Attachment 02.04.03-08O
TVA letter dated February 2, 2010
RAI Response

ASSOCIATED ATTACHMENTS/ENCLOSURES:

Attachment 02.04.03-8O: Dam Rating Curves, Nickajack

(424 Pages including Cover Sheet)

NPG CALCULATION COVERSHEET/CCRIS UPDATE

REV 0 EDMS/RIMS NO.	EDMS TYPE:	EDMS ACCESSION NO (N/A for REV. 0)
L58 090216 007	Calculations (nuclear)	L58 091230 026

Calc Title: Initial Dam Rating Curves, Nickajack

CALC ID	TYPE	ORG	PLANT	BRANCH	NUMBER	CUR REV	NEW REV	REVISION APPLICABILITY
CURRENT	CN	NUC	GEN	CEB	CDQ000020080014	0	1	Entire calc ☒ Selected pages ☐
NEW	CN	NUC						

ACTION	NEW ☐ REVISION ☒	DELETE ☐ RENAME ☐	SUPERSEDE ☐ DUPLICATE ☐	CCRIS UPDATE ONLY ☐ (Verifier Approval Signatures Not Required)	No CCRIS Changes ☐ (For calc revision, CCRIS been reviewed and no CCRIS changes required)

UNITS	SYSTEMS	UNIDS
N/A	N/A	N/A

DCN,EDC,N/A	APPLICABLE DESIGN DOCUMENT(S)	CLASSIFICATION
See below	N/A	E

QUALITY RELATED?	SAFETY RELATED? (If yes, QR = yes)	UNVERIFIED ASSUMPTION	SPECIAL REQUIREMENTS AND/OR LIMITING CONDITIONS?	DESIGN OUTPUT ATTACHMENT?	SAR/TS and/or ISFSI SAR/CoC AFFECTED
Yes ☒ No ☐	Yes ☒ No ☐	Yes ☐ No ☒	Yes ☐ No ☒	Yes ☐ No ☒	Yes ☐ No ☒

PREPARER ID	PREPARER PHONE NO	PREPARING ORG (BRANCH)	VERIFICATION METHOD	NEW METHOD OF ANALYSIS
C. J. Grace	205-298-6074	CEB	Design Review	☐ Yes ☒ No

PREPARER SIGNATURE	DATE	CHECKER SIGNATURE	DATE
Chris J. Grace	12/22/2009	L. Yu Lin L. Lin	12/22/09
VERIFIER SIGNATURE	**DATE**	**APPROVAL SIGNATURE**	**DATE**
L. Yu Lin L. Lin	12/22/09	K.E. Spates	12/23/09

STATEMENT OF PROBLEM/ABSTRACT

12/24/09

Initial dam rating curves (headwater rating curves) are required as inputs to TVA's SOCH and TRBROUTE models, which perform flood-routing calculations for the Tennessee River and tributaries. The initial dam rating curves provide total dam discharge as a function of headwater elevation and are used to define the beginning conditions for the hydraulic analysis. The final dam rating curve is confirmed and documented in the SOCH Probable Maximum Flood model calculation by validating the headwater-tailwater relationship across the modeled dam configuration. This calculation presents initial dam rating curves for Nickajack Dam.

EDCN 22404A (SQN), EDCN 54018A (WBN), EDCN Later (BFN)

This calculation contains electronic attachments and must be stored in EDMS as an Adobe .pdf file to maintain the ability to retrieve the electronic attachments.

MICROFICHE/EFICHE Yes ☐ No ☒ FICHE NUMBER(S)

☐ LOAD INTO EDMS AND DESTROY.
☒ LOAD INTO EDMS AND RETURN CALCULATION TO CALCULATION LIBRARY. ADDRESS: LP4D-C.
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NPG CALCULATION COVERSHEET/CCRIS UPDATE

REV 0 EDMS/RIMS NO.	EDMS TYPE:	EDMS ACCESSION NO (N/A for REV. 0)
L58 090216 007	Calculations (nuclear)	N/A

Calc Title: Dam Rating Curves, Nickajack

CALC ID	TYPE	ORG	PLANT	BRANCH	NUMBER	CUR REV	NEW REV	REVISION APPLICABILITY
CURRENT	CN	NUC						Entire calc ☐ Selected pages ☐
NEW	CN	NUC	GEN	CEB	CDQ000020080014	N/A	0	

ACTION	NEW ☒ REVISION ☐	DELETE ☐ RENAME ☐	SUPERSEDE ☐ DUPLICATE ☐	CCRIS UPDATE ONLY ☐ (Verifier Approval Signatures Not Required)	No CCRIS Changes ☐ (For calc revision, CCRIS been reviewed and no CCRIS changes required)

UNITS	SYSTEMS	UNIDS
N/A	N/A	N/A

DCN,EDC,N/A	APPLICABLE DESIGN DOCUMENT(S)	CLASSIFICATION
N/A	N/A	E

QUALITY RELATED?	SAFETY RELATED? (If yes, QR = yes)	UNVERIFIED ASSUMPTION	SPECIAL REQUIREMENTS AND/OR LIMITING CONDITIONS?	DESIGN OUTPUT ATTACHMENT?	SAR/TS and/or ISFSI SAR/CoC AFFECTED
Yes ☒ No ☐	Yes ☒ No ☐	Yes ☒ No ☐	Yes ☐ No ☒	Yes ☐ No ☒	Yes ☐ No ☒

PREPARER ID	PREPARER PHONE NO	PREPARING ORG (BRANCH)	VERIFICATION METHOD	NEW METHOD OF ANALYSIS
G. A. SCHOHL	632-3968	CEB	Design Review	☐ Yes ☒ No

PREPARER SIGNATURE	DATE	CHECKER SIGNATURE	DATE
Gerald A. Schohl Gerald A. Schohl	1/20/2009	Chris Triplett Chris Triplett	1/20/09
VERIFIER SIGNATURE	**DATE**	**APPROVAL SIGNATURE**	**DATE**
L. Lin DAVID HUNT L. Lin David Hunt 1/20/09	1/20/09	K.R. Spates K.R. Spates	2/12/09

STATEMENT OF PROBLEM/ABSTRACT

Dam rating curves (headwater rating curves) for 20 dams are required as inputs to TVA's SOCH and TRBROUTE models, which perform flood-routing calculations for the Tennessee River and tributaries. The dam rating curves provide total dam discharge as a function of headwater elevation. This calculation presents dam rating curves for Nickajack Dam.

This calculation contains electronic attachments and must be stored in EDMS as an Adobe .pdf file to maintain the ability to retrieve the electronic attachments.

MICROFICHE/EFICHE Yes ☐ No ☒ FICHE NUMBER(S)

☐ LOAD INTO EDMS AND DESTROY
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NPG CALCULATION COVERSHEET/CCRIS UPDATE

CALC ID	TYPE	ORG	PLANT	BRANCH	NUMBER	REV
	CN	NUC	GEN	CEB	CDQ000020080014	1

ALTERNATE CALCULATION IDENTIFICATION

BLDG	ROOM	ELEV	COORD/AZIM	FIRM BWSC	Print Report Yes ☐

CATEGORIES N/A

KEY NOUNS (A-add, D-delete)

ACTION (A/D)	KEY NOUN	A/D	KEY NOUN

CROSS-REFERENCES (A-add, C-change, D-delete)

ACTION (A/C/D)	XREF CODE	XREF TYPE	XREF PLANT	XREF BRANCH	XREF NUMBER	XREF REV
A	P	EN	WBN	CEB	54018	
A	P	EN	SQN	CEB	22404	
A	S	CN	GEN	CEB	CDQ000020080040	

CCRIS ONLY UPDATES:
Following are required only when making keyword/cross reference CCRIS updates and page 1 of form NEDP-2-1 is not included:

PREPARER SIGNATURE	DATE	CHECKER SIGNATURE	DATE

PREPARER PHONE NO.	EDMS ACCESSION NO.

NPG CALCULATION RECORD OF REVISION	
CALCULATION IDENTIFIER CDQ000020080014	
Title Initial Dam Rating Curves, Nickajack	
Revision No.	DESCRIPTION OF REVISION
0	Initial issue Total pages: 139

1	This calculation was revised to address the following:
	• PER 203951. The verification of the previous calculation was completed by personnel who had not completed the required NEDP-7 Job Performance Record (JPR). A verification JPR is now in place for all personnel engaged in verification tasks. Checking includes only changes made in this revision as the checking of the calculation was not impacted by PER 203951. The verification is inclusive of work completed prior to this revision.
	• PER 203872. Replaced NEDP-2 forms on Pages 1 through 7 with the forms from the NEDP-2 Revision in effect at the time of calculation's issuance.
	• Change title to "Initial Dam Rating Curves, Nickajack" throughout the calculation.
	• Update "Statement of Problem" on coversheet and first paragraph of "Purpose" in section 1.
	• UVA 3.2.1. Removed and replaced with Assumption 3.1.5 based on References 34 and 36.
	• UVA 3.2.2. Removed and replaced with Assumption 3.1.5 based on References 34 and 36.
	• UVA 3.2.3. Removed and replaced with:
	  o Assumption 3.1.6 based on Reference 33.
	  o Assumption 3.1.7 based on Appendix B.
	
	Significant changes to text in Revision 1 are marked with a right hand margin revision bar. Administrative changes and typos are excluded.
	
	Pages Deleted: None
	Pages Revised: 1-5, 7-11, 25, 26, 27, References 33-36
	New Pages Added: 1a, 6, B1, B2, B3
	
	Total pages Revision 1: 143
	
	Additional Comments:
	• Rev 0 coversheet is page 1a
	• Coversheet and CCRIS forms updated
	• Updated page numbers
	• Included number of pages per attachment in Table of Contents
	• Added Verification Form as page 6
	• Added Appendix B

NPG CALCULATION TABLE OF CONTENTS

Calculation Identifier: CDQ000020080014 | Revision: 1

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6	Turbine Operating Characteristics for Units 1 through 4 (Refs. 26, 27, 28, 29)	4 pages
7	Sketch illustrating south embankment overflow (Ref. 1)	1 page
8	Auxiliary lock upper miter gate details (Refs. 2, 30, 31, 32)	4 pages
9	Hydraulic Design Chart 711 (Ref. 6)	1 page
10	Polynomial fit to HDC 711 suggested design curve for submergence factor (Ref. 6)	1 page
11	Discharge parameters for trashway (Refs. 7, 8)	6 pages
12	Spillway, powerhouse, nonoverflow dam (Ref. 9)	1 page
13	Flow over tops of wide-open tainter gates (Ref. 10)	3 pages
14	Overflow parameters for spillway piers and powerhouse (Refs. 11, 12)	3 pages
15	Overflow parameters for navigation locks (Refs. 13, 14, 15)	6 pages
16	Overflow parameters for north (right) embankment before failure (Refs. 16, 17, 18)	6 pages
17	Overflow parameters for south (left) embankment before failure (Refs. 19, 20)	4 pages
18	Overflow parameters for roller compacted concrete and sheet pile dam (Refs. 21, 22, 23, 24)	7 pages
19	Nickajack Rating Curves.xls	N/A
20	Nickajack WCP Manual.pdf	44 pages
21	Nickajack Spillway Discharge Tables.pdf	194 pages
22	Bradley, Rating Curves for Flow over Drum Gates.pdf	16 pages
23	10W200,R8.PDF	1 page
24	54N220,R1.PDF	1 page
25	10W201,R6.PDF	1 page
26	46W401,R5.PDF	1 page
27	61N200,R5.PDF	1 page
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NPG CALCULATION TABLE OF CONTENTS (CONTINUED)

Calculation Identifier: CDQ000020080014 | Revision: 1

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A3	Measured gate openings (Ref. A2)	1 page
A4	Definition sketch for spillway discharge	1 page
A5	Pages 490 and 491 from Reference 7 (model scale ratios) (Ref. A5)	1 page
A6	Geometry for flow under an open tainter gate	5 pages
A7	Radial gates arrangement, TVA drawing no: 54N200, R1 (Ref. A6)	1 page
A8	Spillway crest details, TVA drawing no: 10W203, R5 (Ref. 7)	1 page
A9	Calculations for free discharge coefficients and submergence (Ref. A3)	2 pages
A10	Free discharge coefficient	1 page
A11	Hydraulic Design Chart 111-3 (Ref. A4)	1 page
A12	Submergence effect on free discharge	1 page
A13	Calculations for unsubmerged orifice discharge coefficients	6 pages
A14	Unsubmerged orifice discharge coefficients plot	1 page
A15	HDC Chart 311-1, Tainter Gates on Spillway Crests, Discharge Coefficients (Ref. A4)	1 page
A16	Calculations for submergence effects on orifice discharge	6 pages
A17	Submergence Factors for Radial Gates on Spillway Crests	1 page
A18	Model test data (Ref. A3)	21 pages
A19	Nickajack Model Data for Dam Rating.xls	N/A
A20	54N200,R1.PDF	1 page
A21	10W203,R5.PDF	1 page
	Note: N/A indicates an electronic file that is not paginated.	

NPG CALCULATION VERIFICATION FORM

Calculation Identifier CDQ000020080014 Revision 1

Method of verification used:

1. Design Review ☒
2. Alternate Calculation ☐
3. Qualification Test ☐

Verifier L. Yu Lin Date 12/22/09

L. Lin

Comments:

This calculation entitled, "Initial Dam Rating Curves, Nickajack," was verified by independent design review. The process involved a critical review of the calculation to ensure that it is correct and complete, uses appropriate methodologies, and achieves its intended purpose. The inputs were reviewed and determined to be appropriate inputs for this calculation. The results of the calculation were reviewed and were found to be reasonable and consistent with the inputs provided. Backup files and documents were consulted as necessary to verify data and analysis details found in the calculation.

Detailed comments and editorial suggestions for the changes made in this revision were transmitted to the author and reviewer by email along with a marked up copy of the calculation.

The methodology used to justify the operability of the gates is based solely on the conclusions of the "Watts Bar Dam – Flood and Earthquake Analysis on Radial Spillway Gates." Appendix B uses the same assumptions, methodology, and approach developed in the Watts Bar radial gate analysis to determine the forces on the radial gates in a closed position with the forces on the gates in the maximum open position. This appendix does not assert that a structural analysis has been performed beyond that found in the Watts Bar radial gate calculation.

(Note: The design verification of this calculation revision is for the total calculation, not just the changes made in the revision. This complete re-verification is performed to disposition PER 203951 as described in the Calculation Revision Log on Page 3).

NPG COMPUTER INPUT FILE
STORAGE INFORMATION SHEET

Document CDQ000020080014	Rev. 1	Plant: GEN	

Subject:
Initial Dam Rating Curves, Nickajack

☐ Electronic storage of the input files for this calculation is not required. Comments:

☒ Input files for this calculation have been stored electronically and sufficient identifying information is provided below for each input file. (Any retrieved file requires re-verification of its contents before use.)

These files are electronically attached to the parent ADOBE.pdf calculation file. All files are therefore stored in an unalterable medium and are retrievable through the EDMS number for this calculation.

Attachment 19: Nickajack Rating Curves.xls
Spreadsheet for dam rating curve calculations
Attachment 20: Complete PDF copy of Reference 3
Attachment 21: Complete PDF copy of Reference 4 (also referenced as A1)
Attachment 22: Complete PDF copy of Reference 10
Attachments 23 through 46 Large resolution PDF files of References 1, 8, 9, and 12-32

Attachment A19: Nickajack Model Data for Dam Ratings.xls
Spreadsheet for model data calculations
Attachment A20: Large resolution PDF file of Reference A6
Attachment A21: Large resolution PDF file of Reference A7

☐ Microfiche/eFiche

1. Purpose

Initial dam rating curves (headwater rating curves) are required as inputs to TVA's SOCH and TRBROUTE models, which perform flood-routing calculations for the Tennessee River. The initial dam rating curves provide total dam discharge as a function of headwater elevation and are used to define the beginning conditions for the hydraulic analysis. The final dam rating curve is confirmed and documented in the SOCH Probable Maximum Flood model calculation (Reference 34) by validating the headwater-tailwater relationship across the modeled dam configuration. This calculation presents initial dam rating curves for Nickajack Dam.

TVA developed methods of analysis, procedures, and computer programs for determining design basis flood levels for nuclear plant sites in the 1970's. Determination of maximum flood levels included consideration of the most severe flood conditions that may be reasonably predicted to occur at a site as a result of both severe hydrometerological conditions and seismic activity. This process was followed to meet Nuclear Regulatory Guide 1.59. At that time, there were no computer programs available that would handle unsteady flow and dam failure analysis. As a result of this early work and method development TVA developed a runoff and stream course modeling process for the TVA reservoir system. This process provided a basis for currently licensed plants (Sequoyah Nuclear Plant, Watts Bar Nuclear Plant, and Browns Ferry Nuclear Plant). The Bellefonte Nuclear Plant (BLN) Units 1 & 2 Final Safety Analysis Report (FSAR) was also based on this process.

BLN Unit 3 & 4 Combined Operating License Application (COLA) was submitted using data and analysis that was determined for the original BLN FSAR (Unit 1 and Unit 2) and was documented in a 1998 reassessment. In 1998, the analysis process and documentation was brought under the nuclear quality assurance process for the first time. A quality assurance audit conducted by NRC staff in early 2007 raised several questions related to past work regarding design basis flood level determinations. This calculation supports a portion of the effort to improve the design basis documentation

Preparation of all calculations supporting nuclear development and licensing are subject to TVA Standard Department Procedure NEDP-2. This standard dictates the process in which calculation are prepared, checked, verified, stored, and cross referenced in a goal to provide the highest quality nuclear design input and output possible.

Figure 1 is a plan and elevation view of Nickajack dam (a portion of Reference 1). A photograph is included as Attachment 2. For headwaters in the normal operating range, discharge is passed through the turbines, the spillway, or the trashway. The spillway consists of ten spillway bays, each with a radial, or tainter, gate to control discharge. The trashway discharge is controlled by a vertical lift gate. If, as during a probable maximum flood (PMF) event, headwater rises above the normal operating range, discharge may pass also over the north embankment (labeled "earth embankment" in Figure 1 and "right embankment" in some drawings), the navigation locks, and the tops of the spillway piers. Discharge is not expected to pass over the south embankment (labeled "earth embankment" in Figure 1 and "left embankment" in some drawings), however, because of dam safety modifications completed in 1992 (Attachment 3). Nevertheless, the rating curves developed in this calculation include headwater elevations above the south embankment to conservatively bound headwater elevations for flood-routing simulations. For headwaters above the top of the south embankment, discharge may pass also over the tops of the open spillway gates, the nonoverflow dam, and the visitor's center overlook.

Initial rating curves are provided for four cases (Figure 7). All cases assume that all spillway gates remain fully open.

1. Pre-failure condition with turbine discharge -- north embankment (overflow elevation 652 feet [4.11.2]) and south embankment (overflow elevation 657 feet [4.13.2]) intact. This rating curve is used for both rising and falling headwaters until the headwater rises far enough for water to enter the powerhouse (headwater elevation 652.6 [4.18.4]), the tailwater rises far enough to wet the switchyard (tailwater elevation 636.0 [4.18.3]), or the headwater rises far enough above the crest of the north embankment to cause its failure. If either of the first two conditions occur, turbine operation is suspended and this rating curve is no longer valid. The dam rating shifts to the Case 2 rating curve. If the third condition occurs before either of the first two conditions, then the dam rating shifts to the Case 3 rating curve and the Case 2 curve is not used.

2. Pre-failure condition without turbine discharge -- north embankment and south embankment intact. This rating curve is used for both rising and falling headwaters after turbine operation has been suspended and before either embankment has failed until the headwater rises far enough above the crest of the north embankment to cause its failure. At that time, this rating curve is no longer valid and the dam rating shifts to the Case 3 rating curve.
3. North earth embankment fails -- south embankment intact. Discharge control shifts to the downstream roller compacted concrete and sheet pile dam. This rating curve is used for both rising and falling headwaters after the north embankment has failed until the headwater rises far enough above the crest of the south embankment to cause its failure. At that time, this rating curve is no longer valid and the dam rating shifts to the Case 4 rating curve.
4. South earth embankment fails -- north embankment already failed. This rating curve is used for both rising and falling headwaters after both the north and south embankments have failed.

