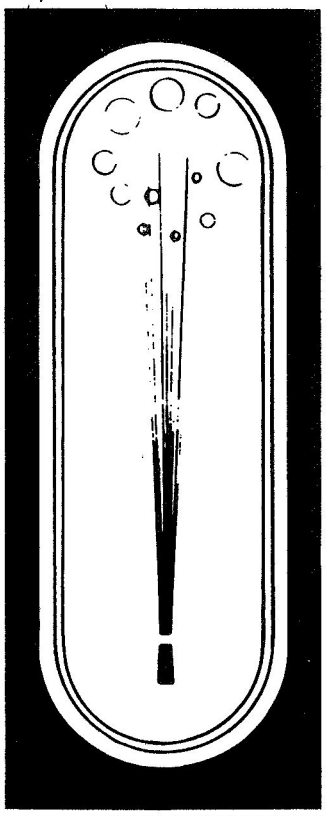

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STUDY OF CRYOGENIC FLUID MIXING TECHNIQUES

Final Report

(JULY 1969-JULY 1970)

Volume II - Large-Scale Mixing Data

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Volume II: Large-Scale Mixing Data

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Prepared for the
George C. Marshall Space Flight Center
National Aeronautics and Space Administration
Huntsville, Alabama

Under

Contract No. NAS8-24882

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F O R E W O R D

This document is Volume II of the final report on NASA Contract NAS8-24882, "Study of Cryogenic Propellant Stratification Reduction Techniques". The study was performed by the Fort Worth Division of General Dynamics Corporation for the George C. Marshall Space Flight Center of the National Aeronautics and Space Administration. The program was conducted under the technical direction of Mr. T. W. Winstead of the MSFC Astronautics Laboratory. His assistance in the performance of this study is gratefully acknowledged.

The final report consists of three volumes:

Volume I.	Large-Scale Experimental Mixing Investigations and Liquid-Oxygen Mixer Design
Volume II.	Large-Scale Mixing Data
Volume III.	Computer Procedure for the Prediction of Stratification in Supercritical Oxygen Tanks

Volume I contains a presentation of the large-scale experimental investigations and liquid-oxygen mixer design study together with a summary of the important findings of the study. Volume II contains a presentation of the experimental data utilized in this study. Volume III describes the computer procedure developed during the study for the prediction of stratification in supercritical oxygen tanks.

TABLE OF CONTENTS

		Page
	FOREWORD	iii
	LIST OF FIGURES	vii
	NOMENCLATURE	xxix
	SUMMARY	xxxi
1.	INTRODUCTION	1
2.	LARGE-SCALE DATA DESCRIPTION	3
	2.1 Transient Temperature Destratification Data	3
	2.2 Dimensionless Mixing Temperature Data	5
	2.3 Energy Integral Data	8
3.	DATA PRESENTATION	15
	REFERENCES	223

LIST OF FIGURES

Figure		Page
1	Transient Temperature Destratification: Run 1	17
2	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 1	18
3	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 1	19
4	Transient Energy Integral: Run 1	20
5	Transient Temperature Destratification: Run 2	21
6	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 2	22
7	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 2	23
8	Transient Energy Integral: Run 2	24
9	Transient Temperature Destratification: Run 3	25
10	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 3	26

LIST OF FIGURES (Cont'd)

Figure		Page
11	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at $\theta = 0.0$ sec; Centerline Surface Temperature Drop Starts at $\theta_1 = 0.0$ sec; Run 3	27
12	Transient Energy Integral: Run 3	28
13	Transient Temperature Destratification: Run 4	29
14	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at $\theta = 0.0$ sec; Average Surface Temperature Drop Starts at $\theta_1 = 0.0$ sec; Run 4	30
15	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at $\theta = 0.0$ sec; Centerline Surface Temperature Drop Starts at $\theta_1 = 0.0$ sec; Run 4	31
16	Transient Energy Integral: Run 4	32
17	Transient Temperature Destratification: Run 5	33
18	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at $\theta = 0.0$ sec; Average Surface Temperature Drop Starts at $\theta_1 = 0.0$ sec; Run 5	34
19	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at $\theta = 0.0$ sec; Centerline Surface Temperature Drop Starts at $\theta_1 = 0.0$ sec; Run 5	35
20	Transient Energy Integral: Run 5	36

LIST OF FIGURES (Cont'd)

Figure		Page
21	Transient Temperature Destratification: Run 6	37
22	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 6	38
23	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 6	39
24	Transient Energy Integral: Run 6	40
25	Transient Temperature Destratification: Run 7	41
26	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 7	42
27	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 7	43
28	Transient Energy Integral: Run 7	44
29	Transient Temperature Destratification: Run 8	45
30	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 8	46

LIST OF FIGURES (Cont'd)

Figure		Page
31	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 8	47
32	Transient Energy Integral: Run 8	48
33	Transient Temperature Destratification: Run 9	49
34	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 9	50
35	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 9	51
36	Transient Energy Integral: Run 9	52
37	Transient Temperature Destratification: Run 10	53
38	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 10	54
39	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 10	55
40	Transient Energy Integral: Run 10	56

LIST OF FIGURES (Cont'd)

Figure		Page
41	Transient Temperature Destratification: Run 11	57
42	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 9.0 sec; Run 11	58
43	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 11	59
44	Transient Energy Integral: Run 11	60
45	Transient Temperature Destratification: Run 12	61
46	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 12	62
47	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 12	63
48	Transient Energy Integral: Run 12	64
49	Transient Temperature Destratification: Run 13	65
50	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 13	66

LIST OF FIGURES (Cont'd)

Figure		Page
51	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 13	67
52	Transient Energy Integral: Run 13	68
53	Transient Temperature Destratification: Run 14	69
54	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 14	70
55	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 14	71
56	Transient Energy Integral: Run 14	72
57	Transient Temperature Destratification: Run 15	73
58	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 15	74
59	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 15	75
60	Transient Energy Integral: Run 15	76

LIST OF FIGURES (Cont'd)

Figure		Page
61	Transient Temperature Destratification: Run 16	77
62	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 16	78
63	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 16	79
64	Transient Energy Integral: Run 16	80
65	Transient Temperature Destratification: Run 17	81
66	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 17	82
67	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 17	83
68	Transient Energy Integral: Run 17	84
69	Transient Temperature Destratification: Run 18	85
70	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 18	86

LIST OF FIGURES (Cont'd)

Figure		Page
71	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 18	87
72	Transient Energy Integral: Run 18	88
73	Transient Temperature Destratification: Run 19	89
74	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 19	90
75	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 19	91
76	Transient Energy Integral: Run 19	92
77	Transient Temperature Destratification: Run 20	93
78	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 20	94
79	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 20	95
80	Transient Energy Integral: Run 20	96

LIST OF FIGURES (Cont'd)

Figure		Page
81	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 21	97
82	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 21	98
83	Transient Temperature Destratification: Run 22	99
84	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 22	100
85	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 22	101
86	Transient Energy Integral: Run 22	102
87	Transient Temperature Destratification: Run 23	103
88	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 23	104
89	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 23	105

LIST OF FIGURES (Cont'd)

Figure		Page
90	Transient Energy Integral: Run 23	106
91	Transient Temperature Destratification: Run 24	107
92	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 24	108
93	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 24	109
94	Transient Energy Integral: Run 24	110
95	Transient Temperature Destratification: Run 25	111
96	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 25	112
97	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 25	113
98	Transient Energy Integral: Run 25	114
99	Transient Temperature Destratification: Run 26	115

LIST OF FIGURES (Cont'd)

Figure		Page
100	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 26	116
101	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 26	117
102	Transient Energy Integral: Run 26	118
103	Transient Temperature Destratification: Run 27	119
104	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 27	120
105	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 27	121
106	Transient Energy Integral: Run 27	122
107	Transient Temperature Destratification: Run 28	123
108	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 28	124

LIST OF FIGURES (Cont'd)

Figure		Page
109	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 28	125
110	Transient Energy Integral: Run 28	126
111	Transient Temperature Destratification: Run 29	127
112	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 29	128
113	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 29	129
114	Transient Energy Integral: Run 29	130
115	Transient Temperature Destratification: Run 30	131
116	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 30	132
117	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 30	133
118	Transient Energy Integral: Run 30	134

LIST OF FIGURES (Cont'd)

Figure		Page
119	Transient Temperature Destratification: Run 31	135
120	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 31	136
121	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 31	137
122	Transient Energy Integral: Run 31	138
123	Transient Temperature Destratification: Run 32	139
124	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 32	140
125	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 32	141
126	Transient Energy Integral: Run 32	142
127	Transient Temperature Destratification: Run 33	143
128	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 33	144

LIST OF FIGURES (Cont'd)

Figure		Page
129	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 33	145
130	Transient Energy Integral: Run 33	146
131	Transient Temperature Destratification: Run 34	147
132	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 34	148
133	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 34	149
134	Transient Energy Integral: Run 34	150
135	Transient Temperature Destratification: Run 35	151
136	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 35	152
137	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 35	153
138	Transient Energy Integral: Run 35	154

LIST OF FIGURES (Cont'd)

Figure		Page
139	Transient Temperature Destratification: Run 36	155
140	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 36	156
141	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 36	157
142	Transient Energy Integral: Run 36	158
143	Transient Temperature Destratification: Run 37	159
144	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 37	160
145	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 37	161
146	Transient Energy Integral: Run 37	162
147	Transient Temperature Destratification: Run 38	163
148	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 38	164

LIST OF FIGURES (Cont'd)

Figure		Page
149	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 38	165
150	Transient Energy Integral: Run 38	166
151	Transient Temperature Destratification: Run 39	167
152	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 39	168
153	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 39	169
154	Transient Energy Integral: Run 39	170
155	Transient Temperature Destratification: Run 40	171
156	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 40	172
157	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 40	173
158	Transient Energy Integral: Run 40	174

LIST OF FIGURES (Cont'd)

Figure		Page
159	Transient Temperature Destratification: Run 41	175
160	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 41	176
161	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 41	177
162	Transient Energy Integral: Run 41	178
163	Transient Temperature Destratification: Run 43	179
164	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 43	180
165	Fraction of Initial Temperature Difference After Surface Temperature Starts to drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 43	181
166	Transient Energy Integral: Run 43	182
167	Transient Temperature Destratification: Run 44	183
168	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 44	184

LIST OF FIGURES (Cont'd)

Figure		Page
169	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 44	185
170	Transient Energy Integral: Run 44	186
171	Transient Temperature Destratification: Run 45	187
172	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 45	188
173	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1= 0.0 sec; Run 45	189
174	Transient Energy Integral: Run 45	190
175	Transient Temperature Destratification: Run 46	191
176	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 46	192
177	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 46	193
178	Transient Energy Integral: Run 46	194

LIST OF FIGURES (Cont'd)

Figure		Page
179	Transient Temperature Destratification: Run 47	195
180	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at 0 = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 47	196
181	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 47	197
182	Transient Energy Integral: Run 47	198
183	Transient Temperature Destratification: Run 48	199
184	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 48	200
185	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 48	201
186	Transient Energy Integral: Run 48	202
187	Transient Temperature Destratification: Run 49	203
188	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 49	204

LIST OF FIGURES (Cont'd)

Figure		Page
189	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 49	205
190	Transient Energy Integral: Run 49	206
191	Transient Temperature Destratification: Run 50	207
192	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 50	208
193	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 50	209
194	Transient Energy Integral: Run 50	210
195	Transient Temperature Destratification: Run 51	211
196	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 51	212
197	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 51	213

LIST OF FIGURES (Cont'd)

Figure		Page
198	Transient Energy Integral: Run 51	214
199	Transient Temperature Destratification: Run 52	215
200	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 52	216
201	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 52	217
202	Transient Energy Integral: Run 52	218
203	Transient Temperature Destratification: Run 53	219
204	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 53	220
205	Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 53	221
206	Transient Energy Integral: Run 53	222

NOMENCLATURE

Symbol	Description	Units
D_o	Nozzle diameter	ft
D_t	Tank diameter	ft
G_o	Volume flow rate	gpm
I_m	Energy integral, $I_m = 1 - \frac{T_s - T_m}{T_s - T_b}$	-
N_i^*	Initial Grashof number divided by the square of the Reynolds number	-
N_{Re}	Reynolds number	-
T_b	Average temperature at nozzle exit	^oF
T_m	Mean water temperature	^oF
T_i	Temperature of a section of the tank as measured by a thermocouple in the section	^oF
T_s	Average surface temperature	^oF
T_{s_1}	Centerline surface temperature	^oF
V_i	Volume of a tank section whose temperature is given by a thermocouple in the section	ft^3
V_o	Nozzle exit velocity	ft/sec
V_t	Tank volume	ft^3
Z_b	Axial distance from nozzle exit to liquid/vapor interface	ft
Z_d	Dye layer thickness	ft
Z_{di}	Initial dye layer thickness	ft
Z_s	Stratified depth	ft
ΔT	T_s-T_b, T_{s_1}-T_b, or T_s-T_m	^oF

N O M E N C L A T U R E (Cont'd)

Symbol	Description	Units
ΔT_i	Initial value of T_s-T_b, T_{s_1}-T_b, or T_s-T_m	^oF
θ	Test time measured from point in time when the pump is turned on	sec
θ_1	Test time measured from point in time when T_s or T_{s1} begins to decrease or when stratified dye layer begins to move	sec
θ_{mix}	Time Required for mixing process to reduce the initial stratification to some percentage of its initial value	sec

SUMMARY

The design of present and future spacecraft utilizing cryogenic fluids requires that adequate prediction and control of thermal stratification be accomplished. In a previous study, (Reference 1) methods were selected for mixing the thermally stratified layer with the remaining colder fluid in the tank and a mixer design procedure was developed. The mixer design procedure was based on small-scale mixing tests in which water was used as the test fluid. In the present study, the validity of scaling small-scale test data for use in designing mixer systems in full-scale tanks has been verified through use of a test tank intermediate in size between the previous small-scale tank and the full-scale tanks of spacecraft.

The experimental mixing investigation involved mixing in a large-scale (10-foot-diameter, 20-foot-long) stratified tank with non-pressurized water used as the test fluid. Tests were conducted to duplicate the range of the previous small-scale test parameters. The data obtained consist of temperature histories in the tank during mixing.

This volume of the final report presents both the basic mixing data and the preliminary dimensionless correlations made for each of the 52 tests run. These data are presented

in this volume for examination and preservation. Correlations and conclusions from the data are presented in Volume I.

SECTION 1

INTRODUCTION

This volume of the final report contains the data utilized from the large-scale tests conducted during this study. The purpose of documenting these data is (1) to provide the detailed test data from which the correlations in Volume I are obtained, and (2) to furnish data for further analyses as required.

The data were obtained from large-scale stratification mixing tests conducted in a vertical, non-pressurized, cylindrical water tank. The tank was 20 feet high and 10 feet in diameter. Stratification was induced in the tank prior to mixing by heating the top layer of fluid. No heat was added during mixing. Complete test details are given in Section 2 of Volume I.

The data are presented in the form of a tabular summary of test conditions and of graphical representations of the test results in both basic and dimensionless form. Data from a total of 52 tests are presented.

The basic data - temperature histories in the tank during axial jet mixing - consists of surface, nozzle exit, and mean fluid temperatures shown as a function of time. Dimensionless

temperature ratios, $(T_s-T_b)/(T_s-T_b)_i$, $(T_{s_1}-T_b)/(T_{s_1}-T_b)_i$, and $(T_s-T_m)/(T_s-T_m)_i$, obtained from the basic data are shown as a function of $V_oD_o\theta_1/D_t^2$. The energy integral, I_m, is shown as a function of $V_oD_o\theta/D_t^2$.

The methods of correlation are discussed in Section 2 of Volume I of this final report. The notations used in the figures and the table are self-explanatory or easily identified in the nomenclature.

SECTION 2

LARGE-SCALE DATA DESCRIPTION

Three types of graphical data are presented for each of 52 tests. These data consist of the basic temperature data during mixing, the dimensionless representations of the temperature decay, and the energy integral obtained from the basic temperature data.

2.1 TEMPERATURE DATA

The temperature data from each test consist of the mean fluid temperature, the fluid temperature at the nozzle exit, the average surface temperature, and the surface temperature at the tank centerline, all shown as a function of time, θ, after the pump is turned on. An example of this type of data is shown in Figure 1 of Section 3.

The nozzle exit temperature, T_b, is considered to be the temperature of the bulk liquid at the level of the nozzle exit. This temperature sometimes decreased slightly during a portion of the mixing time because of the motion of colder fluid from the tank bottom.

Two values of the surface temperature are presented: an average value, T_s, and a tank centerline value, T_{s1}. The

average value consists of a numerical average of the surface temperatures measured by four thermocouples located radially outward from the tank center and approximately ½ inch beneath the liquid surface. The thermocouples were positioned such that equal-volume annular sections are obtained when boundaries between sections are located halfway between adjacent thermocouples. The numerical averaging assumes that the temperature measured by each thermocouple represents the temperature of an equal volume of fluid at a uniform temperature. This value of the surface temperature provides a good indication of the overall condition of the surface, especially when the surface fluid initially begins to mix under the action of an axial jet impinging on the interface, since a large temperature gradient can exist across the liquid surface as cool fluid flows radially outward toward the wall. It should be pointed out, however, that the use of an average value of the surface temperature, in a correlation presenting the extent to which mixing has occurred, has a tendency to moderate the rate at which mixing appears to take place. T_{s_1}, the temperature of the surface at the tank centerline where the jet impinges, provides a good indication of when the axial jet penetrates the stratified layer and tank mixing starts. This temperature also provides an indication of either a sharp and complete penetration or a gradual penetration characterized

by the jet slowly erroding away the stratified layer.

The mean temperature of the fluid is a constant value during a given mixing test since no heat (except from environmental heating or cooling) was added to or removed from the fluid during mixing. The value of the mean temperature was taken as the temperature of the fluid at the end of mixing when the temperature is uniform in the tank. As a check, mixed temperatures were found to agree with the volume weighted mean temperature defined by

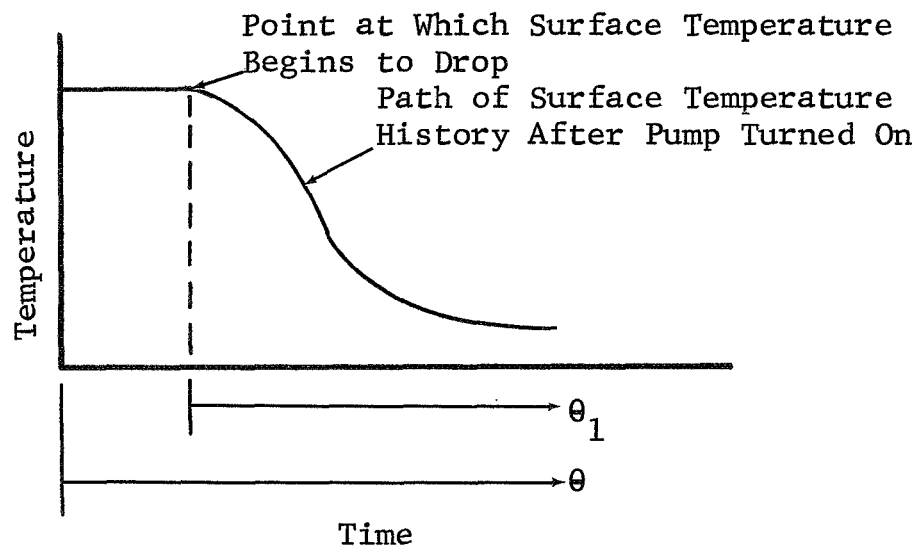
$$T_m = \frac{1}{V_t} \sum_{i=o}^{n} T_i V_i$$

Figure 1 in Section 3 is an example of the temperature data presented. The data points representing the centerline surface temperature are shown only for the time in which there is a differential between the average and centerline values.

2.2 DIMENSIONLESS MIXING TEMPERATURE DATA

The dimensionless mixing temperature data consist of values of $\Delta T/\Delta T_i$ as a function of $V_o D_o \theta_1 / D_t^2$. These data provide a measure of the extent to which mixing has reduced the thermal stratification existing in the tank. The time variable θ_1 is defined as zero at the point in time at which the sur-

face temperature begins to drop. This initial reference point is used rather than the point in time at which the pump is turned on because this initial reference point is an indication of when the surface fluid actually started to mix. The variable θ_1 described in the first paragraph of Subsection 2.1, is simply θ_1 plus the time interval from the point in time when the pump is turned on to the point in time when the surface temperature begin to drop. The following sketch illustrates this relationship



Two sets of this type of data are given. The first set consists of ΔT's given by T_s-T_b and T_s-T_m. The T_s-T_b data reflect the extent to which the surface temperature has been reduced compared with the bottom temperature. This is a measure of the total stratification existing in the fluid. The T_s-T_m data represent the differential between the surface

temperature and the mean tank temperature. This provides an indication of the extent of the surface temperature variation from the mean tank temperature. Figure 2 in Section 3 is an example of this type of data. Also shown on this plot are values of N_i^*, N_{Re}, Z_b/D_t, Z_b/D_o, and $V_oD_o(\theta-\theta_1)/D_t^2$. The value of $V_oD_o(\theta-\theta_1)/D_t^2$ is a measure of the dimensionless time interval between mixer activation and the initial drop in the surface temperature; it reflects jet transit time and the effect of buoyancy on mixing.

Also shown on the graph of Figure 2 is an analytical prediction from the previous study (Reference 1) of the movement of the dye layer interface down the tank during mixing. Although the two terms $\Delta T/\Delta T_i$ and Z_d/Z_{di} reflect entirely different quantities of temperature and distance, they both reflect the degree of mixing that has occurred in the tank. The prediction is shown here for comparison, since it was found (Reference 1) that small-tank transient temperature data indicate faster mixing than the predicted analytically when N_i^* is less than approximately 50. Similarly, when N_i^* is greater than approximately 50, the transient temperature decay in the small-scale tests will occur slower than that predicted analytically.

The second set of dimensionless mixing temperature data consists of ΔT's given by $T_{s1}-T_b$. These data reflect the surface temperature decay due to the mixing action of the jet at the center of the liquid surface. In general, these data show a faster response to mixing than do the correlations based on the average surface temperature. The dimensionless variables and the analytical prediction of dye motion, which were discussed previously, are also shown on this set of data. Figure 3 in Section 3 is an example of this type of data.

A summary of the parameters shown on all the graphs is given in Table 1. Also given are the basic test conditions.

2.3 ENERGY INTEGRAL DATA

The final type of data presented in this volume consists of the transient energy integral of each test. This term is given by

$$I_m = 1 - \frac{T_s - T_m}{T_s - T_b}$$

and is shown as a function of θ.

