10CFR50
Appendix R

BOSTON EDISON
Executive Offices
800 Boylston Street
Boston, Massachusetts 02199

January 19, 1988

Ralph G. Bird
Senior Vice President — Nuclear

BECo 88-010

U. S. Nuclear Regulatory Commission
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Washington, DC 20555

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Docket 50-293

10CFR50 APPENDIX R EXEMPTION REQUESTS
SUPPLEMENTAL INFORMATION

References:
1. BECo letter to NRC (dated November 16, 1983) Subject: 10CFR50 Appendix R Exemption Requests (BECo Letter No. 83-281).
2. BECo letter to NRC (dated December 27, 1984) Subject: 10CFR50 Appendix R Exemption Requests, Calculations used in Evaluation of Structural Steel Supports (BECo Letter No. 84-214).
3. NRC letter to BECo (dated December 10, 1987) Subject: Meeting Between Boston Edison Company and NRC on November 24, 1987.

This letter provides additional information for consideration by the staff in its evaluation of BECo Exemption Requests 11, 12, 13 and 14. The need to supplement our previous submittals (References 1 and 2) resulted from discussions in our November 24, 1987 meeting (Reference 3). The information is presented in four attachments.

Attachment 1, entitled Combustible Loading, contains maximum permitted fire loadings which we propose for various fire zones discussed in Exemption Requests 11 and 12. These loading limits were conservatively selected to be well below those that may constitute a challenge to the fire area barriers and their ability to prevent fire propagation. These limits supplement our exemption request. We anticipate no circumstances where transient combustibles combined with fixed combustibles would exceed them.

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F PDR ~~DCD~~

Attachments 2 and 3 are BECo calculations M-197, Revision 2, Fire Resistance of Structural Steel in the Torus Area (EL -17'-6"), and M-198, Revision 1, Fire Resistance of Structural Steel in the Steam Tunnel. These documents provide the basis for Exemption Requests 13 and 14 and are updated versions of those used for our earlier submittals (References 1 and 2). These versions incorporate a more rigorous analytical methodology to compute temperature rise in the structural steel supporting the fire barrier. These new calculations show that postulated fires in the Torus Area or Steam Tunnel will produce temperature rises in the unprotected steel that are well below the failure temperature. This means the conclusions of the previous calculations (the steel and fire barrier are safe from collapse) remain unchanged. Please note that some of the numerical results and statements presented in References 1 and 2, which were based on the old methodology, are superseded by these revised calculations.

Attachment 4 is furnished for the convenience of the NRC staff reviewers. It shows how the new M197/M198 calculation methodology was applied to determine the proposed Torus Area and Steam Tunnel combustible loading limits were safe.

We request that the NRC incorporate this information into its review of the affected exemption requests.

RG Bird
R. G. Bird

GD/amm/1619

cc: Mr. D. McDonald, Project Manager
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Senior NRC Resident Inspector
Pilgrim Nuclear Power Station

Attachments:
1. Table: Combustible Loading
2. BECo Calculation M197, Rev. 2
3. BECo Calculation M198, Rev. 1
4. Application of M197/M198 Calculation Methodology

ATTACHMENT 1 TO BECO LETTER 88-010

COMBUSTIBLE LOADING

Fire Zone	Proposed Maximum Permitted Loading (BTU/SF)
SE Quad FZ 1.1	40,000 (1)
NW Quad FZ 1.2	40,000 (1)
NE Quad FZ 1.6/1.8	40,000 (1)
Torus Area FZ 1.30A	14,000 (2)
Steam Tunnel FZ 1.32	8,200 (2)

NOTES

1. The proposed maximum permitted loading for the Quad zones is equivalent to a "30 minute" fire hazard. This loading was administratively selected to represent a limit which provides assurance against spread of a fire beyond the affected zone, and is based on the realistic analysis described in Exemption Requests 11 and 12.

2. The proposed maximum permitted loadings for the Torus Area and Steam Tunnel are essentially equivalent to those calculated to produce a maximum average steel temperature of 255°F using the methodology of calculation M197, Rev. 2 and M198, Rev. 1, and are well below those needed to produce the theoretical steel failure temperature of 1000°F used by the fire protection industry.

ATTACHMENT 2 TO BECO LETTER 88-010

BECo Calculation M197, Revision 2
TORUS AREA

BOSTON Edison COMPANY

CALCULATION COVER SHEET

PILGRIM UNIT 1

CAPITAL AUTHORIZATION NO ____

Sheet 1 of 25

CALC NO. M-197 REV. 2 File No. ____

Subject FIRE RESISTANCE OF STRUCTURAL STEEL IN THE TORUS AREA - (EL. -17'6")

Discipline Group Leader TJ TRACY / WS CLANCY

Approval /s/ TJ Tracy by TJ 9-29-86 / W S Clancy 10/14/86 Date ____

SR ☒

NSR ☐

Preliminary Calc. ☐

Finalization due date ____

Final Calc. ☒

Independent Verifier Joseph L. Jez / CIVIL/STRUCTURAL 9/26/86 ____ Statement Attached ☑

Page(s)		Date		Date	Agree
ALL	By J.F. BIENKIEWICZ /s/ J F Bienkiewicz	8/23/86 9/23/86	JOHN T. FRAWLUCKI Chk'd Michael J DiMeo /s/ M J DiMeo John T. Frawlucki JTF	9/23/86 9/23/86	X

THIS CALCULATION VERIFIES THE ADEQUACY OF FIRE BARRIERS, FOR THE ABOVE AREAS, BY EVALUATING THE UNPROTECTED STRUCTURAL STEEL WHICH IS PART OF OR SUPPORTS THE FIRE BARRIER.

THIS CALCULATION SUPERSEDES M-197 R 1 TO PRESENT THE CALCULATION IN AN EASY TO FOLLOW FORMAT AND CLARIFY AREAS OF THE CALCULATION TO ELIMINATE CONFUSION.

THIS CALCULATION REVISION SUPPORTS THE ORIGINAL CALCULATION CONCLUSION, THAT THE STEEL WILL NOT ATTAIN A MAXIMUM AVERAGE TEMPERATURE OF 1,000 °F, AND THEREBY CONFIRMS THE ADEQUACY OF THE UNPROTECTED STRUCTURAL STEEL TO SUPPORT THE FIRE BARRIER DURING A FIRE. SEE ATTACHMENT II FOR INDEPENDENT VERIFICATION STATEMENT FOR CIVIL/STRUCTURAL; AND ATTACHMENT III FOR FS&MC INDEPENDENT VERIFICATION.

THIS CALCULATION SUPPORTS ENGINEERING EVALUATION NO. 859.

Minor revision(s) made on page(s) ____ of this calculation. See next revision.

Replaces calc = ____

Voided by calc # ____ or attache

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☐ PRELIMINARY
REV ___ DATE ________

☒ FINAL M197
REV 2 DATE ________

SUBJECT: TORUS AREA STEEL

CALCULATION SHEET

BOSTON Edison COMPANY

CAPITAL AUTHORIZATION NO. ________
PREPARED BY JFB DATE 9/23/86
CHECKED BY mp DATE 9/23/86
APPVD BY LML DATE 10/14/86
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NSR ☐

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CALCULATION SHEET

BOSTON Edison COMPANY

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CHECKED BY ________ DATE 9/25/86

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BJECT: TORUS AREA STEEL

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1.0 PURPOSE

THE PURPOSE OF THIS CALCULATION IS TO ESTIMATE THE MAXIMUM AVERAGE UNIFORM TEMPERATURE THAT STEEL IN THE TORUS AREA (-17'6").

MAY ATTAIN DUE TO A POSTULATED FIRE. THE FAILURE POINT FOR STEEL WIII BE DEFINED AS A MAXIMUM AVERAGE TEMPERATURE OF GREATER THAN 1,000 °F.

2.0 SUMMARY OF RESULTS

THE NUMERICAL ANALYSIS PRESENTED IN TABLE B. AUGMENTED BY THE DISCUSSION OF CONSERVATIVE ESTIMATES AND ASSUMPTIONS CONCLUDES THAT THE MAXIMUM AVERAGE UNIFORM TEMPERATURE OF STEEL IN THE TORUS AREA -EL-17'6", SHALL NOT EXCEED 137°F, BASED UPON 40% OF THE CONSERVATIVE THEORETICAL FIRE LOAD (Ref 3.0+4.0). SINCE THE FINAL TEMPERATURE IS LESS THAN THE 1,000°F, IT IS DETERMINED THAT THE STRUCTURAL STEEL WILL NOT DEGRADE THE FIRE BARRIER

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REV ___ DATE ________

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PREPARED BY JEB GPB 9/23/80 DATE 8/22/80

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SHEET 4 OF 25

SUBJECT: TORUS AREA STEEL

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3.0 METHODOLOGY

3.1 THE TEMPERATURE WITHIN THE TORUS AREA - EL (-)17'6" SHALL BE MODELED TO FOLLOW THE TEMPERATURE PROFILE PRESENTED BY THE STANDARD TIME-TEMPERATURE CURVE IN ASTM-E-119. THE MODEL SHALL ASSUME AMBIENT TEMPERATURE OF 68°F.

3.2 AS THE TEMPERATURE OF THE MODELED SPACE RISES (PER ASTM-E-119) THE TEMPERATURE DIFFERENCE, BETWEEN THE SPACE (T_o) AND THE SPACE BOUNDARY (T_w) IS CALCULATED (ΔT). THIS INITIAL TEMPERATURE DIFFERENCE IS UTILIZED TO DETERMINE THE COMBINED CONVECTION AND RADIATION COEFFICIENTS ($h_c + h_r$) = h REQUIRED TO CALCULATE THE HEAT FLUX (F_o) PER UNIT AREA.

$$\boxed{F_o = \Delta T \, h}$$

3.3 THE HEAT FLUX PER UNIT AREA (F_o) IS THEN UTILIZED TO TO INDEPENDENTLY

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☐ PRELIMINARY
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SUBJECT: TORUS AREA STEEL

CALCULATION SHEET

BOSTON Edison COMPANY

CAPITAL AUTHORIZATION NO. ________
PREPARED BY JAB JAB DATE 9/23/86 9/23/86
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CALCULATE THE NEW SPACE BOUNDARY SURFACE TEMPERATURE OF STEEL (T_{w_s}) AND CONCRETE (T_{w_c}).

$$\boxed{T_w = T_o + 2\left(\frac{F_o}{K}\right)\left(\frac{\partial b}{3.14}\right)^{1/2}}$$

3.4 THE TOTAL HEAT ABSORBED BY THE SPACE BOUNDARY IS CALCULATED (Q_s : Q_c),

$$\boxed{Q_s = F_{o_s} A_s \;;\; Q_c = F_{o_c} A_c}$$

3.5 THE THEORETICAL FIRE LOADING OF THE SPACE SHALL BE CALCULATED.

FIRE LOADING	= COMBUSTIBLES	× HEAT OF COMBUSTION
BTU	= (LB.	× BTU/LB)

3.6 THE THEORETICAL FIRE LOADING SHALL BE REDUCED TO A NET FIRE LOADING BASED UPON PUBLISHED INDUSTRY DATA AND CALCULATION SUPPORTED ASSUMPTIONS. THE NET FIRE LOAD SHALL BE UTILIZED TO IDENTIFY THE MAXIMUM AVERAGE STEEL TEMPERATURE

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REV 2 DATE _

SUBJECT: TORUS AREA STEEL

AUTHORIZATION NO ________

PREPARED BY JTB JTB DATE 8/23/86 9/23/86

CHECKED BY DATE 9/22/86

APPVD BY DATE 10/14/86

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4.0 REFERENCES:

1. FIRE TEST STANDARDS, FIRST EDITION, 1982 ASTM-E-119, TABLE X1, PAGE 53.
2. STANDARD HANDBOOK FOR MECHANICAL ENGINEERS, SEVENTH EDITION, TABLE 11, PAGE 4-106, AND FORMULA (15), (ATTACHED)
3. THERMAL CONDUCTIVITY:

   STEEL - ASME VIII - DIVISION 2 - TABLE 1 (ATTACHED)

   CONCRETE - STANDARD HANDBOOK FOR MECHANICAL ENGINEERS, SEVENTH EDITION, TABLE 3, PAGE 4-95. (ATTACHED)
4. FOR STEEL - THERMAL DIFFUSIVITY - ASME VIII - DIVISION 2 - TABLE 1 (ATTACHED).
5. CONDUCTION OF HEAT IN SOLIDS. Pg 75, PARA 2.9 - CARSLAW & JAEGER (ATTACHED)
6. NATIONAL RESEARCH COUNCIL OF CANADA, FIRE RESISTANCE OF UNPROTECTED STEEL COLUMNS, RESEARCH PAPER N677, MAY 23, 1973 - (ATTACHED).
7. FIRE TECHNOLOGY, NFPA, ASSESSMENT OF FIRE RESISTANCE REQUIREMENTS, VOL 17, NOVEMBER 1981. (ATTACHED)
8. 1978 STRUCTURAL STEEL SHAPES, BETHLEHEM CATALOG 3277, 1978 EDITION.
9. DRAWING REFERENCES ARE CALLED OUT IN SECT. 6.3

3-CONT. - CONCRETE THERMAL DIFFUSIVITY; "HEAT, MASS, AND MOMENTUM TRANSFER", W.M. ROHSENOW & H.Y. CHOI - PRENTICE HALL INC (ATTACHED)

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BOSTON Edison COMPANY

AUTHORIZATION NO ______

PREPARED BY JPB JPD DATE 8/23/86 9/23/86

CHECKED BY mgD DATE 9/23/86

APPVD BY DATE 10/4/86

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BJECT: TORUS AREA STEEL

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5.0 ASSUMPTIONS

1. AREA TEMPERATURE ASSUMED TO BE 68°F @ T_o.
2. THE COMBINED CONVECTION AND RADIATION COEFFICIENT VALUES ASSUME LINEAR APPROXIMATION BETWEEN TABLE TEMPERATURE VALUES.
3. THE THERMAL CONDUCTIVITY - ASSUME - LINEAR APPROXIMATION BETWEEN TABLE TEMPERATURE VALUES FOR STEEL. THE CONCRETE THERMAL CONDUCTIVITY IS ASSUMED CONSTANT OVER TEMPERATURE RANGE.
4. THE STEEL THERMAL DIFFUSIVITY - ASSUME LINEAR APPROXIMATION BETWEEN TABLE TEMPERATURE VALUES FOR STEEL. THE CONCRETE THERMAL DIFFUSIVITY IS ASSUMED CONSTANT OVER TEMPERATURE RANGE
5. STEEL IS ASSUMED TO FAIL WHEN IT REACHES AN ESTIMATED MAXIMUM UNIFORM AVERAGE TEMPERATURE OF 1,000 °F.
6. THE STEEL IS ASSUMED TO HEAT UNIFORMILY.
7. COMBUSTIBLE MATERIAL IS ASSUMED TO RELEASE AN AMOUNT OF HEAT EQUIVALENT TO THE THEORITICAL HEAT OF COMBUSTION.
8. [BLANK]

~~9. EMISSIVITY OF STEEL EQUALS ABSORPTIVITY OF CONCRETE~~.

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BOSTON Edison COMPANY

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SUBJECT: TORUS AREA STEEL

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ASSUMPTIONS - CON'T

10. STEEL AND CONCRETE ACT AS SEMI-INFINITE SOLIDS.
11. INSULATION - HEAT OF COMBUSTION ASSUMED TO BE 21000 BTU/Lb WHICH IS MAXIMUM FOR CABLES IN THIS AREA.
12. [BLANK]
13. ALTHOUGH THE NOTE ON TABLE II (REF 2) INDICATES THE VALUES OF h ARE BASED ON AN 80°F ROOM TEMPERATURE, FOR THIS CALCULATION THE VALUES ARE ACCEPTABLE FOR DETERMINING AN ORDER OF VALUE FOR THE COMBINED COEFFICIENT.

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JBJECT: TORUS AREA STEEL

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6.0 DETAILED CALCULATION

6.1 CALCULATION DATA IS PRESENTED IN TABULAR FORM ON TABLE A.

COLUMN NUMBER 1 IS THE TIME - IN MINUTES - RELATIVE TO THE TIME TEMPERATURE CURVE IN ASTM E-119.

COLUMN NUMBER 2 IS THE TEMPERATURE OF THE FIRE RELATIVE TO THE TIME TEMPERATURE CURVE IN ASTM-E 119.

COLUMN NUMBER 3 IS THE TEMPERATURE OF THE SURFACE BOUNDARY WHICH INCREASES OVER TIME AND TEMPERATURE.

COLUMN NUMBER 4 IS THE DIFFERENCE IN TEMPERATURE BETWEEN COLUMN NUMBER 2 AND 3

COLUMN NUMBER 5 IS THE COMBINED CONVECTION AND RADIATION COEFFICIENT BASED ON THE TEMPERATURE DIFFERENCE IN COLUMN NUMBER 4

COLUMN NUMBER 6 IS THE FLUX PER UNIT AREA WHICH IS EQUAL TO COLUMN NUMBER 4 MULTIPLIED BY COLUMN NUMBER 5.

COLUMN NUMBER 7 IS THE THERMAL CONDUCTIVITY OF THE MATERIAL.

COLUMN NUMBER 8 IS THE THERMAL DIFFUSIVITY OF THE MATERIAL.

COLUMN NUMBER 9 IS THE TEMPERATURE DIFFERENCE (INCREASE) IN THE SURFACE BOUNDARY, WHICH IS CALCULATED AS FOLLOWS:

$\Delta T_w = \frac{2F_o}{K}\left(\frac{\partial b}{3.14}\right)^{1/2}$ WHICH IS $\Delta T_w = 2\left(\frac{CN6}{CN7}\right)\left(\frac{CN8 \times (\overset{(CN1)}{\tau_N - \tau_{N-1}})}{3.14}\right)^{1/2}$

WHERE CN = COLUMN NUMBER

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COLUMN NUMBER 10 IS THE NEW SURFACE TEMPERATURE AFTER TIME τ.

$$T_{W2} = T_{W1} + \Delta T_W$$

$$CN10 = CN3 + CN9$$

WHERE CN = COLUMN NUMBER

COLUMN NUMBER 11 IS THE TOTAL NUMBER OF BTU'S APPLIED TO THE STEEL OR CONCRETE.

$$Q_s = F_{O_s} \times A_s \times (\tau_n - \tau_{n-1})$$

WHERE: s = STEEL

A_s = AREA STEEL FROM TABLE B

$(\tau_n - \tau_{n-1})$ = TIME IN MINUETS

$$\therefore CN11 = CU6 \times A_s \times \overset{CN1}{(\tau_n - \tau_{n-1})}$$

WHERE CU = COLUMN NUMBER

SUBSCRIPT c IS SUBSTITUTED FOR s TO IDENTIFY Q_c FOR CONCRETE.

COLUMN NUMBER 12 IS THE CUMULATIVE SUM OF $Q_{s/c}$ FROM CN11.

REFER TO TABLE A FOR A SAMPLE OF THE CALCULATION TABLE AND LEGEND - WHICH ITEMIZES REFERENCES AND ASSUMPTIONS.

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CALCULATION SHEET

BOSTON Edison

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SUBJECT: TORUS AREA STEEL

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6.2 CALCULATION TABLE & LEGEND

TABLE A

☒ SR	☐ NSR	1	2	3	4	5	6	7	8	9	10	11	12
		τ MIN	T_F °F	T_{W_1} °F	ΔT $(T_F - T_W)$	h @ ΔT	F_0 BTU/FT²·HR	K	a	ΔT_W °F	T_{W_2} °F	$Q_{c/s}$ BTU	$\Sigma Q_{c/s}$ BTU

LEGEND:

1. τ - MIN. REF 1

2. T_F = TEMP(°F) @ τ REF 1

3. T_{W_1} = TEMP(°F) OF SPACE SURFACE AT τ

4. ΔT = TEMP DIFFERENCE - °F = $(T_F - T_W)$.

5. $h_{@\Delta T}$ = COMBINED CONVECTION AND RADIATION COEFFICIENT = (BTU/HR-FT²·°F) = $(h_c + h_r)$. REF 2; ASSUMPTION 2 & 13

6. $F_0 = \Delta T h$ = HEAT FLUX PER UNIT AREA - BTU/HR-FT² - REF 2.

7. K = THERMAL CONDUCTIVITY - BTU/°F-HR-FT - REF 3; ASSUMPTION 3.

8. a = THERMAL DIFFUSIVITY - REF 4; ASSUMPTION 4; REF. 3.

9. ΔT_W = INCREASE IN SURFACE TEMP °F FROM $\Delta T_W = 2\left(\frac{F_0}{K}\right)\left(\frac{a b^*}{3.14}\right)^{1/2}$ [b^* = TIME IN HOURS]

10. T_{W_2} = TEMP. OF SPACE SURFACE AFTER TIME τ

$$T_{W_2} = T_{W_1} + \Delta T_W$$

11. $Q_{s/c}$ = TOTAL HEAT IN BTU Q_s (STEEL) / Q_c (CONCRETE) × 10^6

12. $\Sigma Q_{s/c}$ = THE TOTAL CUMULATIVE HEAT IN BTU'S × 10^6.

13. b = TIME IN HOURS

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CALCULATION SHEET OF STRUCT STEEL & CONC AREAS FOR TORUS AREA (EL.-17'-6" TO 23')

BOSTON Edison COMPANY

CAPITAL AUTHORIZATION NO. ______
PREPARED BY JFB ~~8/23/86~~ DATE 9/23/86
CHECKED BY JP mD DATE 9/23/86 9/24/86
APPVD BY [illegible] DATE 10/4/86
SHEET 12 OF 25

SUBJECT: TORUS AREA STEEL & CONC.

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6.3 CALCULATION OF STEEL & CONCRETE AREA

SHEET NO.	12.	SUMMARY
	13.	STEEL TABLE
	14.	5,758.88 S.F.
	15.	4,033.69
	16.	3,826.88
TORUS SHELL & SUPPORT	17.	32,532.91
METAL DECKING	18	10,658.00
TORUS		56,810.36 S.F AREA STEEL
TORUS CONCRETE SHEET	19.	36,026.54 S.F. AREA CONC.

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CALCULATION SHEET

Boston Edison Company

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SHEET 13 OF 25

SUBJECT:

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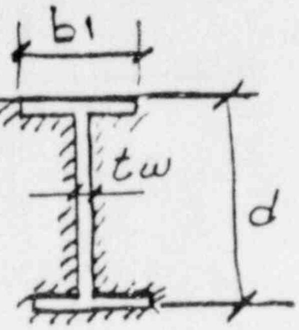

$2 \times d + .3 \times b1 - 2 \times tw =$

	d	b1	tw	PERIMETER INCHES	PERIMETER FT.
14 WF 43	13 5/8"	8"	5/16"	50.62	4.22
30 WF 99	29 5/8	10 1/2	1/2	89.75	7.48
30 WF 108	29 7/8	10 1/2	9/16	90.13	7.51
30 WF 124	30 1/8	10 1/2	9/16	90.63	7.55
30 WF 172	29 7/8	15	5/8	103.5	8.62
30 WF 190	30 1/8	15	11/16	103.87	8.65
30 WF 210	30 3/8	15 1/8	3/4	104.62	8.72
36 WF 170	36 1/8	12	11/16	106.87	8.9
36 WF 230	35 7/8	16 1/2	3/4	119.75	9.98
36 WF 300	36 3/4	16 5/8	15/16	121.5	10.125

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CALCULATION SHEET

BOSTON Edison COMPANY

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CHECKED BY JJMQ DATE 9/23/86 9/23/86

APPVD BY DATE 10/4/86

SHEET 14 OF 25

(TORUS) EL. 23'-0" TORUS

SUBJECT: STEEL DWG. C.132 BY BECHTEL

SR	☒
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PCC	SIZE	LENGTH EXPOSED	EXPOSED SQ. FT.	
EW 4	30WF 99	11'	329.12	
EW 1	30WF 124	19'	143.45	
EW 1	30 99	19'	142.12	
2	30 108	19'	285.38	
1	30 190	27'	233.55	
1	30 172	27'	197.8 JFB	T/S: 20'-4" 9" 19'-7" FOR 14'
1	30 172	27'	232.74	
1	30 108	27'	202.77	
1	30 190	34'	294.1	
1	30 172	34	221.	19'-7"
1	30 190 PL. 1"x12" (.17)	34	299.88	(.17)
GIR ② 1		34	334.33 (52x1")	4' OR CONC. 30 1'-10" 26x2½"
1	30 172	42	362.04	
1	30 172	42	318 JFD	19'-7" FOR 23'
1	30 210	42	369.64	12"x1"x20'
GIR ① 1		42	415.	(52"x1") 1'-10" 28x2½"
1	30 210	38	331.36	
1	30 210	38	378.86	SAY 5' W.S. (+1.25) ✓
2	30WF 172	38	655.2	
			≈ 5,758.88 □'	

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Boston Edison Company

CAPITAL AUTHORIZATION NO. ________

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TORUS

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TORUS - STEEL

SUBJECT: REF DWG C-132

SR ☒

NSR ☐

PCS	SIZE	LENGTH EXPOSED	EXPOSED SQ. FT	
4	30WF 172	34'	1172.32	
6	30WF 172	30	1551.6	
7	14 43	8.5'	≈251.1	} approximate values
EW 2	14 43	6'	≈50.64	
2	36WF230	34'	546.83	I ≠ 6¾"
1	36WF230	30'	241.2	I ≠ 6¾"
2	36WF170	30'	220.	I ≠ 6¾"
			4,033.69 □'	

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☒ FINAL M-197
REV 2 DATE ______

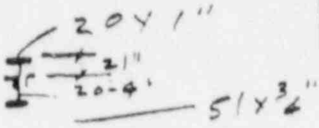
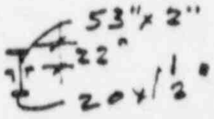
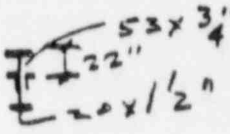
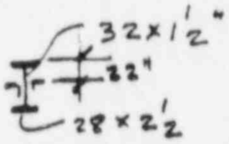
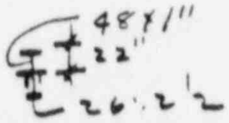
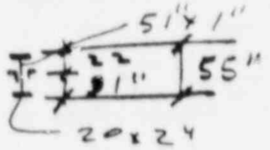
CALCULATION SHEET