The initial dam rating curves are based on the current configuration of Nickajack Dam as defined on the current design drawings. The purpose of this calculation does not evaluate the design loading conditions for the dam or embankments.

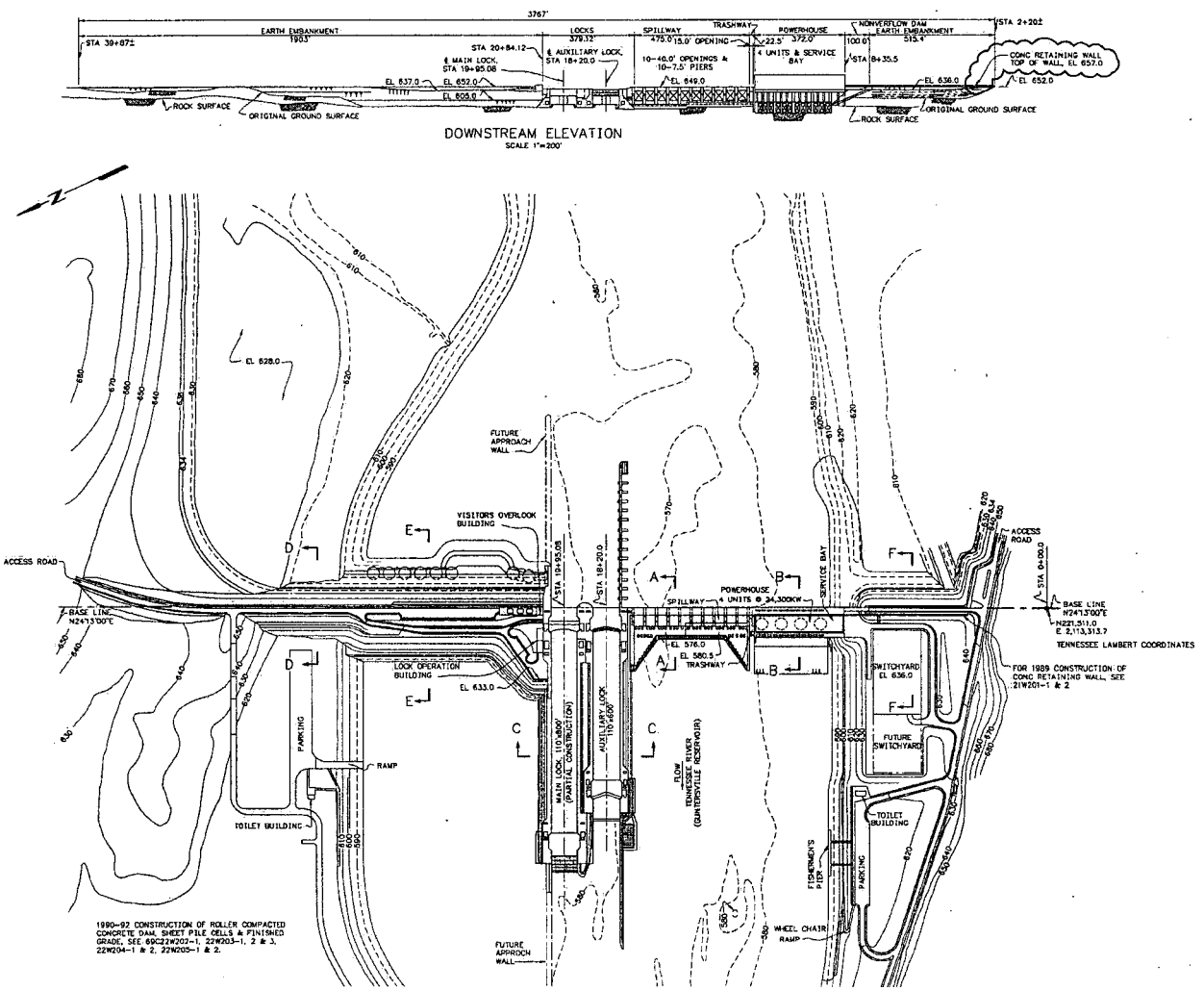


Figure 1 – Nickajack Dam, General Plan and Elevation (Ref. 1).

2. References

1. TVA drawing no: 10W200, R8 (Attachments 1 and 23).
2. TVA memorandum, "Dam Safety Program -- Probable Maximum Flood -- Nickajack Auxiliary Lock Miter Gates," RIMS No. B65 910322 176 (Attachment 8-1).
3. TVA Water Control Project Manual (Blue Book) for Nickajack Dam, TVA River Operations, April, 2000 (Attachment 20).
4. "Nickajack Dam Spillway Discharge Tables," River Operations, Tennessee Valley Authority, 2000, RIMS No. L58 081211 806 (Attachment 21).
5. "Hydraulic Design Criteria," USACE (U. S. Army Engineer Waterways Experiment Station), Eighteenth issue, Vicksburg, MS, 1988.
6. Hydraulic Design Chart 711 (HDC 711) from Reference 5 (Attachment 9 in this calculation).
7. Open Channel Flow, F. M. Henderson, Macmillan, New York, 1966.
8. TVA drawing no: 54N220, R1 (Attachments 11-4 and 24)
9. TVA drawing no: 10W201, R6 (Attachments 12 and 25)
10. "Rating Curves for Flow over Drum Gates," Joseph N. Bradley, Paper No. 2677, Transactions of the American Society of Civil Engineers, vol. 119, pp. 403-433, 1954 (Attachment 22).
11. TVA drawing no: 10W203, R5 (Attachments 14-2 and A21).
12. TVA drawing no: 46W401, R5 (Attachments 14-3 and 26).
13. TVA drawing no: 61N200, R5 (Attachments 15-4 and 27).
14. TVA drawing no: 61N206, R4 (Attachments 15-5 and 28).
15. TVA drawing no: 66K101, R0 (Attachments 15-6 and 29).
16. TVA drawing no: 22W205-1, R2 (Attachments 16-4 and 30).
17. TVA drawing no: 22W205-2, R2 (Attachments 16-5 and 31).
18. TVA drawing no: 22N220, R3 (Attachments 16-6 and 32).
19. TVA drawing no: 23W800, R5 (Attachments 17-3 and 33).
20. TVA drawing no: 21W201-1, R2 (Attachments 17-4 and 34).
21. TVA drawing no: 22W204-1, R2 (Attachments 18-4 and 35).
22. TVA drawing no: 22W203-1, R1 (Attachments 18-5 and 36).
23. TVA drawing no: 22W204-2, R2 (Attachments 18-6 and 37).
24. TVA drawing no: 22W203-2, R2 (Attachments 18-7 and 38).
25. TVA drawing no: 23W201, R3 (Attachment 39).
26. TVA drawing no: 47K1102-1, R0 (Attachments 6-1 and 40).
27. TVA drawing no: 47K1102-2, R0 (Attachments 6-2 and 41).
28. TVA drawing no: 47K1102-3, R0 (Attachments 6-3 and 42).
29. TVA drawing no: 47K1102-4, R0 (Attachments 6-4 and 43).
30. TVA drawing no. 64N511, R1 (Attachments 8-2 and 44).
31. TVA drawing no. 64N504, R1 (Attachments 8-3 and 45).
32. TVA drawing no. 64N505, R1 (Attachments 8-4 and 46).
33. "Basis for Dam Spillway Gate/Outlet Open Configuration for Flood Analyses," Tennessee Valley Authority, May 29, 2009 (EDMS No. L58 090529 800).
34. "PMF Determination for Tennessee Rive Watershed," Tennessee Valley Authority, CDQ000020080054.
35. "Dam Lock Gate Technical Evaluation for the PMF," Tennessee Valley Authority, 2009, (EDMS No. L58 090908 001).
36. "SOCH Model Calibration, Guntersville," Tennessee Valley Authority, CDQ000020080041. (EDMS No. L58 090603 003)

3. Assumptions & Methodology

The initial dam rating curves developed in these calculations will be used in simulations of probable maximum flood events. Consequently, the rating curves have been calculated well above the normal operating range and several feet above the top of the dam.

3.1 Assumptions

3.1.1 Assumption: The trash gate will be set to its maximum opening position.
Technical Justification: It is expected that the trashway gate would be raised to its maximum opening position during a PMF event to pass as much discharge as possible through the dam. This assumption is conservative for predicting flood levels at the Bellefonte site since an open trashway increases the total dam discharge, but the added discharge due to the trashway is extremely small (less than 1 percent of the total dam discharge).

3.1.2 Assumption: If overtopped, the north embankment will fail and discharge control will shift to the downstream roller compacted concrete and sheet pile dam.
Technical Justification: The dam safety modifications completed in 1992 included adding the roller compacted concrete and sheet pile dam to "maintain the normal pool elevation on the north embankment" (Reference 3; page included as Attachment 3) after the north embankment fails.

3.1.3 Assumption: If overtopped, the south embankment will fail to the original, natural ground elevation.
Technical Justification: Original ground elevation represents the most probable extent to which the embankment would fail. It may erode less than this but would not be expected to erode further.

3.1.4 Assumption: The upper gate of the navigation lock will not fail during PMF overflow but the bridge and bulkhead that sits atop it will fail.
Technical Justification: Reference 2 (included as Attachment 8-1) describes modifications made to the upper miter gate to ensure its survival under PMF overflow conditions. Reference 2 also states that the bulkhead on top of the gate will fail under PMF overflow. Attachment 8-2 verifies that the stiffeners required for the gate leave's top girder were designed and added. Also, see "Dam Lock Gate Technical Evaluation for the PMF" (Reference 35).

3.1.5 Assumption: The tailwater rating curve included as Attachment 4 and provided by the TVA River Operations Risk Section, is acceptable for use in development of the initial dam rating curve.
Technical Justification: The final tailwater curve is validated in the unsteady SOCH PMF calculation (Reference 34) by ensuring consistency with the headwater-tailwater relationship across the modeled dam configuration. This calculation provides the initial dam rating curve for the SOCH PMF calculation.

3.1.6: Assumption: All spillway gates will be set to the maximum openings specified in the spillway discharge tables.
Technical Justification: See "Basis for Dam Spillway Gate/Outlet Open Configuration for Flood Analyses" (Reference 33) for technical justification.

3.1.7 Assumption: All spillway gates will remain operable in the closed position and in the maximum opened position as specified in the spillway discharge tables.
Technical Justification: The radial gates will remain operable in the maximum opened position based on the findings of the "Watts Bar Dam – Flood and Earthquake Analysis on Radial Spillway Gates" (Reference B1). Appendix B uses the same assumptions, methodology, and approach as the Watts Bar radial gate analysis to compare forces on the gates in a closed position with forces on the gates in the maximum open position to provide technical justification for the gates to remain operable in the maximum open position during a PMF.

3.2 Unverified Assumptions

None.

3.3 Methodology -- Discharge Equations

Discharges past the dam are computed as either "free" discharge or "orifice" discharge. Free discharge refers to free surface overflow and is computed using a weir-type equation as follows (Reference 5 shows weir flow equations for overflow discharges):

$$Q_f = C_f L H_c^{1.5} \quad (1)$$

in which Q_f = free discharge (cfs), C_f = free discharge coefficient (dimensionless -- may vary with HW), L = length of overflowing section (ft), H_c = head on crest (ft) = HW - Z_c, HW = headwater elevation (ft), and Z_c = top, or crest, elevation of overflowing section (ft). This equation is modified to account for tailwater submergence as follows:

$$Q_{fs} = Q_f S_f \quad (2)$$

in which Q_{fs} = "corrected" free discharge (cfs) and S_f = tailwater submergence factor (dimensionless -- varies between 0 and 1). S_f varies with d/H_c where d = TW - Z_c (ft) and TW = tailwater elevation (ft).

Flow over the trashway, north (right) embankment, roller compacted concrete and sheet pile dam, the navigation locks, the tops of the open spillway gates, the tops of the spillway piers, the nonoverflow dam, the visitor's center overlook, the south (left) embankment, and the failed portion of the south embankment is treated as free discharge. Flow over the spillway crest is treated as free discharge for headwater elevations below $H_c = H_{Lmin}$, the head at which the overflowing nappe first touches the bottoms of the open gates (see Attachment A4). H_{Lmin} varies with gate opening, V, defined as the vertical distance between the bottom of the gate and the spillway crest.

For headwater elevations above $H_c = H_{Lmin}$ flow through the spillway gates is treated as orifice discharge. Orifice discharge refers to flow passing through a contracted opening and is computed using an orifice-type equation as follows (e.g., Reference 5, Hydraulic Design Chart 311-1):

$$Q_g = C_g G_n L \sqrt{2g(H_c - H_{mp})} \quad (3)$$

in which Q_g = orifice discharge (cfs), C_g = orifice discharge coefficient (dimensionless -- varies with gate opening and H_c), G_n = effective gate opening = minimum distance between the gate lip and the crest (ft), g = acceleration of gravity, and H_{mp} = vertical distance between the mid-point of G_n and the crest. This equation is modified to account for tailwater submergence as follows:

$$Q_{gs} = S_g Q_g \quad (4)$$

in which Q_{gs} = "corrected" orifice discharge (cfs) and S_g = tailwater submergence factor (dimensionless -- varies with d/H_c and gate opening, G_n).

3.4 Methodology -- Spillway Discharge Calculations

The discharge coefficient, C_f, for free discharge over a spillway crest varies with head, H_c (Reference 5 provides this kind of data). For the Nickajack spillway crest, the relationships $H_{Lmin}(V)$, $C_f(H_c)$, and $S_f(d/H_c)$ are available from model test data (Appendix A). The relationships between orifice discharge coefficient, C_g, and head, H_c, and between submergence factor, S_g, and submergence ratio, d/H_c, for various gate openings, V (up to V = 36.8717 feet), are also available from the model test data. The crest length, L, and crest elevation, Z_c, are shown on TVA drawings (e.g., Reference 1). The parameters G_n and H_{mp} are determined from geometry (Appendix A).

The physical model used to measure spillway discharge included several bays and the piers between them. Consequently, pier contraction effects are implicitly included in the discharge coefficients derived from the model test data.

Under the assumption that all spillway gates are fully open, the two end bays (first and last) are the only spillway bays subject to end contraction effects. These effects, which may reduce discharge through these two bays by a few percent, are neglected in this calculation. Neglecting this minor effect has negligible impact on the dam rating curve.

3.5 Methodology -- Discharge Coefficients and Submergence Factors for Overflow Sections

Values of the discharge coefficient, C_f, and the submergence factor, S_f, for flows over the north embankment (before failure), the roller compacted concrete and sheet pile dam built downstream from the north embankment (after its failure), the navigation locks, the tops of the spillway piers, the tops of the open spillway gates, the trashway (until the nappe touches its raised gate), the nonoverflow dam, the south embankment before failure, and the south embankment after failure are estimated using Hydraulic Design Chart 711 which is included as Attachment 9. Length, L, and crest elevation, Z_c, in each case is determined from TVA drawings (all relevant drawings are listed as References).

The upper plot of HDC 711 (Attachment 9) shows that C_f is about 2.65 for very broad crests ($H_1/B < 0.4$ where $H_1 = H_c$ and B = streamwise length of the crest) and gradually increases to 3.1, the maximum value for a "broad-crested" weir, as H_1/B increases to about 1.2. As H_1/B increases above 1.2, C_f continues to increase as the weir transitions from broad-crested to sharp-crested at about $H_1/B = 2.0$. Since the estimation of discharge over the top of various sections of a dam and its embankments is an approximation, small variations in C_f with H_c are not modeled and the effects of end contractions are neglected. A single representative value for C_f within the range of its variation is used for all headwater elevations included in the rating. Neglecting minor variations in C_f values and end contractions has negligible impact on the dam rating curve.

The lower plot of HDC 711 shows several curves of C_s/C_f (equivalent to S_f) versus H_2/H_1 (equivalent to d/H_c). As illustrated in Attachment 10, the curve labeled "suggested for design (broad crests)" is well-represented by the following polynomial:

$$S_f = 1.0 + 0.023\sigma - 5.0259\sigma^2 + 18.266\sigma^3 - 44.658\sigma^4 \quad \text{for} \quad 0 \le \sigma \le 0.37 \quad \text{broad crest} \qquad (5)$$

in which $\sigma = d/H_c - 0.6$. According to this relationship, submergence affects discharge over a broad-crested weir for $d/H_c > 0.6$.

4. Design Input

Sect.	Input Parameter	Source	Symbol	Value
4.1	Acceleration of gravity	Common knowledge, Ref. 5, sheet. 000-1 for example	g	32.2 ft/sec^2
4.2	Upper limit on headwater elevation for rating	Paragraph 4.20		660 feet
4.3	**Spillway crest parameters**			
4.3.1	Crest length	10 40-foot wide bays; Att. 1 or Att. 12	L	400 feet
4.3.2	Crest elevation	Att. 1 or Att. 12	Z_c	595 feet
4.3.3	Free discharge coefficient	Polynomial fit to model data given in Att. A10 and discussed in Appendix A	$C_f(H_c)$	Equation A5
4.3.4	Submergence factor for free discharge	Curve fit to model data given in Att. A12 and discussed in Appendix A	$S_f(d/H_c)$	Equation A6
4.4	**Spillway gate parameters**			
4.4.1	Vertical opening	Field measurements given in Att. A3 and discussed in Appendix A	V	42.4917 feet
4.4.2	Effective gate opening	Computed in Appendix A	G_n	42.755 feet
4.4.3	Mid-point elevation of opening relative to crest	Computed in Appendix A	H_{mp}	21.187 feet
4.4.4	Headwater elevation at which nappe touches gates	H_{Lmin} estimated in Appendix A	$H_{Lmin} + Z_c$	646.0 feet
4.4.5	Orifice discharge coefficient	Extrapolated curve given graphically and digitally in Att. A14 and discussed in Appendix A	$C_g(H_c)$	Interpolate between points listed in Att. A14
4.4.6	Submergence factors for orifice discharge	Family of curves given in Att. A17 and Table A3 and discussed in Appendix A	$S_g(d/H_c, H_c/G_n)$	Interpolate between points in Table A3
4.5	**Trashway crest parameters**			
4.5.1	Crest length	Att. 11-4	L	15.0 feet
4.5.2	Crest elevation	Att. 11-4	Z_c	625 feet
4.5.3	Free discharge coefficient	Justification in Att. 11	C_f	3.0
4.5.4	Submergence factor	Justification in Att. 11	S_f	Equation 5
4.6	**Trashway gate parameters**			
4.6.1	Bottom elev. of raised gate	Att. 11-4	none	638 feet
4.6.2	Effective gate opening	Justification in Att. 11	G_n	13 feet
4.6.3	Mid-point elevation of	Justification in Att. 11	H_{mp}	6.5 feet
4.6.4	Headwater elevation at which nappe touches gate	Justification in Att. 11	H_{Lmin}	652.8 feet
4.6.5	Orifice discharge coefficient	Justification in Att. 11	C_g	0.9133
4.6.6	Submergence factor for orifice discharge	Justification in Att. 11	S_g	Equation 5
4.7	**Spillway gate overflow**	Symbol notation is defined in Att. 13-1		
4.7.1	Overflow discharge coeff.	Justification in Att. 13	C_{fo}	3.15
4.7.2	Overflow elevation	Computed in Appendix A	Z_{co}	658.50 feet
4.7.3	Overflow length	Same as spillway crest, Att. 1 or Att. 12	L	400 feet