The energy integral is a measure of the energy distribution in the tank; it provides a measure of the extent of stratification. When this value is initially zero, the mean tank temperature is equal to the nozzle exit temperature, and the stratified layer is probably relatively thin. As I_m

Table 1

EXPERIMENTAL MIXING TESTS

Run	G_o (gpm)	D_o (in.)	Z_b (ft)	ΔT_i (^oF)	Z_s (ft)	θ_{mix}[a] (sec)	Z_b/D_t	Z_b/D_o	N_{Re}	N_i^*
1	83.0	0.875	18.5	8.6	2.5	263	1.85	253.7	2.6×10^5	12.90
2	83.0	0.875	18.5	5.0	18.5	220	1.85	253.7	2.5×10^5	6.32
3	120.0	0.875	18.5	66.9	2.0	186	1.85	253.7	2.8×10^5	60.40
4	20.8	0.875	18.5	79.6	2.0	4235	1.85	253.7	6.9×10^4	1993.64
5	65.0	0.875	18.5	92.3	2.5	220	1.85	253.7	1.9×10^5	188.5
6	80.0	0.875	18.5	93.7	2.5	65	1.85	253.7	2.7×10^5	186.92
7	120.0	0.875	18.5	7.8	4.0	160	1.85	253.7	4.1×10^5	7.29
8	120.0	0.875	18.5	16.2	11.5	188	1.85	253.7	4.4×10^5	17.6
9	102.0	0.875	18.5	29.2	15.5	284	1.85	253.7	2.9×10^5	20.83
10	85.0	0.875	18.5	32.2	3.5	101	1.85	253.7	2.4×10^5	32.98
11	37.0	0.875	18.5	37.0	5.5	1430	1.85	253.7	1.1×10^5	236.44
12	104.0	0.875	18.5	18.5	6.0	178	1.85	253.7	2.8×10^5	10.41
13	102.0	0.875	18.5	49.7	13.5	247	1.85	253.7	3.0×10^5	38.66

[a] θ_{mix} defined as the time required to reduce the initial stratification, ΔT_i to 0.1 ΔT_i

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Table 1 (Cont'd)

Run	G_o (gpm)	D_o (in.)	Z_b (ft)	ΔT_i (^oF)	Z_s (ft)	θ_{mix}[a] (sec)	Z_b/D_t	Z_b/D_o	N_{Re}	N_i^*
14	35.1	0.875	18.5	22.1	15.5	1355	1.85	253.71	0.962×10^5	113.55
15	63.25	0.875	18.5	32.8	17.5	571	1.85	253.71	1.915×10^5	77.30
16	29.8	0.625	18.2	90.0	2.5	1193	1.82	349.44	1.089×10^5	251.97
17	29.5	0.625	18.2	37.0	14.0	1645	1.82	349.44	1.236×10^5	186.38
18	29.5	0.625	18.2	18.3	5.5	1219	1.82	349.44	1.461×10^5	157.95
19	52.0	0.625	18.2	22.3	7.5	522	1.82	349.44	2.400×10^5	49.65
20	60.0	0.625	18.2	18.0	9.5	172	1.82	349.44	3.083×10^5	39.09
21	50.0	0.625	18.2	14.3	17.0	348	1.82	349.44	2.545×10^5	43.26
22	90.55	0.625	18.2	11.7	9.5	160	1.82	349.44	4.697×10^5	12.52
23	89.5	0.625	18.2	7.5	9.5	132	1.82	349.44	5.230×10^5	9.38
24	29.5	0.625	18.2	6.4	5.5	175	1.82	349.44	1.724×10^5	73.61
25	28.4	0.625	18.2	8.4	9.5	170	1.82	349.44	1.487×10^5	89.58
26	30.0	0.625	18.2	3.7	4.5	44	1.82	349.44	1.634×10^5	36.98
27	30.0	0.625	18.2	1.5	1.5	32	1.82	349.44	1.667×10^5	15.38

[a] θ_{mix} defined as the time required to reduce the initial stratification, ΔT_i, to $0.1 \Delta T_i$

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Table 1 (Cont'd)

Run	G_o (gpm)	D_o (in)	Z_b (ft)	ΔT_i (°F)	Z_s (ft)	θ_{mix}[a] (sec)	Z_b/D_t	Z_b/D_o	N_{Re}	N_i^*
28	26.5	0.625	18.2	4.5	5.5	65	1.82	349.44	1.473×10^5	59.11
29	24.8	0.625	18.2	2.6	4.5	60	1.82	349.44	1.393×10^5	38.29
30	24.9	0.625	18.2	2.3	4.5	60	1.82	349.44	1.420×10^5	35.68
31	24.6	0.625	18.2	14.9	9.5	530	1.82	349.44	1.418×10^5	251.30
32	11.7	0.625	8.7	9.2	2.0	1985	0.87	167.04	0.490×10^5	32.42
33	60.0	0.625	9.7	20.4	4.5	78	0.97	186.24	2.850×10^5	5.50
34	41.0	0.625	8.7	33.0	3.0	392	0.87	167.04	2.107×10^5	16.83
35	46.0	0.875	8.9	30.5	2.5	383	0.89	122.06	1.302×10^5	11.67
36	74.0	0.875	8.9	27.2	2.0	193	0.89	122.06	2.370×10^5	6.33
37	41.0	0.875	8.9	31.5	2.5	792	0.89	122.06	1.650×10^5	30.77
38	73.0	0.875	8.9	8.7	3.5	26	0.89	122.06	3.329×10^5	3.61
39	41.0	0.875	8.9	16.1	2.5	240	0.89	122.06	1.899×10^5	21.11
40	30.2	0.875	8.9	21.0	3.5	895	0.89	122.06	1.436×10^5	51.54
41	136.5	0.875	8.9	23.9	4.5	70	0.89	122.06	4.335×10^5	0.93
42	50.0	0.875	8.9	8.5	3.5	540	0.89	122.06	1.815×10^5	4.13

[a] θ_{mix} defined as the time required to reduce the initial stratification, ΔT_i, to 0.1 ΔT_i

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Table 1 (Cont'd)

Run	G_o (gpm)	D_o (in.)	Z_b (ft)	ΔT_i (°F)	Z_s (ft)	θ_{mix}[a] (sec)	Z_b/D_t	Z_b/D_o	N_{Re}	N_i^*
43	127.0	0.875	18.2	19.5	1.5	20.0	1.85	253.71	5.02×10^5	21.71
44	125.5	0.875	18.2	16.4	2.5	27.0	1.85	253.71	5.11×10^5	19.63
45	125.5	0.875	18.2	18.2	1.5	11.5	1.85	253.71	5.17×10^5	22.08
46	125.5	0.875	18.2	14.8	4.0	162.0	1.85	253.71	5.40×10^5	19.28
47	125.5	0.875	18.2	18.9	8.0	297.0	1.85	253.71	6.03×10^5	28.16
48	134.0	0.875	8.9	5.9	0.5	12.0	0.89	122.06	4.87×10^5	0.57
49	134.0	0.875	8.9	14.2	0.5	3.8	0.89	122.06	5.08×10^5	1.54
50	134.0	0.875	8.9	26.5	0.5	19.5	0.89	122.06	5.49×10^5	3.21
51	124.0	0.875	8.9	13.2	1.0	3.0	0.89	122.06	4.83×10^5	1.97
52	134.0	0.875	8.9	21.2	0.5	16.5	0.89	122.06	5.86×10^5	2.92
53	58.0	0.875	8.9	10.5	0.5	20.0	0.89	122.06	2.56×10^5	7.82

[a] θ_{mix} defined as the time required to reduce the initial stratification, ΔT_i, to 0.1 ΔT_i

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approaches 1, the tank fluid is relatively well mixed, although there may be some stratification remaining as indicated by T_s-T_b. When I_m is greater than 1 the tank fluid has undergone a temporary inverse stratification. Values greater than 1 exist only for a short time, and the data are sometimes doubtful since the temperature differences are often very small. Consequently, when this type of condition is encountered, the plots will often show a break in the data. Figure 4 in Section 3 is an example of this type of data.