BOSTON Edison COMPANY

CAPITAL
AUTHORIZATION NO. ______
PREPARED BY JFB JFB DATE ~~8/22/86~~ 9/23/86
CHECKED BY GMP DATE 9/23/86 9/23/86
APPVD BY DATE 10/4/86
TORUS
SHEET 16 OF 25

TORUS - STEEL
SUBJECT: REF DWG. C-132

SR ☒
NSR ☐

PCS	SIZE	LENGTH EXPOSED	EXPOSED SQ. FT.
NS 8	14 WF 43	8.6'	290.336
GRD ⑧ 2	@ J-15	8'	147.  20 x 1" 21" 20-4' 51 x 3/4"
NS 2	36 WF 300 + PL 1 1/4 x 18" + (.2)	37'	638.75 JFB I
1	30 WF 190 + (.25)	35'	302 JFB
GRD. ⑥ 1	+ STIFF. PLS 1 END, 3/4"	33'	297.0 15. S. PLS 312. ←  53" x 2" 22" 20 x 1/2"
GRD ⑤ 1	+ STIFF PLS 1 END 3/4"	33'	312.5  53 x 3/4" 22" 20 x 1/2"
3	30 WF 108	30'	675.9
1	30 WF 210	35'	305.2
GRD ④ 1		37'	396 JFB  32 x 1 1/2" 22" 28 x 2 1/2
M.P GRD ⑦ 1		37'	360 JFB  48 x 1" 22" 26 x 2 1/2
14.6 GRD ③ 1		13	116.  51" x 1" 22 21" 55" 20 x 24
			≈ 3,826.88 □

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B.E.Co. FORM 3930

NED-1001

☐ PRELIMINARY

REV ___ DATE ______

☒ FINAL M-197

REV 2 DATE ______

CALCULATION SHEET

Boston Edison Company

CAPITAL AUTHORIZATION NO. ______

PREPARED BY JB 9/10 DATE 9/23/80 8/22/82

CHECKED BY AJ RMP DATE 9/23/82 9/23/80

APPVD BY [illegible] DATE 10/4/82

SHEET 17 OF 25

SUBJECT: TORUS

SR ☒

NSR ☐

REF. DWG. M-15 REV. E3

TORUS CIRCUM = 92.68'

$92.68' \times 20' \times 16 = 29{,}657.6\ \square'$

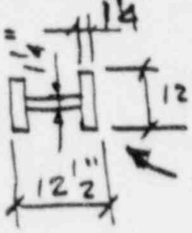
CIRCUM. L SEGMENTS

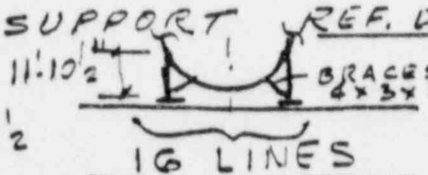
TORUS 16 SEGMENTS

TORUS SHELL

AREA STEEL 29,657.6 □'

TORUS SUPPORT REF. DWG C-60 & CHICAGO BRIDGE FSAR DWG FIGURE L.2.21 BECO DWG NO.S C1A52-5 & C1A159-1





SIDES 12½"

$6 \times 1.0417' = 6.25$

$- .21$ (2 WEB T'S)

$10.75' \times 6.04' = 64.9\ \square' \times 32 = 2{,}077$ COLS □'

LENGTH EA. COL

COL. BASE PLATES $2.5833' \times 2.5833' \times 32 = 213.55\ \square'$

$4 \times 3 \times 3/16$ L + 2 PLs

$1.16' \times \approx 7.5' = 8.7\ \square'$ L

2. PLs

EA. BRACE $10.7\ \square' \times 32 =$ PL & BRACES $\approx 342.4\ \square'$

TORUS SHELL + SUPPORTS = TOTAL $\approx 32{,}532.91\ \square'$

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☐ PRELIMINARY
REV ___ DATE ______
☒ FINAL M-197
REV 2 DATE ______

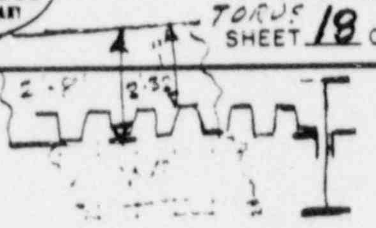
CALCULATION SHEET

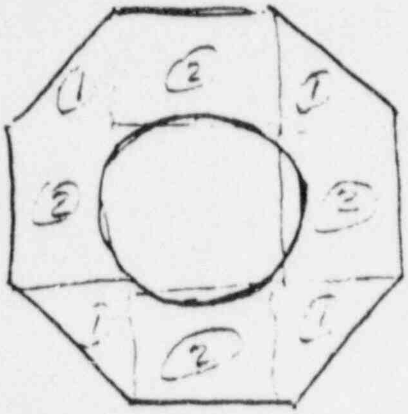
CAPITAL AUTHORIZATION NO. ______
PREPARED BY JPB JPB DATE ~~8/23/86~~ 9/23/86
CHECKED BY ~~[illegible]~~ PMP DATE 9/23/86 9/23/86
APPVD BY [illegible] DATE 10/[illegible]/86
TORUS SHEET 18 OF 25

SUBJECT:

SR ☒
NSR ☐

METAL DECK 4 1/2" DP.
(EL. 23'-0" FIN. FL.) (DWG. C-122)





TOP OF STEEL
EL. 20'-4"

			AREA
①	39' x 39' ÷ 2 = 760.5 □' x 4	=	3,042 □'
②	56 x 34 = 1904 x 4	=	7616 □'
	METAL DECK TOTAL		10,658 □'

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☒ FINAL M-197

REV. DATE —

CALCULATION SHEET

Boston Edison Company

CAPITAL AUTHORIZATION NO. ______

PREPARED BY JPB JPB DATE ~~8/22/86~~ 9/23/86

CHECKED BY RMP DATE 9/23/86 9/23/86

APPVD BY ______ DATE 10/14/86

SUBJECT: CONCRETE

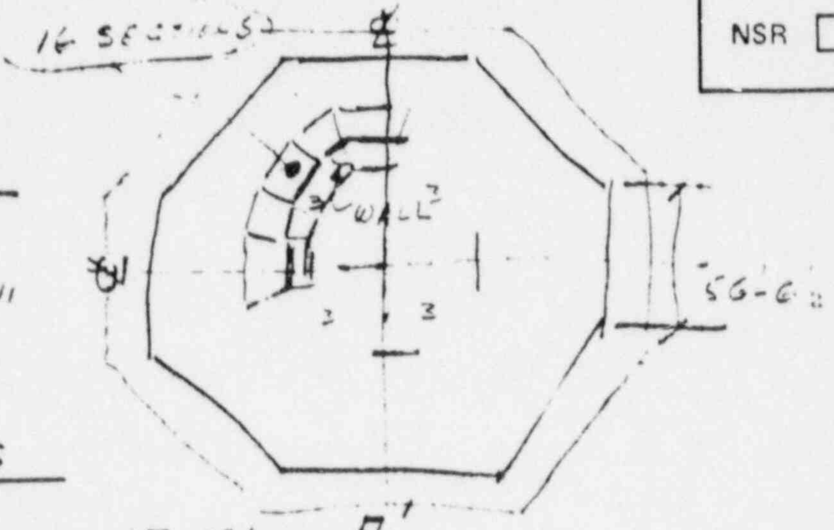
TORUS SHEET 19 OF 25

☒ SR

☐ NSR

CONCRETE REF. DWGS C-60, C-61, C-62 & C-72

WALLS



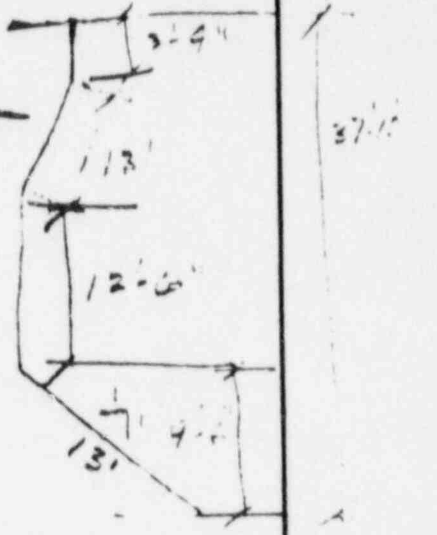
T.W EL. 20'-4"
B.W EL. -17'-6
37'-10"

37.83' × 56'-6½"

OUTBOARD WALLS

37.83' HT × 56.54 LGTH × 8 = 17,111.26 □'

INBOARD WALLS



28.83 HT × 13.5 L × 16 = 6,227.28 □'

DIAG AT EL. -17'-6"

15' × 13' × 16 = 3,120 □'

{ OUTBOARD & INBOARD TOTAL WALL AREA 26,458.54 □'

SLAB AT EL. -17'-6"

26 × 46 × 8 = 9,568 □'

36,026.54 S.F.

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☒ FINAL M-197
REV 2 DATE ______

CALCULATION SHEET

Boston Edison Company

CAPITAL AUTHORIZATION NO. ______
PREPARED BY JFD JPD DATE 9/23/86 2/22/86
CHECKED BY MJD DATE 2/23/86
APPVD BY DATE 10/4/86
SHEET 20 OF 25

SUBJECT: TORUS AREA (-17'6")

SR ☒
NSR ☐

1.4 THEORETICAL FIRE LOADING

A. FUEL LOADING:

1. CABLE INSULATION	24 Lb.
2. WOOD	8200 Lb

B HEAT OF COMBUSTION:

1. INSULATION	21,000 BTU/Lb
2. WOOD	8,000 BTU/Lb

C. TOTAL THEORETICAL LOAD:

1 INSULATION

24 Lb x 21,000 BTU/Lb = 504,000 BTU

2 WOOD

8200 Lb x 8,000 BTU/Lb = 65,600,000 BTU

SAY 66,000,000 BTU

THEORETICAL FIRE LOAD APPLIED TO SPACE BOUNDARY:

66×10^6 BTU x 40% = 26.4×10^6 BTU

[REF. 7]

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CALCULATION SHEET

Edison

CAPITAL AUTHORIZATION NO. ______
PREPARED BY JFB JTD DATE 9/23/86 8/23/86
CHECKED BY MJP DATE 9/23/86
APPVD BY ______ DATE 10/14/86
SHEET 21 OF 25

SUBJECT: TORUS AREA (-17'6")

SR ☒
NSR ☐

TABLE 6.5 TORUS AREA - FA

		STEEL 56810 say 56,000 FT²										CONCRETE 36,026 say 36000 FT²							
1 τ	2 TF	3 Tw	4 ΔT	5 h	6 Fo	7 K	8 a	9 ΔT	10 Th	11 Qs	12 ΣQs	3 Tw	4 ΔT	5 h	6 Fo	9 ΔT	10 TM	11 Qc	12 ΣQc
0.00	-	68	—	—	—	—	—	—	—	—	—	68	–	–	–	–	–	–	–
0.01	600	—	—	—	—	—	—	—	—	—	—	68	532	5.1	2713	53	121	1.6	1.6
0.02	700	—	—	—	—	—	—	—	—	—	—	121	579	5.5	3189	63	184	1.9	3.5
0.03	800	—	—	—	—	—	—	—	—	—	—	184	616	5.8	3572	68	252	2.1	3.6
0.04	900	—	—	—	—	—	—	—	—	—	—	252	648	6.2	4017	77	329	2.4	8.0
0.05	1000	68	932	9.6	8947	35.1	.69	69	137	42.35	42.35	329	671	6.4	4294	81	410	2.5	10.5 ←
~~0.10~~	~~1300~~	~~137~~	~~1163~~	~~13.4~~	~~15584~~	~~34.6~~	~~.65~~	~~118~~	~~285~~	73.77	116.12	~~410~~	~~890~~	~~9.1~~	~~8099~~	~~354~~	~~764~~	~~24.2~~	~~34.7~~
~~0.15~~	~~1399~~	~~255~~	~~1144~~	~~13.0~~	~~14472~~	~~32.9~~	~~.59~~	~~110~~	~~365~~	67.5	183.6	~~764~~	~~635~~	~~6.0~~	~~3810~~	~~166~~	~~930~~	~~11.4~~	~~46.1~~
~~0.20~~	~~1462~~	~~365~~	~~1097~~	~~12.3~~	~~13492~~	~~31.4~~	~~.54~~	~~99~~	~~464~~			~~930~~	~~532~~	~~5.1~~	~~2713~~	~~118~~	~~1048~~		
~~0.25~~	~~1510~~	~~464~~	~~1046~~	~~11.4~~	~~11924~~	~~30.0~~	~~.49~~	~~90~~	~~554~~			~~1048~~	~~462~~	~~4.5~~	~~2079~~	~~91~~	~~1139~~		
~~0.30~~	~~1550~~	~~554~~	~~996~~	~~10.6~~	~~10560~~	~~28.8~~	~~.45~~	~~78~~	~~710~~			~~1139~~	~~411~~	~~4.1~~	~~1665~~	~~73~~	~~1212~~		
~~0.35~~	~~1584~~	~~710~~	~~874~~	~~8.8~~	~~7691~~	~~26.8~~	~~.38~~	~~57~~	~~767~~			~~1212~~	~~372~~	~~3.8~~	~~1415~~	~~62~~	~~1274~~		
~~0.40~~	~~1613~~	~~767~~	~~846~~	~~8.5~~	~~7191~~	~~25.7~~	~~.37~~	~~55~~	~~822~~			~~1274~~	~~339~~	~~3.6~~	~~1220~~	~~54~~	~~1328~~		
~~0.45~~	~~1638~~	~~822~~	~~816~~	~~8.1~~	~~6609~~	~~24.9~~	~~.35~~	~~51~~	~~873~~			~~1328~~	~~310~~	~~3.4~~	~~1054~~	~~46~~	~~1374~~		
~~0.50~~	~~1661~~	~~873~~	~~788~~	~~77~~	~~6085~~	~~24.2~~	~~.32~~	~~46~~	~~919~~			~~1374~~	~~287~~	~~3.1~~	~~890~~	~~39~~	~~1413~~		
~~0.55~~	~~1681~~	~~919~~	~~762~~	~~7.4~~	~~5660~~	~~235~~	~~.31~~	~~44~~	~~963~~			~~1413~~	~~268~~	~~3.0~~	~~804~~	~~35~~	~~1448~~		

TABLE "B"

FOR INFORMATION ONLY

☐ PRELIMINARY CALCULATION SHEET

REV ___ DATE ______

☒ FINAL M-197

REV 2 DATE ______

CAPITAL AUTHORIZATION NO. ______

PREPARED BY JGB JPD DATE 9/23/80

CHECKED BY sage DATE 9/23/80

APPVD BY ______ DATE 10/4/82

SHEET 22 OF 25

SUBJECT: TORUS AREA (-17'6")

SR ☒

NSR ☐

ENTERRING TABLE "B" @ 26.4×10^6 BTU

ie @ $\Sigma Q_S + \Sigma Q_C = (42.35 + 105) \times 10^6$ BTU

we envelope the 26.4×10^6 BTU LOADING AND DETERMINE THE MAXIMUM AVERAGE STEEL TEMPERATURE SHALL BE 137°F.

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REV ___ DATE ______

☒ FINAL M-197

REV 2 DATE ______

CALCULATION SHEET

BOSTON Edison COMPANY

CAPITAL AUTHORIZATION NO. ______

PREPARED BY JB JPB DATE 9/23/86 8/23/86

CHECKED BY DATE 9/23/86

APPVD BY DATE 10/14/86

SHEET 23 OF 25

SUBJECT: TORUS AREA (LL-17c)

SR ☒

NSR ☐

6.6 DISCUSSION

AN EVALUATION OF THE CALCULATIONS INPUT VARIABLES AND CONSERVATIVE ESTIMATES AND ASSUMPTIONS WILL CONCLUDE THAT THE ACTUAL AVERAGE ESTIMATED STEEL TEMPERATURE WILL MOST PROBABLY BE SUBSTANTIALLY LESS THAN THE CALCULATED TEMPERATURE OF 137°F.

THE FOLLOWING IS A REVIEW OF ESTIMATES AND ASSUMPTIONS:

1. THE AMOUNT OF COMBUSTIBLES IS CONSERVATIVELY ESTIMATED.
2. THE HEAT OF COMBUSTION IS THE AMOUNT OF HEAT RELEASED DURING A SUBSTANCES COMPLETE OXIDATION (COMBUSTION). THE HEAT OF COMBUSTION IS DETERMINED IN A LABORATORY UTILIZING A "BOMB CALORIMETER", IN WHICH A KNOWN MASS OF FUEL IS BURNT COMPLETELY IN ATMOSPHERE OF PURE OXYGEN

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CALCULATION SHEET

BOSTON Edison COMPANY

CAPITAL AUTHORIZATION NO. ______
PREPARED BY JB DATE 9/23/86 8/23/86
CHECKED BY ______ DATE 7/23/86
APPVD BY ______ DATE 10/4/86
SHEET 24 OF 25

SUBJECT: TORUS AREA (EL-17'6")

SR ☒
NSR ☐

THE ACTUAL HEAT LOAD WILL BE SUBSTANTIALLY LESS DUE TO ACTUAL FIELD CONDITIONS IN LIEU OF LABORATORY CONDITIONS.

3 REFERENCE NO 7 INDICATES THAT THE NORMALIZED HEAT LOAD ON THE COMPARTMENT BOUNDARIES IS ONLY 10-40% OF "Hm". 'WHERE Hm IS THE CONCIEVEABLE ABSOLUTE MAXIMUM HEAT LOAD". Applying THE MAXIMUM 40% FACTOR, THE CALCULATED TEMPERATURE OF STEEL IS 137 °F.

THIS CALCULATION ASSUMES THE INTERNAL TEMPERATURE OF THE STEEL IS IDENTICAL TO THE SURFACE TEMPERATURE, THIS IS A CONSERVATIVE ASSUMPTION SINCE THE SURFACE HEATS UP FASTER AND IS 100-200 DEGREES HOTTER AFTER EXPOSURE TO THE STANDARD FIRE, i.e. ASTM-E-119 FOR UP TO 60 MIN (R/6)

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B.E.Co. FORM 3930

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CALCULATION SHEET

BOSTON Edison COMPANY

CAPITAL AUTHORIZATION NO. ________
PREPARED BY JFB JPB DATE 9/23/86 8/27/86
CHECKED BY DATE 9/23/86
APPVD BY DATE 10/14/86
SHEET 25 OF 25

SUBJECT: TORUS AREA (-17'6")

SR ☒
NSR ☐

7.0 CALCULATION CONCLUSION

BASED UPON TABLE "B" AND REASONABLE ENGINEERING JUDGEMENT, AS SUPPORTED BY THE DISCUSSION OF THIS CALCULATION'S CONSERVATIVE ESTIMATES AND ASSUMPTIONS, IT IS REASONABLE TO DEDUCE THAT THE STRUCTURAL STEEL IN THE TORUS COMPARTMENT (-17'6") WILL **NOT** REACH AN AVERAGE MAXIMUMUM ESTIMATED TEMPERATURE OF 1,000°F AND THEREFORE IS ASSUMED **NOT** TO FAIL.

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SUBJECT:

CALCULATION SHEET

BOSTON Edison COMPANY

CAPITAL AUTHORIZATION NO. ______
PREPARED BY JPB DATE 8/23/86
CHECKED BY mD DATE 9/23/86
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SHEET 1 OF 29

SR ☒
NSR ☐

ATTACHMENT NUMBER I

REFERENCE	NO OF PAGES
2	1
3 & 4	1
5	1
6	20
7	2

TOTAL NUMBER OF PAGES IN ATT.1 [redacted] + COVER PAGE
28

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REF NO 2
ERM 197 REV-2
ATTACH. I

Pg 2/29

Table 10. Maximum Flux and Corresponding Over-all Temperature Difference for Liquids Boiled at 1 Atm with a Submerged Horizontal Steam-heated Tube

Liquid	Aluminum		Copper		Chromium-plated copper		Steel	
	$\frac{q/A}{1000}$	$(\Delta t)_o$	$\frac{q/A}{1000}$	$(\Delta t)_o$	$\frac{q/A}{1000}$	$(\Delta t)_o$	$\frac{q/A}{1000}$	$(\Delta t)_o$
Ethyl acetate	41	70	61	55	77	55		
Benzene	51	80	58	70	73	100	82	100
Ethyl alcohol	55	80	85	65	124	65		
Methyl alcohol	..	..	100	95	110	110	155	110
Distilled water	..	..	230	85	350	75	410	150

For forced-circulation evaporators, vapor binding is also encountered. Thus with liquid benzene entering a 4-pass steam-jacketed pipe at 0.9 fps, up to the point where 60 percent by weight was vaporized, the maximum flux of 60,000 Btu per hr per sq ft was obtained at an over-all temperature difference of 60 F; beyond this point, the coefficient and flux decreased rapidly, approaching the values obtained in superheating vapor, see Eq. (**6b**). For comparison, in a natural convection evaporator, a maximum flux of 73,000 Btu per hr per sq ft was obtained at $(\Delta t)_o$ of 100 F.

Combined Convection and Radiation Coefficients. In some cases of heat loss, such as that from bare and insulated pipes, where loss is by convection to the air and radiation to the walls of the enclosing space it is convenient to use a combined convection and radiation coefficient $(h_c + h_r)$. The rate of heat loss thus becomes

$$q = (h_c + h_r)A(\Delta t)_s \tag{15}$$

where $(\Delta t)_s$ is the temperature difference, deg F, between the surface of the hot body and the walls of the space. In evaluating $(h_c + h_r)$, h_c should be calculated by the appropriate convection formula [see Eqs. (**11c**) to (**11g**)] and h_r from the equation

$$h_r = 0.00685\epsilon(T_{av}/100)^3$$

where ϵ is the black body coefficient of the radiating surface, p. 4-111, T_{av} is the average temperature of the surface and the enclosing walls, deg R. For oxidized bare steel pipe, the sum $h_c + h_r$ may be taken directly from Table 11.

Table 11. Values of $(h_c + h_r)$

(For horizontal bare or insulated standard steel pipe of various sizes and for flat plates in a room at 80 F)

Nominal pipe diam, in.	$(\Delta t)_s$, temperature difference, deg F, from surface to room														
	50	100	150	200	250	300	400	500	600	700	800	900	1000	1100	1200
½	2.12	2.48	2.76	3.10	3.41	3.75	4.47	5.30	6.21	7.25	8.40	9.73	11.20	12.81	14.65
1	2.03	2.38	2.65	2.98	3.29	3.62	4.33	5.16	6.07	7.11	8.25	9.57	11.04	12.65	14.48
2	1.93	2.27	2.52	2.85	3.14	3.47	4.18	4.99	5.89	6.92	8.07	9.38	10.85	12.46	14.28
4	1.84	2.16	2.41	2.72	3.01	3.33	4.02	4.83	5.72	6.75	7.89	9.21	10.66	12.27	14.09
8	1.76	2.06	2.29	2.60	2.89	3.20	3.88	4.68	5.57	6.60	7.73	9.05	10.50	12.10	13.93
12	1.71	2.01	2.24	2.54	2.82	3.13	3.83	4.61	5.50	6.52	7.65	8.96	10.42	12.03	13.84
24	1.64	1.93	2.15	2.45	2.72	3.03	3.70	4.48	5.37	6.39	7.52	8.83	10.28	11.90	13.70
FLAT PLATES															
Vertical	1.82	2.13	2.40	2.70	2.99	3.30	4.00	4.79	5.70	6.72	7.86	9.18	10.64	12.25	14.06
HFU	2.00	2.35	2.65	2.97	3.26	3.59	4.31	5.12	6.04	7.07	8.21	9.34	11.01	12.63	14.45
HFD	1.58	1.85	2.09	2.36	2.63	2.93	3.61	4.38	5.27	6.27	7.40	8.71	10.16	11.76	13.57

HFU, horizontal, facing upward; HFD, horizontal, facing downward.