Sect.	Input Parameter	Source	Symbol	Value
4.8	**Spillway piers and powerhouse overflow**			
4.8.1	Discharge coefficient	Justification in Att. 14	C_f	2.65
4.8.2	Overflow elevation	Att. 1 and Att. 12	Z_c	649 feet
4.8.3	Overflow length	Determined in Att. 14	L	90 feet
4.9	**Auxiliary lock upper gate overflow**			
4.9.1	Discharge coefficient	Justification in Att. 15	C_f	2.9
4.9.2	Overflow elevation	Justification in Att. 15	Z_c	639 feet
4.9.3	Overflow length	Justification in Att. 15	L	110 feet
4.10	**Navigation lock overflow**			
4.10.1	Discharge coefficient	Justification in Att. 15	C_f	2.87
4.10.2	Overflow elevation	Att. 1 and Att. 15-4	Z_c	645 feet
4.10.3	Overflow length	Determined in Att. 15	L	325 feet
4.11	**North (right) embankment overflow**			
4.11.1	Discharge coefficient	Justification in Att. 16	C_f	2.66
4.11.2	Overflow elevation	Determined in Att. 16	Z_c	652 feet
4.11.3	Overflow length	Determined in Att. 16	L	1878 feet
4.12	**Visitor's center overlook overflow**			
4.12.1	Discharge coefficient	Justification in Att. 16	C_f	3.33
4.12.2	Overflow elevation	Determined in Att. 16	Z_c	657 feet
4.12.3	Overflow length	Determined in Att. 16	L	27 feet
4.13	**South (left) embankment and nonoverflow dam overflow**			
4.13.1	Discharge coefficient	Justification in Att. 17	C_f	3.1
4.13.2	Overflow elevation	Determined in Att. 17	Z_c	657 feet
4.13.3	Overflow length	Determined in Att. 17	L	628 feet
4.14	**Failed north (right) embankment -- north section**			
4.14.1	Discharge coefficient	Justification in Att. 18	C_f	2.65
4.14.2	Overflow elevation	Determined in Att. 18	Z_c	648.5 feet
4.14.3	Overflow length	Determined in Att. 18	L	181
4.15	**Failed north (right) embankment -- center section**			
4.15.1	Discharge coefficient	Justification in Att. 18	C_f	3.14
4.15.2	Overflow elevation	Determined in Att. 18	Z_c	634 feet
4.15.3	Overflow length	Determined in Att. 18	L	1797
4.16	**Failed north (right) embankment -- south section**			
4.16.1	Discharge coefficient	Justification in Att. 18	C_f	3.33
4.16.2	Overflow elevation	Determined in Att. 18	Z_c	637 feet
4.16.3	Overflow length	Determined in Att. 18	L	100
4.17	**Failed south (left) embankment**			
4.17.1	Discharge coefficient	Paragraph [4.23]	C_f	2.65
4.17.2	Overflow elevation	Paragraph [4.23]	Z_c	607 feet
4.17.3	Overflow length	Paragraph [4.23]	L	500 feet
4.18	**Turbine Discharge**			
4.18.1	Discharge, Case 1	Paragraph [4.22]		35,000 cfs
4.18.2	Discharge, Case 2, 3, & 4	Paragraph [4.22]		0
4.18.3	Maximum TW Elev.	Paragraph [4.22]		636 feet
4.18.4	Maximum HW Elev.	Paragraph [4.22]		652.6 feet
4.18.5	Minimum Gross Head	Gross head = HW - TW, Paragraph [4.22]		10 feet
4.19	**Tailwater Rating Curve**			
4.19.1	TW vs. total discharge, Q	Paragraph [4.21]	TW(Q)	Equation 6

4.20 Upper Limit on Headwater Elevation Included in Rating Curves

The dam rating curves need to include all headwater elevations that may occur during a PMF event. Because the south embankment is postulated to fail after overtopping, the headwater at Nickajack Dam is not expected to rise past 660 feet, which is 3 feet above the top of the embankment (elevation 657 feet [4.13.2]).

4.21 Tailwater rating curve

The tailwater rating curve used in this calculation [3.2.1] is shown in Attachment 4. Attachment 5 lists points from this plot and shows a polynomial fit to the result. The polynomial indicated in Attachment 5 and repeated below is used for the dam rating curve calculations.

$$TW = 592.6 + 0.1162Q - 1.353\times10^{-4}Q^2 + 9.204\times10^{-8}Q^3 - 2.346\times10^{-11}Q^4 \qquad (6)$$

in which Q = total discharge past the dam in cfs divided by 1000 ("1000 cfs").

4.22 Turbine Discharge

Nickajack Dam has four turbines (see Attachment 1). The turbines will be operated during a PMF until the tailwater or headwater reaches a level at which electrical components will get wet or excessive vibration occurs. The occurrence of excessive vibration is not predictable so turbine discharge is added to the total dam discharge until the limiting tailwater or headwater elevations are reached.

Electrical components may get wet if the tailwater rises above the level of the switchyard or if the tailwater or headwater rise to a level where water may enter the powerhouse. Once water enters the powerhouse, generation will be suspended and the units will not be restarted until a thorough inspection of the electrical equipment is done. Attachment 1 indicates that the switch yard would be under water for tailwater elevations above 636 feet, which is therefore the maximum tailwater elevation for turbine operation. Section B-B on Attachment 1 verifies that water cannot enter the powerhouse for tailwater elevations below 636 feet. For headwater elevations above 649 feet, water will flow over the intake deck as illustrated in Section B-B. However, water will not enter the powerhouse until the headwater rises above the curb with top elevation 652.6 feet (shown on Attachment 14-3). Therefore, the maximum headwater for turbine operation is 652.6 feet.

Turbine discharge is included for Case 1, but not for Cases 2, 3, or 4. The Case 2 rating curve is used when turbine discharge has been suspended before either the north or south embankments have failed. The Case 3 and Case 4 rating curves are used only after the north embankment has failed (and the south embankment for Case 4), which occurs after the headwater elevation rises a few feet above its crest at 652 feet. Turbine generation would be suspended before the failure since water can enter the powerhouse for headwater elevations above 652.6 feet, only 0.6 feet above the embankment crest. As stated above, the units would not be restarted until a thorough inspection indicated that all electrical components were undamaged.

Turbine discharge versus gross head, where gross head is the difference between the headwater elevation and the tailwater elevation, is estimated from the operating characteristics included as Attachments 6-1 through 6-4. The turbines are expected to be operated for maximum capacity, with the wicket gates open as far as possible (99.1% on Attachments 6-1 and 6-2 and 100% on Attachments 6-3 and 6-4). The lowest gross head included in the characteristics is 21 feet. Because the dam rating curves are used only when all spillway gates are fully open, resulting in much higher than normal tailwater elevations, turbine discharges for gross heads lower than 21 feet are needed for the rating curves. The turbine discharges for lower values of gross head are determined by linear extrapolation from the points given for maximum gate opening. As shown on Attachments 6-1 through 6-4, generator output would be less than zero for gross heads below about 10 feet. Therefore, the minimum gross head for turbine operation is 10 feet.

The results for Case 1 show several headwaters below 631 feet at which gross head is greater than 10 feet but turbine discharge is zero. In those cases the gross heads are greater than 10 feet with the turbines off but less than 10 feet with the turbines on. For the rating curves, turbine discharge is set to zero if the gross head with turbines operating is below 10 feet.

The Case 1 rating curve was computed first without turbine discharge to determine the range of gross heads that occur during the PMF. Then, discharges for Units 1, 2, 3 and 4 at a nominal gross head within the range of variation above the lower limit of 10 feet were estimated from Attachments 6-1 though 6-4. The total discharge at this nominal head is used for all headwaters at which turbine discharge is expected. Table 1 summarizes the results. Use of a nominal gross head within the range of variation to estimate turbine discharge for all headwater elevations and rounding the turbine discharge does not significantly affect the results since the turbine discharge is a small percentage of the total dam discharge.

Table 1: Turbine Discharge for Case 1 Rating Curve

Case	Gross Head Range feet	Nominal Gross Head feet	Discharge at Nominal Gross Head, cfs				
			Unit 1	Unit 2	Unit 3	Unit 4	Total
1	10->20	15	8,100	7,900	9,450	9,450	35,000

4.23 South Embankment Failure

The south earth embankment is expected to fail if overtopped. Attachment 7 illustrates the postulated failure section, which includes the 100-foot long nonoverflow dam between the powerhouse and the earth embankment and 400 feet of the embankment. The nonoverflow dam is included in the failure section because flow around it will undercut it leading to eventual failure. A total length of 500 feet for the failure section was postulated in the FSAR as the design basis for the Bellefonte site and is adopted as a reasonable approximation of the extent of failure for this calculation, as well as for other design basis flood-routing simulations (including Browns Ferry Nuclear Plant) downstream of the Nickajack dam. The 500 foot length ends the failure section just north of the paved access road, near where the topography begins sloping upward. The embankment is assumed [3.1.3] to fail to the original ground elevation under it, which is approximately 607 feet (Attachment 39). The original ground elevation is higher than 607 feet near the north end of the failure section so the postulated section provides a conservatively large flow area resulting in conservatively large estimates of discharge through the failed section.

Discharge through the breach in the south embankment following its failure is controlled by critical flow for tailwater elevations below the overflow elevation of 607 feet. As tailwater rises above 607 feet, it eventually reaches a level at which it submerges and reduces the discharge through the breach. This behavior, discharge controlled by critical flow and reduced by submergence effects, is well represented by a broad-crested weir model as described in [3.5]. This model is used to estimate discharge through the south embankment because the uncertainties in the breach geometry and energy losses for discharge through the breach do not justify, or allow, a more rigorous approach.

Attachment 7 depicts flow through the breach and includes an elevation sketch in the lower right-hand corner illustrating the flow profile for low tailwater. Attachment 9 is used to estimate C_f for this "weir." The maximum head (H_1 in Attachment 9) is 53 feet for the upper limit headwater of 660 feet [4.2]. The streamwise length (B in Attachment 9) is variable, depending on flow path as illustrated in Attachment 7, but is on the order of 1000 feet (rough scaling) on average (measured from point 2 to point 3). These values result in $H_1/B = 0.05$ approximately, which indicates $C_f = 2.65$.

5. Special Requirements/Limiting Conditions

N/A

6. Calculations

The calculations consist of computing spillway and overflow discharges (from Equations 1 through 4) for a list of headwater elevations ranging from the minimum for which discharge exceeds zero up to 660 feet [4.2], which is three feet above the south embankment. Turbine discharge is added to the total discharge where applicable. Headwaters only a few feet above the south embankment are included because the embankment is expected to fail soon after being overtopped. The dam rating curve for each case is a plot of headwater elevation versus total dam discharge.

6.1 Case 1, Pre-Failure Condition with Turbine Discharge

For the pre-failure condition, discharges are computed for headwaters ranging from 595 feet, the spillway crest elevation, to 660 feet, three feet above the top of the south embankment. Discharge passes through the spillway section, the trashway, and the various overflow sections as headwater rises above the crest elevations in each case. The turbines pass discharge for a limited range of headwater elevations where the headwater, tailwater, and gross head constraints are satisfied. Total discharge, given in "1000 cfs" is the sum of all discharges in cfs past the dam divided by 1000.

Figure 2 shows the spreadsheet calculations for the pre-failure dam rating curve with turbine discharge (spreadsheet included as Attachment 19). The final result, the rating curve, is defined by the first two columns, HW vs. Total Discharge. The third column (TW) gives the tailwater associated with the "Total Discharge" from the tailwater rating curve polynomial fit [4.19.1]. This is computed to check for tailwater submergence effects on the discharge.

Spillway discharge in cfs is computed in the next five columns (under the header "Spillway"), H_c, $C_f|C_g$, d/H_c, $S_f|S_g$ and $Q_f|Q_g$. Free discharge occurs for headwater elevations 646.0 feet [4.4.4] and below. Orifice discharge occurs for headwaters above 646.0 feet. The transition point is indicated by a horizontal line. Above the line, the listed discharge coefficient is C_f [4.3.3], computed from Equation (A5), and the listed submergence factor is S_f [4.3.4], computed from Equation (A6). Below the line the listed discharge coefficient is C_g [4.4.5], computed by interpolation between the points in the table at the top of Attachment A14, and the listed submergence factor is S_g [4.4.6], computed by interpolation between the points in Table A3. Column $Q_f|Q_g$ is the spillway discharge computed from Equation 1 for free discharge and from Equation 3 for orifice discharge. Tailwater affects the spillway discharge for headwater elevations 621 feet and above ($d/H_c >= 0.6$). Consequently, it is necessary to iterate through different tailwater elevations until the total computed discharge fits the tailwater rating curve [4.19.1]. Figure 2 shows the final results but does not show the iteration steps. The results are readily checked by computing the individual discharges (the only discharge affected by tailwater is the spillway discharge), adding them up to compute total discharge, and then making sure the listed tailwater and total discharge agree with the tailwater rating curve.

Turbine discharge [4.18.1] is listed in the column following the spillway discharge column. Turbine discharge is zero when the headwater, tailwater, and gross head constraints ([4.18.3], [4.18.4], and [4.18.5]) are not all satisfied. Gross heads would be lower than the minimum gross head [4.18.5] if turbines were operating at headwater elevations below 631 feet.

The next column shows "C_g=", "G_n=", "C_f=", "Z_c=", and "L=" in five rows to indicate the meaning of the values included in those rows in the "Overflow Discharge" columns. The "Trash Gate" column is the only one that defines values for C_g and G_n because flow through the trash gate transitions from free discharge to orifice discharge for headwaters above 652 feet [4.6.4]. Parameter "H_{mp}," needed for computing orifice discharge from Equation 3, is not explicitly listed because, for the trash gate, it equals $G_n/2$ [4.6.3] and is easily included in this form within the spreadsheet cell formula for discharge.

The next eight columns are overflow discharges in cfs for the trash gate, spillway gates, spillway piers, auxiliary lock gate, navigation locks, north (right) embankment, visitor's overlook, and south (left) embankment. The overflow discharge coefficient C_f ([4.5.3], [4.7.1], [4.8.1], [4.9.1], [4.10.1], [4.11.1], [4.12.1], [4.13.1]), elevation Z_c ([4.5.2], [4.7.2], [4.8.2], [4.9.2], [4.10.2], [4.11.2], [4.12.2], [4.13.2]), and length L ([4.5.1], [4.7.3], [4.8.3], [4.9.3], [4.10.3], [4.11.3], [4.12.3], [4.13.3]) in each case is indicated in the three rows above the computed discharges. All overflow discharges are computed using Equation 1 except those below the horizontal line indicating the transition from free discharge to orifice discharge for the trash gate. Discharges below that line are computed using Equation 3.

The last column is d/H_c for the trash gate since the tailwater elevation is higher than its crest elevation for headwaters 638 feet and above. The trash gate discharge is not affected by tailwater because d/Hc < 0.6 [3.5, Equation 5].

Pre-Failure with Turbine Discharge, North and South Embankments Intact

g = 32.2 ft/s^2

Spillway Parameters
L = 400 feet
Z_c = 595 feet
G_n = 42.755 feet
H_{mp} = 21.187 feet

HW	Q Total Discharge 1000 cfs	TW feet	Spillway feet H_c	C_f/C_g	d/H_c	S_f/S_g	cfs Q_f/Q_g	Turbine Q cfs	Overflow Discharge, Q_f in cfs: Trash Gate	Spill Gate Overflow	Spill Piers	Aux. Lock Gate	Locks	North Emb.	Visit. Over Look	South Emb.	Trash Gate d/Hc
								C_g =	0.9133								
								G_n =	13								
								C_f =	3.0	3.15	2.65	2.9	2.87	2.66	3.33	3.1	
								Z_c =	625	658.5	649	639	645	652	657	657	
								L =	15	400	90	110	325	1878	27	628	
595	0.00	592.60	0			1	0	0	0	0	0	0	0	0	0	0	
597	3.61	593.02	2	3.191		1	3610	0	0	0	0	0	0	0	0	0	
599	10.46	593.80	4	3.268		1	10459	0	0	0	0	0	0	0	0	0	
601	19.60	594.83	6	3.334		1	19600	0	0	0	0	0	0	0	0	0	
603	30.68	596.04	8	3.390	0.130	1	30680	0	0	0	0	0	0	0	0	0	
605	43.48	597.40	10	3.437	0.240	1	43476	0	0	0	0	0	0	0	0	0	
607	57.83	598.88	12	3.478	0.324	1	57825	0	0	0	0	0	0	0	0	0	
609	73.60	600.46	14	3.513	0.390	1	73604	0	0	0	0	0	0	0	0	0	
611	90.72	602.09	16	3.544	0.443	1	90716	0	0	0	0	0	0	0	0	0	
613	109.09	603.78	18	3.571	0.488	1	109089	0	0	0	0	0	0	0	0	0	
615	128.67	605.50	20	3.596	0.525	1	128670	0	0	0	0	0	0	0	0	0	
617	149.42	607.24	22	3.620	0.556	1	149422	0	0	0	0	0	0	0	0	0	
619	171.32	608.98	24	3.643	0.582	1	171318	0	0	0	0	0	0	0	0	0	
621	193.70	610.67	26	3.665	0.603	0.997	193701	0	0	0	0	0	0	0	0	0	
623	217.51	612.37	28	3.686	0.620	0.996	217515	0	0	0	0	0	0	0	0	0	
625	242.36	614.04	30	3.708	0.635	0.994	242357	0	0	0	0	0	0	0	0	0	
627	268.34	615.70	32	3.729	0.647	0.993	268213	0	127	0	0	0	0	0	0	0	
629	295.43	617.32	34	3.750	0.656	0.992	295067	0	360	0	0	0	0	0	0	0	
631	355.77	620.58	36	3.770	0.711	0.983	320107	35000	661	0	0	0	0	0	0	0	
633	384.87	622.01	38	3.789	0.711	0.983	348857	35000	1018	0	0	0	0	0	0	0	
634	399.79	622.71	39	3.797	0.711	0.983	363577	35000	1215	0	0	0	0	0	0	0	
636	430.28	624.08	41	3.813	0.709	0.983	393638	35000	1642	0	0	0	0	0	0	0	
638	461.51	625.39	43	3.825	0.707	0.984	424404	35000	2109	0	0	0	0	0	0	0	0.030
640	493.58	626.67	45	3.833	0.704	0.984	455651	35000	2614	0	0	319	0	0	0	0	0.111
642	526.89	627.92	47	3.836	0.700	0.985	487075	35000	3154	0	0	1658	0	0	0	0	0.172
644	560.69	629.12	49	3.832	0.696	0.986	518398	35000	3727	0	0	3567	0	0	0	0	0.217
645	577.62	629.70	50	3.827	0.694	0.986	533908	35000	4025	0	0	4688	0	0	0	0	0.235
646	595.35	630.30	51	3.820	0.692	0.987	549178	35000	4331	0	0	5908	933	0	0	0	0.252
647	592.28	630.20	52	0.722	0.677	0.987	542782	35000	4644	0	0	7218	2638	0	0	0	0.236
648	593.85	630.25	53	0.706	0.665	0.989	540431	35000	4964	0	0	8613	4847	0	0	0	0.228
649	604.51	630.60	54	0.703	0.659	0.990	546666	35000	5291	0	0	10088	7462	0	0	0	0.233
650	615.60	630.96	55	0.699	0.654	0.990	552667	35000	5625	0	239	11638	10428	0	0	0	0.238
652	638.62	631.70	57	0.692	0.644	0.991	563842	35000	6313	0	1239	14952	17275	0	0	0	0.248
654	646.30	631.94	59	0.690	0.626	0.994	579007	0	6779	0	2667	18532	25184	14129	0	0	0.239
656	701.19	633.62	61	0.690	0.633	0.993	593350	0	7074	0	4417	22360	34029	39964	0	0	0.278
657	731.87	634.52	62	0.690	0.637	0.992	600272	0	7217	0	5397	24361	38774	55851	0	0	0.298
658	766.35	635.52	63	0.690	0.643	0.991	606954	0	7357	0	6440	26419	43720	73418	90	1947	0.319
659	804.54	636.61	64	0.690	0.650	0.990	613390	0	7495	445	7542	28532	48860	92518	254	5506	0.342
660	846.05	637.78	65	0.690	0.658	0.987	618902	0	7630	2315	8701	30699	54188	113035	467	10116	0.365

Figure 2 – Calculations for Case 1, Pre-Failure Condition with Turbine Discharge

6.2 Case 2, Pre-Failure Condition without Turbine Discharge

The calculations for the Case 2 rating curve are identical to those for the Case 1 rating curve, except that turbine discharge is zero for all headwater elevations. Figure 3 shows the spreadsheet calculations.