SECTION 3

DATA PRESENTATION

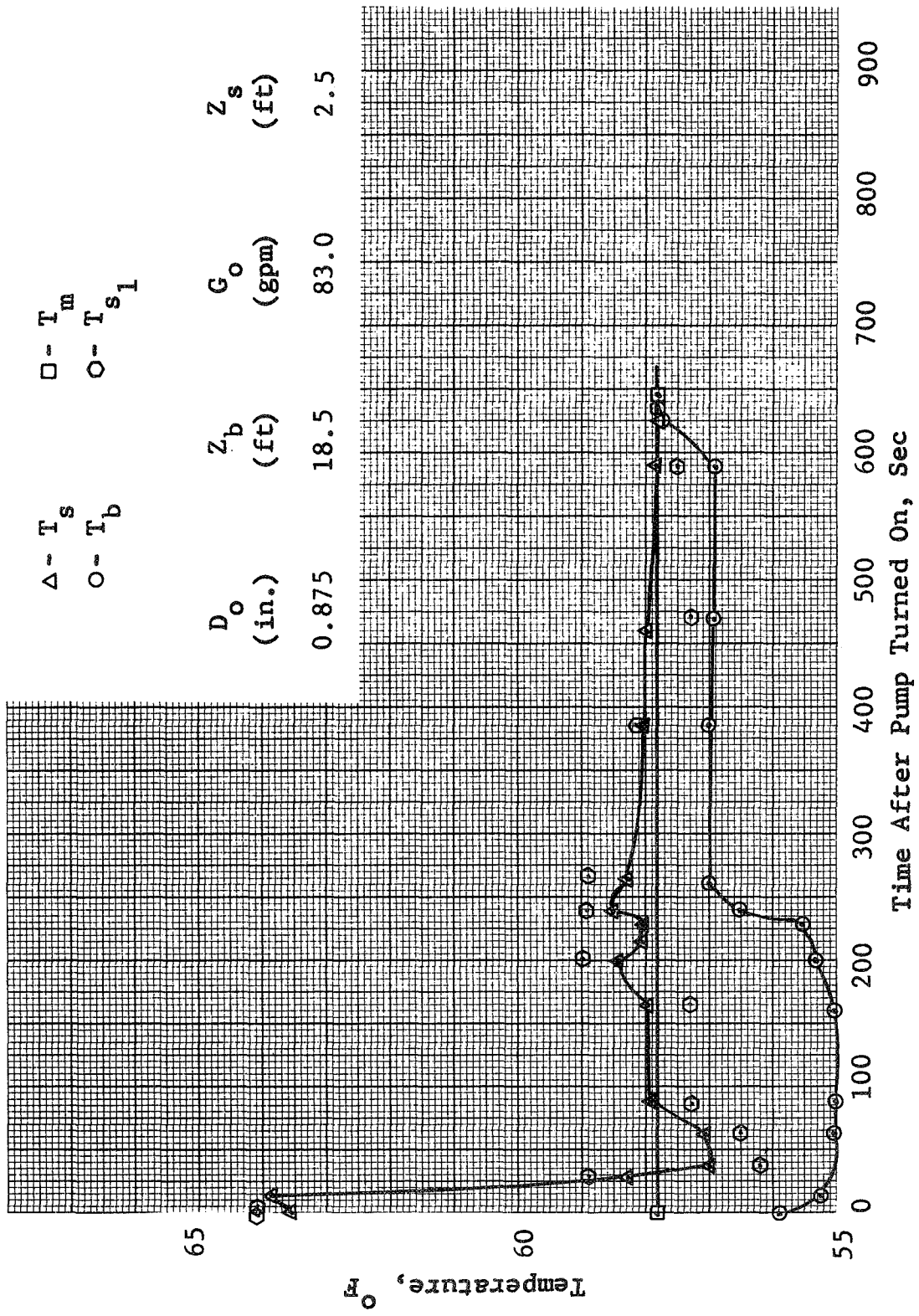

Figure 1 Transient Temperature Destratification: Run 1

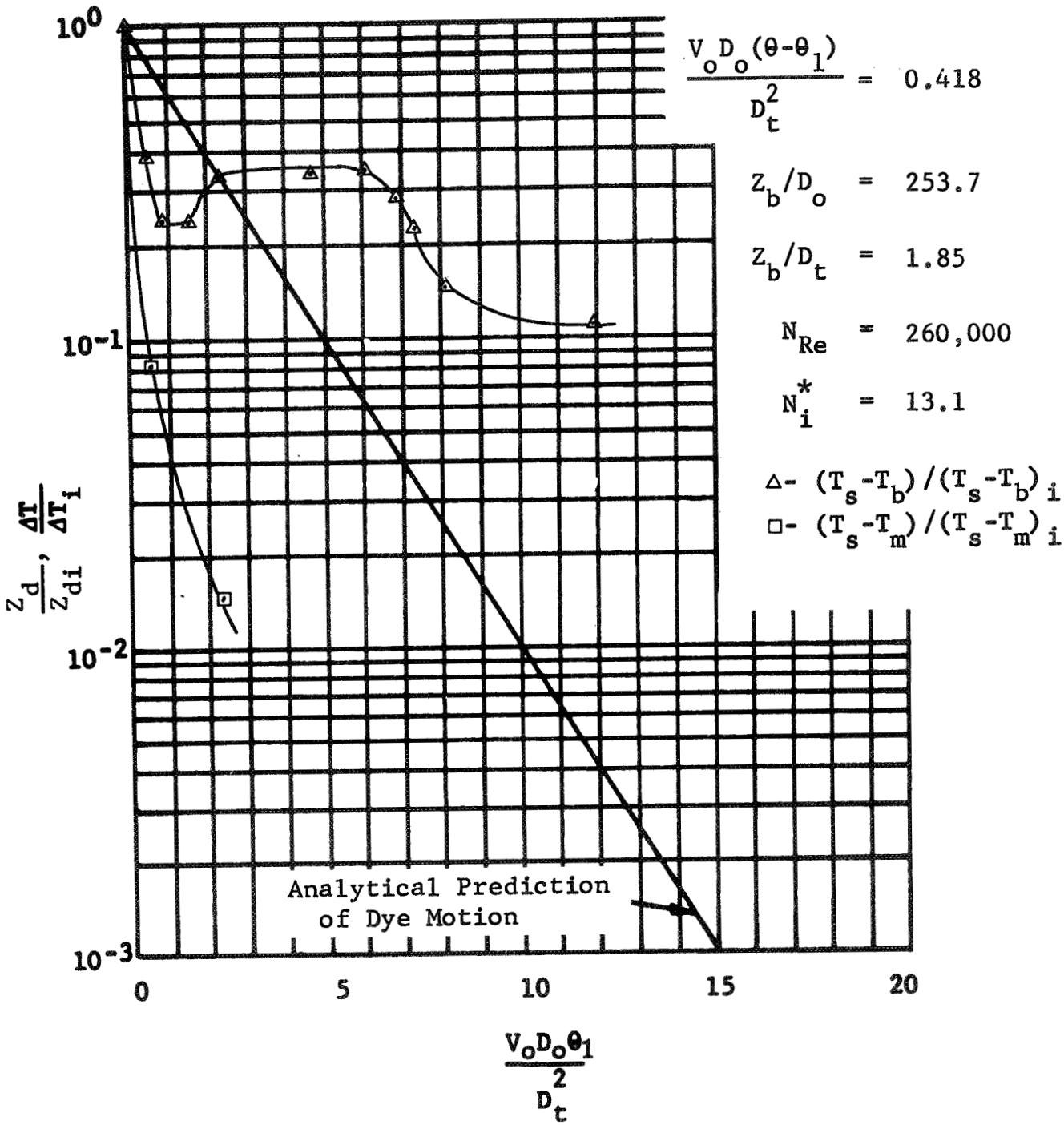

Figure 2 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 1

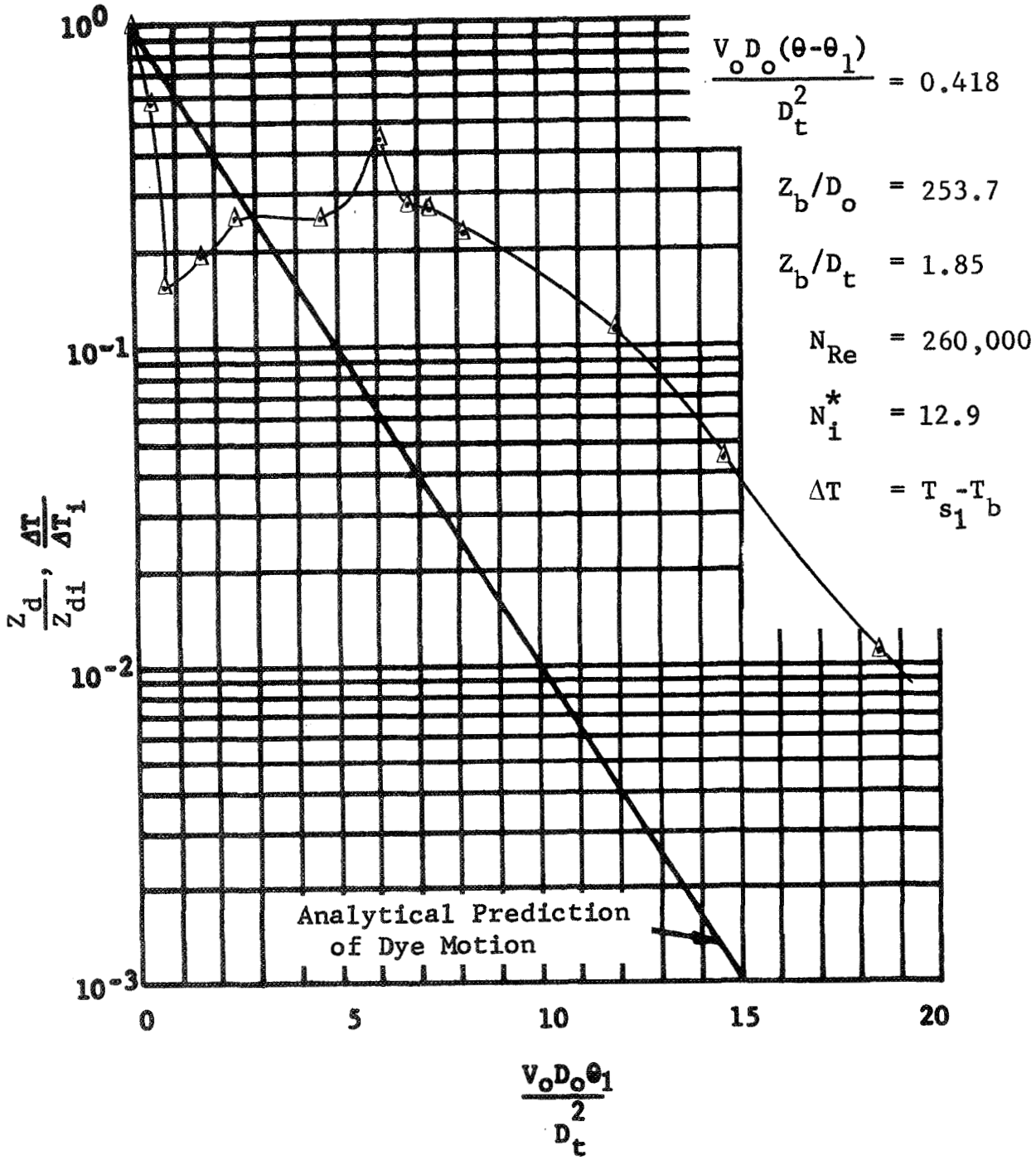

Figure 3 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 1

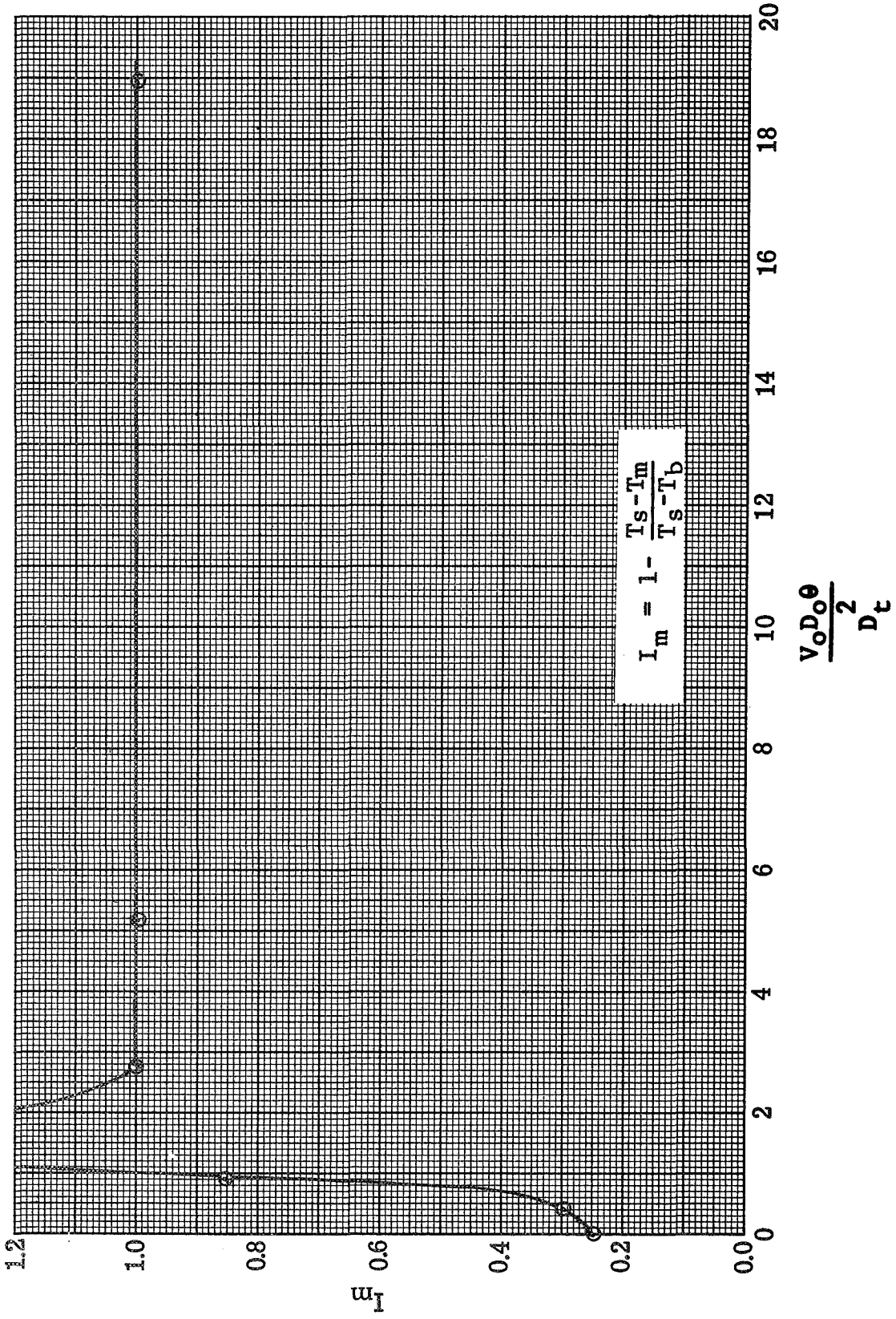

Figure 4 Transient Energy Integral: Run 1

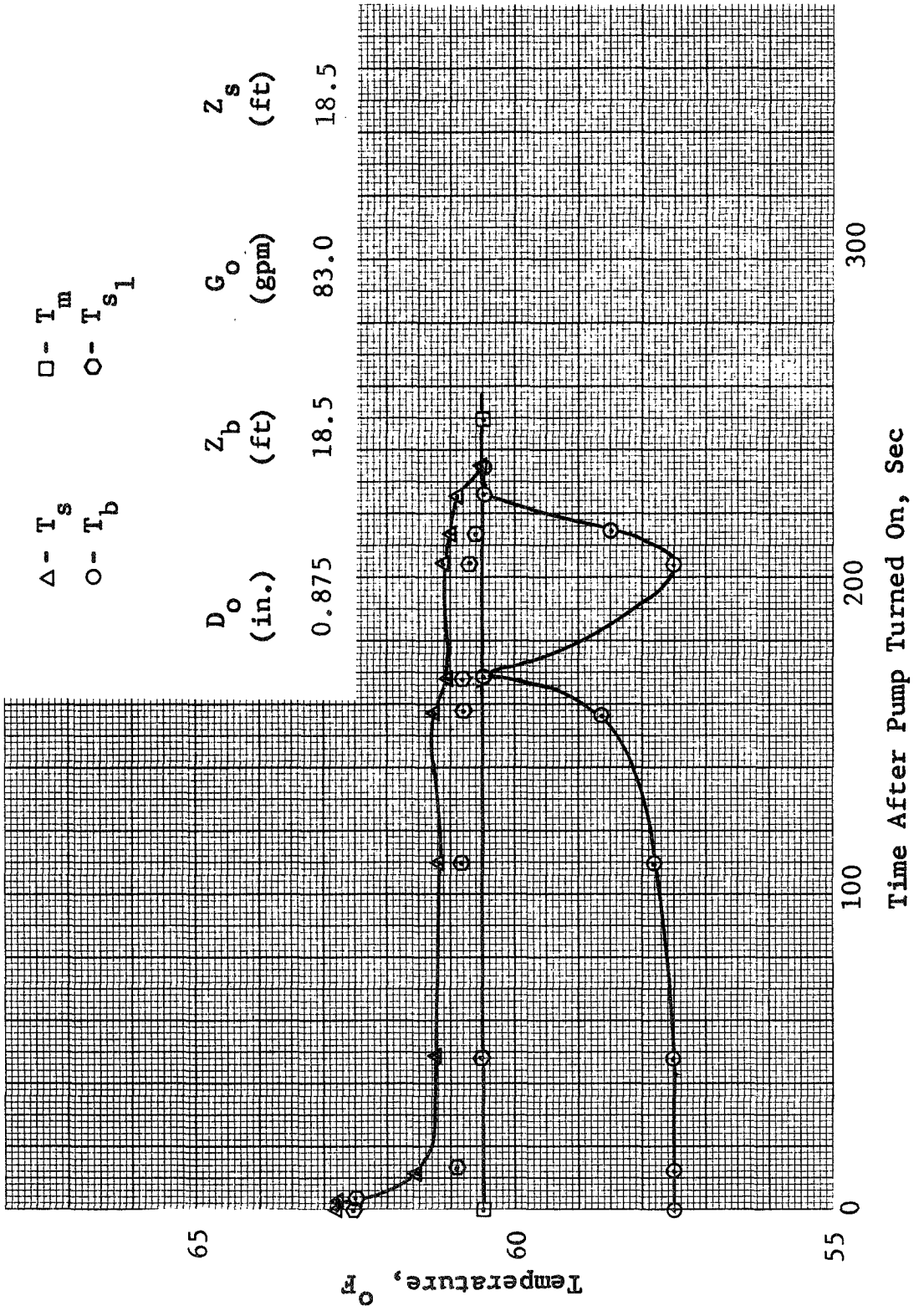

Figure 5 Transient Temperature Destratification: Run 2

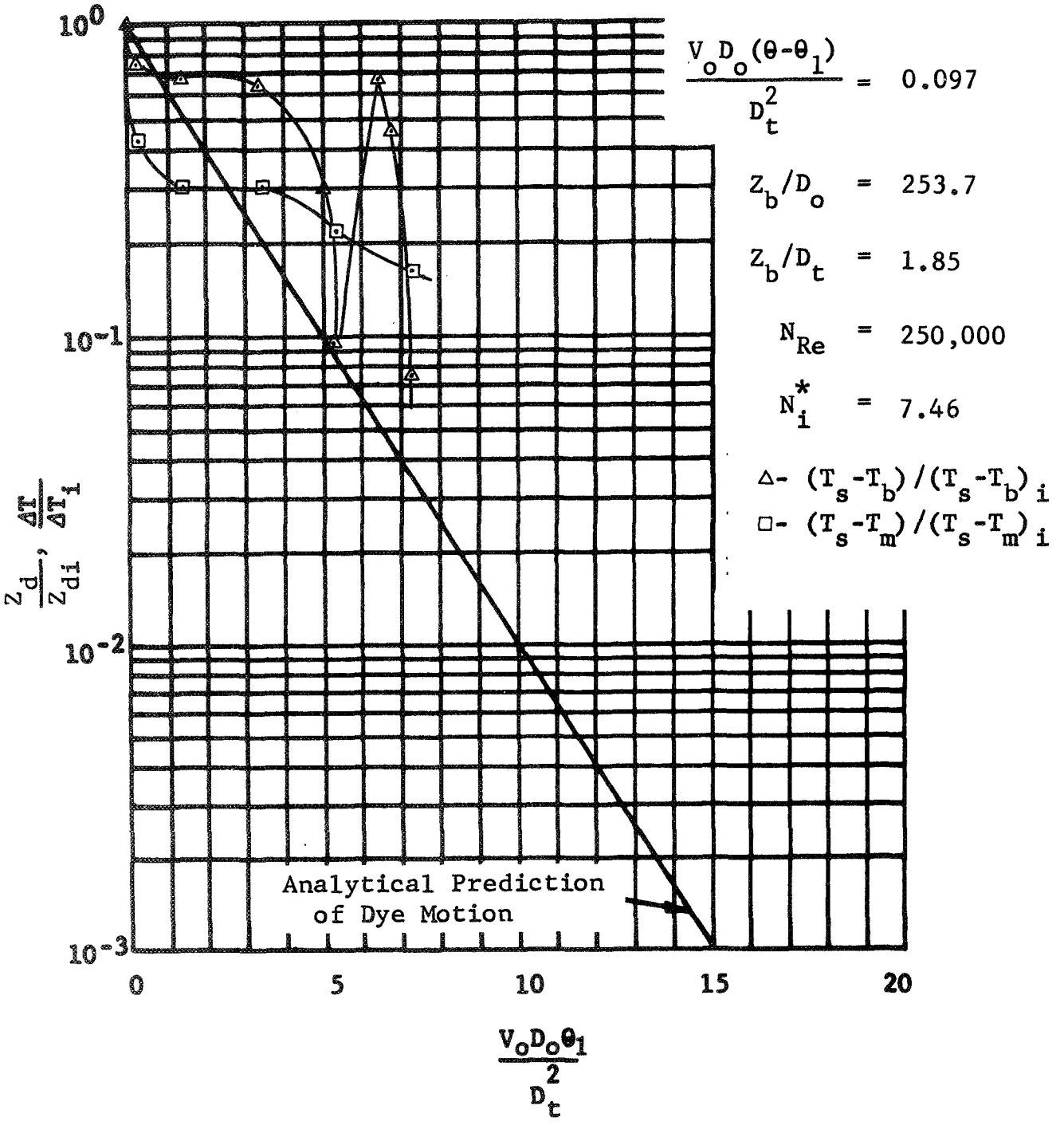

Figure 6 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 2

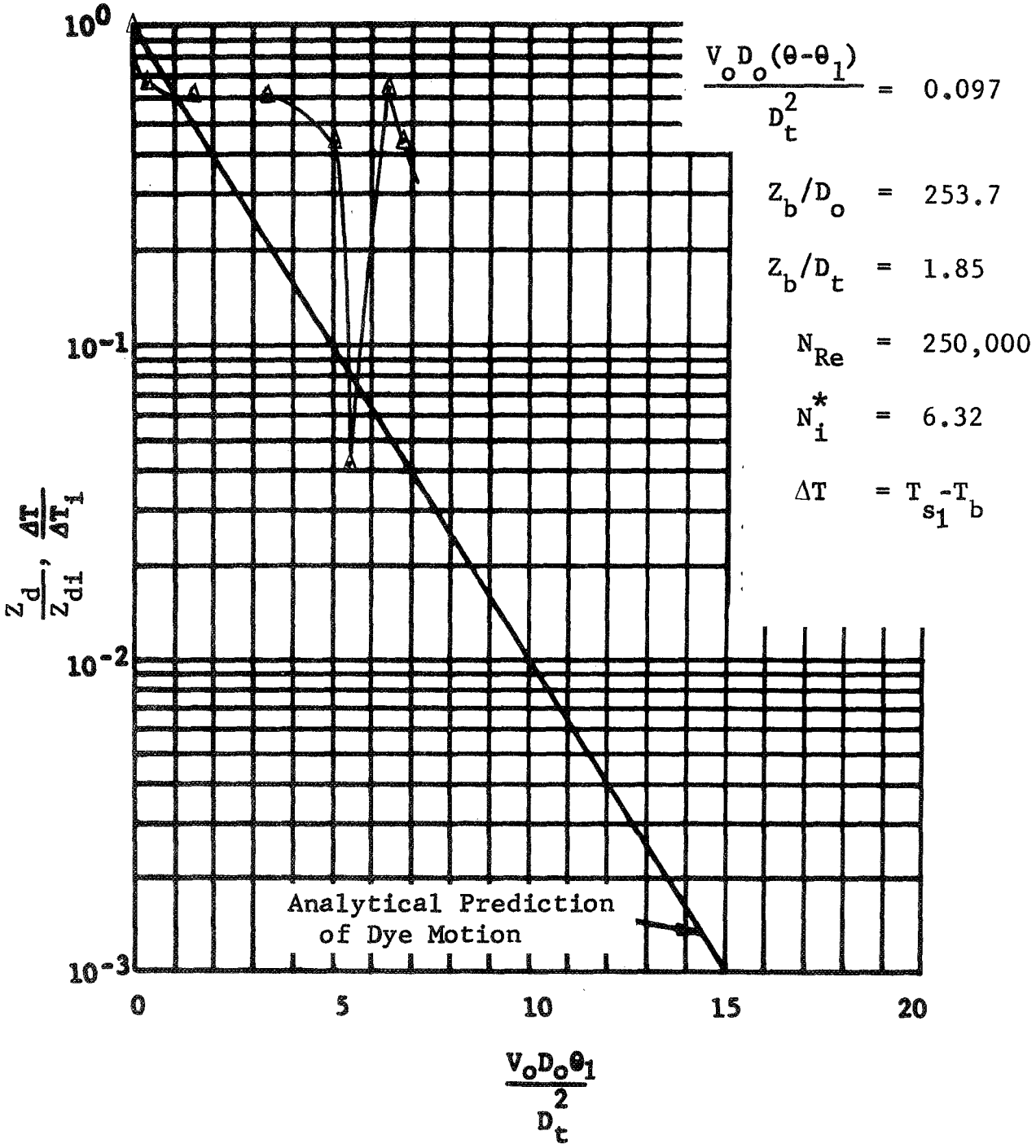

Figure 7 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 2