Heat Transmission through Pipe Insulation. (McMillan, *Trans. ASME*, 1915.) For any number of layers of insulation on any size of pipe, Eqs. (**2**), (**4**), and (**15**)

combine to give

where q_o/A_o is the Btu
all temperature differ

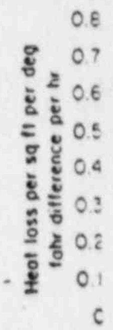

FIG. 6. Variation with
for $k = 0.042$.

outer surface; r_1 is th
layer of insulation, fo
etc., are the conducti
$h_c + h_r$ is often taken
will have but little eff
U_o with pipe size and
tures of 375 and 75 F

FOR INFORMATION ONLY

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TABLE 1

NOMINAL COEFFICIENTS OF THERMAL CONDUCTIVITY (TC) AND THERMAL DIFFUSIVITY (TD)*

Carbon and Low Alloy Steels

	Plain Carbon		Carbon-Silicon		C–Mn		C–Mn–Si		Mat'l. Group A[1]		Mat'l. Group B[2]		Mat'l. Group C[3]	
Temp., °F	TC	TD α	TC	TD	TC	TD	TC	TD	TC	TD	TC	TD	TC	TD
70	35.1	0.695	30.0	0.582	27.5	0.529	23.6	0.454	24.8	0.482	21.3	0.414	24.2	0.471
100	34.7	0.674	29.9	0.567	27.6	0.512	23.9	0.443	25.0	0.477	21.5	0.409	24.3	0.464
150	34.1	0.645	29.6	0.544	27.6	0.496	24.2	0.433	25.1	0.466	21.8	0.400	24.4	0.452
200	33.6	0.617	29.2	0.521	27.6	0.486	24.4	0.422	25.2	0.454	21.9	0.391	24.4	0.439
250	32.9	0.595	28.9	0.502	27.4	0.467	24.4	0.414	25.2	0.442	22.0	0.382	24.3	0.426
300	32.3	0.561	28.4	0.481	27.2	0.453	24.4	0.406	25.1	0.430	22.0	0.373	24.2	0.414
350	31.6	0.534	28.0	0.464	27.0	0.440	24.3	0.396	25.0	0.418	22.0	0.365	24.0	0.402
400	30.9	0.512	27.6	0.447	26.7	0.428	24.2	0.386	24.8	0.405	21.9	0.356	23.9	0.390
450	30.3	0.495	27.1	0.430	26.3	0.413	23.9	0.375	24.6	0.394	21.8	0.347	23.6	0.378
500	29.5	0.472	26.6	0.414	25.9	0.398	23.7	0.364	24.3	0.381	21.7	0.337	23.4	0.367
550	28.8	0.452	26.1	0.398	25.5	0.387	23.4	0.355	24.0	0.370	21.5	0.327	23.1	0.355
600	28.0	0.432	25.6	0.385	25.0	0.374	23.1	0.346	23.7	0.359	21.3	0.320	22.7	0.344
650	27.3	0.414	25.1	0.370	24.5	0.360	22.7	0.333	23.4	0.348	21.0	0.310	22.3	0.333
700	26.6	0.394	24.6	0.355	24.0	0.346	22.4	0.320	23.0	0.335	20.8	0.299	22.0	0.320
750	25.9	0.374	24.0	0.337	23.5	0.332	22.0	0.308	22.6	0.322	20.5	0.288	21.6	0.307
800	25.2	0.355	23.5	0.323	23.0	0.318	21.7	0.298	22.2	0.308	20.2	0.278	21.2	0.295
850	24.5	0.335	23.0	0.309	22.6	0.305	21.2	0.286	21.9	0.297	20.0	0.268	20.9	0.283
900	23.8	0.317	22.5	0.296	22.1	0.291	20.9	0.274	21.4	0.283	19.7	0.258	20.5	0.271
950	23.1	0.301	21.9	0.281	21.5	0.277	20.5	0.262	20.9	0.269	19.4	0.248	20.1	0.259
1000	22.4	0.282	21.4	0.267	21.0	0.263	20.0	0.248	20.4	0.256	19.1	0.238	19.8	0.248
1050	21.6	0.265	20.8	0.252	20.5	0.249	19.6	0.237	19.9	0.242	18.8	0.227	19.4	0.236
1100	20.9	0.250	20.2	0.236	19.9	0.237	19.2	0.228	19.5	0.230	18.5	0.216	19.1	0.225
1150	20.2	0.234	19.6	0.221	19.3	0.219	18.7	0.213	18.9	0.215	18.2	0.204	18.7	0.213
1200	19.5	0.218	19.0	0.206	18.7	0.202	18.2	0.197	18.4	0.202	17.7	0.192	18.2	0.199
1250	18.7	0.197	18.3	0.189	18.0	0.184	17.5	0.179	17.7	0.185	17.2	0.178	17.6	0.184
1300	18.0	0.180	17.6	0.172	17.1	0.159	16.7	0.155	16.7	0.164	16.5	0.161	16.9	0.166
1350	17.2	0.134	16.8	0.151	16.2	0.122	15.8	0.119	15.9	0.142	15.3	0.138	15.6	0.139
1400	16.4	0.097	16.2	0.082	15.6	0.078	15.3	0.077	15.3	0.077	15.0	0.076	15.3	0.077
1450	15.9	0.147	15.7	0.137	15.2	0.155	15.1	0.154	15.0	0.128	14.9	0.130	15.1	0.128
	15.7	0.162	15.6	0.180	15.1	0.169	15.1	0.169	15.0	0.199	14.8	0.171	15.0	0.199

ASME SECTION VIII — DIVISION 2 Table 1

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2.9. The semi-infinite solid. The flux of heat at $x = 0$ a prescribed function of the time. Zero initial temperature

(i) *Constant flux, F_0 per unit time per unit area.* BTU/FT².HR

The flux
$$f = -K\frac{\partial v}{\partial x}, \tag{1}$$
satisfies the same differential equation as v, namely

[illegible] FT²/HR
$$\boxed{\kappa}\frac{\partial^2 f}{\partial x^2} = \frac{\partial f}{\partial t}, \quad x > 0,\ t > 0. \tag{2}$$

The solution of (2) with
$$f = F_0, \quad \text{constant},\ x = 0,\ t > 0, \tag{3}$$
is, by 2.4 (10),
$$f = F_0 \operatorname{erfc}\frac{x}{2\sqrt{(\kappa t)}}. \tag{4}$$

Thus, from (1), using Appendix II, (9) and (11),
$$v = \boxed{\frac{F_0}{K}}\int_x^\infty \operatorname{erfc}\frac{x}{2\sqrt{(\kappa t)}}\,dx \tag{5}$$

THERMAL CONDUCTIVITY BTU/°F·HR·FT

$$= \frac{2F_0\sqrt{(\kappa t)}}{K}\operatorname{ierfc}\frac{x}{2\sqrt{(\kappa t)}} \tag{6}$$
$$= \frac{2F_0}{K}\left\{\left(\frac{\kappa t}{\pi}\right)^{\frac{1}{2}}e^{-x^2/4\kappa t} - \frac{x}{2}\operatorname{erfc}\frac{x}{2\sqrt{(\kappa t)}}\right\}. \tag{7}$$

A table of values of the function ierfc x is given in Appendix II. The temperature at $x = 0$ is given by
$$\boxed{\frac{2F_0}{K}\left(\frac{\kappa t}{\pi}\right)^{\frac{1}{2}}}. \tag{8}$$

The boundary condition of constant flux is of considerable practical importance. It appears if heat is generated by a flat heating element carrying electric current, if heat is generated by friction, and as an approximation in the early stages of heating a furnace or a room. It has also important applications to problems on diffusion. The cooling of the Earth's surface after sunset on a clear windless night† is very nearly that due to removal of heat at a constant rate per unit area per unit time, thus (8) gives the way in which the surface temperature falls after sunset.

The results above apply also to the case of the region $-\infty < x < \infty$ with heat supply $2F_0$ in the plane $x = 0$. The corresponding results for

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† Cf. Brunt, *Quart. J. R. Met. Soc.* **58** (1932) 389.

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FIRE RESISTANCE OF UNPROTECTED STEEL COLUMNS

BY

W. W. STANZAK AND T. T. LIE

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LA RESISTANCE AU FEU DES POUTRES D'ACIER NON PROTEGEES

SOMMAIRE

Les auteurs étudient la résistance au feu des poutres d'acier non protégées au moyen d'essais d'incendie standards et de l'analyse numérique. On a découvert que la durée de la résistance au feu varie selon le facteur forme du poids de la poutre divisé par le périmètre chauffé. Les auteurs ont établi deux équations simples pour calculer les durées de résistance au feu des poutres d'acier non protégées et ils recommandent de les utiliser dans les normes du bâtiment.

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FIRE RESISTANCE OF UNPROTECTED STEEL COLUMNS

By W. W. Stanzak[1] and T. T. Lie[2]

In the past the fire resistance of unprotected steel columns has been considered so small a quantity that it could be ignored. Fire experience and controlled fire tests on structural steel columns of small cross-sectional area showed that unprotected steel columns could not survive the effects of fire exposure for more than 10 min to 20 min. However, it will now be shown that the heavier columns required to carry the vertical loads in modern high-rise buildings are capable of much better fire performance than had previously been realized, and that some can attain fire resistance classifications of 1 hr or better.

Fire fatality statistics (1) show that the number of deaths attributable to structural collapse during a building fire is negligible. The main causes of life loss have been shown to be asphyxiation and burns (1,3,7). Therefore, to provide life safety to occupants, enough fire resistance to allow people time to escape must be provided. Except where escape routes are extremely long or the number of occupants is very large, 10 min to 20 min is usually assumed to be sufficient. However, with very tall buildings it has become evident that evacuation by stairs can be so time consuming that complete evacuation is impractical (4). In such buildings sufficient fire resistance to withstand a burnout of the contents must be provided.

Provision of fire resistance beyond that required to prevent life loss is determined largely be economic considerations. A recent study on the optimum fire resistance of structures (11) has shown that for buildings with a small-loss poten-

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tial it would be uneconomical to provide any fire protection beyond that inherent in the structure, provided such fire resistance is sufficient to allow evacuation by the occupants. Buildings representing a small-loss expectation are those that are small in size and not valuable; those with no valuable contents; those for which the probability of a serious fire is low (e.g., completely sprinklered buildings); or those having a low fire load. The use of unprotected steel columns in such buildings is generally justified if these elements have the minimal fire resistance required to prevent loss of life.

Accordingly, the writers have investigated the fire resistance of unprotected steel columns by methods of numerical calculation and by full-scale fire tests in their laboratory, with a view to developing simple expressions for calculating the fire resistance of these building elements.

TEST METHODS AND CRITICAL TEMPERATURE

On this continent, two test methods are acceptable. The most recent ASTM Standard prescribing these is E119-71 (16).

The older load test requires a sample at least 9 ft in length to be tested under an applied load calculated to develop theoretical working stresses contemplated by the design. The column is required to sustain the applied load for a period of fire exposure equal to that for which classification is desired.

The newer alternate test of protection for structural steel columns requires that a sample at least 8 ft in length be tested in a vertical position without applied load. This test is applicable when the protection is not required by design to carry any part of the column load. The applied protection must be restrained against longitudinal thermal expansion greater than that of the steel column. Temperatures are measured by at least three thermocouples located at each of four levels (cross sections). The upper and lower levels are 2 ft from the ends of the steel column, and the two intermediate levels are equally spaced. The test is considered successful if the transmission of heat through the protection, during the period of fire exposure for which classification is desired, does not raise the average (arithmetical) temperature of the steel to any level above 1,000° F (538° C), or above 1,200° F (649° C) at any one of the measured points.

The 1,000° F average allowable temperature that usually determines the fire endurance time in a test may be regarded as a critical temperature for structural failure established for protected columns as a result of many fire tests on axially loaded column sections. Thus, for the analysis in this paper, it has been assumed that structural failure is imminent when the steel cross section attains an average temperature of 1,000° F as all calculations and fire tests were made on the basis of heat conduction alone.

While complete theoretical justification for the use of temperature criteria is beyond the scope of this paper, it can readily be shown that 1,000° F is a reasonable value. For long columns, assuming that the member is uniformly heated, the buckling stress is given by Euler's formula:

$$\sigma_{cr} = \frac{\pi^2 E_t}{\lambda^2} \quad (1)$$

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and the allowable design stress for long columns is given by CSA S16-1969 (17) as:

$$\sigma_a = \frac{\pi^2 E_o}{1.92 \lambda^2} \qquad (2)$$

in which 1.92 is a safety factor prescribed by the Code and $\sqrt{286{,}000/\sigma_y}$ ($= 131$) $< \lambda \leq 200$.

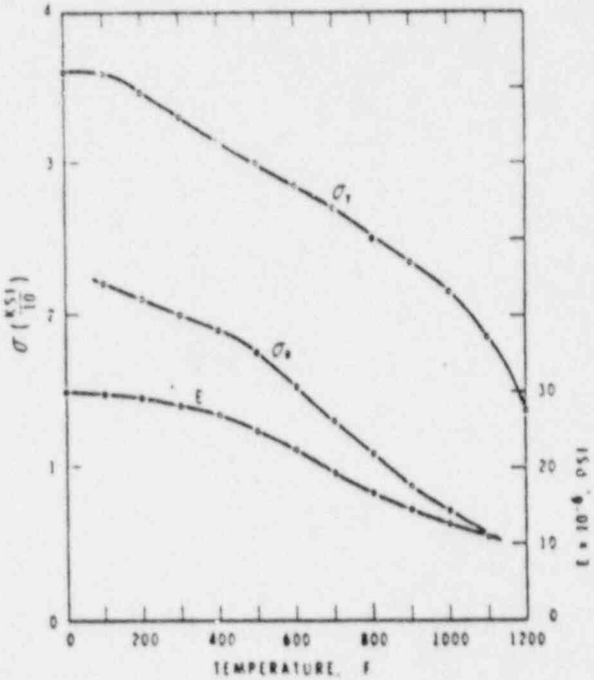

FIG. 1.—Average Compressive Properties of ASTM A36 Structural Steel

At elevated temperatures failure is due to occur when the left-hand sides of the equations are equal, i.e.:

$$E_t = \frac{E_o}{1.92} \qquad (3)$$

Accepting the commonly assumed value for carbon steels of $E_o = 29 \times 10^3$ ksi, then

$$E_t = 15.1 \times 10^3 \text{ ksi } (104 \times 10^9 \text{ N/m}^2) \qquad (4)$$

Using Fig. 1, based on data reported by Ingberg and Sale (10), it is found that the temperature at buckling is approximately 880° F (471° C). Fire tests of loaded columns (9) have shown that the point of maximum expansion (approximately the point at which the column buckles) is followed by a further 100° F-150°

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F (55° C-83° C) rise in temperature before complete failure of the column occurs. Thus failure of columns can be expected at cross-sectional temperatures of from 950° - 1,050° F, (510° C-565° C), depending on the design method and slenderness ratio. A value of 1,000° F has been assumed as a reasonable average for any column, as has been indicated by the ASTM fire test standard.

TEMPERATURE RISE IN UNPROTECTED STEEL COLUMNS

The column is exposed on four sides to the heat of a fire that follows approximately the temperature-time course prescribed in *ASTM E119* for the standard fire of "controlled extent and severity." Heat is transferred from the flames in the furnace and from the furnace walls to the specimen by convection and radiation, with radiation as the primary mechanism when the flames have sufficient thickness (18). The coefficient of heat transfer (the quantity of heat received per unit area of the column, per unit time, and temperature difference between the column surface and fire) depends on many factors. The most significant are: emissivity of the flames; thickness of the flames between furnace walls and column; size of specimen; and thermal properties of the furnace walls. Experimental data (5) have indicated that the heat transfer to the specimen in test furnaces approximates the radiative heat transfer from a black body at the so-called "furnace temperature." Similar heat transfer may also be expected in most building fires because the flames are luminous and usually have considerable thickness, giving them a correspondingly high emissivity.

The coefficient of heat transfer can vary significantly, however, for different individual conditions, and the effect of varying this quantity will be examined later herein.

CALCULATION OF TEMPERATURE RISE

Two-Dimensional Numerical Procedure.—To determine the temperature distribution in massive square steel columns, a number of calculations based on a two-dimensional procedure (12) were carried out. In these tests black body radiation at the prescribed furnace temperature was assumed as the only mechanism of heat transfer. The two equations used for the calculation are:

$$T^{t+1}_{1,n} = T^{t}_{1,n} + \frac{\Delta t}{(\rho c)^{t}_{1,n}(\Delta \xi)^{2}} \{[k^{t}_{2,(n-1)} + k^{t}_{1,n}][T^{t}_{2,(n-1)} - T^{t}_{1,n}] + [k^{t}_{2,(n+1)} + k_{1,n}][T^{t}_{2,(n+1)} - T^{t}_{1,n}] + 2\sqrt{2}\,\Delta \xi\, \sigma\, \epsilon_{r}[(T^{t}_{f})^{4} - (T_{1,n})^{4}]\} \quad \ldots (5)$$

for the temperature of an elementary surface element of the column, and

$$T^{t+1}_{m,n} = T^{t}_{m,n} + \frac{1}{2}\frac{\Delta t}{(\rho c)^{t}_{m,n}(\Delta \xi)^{2}} \{[k^{t}_{(m-1),(n-1)} + k^{t}_{m,n}][T^{t}_{(m-1),(n-1)} - T^{t}_{m,n}] + [k^{t}_{(m+1),(n-1)} + k^{t}_{m,n}][T^{t}_{(m+1),(n-1)} - T^{t}_{m,n}][k^{t}_{(m-1),(n+1)} + k^{t}_{m,n}][T^{t}_{(m-1),(n+1)} - T^{t}_{m,n}] + [k^{t}_{(m+1),(n+1)} + k^{t}_{m,n}][T^{t}_{(m+1),(n+1)} - T^{t}_{m,n}]\} \quad \ldots (6)$$

for the temperature at any point inside the steel cross section, in which T is expressed in degrees Rankine and t in hours. It should be noted that the

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term, ϵ_c, in Eq. 5 is, strictly speaking, a material and temperature dependent quantity, but it is sufficiently accurate, for the purpose of this study, to be regarded as a constant. Also, since most building materials have emissivities in the range of 0.85 to 0.95 (13) a value of 0.9 was used, although the results indicated that a value of 0.95 would have been more appropriate.

The dependence of the thermal properties of steel on temperature was taken into account in the calculations. The material properties used were derived from available data (15) and are reproduced in Table 1. As is apparent, the involved nature of the calculation makes utilization of a high speed digital computer almost mandatory.

TABLE 1.—Thermal Properties of Steel

Temperature, in degrees Fahrenheit (1)	Volumetric heat capacity, in British thermal units per cubic foot-degrees Fahrenheit (2)	Thermal conductivity, in British thermal units per foot-hour-degrees Fahrenheit (3)
70	54.30	26.60
100	54.86	26.60
200	56.36	26.82
300	58.27	26.43
400	60.35	25.87
500	62.44	25.34
600	64.90	24.71
700	67.52	23.72
800	70.56	22.80
900	74.59	21.86
1,000	80.32	21.06
1,100	85.72	20.07
1,200	90.52	18.98
1,250	94.29	18.55
1,300	127.85	18.16
1,350	164.15	17.87
1,400	117.75	17.60
1,450	84.58	17.34
1,500	66.16	16.78
1,550	62.23	15.69
1,600	60.74	15.26
1,650	62.01	15.45
1,700	66.09	15.48
1,900	67.96	16.03
2,100	69.65	16.85
2,350	70.97	17.56

Calculated temperature profiles for a 6-in. (0.152-m) square unprotected steel column are shown in Fig. 2 at 10-min intervals. Similar profiles for a 12-in. (0.304-m) square column are shown in Fig. 3 after 50-min and 60 min of fire exposure. Fig. 3(*b*) shows that at 60 min the maximum temperature difference between the surface and the core was 225° F (125° C) and the temperature at

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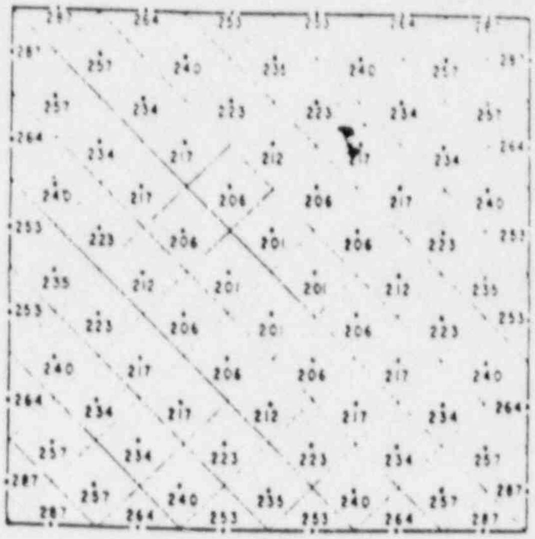
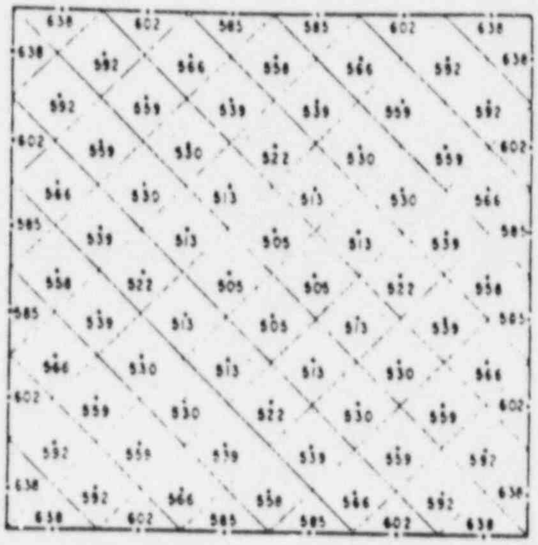


(a) 10 MIN



(b) 20 MIN

FIG. 2.—Temperature Rise in Unprotected Steel Square Column (6 in.)

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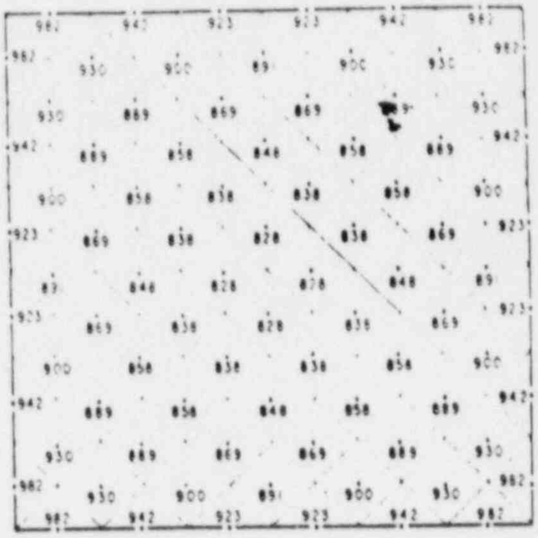
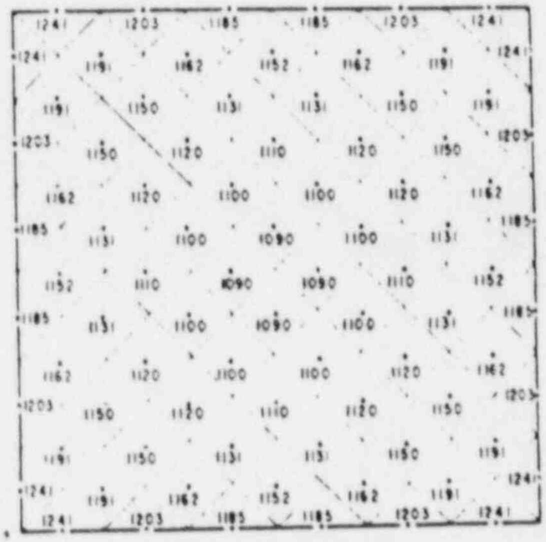


(c) 30 MIN



(d) 40 MIN

FIG. 2.—*Continued*

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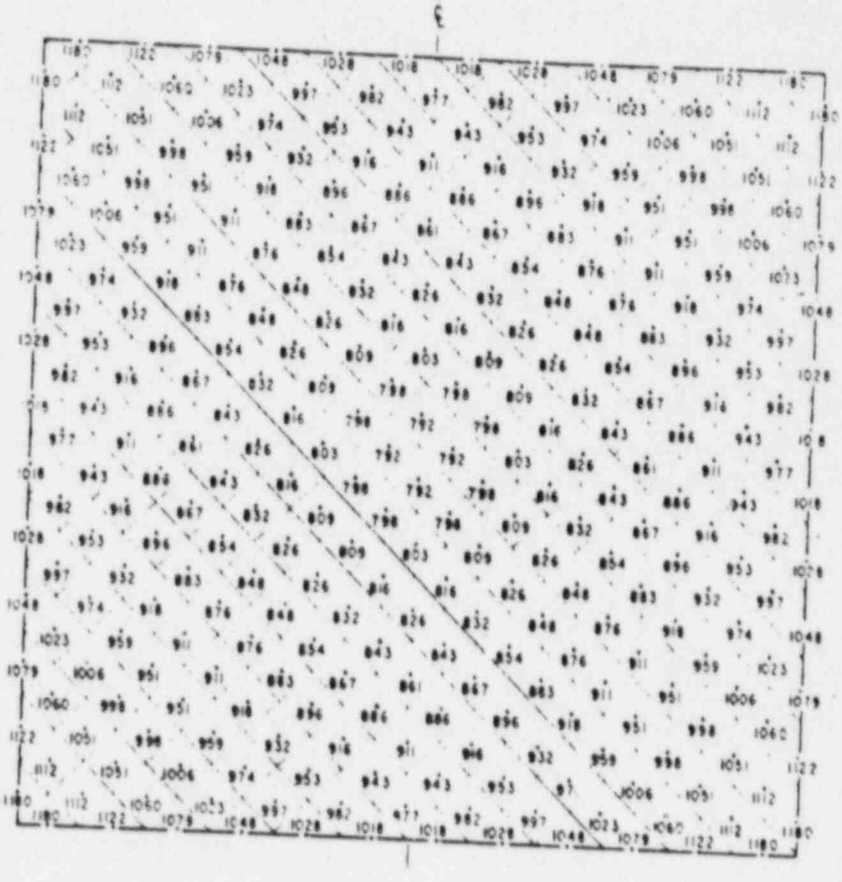
the point midway between the surface and core was about 1,000° F. From Figs. 2(c) and 2(d) it is seen that the maximum temperature difference between the surface of the 6-in. column and the core is about 100° F. This can be regarded as a reasonable maximum for most steel columns likely to be encountered in building practice. For the purpose of determining fire endurance time by temperature rise, the temperature at the point halfway between the surface and core of the cross section (or flange in the case of a wide flange section) may be regarded as representing the average temperature of the cross section. For all but very thick sections this temperature will be almost equal to the temperature at the column surface.

Fig. 4 shows temperature rise curves for a 6-in. square column (calculated or measured as was just described). As is seen, the assumption of radiative heat transfer only does not adequately represent the conditions prevailing in



(a) 50 MIN

FIG. 3.—Temperature Rise in Unprotected Steel Square Column (12 in.)

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the DBR/NCR furnace when short fire endurance times are involved. The curve labeled (2) in Fig. 4 was calculated by assuming that 20% of the heat transfer is due to convection and produces good agreement with the experimental result. Unfortunately, this finding is of no general value because the convective heat transfer varies with each individual situation. With most fires of short duration the convection component of heat transfer can be in the order of 10% to 20%. In the calculation the effect of convective heat transfer was simulated by raising ε from 0.9 to the ficticious value of 1.1.

10
2

1.1

The heat transfer coefficients to columns of square cross section were calculated based on an emissivity (ε) of 0.5 using results obtained by Eqs. 5 and 6. The results are shown in Fig. 5, where the coefficient of heat transfer has been plotted as a function of the duration of standard fire exposure. As is seen, the heat transfer coefficient rises almost linearly with time, and the smaller

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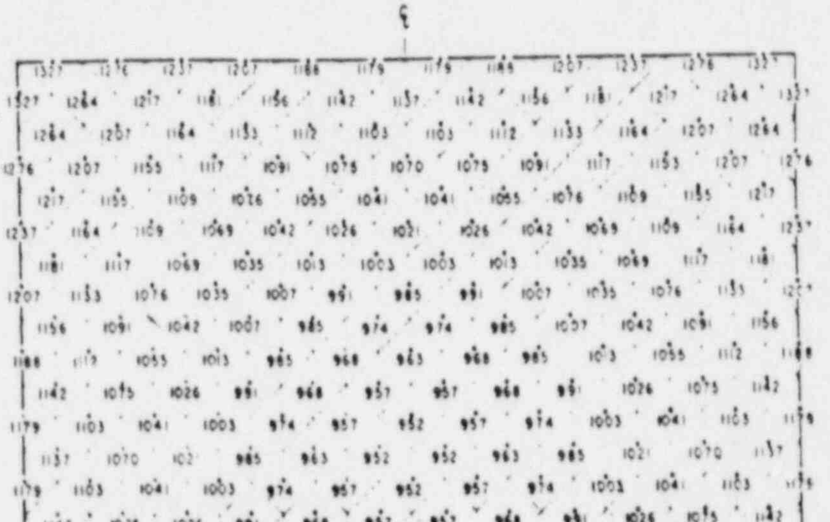

(b) 60 MIN

FIG. 3.—*Continued*

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the column the higher the coefficient of heat transfer.