Pre-Failure without Turbine Discharge, North and South Embankments Intact

g = 32.2 ft/s^2

Spillway Parameters
L = 400 feet
Z_c = 595 feet
G_n = 42.755 feet
H_{mp} = 21.187 feet

								Overflow Discharge, Q_f in cfs								
								Trash Gate	Spill Gate	Spill Piers	Aux. Lock Gate	Locks	North Emb.	Visit. Over Look	South Emb.	
								C_g = 0.9133								
								G_n = 13	Overflow							
	Q Total		Spillway					C_f = 3.0	3.15	2.65	2.9	2.87	2.66	3.33	3.1	Trash
	Discharge	TW	feet				cfs	Z_c = 625	658.5	649	639	645	652	657	657	Gate
HW	1000 cfs	feet	H_c	C_f/C_g	d/H_c	S_f/S_g	Q_f/Q_g	L = 15	400	90	110	325	1878	27	628	d/Hc
595	0.00	592.60	0			1	0	0	0	0	0	0	0	0	0	
597	3.61	593.02	2	3.191		1	3610	0	0	0	0	0	0	0	0	
599	10.46	593.80	4	3.268		1	10459	0	0	0	0	0	0	0	0	
601	19.60	594.83	6	3.334		1	19600	0	0	0	0	0	0	0	0	
603	30.68	596.04	8	3.390	0.130	1	30680	0	0	0	0	0	0	0	0	
605	43.48	597.40	10	3.437	0.240	1	43476	0	0	0	0	0	0	0	0	
607	57.83	598.88	12	3.478	0.324	1	57825	0	0	0	0	0	0	0	0	
609	73.60	600.46	14	3.513	0.390	1	73604	0	0	0	0	0	0	0	0	
611	90.72	602.09	16	3.544	0.443	1	90716	0	0	0	0	0	0	0	0	
613	109.09	603.78	18	3.571	0.488	1	109089	0	0	0	0	0	0	0	0	
615	128.67	605.50	20	3.596	0.525	1	128670	0	0	0	0	0	0	0	0	
617	149.42	607.24	22	3.620	0.556	1	149422	0	0	0	0	0	0	0	0	
619	171.32	608.98	24	3.643	0.582	1	171318	0	0	0	0	0	0	0	0	
621	193.70	610.67	26	3.665	0.603	0.997	193701	0	0	0	0	0	0	0	0	
623	217.51	612.37	28	3.686	0.620	0.996	217514	0	0	0	0	0	0	0	0	
625	242.36	614.04	30	3.708	0.635	0.994	242357	0	0	0	0	0	0	0	0	
627	268.34	615.70	32	3.729	0.647	0.993	268212	127	0	0	0	0	0	0	0	
629	295.43	617.32	34	3.750	0.656	0.992	295067	360	0	0	0	0	0	0	0	
631	323.56	618.89	36	3.770	0.664	0.991	322897	661	0	0	0	0	0	0	0	
633	352.67	620.43	38	3.789	0.669	0.991	351652	1018	0	0	0	0	0	0	0	
634	367.57	621.18	39	3.797	0.671	0.990	366356	1215	0	0	0	0	0	0	0	
636	397.99	622.63	41	3.813	0.674	0.990	396351	1642	0	0	0	0	0	0	0	
638	429.12	624.03	43	3.825	0.675	0.990	427010	2109	0	0	0	0	0	0	0	
640	461.06	625.37	45	3.833	0.675	0.990	458126	2614	0	0	319	0	0	0	0	0.025
642	494.22	626.69	47	3.836	0.674	0.990	489410	3154	0	0	1658	0	0	0	0	0.100
644	527.87	627.95	49	3.832	0.673	0.990	520581	3727	0	0	3567	0	0	0	0	0.155
645	544.72	628.56	50	3.827	0.671	0.990	536005	4025	0	0	4688	0	0	0	0	0.178
646	562.38	629.18	51	3.820	0.670	0.990	551207	4331	0	0	5908	933	0	0	0	0.199
647	559.89	629.09	52	0.722	0.656	0.991	545390	4644	0	0	7218	2638	0	0	0	0.186
648	561.16	629.14	53	0.706	0.644	0.993	542741	4964	0	0	8613	4847	0	0	0	0.180
649	571.60	629.50	54	0.703	0.639	0.993	548759	5291	0	0	10088	7462	0	0	0	0.187
650	582.51	629.87	55	0.699	0.634	0.994	554584	5625	0	239	11638	10428	0	0	0	0.195
652	605.49	630.63	57	0.692	0.625	0.995	565709	6313	0	1239	14952	17275	0	0	0	0.209
654	646.30	631.94	59	0.690	0.626	0.994	579008	6779	0	2667	18532	25184	14129	0	0	0.239
656	701.19	633.62	61	0.690	0.633	0.993	593350	7074	0	4417	22360	34029	39964	0	0	0.278
657	731.87	634.52	62	0.690	0.637	0.992	600272	7217	0	5397	24361	38774	55851	0	0	0.298
658	766.35	635.52	63	0.690	0.643	0.991	606954	7357	0	6440	26419	43720	73418	90	1947	0.319
659	804.54	636.61	64	0.690	0.650	0.990	613390	7495	445	7542	28532	48860	92518	254	5506	0.342
660	846.05	637.78	65	0.690	0.658	0.987	618902	7630	2315	8701	30699	54188	113035	467	10116	0.365

Figure 3 – Calculations for Case 1, Pre-Failure Condition without Turbine Discharge

6.3 Case 3, North Earth Embankment Fails

Figure 3 shows the spreadsheet calculations for the dam rating curve after the north earth embankment fails and control shifts to the downstream roller compacted concrete and sheet pile dam. As for the pre-failure conditions, discharges are computed for headwaters ranging from 595 feet to 660 feet. The final result, the rating curve, is defined by the first two columns, HW vs. Total Discharge. The third column (TW) gives the tailwater associated with the "Total Discharge" from the tailwater rating curve polynomial fit [4.19.1].

Spillway discharge in cfs is computed in the next five columns (under the header "Spillway"), H_c, $C_f|C_g$, d/H_c, $S_f|S_g$ and $Q_f|Q_g$. Free discharge occurs for headwater elevations 646.0 feet [4.4.4] and below. Orifice discharge occurs for headwaters above 646.0 feet. The transition point is indicated by a horizontal line. Above the line, the listed discharge coefficient is C_f [4.3.3], computed from Equation (A5), and the listed submergence factor is S_f [4.3.4], computed from Equation (A6). Below the line the listed discharge coefficient is C_g [4.4.5], computed by interpolation between the points in the table at the top of Attachment A14, and the listed submergence factor is S_g [4.4.6], computed by interpolation between the points in Table A3. Column $Q_f|Q_g$ is the spillway discharge computed from Equation 1 for free discharge and from Equation 3 for orifice discharge. Tailwater affects the spillway discharge for headwater elevations 621 feet and above ($d/H_c >= 0.6$). As for Case 1, Figure 3 shows the final results of iterations for tailwater elevation but does not show the iteration steps.

The column following the spillway discharge column shows "C_g=", "G_n=", "C_f=", "Z_c=", and "L=" in five rows to indicate the meaning of the values included in those rows in the "Overflow Discharge" columns.

Trash gate discharge in cfs is computed in the next three columns. As for the spillway, a horizontal line indicates the transition from free discharge to orifice discharge. The orifice discharge is computed from Equation 4 using C_g, G_n, and L as listed above the discharge values and with $H_{mp} = G_n/2$. Equation 5 for S_f is used to approximate S_g as justified in Attachment 11 [4.6.6]. Tailwater affects the discharge for headwater elevations 652 feet and above ($d/H_c >= 0.6$).

The next five columns are overflow discharges in cfs for the spillway gates, spillway piers, auxiliary lock gate, navigation locks, and south embankment. The overflow discharge coefficient C_f ([4.7.1], [4.8.1], [4.9.1], [4.10.1], [4.13.1]), elevation Z_c ([4.7.2], [4.8.2], [4.9.2], [4.10.2], [4.13.2]), and length L ([4.7.3], [4.8.3], [4.9.3], [4.10.3], [4.13.3]) in each case is indicated in the three rows above the computed discharges. All overflow discharges are computed using Equation 1. Note that these five overflow discharges are the same as computed for the pre-failure case.

Discharge over the roller compacted concrete and sheet pile dam that controls flow on the north side of the dam after the north embankment fails is computed in the next five columns. Three sections (north, center, and south) are defined, each with different overflow elevations. The overflow discharge coefficients C_f ([4.14.1], [4.15.1], [4.16.1]), elevations Z_c ([4.14.2], [4.15.2], [4.16.2]), and lengths L ([4.14.3], [4.15.3], [4.16.3]) are indicated in the three rows above the computed discharges. The center section includes columns for d/H_c and S_f because its discharge is affected by tailwater ($d/Hc > 0.6$) for headwater elevations 658 feet and above. Submergence factor, S_f, is computed from Equation 5. All overflow discharges are computed using Equations 1 or 2.

Figure 3 does not include a column for visitor's overlook overflow because the overlook is included in that portion of the north embankment that is postulated to fail.

The last column is d/H_c for the south section of the failed north embankment, which has the next lowest overflow crest elevation after the trash gate and center section of the failed north embankment, and the tailwater elevation exceeds its crest elevation for headwaters 648 feet and above. The submergence ratio, d/H_c, exceeds 0.6 [3.5, Equation 5] for headwater elevation 660 feet, where it reaches 0.616, but is lower than 0.6 for lower headwater elevations. Equation 5 gives $S_f = 0.9992$ for $d/H_c=0.616$ so the effect of submergence on the south section can be considered negligible at all headwater elevations without significantly affecting the results. The overflow discharges with higher crest elevations have even lower values of d/H_c and are not affected by tailwater.

After North Embankment Failure

g = 32.2 ft/s^2

Spillway Parameters
L = 400 feet
Z_c = 595 feet
G_n = 42.755 feet
H_{mp} = 21.187 feet

Overflow Discharge, Q_f in cfs

										Trash Gate			Spill		Aux.				Failed N. Emb. - Roller Compacted						
									C_g =			0.9133	Gate	Spill	Lock		South	Concrete and Sheet Pile Dam						
									G_n =			13	Overflow	Piers	Gate	Locks	Emb.	north	center			south	N.
	Total		Spillway						C_f =			3.0	3.15	2.65	2.9	2.87	3.1	2.65			3.14	3.33	Emb.
	Discharge		feet				cfs		Z_c =			625	658.5	649	639	645	657	648.5			634	637	south
HW	1000 cfs	TW	H_c	C_f/C_g	d/H_c	S_f/S_g	Q_f/Q_g	L =	d/H_c	S_f/S_g	15	400	90	110	325	628	181	d/H_c	S_f	1797	100	d/Hc
595	0.00	592.60	0			1	0				0	0	0	0	0	0	0			0	0	
597	3.61	593.02	2	3.191		1	3610				0	0	0	0	0	0	0			0	0	
599	10.46	593.80	4	3.268		1	10459				0	0	0	0	0	0	0			0	0	
601	19.60	594.83	6	3.334		1	19600				0	0	0	0	0	0	0			0	0	
603	30.68	596.04	8	3.390	0.130	1	30680				0	0	0	0	0	0	0			0	0	
605	43.48	597.40	10	3.437	0.240	1	43476				0	0	0	0	0	0	0			0	0	
607	57.83	598.88	12	3.478	0.324	1	57825				0	0	0	0	0	0	0			0	0	
609	73.60	600.46	14	3.513	0.390	1	73604				0	0	0	0	0	0	0			0	0	
611	90.72	602.09	16	3.544	0.443	1	90716				0	0	0	0	0	0	0			0	0	
613	109.09	603.78	18	3.571	0.488	1	109089				0	0	0	0	0	0	0			0	0	
615	128.67	605.50	20	3.596	0.525	1	128670				0	0	0	0	0	0	0			0	0	
617	149.42	607.24	22	3.620	0.556	1	149422				0	0	0	0	0	0	0			0	0	
619	171.32	608.98	24	3.643	0.582	1	171318				0	0	0	0	0	0	0			0	0	
621	193.70	610.67	26	3.665	0.603	0.997	193701				0	0	0	0	0	0	0			0	0	
623	217.51	612.37	28	3.686	0.620	0.996	217514				0	0	0	0	0	0	0			0	0	
625	242.36	614.04	30	3.708	0.635	0.994	242357				0	0	0	0	0	0	0			0	0	
627	268.34	615.70	32	3.729	0.647	0.993	268212			1	127	0	0	0	0	0	0			0	0	
629	295.43	617.32	34	3.750	0.656	0.992	295067			1	360	0	0	0	0	0	0			0	0	
631	323.56	618.89	36	3.770	0.664	0.991	322897			1	661	0	0	0	0	0	0			0	0	
633	352.67	620.43	38	3.789	0.669	0.991	351652			1	1018	0	0	0	0	0	0			0	0	
634	367.57	621.18	39	3.797	0.671	0.990	366356			1	1215	0	0	0	0	0	0			0	0	
636	412.84	623.31	41	3.813	0.690	0.987	395239			1	1642	0	0	0	0	0	0		1	15960	0	
638	471.03	625.78	43	3.825	0.716	0.981	423450		0.060	1	2109	0	0	0	0	0	0		1	45141	333	
640	538.35	628.33	45	3.833	0.741	0.974	450754		0.222	1	2614	0	0	319	0	0	0		1	82929	1730	
642	613.07	630.88	47	3.836	0.763	0.964	476857		0.346	1	3154	0	0	1658	0	0	0		1	127677	3723	
644	693.39	633.38	49	3.832	0.783	0.954	501492		0.441	1	3727	0	0	3567	0	0	0		1	178434	6167	
645	735.21	634.62	50	3.827	0.792	0.948	513109		0.481	1	4025	0	0	4688	0	0	0		1	205858	7535	
646	778.71	635.88	51	3.820	0.801	0.942	523986		0.518	1	4331	0	0	5908	933	0	0	0.156	1	234558	8991	
647	793.07	636.29	52	0.722	0.794	0.915	503564		0.513	1	4644	0	0	7218	2638	0	0	0.176	1	264480	10530	
648	825.36	637.20	53	0.706	0.796	0.913	499210		0.530	1	4964	0	0	8613	4847	0	0	0.229	1	295576	12149	0.018
649	865.31	638.32	54	0.703	0.802	0.906	500649		0.555	1	5291	0	0	10088	7462	0	170	0.288	1	327804	13843	0.110
650	905.81	639.45	55	0.699	0.808	0.896	500268		0.578	1	5625	0	239	11638	10428	0	881	0.341	1	361125	15608	0.189
652	990.56	641.82	57	0.692	0.821	0.875	497392		0.623	0.998	6301	0	1239	14952	17275	0	3141	0.434	1	430910	19346	0.321
654	1075.40	644.18	59	0.690	0.834	0.838	488121		0.661	0.986	6685	0	2667	18532	25184	0	6187	0.509	1	504688	23341	0.422
656	1159.47	646.51	61	0.690	0.844	0.790	472119		0.694	0.970	6859	0	4417	22360	34029	0	9852	0.568	1	582253	27579	0.500
657	1202.34	647.67	62	0.690	0.850	0.765	462807		0.708	0.961	6932	0	5397	24361	38774	0	11886	0.594	1	622400	29784	0.533
658	1246.68	648.85	63	0.690	0.855	0.739	452437		0.723	0.951	6995	0	6440	26419	43720	1947	14045	0.619	0.999	662631	32046	0.564
659	1291.66	650.00	64	0.690	0.859	0.713	442014		0.735	0.941	7055	445	7542	28532	48860	5506	16320	0.640	0.994	701026	34362	0.591
660	1339.15	651.16	65	0.690	0.864	0.690	432520		0.747	0.932	7108	2315	8701	30699	54188	10116	18706	0.660	0.987	738066	36731	0.616

Figure 4 – Calculations for Case 3, North Embankment Failure

6.4 Case 4, South Earth Embankment Fails

Figure 4 shows the spreadsheet calculations for the dam rating curve after the both the north and south embankments have failed. The north embankment will fail first because its overflow elevation is 5 feet below the overflow elevation of the south embankment. As for the pre-failure conditions, discharges are computed for headwaters ranging from 595 feet to 660 feet. Turbine discharge is not included because gross heads are below the minimum [4.18.5] for all headwaters. The final result, the rating curve, is defined by the first two columns, HW vs. Total Discharge. The third column (TW) gives the tailwater associated with the "Total Discharge" from the tailwater rating curve polynomial fit [4.19.1].

Spillway discharge in cfs is computed in the next five columns (under the header "Spillway"), H_c, $C_f|C_g$, d/H_c, $S_f|S_g$ and $Q_f|Q_g$. Free discharge occurs for headwater elevations 646.0 feet [4.4.4] and below. Orifice discharge occurs for headwaters above 646.0 feet. The transition point is indicated by a horizontal line. Above the line, the listed discharge coefficient is C_f [4.3.3], computed from Equation (A5), and the listed submergence factor is S_f [4.3.4], computed from Equation (A6). Below the line the listed discharge coefficient is C_g [4.4.5], computed by interpolation between the points in the table at the top of Attachment A14, and the listed submergence factor is S_g [4.4.6], computed by interpolation between the points in Table A3. Column $Q_f|Q_g$ is the spillway discharge computed from Equation 1 for free discharge and from Equation 3 for orifice discharge. Tailwater affects the spillway discharge for headwater elevations 615 feet and above ($d/H_c >= 0.6$). As for Cases 1 and 2, Figure 4 shows the final results of iterations for tailwater elevation but does not show the iteration steps.

The column following the spillway discharge column shows "C_g=", "G_n=", "C_f=", "Z_c=", and "L=" in five rows to indicate the meaning of the values included in those rows in the "Overflow Discharge" columns.

Trash gate discharge in cfs is computed in the next three columns. As for the spillway, a horizontal line indicates the transition from free discharge to orifice discharge. The orifice discharge is computed from Equation 4 using C_g, G_n, and L as listed above the discharge values and with $H_{mp} = G_n/2$. Equation 5 for S_f is used to approximate S_g as justified in Attachment 11 [4.6.6]. Tailwater affects the discharge for headwater elevations 642 feet and above ($d/H_c >= 0.6$).

The next eight columns compute overflow discharges in cfs for the spillway gates, spillway piers, auxiliary lock gate (uses three columns) and navigation locks (uses three columns). The overflow discharge coefficient C_f ([4.7.1], [4.8.1], [4.9.1], [4.10.1]), elevation Z_c ([4.7.2], [4.8.2], [4.9.2], [4.10.2]), and length L ([4.7.3], [4.8.3], [4.9.3], [4.10.3]) in each case is indicated in the three rows above the computed discharges. Tailwater affects the auxiliary lock gate discharge for headwater elevations 654 and above and the locks discharge for headwater elevations 659 feet and above. The submergence factor, S_f, is computed from Equation 5. All overflow discharges are computed using Equation 1 or Equation 2.

Discharge over the roller compacted concrete and sheet pile dam that controls flow on the north side of the dam after the north embankment fails is computed in the next seven columns. Three sections (north, center, and south) are defined, each with different overflow elevations. The overflow discharge coefficients C_f ([4.14.1], [4.15.1], [4.16.1]), elevations Z_c ([4.14.2], [4.15.2], [4.16.2]), and lengths L ([4.14.3], [4.15.3], [4.16.3]) are indicated in the three rows above the computed discharges. The center and south sections include columns for d/H_c and S_f because their discharges are affected by tailwater ($d/Hc > 0.6$) for headwater elevations above 649 feet and 652 feet, respectively. The submergence factors, S_f, are computed from Equation 5. All overflow discharges are computed using Equations 1 or 2.

Discharge over the failed south embankment is computed in the next three columns. Tailwater affects the discharge for HW greater than 621 feet ($d/Hc > 0.6$).

The last column is d/H_c for the north section of the roller compacted concrete and sheet pile dam, which has the lowest overflow crest elevation (648.5 feet) of those overflows shown as unaffected by tailwater submergence. The tailwater elevation exceeds 648.5 feet for headwaters 654 feet and above. Since $d/H_c <0.6$ [3.5, Equation 5] for all headwater elevations, the north section overflow discharge is not affected by tailwater. The overflow discharges with higher crest elevations have even lower values of d/H_c so they also are not affected by tailwater.

