Profit	934
			Total Construction Cost	7,158
			25% Engineering, Design, and Administration	1,790
			Total Cost	8,948

Table C5

Cost Estimates for New Tank at Navy Annex

Construction Category	Total Length ft	Diameter in.	Unit Cost $	Total Cost Thousands of Dollars
1	0	--	--	0
2	1,500	16	76	114
3	0	--	--	0
4	0	--	--	0
5	0	--	--	0
6	0	--	--	0
7	0	--	--	0
	Additional Items:	1.8 MG Hydropillar		1,300
			Subtotal	1,414
			15% Overhead and Profit	212
			Total Construction Cost	1,626
			25% Engineering, Design, and Administration	407
			Total Cost	2,033

Table C6

Cost Estimates for Paralleling 30-in. Federally Owned Water Main (FOWM) Transmission Main

Construction Category	Total Length ft	Diameter in.	Unit Cost $	Total Cost Thousands of Dollars
1	0	--	--	0
2	0	--	--	0
3	0	--	--	0
4	6,000	16	148	888
5	0	--	--	0
6	0	--	--	0
7	0	--	--	0
	Additional Items: Connections between existing 30- and 16-in. FOWM mains			
	Key Bridge Connection			85
	George Washington Parkway Connection			30
	Subtotal			1,003
	15% Overhead and Profit			150
	Total Construction Cost			1,153
	25% Engineering, Design, and Administration			288
	Total Cost			1,441

Table C7

Cost Estimates for New Airport Feed

Construction Category	Total Length ft	Diameter in.	Unit Cost $	Total Cost Thousands of Dollars
1	0	--	--	0
2	0	--	--	0
3	0	--	--	0
4	1,120	16	148	166
4	6,900	24	212	1,463
5	0	--	--	0
6	0	--	--	0
7	0	--	--	0
			Additional Items: None	0
			Subtotal	1,629
			15% Overhead and Profit	244
			Total Construction Cost	1,873
			25% Engineering, Design, and Administration	468
			Total Cost	2,341

Table C8

Cost Estimates for Closing Pentagon Loop

Construction Category	Total Length ft	Diameter in.	Unit Cost $		Total Cost Thousands of Dollars
1	0	--	--		0
2	0	--	--		0
3	0	--	--		0
4	1,120	16	148		166
5	0	--	--		0
6	0	--	--		0
7	0	--	--		0
				Additional Items: None	0
				Subtotal	166
				15% Overhead and Profit	25
				Total Construction Cost	191
				25% Engineering, Design, and Administration	48
				Total Cost	239

Table C9

Cost Estimates for New Pentagon Loop

Construction Category	Total Length ft	Diameter in.	Unit Cost $	Total Cost Thousands of Dollars
1	0	--	--	0
2	550	12	68	37
3	0	--	--	0
4	0	--	--	0
5	0	--	--	0
6	0	--	--	0
7	0	--	--	0
		Additional Items: None		0
			Subtotal	37
			15% Overhead and Profit	6
			Total Construction Cost	43
			25% Engineering, Design, and Administration	11
			Total Cost	54