One-Dimensional Numerical Procedure.—The temperature distributions, determined by the two-dimensional calculation method described previously, show that the temperature differences in the steel are relatively small, except for very thick sections. Most columns used in buildings have sections less than 10 in. (0.25 m) thick. In such cases detailed calculation of temperature distribution in the steel cross section is unnecessary, and a one-dimensional model of the

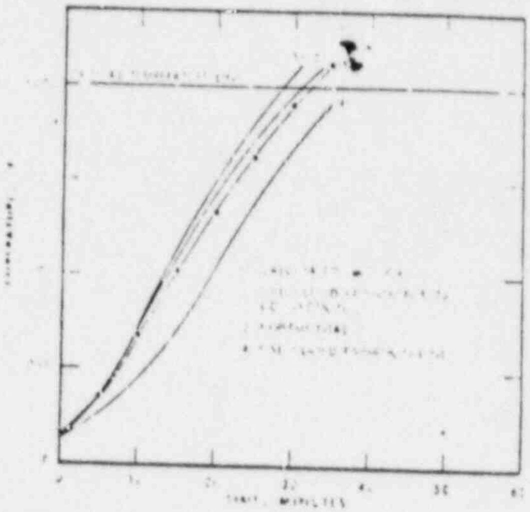

FIG. 4.—Temperature Rise Curves, 6 × 6 Solid Column

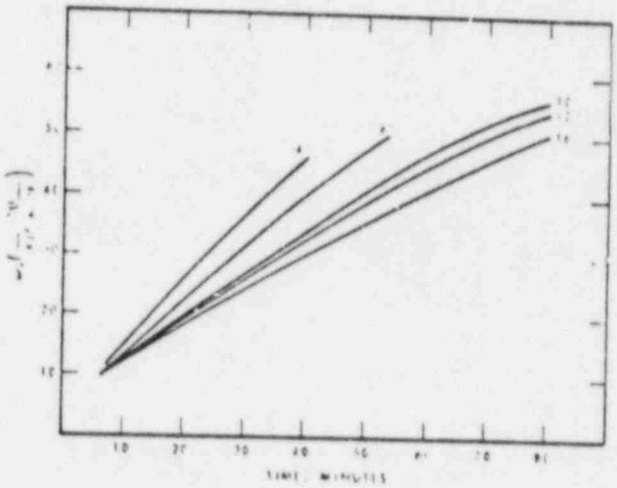

FIG. 5.—Coefficients of Heat Transfer for Unprotected Columns During Exposure to Standard Fire

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heated column can be usefully employed. The model consists of a steel plate having the same cross-sectional and surface areas per unit height as the four sides of the heated column, with the edges and unexposed side perfectly insulated. This model permits use of a one-dimensional numerical procedure by which

TABLE 2.—Sample Calculation for 10-in. Square Column

t (1)	T_f (2)	T_a (3)	$(T_a - T_s)$ (4)	ΔT_s (5)	T_s (6)
0	70	535	465	58	70
5	1,000	1,150	1,022	128	128
10	1,300	1,350	1,094	137	256
15	1,399	1,431	1,038	130	393
20	1,462	1,486	963	120	523
25	1,510	1,530	887	111	643
30	1,550	1,567	813	102	754
35	1,584	1,599	743	93	856
40	1,613	1,626	677	85	949
45	1,638				1,034

Note: α = 18.45; c = 0.12; D = 3.33; W = 340. ΔT_s = 0.125 $(T_f - T_s)$ for Δt = 1/12 hr.

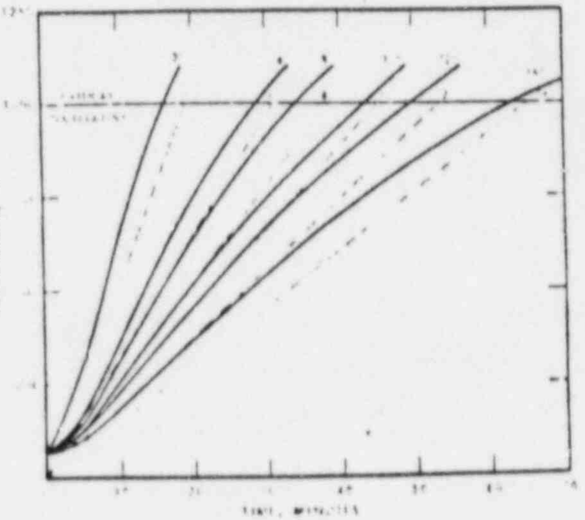

FIG. 6.—Temperature Rise of Square Solid Steel Columns (Calculated, α = 18.45)

the temperature of the steel cross section can be calculated with only a desk calculator or slide rule. In the calculation, with each interval of time, Δt, the rise in steel temperature, ΔT_s, is given by:

$$\Delta T_s = \frac{\alpha}{c}\,\frac{D}{W}\,(T_f - T_s)\,\Delta t \quad \text{.......................... (7)}$$

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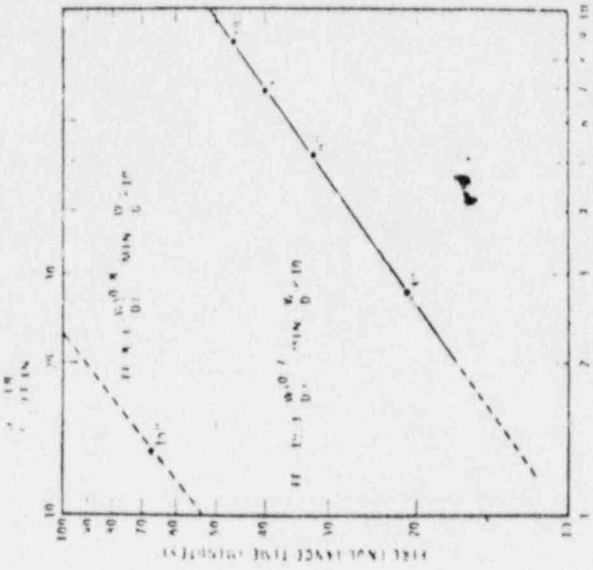

FIG. 8.—Fire Endurance of Square Columns (Experimental)

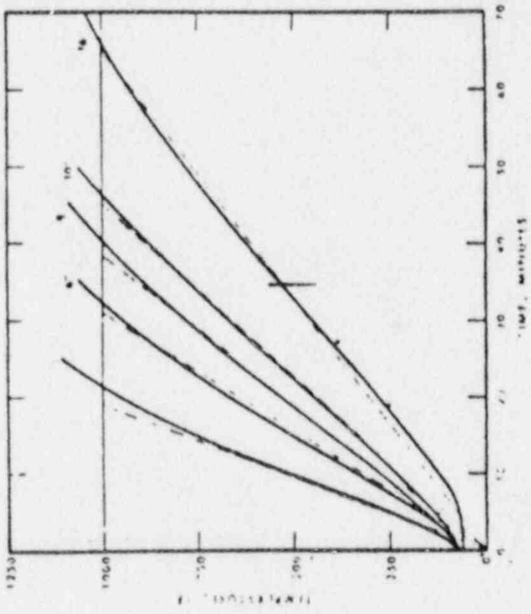

FIG. 7.—Temperature Rise of Square Solid Steel Columns (Experimental data)

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in which Δt is expressed in hours. The results of sample calculation for a 10-in. square column with a = 18.45 (104.8) and c = 0.12 (502) are shown in Table 2. A family of temperature rise curves obtained by similar calculations is shown by the solid lines in Fig. 6.

Experimental Results.—To obtain information on the temperature rise of unprotected steel columns in the DBR/NRC floor furnace, five fire tests were carried out on square solid columns of various cross sections. The temperatures measured at the point halfway between the surface and the core at mid-height of the columns are plotted in Fig. 7. Fig. 8 shows a plot of fire endurance time versus the dimensional parameter, W/D, on logarithmic scales. As is seen, the relationship is linear and, from the graph, it is possible to obtain the following relation directly:

29.5

$$t = 10.3\left(\frac{W}{D}\right)^{0.7} \qquad (8)$$

in which $W/D < 10$. To obtain a relation for columns whose $W/D \geq 10$,

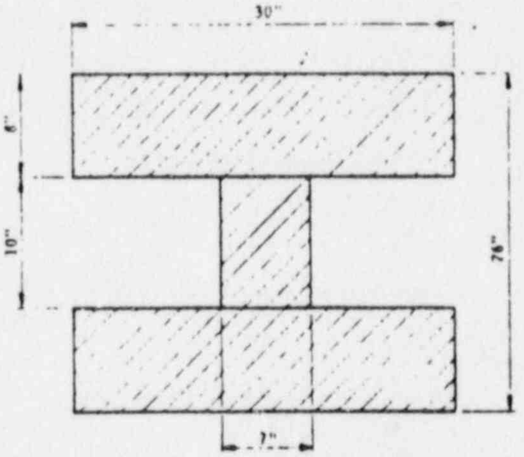

FIG. 9.—Built-up Column—3 Plates

a straight line temperature rise for the 16-in. square column is assumed, as shown by the dashed line in Fig. 7. From this it is possible to obtain the relation:

$$T_s = 120\left(\frac{D}{W}\right)^{0.8} \qquad (9)$$

and by setting T_s equal to the critical temperature of 1,000° F:

$$t = 8.3\left(\frac{W}{D}\right)^{0.8} \qquad (10)$$

The lines resulting from Eq. 9 are plotted in Figs. 6 and 7 (dashed lines). The line resulting from Eq. 10 is plotted in Fig. 8 and that equation should be used for columns having $W/D \geq 10$. However, as is seen from Fig. 7,

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it can be conservatively applied to any column section, and provides a relation that could readily be incorporated into a building by-law. (Although the experi~~mental data are confined to solid square columns, numerical~~ analyses show that Eqs. 9 and 10 can apply to any shape of cross section.)

As an example of the fire resistance typical in columns of very tall buildings, a calculation for the section shown in Fig. 9, one of several massive sections used in Toronto's 56-story Toronto Dominion Centre, is worked out:

$$D = 2(30 + 16) + 2(30 - 7) + 2(10) = 174 \text{ in.} \qquad (11)$$

$$W = 1{,}870 \text{ lb per ft}, \ \frac{W}{D} = 10.75 \qquad (12)$$

Eq. 10 yields a fire endurance time of:

$$t = 8.3(10.75)^{0.8} = 56 \text{ min} \qquad (13)$$

As is seen, these massive sections can have fire endurance times approaching 1 hr, even when unprotected.

Recent North American practice has seen increased installation of sprinkler systems in large (especially tall) buildings, including some that are not considered to have a very high fire load (2,6). ~~Once complete sprinklering of high buildings becomes more common,~~ the use of unprotected massive column sections with a fire resistance capability of about 1 hr should prove adequate for fire safety, provided that the fire load is no more than 5 lb/sq ft to 10 lb/sq ft, which should not result in a fire of severity greater than a 1-hr standard fire (8). (Fire load is the heat of combustion of the combustible contents expressed in equivalent pounds of wood per unit floor area.) It can be reasonably deduced from Refs. 4 and 14 that no safety factor need be applied to the actual fire load if the building is fully sprinklered, although such a safety factor is implied by all current North American building regulations now in force.

ACKNOWLEDGMENTS

This paper is a contribution from the Division of Building Research, National Research Council of Canada, and is published with the approval of the Director of the Division.

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Appendix II.—Notation

The following symbols are used in this paper:

c = specific heat of steel, in British thermal units per pound—degrees Fahrenheit (or degrees Rankine) (joules per kilogram—degrees Kelvin);

D = heated perimeter, in inches (meters);

E = modulus of elasticity of steel, in kips per square inch (newtons per square meter);

FE = fire endurance time, in minutes;

k = thermal conductivity, in British thermal units per foot-hour-degrees Fahrenheit (watts per meter-degrees Kelvin);

T = temperature, in degrees Fahrenheit (degrees Celsius);

t = time, in minutes (unless specified otherwise);

W = mass of steel section, in pounds per foot (kilograms per meter);

α = coefficient of heat transfer, in British thermal units per foot-hour-degrees Fahrenheit (watts per meter-degrees Kelvin);

Δ = increment;

$\Delta\xi$ = mesh width, in feet (meters);

ϵ = emissivity;

λ = slenderness ratio;

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ρ = density of steel, in pounds per cubic foot (kilograms per cubic meter); and

σ = stress, ksi (N/m^2); Stefan-Boltzmann constant, 0.1713×10^{-8}, in British thermal units per hour-square foot-degrees Rankine to the fourth power (watts per square meter—degrees Kelvin to the fourth power);

Subscripts

a = allowable, average;
cr = critical;
f = of furnace;
m = at or around mesh point in mth row;
n = at or around mesh point in nth column;
o = at room temperature;
s = of steel cross section;
T = at temperature T; and
y = at yield stress.

Superscripts

j = at $t = j\Delta t$.

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9719 FIRE RESISTANCE OF UNPROTECTED STEEL COLUMNS

KEY WORDS: **Buildings (codes); Columns; Fire protection;** Fire resistance; Heat transfer; Steel; **Structural engineering; Temperature**

ABSTRACT: Fire resistance of unprotected steel columns is examined by standard fire test and numerical analyses based on a 1,000 D F (538 D-C) critical temperature for failure. It is shown that fire resistance time varies with the shape factor of column weight divided by the heated perimeter, and two simple equations for calculating the fire resistance times of unprotected steel columns are established. A practical example shows that large columns used in high-rise buildings can have fire resistance times of up to one hr. The more conservative of the two equations is recommended for use in building standards.

REFERENCE: "Fire Resistance of Unprotected Steel Columns," *Journal of the Structural Division*, ASCE, Vol. 99, No. ST5, **Proc. Paper 9719**, May, 1973, pp. 837-852

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Fire Technology
Nov

Assessment of Fire Resistance Requirements

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Division of Building Research

The calculation of normalized heat load, a succinct quantifier of the potential of compartment fires to spread by destruction, is greatly simplified by the introduction of two semi-empirical equations. These afford direct insight into the relation between the destructive potential of fire and the principal characteristics of the fire compartment and its contents of combustibles.

ALTHOUGH the bases on which code writers bring down their decisions on fire resistance requirements have changed over the years, the influence of Ingberg's fire load concept[1] is still recognizable. That concept, developed some 40 years ago, claims that the destructive potential of compartment fires is proportional to the specific fire load (mass of combustibles per unit floor area), and that the fire resistance requirement for compartment boundaries should also be allocated in proportion to the specific fire load.

Although still widely used, the concept was soundly disproved by the results of subsequent experimental research. The outlines of a rational way of assigning fire resistance requirements has recently emerged, following the identification of a parameter as a unique quantifier of the potential of enclosure fires for destructive spread.[2] With this new understanding, decisions regarding fire resistance requirements are a matter of matching the of the parameter calculated for real-world conditions with those ed for test conditions.

calculation of the parameter quantifying the destructive spread l of fires under real-world conditions is quite straightforward; but involves an iterative technique, it may prove somewhat time con- for those who attempt to perform it without a programmable or. To eliminate the need for iteration, the feasibility of expressing rameter by an approximate empirical equation has been examined. ults of the examination are reported in this paper.

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theorem of uniformity of normalized heat load.

SEMI-EMPIRICAL EXPRESSION FOR THE NORMALIZED HEAT LOAD

According to statistical data, the fire load in modern buildings, despite the increasing use of plastics, consists predominantly of cellulosics. Since, in addition, fires of cellulosics excel in their destructive potential,[4] it appears to be a safe practice to assume that the fire load consists fully of cellulosics.

By reflecting on the meaning of Ingberg's fire load concept,[1] one recognizes that it has been built on the implicit assumption that in a fire the bulk of the fuel energy is eventually absorbed by the compartment boundaries. The normalized heat load pertaining to the assumption that *all* heat release by the fuel is absorbed within the compartment is

$$H_m = \frac{1}{\sqrt{k\rho c}} \; \frac{G\Delta H}{A_t} \qquad (6)$$

where the subscript *m* has been affixed to *H* to indicate that it represents the conceivable absolute maximum, *G* is the total fire load (total fuel mass), and ΔH is the heat of combustion of the fuel.

Fortunately it has been found that the normalized heat load on the compartment boundaries is only 10 to 40 percent of H_m. Some of the fuel energy is released outside the compartment, but even of the portion released inside some energy will leave the compartment with the fire gases as sensible heat and some will be lost by radiation through the ventilation opening. A multitude of calculations performed by the detailed iterative technique mentioned earlier indicates that the normalized heat load, in other words the potential of fire for destructive spread,

- increases less than in proportion to the fire load,
- decreases as the ventilation of the compartment increases, and
- decreases as the thermal inertia of the boundaries increases.

The numerical results of these calculations formed the basis for an investigation that resulted in the following semi-empirical equation:

$$H = 10^6 \frac{(11.0\,\delta + 1.6)\,G}{A_t\sqrt{k\rho c} + 935\sqrt{\Phi G}} \qquad (7)$$

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where δ is a factor that characterizes the fraction of the fuel energy released inside the compartment. It is to be estimated from the following equation:

$$\delta = \begin{cases} 0.79\sqrt{h_c^3}/\Phi \\ 1 \end{cases} \quad \text{whichever is less} \qquad (8)$$

where h_c is the height of the compartment.

Φ is a variable that characterizes the ventilation of the compartment. It is defined as

$$\Phi = \rho_a A_v \sqrt{gh} \qquad (9)$$

where ρ_a is the density of environmental atmosphere, A_v is the area of ventilation opening (window or door), *h* is the height of the ventilation opening, and *g* is the acceleration due to gravity. The considerations that have led to the development of Equation 7 are discussed in the Appendix.

As the specific fire load G/A_t (where A_t is the floor area of the compartment) may vary rather markedly from compartment to compartment, the selection of the value of *G* for the fire safety design must be based on an analysis of statistical data. If the compartment boundaries are simple "dividing elements" without essential structural functions, the design value for G/A_t is usually taken as the 80th percentile in the cumulative plot for the applicable occupancy. If, on the other hand, the compartment boundaries are "key elements" that play an important part in the structural performance of the building as a whole, some extra degree of safety is justified. The selection of *G* may be based on considerations propounded by Lie[3] and outlined later by Harmathy.[4]

The ventilation parameter, Φ, is a measure of the minimum ventilation of the compartment. This occurs under "classic" draft-free conditions. As discussed by Harmathy,[4] the presence of drafts causes the value of Φ to increase over that calculated from Equation 9 and thus (by virtue of Equation 7) to reduce the value of the normalized heat load, a value for Φ obtained from Equation 9 may be used in assessing the potential of fires for destructive spread.

It is of interest to examine the normalized heat load in relation to its limiting value, as expressed by Equation 6. Combining Equations 6 and 7 and using $\Delta H = 18.8 \times 10^6$ J kg^{-1} in the former (because the fire load is assumed to be cellulosic), the following equation is obtained:

$$\frac{H}{H_m} = \frac{0.585\,\delta + 0.085}{1 + 935\dfrac{\sqrt{G\Phi}}{A_t\sqrt{k\rho c}}} \qquad (10)$$

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HEAT, MASS,
AND
MOMENTUM TRANSFER

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TABLE E.1—Continued

(2) Nonmetals	T (°F)	ρ (lb_m/ft^3)	c_p (Btu/lb_m F)	k (Btu/hr ft F)	α (ft^2/hr)
Aerogel, silica	100	5.3	0.205	0.013	0.012
Asbestos	32	36	0.25	0.08	0.010
	800	36		0	
Brick, common	68	100	0.20	0.20∼.10	0.01-0.02
fire clay	1472	145	0.23	0.79	0.024
Bakelite	68	79.5	0.38	0.134	0.0044
Concrete	68	119-144	0.21	0.47-0.81	0.019-0.027
Corkboard	100	10	0.4	0.025	0.006
Diatomaceous earth, powdered	100	14	0.21	0.030	0.01
Fiber insulating board	100	14.3		0.024	
Glass, window	68	162	0.16	0.51	0.020
Glass wool, fine	100	1.5		0.031	
packed	100	6.0		0.022	
Ice	32	57	0.46	1.28	0.048
Magnesia, 85%	100	17		0.039	
Marble	68	156-169	0.193	1.6	0.054
Paper				0.075	
Rock wool	100	12		0.023	
Rubber, hard	32	74.8	0.48	0.087	0.0024
Wood, oak, ⊥ to grain	70	51	0.57	0.12	0.004
Wood, oak, ∥ to grain	70	51	0.57	0.23	0.0069

SOME SOLIDS

k (Btu/hr ft F) F)	(212 F)	(1,12 F)	α (ft^2/hr) (68 F)
	119		3.665
	74		1.322
	–		
	13		0.237
	219	204	4.353
	39	23	0.785
			0.666
	33	21	0.634
	19.3		0.924
	97		3.762
	68	61	2.074
	48		0.882
	37	32	0.677
2	240		6.601
5	25	19	0.452
9.4	10	13	0.172
7	34		1.505
4	87	65	2.430
4.8	63		1.591

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600	800	1000
0.0266	0.0303	0.0337
0.0238	0.0292	0.0345

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Table 3. Thermal Conductivities of Miscellaneous Solid Substances*

(Values of k are to be regarded as rough average values for the temperature range indicated)

Material	Bulk density, lb per cu ft	Temp, deg F	k	Material	Bulk density, lb per cu ft	Temp, deg F	k
Asbestos board, compressed asbestos and cement	123.	86.	0.225	Quartz, crystal, parallel to C-axis	...	−300.	25.0
Asbestos millboard	60.5	86.	0.070			0.	8.3
Asbestos wool	25.	212.	0.058			300.	4.2
Ashes, soft wood	12.5	65.	0.018	Rubber, hard	74.3	100.	0.092
Ashes, volcanic	51.	300.	0.123	Rubber, soft, vulcanized	68.6	86.	0.08
Carbon black	12.	133.	0.012	Sand, dry	94.8	68.	0.188
Cardboard, corrugated	...	...	0.037	Sawdust, dry	13.4	68.	0.042
Celluloid	87.3	86.	0.12	Silica, fused	...	200.	0.83
Cellulose sponge, du Pont	3.4	82.	0.033	Silica gel, powder	32.5	131.	0.049
Concrete, sand and gravel	142.	75.	1.05	Soil, dry	...	68.	0.075
Concrete, cinder	97.	75.	0.41	Soil, dry, including stones	127.	68.	0.30
Charcoal, powder	11.5	63.	0.029	Snow	7-31	32.	0.34-1.3
Cork, granulated	5.4	23.	0.028	Titanium oxide, finely ground	52.	1000.	0.041
Cotton wool	5.0	100.	0.035	Wool, pure	5.6	86.	0.021
Diamond	151.	70.	320.	Zirconia grain	113.	600.	0.11
Earth plus 42% water	108.	0.	0.62	Woods, oven dry, across grain†:			
Fiber, red	80.5	68.	0.27	Aspen	26.	85.	0.069
"Flotofoam" (U.S. Rubber Co.)	1.6	92.	0.017	Bald cypress	24.	85.	0.063
Glass, pyrex	139	200.	0.59	Balsa	10.	85.	0.034
Glass, soda lime	...	200.	0.59	Basswood	24.	85.	0.058
Graphite, solid	93.5	122.	87.	Douglas Fir	29.	85.	0.063
Gravel	116.	68.	0.22	Elm, rock	48.	85.	0.097
Gypsum board	51.	99.	0.062	Fir, white	26.	85.	0.069
Ice	57.5	...	1.26	Hemlock	29.	85.	0.066
Kaolin wool	10.6	800.	0.059	Larch, western	36.	85.	0.078
Leather, sole	62.4	...	0.092	Maple, sugar	43.	85.	0.094
Mica	122.	...	0.25	Oak, red	42.	85.	0.099
Pearlite, Arizona, spherical shell of siliceous material	9.1	112.	0.035	Pine, southern yellow	35.	85.	0.078
Polystyrene, expanded "Styrofoam"	1.7	...	0.021	Pine, white	25.	85.	0.060
Pumice, powdered	49.	300.	0.11	Red cedar, western	21.	85.	0.053
Quartz, crystal, perpendicular to C-axis	...	−300.	12.5	Redwood	25.	85.	0.062
		0.	4.3	Spruce	21.	85.	0.052
		300.	2.3				

---

* The thermal conductivity of different materials varies greatly. For metals and alloys k is high, while for certain insulating materials, such as glass wool, cork, and kapok, it is very low. In general, k varies with the temperature, but in the case of metals, the variation is relatively small. With most other substances, k increases with rising temperatures, but in the case of many crystalline materials, the reverse is true.

† With heat flow parallel to the grain, k may be 2 to 3 times that with heat flow perpendicular to the grain; the values for wood are taken chiefly from J. D. MacLean, *Trans. ASHRAE*, 47, 1941, p. 323.

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M-197 REV. 2

Attachment II - Independent Verification Statement (CIVIL/STRUCTURAL)

Calculation # M197, Revision # 2 *(SEE NOTES BELOW) has been independently verified by the following method(s), as noted below:

Design Review ☒ including verification that:

- * Design inputs were correctly selected and included in the calculation.
- * Assumptions are adequately described and are reasonable.
- * Input or assumptions requiring confirmation are identified, and if any exist, the calculation has been identified as "Preliminary" and a "Finalization Due Date" has been specified.
- * Design requirements from applicable codes, standards and regulatory documents are identified and reflected in the design.
- * Applicable construction and operating experience was considered in the design.
- * The calculation number has been properly obtained and entered.
- * An appropriate design method or computer code was used.
- ° A mathematical check has been performed.
- ° The output is reasonable compared to the input.

Alternate Calculation ☐ including verification of asterisked items noted above. The alternate calculation (pages) is attached.