TVA

Calculation No. CDQ000020080014	Rev: 0	Plant: GEN	Page: 24
Subject: Initial Dam Rating Curves, Nickajack		Prepped	G. Schohl
		Checked	JCT

After North and South Embankment Failures

g = 32.2 ft/s^2

Spillway Parameters
L = 400 feet
Z_c = 595 feet
G_n = 42.755 feet
H_{mp} = 21.187 feet

Overflow Discharge, Q_f in cfs

			Spillway																												
									Trash Gate			Spill											Failed N. Emb. - Roller Compacted Concrete and Sheet Pile Dam									
												Gate	Spill										north			center			south			
	Total							C_g =			0.9133	Overflow	Piers	Aux. Lock Gate			Locks													Failed South Emb.			N.
								G_n =			13																					Emb.
	Discharge		feet				cfs	C_f =			3.0	3.15	2.65			2.9			2.87	2.65			3.14			3.33			2.65			north
								Z_c =			625	658.5	649			639			645	648.5			634			637			607			
HW	1000 cfs	TW	H_c	$C_f\|C_g$	d/H_c	$S_f\|S_g$	$Q_f\|Q_g$	L =	d/H_c	$S_f\|S_g$	15	400	90	d/H_c	S_f	110	d/H_c	S_f	325	181	d/H_c	S_f	1797	d/H_c	S_f	100	d/H_c	S_f	500	d/Hc
595	0.00	592.60	0			1	0				0	0	0			0			0	0			0			0			0	
597	3.61	593.02	2	3.191		1	3610				0	0	0			0			0	0			0			0			0	
599	10.46	593.80	4	3.268		1	10459				0	0	0			0			0	0			0			0			0	
601	19.60	594.83	6	3.334		1	19600				0	0	0			0			0	0			0			0			0	
603	30.68	596.04	8	3.390	0.130	1	30680				0	0	0			0			0	0			0			0			0	
605	43.48	597.40	10	3.437	0.240	1	43476				0	0	0			0			0	0			0			0			0	
607	57.83	598.88	12	3.478	0.324	1	57825				0	0	0			0			0	0			0			0		1	0	
609	77.35	600.82	14	3.513	0.416	1	73604				0	0	0			0			0	0			0			0		1	3748	
611	101.32	603.08	16	3.544	0.505	1	90716				0	0	0			0			0	0			0			0		1	10600	
613	128.56	605.49	18	3.571	0.583	1	109089				0	0	0			0			0	0			0			0		1	19473	
615	157.81	607.91	20	3.596	0.646	0.993	127825				0	0	0			0			0	0			0			0	0.114	1	29981	
617	189.20	610.34	22	3.620	0.697	0.986	147304				0	0	0			0			0	0			0			0	0.334	1	41900	
619	222.14	612.69	24	3.643	0.737	0.975	167057				0	0	0			0			0	0			0			0	0.474	1	55079	
621	256.47	614.95	26	3.665	0.767	0.963	187058				0	0	0			0			0	0			0			0	0.568	1	69408	
623	291.96	617.11	28	3.686	0.790	0.950	207492				0	0	0			0			0	0			0			0	0.632	0.996	84470	
625	328.06	619.14	30	3.708	0.805	0.939	228886				0	0	0			0			0	0			0			0	0.674	0.980	99174	
627	365.59	621.08	32	3.729	0.815	0.931	251281			1	127	0	0			0			0	0			0			0	0.704	0.963	114180	
629	404.94	622.95	34	3.750	0.822	0.924	274798			1	360	0	0			0			0	0			0			0	0.725	0.949	129778	
631	446.25	624.76	36	3.770	0.827	0.920	299507			1	661	0	0			0			0	0			0			0	0.740	0.938	146084	
633	489.63	626.52	38	3.789	0.829	0.917	325435		0.189	1	1018	0	0			0			0	0			0			0	0.751	0.929	163174	
634	512.12	627.37	39	3.797	0.830	0.916	338866		0.264	1	1215	0	0			0			0	0			0			0	0.755	0.925	172041	
636	568.53	629.39	41	3.813	0.839	0.906	362841		0.399	1	1642	0	0			0			0	0		1	15960			0	0.772	0.909	188086	
638	634.91	631.58	43	3.825	0.851	0.891	384548		0.506	1	2109	0	0			0			0	0		1	45141		1	333	0.793	0.887	202783	
640	708.36	633.83	45	3.833	0.863	0.874	404382		0.589	1	2614	0	0		1	319			0	0		1	82929		1	1730	0.813	0.861	216386	
642	787.01	636.11	47	3.836	0.875	0.854	422065		0.654	0.989	3120	0	0		1	1658			0	0	0.264	1	127677		1	3723	0.832	0.834	228763	
644	868.80	638.42	49	3.832	0.886	0.832	437260		0.706	0.962	3585	0	0		1	3567			0	0	0.442	1	178434	0.203	1	6167	0.849	0.804	239786	
645	910.33	639.58	50	3.827	0.892	0.820	443733		0.729	0.946	3808	0	0	0.097	1	4688			0	0	0.507	1	205858	0.323	1	7535	0.857	0.788	244706	
646	952.53	640.76	51	3.820	0.897	0.807	449097		0.750	0.929	4024	0	0	0.251	1	5908		1	933	0	0.563	1	234558	0.417	1	8991	0.866	0.772	249018	
647	965.73	641.12	52	0.722	0.887	0.744	409413		0.733	0.943	4380	0	0	0.266	1	7218		1	2638	0	0.548	1	264480	0.412	1	10530	0.853	0.797	267075	
648	1001.07	642.11	53	0.706	0.889	0.732	400270		0.744	0.935	4639	0	0	0.346	1	8613		1	4847	0	0.579	1	295576	0.465	1	12149	0.856	0.790	274972	
649	1039.98	643.19	54	0.703	0.892	0.715	394735		0.758	0.922	4880	0	0	0.419	1	10088		1	7462	170	0.613	1	327639	0.516	1	13843	0.862	0.780	281165	
650	1078.67	644.27	55	0.699	0.896	0.697	388702		0.771	0.910	5120	0	239	0.479	1	11638		1	10428	881	0.642	0.993	358718	0.559	1	15608	0.867	0.769	287333	
652	1155.63	646.40	57	0.692	0.902	0.660	375373		0.793	0.887	5600	0	1239	0.569	1	14952	0.200	1	17275	3141	0.689	0.972	419006	0.627	1	19295	0.876	0.749	299752	
654	1233.84	648.51	59	0.690	0.907	0.621	361701		0.811	0.865	5861	0	2667	0.634	0.996	18451	0.390	1	25184	6187	0.726	0.949	478825	0.677	0.979	22844	0.883	0.731	312120	0.002
656	1315.35	650.59	61	0.690	0.911	0.584	348988		0.825	0.844	5968	0	4417	0.682	0.976	21829	0.508	1	34029	9852	0.754	0.926	539086	0.715	0.956	26364	0.890	0.715	324813	0.279
657	1358.32	651.61	62	0.690	0.913	0.567	343179		0.831	0.834	6022	0	5397	0.700	0.966	23523	0.551	1	38774	11886	0.766	0.915	569759	0.730	0.945	28151	0.892	0.708	331631	0.366
658	1403.60	652.60	63	0.690	0.914	0.552	338022		0.836	0.826	6080	0	6440	0.716	0.956	25245	0.585	1	43720	14045	0.775	0.906	601088	0.743	0.935	29972	0.894	0.702	338987	0.432
659	1452.79	653.56	64	0.690	0.915	0.539	333815		0.840	0.820	6147	445	7542	0.728	0.947	27015	0.612	1.000	48842	16320	0.783	0.898	633571	0.753	0.927	31851	0.895	0.699	347247	0.482
660	1509.89	654.49	65	0.690	0.915	0.532	333200		0.842	0.816	6227	2315	8701	0.737	0.940	28848	0.632	0.996	53973	18706	0.788	0.892	667540	0.760	0.920	33805	0.896	0.697	356574	0.521

Figure 5 – Calculations for Case 4, South Embankment Failure

7. Results/Conclusions

For convenience, the initial dam rating results, separate from the calculation details provided above, are tabulated as total discharge in cfs vs. headwater elevation in feet in Figure 5. The initial dam rating curves (along with the tailwater rating curve) are plotted in Figure 6.

The initial dam rating curves developed in this calculation provide Nickajack total dam discharge vs. headwater elevation for use in TVA's SOCH and TRBROUTE models for simulation conditions satisfying the assumptions in [3.1], which apply specifically to the PMF. In particular, the spillway gates must all be fully raised. The Case 1 (pre-failure with turbine discharge) curve is used for both rising and falling headwaters until the headwater rises above 652.6 feet or the tailwater rises above 636 feet, at which time the turbines would be shut down, or until the north embankment is judged to fail, sometime after the headwater rises above its overflow elevation of 652 feet. If the turbines are shut down before the north embankment has failed, then the Case 2 (pre-failure without turbine discharge) curve is used for both rising and falling headwaters until the north embankment is judged to fail. Once the north embankment has failed, the Case 3 (north earth embankment fails) curve is used for both rising and falling headwaters until the south embankment is judged to fail, sometime after the headwater rises above its overflow elevation of 657 feet. After that the Case 4 (south earth embankment fails) curve is used for both rising and falling headwaters.

Case 1 Pre-Failure with Turbine Discharge		Case 2 Pre-Failure without Turbine Discharge		Case 3 Failed North Embankment		Case 4 Failed North and South Embankments	
HW feet	Total Discharge 1000 cfs	HW feet	Total Discharge 1000 cfs	HW feet	Total Discharge 1000 cfs	HW feet	Total Discharge 1000 cfs
595	0.00	595	0.00	595	0.00	595	0.00
597	3.61	597	3.61	597	3.61	597	3.61
599	10.46	599	10.46	599	10.46	599	10.46
601	19.60	601	19.60	601	19.60	601	19.60
603	30.68	603	30.68	603	30.68	603	30.68
605	43.48	605	43.48	605	43.48	605	43.48
607	57.83	607	57.83	607	57.83	607	57.83
609	73.60	609	73.60	609	73.60	609	77.35
611	90.72	611	90.72	611	90.72	611	101.32
613	109.09	613	109.09	613	109.09	613	128.56
615	128.67	615	128.67	615	128.67	615	157.81
617	149.42	617	149.42	617	149.42	617	189.20
619	171.32	619	171.32	619	171.32	619	222.14
621	193.70	621	193.70	621	193.70	621	256.47
623	217.51	623	217.51	623	217.51	623	291.96
625	242.36	625	242.36	625	242.36	625	328.06
627	268.34	627	268.34	627	268.34	627	365.59
629	295.43	629	295.43	629	295.43	629	404.94
631	355.77	631	323.56	631	323.56	631	446.25
633	384.87	633	352.67	633	352.67	633	489.63
634	399.79	634	367.57	634	367.57	634	512.12
636	430.28	636	397.99	636	412.84	636	568.53
638	461.51	638	429.12	638	471.03	638	634.91
640	493.58	640	461.06	640	538.35	640	708.36
642	526.89	642	494.22	642	613.07	642	787.01
644	560.69	644	527.87	644	693.39	644	868.80
645	577.62	645	544.72	645	735.21	645	910.33
646	595.35	646	562.38	646	778.71	646	952.53
647	592.28	647	559.89	647	793.07	647	965.73
648	593.85	648	561.16	648	825.36	648	1001.07
649	604.51	649	571.60	649	865.31	649	1039.98
650	615.60	650	582.51	650	905.81	650	1078.67
652	638.62	652	605.49	652	990.56	652	1155.63
654	646.30	654	646.30	654	1075.40	654	1233.84
656	701.19	656	701.19	656	1159.47	656	1315.35
657	731.87	657	731.87	657	1202.34	657	1358.32
658	766.35	658	766.35	658	1246.68	658	1403.60
659	804.54	659	804.54	659	1291.66	659	1452.79
660	846.05	660	846.05	660	1339.15	660	1509.89

Figure 6 – Initial Dam Rating Results for Cases 1, 2, 3, and 4

Nickajack Initial Dam Rating Curves

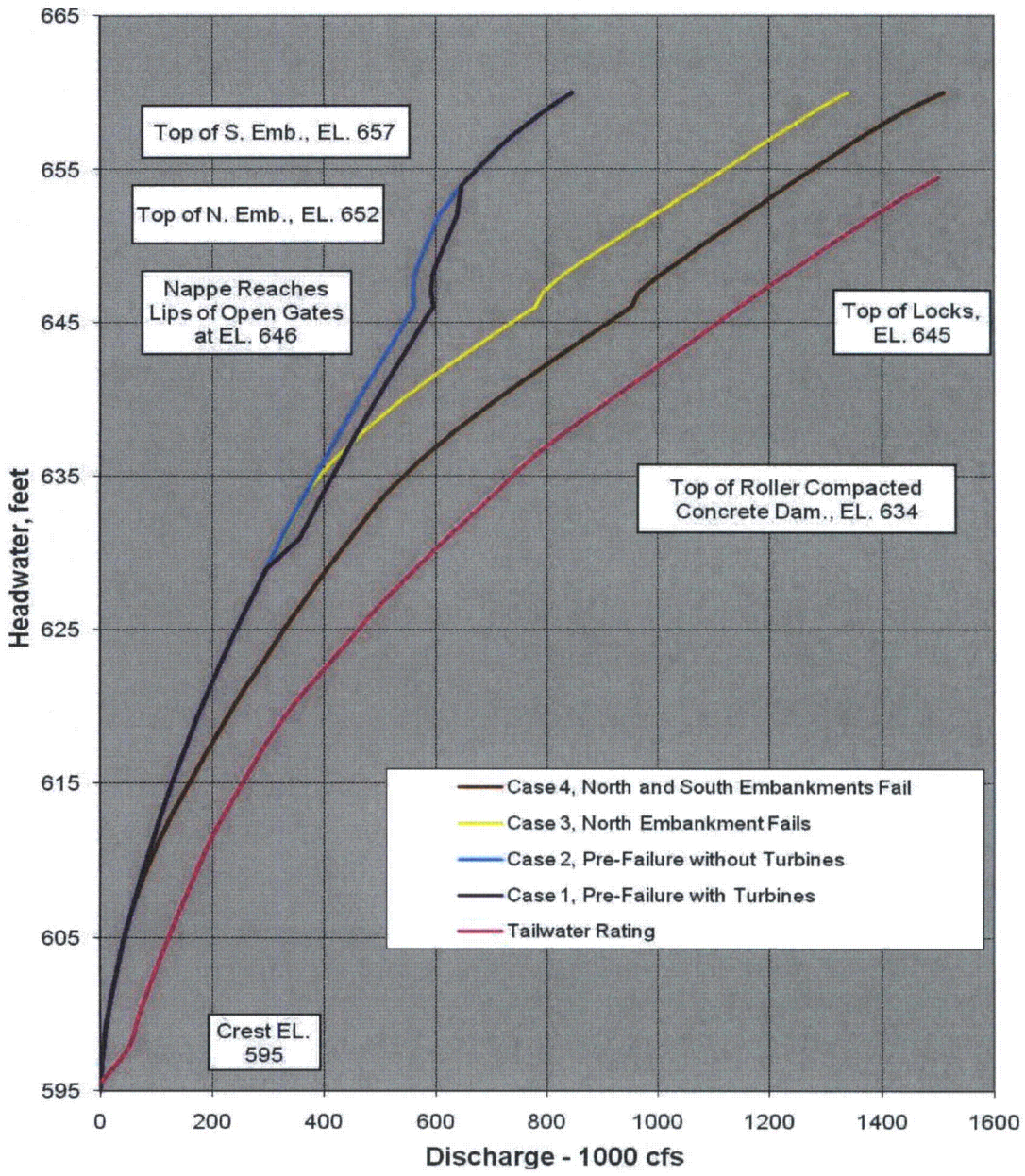


Figure 7 – Initial Dam Rating Curves for Cases 1, 2, 3, and 4

Appendix A: Spillway Discharge Coefficients and Submergence Factors for Nickajack Dam from 1:35 Scale Model Test Data

TVA has model test data describing the relationships between discharge, headwater, tailwater, and gate opening for most of its spillways. These data, which are the basis for the spillway discharge tables developed for each dam, are used in the dam rating curve calculations. Use of reference book discharge coefficients for standard crests would result in inferior results because TVA's spillway crests are not standard.

Nickajack dam has ten spillway bays, each controlled by a radial (tainter) gate as illustrated in Attachment A1. For dam rating curve calculations the gates are assumed to be open to their maximum opening position as specified in the Spillway Gate Arrangements table in Reference A1 and included as Attachment A2. As shown in this table, the maximum opening corresponds to reading "45.43" on the gate opening indicators for the spillway. Field measurements of V, the vertical distance between the bottom lip of a raised spillway gate and the spillway crest, are summarized in Attachment A3. For dial indicator reading "45.43" the average value of V is 42.4917 feet (average for all 10 gates).

Test data from a 1:35 scale model collected in 1967 are available (Attachment A18) for V = 42.4917 feet and for the other openings indicated in Attachment A3. However, the test data for V = 42.4917 feet are limited to free discharge over the crest because under normal operating conditions the overflowing nappe will never touch the bottom of a gate open this far. But under the PMF conditions considered for the dam rating curves the nappe will touch the gate in this position. Consequently, the data for gate openings V = 36.8717, 29.0486, 22.1753, and 16.4338 feet are used here to estimate gated flow discharge characteristics for V = 42.4917 feet.

A.1References

A1. "Nickajack Dam Spillway Discharge Tables," River Operations, Tennessee Valley Authority, 2000, RIMS No. L58 081211 806 (Attachment 21).
A2. TVA files, Binder "Nickajack Spillway Data, Miscellaneous Data, 1967.
A3. TVA files, Binder "Nickajack Spillway Rating, Basic Data, Vol. II of II, 1967.
A4. "Hydraulic Design Criteria," USACE (U. S. Army Engineer Waterways Experiment Station), Eighteenth issue, Vicksburg, MS, 1988.
A5. Open Channel Flow, F. M. Henderson, Macmillan, New York, 1966.
A6. TVA drawing no: 54N200, R1 (Attachments A6 and A20)
A7. TVA drawing no: 10W203, R5 (Attachments A7 and A21)

A.2 Discharge Equations

Attachment A4 is a definition sketch for flow over the Nickajack Dam spillway. Free discharge occurs for headwater elevations below the elevation at which the overflowing nappe first touches the bottom lip of the gate, or $H_c <= H_{Lmin}$, and is computed using a weir equation (e.g., Reference A4):

$$Q_f = C_f L H_c^{1.5} \qquad \text{(A1)}$$

in which Q_f = free discharge (cfs), C_f = free discharge coefficient (varies with H_c), L = length of overflowing section (ft), H_c = head on crest (ft) = HW - Z_c, HW = headwater elevation (ft), and Z_c = top, or crest, elevation of overflowing section (ft). This equation is modified to account for tailwater submergence as follows:

$$Q_{fs} = Q_f S_f \qquad \text{(A2)}$$

in which Q_{fs} = "corrected" free discharge (cfs), S_f = tailwater submergence factor (dimensionless -- varies with d / H_c), d = height of tailwater above crest (ft) = TW - Z_c, and TW = tailwater elevation (ft).

For headwater elevations above the elevation at which the nappe touches the gate lip, or $H_c > H_{Lmin}$, orifice flow occurs and is computed from (e.g., Reference A4)

$$Q_g = C_g G_n L \sqrt{2g(H_c - H_{mp})} \qquad \text{(A3)}$$

in which Q_g = orifice discharge (cfs), C_g = orifice discharge coefficient (dimensionless -- varies with gate opening and H_c), G_n = effective gate opening = minimum distance between the gate lip and the crest (ft), g = acceleration of gravity (32.2 ft/s^2 -- common knowledge, Reference A4, sheet. 000-1 for example), and H_{mp} = vertical distance between the mid-point of G_n and the crest. This equation is modified to account for tailwater submergence as follows:

$$Q_{gs} = S_g Q_g \qquad \text{(A4)}$$

in which in which Q_{gs} = "corrected" orifice discharge (cfs) and S_g = tailwater submergence factor (dimensionless -- varies with d / H_c and gate opening, V).