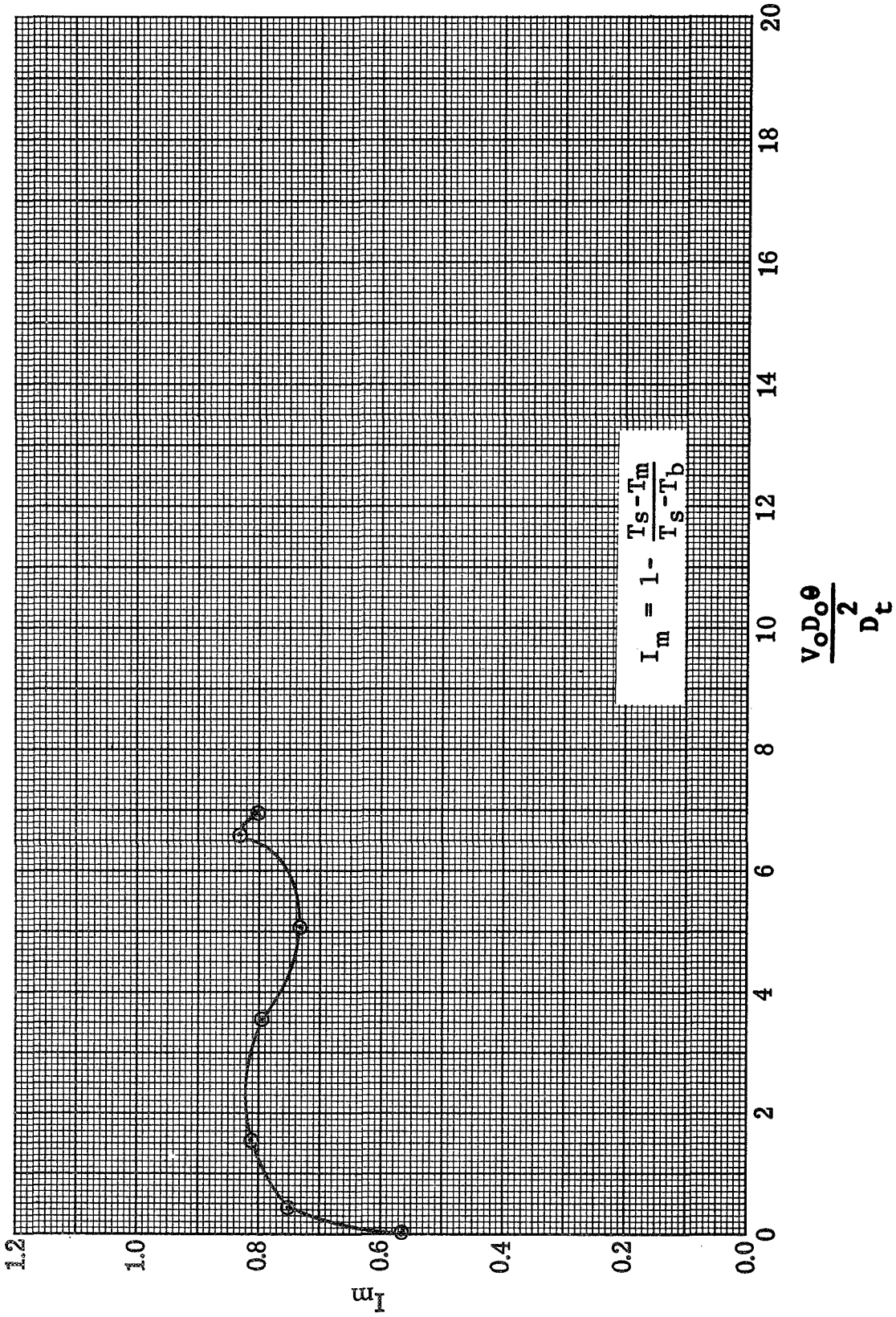

Figure 8 Transient Energy Integral: Run 2

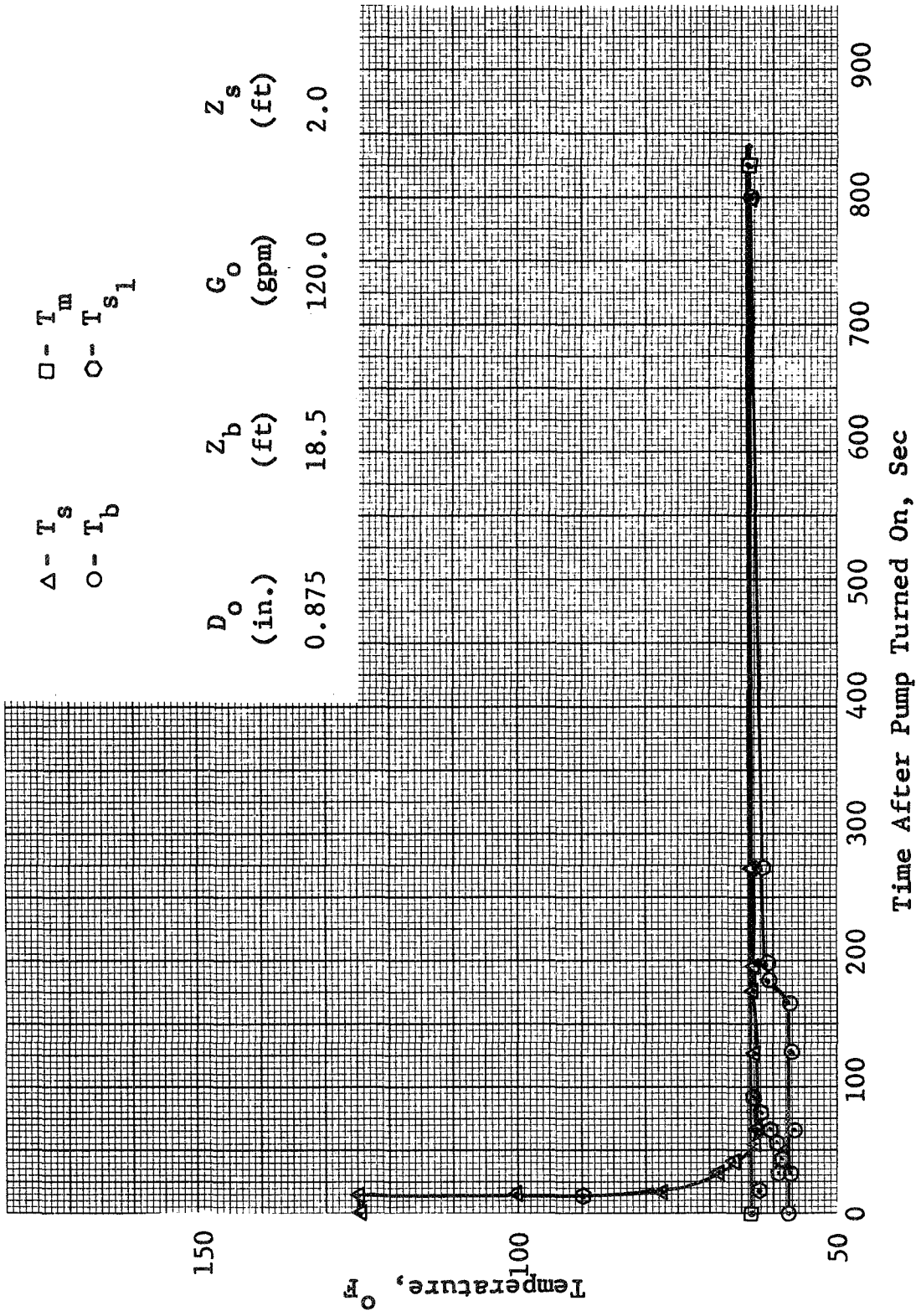

Figure 9 Transient Temperature Destratification : Run 3

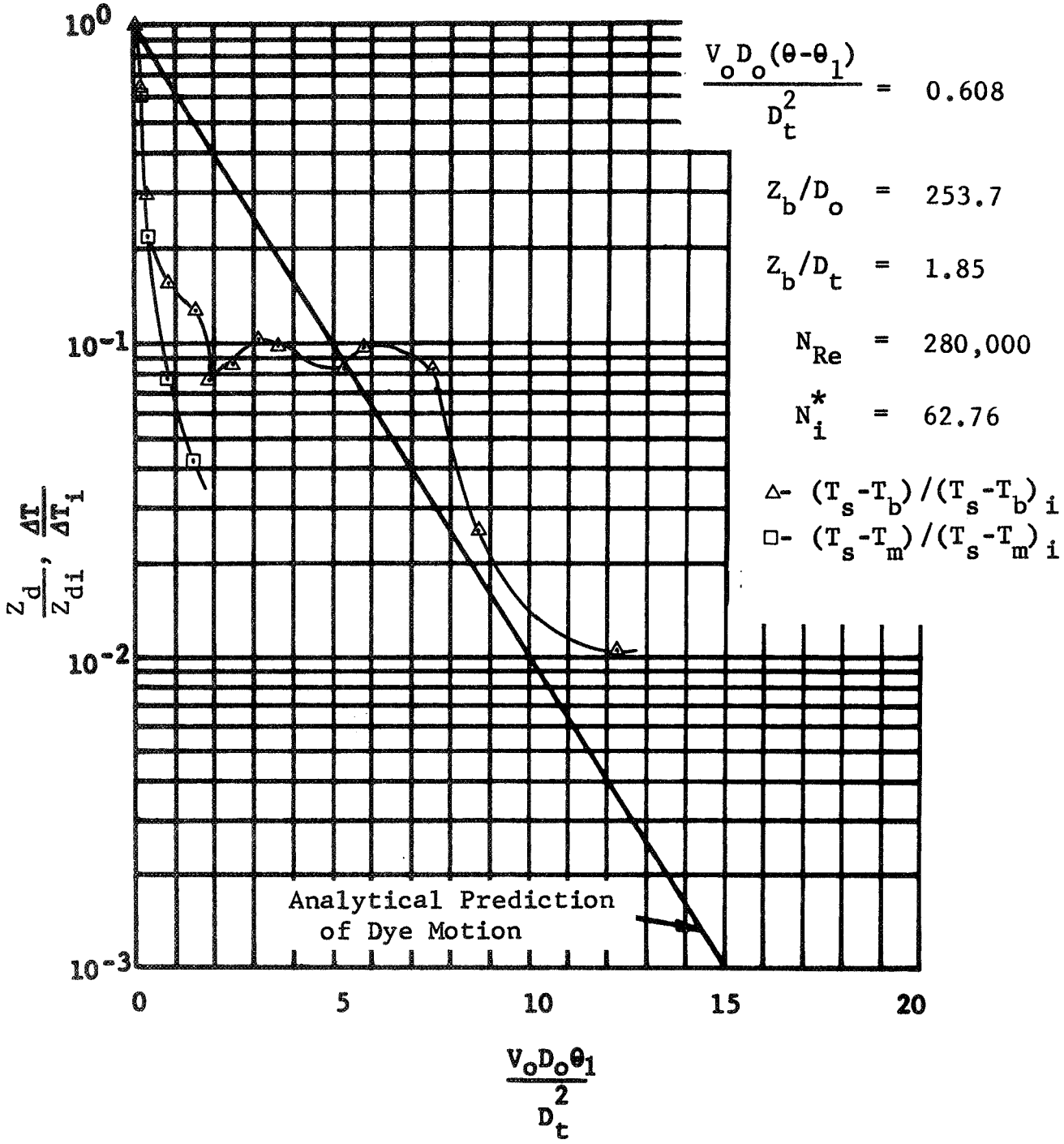

Figure 10 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 3

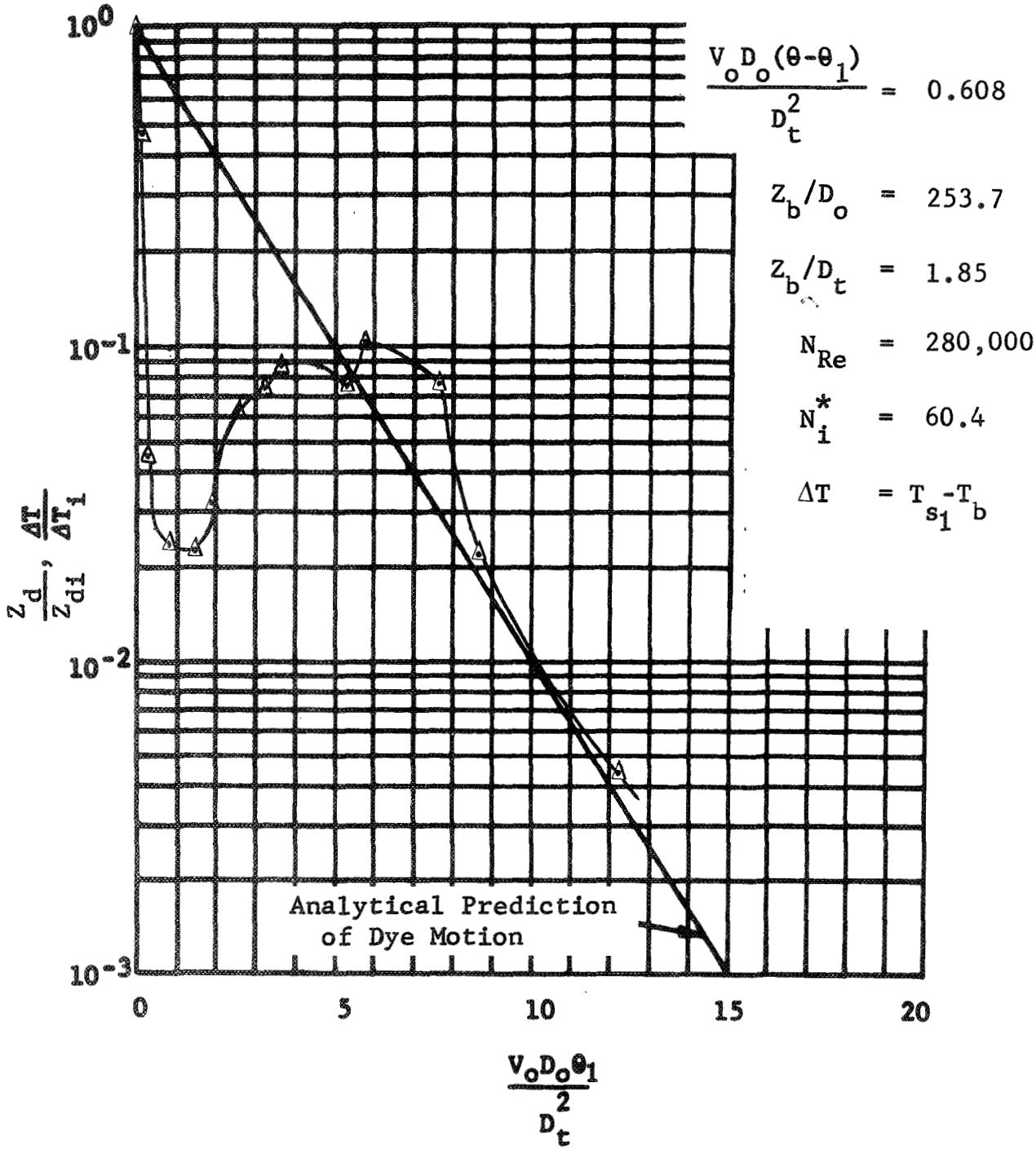

Figure 11 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 3

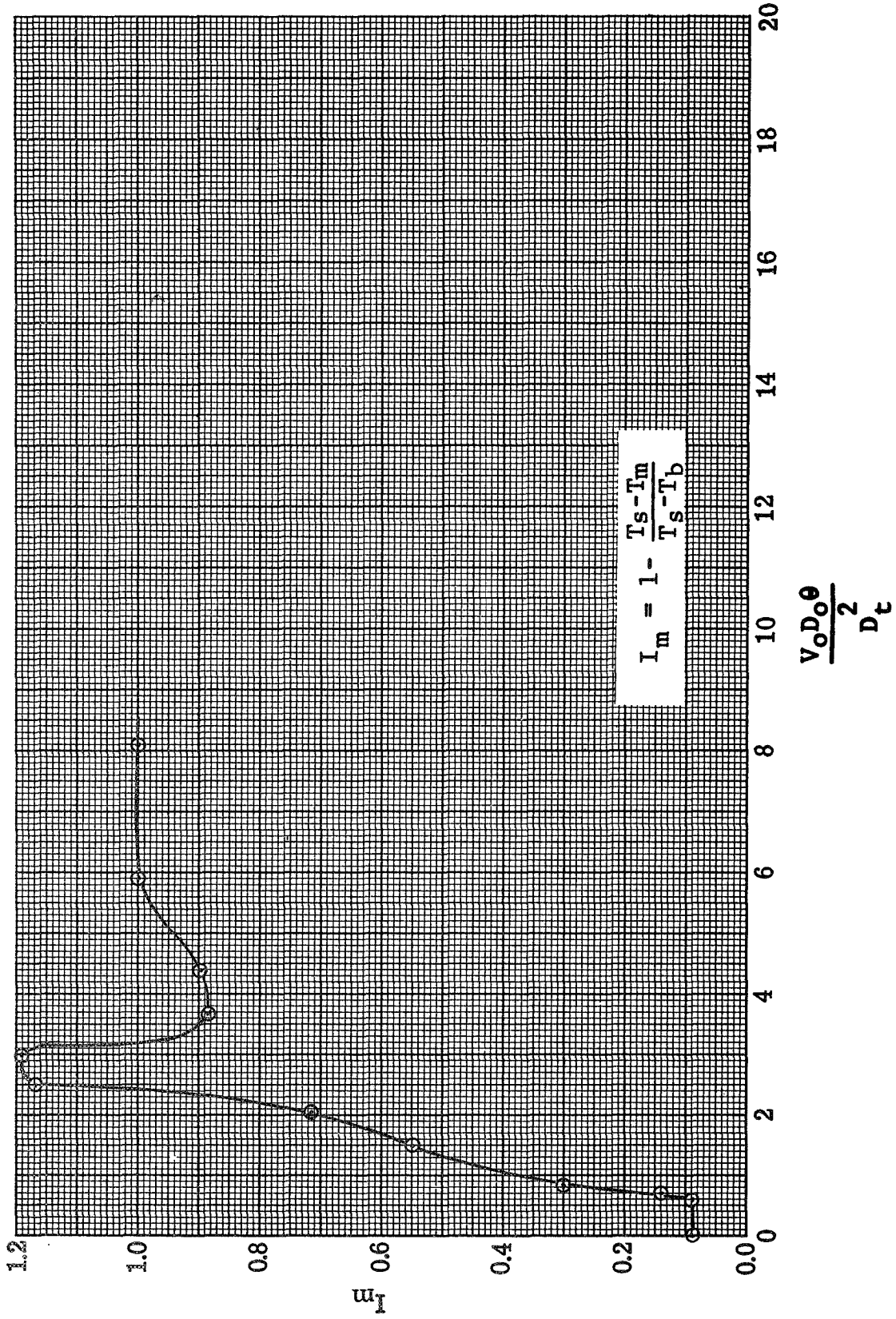

Figure 12 **Transient Energy Integral:** Run 3

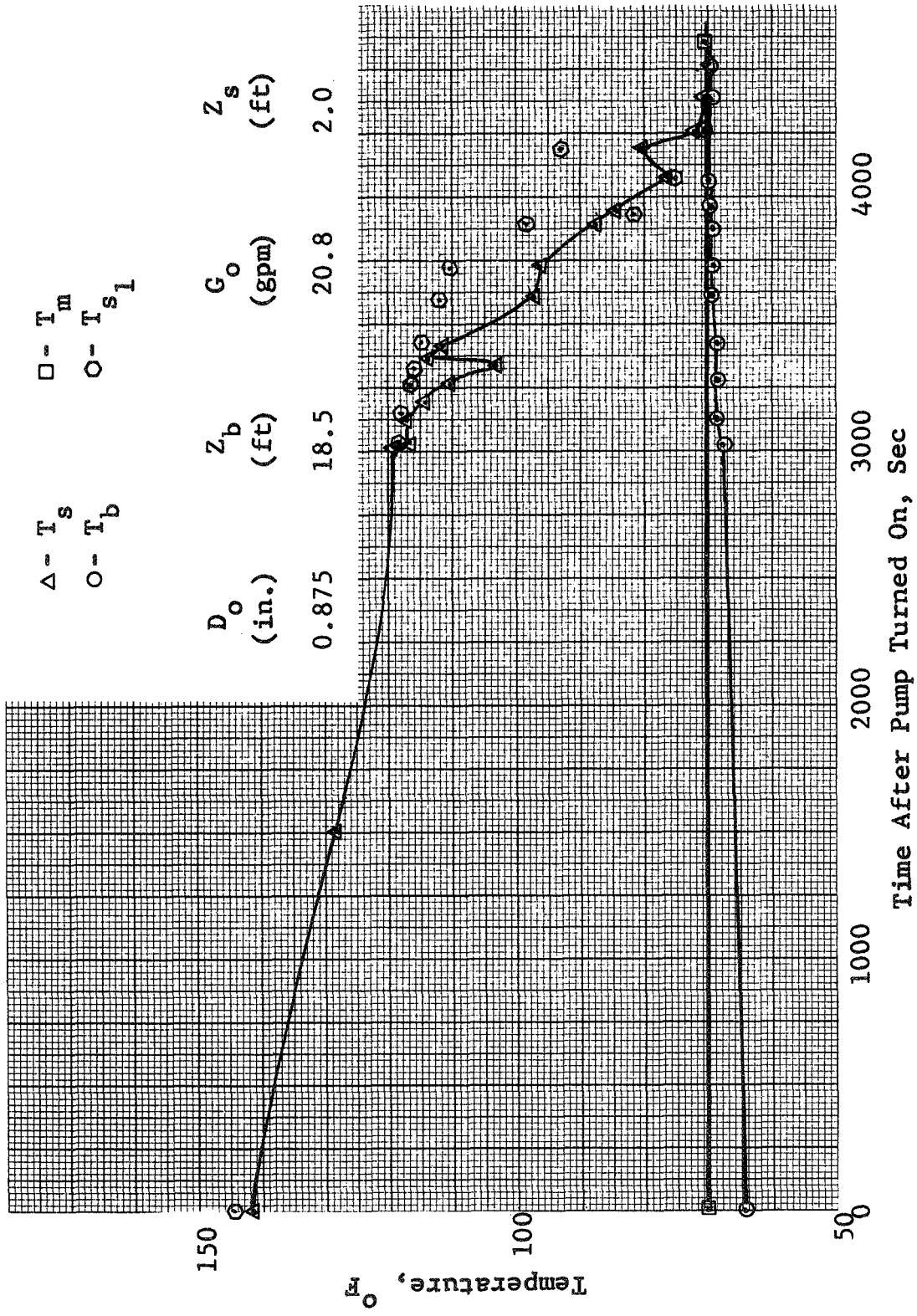

Figure 13 Transient Temperature Destratification : Run 4

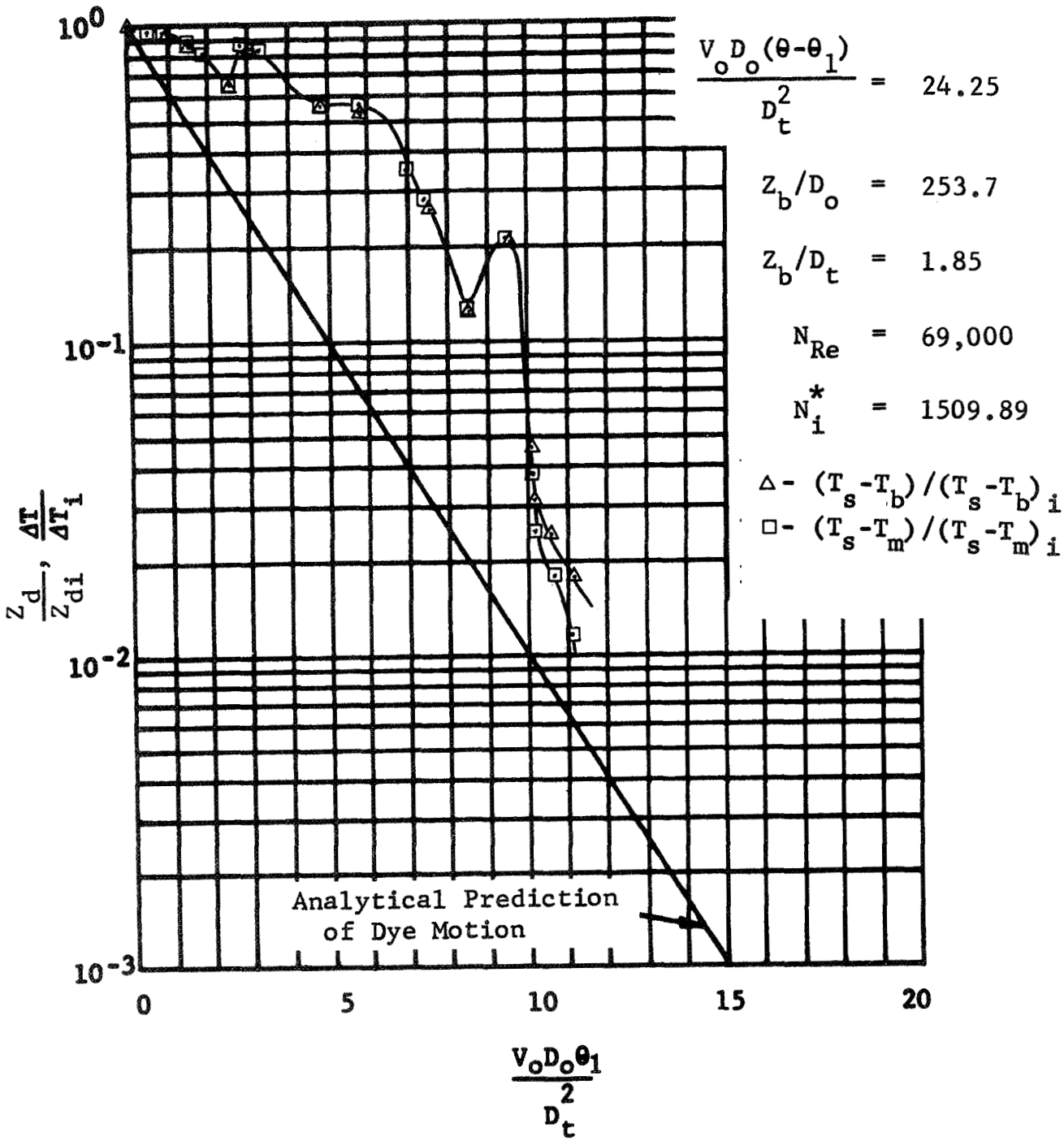

Figure 14 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 4

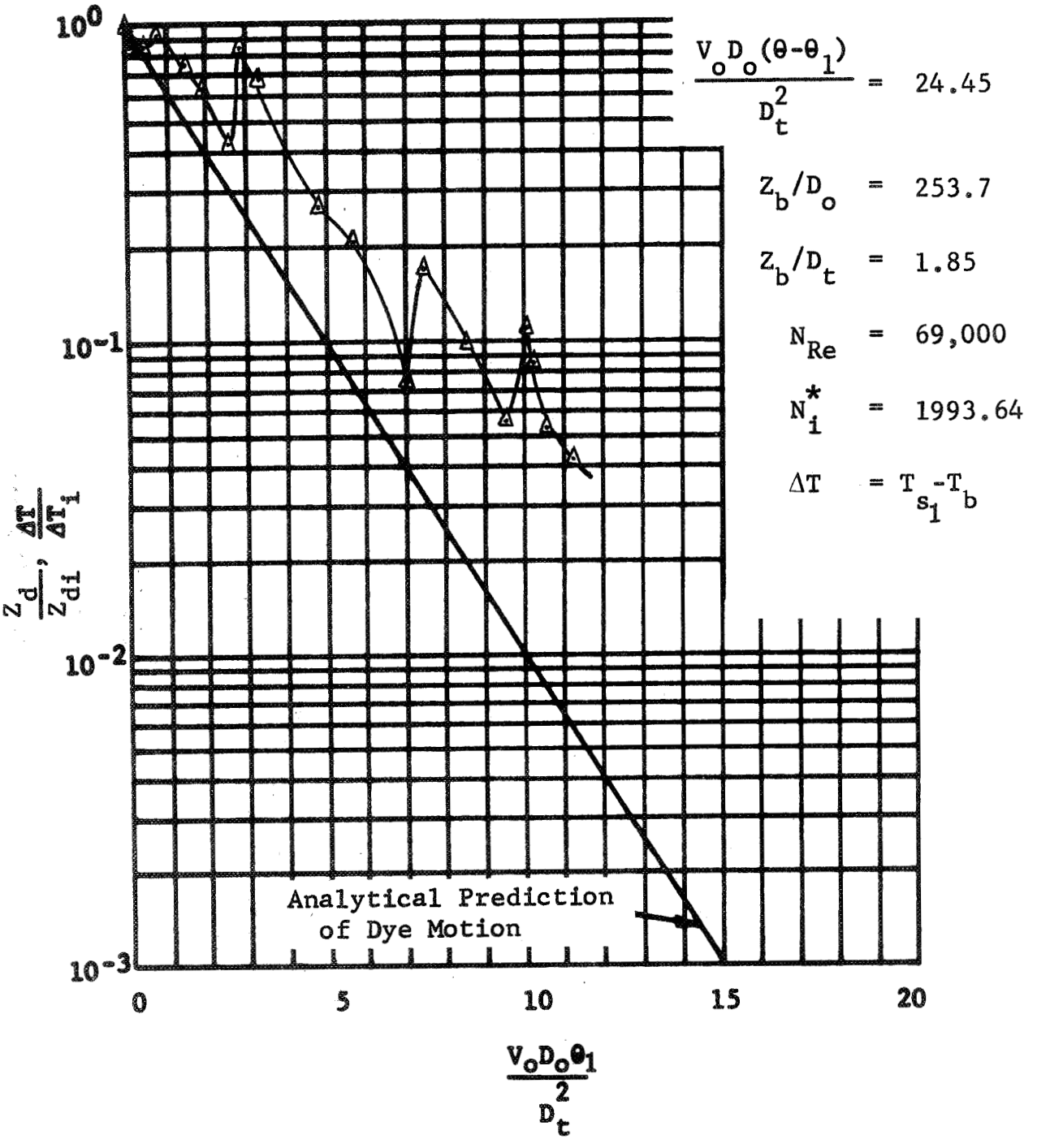

Figure 15 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 4