Qualification Testing ☐ for design feature ______________ including verification of asterisked items noted above and the following:

- ° The test was performed in accordance with written test procedures.
- ° Most adverse design conditions were used in the test.
- ° Scaling laws were established and verified and error analyses were performed, if applicable.
- ° Test acceptance criteria were clearly related to the design calculation.
- ° Test results (documented in ______________) were reviewed by the calculation Preparer or other cognizant engineer.

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* NOTES:
Independent Verifier Comments: 1. THE SCOPE OF THIS INDEPENDENT VERIFICATION IS LIMITED TO THE REVIEW OF THE CONCRETE AND STEEL SURFACE AREA CALCULATIONS ON PAGES 12 THROUGH 19 ; AND ITEM # 2 BELOW.

See NED Procedure 3.05, Sec. 7.1.1

/s/ Joseph L. Jerz 9/26/86
Independent Verifier Date

Preparer concurrence with findings and comment resolution

/s/ John T. Prawlucki 9/23/86
Preparer or other cognizant engineer Date

Exhibit 3.05-Q Rev. 5

2. REFER TO INDEPENDENT REVIEW STATEMENT ATTACHMENT II TO CALCULATION NO. FP 26 REV. 1 DATED 9-23-8 "DOCUMENTATION OF STRUCTURAL PERFORMANCE OF STE ELEVATED TEMPERATURES" BY J. PRAWLUCKI DATED [redacted] [redacted] THIS PROVIDES FURTHER JUSTIFICATION OF THE USE OF 1000 F AS A TEMPERATURE LIMIT FOR UNPROTECTED STRUCTURAL STEEL.

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M197

Attachment ~~I~~ III - Independent Verification Statement (FS&MC)

Calculation # M197 Revision # 2 has been independently verified by the following method(s), as noted below:

Design Review ☒ including verification that:

- * Design inputs were correctly selected and included in the calculation.
- * Assumptions are adequately described and are reasonable.
- * Input or assumptions requiring confirmation are identified, and if any exist, the calculation has been identified as "Preliminary" and a "Finalization Due Date" has been specified.
- * Design requirements from applicable codes, standards and regulatory documents are identified and reflected in the design.
- * Applicable construction and operating experience was considered in the design.
- * The calculation number has been properly obtained and entered.
- * An appropriate design method or computer code was used.
- ∘ A mathematical check has been performed.
- ∘ The output is reasonable compared to the input.

Alternate Calculation ☐ including verification of asterisked items noted above. The alternate calculation (___ pages) is attached.

Qualification Testing ☐ for design feature ______________________ including verification of asterisked items noted above and the following:

- ∘ The test was performed in accordance with written test procedures.
- ∘ Most adverse design conditions were used in the test.
- ∘ Scaling laws were established and verified and error analyses were performed, if applicable.
- ∘ Test acceptance criteria were clearly related to the design calculation.
- ∘ Test results (documented in ______________________) were reviewed by the calculation Preparer or other cognizant engineer.

Independent Verifier Comments: see attached sheet comments resolved *

See NED Procedure 3.05, Sec. 7.1.1

/s/ J S Roberts 10/2/86
Independent Verifier Date

Preparer concurrence with findings and comment resolution

/s/ J F Bienkiewicz 10/3/86
Preparer or other cognizant engineer Date

Exhibit 3.05-Q Rev. 5

FOR INFORMATION ONLY

ATTACHMENT III - INDEPENDENT VERIFICATION
ES&MC

QUESTIONS / COMMENTS

CALC M197
PAGE 2 OF 4

Q1 SHOULD THE STANDARD TIME TEMPERATURE CURVE (ASTM-E-119) BE INCLUDED AS AN ATTACHMENT TO THE CALCULATION?

Q_2 HOW WERE THE TEMPERATURES DETERMINED FOR TIME INCREMENTS FOR THE CALCULATION?

Q_3 CLARIFY TABLE 6.5. WHY IS TABLE DEVELOPED FOR COMBUSTIBLE LOADINGS GREATER THAN FOUND IN AREAS ANALYSED?

Q_4 WHAT IS THE RELATIONSHIP BETWEEN FIRE LOADING AND HEAT FLUX? DOES FIRE LOADING EQUAL HEAT FLUX AT EQUILIBRIUM?

Q_5 WHAT IS THICKNESS OF THE CONCRETE FIRE BARRIERS?

Q_6 SHOULD THE TEMPERATURE COMPUTATION BE IN UNITS OF °R?

Q_7 CLEARLY IDENTIFY THE NEW SURFACE TEMPERATURE IN CALCULATION.

Q_8 DOES ASSUMPTION 9 APPLY TO THIS CALCULATION?

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ATTACHMENT III - INDEPENDENT VERIFICATION
FSMC

ANSWERS/COMMENTS

CALC M197
PAGE 3 OF 4

A1. THE STANDARD-TIME-TEMPERATURE CURVE IS FROM A NATIONAL STANDARD (ASTM) AND WAS NOT INCLUDED IN THE CALCULATION TEXT. THE "STT" CURVE DOES, HOWEVER, APPEAR IN ATTACHMENT II, pg 8 OF 22.

A2. THE TEMPERATURES FOR THIS CALCULATION WERE TAKEN FROM APPENDIX "B" OF THE NATIONAL FIRE CODES; VOLUMN 10; 1981; SECTION 251. APPENDIX "B" IS ACTUALLY THE ASTM-E-119 CURVE IN TABULAR FORM.

A3. TABLE 6.5 HAS BEEN MARKED-UP TO CLEARLY IDENTIFY STEEL TEMPERATURES. PORTIONS OF THE TABLE, WHICH EXCEED THE COMBUSTIBLE HEAT LOAD WHICH IS APPLIED TO THE AREA BOUNDARY, HAVE BEEN ELIMINATED.

A4. THE HEAT FLUX IS DETERMINED BY COLUMNS 1 THRU 6 (TABLE A). IT IS A FUNCTION OF ΔT AND THE COMBINED CONVECTION AND RADIATION COEFFICIENTS. THE HEAT FLUX IS USED TO DETERMINE THE GROSS HEAT APPLIED TO THE

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ATTACHMENT III - INDEPENDENT VERIFICATION
FS&MC

CALC M197
PAGE 4 OF 4

ANSWERS/COMMENTS

A4.(CON'T) BOUNDARIES. WHEN THE TOTAL GROSS HEAT APPLIED $(\Sigma Q_s + \Sigma Q_c)$ IS EQUAL TO 40% OF THE THEORITICAL FIRE LOAD, THE TEMPERATURE OF THE STEEL IS IDENTIFIED.

A5. THE THICKNESS OF THE CONCRETE FIRE BARRIERS IS NOT REQUIRED FOR THIS CALCULATION. THE CONCRETE THICKNESS MEETS OR EXCEEDS THE THICKNESS REQUIRED FOR THE FIRE BARRIER RATING.

A6. THE TEMPERATURE COMPUTATION, IN DEGREES FAHRENHEIT, IS ACCEPTABLE:

a) $F_o = \Delta T h$

b) $$T_w = T_{w_1} + 2\left(\frac{F_o}{K}\right)\left(\frac{ab}{3.14}\right)^{1/2}$$

ABOVE FORMULA UTILIZES A ΔT FOR a) ∴ ΔT OF 1°F = ΔT OF 1°R

A7. DONE

A8. ASSUMPTION 9 HAS BEEN DELETED FROM THE CALCULATION ASSUMPTIONS. THIS ASSUMPTION IS NOT REQUIRED.

ATTACHMENT 3 TO BECO LETTER 88-010

BECo Calculation M198, Revision 1

STEAM TUNNEL

Boston Edison Company

CALCULATION COVER SHEET

CAPITAL AUTHORIZATION NO ______

PILGRIM UNIT 1

Sheet 1 of 21

M198 REV. 1 File No. ______

Subject FIRE RESISTANCE OF STRUCTURAL STEEL IN THE STEAM TUNNEL

Discipline Group Leader TJ TRACY / WS CLANCY

Approval /s/ TJ Tracy by [illegible] 9-24-86 / W S Clancy 10/4/86 Date ______

SR ☒

NSR ☐

Preliminary Calc. ☐

Finalization due date ______

Final Calc. ☒

Independent Verifier CIVIL/STRUCTURAL 9/26/86 Statement Attached ☒

Page(s)	By	Date	Chk'd	Date	Agree
All	By J.F. Bienkiewicz /s/ J F Bienkiewicz JFB	8/29/86 9/23/86	Chk'd ~~Michael J Di Meo~~ John T. Frawlucki /s/ M J Di Meo John T. Frawlucki 9/23/86	9/23/86	X

THIS CALCULATION VERIFIES THE ADEQUACY OF FIRE BARRIERS, FOR THE ABOVE AREAS, BY EVALUATING THE UNPROTECTED STRUCTURAL STEEL WHICH IS PART OF OR SUPPORTS THE FIRE BARRIER.

THIS CALCULATION SUPERSEDES M-198 R 0 TO PRESENT THE CALCULATION IN AN EASY TO FOLLOW FORMAT AND CLARIFY AREAS OF THE CALCULATION TO ELIMINATE CONFUSION.

THIS CALCULATION REVISION SUPPORTS THE ORIGINAL CALCULATION CONCLUSION, THAT THE STEEL WILL NOT ATTAIN A MAXIMUM AVERAGE TEMPERATURE OF 1000°F, AND THEREBY CONFIRMS THE ADEQUACY OF THE UNPROTECTED STRUCTURAL STEEL TO SUPPORT THE FIRE BARRIER DURING A FIRE. REFER TO ATTACHMENT II FOR INDEPENDENT VERIFICATION STATEMENT (CIVIL/STRUCTURAL) AND ATTACHMENT III FOR FS&MC INDEPENDENT VERIFICATION STATEMENT.

Minor revision(s) made on page(s) ______ of this calculation. See next revision.

Replaces calc # ______

Voided by calc # ______ or attached memo

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REV ___ DATE ______

☒ FINAL M198
REV 1 DATE ______

SUBJECT:

CALCULATION SHEET

BOSTON Edison COMPANY

CAPITAL AUTHORIZATION NO. ______ 9/23/86
PREPARED BY JPD JPD DATE 8/27/86
CHECKED BY mp DATE 9/23/86
APPVD BY ______ DATE 10/9/86
SHEET 2 OF 21

SR ☒
NSR ☐

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SUBJECT:

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1.0 PURPOSE

THE PURPOSE OF THIS CALCULATION IS TO ESTIMATE THE MAXIMUM AVERAGE UNIFORM TEMPERATURE THAT STEEL IN THE STEAM TUNNEL MAY ATTAIN DUE TO A POSTULATED FIRE. THE FAILURE POINT FOR STEEL WILL BE DEFINED AS A MAXIMUM AVERAGE TEMPERATURE OF GREATER THAN 1,000 °F.

2.0 SUMMARY OF RESULTS

THE NUMERICAL ANALYSIS PRESENTED IN TABLE B. AUGMENTED BY THE DISCUSSION OF CONSERVATIVE ESTIMATES AND ASSUMPTIONS CONCLUDES THAT THE MAXIMUM AVERAGE UNIFORM TEMPERATURE OF STEEL IN THE STEAM TUNNEL WILL NOT EXCEED 255°F. SINCE THE FINAL TEMPERATURE IS LESS THAN 1000°F, IT IS ASSUMED THAT THE STRUCTURAL STEEL WILL NOT DEGRADE THE FIRE BARRIER

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3.0 METHODOLOGY

3.1 THE TEMPERATURE WITHIN THE STEAM TUNNEL SHALL BE MODELED TO FOLLOW THE TEMPERATURE PROFILE PRESENTED BY THE STANDARD TIME-TEMPERATURE CURVE IN ASTM-E-119. THE MODEL SHALL ASSUME AMBIENT TEMPERATURE OF 68°F.

3.2 AS THE TEMPERATURE OF THE MODELED SPACE RISES (PER ASTM-E-119) THE TEMPERATURE DIFFERENCE, BETWEEN THE SPACE (T_F) AND THE SPACE BOUNDARY (T_w) IS CALCULATED (ΔT). THIS INITIAL TEMPERATURE DIFFERENCE IS UTILIZED TO DETERMINE THE COMBINED CONVECTION AND RADIATION COEFFICIENTS ($h_c + h_r$) = h REQUIRED TO CALCULATE THE HEAT FLUX (F_o) PER UNIT AREA.

$$\boxed{F_o = \Delta T\, h}$$

3.3 THE HEAT FLUX PER UNIT AREA (F_o) IS THEN UTILIZED TO TO INDEPENDENTLY

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SUBJECT:

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CALCULATE THE NEW SPACE BOUNDARY SURFACE TEMPERATURE OF STEEL (T_{w_s}) AND CONCRETE (T_{w_c}).

$$\boxed{T_w = T_o + 2\left(\frac{F_o}{K}\right)\left(\frac{\partial b}{3.14}\right)^{1/2}}$$

3.4 THE TOTAL HEAT ABSORBED BY THE SPACE BOUNDARY IS CALCULATED (Q_s ; Q_c),

$$\boxed{Q_s = F_{o_s} A_s \; ; \quad Q_c = F_{o_c} A_c}$$

3.5 THE THEORETICAL FIRE LOADING OF THE SPACE SHALL BE CALCULATED.

FIRE LOADING = COMBOSTIBLES × HEAT OF COMBUSTION
BTU = (LB. × BTU/LB.)

3.6 THE THEORETICAL FIRE LOADING SHALL BE REDUCED TO A NET FIRE LOADING BASED UPON PUBLISHED INDUSTRY DATA AND CALCULATION SUPPORTED ASSUMPTIONS. THE NET FIRE LOAD SHALL BE UTILIZED TO IDENTIFY THE MAXIMUM AVERAGE STEEL TEMPERATURE

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NSR ☐

4.0 REFERENCES:

1. FIRE TEST STANDARDS, FIRST EDITION, 1982 ASTM-E-119, TABLE X1, PAGE 53.
2. STANDARD HANDBOOK FOR MECHANICAL ENGINEERS, SEVENTH EDITION, TABLE 11, PAGE 4-106, AND FORMULA (15). (ATTACHED)
3. THERMAL CONDUCTIVITY:

   STEEL - ASME VIII - DIVISION 2 - TABLE 1 (ATTACHED)

   CONCRETE - STANDARD HANDBOOK FOR MECHANICAL ENGINEERS. SEVENTH EDITION. TABLE 3, PAGE 4-95. (ATTACHED)
4. FOR STEEL - THERMAL DIFFUSIVITY - ASME VIII - DIVISION 2 - TABLE 1 (ATTACHED).
5. CONDUCTION OF HEAT IN SOLIDS. Pg 75, PARA 2.9 - CARSLAW & JAEGER (ATTACHED)
6. NATIONAL RESEARCH COUNCIL OF CANADA, FIRE RESISTANCE OF UNPROTECTED STEEL COLUMNS, RESEARCH PAPER N677. MAY 23. 1973 - (ATTACHED).
7. FIRE TECHNOLOGY, NFPA, ASSESSMENT OF FIRE RESISTANCE REQUIREMENTS. VOL 17, NOVEMBER 1981. (ATTACHED)
8. 1978 STRUCTURAL STEEL SHAPES. BETHLEHEM CATALOG 3277. 1978 EDITION.
9. DRAWING REFERENCES ARE IDENTIFIED IN SECTION 6.3

3 CON'T - CONCRETE THERMAL DIFFUSIVITY; "HEAT, MASS, AND MOMENTUM TRANSFER", W.M. ROHSENOW + H.Y. CHOI - PRENTICE HALL INC (ATTACHED)

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5.0 ASSUMPTIONS

1. AREA TEMPERATURE ASSUMED TO BE 68°F @ T_o.
2. THE COMBINED CONVECTION AND RADIATION COEFFICIENT VALUES ASSUME LINEAR APPROXIMATION BETWEEN TABLE TEMPERATURE VALUES.
3. THE THERMAL CONDUCTIVITY - ASSUME - LINEAR APPROXIMATION BETWEEN TABLE TEMPERATURE VALUES FOR STEEL. THE CONCRETE THERMAL CONDUCTIVITY IS ASSUMED CONSTANT OVER TEMPERATURE RANGE.
4. THE STEEL THERMAL DIFFUSIVITY - ASSUME LINEAR APPROXIMATION BETWEEN TABLE TEMPERATURE VALUES FOR STEEL. THE CONCRETE THERMAL DIFFUSIVITY IS ASSUMED CONSTANT OVER TEMPERATURE RANGE
5. STEEL IS ASSUMED TO FAIL WHEN IT REACHES AN ESTIMATED MAXIMUM UNIFORM AVERAGE TEMPERATURE OF 1,000 °F.
6. THE STEEL IS ASSUMED TO HEAT UNIFORMILY.
7. COMBUSTIBLE MATERIAL IS ASSUMED TO RELEASE AN AMOUNT OF HEAT EQUIVALENT TO THE THEORITICAL HEAT OF COMBUSTION.
8. [BLANK]
9. ~~EMISSIVITY OF STEEL EQUALS ABSORPTIVITY OF CONCRETE.~~ JPP

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REV. 1 DATE ________

SUBJECT:

Boston Edison Company

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NSR ☐

ASSUMPTIONS - CON'T

10. STEEL AND CONCRETE ACT AS SEMI-INFINITE SOLIDS.
11. INSULATION - HEAT OF COMBUSTION ASSUMED TO BE 21000 BTU/Lb WHICH IS MAXIMUM FOR CABLES IN THIS AREA.
12. [BLANK]
13. ALTHOUGH THE NOTE ON TABLE 11 (REF 2) INDICATES THE VALUES OF h ARE BASED ON AN 80°F ROOM TEMPERATURE, FOR THIS CALCULATION THE VALUES ARE ACCEPTABLE FOR DETERMINING AN ORDER OF VALUE FOR THE COMBINED COEFFICIENT.

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CALCULATION SHEET

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6.0 DETAILED CALCULATION

6.1 CALCULATION DATA IS PRESENTED IN TABULAR FORM ON TABLE A.

COLUMN NUMBER 1 IS THE TIME - IN MINUTES - RELATIVE TO THE TIME TEMPERATURE CURVE IN ASTM E-119.

COLUMN NUMBER 2 IS THE TEMPERATURE OF THE FIRE RELATIVE TO THE TIME TEMPERATURE CURVE IN ASTM-E 119.

COLUMN NUMBER 3 IS THE TEMPERATURE OF THE SURFACE BOUNDARY WHICH INCREASES OVER TIME AND TEMPERATURE.

COLUMN NUMBER 4 IS THE DIFFERENCE IN TEMPERATURE BETWEEN COLUMN NUMBER 2 AND 3

COLUMN NUMBER 5 IS THE COMBINED CONVECTION AND RADIATION COEFFICIENT BASED ON THE TEMPERATURE DIFFERENCE IN COLUMN NUMBER 4

COLUMN NUMBER 6 IS THE FLUX PER UNIT AREA WHICH IS EQUAL TO COLUMN NUMBER 4 MULTIPLIED BY COLUMN NUMBER 5.

COLUMN NUMBER 7 IS THE THERMAL CONDUCTIVITY OF THE MATERIAL.

COLUMN NUMBER 8 IS THE THERMAL DIFFUSIVITY OF THE MATERIAL.

COLUMN NUMBER 9 IS THE TEMPERATURE DIFFERENCE (INCREASE) IN THE SURFACE BOUNDARY, WHICH IS CALCULATED AS FOLLOWS:

$\Delta T_w = \frac{2F_o}{K}\left(\frac{\alpha\theta}{3.14}\right)^{1/2}$ WHICH IS $\Delta T_w = 2\left(\frac{CN6}{CN7}\right)\left(\frac{CN8 \times \overset{(CN1)}{(\tau_n - \tau_{n-1})}}{3.14}\right)^{1/2}$

WHERE CN = COLUMN NUMBER

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Boston Edison Company

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COLUMN NUMBER 10 IS THE NEW SURFACE TEMPERATURE AFTER TIME τ.

$$T_{W2} = T_{W1} + \Delta T_W$$

$$CN10 = CN3 + CN9$$

WHERE CN = COLUMN NUMBER

COLUMN NUMBER 11 IS THE TOTAL NUMBER OF BTU'S APPLIED TO THE STEEL OR CONCRETE.

$$Q_s = F_{O_s} \times A_s \times (\tau_n - \tau_{n-1})$$

WHERE: s = STEEL

A_s = AREA STEEL FROM TABLE B

$(\tau_n - \tau_{n-1})$ = TIME IN MINUETS

$$\therefore CN11 = CN6 \times A_s \times \overset{CN1}{(\tau_n - \tau_{n-1})}$$

WHERE CN = COLUMN NUMBER

SUBSCRIPT c IS SUBSTITUTED FOR s TO IDENTIFY Q_c FOR CONCRETE.

COLUMN NUMBER 12 IS THE CUMULATIVE SUM OF $Q_{s/c}$ FROM CN11.

REFER TO TABLE A FOR A SAMPLE OF THE CALCULATION TABLE AND LEGEND - WHICH ITEMIZES REFERENCES AND ASSUMPTIONS.

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CALCULATION SHEET

Edison

CAPITAL AUTHORIZATION NO ______ 9/27/78
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6.2 CALCULATION TABLE & LEGEND

TABLE A

☒ SR	☐ NSR	1	2	3	4	5	6	7	8	9	10	11	12
		τ MIN	T_F °F	T_{w_1} °F	ΔT $(T_F - T_w)$	h @ ΔT	F_0 BTU/hr-ft²	K	a	ΔT_w °F	T_{w_2} °F	$Q_{c/s}$ BTU	$\Sigma Q_{c/s}$ BTU

LEGEND:

1. τ - MIN. REF 1 °R ?

2. T_F = TEMP(°F) @ τ REF 1

3. T_{w_1} = TEMP(°F) OF SPACE SURFACE AT τ.

$$°F = \frac{BTU}{\cancel{HR}\,ft^2} \cdot \frac{°F\text{-}\cancel{HR}\text{-}FT}{\cancel{BTU}} \left(\frac{\cancel{hr}\cdot ft^2}{\cancel{hr}}\right)^{1/2}$$

4. ΔT = TEMP DIFFERENCE - °F = $(T_F - T_w)$.

5. $h_{@\Delta T}$ = COMBINED CONVECTION AND RADIATION COEFFICIENT = (BTU/HR-FT²-°F) = $(h_c + h_r)$. REF 2; ASSUMPTION 2 & 13

6. $F_0 = \Delta T h$: HEAT FLUX PER UNIT AREA - BTU/HR-FT² - REF 2.

7. K = THERMAL CONDUCTIVITY - BTU/°F-HR-FT - REF 3; ASSUMPTION 3.

8. a = THERMAL DIFFUSIVITY - REF 4; ASSUMPTION 4 $\frac{ft^2}{hr} = (K)(e)(S_f)$

9. ΔT_w = INCREASE IN SURFACE TEMP °F FROM $\Delta T_w = 2\left(\frac{F_0}{K}\right)\left(\frac{a\tau^{*}}{\underset{\pi}{3.14}}\right)^{1/2}$ * [WHERE b EQUALS TIME IN HOURS]

10. T_{w_2} = TEMP. OF SPACE SURFACE AFTER TIME τ

$$T_{w_2} = T_{w_1} + \Delta T_w$$

11. $Q_{s/c}$ = TOTAL HEAT IN BTU Q_s (STEEL) / Q_c (CONCRETE) x 10⁶

12. $\Sigma Q_{s/c}$ = THE TOTAL CUMULATIVE HEAT IN BTU'S x 10⁶.

S_f - specific heat $\frac{BTU}{lb\text{-}°F}$

e = density $\frac{lb}{ft^3}$

$K = \frac{BTU}{hr\,ft\,°R}$

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CALCULATION SHEET OF STEEL & CONC. EXPOSED AREAS FOR THE STEAM TUNNEL (FROM EL. 22 T 46 COLS H TO J & COL. 9.9 TO 12.1)

BOSTON Edison COMPANY

CAPITAL AUTHORIZATION NO. ________
PREPARED BY JRP DATE 8/24/86 9/23/86
CHECKED BY APm DATE 9/23/86 9/25/
APPVD BY ____ DATE 10/14/86
SHEET 12 OF 21

SUBJECT: STEAM TUNNEL STEEL & CONC.

SR ☒
NSR ☐

6.3 CALCULATION OF CONCRETE & STEEL AREA

STEAM TUNNEL CONCRETE

SUMMARY

3,664 S.F AREA CONC.

STEEL

STEEL TABLE

1,640.09 S.F. AREA STEEL

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CALCULATION SHEET

Boston Edison Company

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CHECKED BY JPmcf DATE 9/23/82 9/23/82
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SHEET 13 OF 21

SUBJECT: CONCRETE - STEAM TUNNEL 24'W x 32'-8"L x 24'H

SR ☒
NSR ☐

REF. DWGS. C-63, C367, C134

AREAS

CONC. FL. 24'-0" x 32.67' = 784□'

CHEEK WALLS:

7'H x 2'W x 24'L

H, L, W, L,
① 7 x 24' x 2 = 336□' + 2' x 24' = 48□' TOTAL 384□'

H-LINE
② 13' x 24 + 3 x 24 384□'

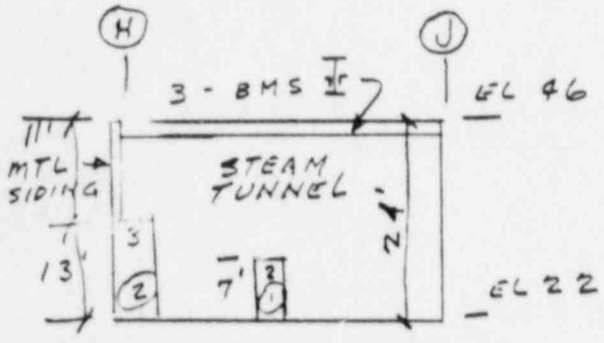
WALLS

J LINE 24' x 24' = 576□'

9.9 LINE 32.67' x 24' = 784□'

12.1 LINE SAME AS 9.9 LINE − OPNGS 752□'
1- 2'-6 x 3'-0", 1-3.5x7' (7.5+24.5□ = 32□')

TOTAL CONCRETE AREA STEAM TUNNEL 3,664 S.F



SECTION

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SUBJECT: STEEL STEAM TUNNEL

CALCULATION SHEET

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NSR ☐

REF. DWG. C-127			PERIM.
W10 x 49	10" $\frac{5}{16}$ I 10"	=	5'
W 12 x 65	12" $\frac{3}{8}$" I 12.125	=	5.96'
TUBE (HORIZ).	12 □ 12"	=	4'
TUBE (VERT). STRUTS	▭ 12" 1'-10" .83		5.66'

STRUCTURAL STEEL FOR PIPE RESTRAINTS SHOWN ON DRAWING C-367 AND COLUMN ALONG "H" ARE NOT INCLUDED IN THIS CALCULATION -(CONSERVATIVE ASSUMPTION).