A.3 Model Test Data

The 1:35 scale model test data are used to determine

- $C_f(H_c)$ and $S_f(d/H_c)$
- H_{Lmin}, $C_g(H_c)$, and $S_g(d/H_c)$ for V = 42.4917 ft.

The relevant model test data copied from Reference A3 are included as Attachment A16. The sheets titled "Computation of Area, Velocity, Velocity Head, and Discharge for One bay" list model values H_1 (column 3, "H_1 Model ft.") and Q_m (column 7, "Q_m 3 bays cfs") for each test (column 1, "Test No.") and gate opening (found in title area, "Gate Opening Proto = 16.4338" for example). Model H_c is computed from these data by adding the upstream velocity head (column 9, "$V^2/2g$ ft.") to H_1. The upstream velocity is computed by dividing the model discharge by the upstream approach area, which is H_1 +.580 feet deep (column 4) times 4.082 feet wide (column 5, "Width Model ft.").

(Note that in the prototype H_c = HW - Z_c without a velocity head correction because HW represents the total energy level in the reservoir rather than the water level upstream from the spillway.)

The "corr. fact." in column 13 accounts for a slight discrepancy between the model crest length, L, and the prototype crest length. Included after test 631 in the data for V = 29.0486 feet, and after test 700 in the data for V = 36.8717 feet are tests labeled "Test Run" and "Test," respectively. These tests provide conditions for $H_c = H_{Lmin}$ as noted by the comment "Nappe touches bottom of gate" on the raw data sheets (also included in the attachment).

The sheets titled "Tailwater Heads" list model values of d (column 2, "Model") for each test (column 1, "Test No.") and gate opening (found in title area, "Proto G.O. = 16.4338" for example).

Model data are scaled to prototype values using the following scale ratios from Attachment A5:

- V_p/V_m, H_p/H_m, and $d_p/d_m = 35$
- $Q_p/Q_m = (35)^{2.5} = 7247.2$

in which H is "head" in feet and represents any water level difference (d or H_c, for example), the p-subscript denotes prototype, and the m-subscript denotes model.

A.4 Geometry

Parameters G_n, H_{mp}, Z_o (gate overflow elevation), and β (angle plotted against discharge coefficient in Attachment A15) are computed from crest and gate geometry as described in Attachment A6. Table A1 gives the values of these parameters for V = 16.4338, 22.1753, 29.0486, 36.8717, and 42.4917 feet.

Table A1: Geometrical Parameters for Relevant Gate Openings

V, feet	G_n, feet	H_{mp}, feet	Z_o, feet	β, deg.
16.4338	16.457	8.210	649.67	79.6
22.1753	22.184	11.085	652.91	88.4
29.0486	29.068	14.520	655.88	97.7
36.8717	36.969	18.414	657.96	107.4
42.4917	42.755	21.187	658.50	114.4

As an example, the procedure for computing the geometrical parameters for V = 42.4917 feet is given here. From Attachment A7,

- R = 41 feet
- Z_c = 595 feet
- Z_{tr} = 617.5 feet
- z_1 = 617.5 - 594.02 = 23.48 feet
- z_2 =635 - 617.5 = 17.5 feet

where the parameters are defined in Attachment A6-2. Referring to Attachment A6:

Angle θ: $$\theta = \sin^{-1}\left(\frac{23.48}{41}\right) + \sin^{-1}\left(\frac{17.5}{41}\right) = 60.2°$$

Angle α: $$\alpha = \tan^{-1}\left(\frac{617.5 - 595 - 42.4917}{\sqrt{41^2 - (617.5 - 595 - 42.4917)^2}}\right) = -29.183°$$

Overflow elevation Z_o: $$Z_o = 617.5 + 41\sin[60.2 - (-29.183)] = 658.5 \text{ feet}$$

Gate lip y-coordinate: $$y_\ell = 617.5 - 595 - 42.4917 = -19.9917 \text{ feet}$$

Gate lip x-coordinate: $$x_\ell = \sqrt{41^2 - (-19.9917)^2} = 35.7957 \text{ feet}$$

From Attachment A8:

$$y_s^* = f(x_s^*) = \frac{x_s^{*1.8}}{45.74} \quad \text{for } 0 \le x_s^* \le 16.48 \text{ feet}$$

in which $y_s^* = y_s - 22.5$ and $x_s^* = 41.8646 - x_s$. In terms of y_s and x_s:

$$y_s = f(x_s) = 22.5 + \frac{(41.8646 - x_s)^{1.8}}{45.74} \quad \text{for} \quad 25.3846 \le x_s \le 41.8646 \text{ feet}$$

and

$$\frac{dy_s}{dx_s} = -\frac{1.8(41.8646 - x_s)^{0.8}}{45.74}$$

To get effective gate opening, G_n, solve the following equation for x_{sn}:

$$x_{sn} - 35.7957 + \left[22.5 + \frac{(41.8646 - x_{sn})^{1.8}}{45.74} - (-19.9917)\right]\left[-\frac{1.8(41.8646 - x_{sn})^{0.8}}{45.74}\right] = 0$$

Solution:

- x_{sn} = 39.3273 feet (by iteration)
- $y_{sn} = 22.5+(41.8646 - 39.3273)^{1.8}/45.74 = 22.6168$
- $G_n = \sqrt{(39.3273 - 35.7957)^2 + (22.6168 - (-19.9917))^2} = 42.755$ feet

and

- $H_{mp} = 42.4917-[22.6168 - (-19.9917)]/2 = 21.187$ feet
- $\beta = \frac{\pi}{2} - \tan^{-1}\left(\frac{-19.9917}{35.7957}\right) - \tan^{-1}\left(\frac{39.3273 - 35.7957}{22.6168 - (-19.9917)}\right) = 90 - (-29.18) - 4.74 = 114.44°$

A.5 Determination of $H_{Lmin}(V)$

The model data do not provide values of H_{Lmin} for all tested gate openings because under normal operation (normal headwater range) the headwater is well above the gate lips for openings V = 22.5713 feet and lower and is below the gate lip for opening V = 42.4917 feet. From data:

- H_{Lmin} = 34.44 feet for V = 29.0486 feet (test "Test Run" following test "631," Attachments A18-10 and A18-11)
- H_{Lmin} = 44.28 feet for V = 36.8717 feet (test "Test" following test "700," Attachments A18-15 and A18-18)
- H_{Lmin} >= 51.0 feet for V = 42.4917 feet (Attachment A18-20)

All data collected for V = 42.4917 feet were for free discharge. Since the largest value of H_c in that data is 51.0 feet (Test 752, Attachment A18-20), H_{Lmin} must be greater than or equal to 51 feet. Note that H_{Lmin}/V = 1.19 for V = 29.0486 feet and 1.20 for V = 44.28 feet. If H_{Lmin}/V =1.2 for V = 42.4917 feet then

- H_{Lmin} = 51.0 feet for V = 42.4917 feet.

This value is used in the dam rating curve calculations.

A.6 Determination of $C_f(H_c)$ and $S_f(d/H_c)$

Attachments A9 through A11 show the calculations and results for determining $C_f(H_c)$ and $S_f(d/H_c)$ from the model data (spreadsheet included as Attachment A19). The first four columns in Attachment A9 are filled with data taken directly from the model data sheets (Attachments A18-9, -10, -12, and -13 for Test No. range 603 to 631; Attachments A18-14 through A18-17 for Test No. range 657 to 700 and 768 to 778; Attachments A18-19 through A18-21 for Test No. range 701 to 767). Only model data for gate openings V = 36.8717 feet and V = 42.4917 feet are used. For V = 36.8717 feet, only data with Hc < 44.28 feet

(H_{Lmin}) were used. Subscript "m" is added to the symbols representing the variables to denote model values. The next three columns in Attachment A9 convert the model data to prototype values with subscript "p" added to the symbols to denote prototype. The equations used for the conversion are shown at the bottom of Attachment A9-2, using the symbols defined at the top of Attachment A9-1. The eighth and ninth columns compute the submergence ratio d/H_c and the quantity C_fS_f from the prototype values in the previous three columns. C_fS_f is equivalent to C_f for data unaffected by submergence ($S_f = 1$). The final two columns are computed after the free discharge coefficient relationship $C_f(H_c)$ is established.

The data are sorted in ascending order of d/H_c which leaves the free discharges unaffected by tailwater at the top of the list, above the horizontal line in Attachment A9-1. Attachment A10 includes a plot of C_fS_f vs. H_c for all values of d/H_c. The highest values of C_fS_f on that plot, those for which $d/H_c < 0.6$, are the values unaffected by submergence. A polynomial is fit to those points and plotted in Attachment A10. The C_fS_f values affected by submergence, those for which $d/H_c>0.6$, lie below the polynomial curve.

The $C_f(H_c)$ polynomial given in Attachment A10 is used for the dam rating calculations:

$$C_f = 3.1 + 0.04932H_c - 0.001977H_c^2 + 4.559\text{x}10^{-5}H_c^3 - 3.992\text{x}10^{-7}H_c^4 \qquad \text{(A5)}$$

This polynomial is fit with the condition that $C_f = 3.1$ at $H_c = 0$, which is the expected value as illustrated in Attachment A11. For $H_c < 30$ feet, the polynomial gives estimated values of C_f that fall on a reasonable curve between the model test data and the value of 3.1 at $H_c = 0$. Because it is unlikely that they would differ from the true values by more than 0.1, the estimated C_f values should be within about 3 percent of the true values.

Column ten in Attachment A9 is C_f computed from Equation (A5) and column eleven is S_f computed by dividing C_fS_f by C_f. Attachment A12 shows the results of plotting S_f vs d/H_c. The following equation was fit to the model data points for $d/H_c > 0.6$:

$$S_f = \left[1 - \left(\frac{d}{H_c}\right)^{10}\right]^{0.52} \quad \text{for } d/H_c > 0.6 \qquad \text{(A6)}$$

with $S_f = 1.0$ for $d/H_c <= 0.6$. This equation is used for the dam rating calculations.

A.7 Determination of $C_g(H_c)$ and $S_g(d/H_c)$

Attachments A13 through A17 show the calculations and results for determining $C_g(H_c)$ and $S_g(d/H_c)$ for various gate openings from the model data. The first column in Attachment A13, "Order No." is included for calculation convenience. The next five columns are filled with data taken directly from the model data sheets. Subscript "m" is added to the symbols representing the variables to denote model values. Similarly, subscript "p" is used to denote prototype values. Model data for $V_p = 16.4338$ (Attachments A18-1 through A18-3), 22.1753 (Attachments A18-4 through A18-6), 29.0486 (Attachments A18-7 through A18-13), and 36.8717 feet (Attachments A18-14 through A18-18) are included in Attachment A13 minus the data used above to determine free discharge characteristics. The next three columns after the model data list prototype geometrical parameters taken from Table A1. Then follow four columns in which model data are converted to prototype values and a geometrical ratio is defined. The equations used are shown at the bottom of Attachment A13-6, using the symbols defined at the top of Attachment A13-1. The first two columns following the "Prototype Values" compute the submergence ratio d/H_c and the quantity C_gS_g from the prototype values. The column labeled "C_gS_g" is computed from Equations (A3) and (A4):

$$C_gS_g = \frac{Q_{gs}}{G_n L\sqrt{2g(H_c - H_{mp})}} \qquad \text{(A7)}$$

where the "p" subscript used on Attachment A13 has been dropped. The final two columns are computed after the unsubmerged gate discharge coefficient relationship $C_g(H_c)$ is established for each gate opening.

In Attachment A13, data lines are added for V = 29.0486, 36.8717, and 42.4917 feet to compute C_g for $H_{cp} = H_{Lmin}$. The discharges (Q_{gsp}) included for these cases is the free discharge computed from Equation (A1) using $C_f(H_c)$ from Equation (A5).

To establish the unsubmerged $C_g(H_c)$ for each gate opening, the data were first sorted in ascending order of V and then in ascending order of d/H_c which left the discharges unaffected by tailwater at the top of the data for each gate opening. Plots of C_gS_g vs. H_c for all values of d/H_c at each gate opening (similar to plot in Attachment A10 for free discharge) indicated negligible tailwater effects for d/H_c less than the values listed in Table A2.

Table A2: Maximum Value of d / H_c without Tailwater Effects

V, feet	d/H_c maximum without tailwater effect
16.4338	0.505
22.1753	0.560
29.0486	0.590
36.8717	0.595

Attachment A14 shows the data for unsubmerged $C_g(H_c)$ for each gate opening with simple, line-segment fits through each set of data. An extrapolated line-segment fit for V = 42.4917 feet is added, passing through the C_g point computed for $H_c = H_{Lmin}$ and having a shape similar to the fit for V = 36.8717 feet. The points defining the line segments are given at the top of Attachment A14.

The extrapolated line segment fit for $C_g(H_c)$ at V = 42.4917 feet is used for the dam rating calculations as a reasonable approximation given the absence of model data. Because it is unlikely that they would differ from the true values by more than 0.02, the estimated C_g values should be within about 3 percent of the true values. As further justification, Attachment A15 shows the Nickajack C_g values at large H_c plotted against angle β on a hydraulic design chart (Reference A4) showing U.S. Army Corps of Engineers data for tainter gates on standard crests. The value of X/H_d for Nickajack is between 0.15 and 0.25 (X = 8.25 feet, Attachment A6), depending on how H_d is defined. Because TVA's spillway crests are not standard, TVA data always lie to the left of the suggested design curves on this chart. Note that $C_g = 0.69$ for V = 42.4917 feet (β = 114.4 degrees) is a very reasonable extrapolation of the Nickajack data curve and appears reasonable compared with the suggested design curves on the chart.

The second to last column in Attachment A13 is C_g computed from the line-segment fits for each valve opening in Attachment A14 and the last column is S_g computed by dividing C_gS_g by C_g. Attachment A16 shows the data sorted in ascending order of the ratio H_c/G_n. Attachment A17 shows the results of plotting S_g vs d/H_c for various ranges of H_c/G_n (data for all four gate openings are included). Curve fits developed for H_c/G_n = 1.2, 1.35, 1.5, 1.7, 2.0, and 2.3 are also indicated on Attachment A17. The coordinates defining the curve fits are given in Table A3.

The curve fits in Attachment A17 giving $S_g(d/H_c)$ for various values of H_c/G_n are used for V = 42.4917 feet in the dam rating calculations. Linear interpolation between points and between the curves is used for in-between values of d/H_c and H_c/G_n.

Table A3: Points Defining Curves Through Nickajack S_g data (Attachment A17).

H_c/G_n =	1.20		H_c/G_n =	1.35		H_c/G_n =	1.50
d / H_c	S_g		d / H_c	S_g		d / H_c	S_g
0.000	1.000		0.000	1.000		0.000	1.000
0.595	1.000		0.595	1.000		0.560	1.000
0.650	0.993		0.650	0.990		0.610	0.997
0.700	0.982		0.700	0.978		0.650	0.990
0.750	0.955		0.750	0.955		0.700	0.975
0.800	0.910		0.800	0.910		0.750	0.945
0.850	0.830		0.830	0.860		0.775	0.920
0.875	0.780		0.875	0.750		0.800	0.870
0.900	0.715		0.900	0.660		0.840	0.770
0.925	0.650		0.925	0.570		0.870	0.680
0.937	0.600		0.940	0.510		0.900	0.590
0.950	0.530		0.960	0.400		0.960	0.380
0.965	0.400						
H_c/G_n =	1.70		H_c/G_n =	2.00		H_c/G_n =	2.30
d / H_c	S_g		d / H_c	S_g		d / H_c	S_g
0.000	1.000		0.000	1.000		0.000	1.000
0.590	1.000		0.560	1.000		0.560	1.000
0.650	0.990		0.600	0.987		0.600	0.983
0.700	0.965		0.660	0.963		0.650	0.910
0.725	0.945		0.680	0.930		0.700	0.810
0.750	0.900		0.700	0.890		0.750	0.720
0.775	0.840		0.750	0.780		0.800	0.630
0.800	0.775		0.800	0.700		0.920	0.400
0.850	0.655		0.830	0.640			
0.900	0.530		0.885	0.520			
0.930	0.440		0.930	0.400			

Appendix B: Hydrostatic Loads on the Spillway Tainter Gates

The hydrostatic loads on the spillway tainter gates for Nickajack Dam can be found in the following calculations.

B1 References

B1. "Watts Bar Dam – Flood and Earthquake Analysis on Radial Spillway Gates, pages 76-100" Tennessee Valley Authority, HEPE3WBHSQN-WBNBLNBFN.

B2. Calculations

Reference B1 evaluates the structural capacity of the radial spillway gates at Watts Bar Dam. This reference was used as a basis for evaluating the margin between the forces on the closed gates (FR_{closed}) when the headwater elevation is at the top of the gate (635 feet) and when the gates are completely open (FR_{open}) and the headwater elevation is at 660 feet at Nickajack Dam. The margin is defined as the ration of FR_{open} to FR_{closed}. The calculation of these forces and the results of this comparison are shown in Figure B1.

Comparison of forces when gates are closed and HW is at 635 feet (top of gate) vs. when gates are fully open and HW at an elevation of 660 feet.

Attribute	Symbol	Value	Unit
top elev	Zo	635	ft
trun elev	Ztr	617.5	ft
sill elev	Zsill	594.02	ft
radius	R	41	ft
length	L	40	ft
angle up	α2	25.27	deg
angle lwr	α	34.94	deg
angle tot	θ	60.20	deg
area of lower slice	Aslice1	883.16	ft^2
proj area	AProjected	1639.20	ft^2
Desgn LdH	FRx	2095841.78	lbs
Result elv	Z1	607.68	ft
Result ang deg		13.86	deg
Result ang rad		0.24	rad
Result Dsgn	Horiz	2034838.86	lbs
Area slice upper	Aslice2	370.65	ft^2
Area triangle	Atriangle	324.43	ft^2
project vert	x1	3.92	ft
vert weight water	FRy	55970.33	lbs
Resultant load - Gates Closed	FR_{closed}	**2096589.00**	lbs
vert open fm calc	calc App A	42.49	ft
max hw	calc	660.00	ft
lwr lip elev	Z2	636.51	ft
bot angle	α3	27.62	deg
top elev	Zo	658.47	ft
project area for h ld	AProjected	878.42	ft^2
Flood LdH	FRx	685702.14	lbs
Height over gate	y1	1.53	ft
Height ratio to orig		1.61	(ratio)
project vert	x2	34.77	ft
Flood LdV1		132745.35	lbs
Flood lLdV2		569170.14	lbs
Total Flood LdV	FRy	701915.49	lbs
Resultant load - Gates Fully Open	FR_{open}	**981260.82**	lbs
Margin	FR_{open}/FR_{closed}	**0.47**	(ratio)

Figure B1: Nickajack Spillway Gate Margin Evaluation

BWSC BARGE WAGGONER SUMNER & CANNON, INC.