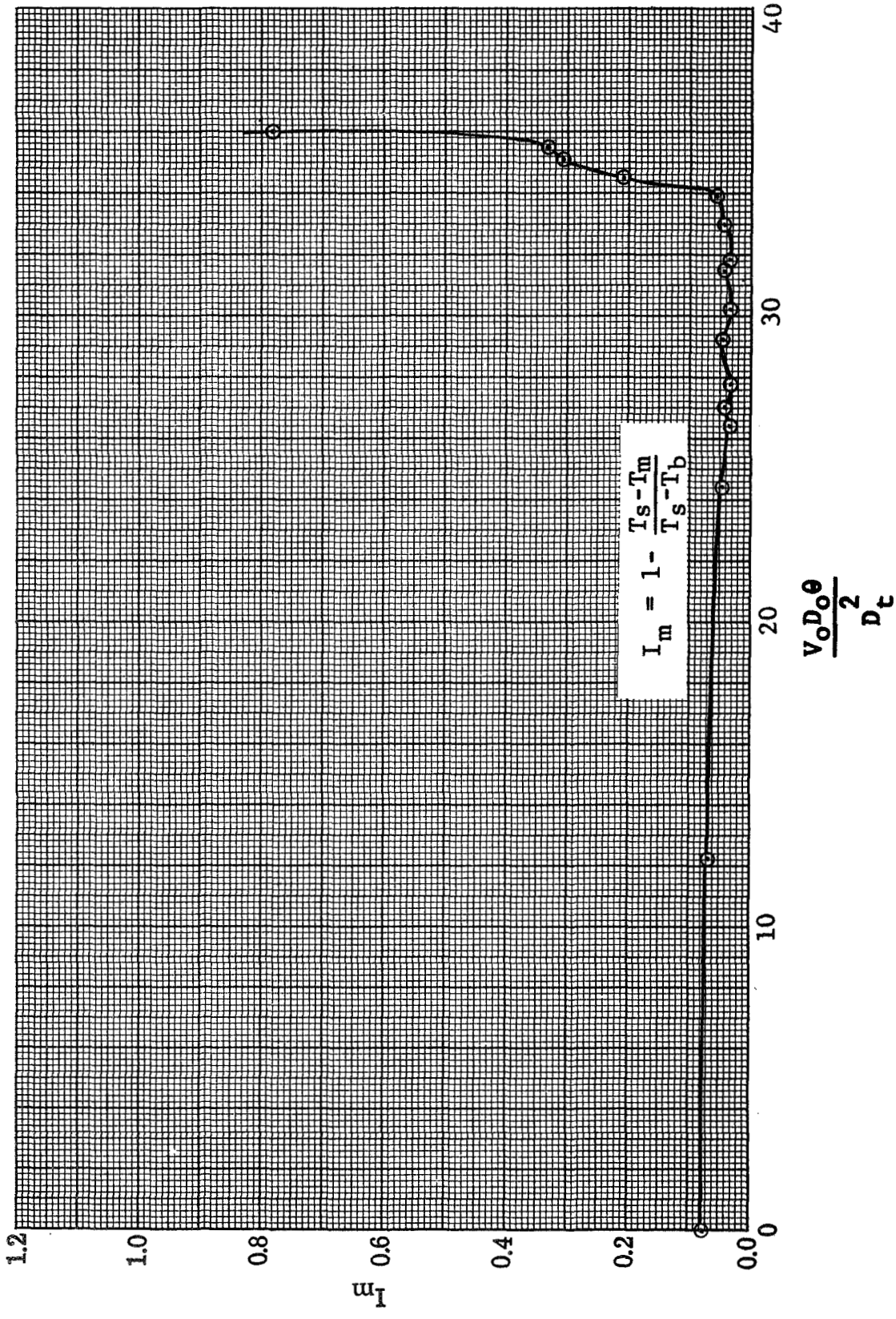

Figure 16 **Transient Energy Integral:** Run 4

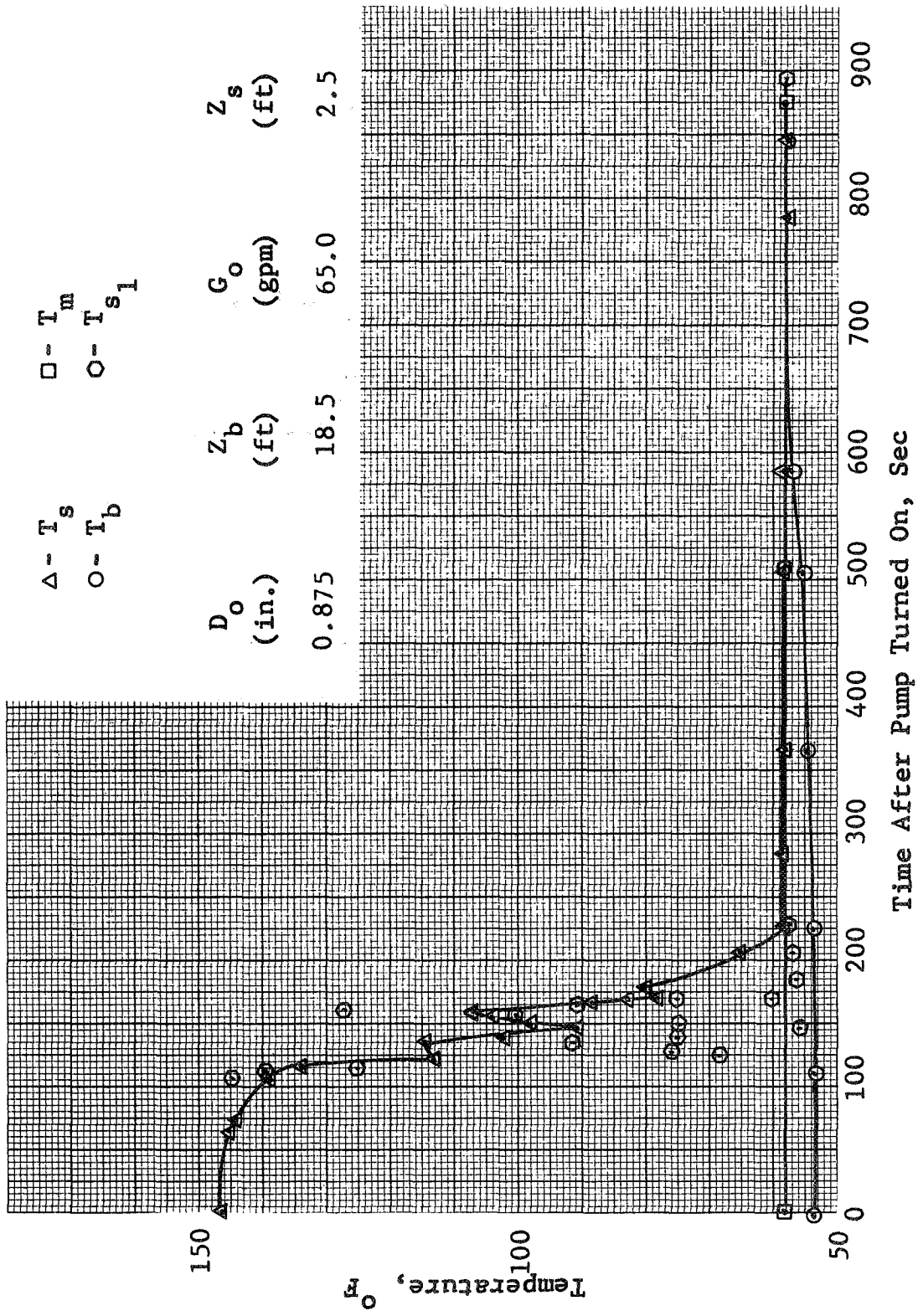

Figure 17 Transient Temperature Destratification: Run 5

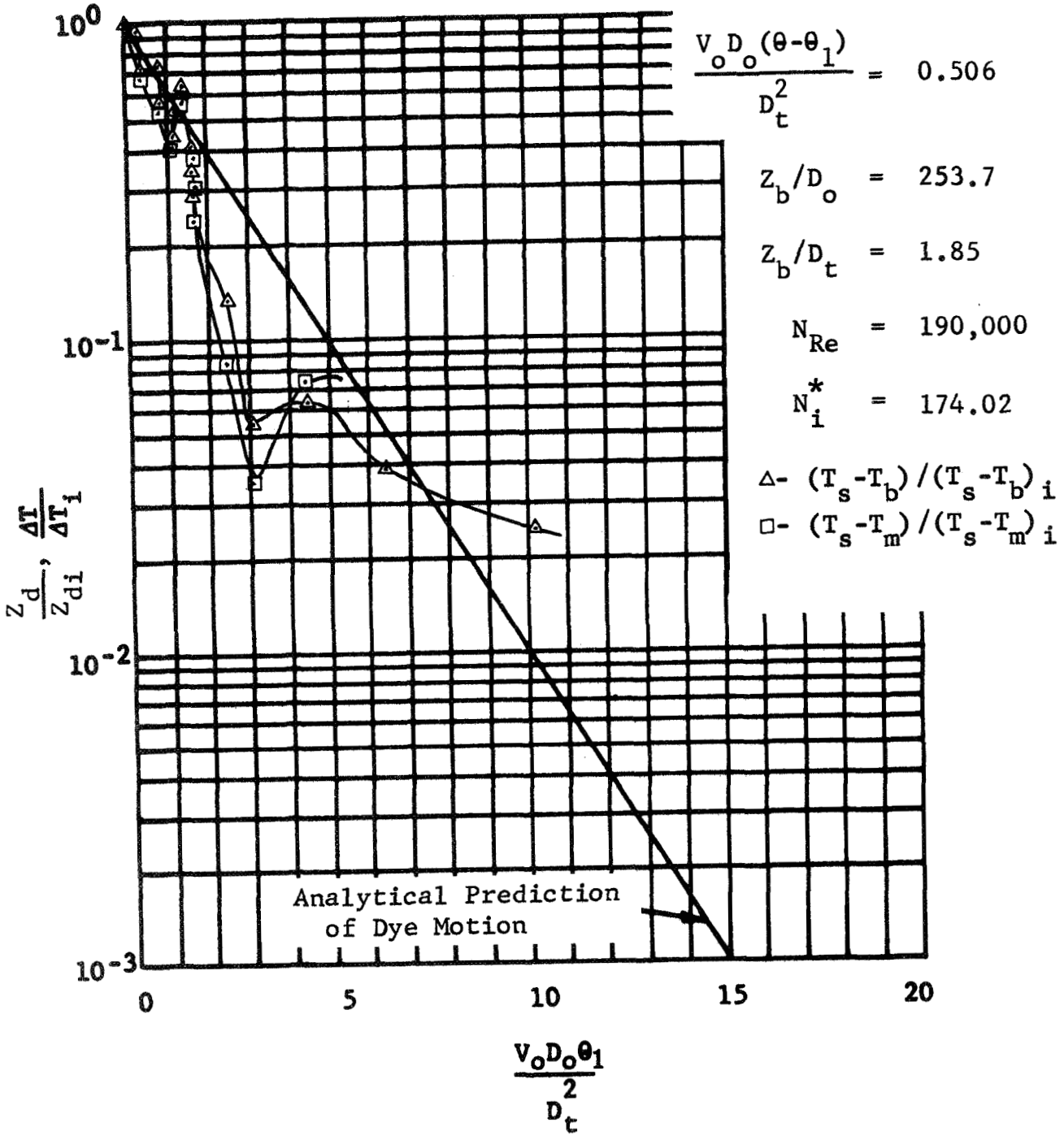

Figure 18 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 5

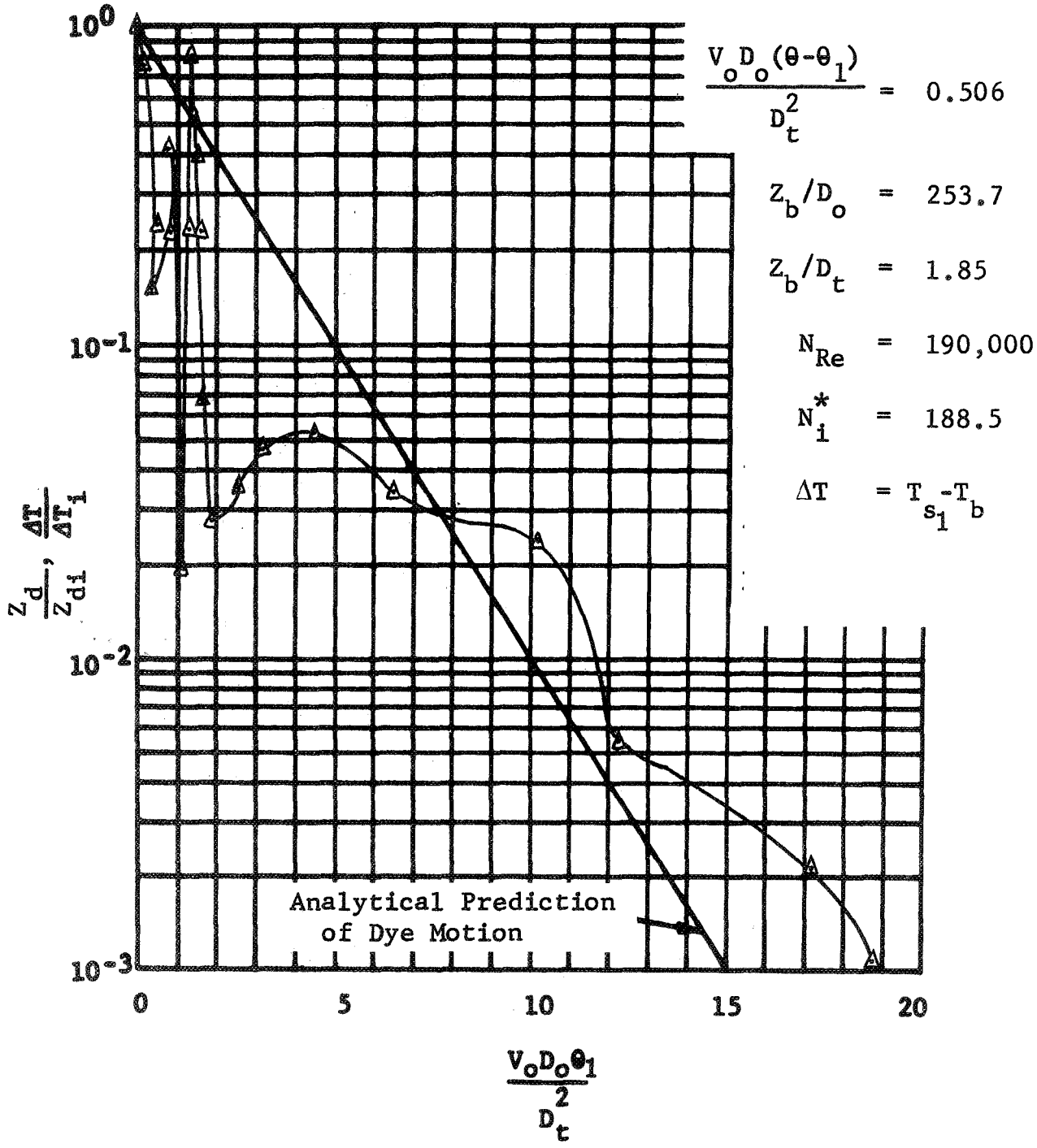

Figure 19 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 5

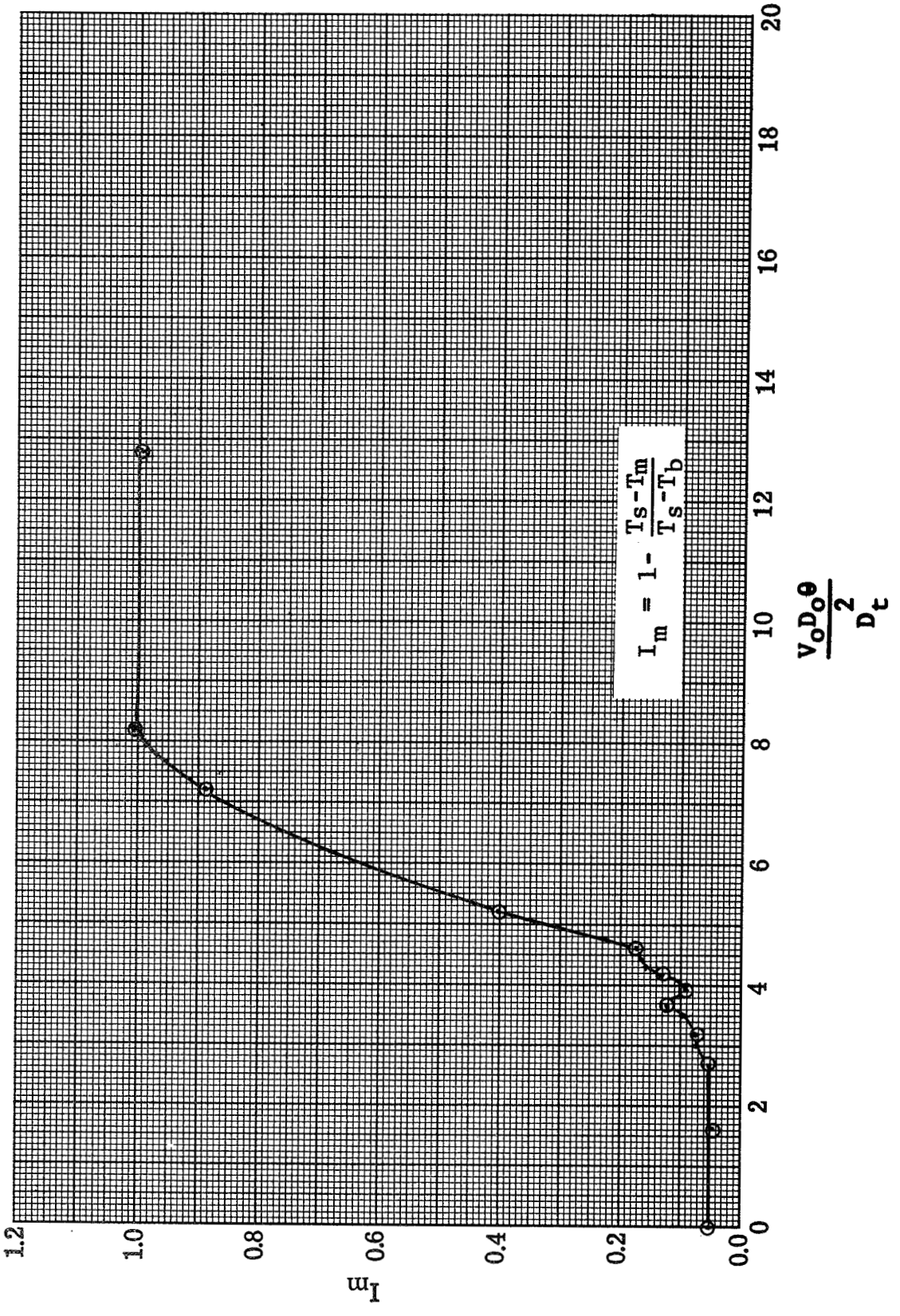

Figure 20 **Transient Energy Integral:** Run 5

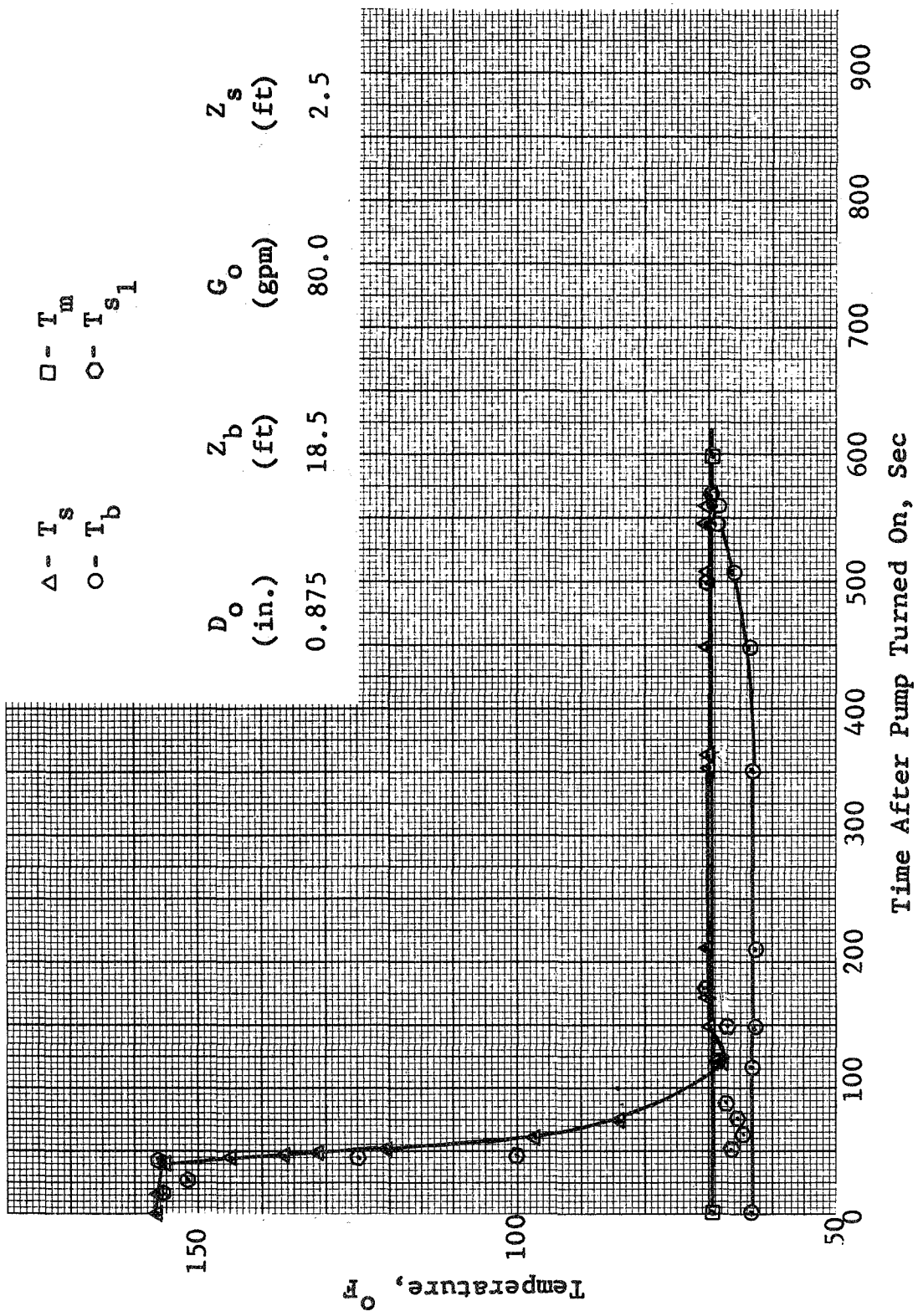

Figure 21 Transient Temperature Destratification: Run 6

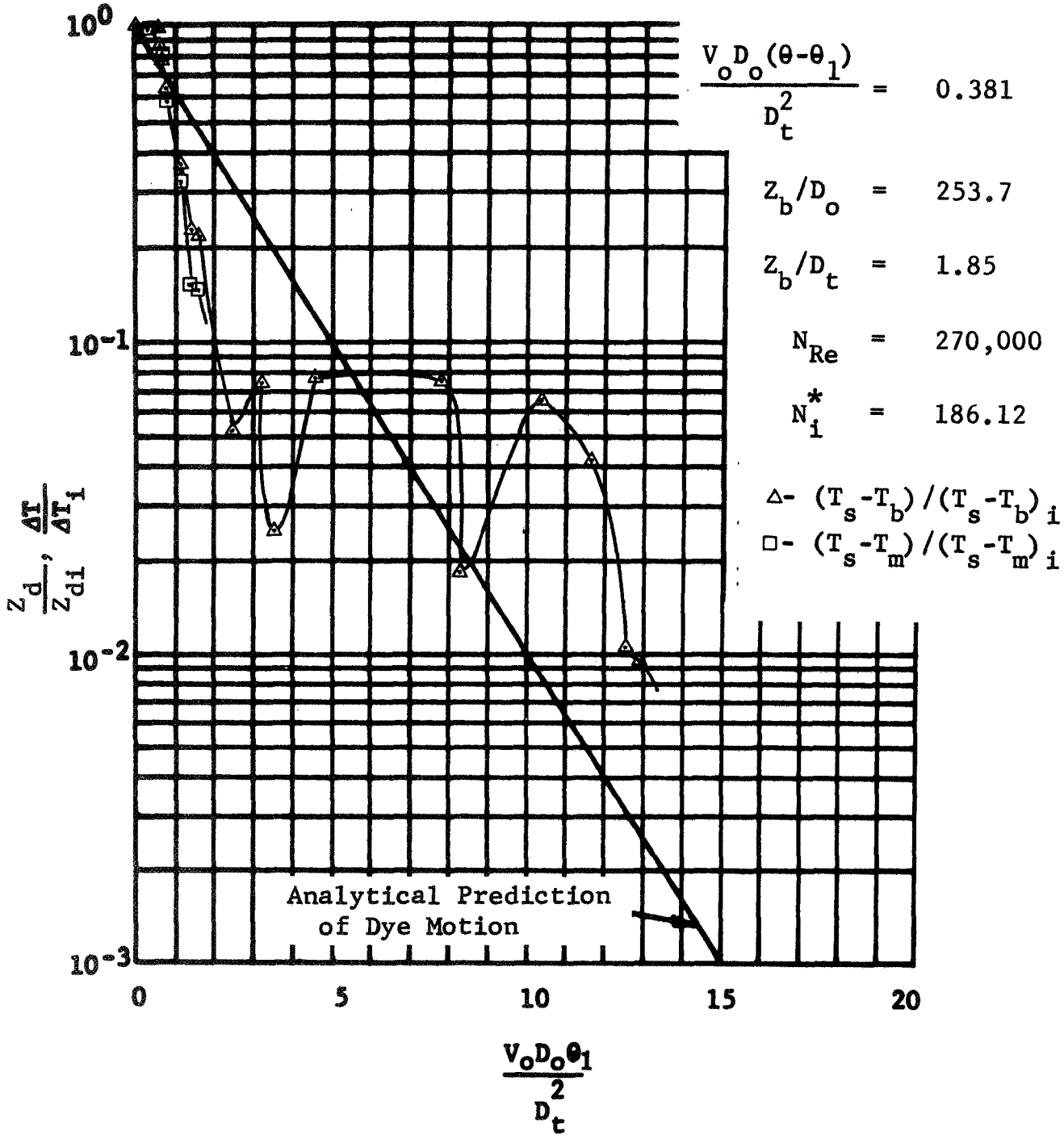

Figure 22 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 6

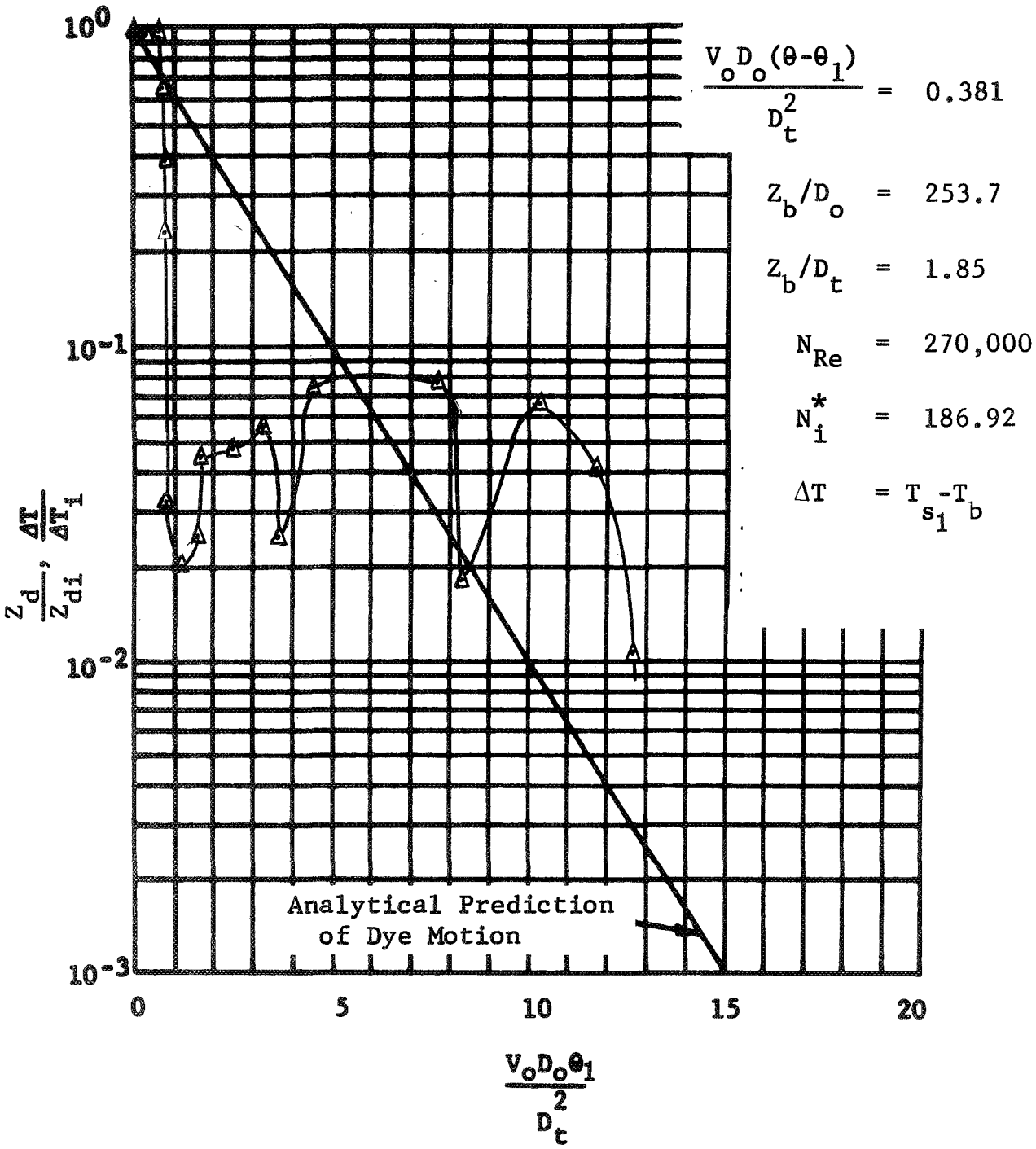