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CALCULATION SHEET

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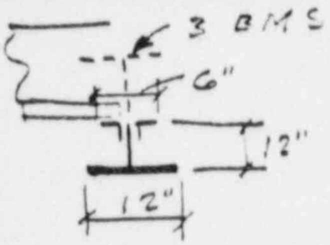
SUBJECT: STEEL STEAM TUNNEL

SR ☒

NSR ☐

METAL SIDING REF. DWG. C-79

		S.F.
H LINE	11' × 24' =	264 □'



53" ÷ 12 = 4.42' × 32.67' × 3 = 433.2

EL. 23'-2" REF. DWG. C-127

(12×12) □	24' × 4' =	96.
10 WF 49 DIAG.	2 × 5' × 10' =	100
"	2 × 5' × 9' =	90

EL. 29'-6¼"

(12×12) □	24' × 4' =	96.
12 WF 65	2 × 5.96' × 7.5' =	89.4
12 WF 65	5.96' × 6.5' =	38.74

EL. 34'-0"

(12×12) □	24' × 4' =	96
12 WF 65	2 × 5.96 × 7.5' =	89.4
12 WF 65	5.96 × 6.5 =	38.74

VERT. STRUTS, ELEVATION DET. $\frac{12}{C\text{-}127}$

EL. 23'-2" UP

	QNT.	
(12 × 1'-10") ▭	2 × 5.66' × 2.5' =	28.3
	2 × 5.66' × 6' =	67.92
	2 × 5.66 × 2' =	22.64
EL. 29'-6¼ UP	4 × 5.66' × 4' =	90.56

STEAM TUNNEL TOTAL STEEL. 1,640.09 S.F

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6.4 THEORETICAL FIRE LOADING

A. FUEL LOAD:
1. CABLE INSULATION 200 Lb

B. HEAT OF COMBUSTION:
1. INSULATION 21,000 BTU/Lb

C. TOTAL THEORETICAL LOAD:
$200 \text{Lb} \times 21{,}000 \text{BTU/Lb} = 4.2 \times 10^6 \text{BTU}$

THEORETICAL FIRE LOAD APPLIED TO SPACE BOUNDARY:

$4.2 \times 10^6 \text{BTU} \times 40\% = 1.7 \times 10^6 \text{BTU}$

[40% ; REF 7]

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TABLE 6.5 STEAM TUNNEL

?

		STEEL SAY 1600 FT²										CONCRETE SAY 3700 FT²							
1 τ	2 TF	3 Tw	4 ΔT	5 h	6 Fo	7 K	8 a	9 ΔT	10 Tn	11 Qs	12 ΣQs	3 Tw	4 ΔT	5 h	6 Fo	9 ΔT	10 Tm	11 Qc	12 ΣQc
0.00	-	68	—	—	—	—	—	—	—	—	—	68	–	–	–	–	–	–	–
0.01	600	—	—	—	—	—	—	—	—	—	—	68	532	5.1	2713	53	121	.1	.1
0.02	700	—	—	—	—	—	—	—	—	—	—	121	579	5.5	3189	63	184	.2	.3
0.03	800	—	—	—	—	—	—	—	—	—	—	184	616	5.8	3572	68	252	.2	.5
0.04	900	—	—	—	—	—	—	—	—	—	—	252	648	6.2	4017	77	329	.2	.7
0.05	1000	68	932	9.6	8947	35.1	.69	69	137	1.1	1.1	329	671	6.4	4294	81	410	.2	.9
0.10	1300	137	1163	13.4	15584	34.6	.65	118	255	2.0	3.1	410	890	9.1	8099	354	764	2.4	3.3
0.15	1399	255	1144	13.0	14472	32.9	.59	110	365			764	635	6.0	3810	166	930		
0.20	1462	365	1097	12.3	13492	31.4	.51	99	464			930	532	5.1	2713	118	1048		
0.25	1510	464	1046	11.4	11924	30.0	.49	90	554			1048	462	4.5	2079	91	1139		
0.30	1550	554	996	10.6	10560	28.8	.45	78	710			1139	411	4.1	1685	73	1212		
0.35	1584	710	874	8.8	7691	26.8	.38	57	767			1212	372	3.8	1413	62	1274		
0.40	1613	767	846	8.5	7191	25.7	.37	55	822			1274	339	3.6	1220	54	1328		
0.45	1638	822	816	8.1	6609	24.9	.35	51	873			1328	310	3.4	1054	46	1374		
0.50	1661	873	788	7.7	6085	24.2	.32	46	919			1374	287	3.1	890	39	1413		
0.55	1681	919	762	7.4	5660	23.5	.31	44	965			1413	268	3.0	804	35	1448		
min																			

Interpolate to Tenths? when flow

TABLE "B"

10/3/86

3.1
3.3
6.4

1.1
.9
2.1

> 1.7

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6.5 CONTINUED

ENTERRING TABLE 'B' AT A TOTAL THEORETICAL HEAT LOAD OF 1.7×10^6 BTU WE SEE THAT AT 0 HRS & 10 MINS THE TOTAL HEAT LOAD IS $\Sigma Q_S + \Sigma Q_C$ OR $3.1 + 3.3 = 6.4 \times 10^6$ BTU @ TEMP OF STEEL = 255° F.

THIS HEAT LOAD ENVELOPES THE ACTUAL LOAD OF 1.7×10^6 BTU WHICH INDICATES THE EXPOSED STEEL AVERAGE UNIFORM TEMPERATURE WILL NOT EXCEED <u>255°F.</u>

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1.6 DISCUSSION

AN EVALUATION OF THE CALCULATIONS INPUT VARIABLES AND CONSERVATIVE ESTIMATES AND ASSUMPTIONS WILL CONCLUDE THAT THE ACTUAL AVERAGE ESTIMATED STEEL TEMPERATURE WILL MOST PROBABLY BE SUBSTANTIALLY LESS THAN THE CALCULATED TEMPERATURE OF 255 °F

1. TRANSIENT COMBUSTIBLES ARE ADMINISTRATIVELY CONTROLLED TO MINIMIZE QUANTITIES IN PLANT AREAS
2. THE HEAT OF COMBUSTION IS THE AMOUNT OF HEAT RELEASED DURING A SUBSTANCES COMPLETE OXIDATATION (COMBUSTION). THE HEAT OF COMBUSTION IS DETERMINED IN A LABORATORY UTILIZING A "BOMB" CALORIMETER", IN WHICH A KNOWN MASS OF FUEL IS BURNT COMPLETELY IN AN ATMOSPHERE OF PURE OXYGEN. THE ACTUAL HEAT LOAD WILL BE SUBSTANTIALLY LE DUE TO ACTUAL FIELD CONDITIONS IN

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LIEU OF LABORATORY CONDITIONS.

3. REFERENCE NO 7 INDICATES THAT THE NORMALIZED HEAT LOAD ON THE COMPARTMENT BOUNDARIES IS ONLY 10-40% OF H_m, "WHERE Hm IS THE CONCIEVEABLE ABSOLUTE MAXIMUM HEAT LOAD." APPLYING THE MAXIMUM 40% FACTOR, THE CALCULATED TEMPERATURE OF STEEL IS 255°F.

THIS CALCULATION ASSUMES THAT THE INTERNAL TEMPERATURE OF THE STEEL IS IDENTICAL TO THE SURFACE TEMPERATURE. THIS IS A CONSERVATIVE ASSUMPTION SINCE THE SURFACE HEATS UP FASTER AND IS 100 - 200 °F HOTTER AFTER EXPOSURE TO THE STANDARD FIRE, i.e. ASTM-E-119, FOR UP TO 60 MIN (Ref 6).

7.0 CALCULATION CONCLUSION

BASED UPON TABLE "B" AND REASONABLE ENGINEERING JUDGEMENT, AS SUPPORTED BY THE DISCUSSION OF THIS CALCULATION'S

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CONSERVATIVE ESTIMATES AND ASSUMPTIONS, IT IS REASONABLE TO DEDUCE THAT THE MAXIMUM AVERAGE ESTIMATED TEMPERATURE WILL BE LESS THAN 1,000°F.

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Table 10. **Maximum Flux and Corresponding Over-all Temperature Difference for Liquids Boiled at 1 Atm with a Submerged Horizontal Steam-heated Tube**

Liquid	Aluminum		Copper		Chromium-plated copper		Steel	
	$\frac{q/A}{1000}$	$(\Delta t)_o$	$\frac{q/A}{1000}$	$(\Delta t)_o$	$\frac{q/A}{1000}$	$(\Delta t)_o$	$\frac{q/A}{1000}$	$(\Delta t)_o$
Ethyl acetate	41	70	61	55	77	55		
Benzene	51	80	58	70	73	100	82	100
Ethyl alcohol	55	80	85	65	124	65		
Methyl alcohol	..	..	100	95	110	110	155	110
Distilled water	..	..	230	85	350	75	410	150

For forced-circulation evaporators, vapor binding is also encountered. Thus with liquid benzene entering a 4-pass steam-jacketed pipe at 0.9 fps, up to the point where 60 percent by weight was vaporized, the maximum flux of 60,000 Btu per hr per sq ft was obtained at an over-all temperature difference of 60 F; beyond this point, the coefficient and flux decreased rapidly, approaching the values obtained in superheating vapor, see Eq. (6b). For comparison, in a natural convection evaporator, a maximum flux of 73,000 Btu per hr per sq ft was obtained at $(\Delta t)_o$ of 100 F.

Combined Convection and Radiation Coefficients. In some cases of heat loss, such as that from bare and insulated pipes, where loss is by convection to the air and radiation to the walls of the enclosing space it is convenient to use a combined convection and radiation coefficient $(h_c + h_r)$. The rate of heat loss thus becomes

$$q = (h_c + h_r)A(\Delta t)_o \tag{15}$$

where $(\Delta t)_o$ is the temperature difference, deg F, between the surface of the hot body and the walls of the space. In evaluating $(h_c + h_r)$, h_c should be calculated by the appropriate convection formula [see Eqs. (11c) to (11g)] and h_r from the equation

$$h_r = 0.00685\epsilon(T_{av}/100)^4$$

where ϵ is the black body coefficient of the radiating surface, p. 4-111, T_{av} is the average temperature of the surface and the enclosing walls, deg R. For oxidized bare steel pipe, the sum $h_c + h_r$ may be taken directly from Table 11.

Table 11. **Values of $(h_c + h_r)$**

(For horizontal bare or insulated standard steel pipe of various sizes and for flat plates in a room at 80 F)

Nominal pipe diam, in.	$(\Delta t)_o$, temperature difference, deg F, from surface to room														
	50	100	150	200	250	300	400	500	600	700	800	900	1000	1100	1200
½	2.12	2.48	2.76	3.10	3.41	3.75	4.47	5.30	6.21	7.25	8.40	9.73	11.20	12.81	14.65
1	2.03	2.38	2.65	2.98	3.29	3.62	4.33	5.16	6.07	7.11	8.25	9.57	11.04	12.65	14.48
2	1.93	2.27	2.52	2.85	3.14	3.47	4.18	4.99	5.89	6.92	8.07	9.38	10.85	12.46	14.28
4	1.84	2.16	2.41	2.72	3.01	3.33	4.02	4.83	5.72	6.75	7.89	9.21	10.66	12.27	14.09
8	1.76	2.06	2.29	2.60	2.89	3.20	3.88	4.68	5.57	6.60	7.73	9.05	10.50	12.10	13.93
12	1.71	2.01	2.24	2.54	2.82	3.13	3.83	4.61	5.50	6.52	7.65	8.96	10.42	12.03	13.84
24	1.64	1.93	2.15	2.45	2.72	3.03	3.70	4.48	5.37	6.39	7.52	8.83	10.28	11.99	13.70
FLAT PLATES															
Vertical	1.82	2.13	2.40	2.70	2.99	3.30	4.00	4.79	5.70	6.72	7.86	9.18	10.64	12.25	14.06
HFU	2.00	2.35	2.65	2.97	3.26	3.59	4.31	5.12	6.04	7.07	8.21	9.54	11.01	12.63	14.45
HFD	1.58	1.85	2.09	2.36	2.63	2.93	3.61	4.38	5.27	6.27	7.40	8.71	10.16	11.76	13.57

HFU, horizontal, facing upward; HFD, horizontal, facing downward.

Heat Transmission through Pipe Insulation. (McMillan, *Trans. ASME*, 1915.) For any number of layers of insulation on any size of pipe, Eqs. (3), (4), and (15)

combine to give

$$\frac{q}{A}$$

where q_o/A_o is the Btu
all temperature differe

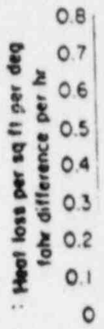

Fig. 6. Variation with
for k = 0.042.

outer surface; r_1 is th
layer of insulation, foo
etc., are the conductiv
$h_c + h_r$ is often taken
will have but little effe
U_o with pipe size and t
tures of 375 and 75 F,

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ASME SECTION VIII — DIVISION 2 Table 1

TABLE 1
NOMINAL COEFFICIENTS OF THERMAL CONDUCTIVITY (TC) AND THERMAL DIFFUSIVITY (TD)*

	Carbon and Low Alloy Steels													
	Plain Carbon		Carbon-Silicon		C–Mn		C–Mn–Si		Mat'l. Group A¹		Mat'l. Group B²		Mat'l. Group C³	
Temp., °F	TC	TD α	TC	TD	TC	TD	TC	TD	TC	TD	TC	TD	TC	TD
70	35.1	0.695	30.0	0.582	27.5	0.529	23.6	0.454	24.8	0.482	21.3	0.414	24.2	0.471
100	34.7	0.674	29.9	0.567	27.6	0.512	23.9	0.443	25.0	0.477	21.5	0.409	24.3	0.464
150	34.1	0.645	29.6	0.544	27.6	0.496	24.2	0.433	25.1	0.466	21.8	0.400	24.4	0.452
200	33.6	0.615	29.2	0.521	27.6	0.486	24.4	0.422	25.2	0.454	21.9	0.391	24.4	0.439
250	32.9	0.585	28.9	0.502	27.4	0.467	24.4	0.414	25.2	0.442	22.0	0.382	24.3	0.426
300	32.3	0.561	28.4	0.481	27.2	0.453	24.4	0.406	25.1	0.430	22.0	0.373	24.2	0.414
350	31.6	0.534	28.0	0.464	27.0	0.440	24.3	0.396	25.0	0.418	22.0	0.365	24.0	0.402
400	30.9	0.517	27.6	0.447	26.7	0.428	24.2	0.386	24.8	0.405	21.9	0.356	23.9	0.390
450	30.3	0.495	27.1	0.430	26.3	0.413	23.9	0.375	24.6	0.394	21.8	0.347	23.6	0.378
500	29.5	0.472	26.6	0.414	25.9	0.398	23.7	0.364	24.3	0.381	21.7	0.337	23.4	0.367
550	28.8	0.452	26.1	0.398	25.5	0.387	23.4	0.355	24.0	0.370	21.5	0.327	23.1	0.355
600	28.0	0.433	25.6	0.385	25.0	0.374	23.1	0.346	23.7	0.359	21.3	0.320	22.7	0.344
650	27.3	0.414	25.1	0.370	24.5	0.360	22.7	0.333	23.4	0.348	21.0	0.310	22.3	0.333
700	26.6	0.394	24.6	0.355	24.0	0.346	22.4	0.320	23.0	0.335	20.8	0.299	22.0	0.320
750	25.9	0.374	24.0	0.337	23.5	0.332	22.0	0.308	22.6	0.322	20.5	0.288	21.6	0.307
800	25.2	0.355	23.5	0.323	23.0	0.318	21.7	0.298	22.2	0.308	20.2	0.278	21.2	0.295
850	24.5	0.335	23.0	0.309	22.6	0.305	21.2	0.286	21.9	0.297	20.0	0.268	20.9	0.283
900	23.8	0.317	22.5	0.296	22.1	0.291	20.9	0.274	21.4	0.283	19.7	0.258	20.5	0.271
950	23.1	0.301	21.9	0.281	21.5	0.277	20.5	0.262	20.9	0.269	19.4	0.248	20.1	0.259
1000	22.4	0.282	21.4	0.267	21.0	0.263	20.0	0.248	20.4	0.256	19.1	0.238	19.8	0.248
1050	21.6	0.265	20.8	0.252	20.5	0.249	19.6	0.237	19.9	0.242	18.8	0.227	19.4	0.236
1100	20.9	0.250	20.2	0.236	19.9	0.237	19.2	0.228	19.5	0.230	18.5	0.216	19.1	0.225
1150	20.2	0.234	19.6	0.221	19.3	0.219	18.7	0.213	18.9	0.215	18.2	0.204	18.7	0.213
1200	19.5	0.218	19.0	0.206	18.7	0.202	18.2	0.197	18.4	0.202	17.7	0.192	18.2	0.199
1250	18.7	0.197	18.3	0.189	18.0	0.184	17.5	0.179	17.7	0.185	17.2	0.178	17.6	0.184
1300	18.0	0.180	17.6	0.172	17.1	0.159	16.7	0.155	16.7	0.164	16.5	0.161	16.9	0.166
1350	17.2	0.134	16.8	0.151	16.2	0.122	15.8	0.119	15.9	0.142	15.3	0.138	15.6	0.135
1400	16.4	0.092	16.2	0.082	15.6	0.078	15.3	0.077	15.3	0.077	15.0	0.076	15.3	0.077
1450	15.9	0.147	15.7	0.137	15.2	0.155	15.1	0.154	15.0	0.128	14.9	0.130	15.1	0.128
1500	15.7	0.152	15.6	0.180	15.1	0.169	15.1	0.169	15.0	0.199	14.8	0.171	15.0	0.199

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2.9. The semi-infinite solid. The flux of heat at $x = 0$ a prescribed function of the time. Zero initial temperature

(i) *Constant flux, F_0 per unit time per unit area.* BTU/FT².HR

The flux
$$f = -K\frac{\partial v}{\partial x}, \tag{1}$$
satisfies the same differential equation as v, namely

THERMAL DIFFUSIVITY FT²/HR
$$\kappa\frac{\partial^2 f}{\partial x^2} = \frac{\partial f}{\partial t}, \quad x > 0, t > 0. \tag{2}$$

The solution of (2) with
$$f = F_0, \quad \text{constant}, x = 0, t > 0, \tag{3}$$
is, by 2.4 (10),
$$f = F_0 \operatorname{erfc}\frac{x}{2\sqrt{(\kappa t)}}. \tag{4}$$

Thus, from (1), using Appendix II, (9) and (11),

THERMAL CONDUCTIVITY BTU/°F·HR·FT
$$v = \frac{F_0}{K}\int_x^\infty \operatorname{erfc}\frac{x}{2\sqrt{(\kappa t)}}\,dx \tag{5}$$
$$= \frac{2F_0\sqrt{(\kappa t)}}{K}\operatorname{ierfc}\frac{x}{2\sqrt{(\kappa t)}} \tag{6}$$
$$= \frac{2F_0}{K}\left\{\left(\frac{\kappa t}{\pi}\right)^{\frac{1}{2}}e^{-x^2/4\kappa t} - \frac{x}{2}\operatorname{erfc}\frac{x}{2\sqrt{(\kappa t)}}\right\}. \tag{7}$$

A table of values of the function $\operatorname{ierfc} x$ is given in Appendix II.

The temperature at $x = 0$ is given by
$$\frac{2F_0}{K}\left(\frac{\kappa t}{\pi}\right)^{\frac{1}{2}}. \tag{8}$$

The boundary condition of constant flux is of considerable practical importance. It appears if heat is generated by a flat heating element carrying electric current, if heat is generated by friction, and as an approximation in the early stages of heating a furnace or a room. It has also important applications to problems on diffusion. The cooling of the Earth's surface after sunset on a clear windless night† is very nearly that due to removal of heat at a constant rate per unit area per unit time, thus (8) gives the way in which the surface temperature falls after sunset.

The results above apply also to the case of the region $-\infty < x < \infty$ with heat supply $2F_0$ in the plane $x = 0$. The corresponding results for

---

† Cf. Brunt, *Quart. J. R. Met. Soc.* **58** (1932) 389.

.5, and we have

$d\mu$. (1)

T. (2)

$\frac{x}{\sqrt{(\kappa t)}} + h\sqrt{(\kappa t)}\Big\} -$

$T))\Big), \quad t > T.$ (3)

$\frac{x)}{} e^{-u^2} u\,du,$ (4)

seen to have the

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FIRE RESISTANCE OF UNPROTECTED STEEL COLUMNS

BY

W. W. STANZAK AND T. T. LIE

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LA RESISTANCE AU FEU DES POUTRES D'ACIER NON PROTEGEES

SOMMAIRE

Les auteurs étudient la résistance au feu des poutres d'acier non protégées au moyen d'essais d'incendie standards et de l'analyse numérique. On a découvert que la durée de la résistance au feu varie selon le facteur forme du poids de la poutre divisé par le périmètre chauffé. Les auteurs ont établi deux équations simples pour calculer les durées de résistance au feu des poutres d'acier non protégées et ils recommandent de les utiliser dans les normes du bâtiment.

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FIRE RESISTANCE OF UNPROTECTED STEEL COLUMNS

By W. W. Stanzak[1] and T. T. Lie[2]

In the past the fire resistance of unprotected steel columns has been considered so small a quantity that it could be ignored. Fire experience and controlled fire tests on structural steel columns of small cross-sectional area showed that unprotected steel columns could not survive the effects of fire exposure for more than 10 min to 20 min. However, it will now be shown that the heavier columns required to carry the vertical loads in modern high-rise buildings are capable of much better fire performance than had previously been realized, and that some can attain fire resistance classifications of 1 hr or better.

Fire fatality statistics (1) show that the number of deaths attributable to structural collapse during a building fire is negligible. The main causes of life loss have been shown to be asphyxiation and burns (1,3,7). Therefore, to provide life safety to occupants, enough fire resistance to allow people time to escape must be provided. Except where escape routes are extremely long or the number of occupants is very large, 10 min to 20 min is usually assumed to be sufficient. However, with very tall buildings it has become evident that evacuation by stairs can be so time consuming that complete evacuation is impractical (4). In such buildings sufficient fire resistance to withstand a burnout of the contents must be provided.

Provision of fire resistance beyond that required to prevent life loss is determined largely he economic considerations. A recent study on the optimum fire resistance of structures (11) has shown that for buildings with a small-loss poten-

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tial it would be uneconomical to provide any fire protection beyond that inherent in the structure, provided such fire resistance is sufficient to allow evacuation by the occupants. Buildings representing a small-loss expectation are those that are small in size and not valuable; those with no valuable contents; those for which the probability of a serious fire is low (e.g., completely sprinklered buildings); or those having a low fire load. The use of unprotected steel columns in such buildings is generally justified if these elements have the minimal fire resistance required to prevent loss of life.

Accordingly, the writers have investigated the fire resistance of unprotected steel columns by methods of numerical calculation and by full-scale fire tests in their laboratory, with a view to developing simple expressions for calculating the fire resistance of these building elements.

TEST METHODS AND CRITICAL TEMPERATURE

On this continent, two test methods are acceptable. The most recent ASTM Standard prescribing these is E119-71 (16).

The older load test requires a sample at least 9 ft in length to be tested under an applied load calculated to develop theoretical working stresses contemplated by the design. The column is required to sustain the applied load for a period of fire exposure equal to that for which classification is desired.

The newer alternate test of protection for structural steel columns requires that a sample at least 8 ft in length be tested in a vertical position without applied load. This test is applicable when the protection is not required by design to carry any part of the column load. The applied protection must be restrained against longitudinal thermal expansion greater than that of the steel column. Temperatures are measured by at least three thermocouples located at each of four levels (cross sections). The upper and lower levels are 2 ft from the ends of the steel column, and the two intermediate levels are equally spaced. The test is considered successful if the transmission of heat through the protection, during the period of fire exposure for which classification is desired, does not raise the average (arithmetical) temperature of the steel to any level above 1,000° F (538° C), or above 1,200° F (649° C) at any one of the measured points.

The 1,000° F average allowable temperature that usually determines the fire endurance time in a test may be regarded as a critical temperature for structural failure established for protected columns as a result of many fire tests on axially loaded column sections. Thus, for the analysis in this paper, it has been assumed that structural failure is imminent when the steel cross section attains an average temperature of 1,000° F as all calculations and fire tests were made on the basis of heat conduction alone.

While complete theoretical justification for the use of temperature criteria is beyond the scope of this paper, it can readily be shown that 1,000° F is a reasonable value. For long columns, assuming that the member is uniformly heated, the buckling stress is given by Euler's formula:

$$\sigma_{cr} = \frac{\pi^2 E_T}{\lambda^2} \qquad (1)$$

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and the allowable design stress for long columns is given by CSA S16-1969 (17) as:

$$\sigma_u = \frac{\pi^2 E_u}{1.92 \lambda^2} \qquad (2)$$

in which 1.92 is a safety factor prescribed by the Code and $\sqrt{286{,}000/\sigma_y} = 131 < \lambda \leq 200$.