Project: Hydrostatic Force on Gate
Description: Diagram
Project No. _____ Sheet No. _____ of _____
Designer: _____ Date: _____
Checker: _____ Date: _____

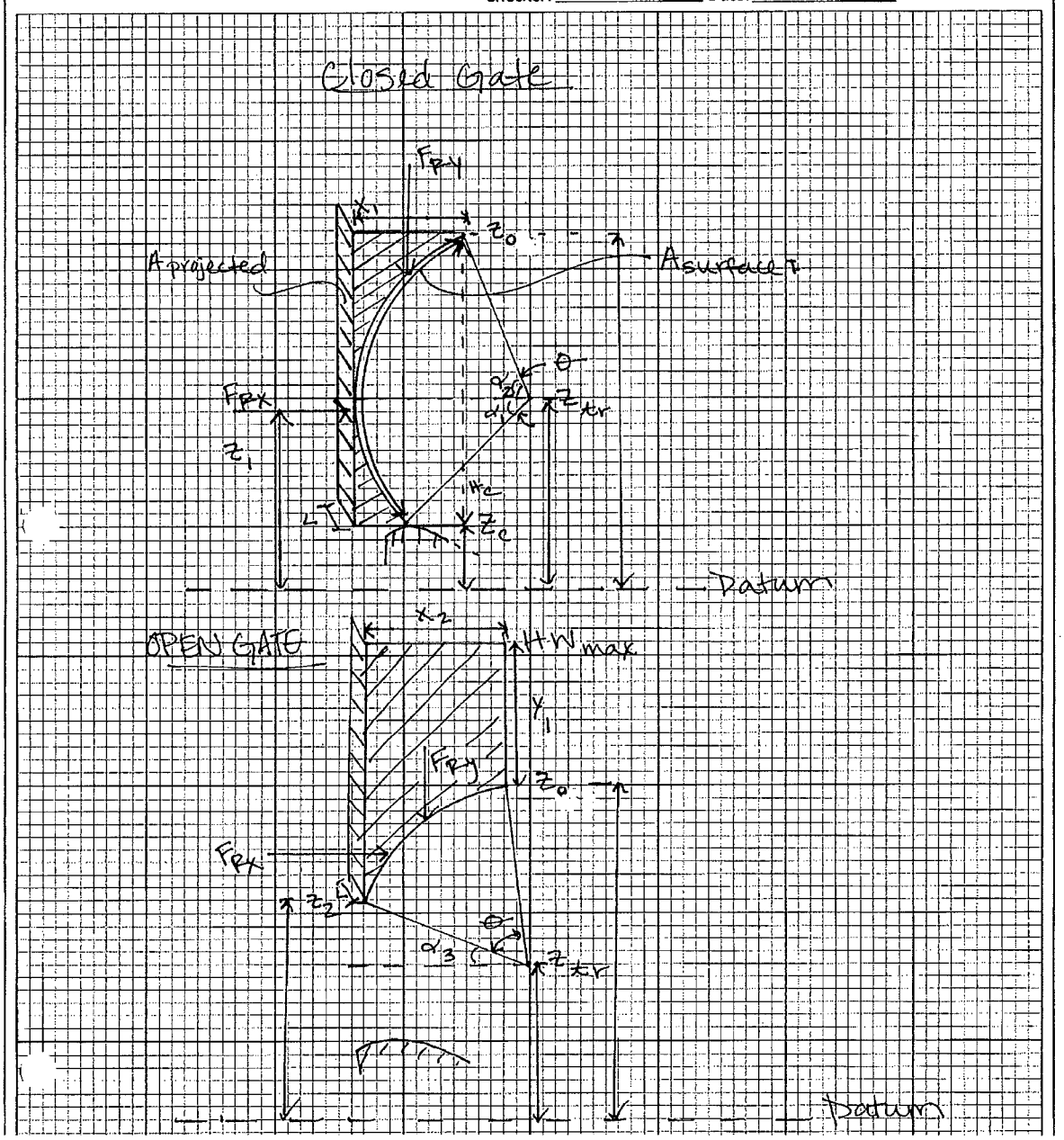
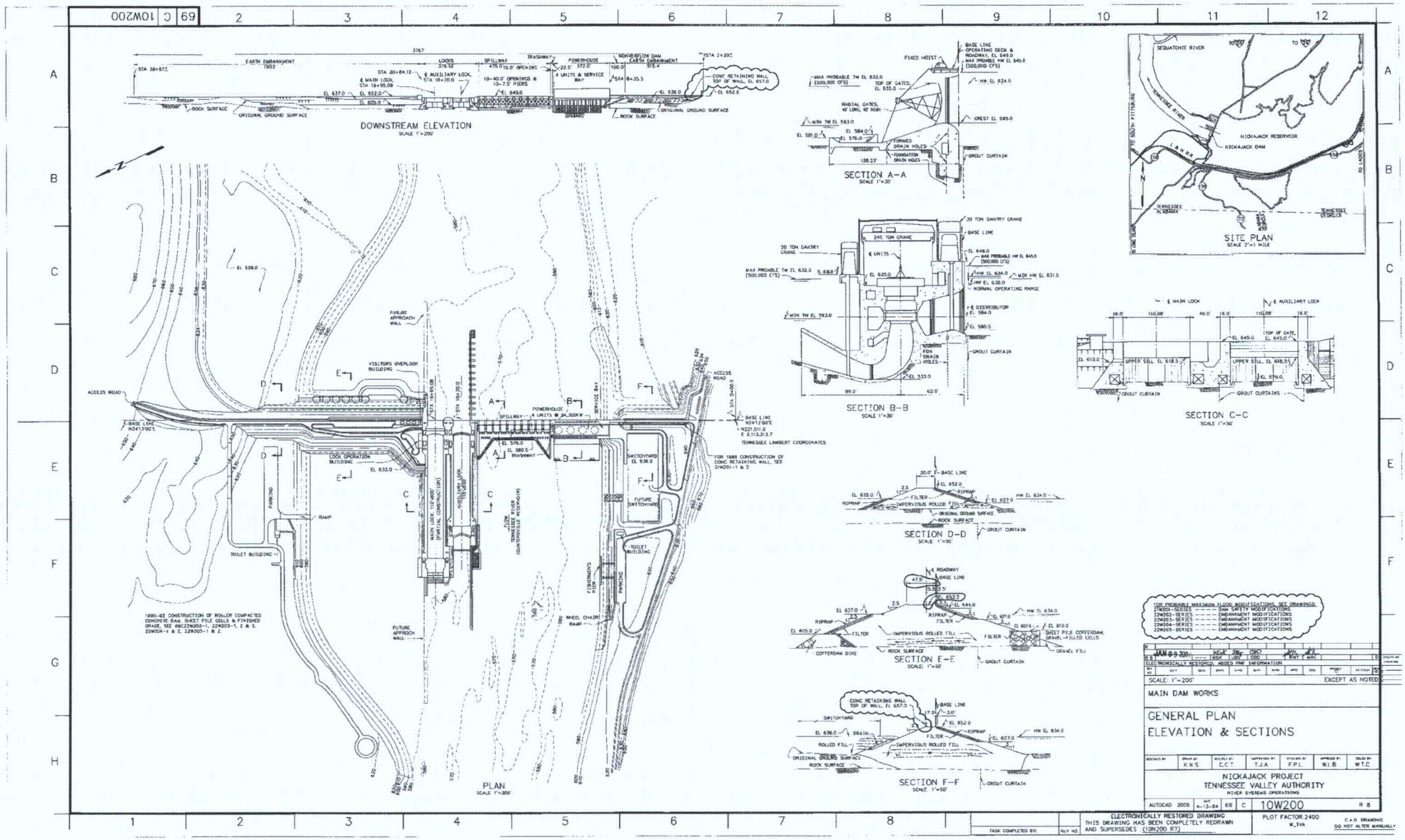


Figure B2: Diagram of Hydrostatic Forces

Attachment 1

Source: Reference 1

Calculation No: CDQ000020080014



Attachment 2

Source: Reference 3

Calculation No: CDQ000020080014

NICKAJACK DAM

December 1999

SAFETY MODIFICATIONS FOR PROBABLE MAXIMUM FLOOD

Chronology

Safety analysis studies for Nickajack Dam for the Probable Maximum Flood(PMF)were started in August 1988 and completed in December 1990. Final design started in April 1989. Onsite construction began in 1990 and was completed on June 30, 1992.

Cost of Modification

Design costs for the capital safety modifications to Nickajack Dam were approximately $1.15 million. This did not include costs for dam safety evaluation studies, which resulted in the modifications. Construction costs were approximately $10.35 million. The total project cost was approximately $11.5 million.

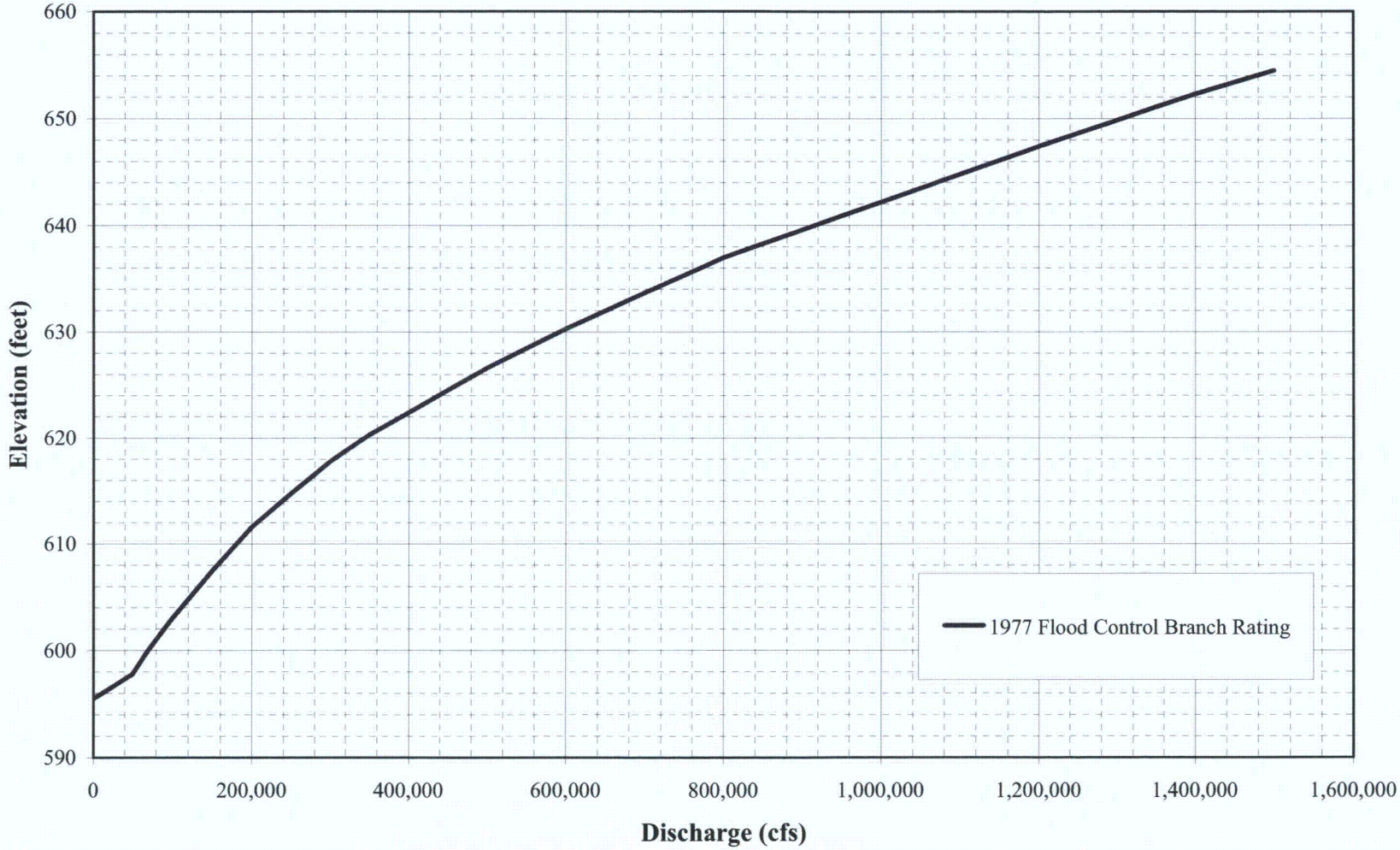
Controlling Features

The south embankment was raised five feet with a concrete wall/earthfill combination. Approximately 1,400 lineal feet of roller compacted concrete (RCC) overflow dam was added below the north embankment at an elevation of 634. An overflow dam consisting of approximately 678 feet of cofferdams was added at the end of the roller compacted concrete. Four hundred thirty-six feet of these cofferdams are at elevation 634 and two hundred forty-two feet of these cofferdams vary from an elevation of 634 to 656. These PMF modifications will prevent overtopping and erosion of the south embankment and maintain the normal pool elevation on the north embankment.

Attachment 4

Calculation No: CDQ000020080014

Nickajack Steady-State Tailwater Rating



Source: TVA River Operations
Flood Risk Section

Nickajack Rating Curves.xls

Book # 107-96.01

Attachment 5

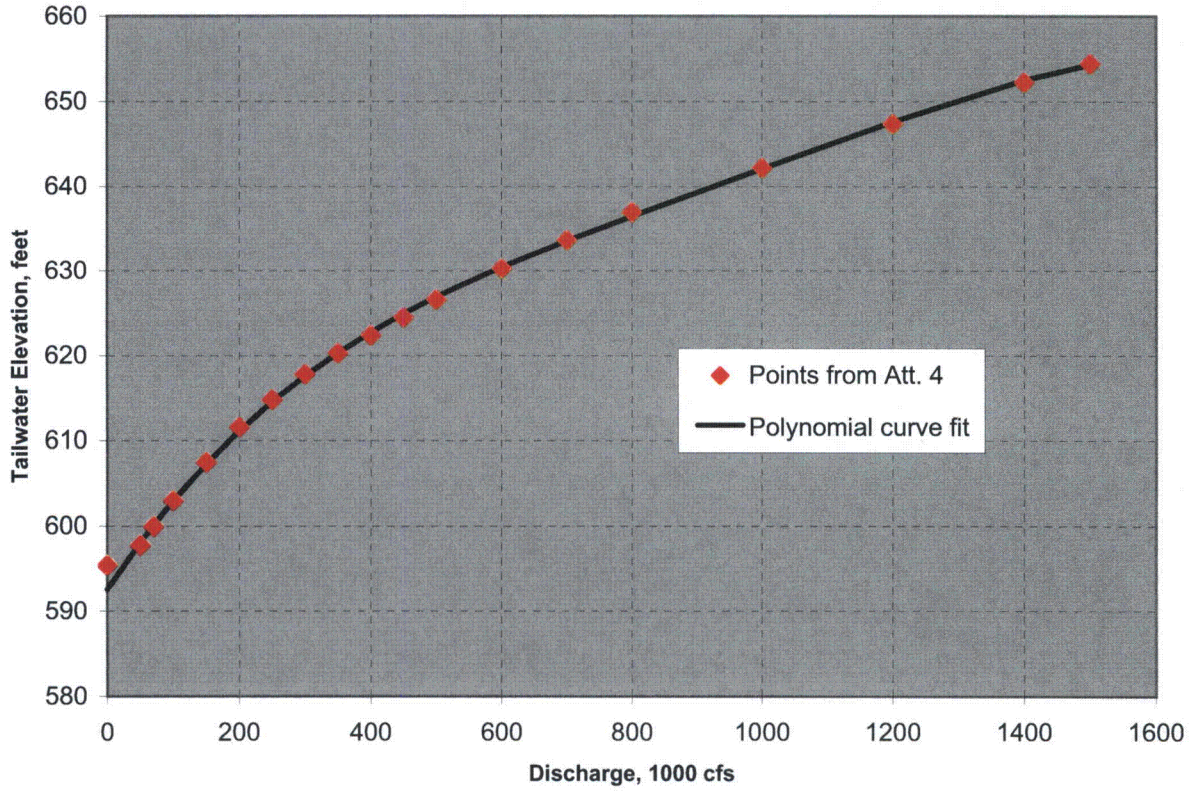
Calculation No: CDQ000020080014

TW-Q points from Attachment 4

Discharge 1000 cfs	TW	TW from polynomial fit
0	595.5	592.6
50	597.8	598.1
70	600.0	600.1
100	603.0	603.0
150	607.5	607.3
200	611.6	611.1
250	614.8	614.5
300	617.8	617.6
350	620.3	620.3
400	622.4	622.7
450	624.5	624.9
500	626.6	626.9
600	630.3	630.5
700	633.7	633.6
800	637.0	636.5
1000	642.2	642.1
1200	647.4	647.6
1400	652.3	652.5
1500	654.5	654.3

Polynomial Curve Fit: $TW = 592.6 + 0.1162Q - 1.353\times10^{-4}Q^2 + 9.204\times10^{-8}Q^3 - 2.346\times10^{-11}Q^4$

where TW = tailwater elevation in feet and Q = discharge in 1000 cfs

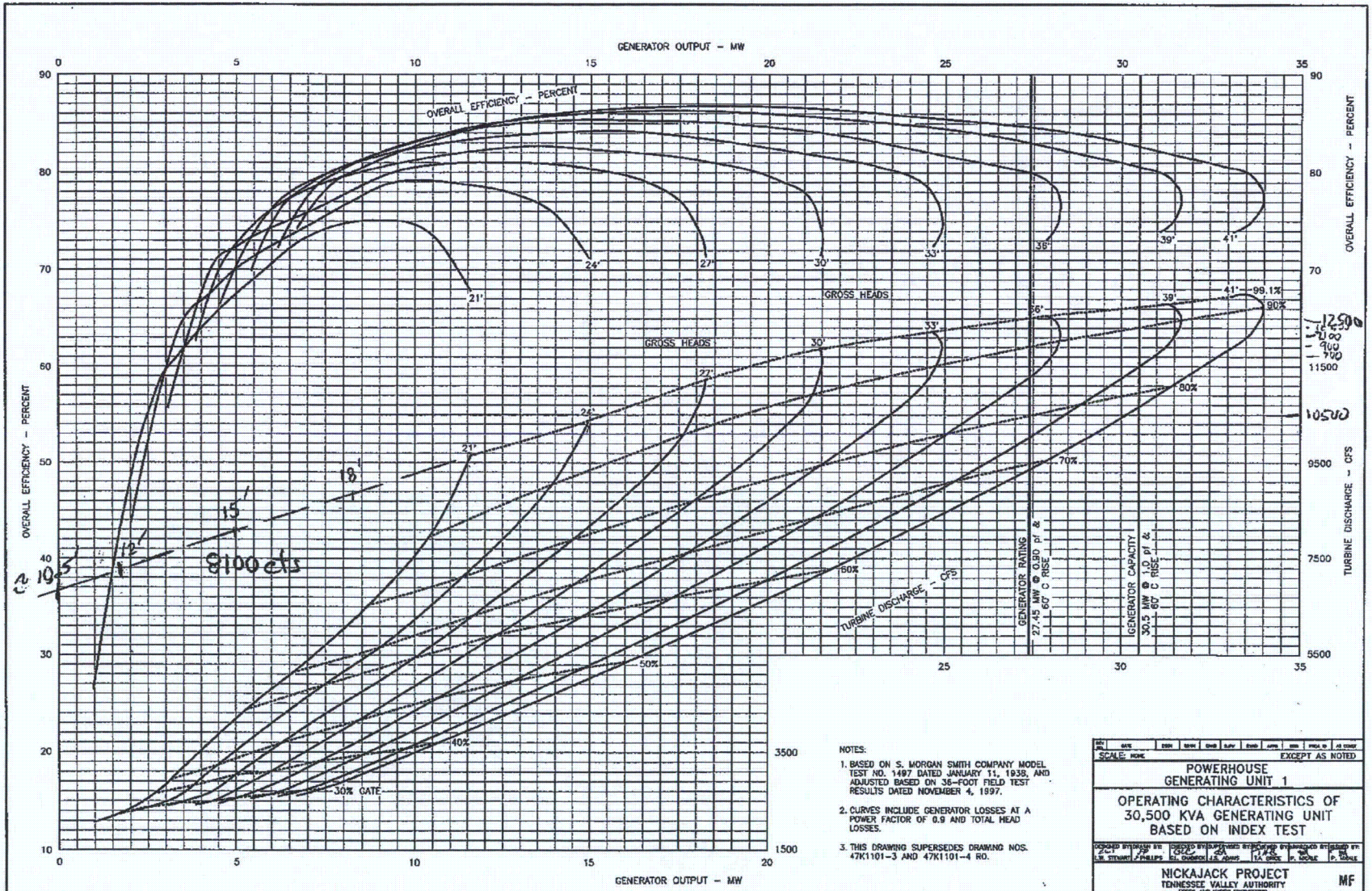


from: Nickajack Rating Curves.xls, TW

Attachment 6-1

Source: Reference 26

Calculation No: CDQ000020080014



NOTES:

1. BASED ON S. MORGAN SMITH COMPANY MODEL TEST NO. 1497 DATED JANUARY 11, 1938, AND ADJUSTED BASED ON 36-FOOT FIELD TEST RESULTS DATED NOVEMBER 4, 1997.
2. CURVES INCLUDE GENERATOR LOSSES AT A POWER FACTOR OF 0.9 AND TOTAL HEAD LOSSES.
3. THIS DRAWING SUPERSEDES DRAWING NOS. 47K1101-3 AND 47K1101-4 R0.