Figure 23 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 6

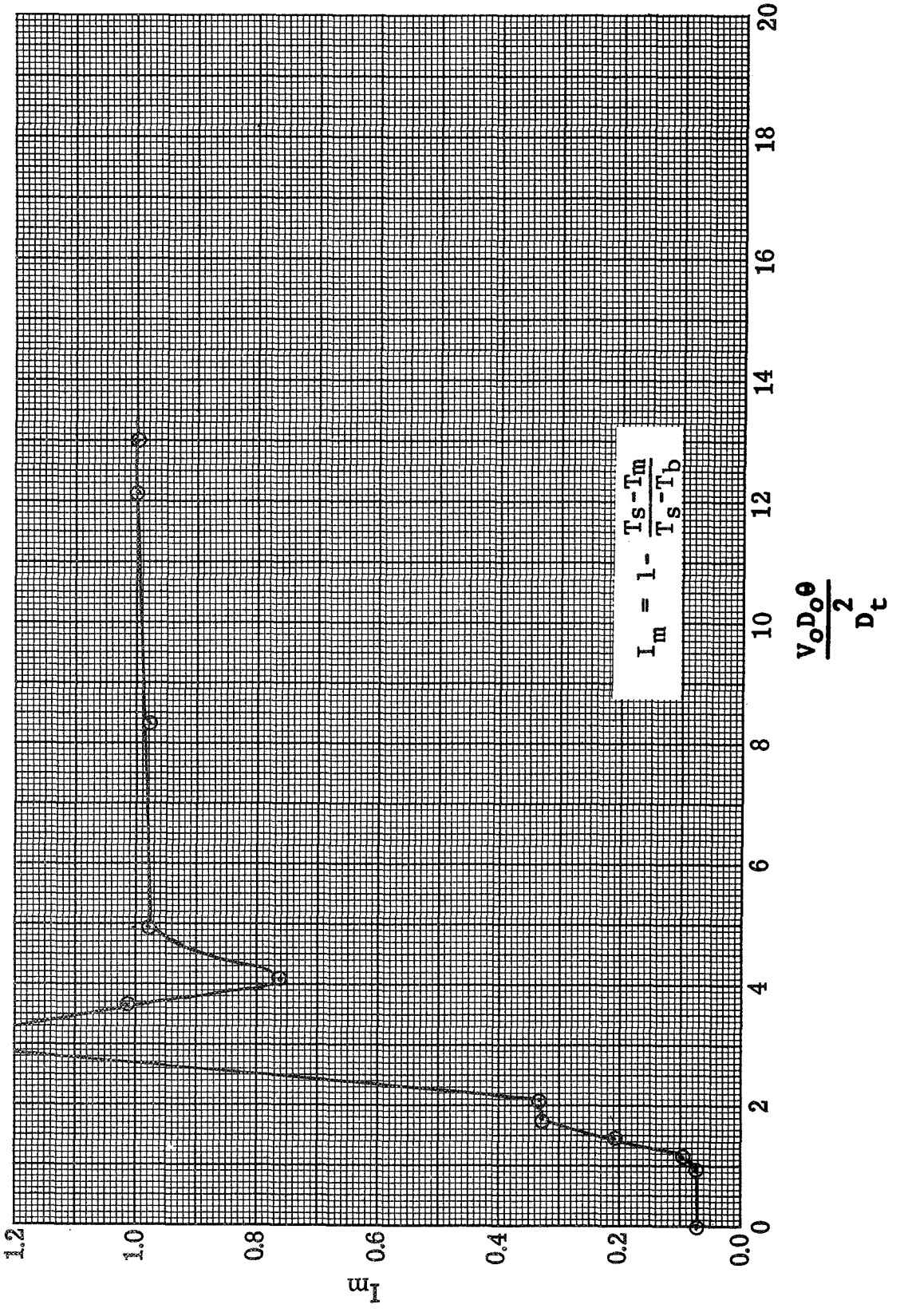

Figure 24 **Transient Energy Integral:** Run 6

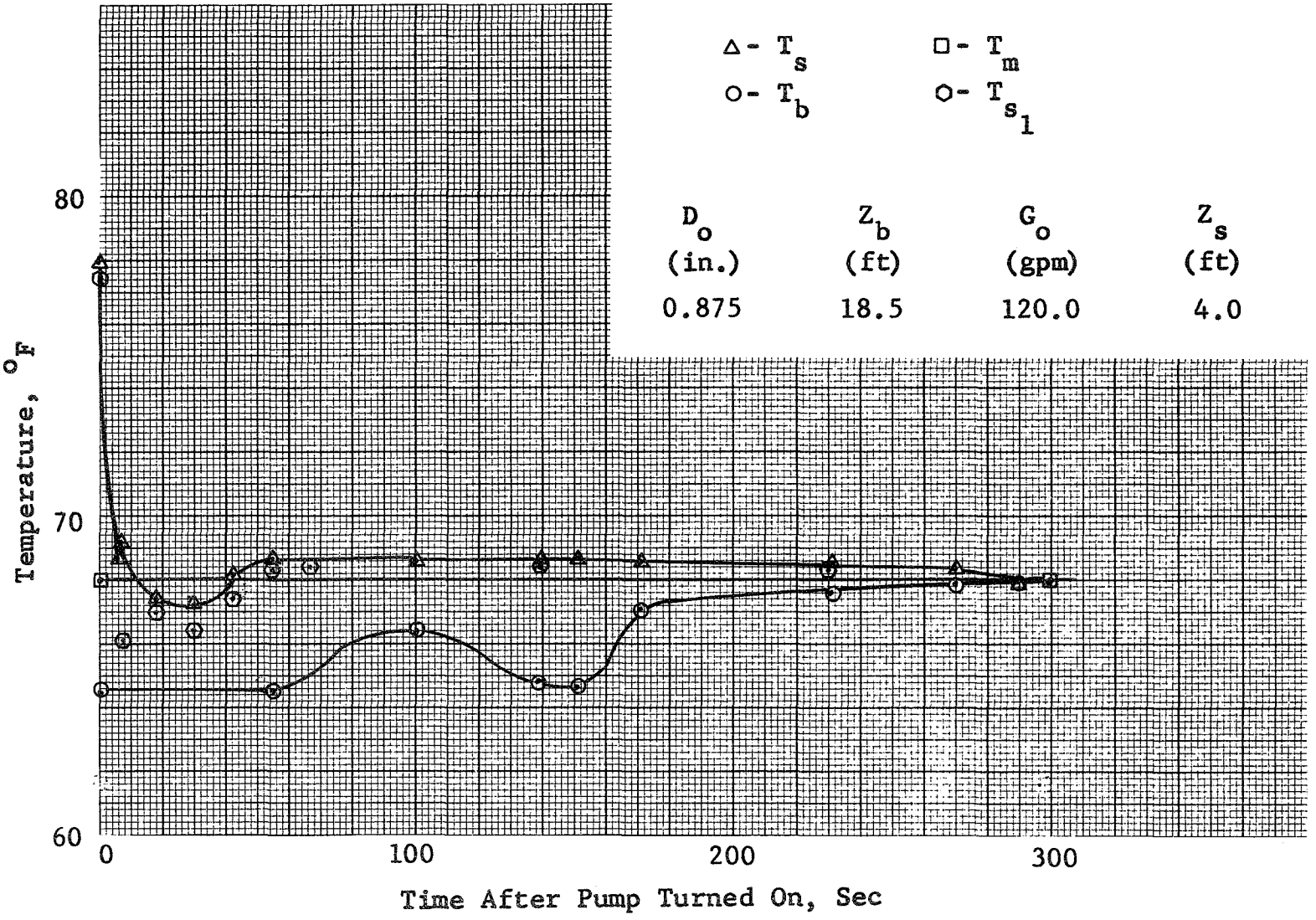

Figure 25 Transient Temperature Destratification: Run 7

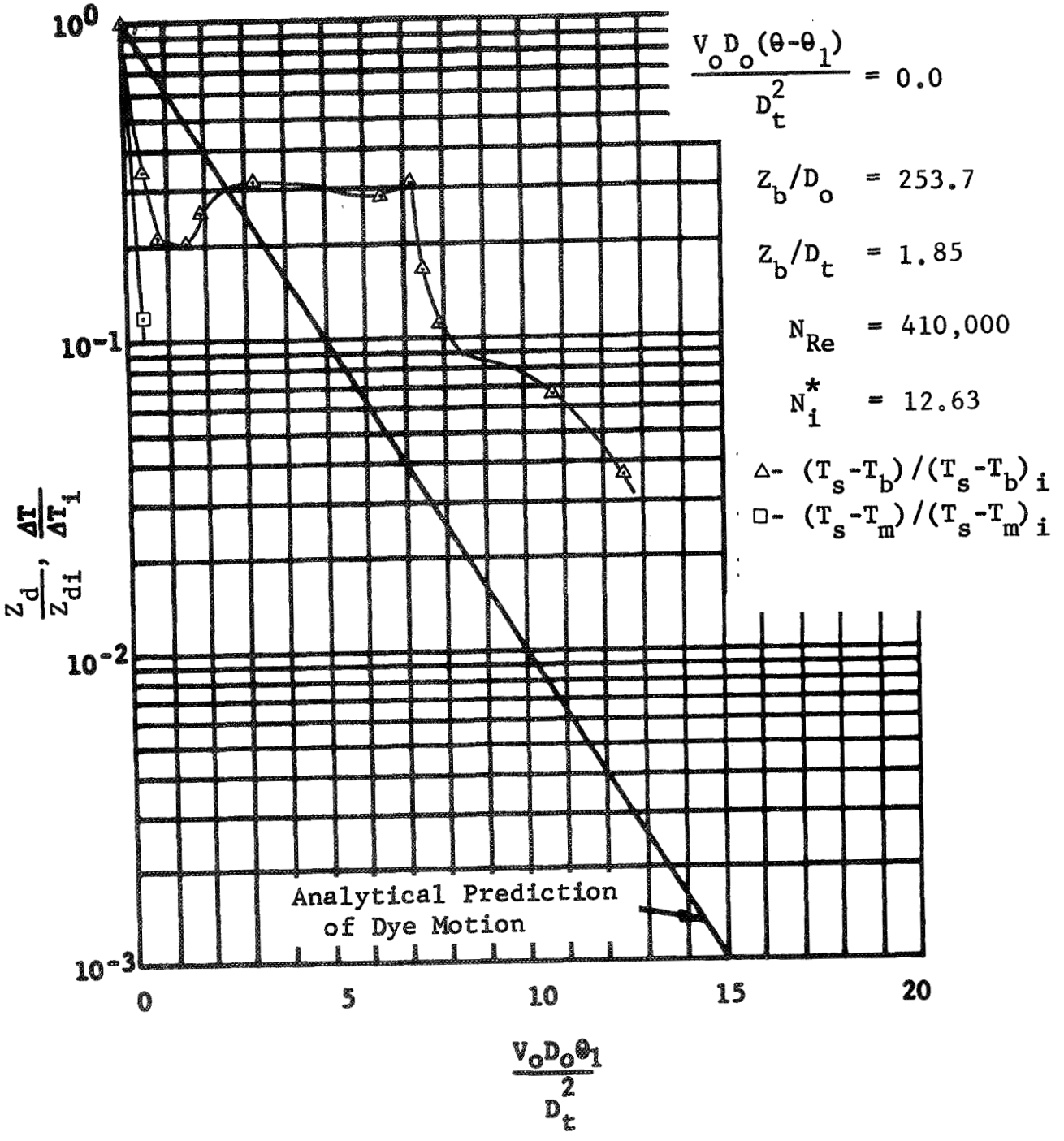

Figure 26 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 7

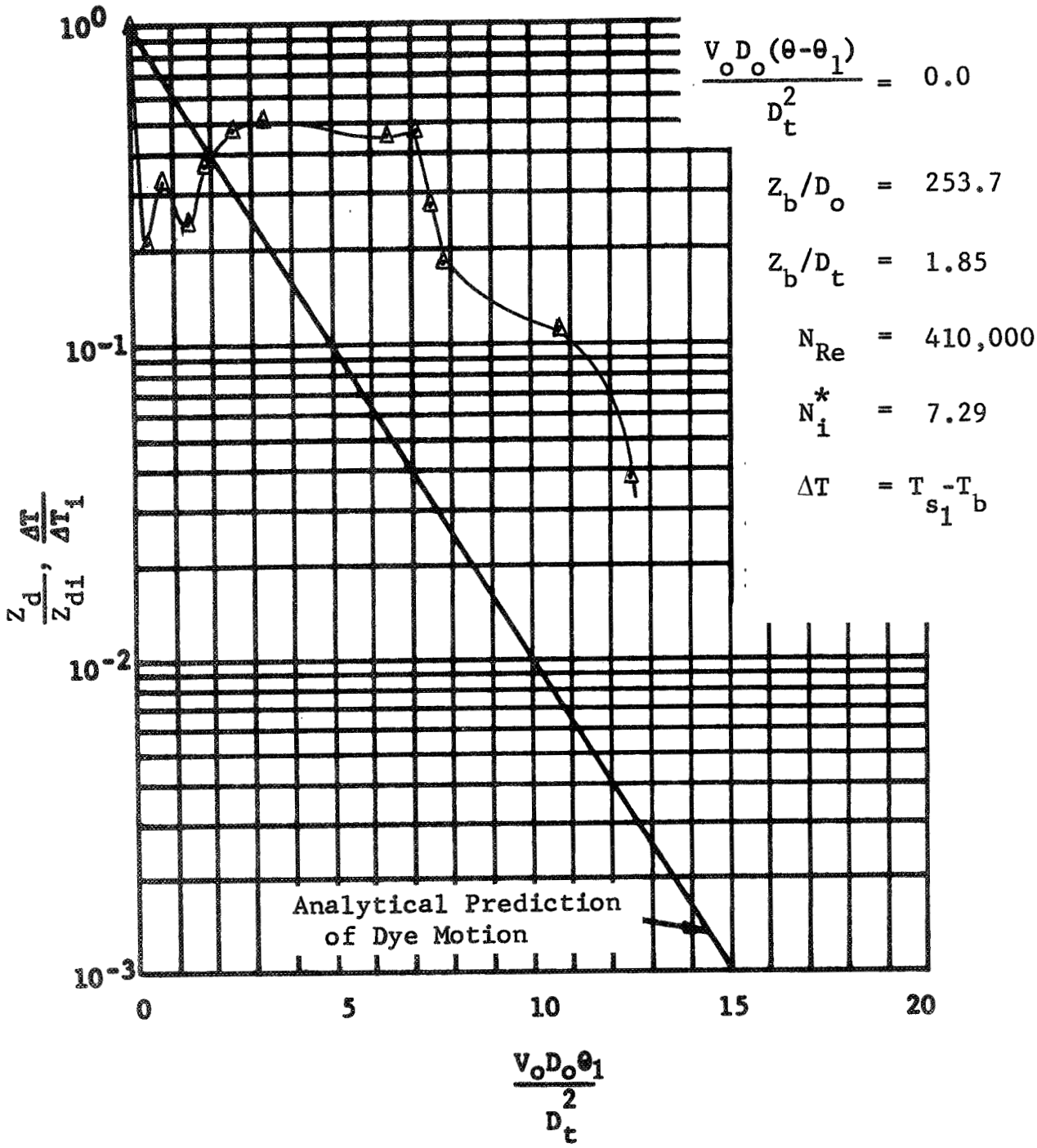

Figure 27 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at $\theta = 0.0$ sec; Centerline Surface Temperature Drop Starts at $\theta_1 = 0.0$ sec; Run 7

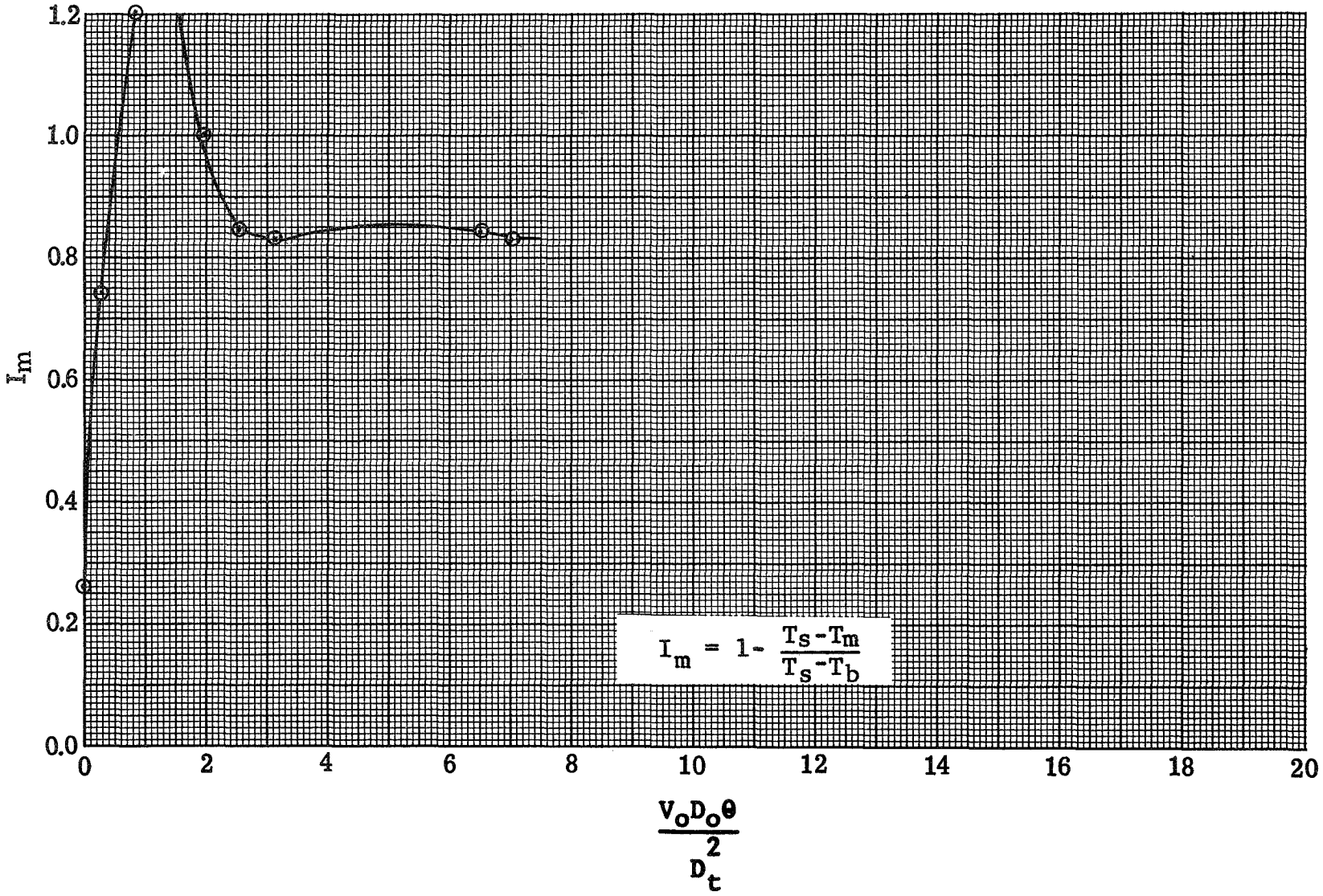

Figure 28 **Transient Energy Integral:** Run 7

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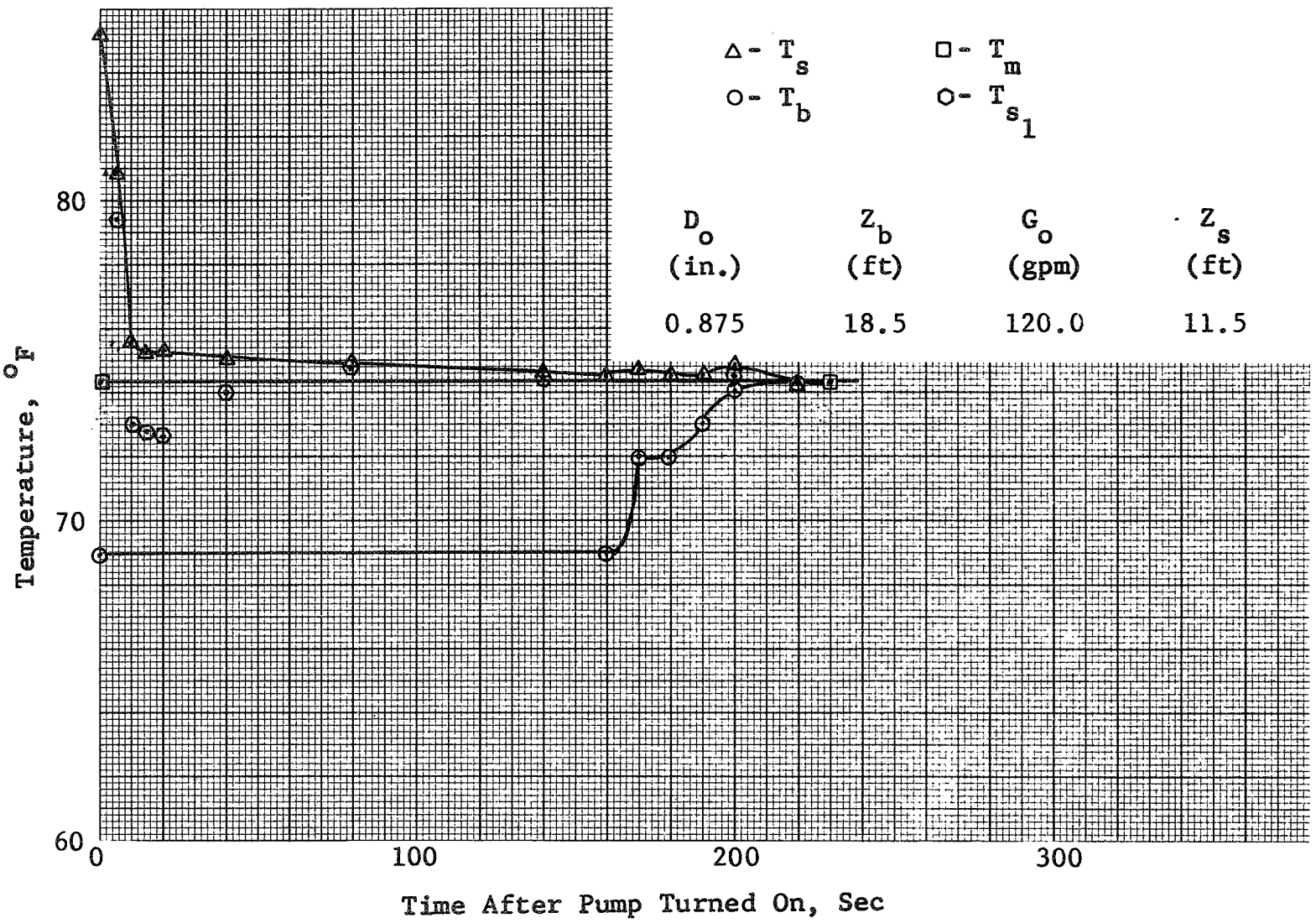