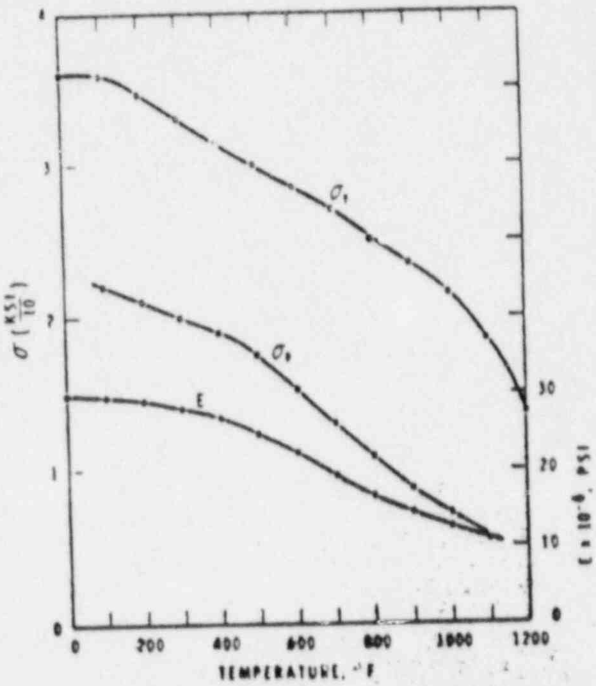

FIG. 1.—Average Compressive Properties of ASTM A36 Structural Steel

At elevated temperatures failure is due to occur when the left-hand sides of the equations are equal, i.e.:

$$E_t = \frac{E_u}{1.92} \qquad (3)$$

Accepting the commonly assumed value for carbon steels of $E_u = 29 \times 10^3$ ksi, then

$$E_t = 15.1 \times 10^3 \text{ ksi } (104 \times 10^9 \text{ N/m}^2) \qquad (4)$$

Using Fig. 1, based on data reported by Ingberg and Sale (10), it is found that the temperature at buckling is approximately 880° F (471° C). Fire tests of loaded columns (9) have shown that the point of maximum expansion (approximately the point at which the column buckles) is followed by a further 100° F-150°

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F (55° C-83° C) rise in temperature before complete failure of the column occurs. Thus failure of columns can be expected at cross-sectional temperatures of from 950° F-1,050° F, (510° C-565° C), depending on the design method and slenderness ratio. A value of 1,000° F has been assumed as a reasonable average for any column, as has been indicated by the ASTM fire test standard.

TEMPERATURE RISE IN UNPROTECTED STEEL COLUMNS

The column is exposed on four sides to the heat of a fire that follows approximately the temperature-time course prescribed in *ASTM E119* for the standard fire of "controlled extent and severity." Heat is transferred from the flames in the furnace and from the furnace walls to the specimen by convection and radiation, with radiation as the primary mechanism when the flames have sufficient thickness (18). The coefficient of heat transfer (the quantity of heat received per unit area of the column, per unit time, and temperature difference between the column surface and fire) depends on many factors. The most significant are: emissivity of the flames; thickness of the flames between furnace walls and column; size of specimen; and thermal properties of the furnace walls. Experimental data (5) have indicated that the heat transfer to the specimen in test furnaces approximates the radiative heat transfer from a black body at the so-called "furnace temperature." Similar heat transfer may also be expected in most building fires because the flames are luminous and usually have considerable thickness, giving them a correspondingly high emissivity.

The coefficient of heat transfer can vary significantly, however, for different individual conditions, and the effect of varying this quantity will be examined later herein.

CALCULATION OF TEMPERATURE RISE

Two-Dimensional Numerical Procedure.—To determine the temperature distribution in massive square steel columns, a number of calculations based on a two-dimensional procedure (12) were carried out. In these tests black body radiation at the prescribed furnace temperature was assumed as the only mechanism of heat transfer. The two equations used for the calculation are:

$$T^{j+1}_{1,n} = T^{j}_{1,n} + \frac{\Delta t}{(\rho c)^{j}_{1,n}(\Delta \xi)^2}\{[k^{j}_{2,(n-1)} + k^{j}_{1,n}][T^{j}_{2,(n-1)} - T^{j}_{1,n}]$$

$$+ [k^{j}_{2,(n+1)} + k_{1,n}][T^{j}_{2,(n+1)} - T^{j}_{1,n}] + 2\sqrt{2}\,\Delta \xi\,\sigma\,\epsilon_f\,[(T^{j}_f)^4 - (T^{j}_{1,n})^4]\} \quad \ldots (5)$$

for the temperature of an elementary surface element of the column, and

$$T^{j+1}_{m,n} = T^{j}_{m,n} + \frac{1}{2}\frac{\Delta t}{(\rho c)^{j}_{m,n}(\Delta \xi)^2}\{[k^{j}_{(m-1),(n-1)} + k^{j}_{m,n}][T^{j}_{(m-1),(n-1)}$$

$$- T^{j}_{m,n}] + [k^{j}_{(m+1),(n-1)} + k^{j}_{m,n}][T^{j}_{(m+1),(n-1)} - T^{j}_{m,n}] + [k^{j}_{(m-1),(n+1)}$$

$$+ k^{j}_{m,n}][T^{j}_{(m-1),(n+1)} - T^{j}_{m,n}] + [k^{j}_{(m+1),(n+1)} + k^{j}_{m,n}][T^{j}_{(m+1),(n+1)} - T^{j}_{m,n}]\} \quad \ldots (6)$$

for the temperature at any point inside the steel cross section, in which T is expressed in degrees Rankine and t in hours. It should be noted that the

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term, ϵ_c, in Eq. 5 is, strictly speaking, a material and temperature dependent quantity, but it is sufficiently accurate, for the purpose of this study, to be regarded as a constant. Also, since most building materials have emissivities in the range of 0.85 to 0.95 (13) a value of 0.9 was used, although the results indicated that a value of 0.95 would have been more appropriate.

The dependence of the thermal properties of steel on temperature was taken into account in the calculations. The material properties used were derived from available data (15) and are reproduced in Table 1. As is apparent, the involved nature of the calculation makes utilization of a high speed digital computer almost mandatory.

TABLE 1.—Thermal Properties of Steel

Temperature, in degrees Fahrenheit (1)	Volumetric heat capacity, in British thermal units per cubic foot-degrees Fahrenheit (2)	Thermal conductivity, in British thermal units per foot-hour-degrees Fahrenheit (3)
70	54.30	26.60
100	54.86	26.60
200	56.36	26.82
300	58.27	26.43
400	60.35	25.87
500	62.44	25.34
600	64.90	24.71
700	67.52	23.72
800	70.56	22.80
900	74.59	21.86
1,000	80.32	21.06
1,100	85.72	20.07
1,200	90.52	18.98
1,250	94.29	18.55
1,300	127.85	18.16
1,350	164.15	17.87
1,400	117.75	17.60
1,450	84.58	17.34
1,500	66.16	16.78
1,550	62.23	15.69
1,600	60.74	15.26
1,650	62.01	15.45
1,700	66.09	15.48
1,900	67.96	16.03
2,100	69.65	16.85
2,350	70.97	17.56

Calculated temperature profiles for a 6-in. (0.152-m) square unprotected steel column are shown in Fig. 2 at 10-min intervals. Similar profiles for a 12-in. (0.304-m) square column are shown in Fig. 3 after 50-min and 60 min of fire exposure. Fig. 3(*b*) shows that at 60 min the maximum temperature difference between the surface and the core was 225° F (125° C) and the temperature at

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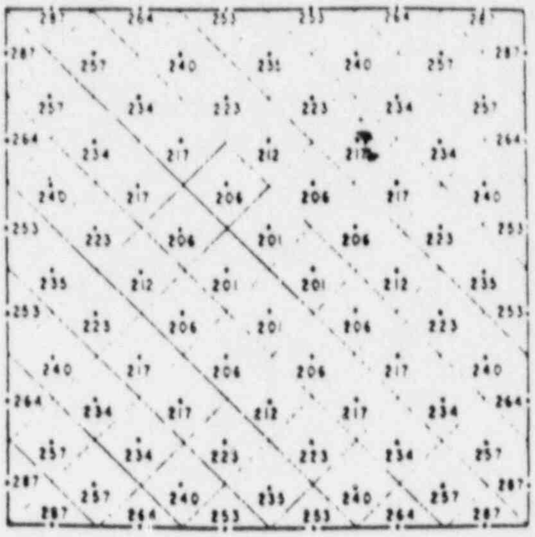
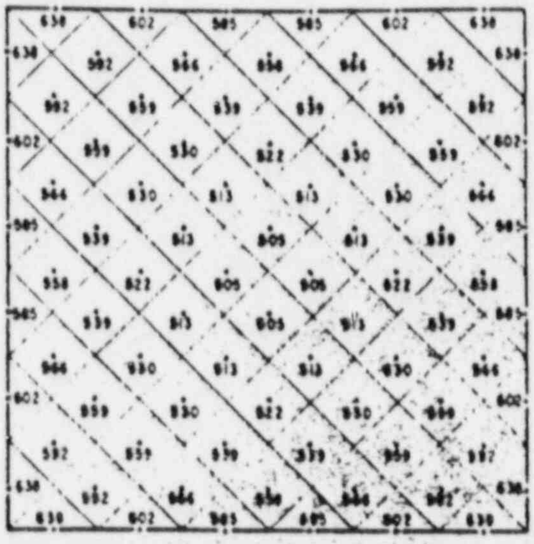


(a) 10 MIN



(b) 20 MIN

FIG. 2.—Temperature Rise in Unprotected Steel Square Column (6 in.)

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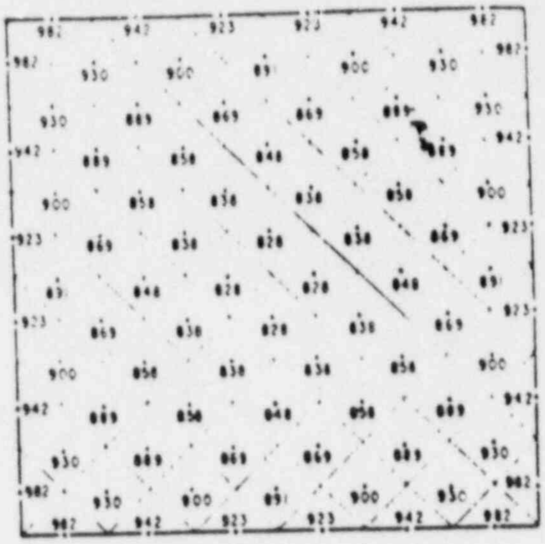
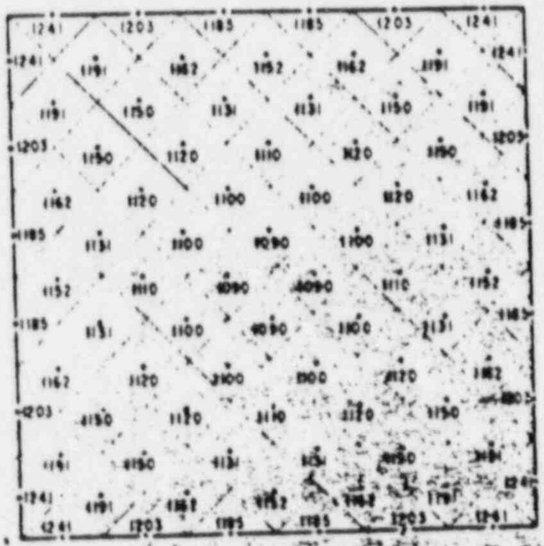


(c) 30 MIN



(d) 40 MIN.

FIG. 2—Continued

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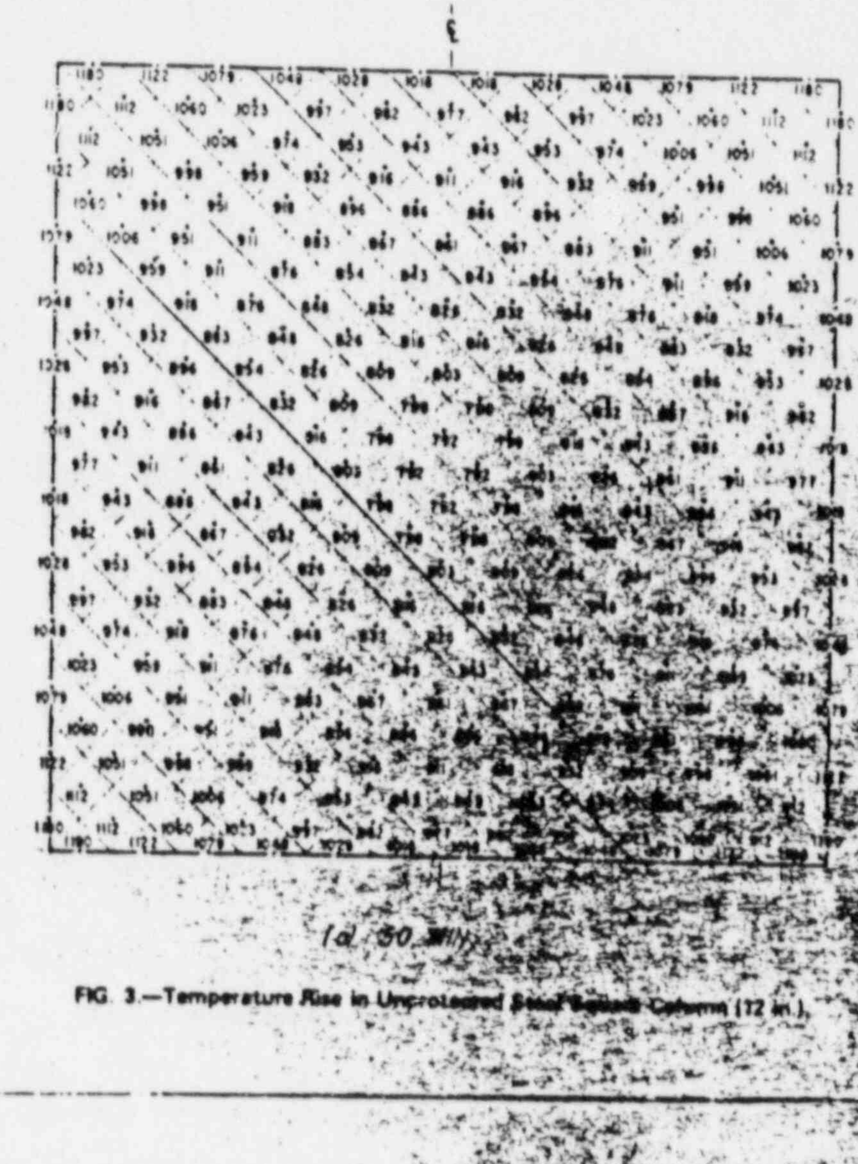
the point midway between the surface and core was about 1,000° F. From Figs. 2(c) and 2(d) it is seen that the maximum temperature difference between the surface of the 6-in. column and the core is about 100° F. This can be regarded as a reasonable maximum for most steel columns likely to be encountered in building practice. For the purpose of determining fire endurance time by temperature rise, the temperature at the point halfway between the surface and core of the cross section (or flange in the case of a wide flange section) may be regarded as representing the average temperature of the cross section. For all but very thick sections this temperature will be almost equal to the temperature at the column surface.

Fig. 4 shows temperature rise curves for a 6-in. square column (calculated or measured as was just described). As is seen, the assumption of radiative heat transfer only does not adequately represent the conditions prevailing in



(a) 30 Min

FIG. 3.—Temperature Rise in Unprotected Steel Square Columns (12 in.).

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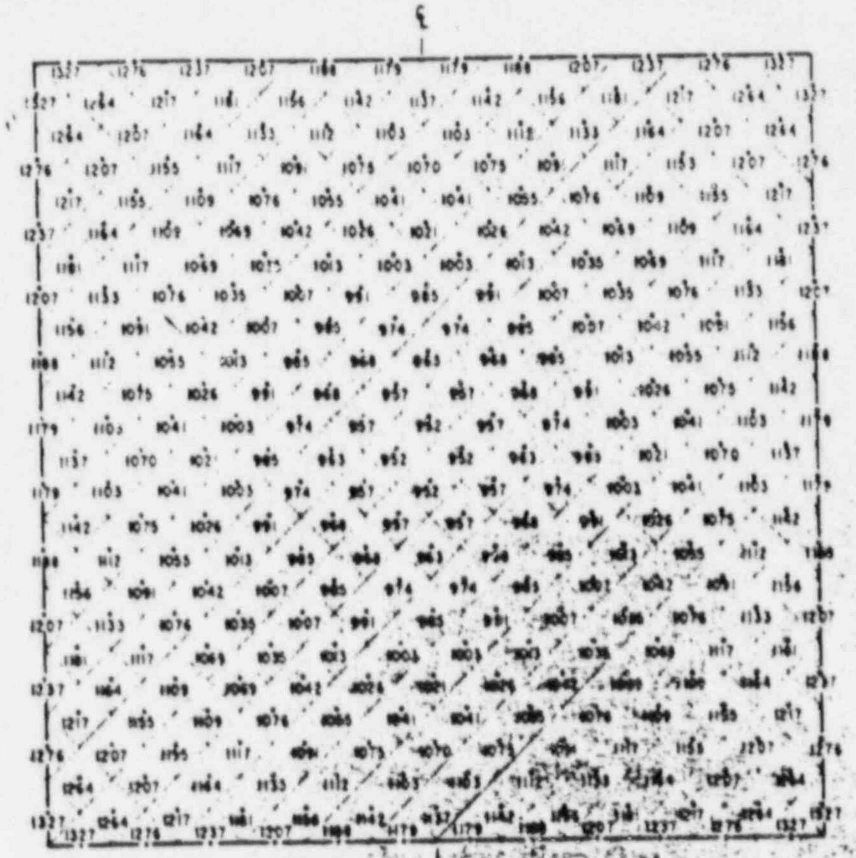
the DBR/NCR furnace when short fire endurance times are involved. The curve labeled (2) in Fig. 4 was calculated by assuming that 20% of the heat transfer is due to convection and produces good agreement with the experimental result. Unfortunately, this finding is of no general value because the convective heat transfer varies with each individual situation. With most fires of short duration the convection component of heat transfer can be in the order of 10% to 20%. In the calculation the effect of convective heat transfer was simulated by raising ϵ_r from 0.9 to the ficticious value of 1.1.

1.1

The heat transfer coefficients to columns of square cross section were calculated based on an emissivity (ϵ_r) of 0.9 using results obtained by Eqs. 5 and 6. The results are shown in Fig. 5, where the coefficient of heat transfer has been plotted as a function of the duration of standard fire exposure. As is seen, the heat transfer coefficient rises almost linearly with time, and the smaller



(b) 60 MIN

FIG. 3.—Continued

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the column the higher the coefficient of heat transfer.

One-Dimensional Numerical Procedure.—The temperature distributions, determined by the two-dimensional calculation method described previously, show

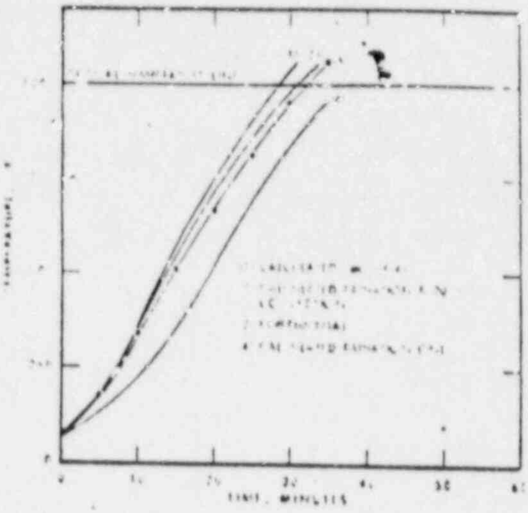

FIG. 4.—Temperature Rise Curves, 6 × 6 Solid Column

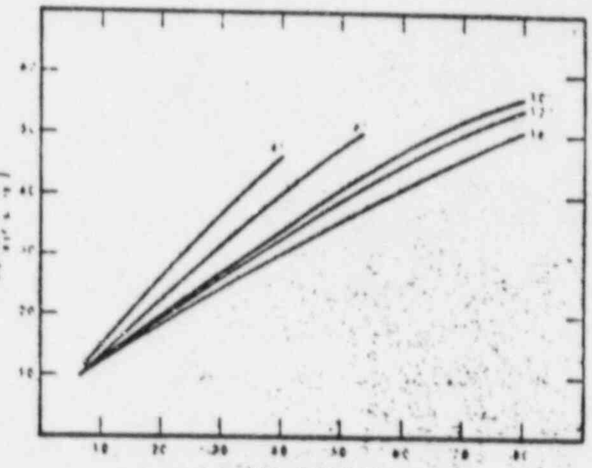

FIG. 5.—Coefficients of Heat Transfer for Unprotected Columns During Exposure to Standard Fire

that the temperature differences in the steel are relatively small, except for very thick sections. Most columns used in buildings have sections less than 10 in. (0.25 m) thick. In such cases detailed calculation of temperature distribution in the steel cross section is unnecessary, and a one-dimensional model of the

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heated column can be usefully employed. The model consists of a steel plate having the same cross-sectional and surface areas per unit height as the four sides of the heated column, with the edges and unexposed side perfectly insulated. This model permits use of a one-dimensional numerical procedure by which

TABLE 2.—Sample Calculation for 10-in. Square Column

t (1)	T_f (2)	T_a (3)	$(T_a - T_s)$ (4)	ΔT_s (5)	T_s' (6)
0	70	533	465	58	70
5	1,000	1,150	1,022	128	128
10	1,300	1,350	1,094	137	256
15	1,399	1,431	1,038	130	393
20	1,462	1,486	963	120	523
25	1,510	1,530	887	111	643
30	1,550	1,567	813	102	754
35	1,584	1,599	743	93	856
40	1,613	1,626	677	85	949
45	1,638				1,034

Note: $\alpha = 18.45$; $c = 0.12$; $D = 3.33$; $W = 340$; $\Delta T_s = 0.125\,(T_f - T_s)$ for $\Delta t = 1/12$ hr.

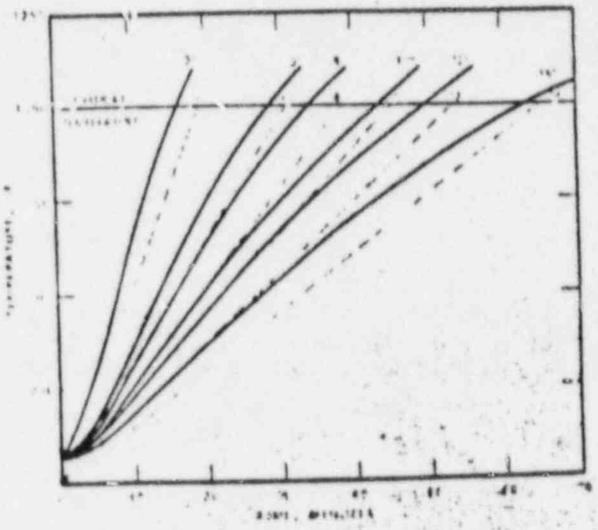

FIG. 6.—Temperature Rise of Square Solid Steel Columns (Calculated, α = 18.45)

the temperature of the steel cross section can be calculated with only a desk calculator or slide rule. In the calculation, with each interval of time, Δt, the rise in steel temperature, ΔT_s, is given by:

$$\Delta T_s = \frac{\alpha}{c}\,\frac{D}{W}\,(T_f - T_s)\,\Delta t \qquad (7)$$

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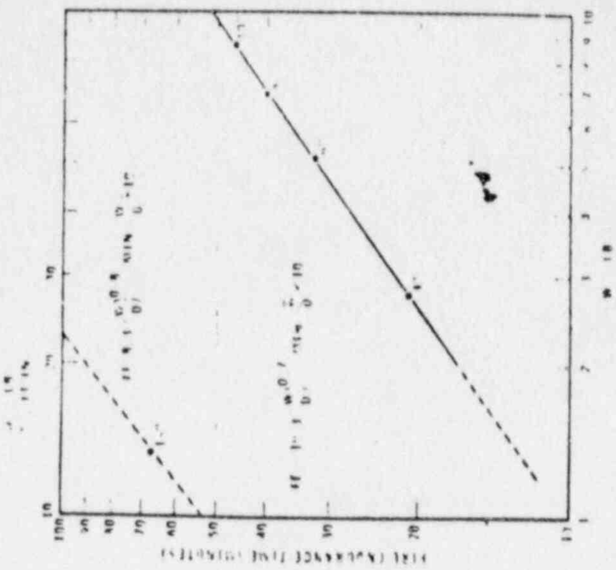

FIG. 8.—Fire Endurance of Square Columns (Experimental)

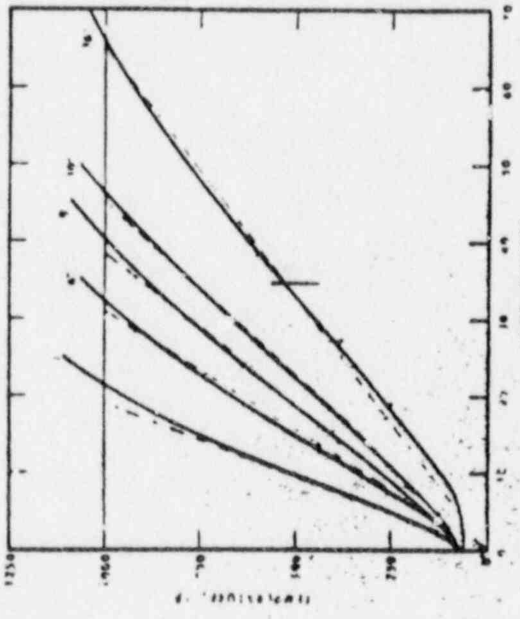

FIG. 7.—Temperature Rise of Square Solid Steel Columns (Experimental data)

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in which Δt is expressed in hours. The results of sample calculation for a 10-in. square column with a = 18.45 (104.8) and c = 0.12 (502) are shown in Table 2. A family of temperature rise curves obtained by similar calculations is shown by the solid lines in Fig. 6.

Experimental Results.—To obtain information on the temperature rise of unprotected steel columns in the DBR/NRC floor furnace, five fire tests were carried out on square solid columns of various cross sections. The temperatures measured at the point halfway between the surface and the core at mid-height of the columns are plotted in Fig. 7. Fig. 8 shows a plot of fire endurance time versus the dimensional parameter, W/D, on logarithmic scales. As is seen, the relationship is linear and, from the graph, it is possible to obtain the following relation directly:

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$$t = 10.3\left(\frac{W}{D}\right)^{\text{[illegible]}} \quad (8)$$

in which $W/D < 10$. To obtain a relation for columns whose $W/D \geq 10$,

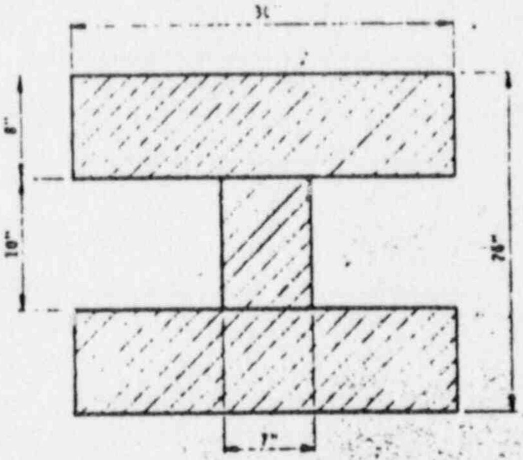

FIG. 9.—Built-up Column—3 Plates

a straight line temperature rise for the 16-in. square column is assumed, as shown by the dashed line in Fig. 7. From this it is possible to obtain the relation:

$$T_s = 120\left(\frac{D}{W}\right)^{\text{[illegible]}} \quad (9)$$

and by setting T_s equal to the critical temperature of 1,000° F:

$$t = 8.3\left(\frac{W}{D}\right)^{\text{[illegible]}} \quad (10)$$

The lines resulting from Eq. 9 are plotted in Figs. 6 and 7 (dashed lines). The line resulting from Eq. 10 is plotted in Fig. 8 and that equation should be used for columns having $W/D \geq 10$. However, as is seen from Fig. 7,

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it can be conservatively applied to any column section, and provides a relation that could readily be incorporated into a building by-law. (Although the experimental data ~~are confined to solid square columns;~~ numerical analyses show that Eqs. 9 and 10 can apply to any shape of cross section.)