SCALE: NONE — EXCEPT AS NOTED

POWERHOUSE
GENERATING UNIT 1

OPERATING CHARACTERISTICS OF
30,500 KVA GENERATING UNIT
BASED ON INDEX TEST

DESIGNED BY: L.W. STEWART — DRAWN BY: J.P. PHILLIPS — CHECKED BY: G.L. CHADICK — CHECKED BY: J.S. ADAMS — DRAWN BY: T.A. GREER — ENGINEERED BY: P. MOULE — ISSUED BY: P. MOULE

NICKAJACK PROJECT
TENNESSEE VALLEY AUTHORITY
FORGE AND HYDRO ENGINEERING

MF

AUTOCAD R12 — DATE 12/15/00 — 69 M — 47K1102-1 R0

CAD SYSTEM DRAWING
DO NOT ALTER MANUALLY

DRAWING PLOT FACTOR: 1=1
INSERTED DRAWING X=1,Y=1.34

ISSUED BY:

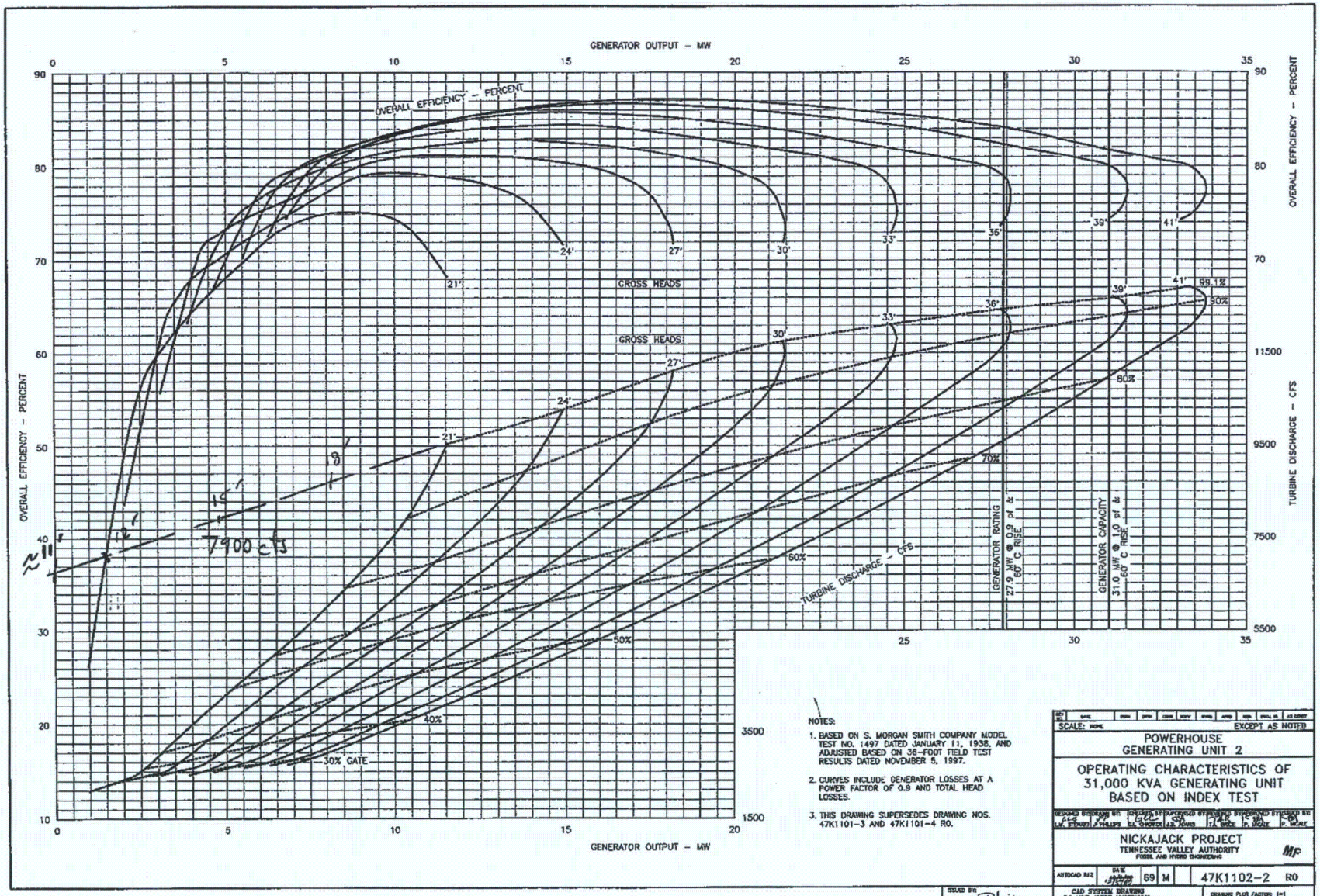
69 M 47K1102-1

Attachment 6-2

Source: Reference 27

Calculation No: CDQ000020080014

69 | M | 47K1102-2



NOTES:

1. BASED ON S. MORGAN SMITH COMPANY MODEL TEST NO. 1497 DATED JANUARY 11, 1938, AND ADJUSTED BASED ON 36-FOOT FIELD TEST RESULTS DATED NOVEMBER 5, 1997.
2. CURVES INCLUDE GENERATOR LOSSES AT A POWER FACTOR OF 0.9 AND TOTAL HEAD LOSSES.
3. THIS DRAWING SUPERSEDES DRAWING NOS. 47K1101-3 AND 47K1101-4 R0.

SCALE: NONE — EXCEPT AS NOTED

POWERHOUSE
GENERATING UNIT 2

OPERATING CHARACTERISTICS OF
31,000 KVA GENERATING UNIT
BASED ON INDEX TEST

NICKAJACK PROJECT
TENNESSEE VALLEY AUTHORITY
FOSSIL AND HYDRO ENGINEERING

AUTOCAD R12 | DATE | 69 | M | 47K1102-2 | R0

CAD SYSTEM DRAWING
DO NOT ALTER MANUALLY

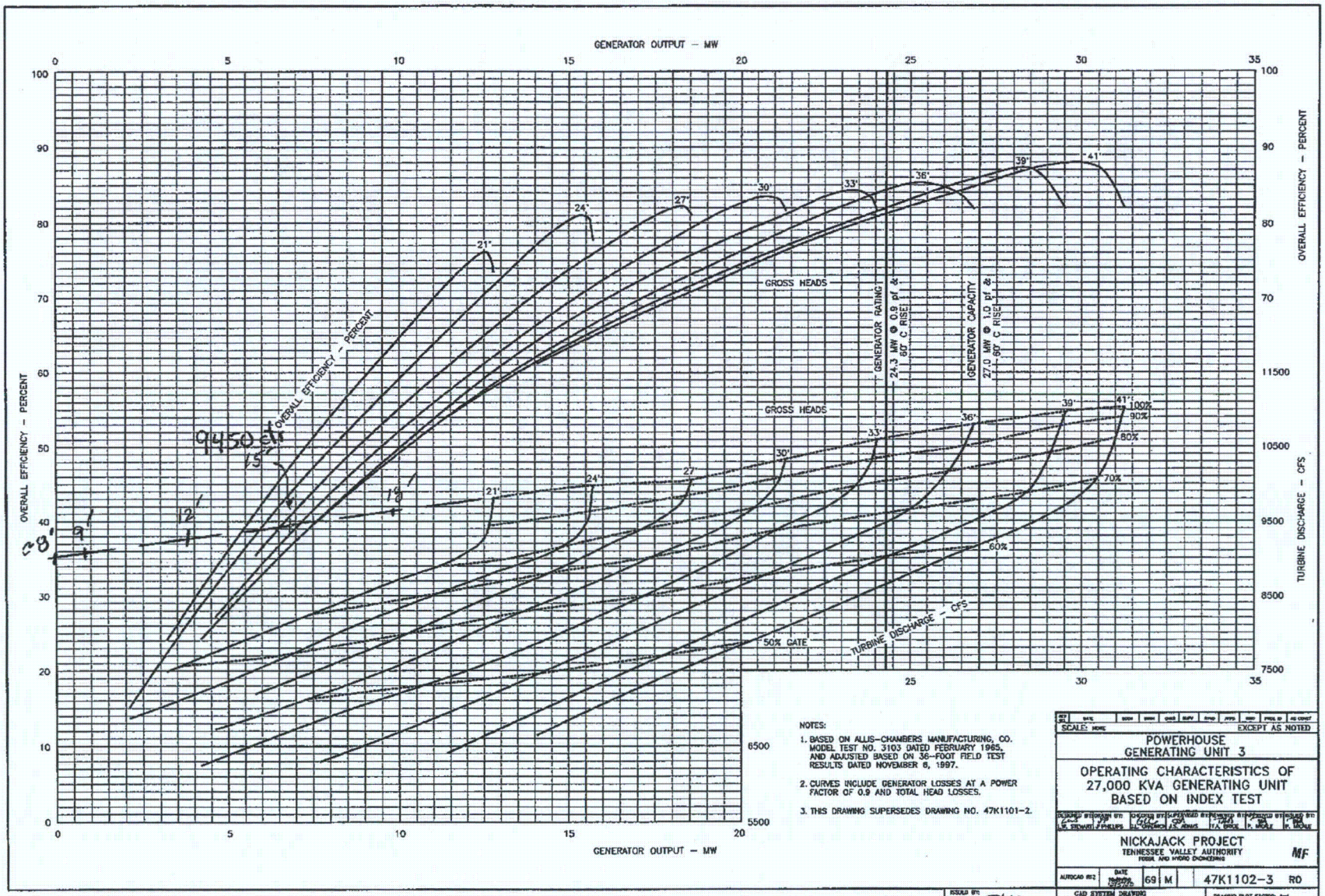
DRAWING PLOT FACTOR 1=1
REDUCED DRAWING 2=1.1=4.08

Attachment 6-3

Source: Reference 28

Calculation No: CDQ000020080014

47K1102-3 | M | 69



NOTES:

1. BASED ON ALLIS-CHAMBERS MANUFACTURING, CO. MODEL TEST NO. 3103 DATED FEBRUARY 1965, AND ADJUSTED BASED ON 36-FOOT FIELD TEST RESULTS DATED NOVEMBER 6, 1997.
2. CURVES INCLUDE GENERATOR LOSSES AT A POWER FACTOR OF 0.9 AND TOTAL HEAD LOSSES.
3. THIS DRAWING SUPERSEDES DRAWING NO. 47K1101-2.

SCALE: NONE — EXCEPT AS NOTED

POWERHOUSE
GENERATING UNIT 3

OPERATING CHARACTERISTICS OF
27,000 KVA GENERATING UNIT
BASED ON INDEX TEST

NICKAJACK PROJECT
TENNESSEE VALLEY AUTHORITY
FOSSIL AND HYDRO ENGINEERING

MF

AUTOCAD R12 | DATE | 69 | M | 47K1102-3 | R0

CAD SYSTEM DRAWING
DO NOT ALTER MANUALLY

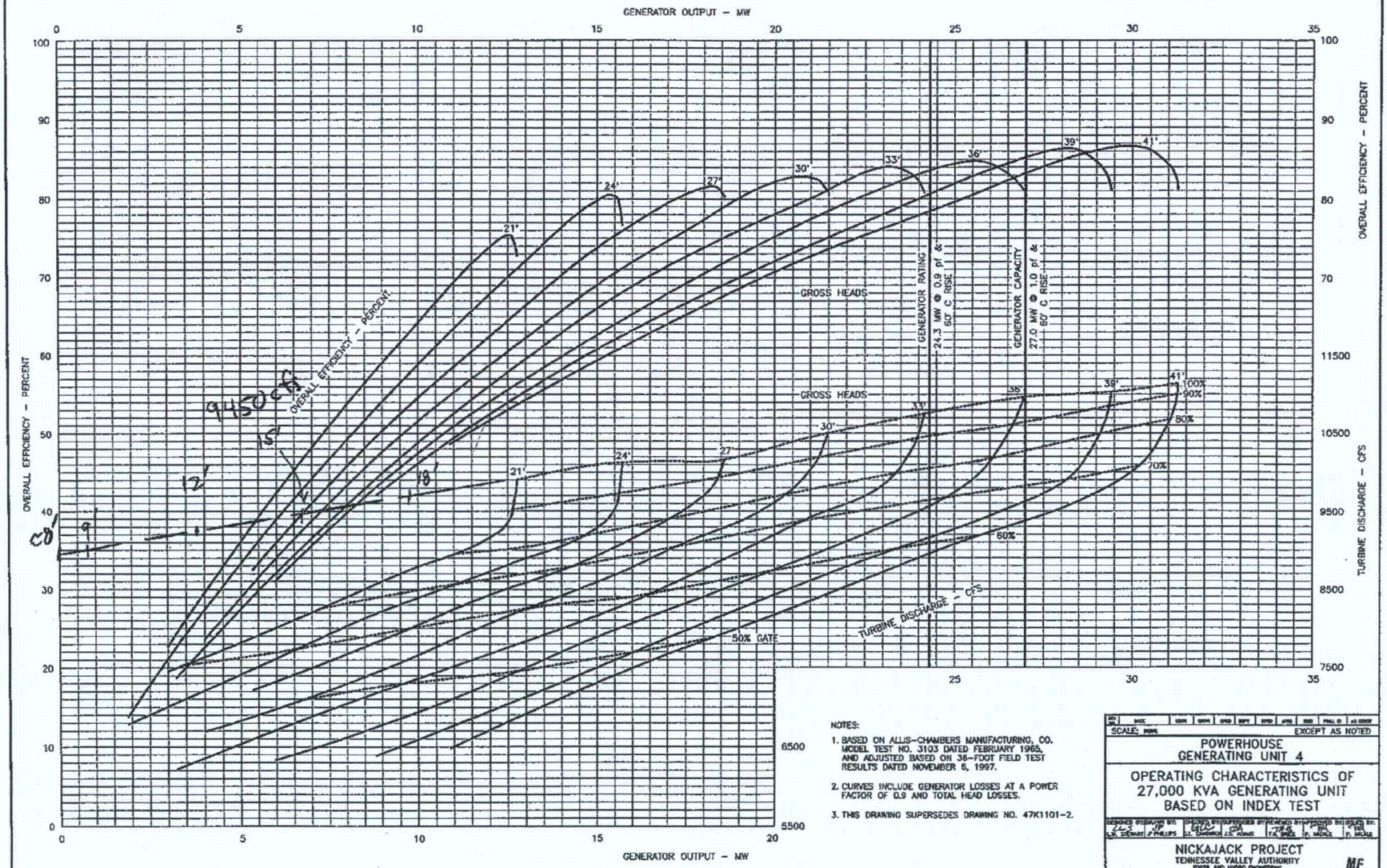
DRAWING PLOT FACTOR: 1=1
MODERED DRAWING: 8=1,3=1

Attachment 6-4

Source: Reference 29

Calculation No: CDQ000020080014

69 | M | 47K1102-4



NOTES:

1. BASED ON ALLIS-CHAMBERS MANUFACTURING CO. MODEL TEST NO. 3103 DATED FEBRUARY 1965, AND ADJUSTED BASED ON 36-FOOT FIELD TEST RESULTS DATED NOVEMBER 6, 1997.
2. CURVES INCLUDE GENERATOR LOSSES AT A POWER FACTOR OF 0.9 AND TOTAL HEAD LOSSES.
3. THIS DRAWING SUPERSEDES DRAWING NO. 47K1101-2.

SCALE: NONE — EXCEPT AS NOTED

POWERHOUSE
GENERATING UNIT 4

OPERATING CHARACTERISTICS OF
27,000 KVA GENERATING UNIT
BASED ON INDEX TEST

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NICKAJACK PROJECT
TENNESSEE VALLEY AUTHORITY
FOSSIL AND HYDRO ENGINEERING

MF

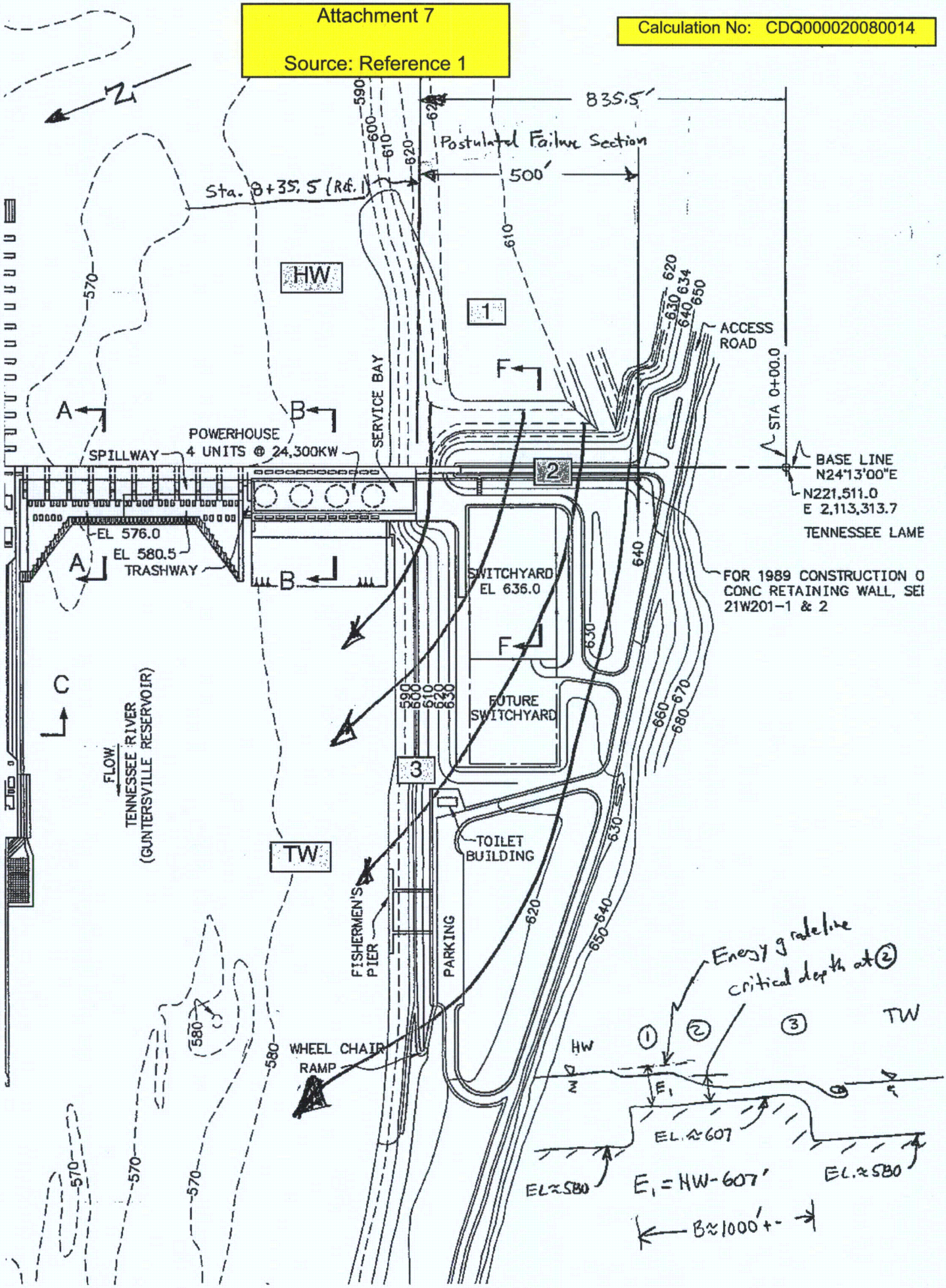
AUTOCAD REV | DATE | 69 | M | 47K1102-4 | R0

CAD SYSTEM DRAWING
DO NOT ALTER MANUALLY

DRAWING PLOT FACTOR: 1=1
INSERTED DRAWING: 1=1.3=1

ISSUED BY:

Attachment 7

Source: Reference 1

Calculation No: CDQ000020080014