Figure 29 Transient Temperature Destratification: Run 8

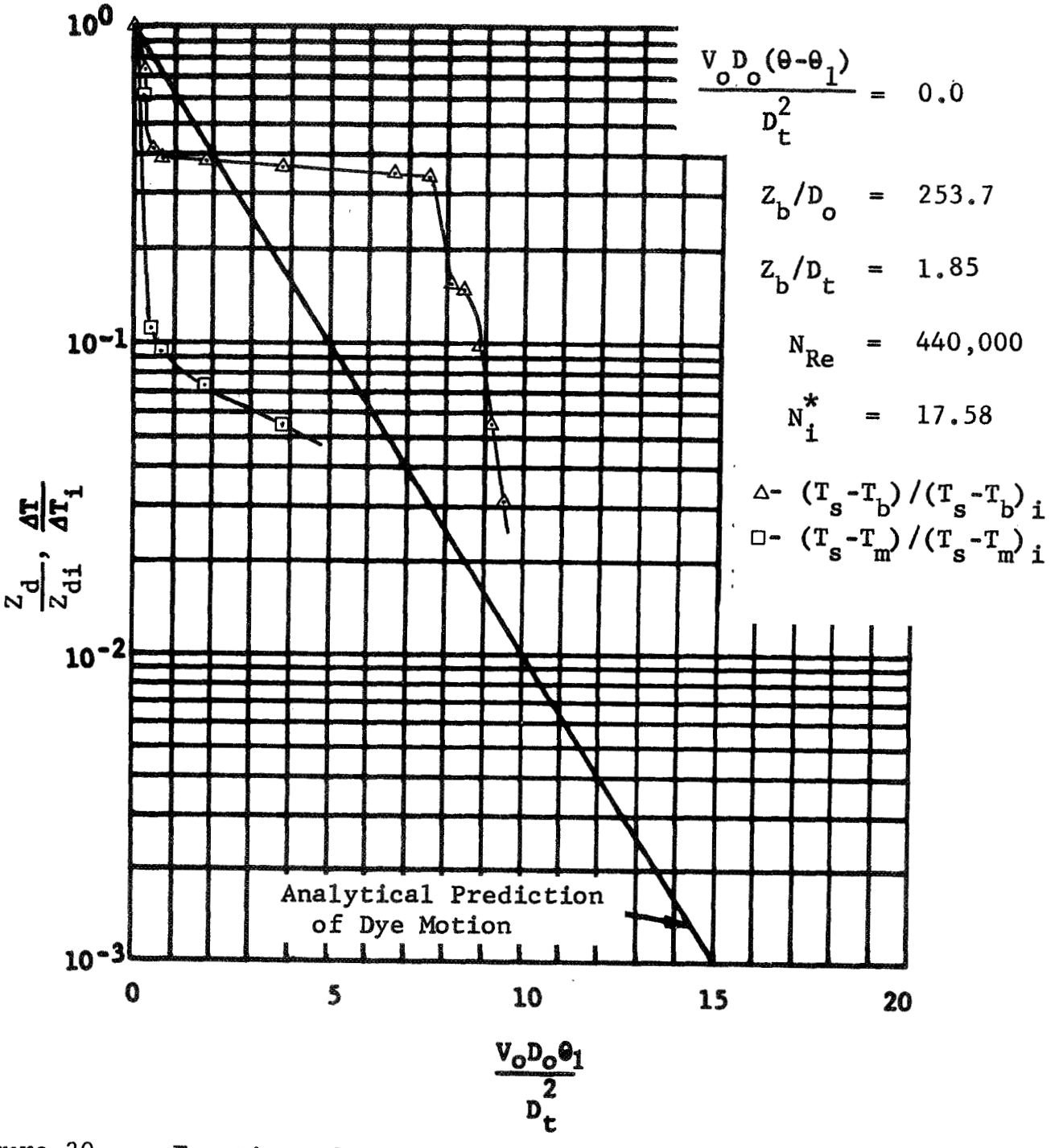

Figure 30 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 8

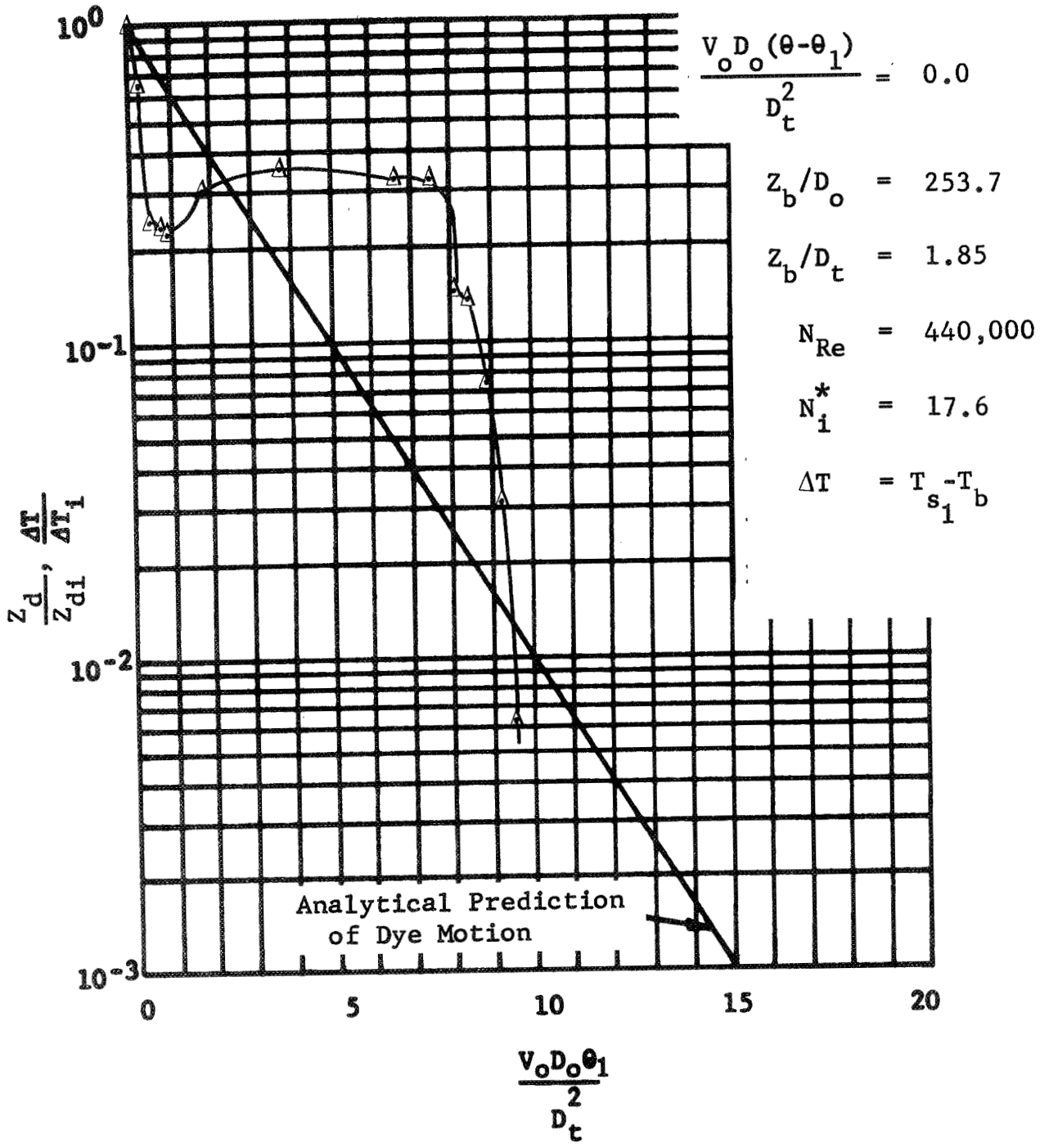

Figure 31 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 8

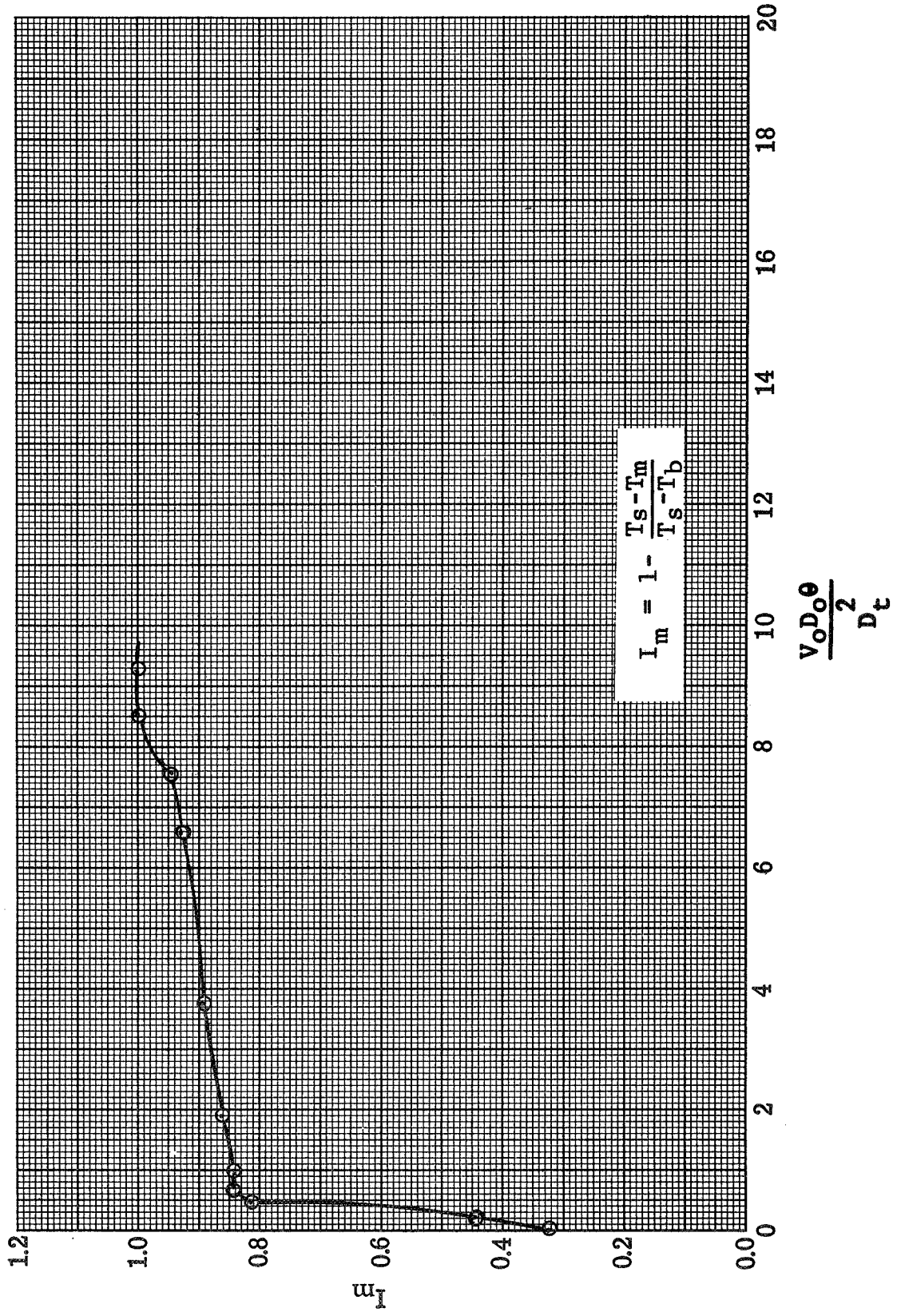

Figure 32 Transient Energy Integral: Run 8

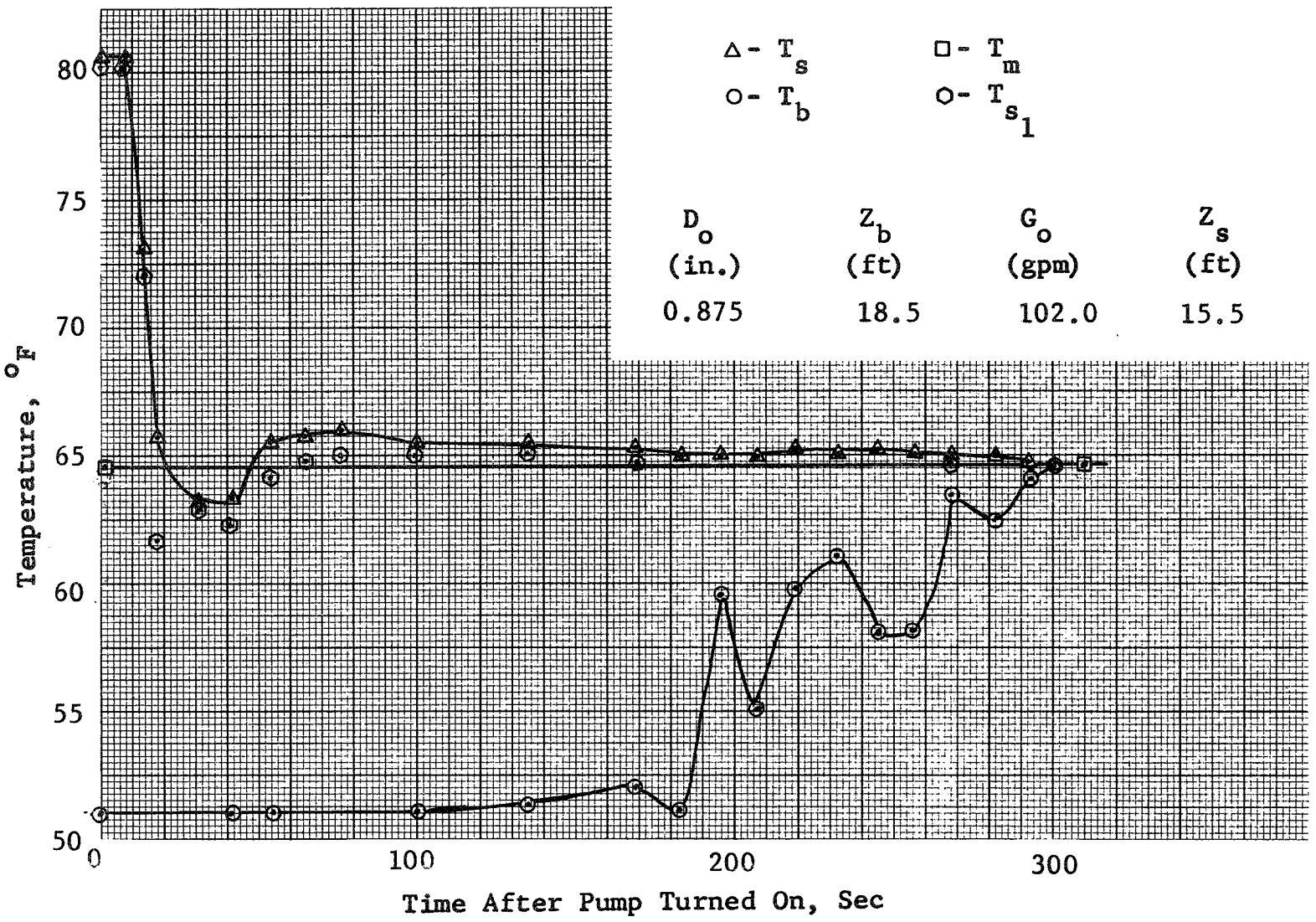

Figure 33 Transient Temperature Destratification: Run 9

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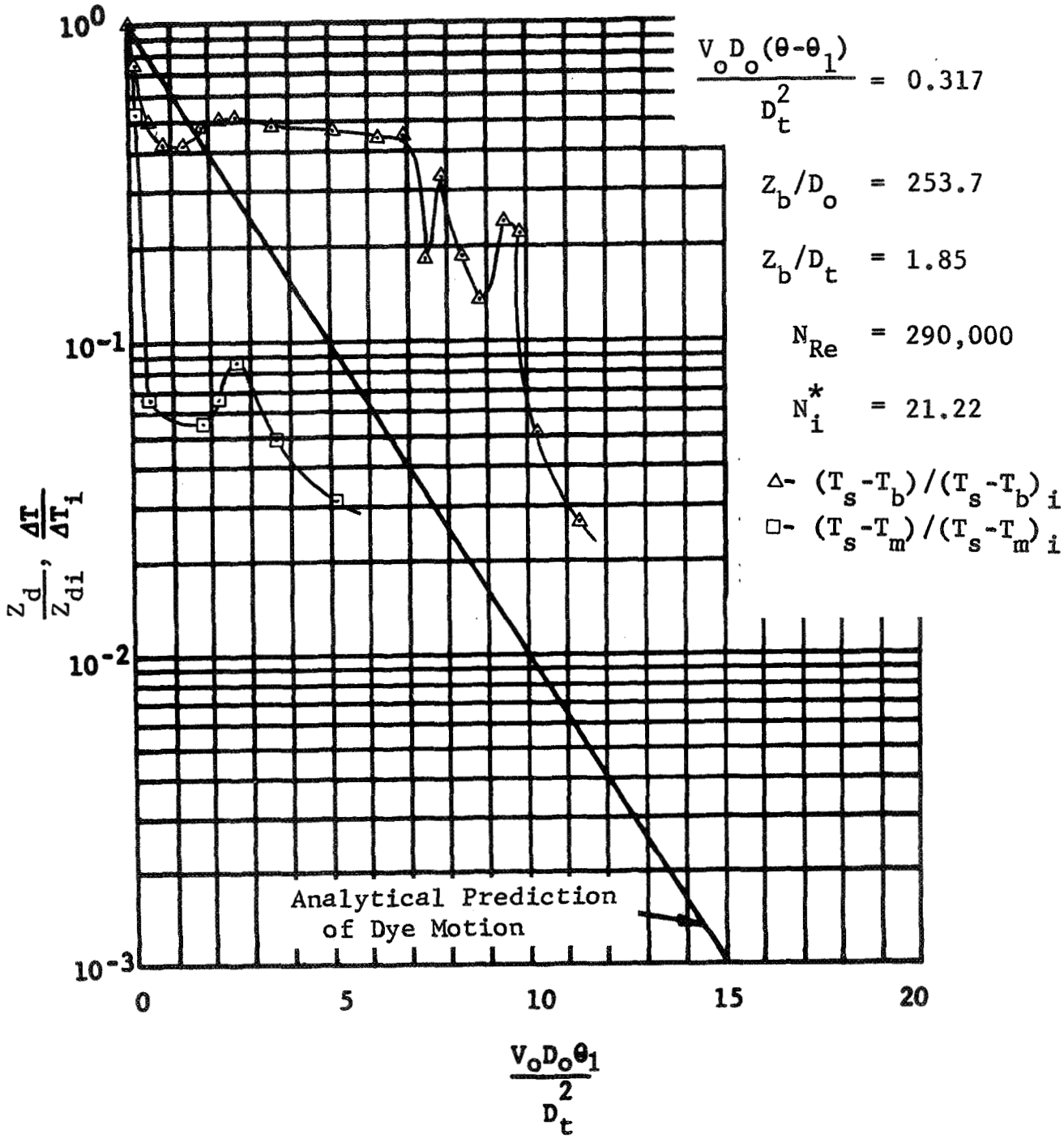