As an example of the fire resistance typical in columns of very tall buildings, a calculation for the section shown in Fig. 9, one of several massive sections used in Toronto's 56-story Toronto Dominion Centre, is worked out:

$$D = 2(30 + 16) + 2(30 - 7) + 2(10) = 174 \text{ in.} \qquad (11)$$

$$W = 1{,}870 \text{ lb per ft}, \frac{W}{D} = 10.75 \qquad (12)$$

Eq. 10 yields a fire endurance time of:

$$t = 8.3(10.75)^{0.8} = 56 \text{ min} \qquad (13)$$

As is seen, these massive sections can have fire endurance times approaching 1 hr, even when unprotected.

Recent North American practice has seen increased installation of sprinkler systems in large (especially tall) buildings, including some that are not considered to have a very high fire load (2,6). ~~Once complete sprinklering of high buildings becomes more common,~~ the use of unprotected massive column sections with a fire resistance capability of about 1 hr should prove adequate for fire safety, provided that the fire load is no more than 5 lb/sq ft to 10 lb/sq ft, which should not result in a fire of severity greater than a 1-hr standard fire (8). (Fire load is the heat of combustion of the combustible contents expressed in equivalent pounds of wood per unit floor area.) It can be reasonably deduced from Refs. 4 and 14 that no safety factor need be applied to the actual fire load if the building is fully sprinklered, although such a safety factor is implied by all current North American building regulations now in force.

ACKNOWLEDGMENTS

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APPENDIX II.—NOTATION

The following symbols are used in this paper:

c = specific heat of steel, in British thermal units per pound—degrees Fahrenheit (or degrees Rankine) (joules per kilogram—degrees Kelvin);
D = heated perimeter, in inches (meters);
E = modulus of elasticity of steel, in kips per square inch (newtons per square meter);
FE = fire endurance time, in minutes;
k = thermal conductivity, in British thermal units per foot-hour-degrees Fahrenheit (watts per meter-degrees Kelvin);
T = temperature, in degrees Fahrenheit (degrees Celsius);
t = time, in minutes (unless specified otherwise);
W = mass of steel section, in pounds per foot (kilograms per meter);
α = coefficient of heat transfer, in British thermal units per foot-hour-degrees Fahrenheit (watts per meter-degrees Kelvin);
Δ = increment;
$\Delta\xi$ = mesh width, in feet (meters);
ϵ = emissivity;
λ = slenderness ratio;

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ρ = density of steel, in pounds per cubic foot (kilograms per cubic meter); and

σ = stress, ksi (N/m^2); Stefan-Boltzmann constant, 0.1713×10^{-8}, in British thermal units per hour-square foot-degrees Rankine to the fourth power (watts per square meter—degrees Kelvin to the fourth power).

Subscripts

a = allowable, average;
cr = critical;
f = of furnace;
m = at or around mesh point in mth row;
n = at or around mesh point in nth column;
o = at room temperature;
s = of steel cross section;
T = at temperature T; and
y = at yield stress.

Superscripts

j = at $t = j\Delta t$.

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9719 FIRE RESISTANCE OF UNPROTECTED STEEL COLUMNS

KEY WORDS: **Buildings (codes); Columns; Fire protection; Fire resistance;** Heat transfer; Steel; **Structural engineering; Temperature**

ABSTRACT: Fire resistance of unprotected steel columns is examined by standard fire test and numerical analyses based on a 1,000 D F (538 D C) critical temperature for failure. It is shown that fire resistance time varies with the shape factor of column weight divided by the heated perimeter, and two simple equations for calculating the fire resistance times of unprotected steel columns are established. A practical example shows that large columns used in high-rise buildings can have fire resistance times of up to one hr. The more conservative of the two equations is recommended for use in building standards.

REFERENCE: "Fire Resistance of Unprotected Steel Columns," *Journal of the Structural Division*, ASCE, Vol. 99, No. ST5, Proc. Paper 9719, May, 1973, pp. 837-852

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Fire Technology
Nov 1981

Assessment of Fire Resistance Requirements

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The calculation of normalized heat load, a succinct quantifier of the potential of compartment fires to spread by destruction, is greatly simplified by the introduction of two semi-empirical equations. These afford direct insight into the relation between the destructive potential of fire and the principal characteristics of the fire compartment and its contents of combustibles.

ALTHOUGH the bases on which code writers bring down their decisions on fire resistance requirements have changed over the years, the influence of Ingberg's fire load concept[1] is still recognizable. That concept, developed some 40 years ago, claims that the destructive potential of compartment fires is proportional to the specific fire load (mass of combustibles per unit floor area), and that the fire resistance requirement for compartment boundaries should also be allocated in proportion to the specific fire load.

Although still widely used, the concept was soundly disproved by the results of subsequent experimental research. The outlines of a rational way of assigning fire resistance requirements has recently emerged, following the identification of a parameter as a unique quantifier of the potential of enclosure fires for destructive spread.[2] With this new understanding, decisions regarding fire resistance requirements are a matter of matching the values of the parameter calculated for real-world conditions with those developed for test conditions.

calculation of the parameter quantifying the destructive spread
l of fires under real-world conditions is quite straightforward, but
involves an iterative technique, it may prove somewhat time con-
for those who attempt to perform it without a programmable
r. To eliminate the need for iteration, the feasibility of expressing
meter by an approximate empirical equation has been examined.
lts of the examination are reported in this paper.

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quirements concerning

same. Conversely, specifying the same fire resistance requirement for all boundar[illegible] an enclosure is a practice that relies on the validity of the theorem [illegible] uniformity of normalized heat load.

SEMI-EMPIRICAL EXPRESSION FOR THE NORMALIZED HEAT LOAD

According to statistical data, the fire load in modern buildings, despite the increasing use of plastics, consists predominantly of cellulosics. Since, in addition, fires of cellulosics excel in their destructive potential,[4] it appears to be a safe practice to assume that the fire load consists fully of cellulosics.

By reflecting on the meaning of Ingberg's fire l[illegible]cept,[1] one recognizes that it has been built on the implicit assumpti[illegible] in a fire the bulk of the fuel energy is eventually absorbed by the c[illegible]rtment boundaries. The normalized heat load pertaining to the assumption that *all* heat release by the fuel is absorbed within the compartment is

$$H_m = \frac{1}{\sqrt{k\varrho c}}\,\frac{G\Delta H}{A_t} \qquad (6)$$

where the subscript *m* has been affixed to *H* to indicate that it represents the conceivable absolute maximum, *G* is the total fire load (total fuel mass), and ΔH is the heat of combustion of the fuel.

Fortunately it has been found that the normalized heat load on the compartment boundaries is only 10 to 40 percent of H_m. Some of the fuel energy is released outside the compartment, but even of the portion released inside some energy will leave the compartment with the fire gases as sensible heat and some will be lost by radiation through the ventilation opening. A multitude of calculations performed by the detailed iterative technique mentioned earlier indicates that the normalized heat load, in other words the potential of fire for destructive spread,

- increases less than in proportion to the fire load,
- decreases as the ventilation of the compartment increases, and
- decreases as the thermal inertia of the boundaries increases.

[illegible] numerical results of these calculations formed the basis for an in[illegible]ion that resulted in the following semi-empirical equation:

$$H = 10^6\,\frac{(11.0\,\delta + 1.6)\,G}{A_t\sqrt{k\varrho c} + 935\sqrt{\Phi G}} \qquad (7)$$

released inside the compartment. It is to be estimated from the following equation:

$$\delta = \begin{cases} 0.79\sqrt{h_c^{3}}/\Phi \\ 1 \end{cases} \quad \text{whichever is less} \qquad (8)$$

where h_c is the height of the compartment.

Φ is a variable that characterizes the ventilation of the compartment. It is defined as

$$\Phi = \varrho_a A_v \sqrt{gh} \qquad (9)$$

where ϱ_a is the density of environmental atmosphere, A_v is the area of ventilation opening (window or door), *h* is the height of the ventilation opening, and *g* is the acceleration due to gravity. The considerations that have led to the development of Equation 7 are discussed in the Appendix.

As the specific fire load G/A_t (where A_t is the floor area of the compartment) may vary rather markedly from compartment to compartment, the selection of the value of *G* for the fire safety design must be based on an analysis of statistical data. If the compartment boundaries are simple "dividing elements" without essential structural functions, the design value for G/A_t is usually taken as the 80th percentile in the cumulative plot for the applicable occupancy. If, on the other hand, the compartment boundaries are "key elements" that play an important part in the structural performance of the building as a whole, some extra degree of safety is justified. The selection of *G* may be based on considerations propounded by Lie[7] and outlined later by Harmathy.[4]

The ventilation parameter, Φ, is a measure of the minimum ventilation of the compartment. This occurs under "classic" draft-free conditions. As discussed by Harmathy,[4] the presence of drafts causes the value of Φ to increase over that calculated from Equation 9 and thus (by virtue of Equation 7) to reduce the value of the normalized heat load, a value for Φ obtained from Equation 9 may be used in assessing the potential of fires for destructive spread.

It is of interest to examine the normalized heat load in relation to its limiting value, as expressed by Equation 6. Combining Equations 6 and 7 and using $\Delta H = 18.8 \times 10^6$ J kg^{-1} in the former (because the fire load is assumed to be cellulosic), the following equation is obtained:

$$\frac{H}{H_m} = \frac{0.585\,\delta + 0.085}{1 + 935\,\dfrac{\sqrt{G\Phi}}{A_t\sqrt{k\varrho c}}}$$

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REF #3

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ATTACH. I

HEAT, MASS, AND MOMENTUM TRANSFER

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TABLE E.1—Continued

(2) Nonmetals	T (°F)	ρ (lb$_m$/ft^3)	c_p (Btu/lb$_m$ F)	k (Btu/hr ft F)	α (ft^2/hr)
Aerogel, silica	100	5.3	0.205	0.013	0.012
Asbestos	32	36	0.25	0.087	0.010
	800	36		0.130	
Brick, common	68	100	0.20	0.20–0.10	0.01–0.02
fire clay	1472	145	0.23	0.79	0.024
Bakelite	68	79.5	0.38	0.134	0.0044
Concrete	68	119–144	0.21	0.47–0.81	0.019–0.027
Corkboard	100	10	0.4	0.025	0.006
Diatomaceous earth, powdered	100	14	0.21	0.030	0.01
Fiber insulating board	100	14.3		0.024	
Glass, window	68	162	0.16	0.51	0.020
Glass wool, fine	100	1.5		0.031	
packed	100	6.0		0.022	
Ice	32	57	0.46	1.28	0.048
Magnesia, 85%	100	17		0.039	
Marble	68	156–169	0.193	1.6	0.064
Paper				0.075	
Rock wool	100	12		0.023	
Rubber, hard	32	74.8	0.48	0.087	0.0024
Wood, oak, ⊥ to grain	70	51	0.57	0.12	0.004
Wood, oak, ‖ to grain	70	51	0.57	0.23	0.0069

perties

SOME [illegible]DS

k (Btu/hr ft F) (212 F)	(1112 F)	α (ft^2/hr) (68 F)
119		3.665
74		1.322

13		
219	204	4.353
39	23	0.785
		0.666
33	21	0.634
19.3		0.924
97		3.762
68	61	2.074
48		0.882
37	32	0.677
240		6.001
25	19	0.452
10	13	0.172
34		1.505
87	65	2.430
63		1.591

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am*

600	800	1000
.0266	0.0303	0.0337
.0238	0.0292	0.0345

al is

(1)

s $\dot{q}_x = -k(\partial t/\partial x)$, and if
x). This states that the
cross-sectional $A(x)$ nor-
$\partial t/\partial x$ along the conduc-
e" thermal conductivity

h temperature, and the

is t' alue of k at the
ness .

(2)

$(A_o - A_i)/\ln(A_o/A_i)$;
apes, Eq. (1) must be
procedure (Awbery and
0) or by the relaxation

[redacted]

REFERENCE #3 CONCRETE M198 REV-1
ATTACH-I
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Table 3. Thermal Conductivities of Miscellaneous Solid Substances*

(Values of k are to be regarded as rough average values for the temperature range indicated)

Material	Bulk density, lb per cu ft	Temp, deg F	k	Material	Bulk density, lb per cu ft	Temp, deg F	k
Asbestos board, compressed asbestos and cement	123.	86.	0.225	Quartz, crystal, parallel to C-axis	...	−300.	25.0
Asbestos millboard	60.5	86.	0.070			0.	8.3
Asbestos wool	25.	212.	0.058			300.	4.2
Ashes, soft wood	12.5	65.	0.018	Rubber, hard	74.3	100.	0.092
Ashes, volcanic	51.	300.	0.123	Rubber, soft, vulcanised	68.6	86.	0.08
Carbon black	12.	133.	0.012	Sand, dry	94.8	68.	0.188
Cardboard, corrugated	...	...	0.037	Sawdust, dry	13.4	68.	0.042
Celluloid	87.3	86.	0.12	Silica, fused	...	200.	0.83
Cellulose sponge, du Pont	3.4	82.	0.033	Silica gel, powder	32.5	131.	0.049
Concrete, sand and gravel	142.	75.	1.05	Soil, dry	...	68.	0.075
Concrete, cinder	97.	75.	0.41	Soil, dry, including stones	127.	68.	0.30
Charcoal, powder	11.5	63.	0.029	Snow	7–31	32.	0.34–1.3
Cork, granulated	5.4	23.	0.028	Titanium oxide, finely ground	52.	1000.	0.041
Cotton wool	5.0	100.	0.035	Wool, pure	5.6	86.	0.021
Diamond	151.	70.	320.	Zirconia grain	113.	600.	0.11
Earth plus 42 % water	108.	0.	0.62	Woods, oven dry, across grain†:			
Fiber, red	80.5	68.	0.27	Aspen	26.	83.	0.069
"Flotofoam" (U.S. Rubber Co.)	1.6	92.	0.017	Bald cypress	[illegible]	[illegible]	0.065
Glass, pyrex	139	200.	0.59	Balsa	[illegible]	[illegible]	[illegible]
Glass, soda lime	...	200.	0.59	Basswood	[illegible]	[illegible]	[illegible]
Graphite, solid	93.5	122.	87.	Douglas Fir	[illegible]	[illegible]	[illegible]
Gravel	116.	68.	0.22	Elm, rock	[illegible]	[illegible]	[illegible]
Gypsum board	51.	99.	0.062	Fir, white	[illegible]	[illegible]	[illegible]
Ice	57.5	...	1.26	Hemlock	[illegible]	[illegible]	[illegible]
Kaolin wool	10.6	800.	0.059	Larch, western	[illegible]	[illegible]	[illegible]
Leather, sole	62.4	...	0.092	Maple, sugar	[illegible]	[illegible]	[illegible]
Mica	122.	...	0.25	Oak, red	[illegible]	[illegible]	[illegible]
Pearlite, Arizona, spherical shell of siliceous material	9.1	112.	0.035	Pine, southern yellow	[illegible]	[illegible]	[illegible]
Polystyrene, expanded "Styrofoam"	1.7	...	0.021	Pine, white	[illegible]	[illegible]	[illegible]
Pumice, powdered	49.	300.	0.41	Red cedar, western	[illegible]	[illegible]	[illegible]
Quartz, crystal, perpendicular to C-axis	...	−300.	12.5	Redwood	[illegible]	[illegible]	[illegible]
		0.	4.5	Spruce	[illegible]	[illegible]	[illegible]
		300.	2.3				

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* The thermal conductivity of different materials varies greatly. [illegible] for certain insulating materials, such as glass wool, cork, and kapok, [illegible] with the temperature, but in the case of metals, the variation is relatively small. [illegible] stances, k increases with rising temperatures, but in the case of many crystalline materials [illegible]

† With heat flow parallel to the grain, k may be 2 to 3 times that with heat flow [illegible] grain; the values for wood are taken chiefly from J. D. MacLean, Trans. ASHVE, 47, [illegible]

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(NUC89-B22)

M-198 REV. 1

Attachment II - Independent Verification Statement (CIVIL/STRUCTURAL)

Calculation # M-198, Revision # 1 *(SEE NOTES BELOW) has been independently verified by the following method(s), as noted below:

Design Review ☒ including verification that:

- * Design inputs were correctly selected and included in the calculation.
- * Assumptions are adequately described and are reasonable.
- * Input or assumptions requiring confirmation are identified, and if any exist, the calculation has been identified as "Preliminary" and a "Finalization Due Date" has been specified.
- * Design requirements from applicable codes, standards and regulatory documents are identified and reflected in the design.
- * Applicable construction and operating experience was considered in the design.
- * The calculation number has been properly obtained and entered.
- * An appropriate design method or computer code was used.
- ° A mathematical check has been performed.
- ° The output is reasonable compared to the input.

Alternate Calculation ☐ including verification of asterisked items noted above. The alternate calculation (____ pages) is attached.

Qualification Testing ☐ for design feature ________________________ including verification of asterisked items noted above and the following:

- ° The test was performed in accordance with written test procedures.
- ° Most adverse design conditions were used in the test.
- ° Scaling laws were established and verified and error analyses were performed, if applicable.
- ° Test acceptance criteria were clearly related to the design calculation.
- ° Test results (documented in ____ ____________________) were reviewed by the calculation Preparer or other cognizant engineer.

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* NOTES: Independent Verifier Comments: 1. THE SCOPE OF THIS INDEPENDENT VERIFICATION IS LIMITED TO THE REVIEW OF THE CONCRETE AND STEEL SURFACE AREA CALCULATIONS ON PAGES 12 THROUGH 15.

See NED Procedure 3.05, Sec. 7.1.1 /s/ Joseph L Jerz 9/26/86
Independent Verifier Date

Preparer concurrence with findings and comment resolution /s/ John F. Prawlucki 9/23/86
Preparer or other cognizant engineer Date

Exhibit 3.05-Q Rev. 5

2. REFER TO INDEPENDENT REVIEW STATEMENT ATTACHMENT II TO CALCULATION NO. FP 26 REV. 1 DATED 9-23-86 FOR "DOCUMENTATION OF STRUCTURAL PERFORMANCE OF STE[illegible] ELEVATED TEMPERATURES" BY J. PRAWLUCKI DATED [redacted] THIS PROVIDES FURTHER JUSTIFI[illegible] THE USE OF 1000 F AS A TEMPERATURE LIMIT FOR UNPROTECTED STRUCTURAL STEEL.

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M198

Attachment ~~I~~ III - Independent Verification Statement (FS & MC)

Calculation # M198 Revision # 1 has been independently verified by the following method(s), as noted below:

Design Review ☒ including verification that:

- * Design inputs were correctly selected and included in the calculation.
- * Assumptions are adequately described and are reasonable.
- * Input or assumptions requiring confirmation are identified, and if any exist, the calculation has been identified as "Preliminary" and a "Finalization Due Date" has been specified.
- * Design requirements from applicable codes, standards and regulatory documents are identified and reflected in the design.
- * Applicable construction and operating experience was considered in the design.
- * The calculation number has been properly obtained and entered.
- * An appropriate design method or computer code was used.
- ° A mathematical check has been performed.
- ° The output is reasonable compared to the input.

Alternate Calculation ☐ including verification of asterisked items noted above. The alternate calculation (___ pages) is attached.

Qualification Testing ☐ for design feature ______________ including verification of asterisked items noted above and the following:

- ° The test was performed in accordance with written test procedures.
- ° Most adverse design conditions were used in the test.
- ° Scaling laws were established and verified and error analyses were performed, if applicable.
- ° Test acceptance criteria were clearly related to the design calculation.
- ° Test results (documented in ______________) were reviewed by the calculation Preparer or other cognizant engineer.

Independent Verifier Comments: see attached sheet – Comments resolved

See NED Procedure 3.05, Sec. 7.1.1 /s/ Joseph S Roberts 9/2/86
Independent Verifier Date

Preparer concurrence with findings and comment resolution /s/ JFBienky 10/3/86
Preparer or other cognizant engineer Date

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ATTACHMENT III - INDEPENDENT VERIFICATION
ES&MC

QUESTIONS/COMMENTS

CALC M198
PAGE 2 OF 4

Q1 SHOULD THE STANDARD TIME TEMPERATURE CURVE (ASTM-E-119) BE INCLUDED AS AN ATTACHMENT TO THE CALCULATION?

Q2 HOW WERE THE TEMPERATURES DETERMINED FOR TIME INCREMENTS FOR THE CALCULATION?

Q3 CLARIFY TABLE 6.5. WHY IS TABLE DEVELOPED FOR COMBUSTIBLE LOADINGS GREATER THAN FOUND IN AREAS ANALYSED?

Q4 WHAT IS THE RELATIONSHIP BETWEEN FIRE LOADING AND HEAT FLUX? DOES FIRE LOADING EQUAL HEAT FLUX AT EQUILIBRIUM?

Q5 WHAT IS THICKNESS OF THE CONCRETE FIRE BARRIERS?

Q6 SHOULD THE TEMPERATURE COMPUTATION BE IN UNITS OF °R?

Q7 CLEARLY IDENTIFY THE NEW SURFACE TEMPERATURE IN CALCULATION.

Q8 DOES ASSUMPTION 9 APPLY TO THIS CALCULATION?

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ATTACHMENT III - INDEPENDENT VERIFICATION

FS&MC

ANSWERS / COMMENTS

CALC M198
PAGE 3 OF 4

A1. THE STANDARD-TIME-TEMPERATURE CURVE is FROM A NATIONAL STANDARD (ASTM) AND WAS NOT INCLUDED IN THE CALCULATION TEXT. THE "STT" CURVE DOES, HOWEVER, APPEAR IN ATTACHMENT II, pg 8 OF 22.

A2. THE TEMPERATURES FOR THIS CALCULATION WERE TAKEN FROM APPENDIX "B" OF THE NATIONAL FIRE CODES; VOLUMN 10; 1981; SECTION 251. APPENDIX "B" is ACTUALLY THE ASTM-E-119 CURVE IN TABULAR FORM.

A3. TABLE 6.5 HAS BEEN MARKED-UP TO CLEARLY IDENTIFY STEEL TEMPERATURES. PORTIONS OF THE TABLE, WHICH EXCEED THE COMBUSTIBLE HEAT LOAD WHICH is APPLIED TO THE AREA BOUNDARY, HAVE BEEN ELIMINATED.

A4. THE HEAT FLUX IS DETERMINED BY COLUMNS 1 THRU 6 (TABLE A). IT is A FUNCTION OF ΔT AND THE COMBINED CONVECTION AND RADIATION COEFFICIENTS. THE HEAT FLUX is USED TO DETER THE GROSS HEAT APPLIED TO THE

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ATTACHMENT III - INDEPENDENT VERIFICATION FS&MC

CALC M198

ANSWERS/COMMENTS

A4.(CON'T) BOUNDARIES. WHEN THE TOTAL GROSS HEAT APPLIED $(\Sigma Q_s + \Sigma Q_c)$ IS EQUAL TO 40% OF THE THEORITICAL FIRE LOAD, THE TEMPERATURE OF THE STEEL IS IDENTIFIED.

A5. THE THICKNESS OF THE CONCRETE FIRE BARRIERS IS NOT REQUIRED FOR THIS CALCULATION. THE CONCRETE THICKNESS MEETS OR EXCEEDS THE THICKNESS REQUIRED FOR THE FIRE BARRIER RATING.

A6. THE TEMPERATURE COMPUTATION, IN DEGREES FAHRENHEIT, IS ACCEPTABLE;

a) $F_0 = \Delta T h$

b) $T_w = T_{w_1} + 2\left(\frac{F_0}{K}\right)\left(\frac{ab}{3.14}\right)^{1/2}$

ABOVE FORMULA UTILIZES A ΔT FOR

a $\therefore$ ΔT OF 1°F = ΔT OF 1°R

A7. DONE

A8. ASSUMPTION 9 HAS BEEN DELETED FROM THE CALCULATION ASSUMPTIONS. THIS ASSUMPTION IS NOT REQUIRED.

ATTACHMENT 4 TO BECO LETTER 88-010

APPLICATION OF M197/M198 CALCULATION METHODOLOGY

- TORUS AREA (See calculation M197, Rev. 2)

Plan View Area = 10,658 SF (P18)

Proposed Maximum = 14,000 BTU/SF X10,658 SF
= 149.21×10^6 BTU

From Table B (P21), the total BTU's absorbed (as a function of time) during a standard ASTM E-119 fire, and the corresponding steel temperature:

t	Sigma (Qs) + Sigma (Qc)	TN (steel)
.05hrs	52.85×10^6BTU	137°F
.10hrs	150.82×10^6BTU	255°F

Since 149.21×10^6 BTU is essentially equivalent to the heat required to raise the steel to only 255°F, the associated proposed maximum loading of 14,000 BTU/SF is safe.

- STEAM TUNNEL (See Calculation M198, Rev. 1)

Plan View Area = 784 SF (P13)

Proposed Maximum = 8200 BTU/SF X 784 SF
= 6.43×10^6 BTU

From Table B (P17), the total BTU's absorbed (as a function of time) during a standard ASTM E-119 fire, and the corresponding steel temperature:

t	Sigma (Qs) + Sigma (Qc)	TN (steel)
.05hrs	2.0×10^6BTU	137°F
.10hrs	6.4×10^6BTU	255°F

Since 6.43×10^6 BTU is essentially equivalent to the heat required to raise the steel to only 255°F, the associated proposed maximum loading of 8,200 BTU/SF is safe.