Figure 34 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 9

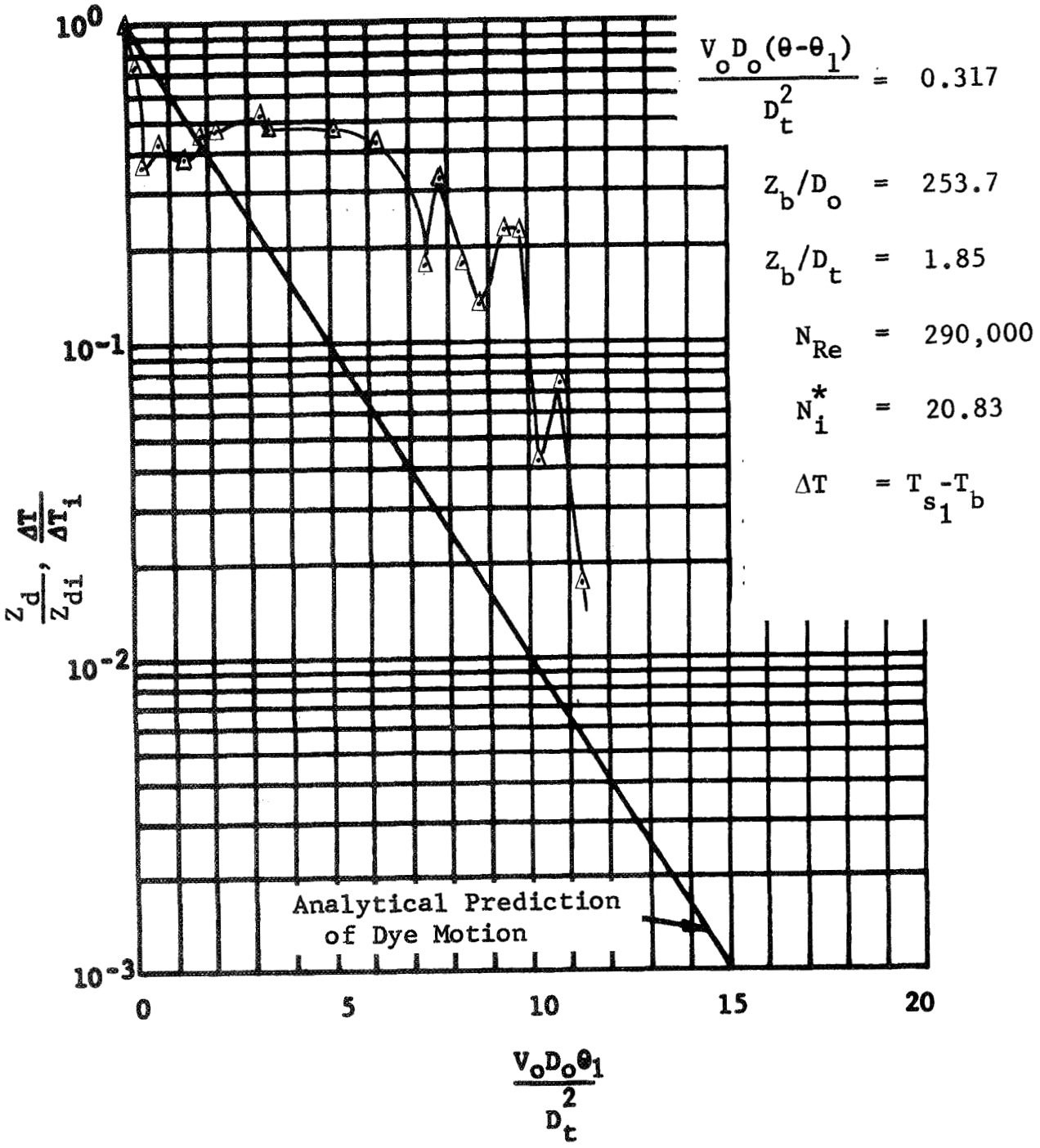

Figure 35 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 9

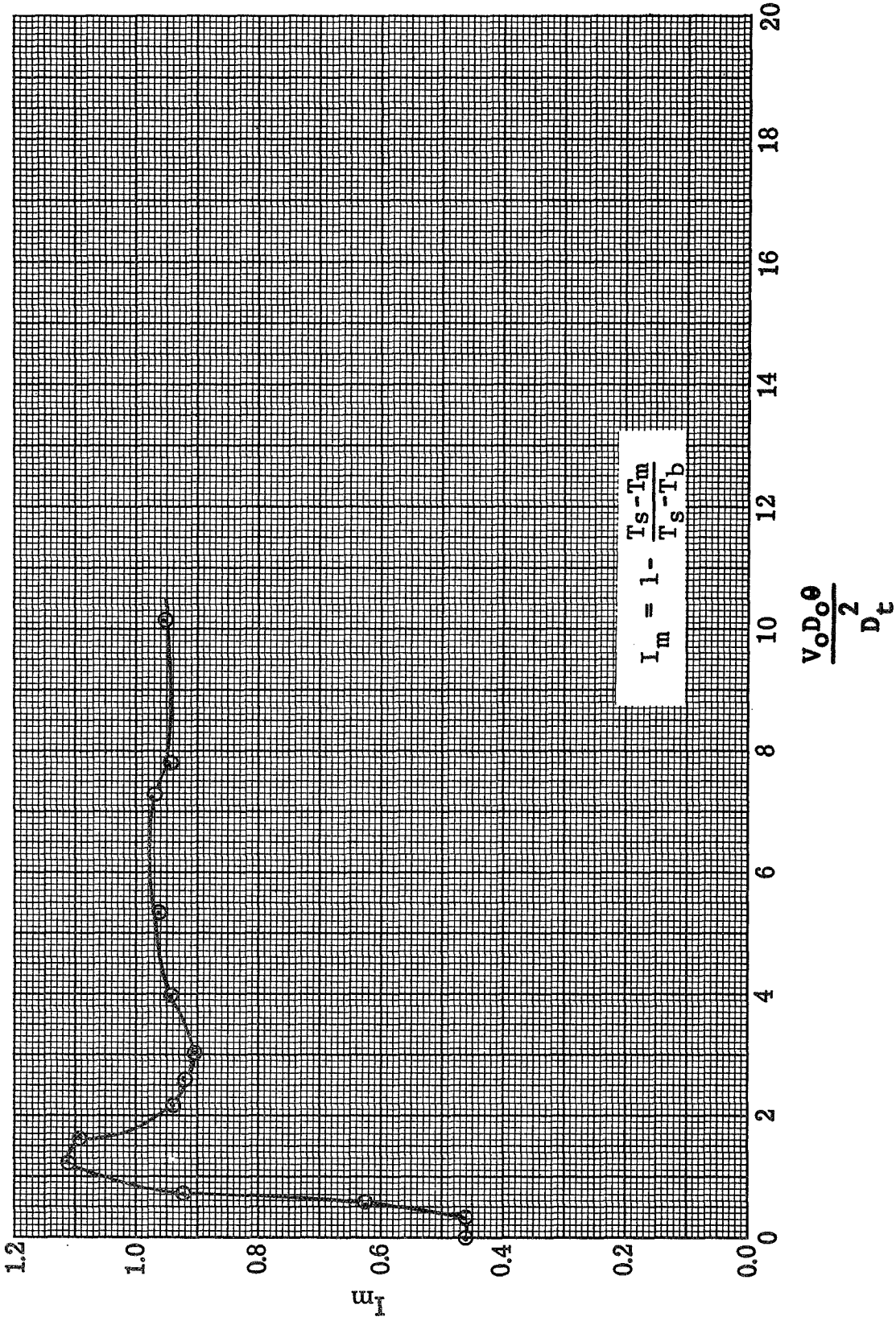

Figure 36 Transient Energy Integral: Run 9

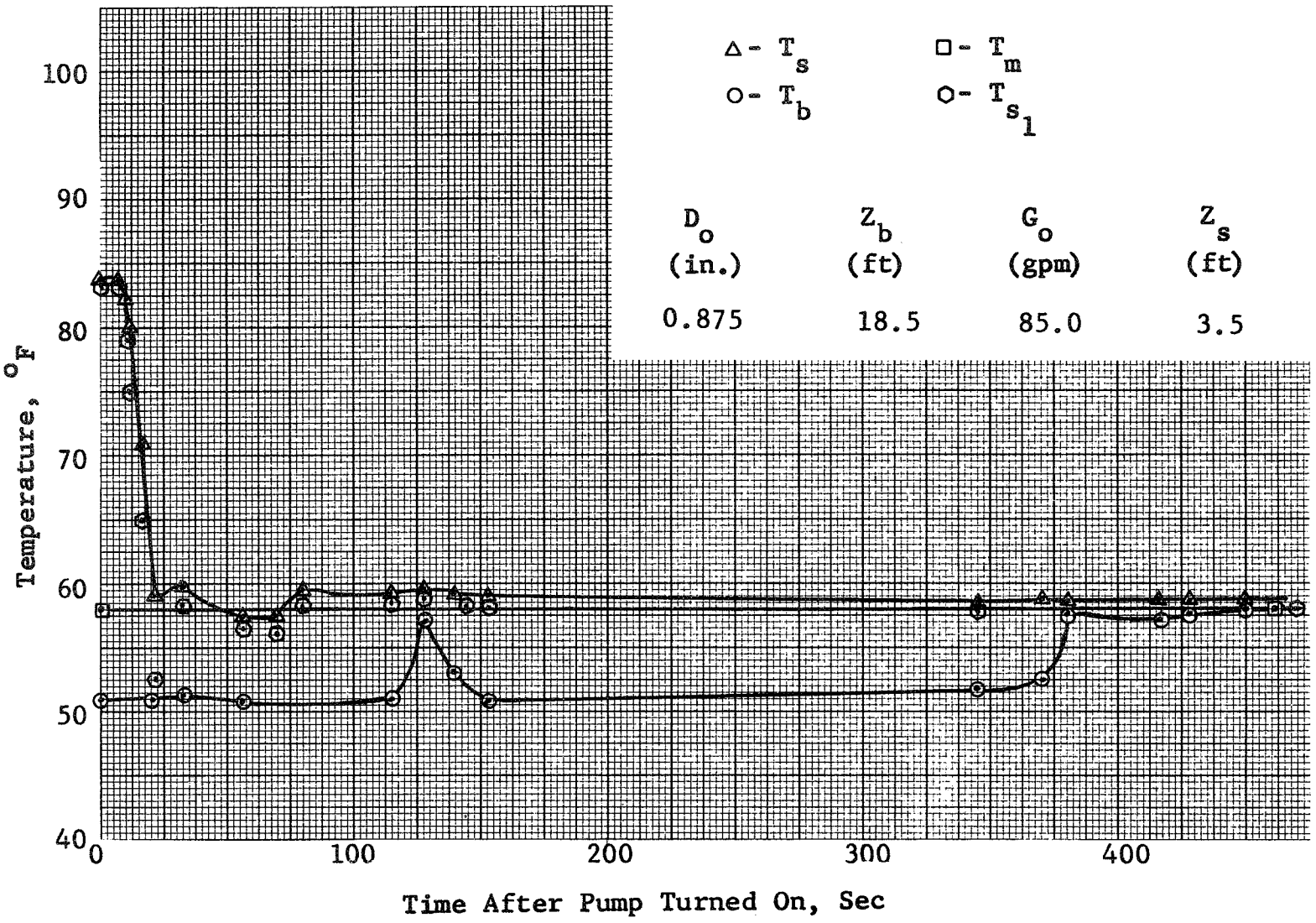

Figure 37 Transient Temperature Destratification: Run 10

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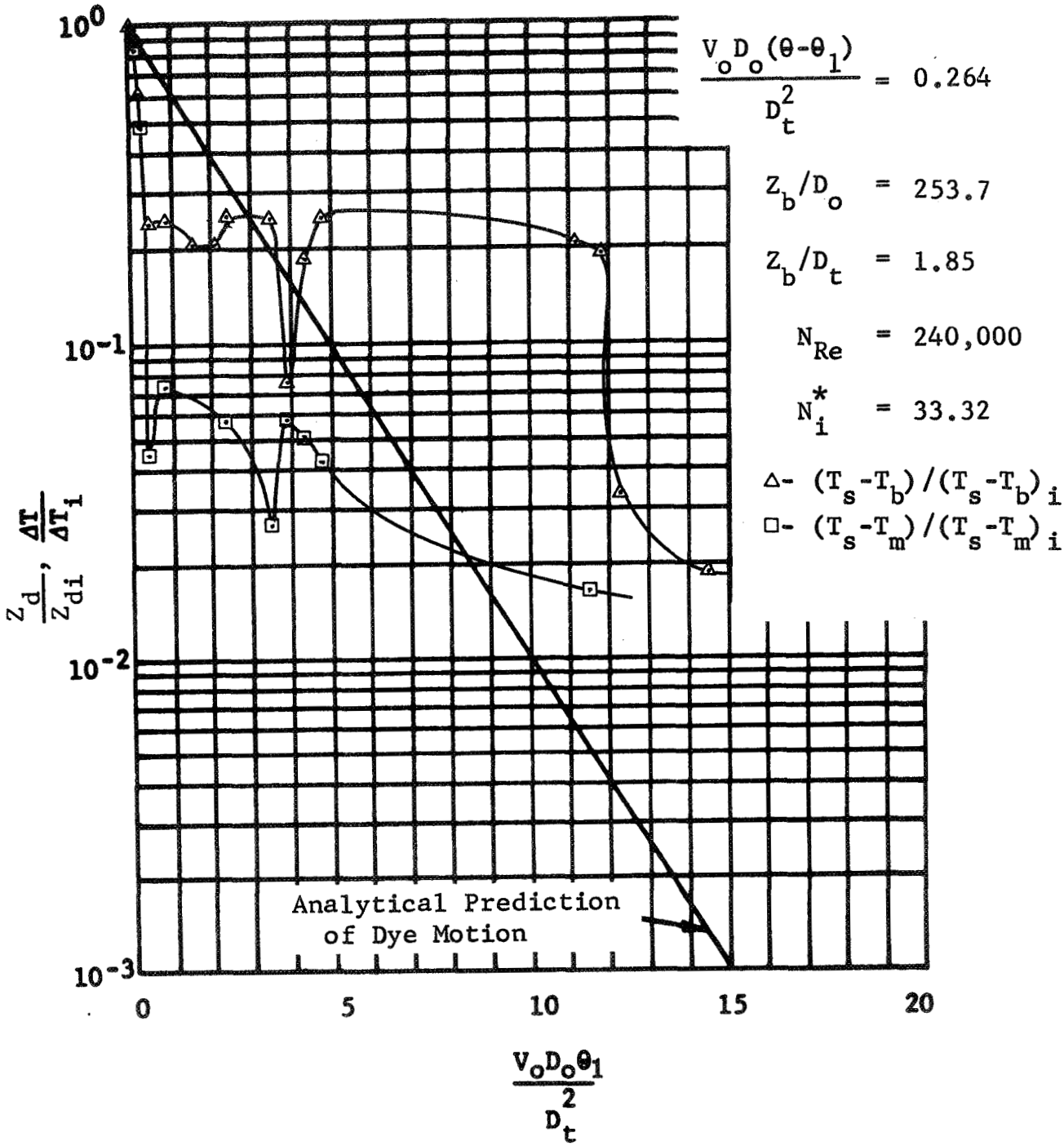

Figure 38 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 10

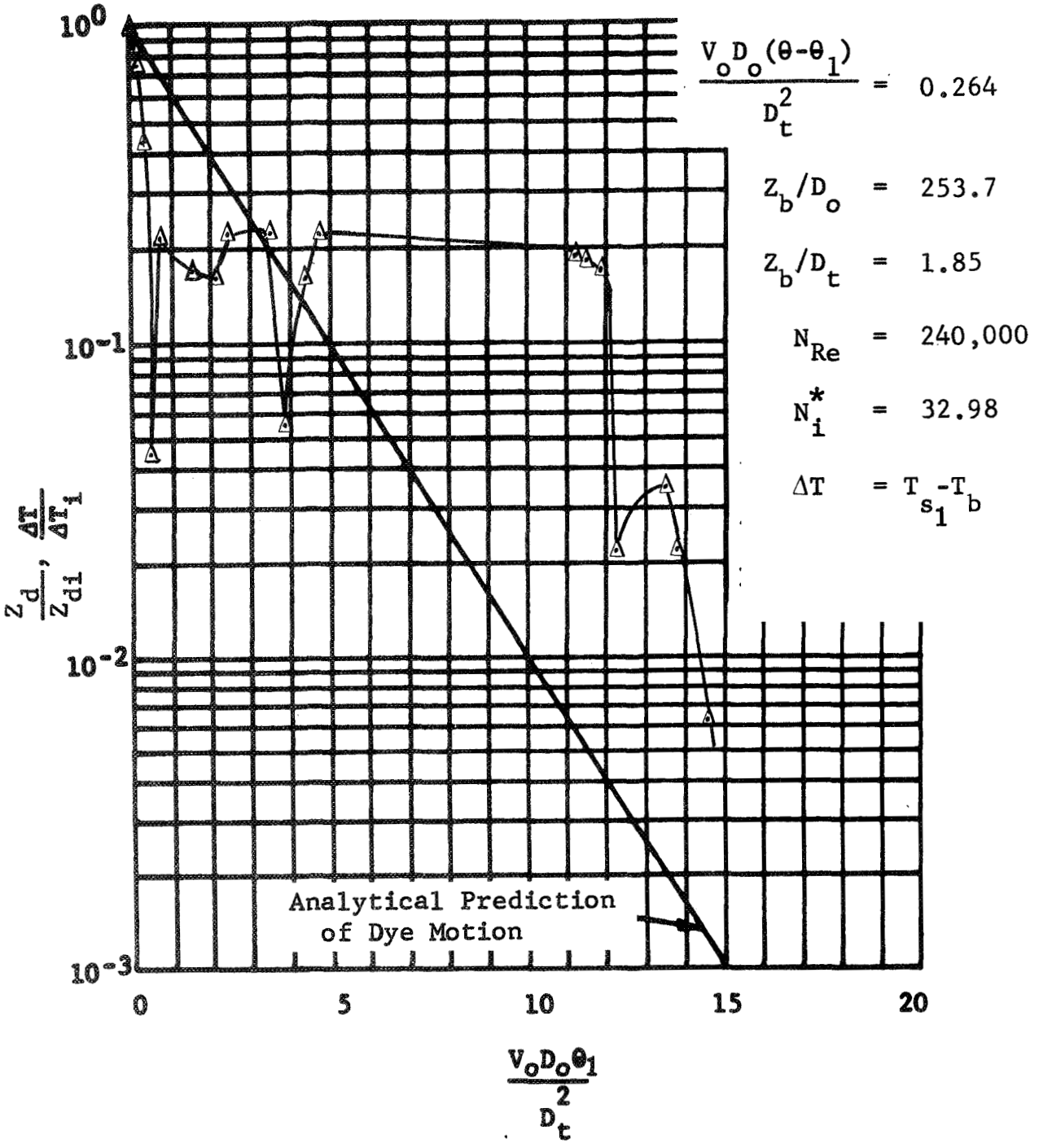

Figure 39 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 10

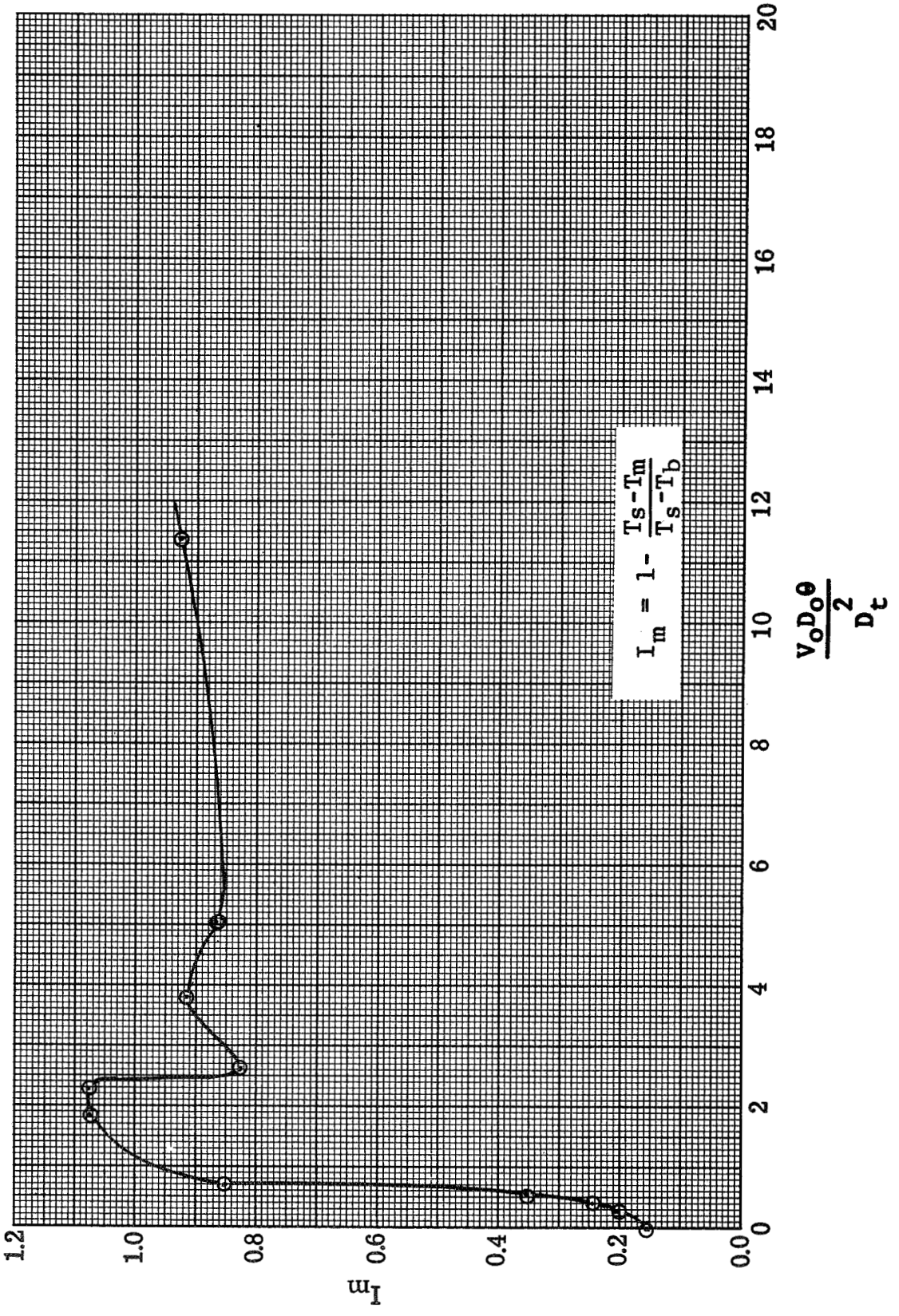

Figure 40 **Transient Energy Integral:** Run 10

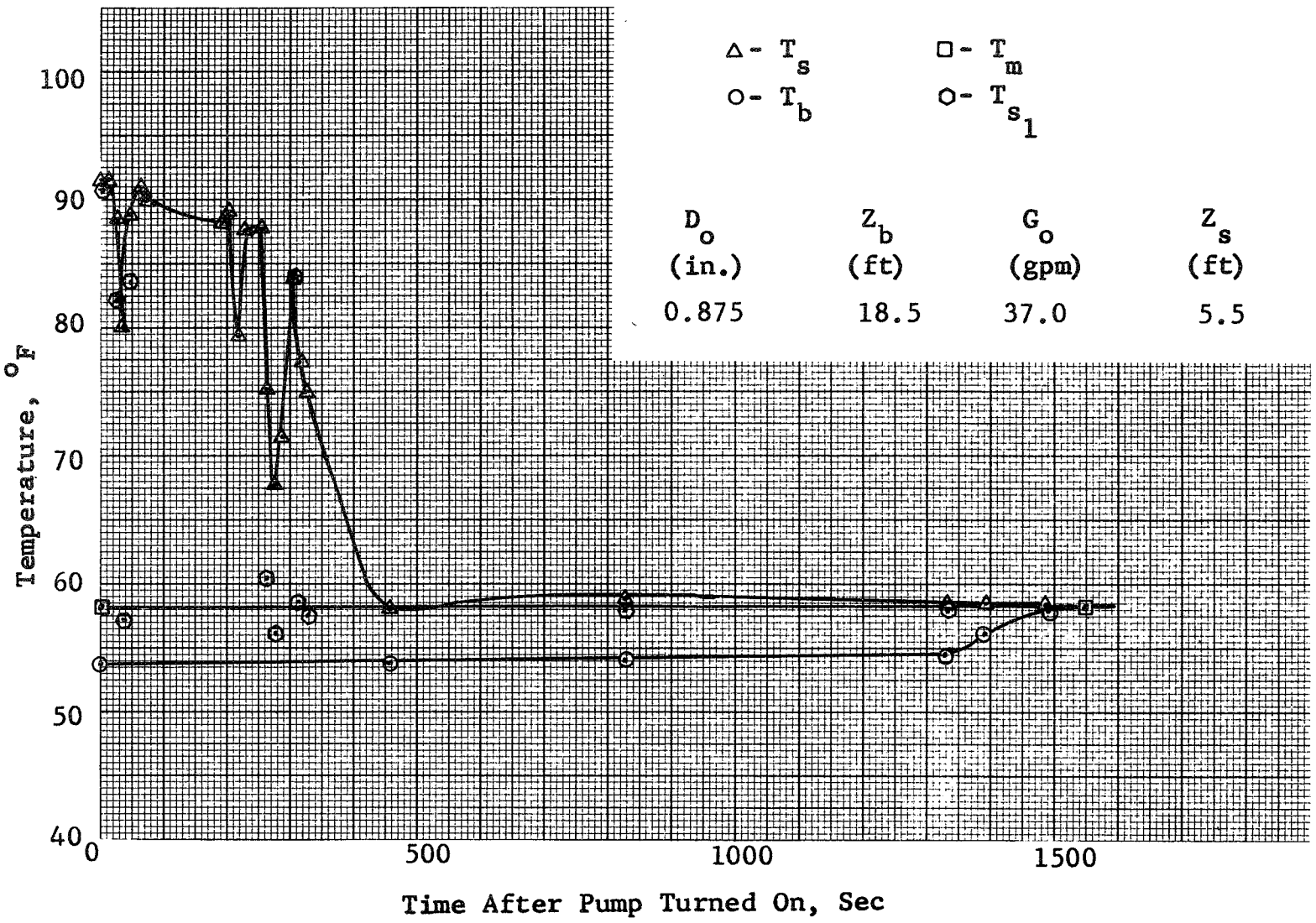

Figure 41 Transient Temperature Destratification: Run 11

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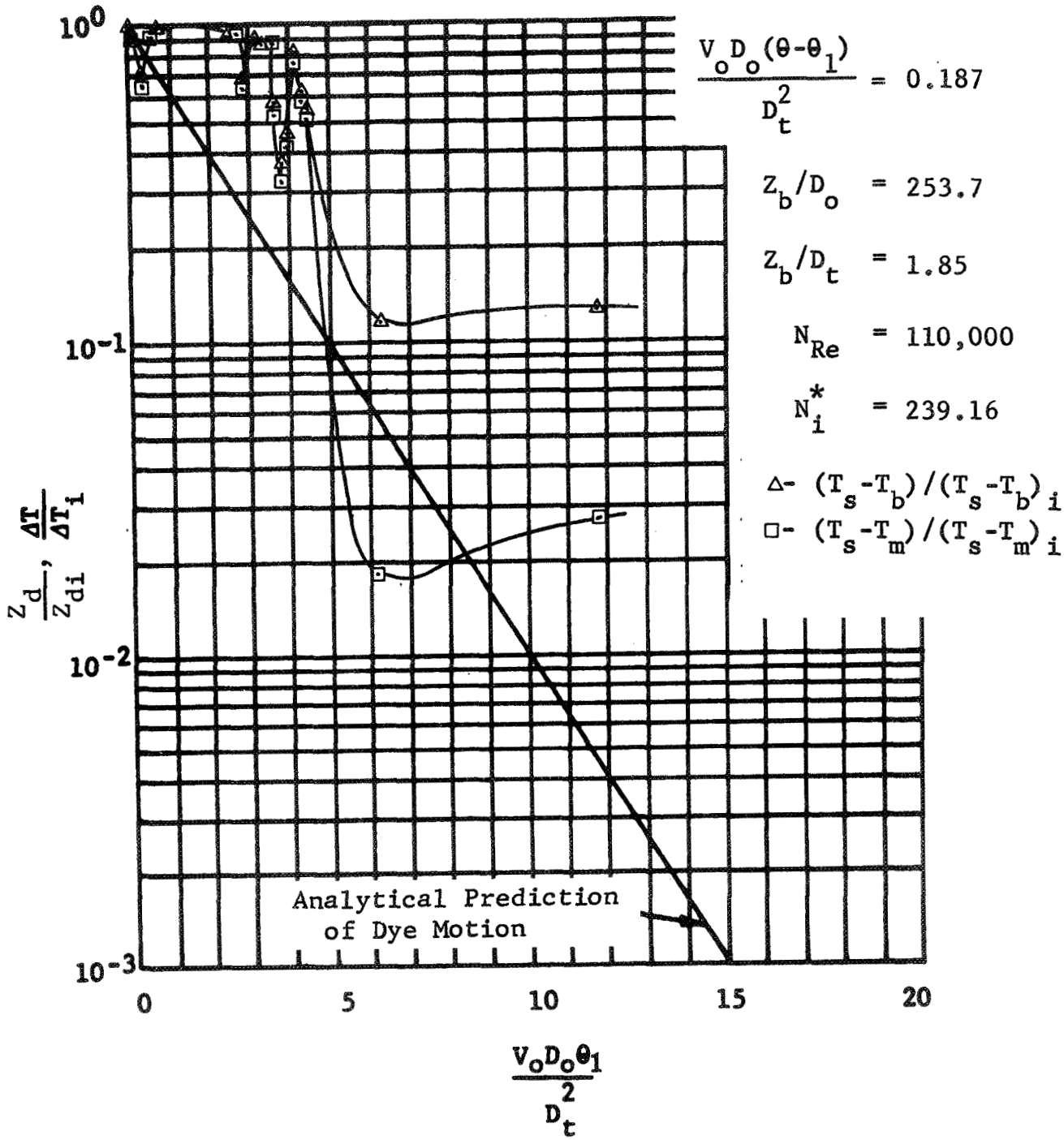

Figure 42 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 11

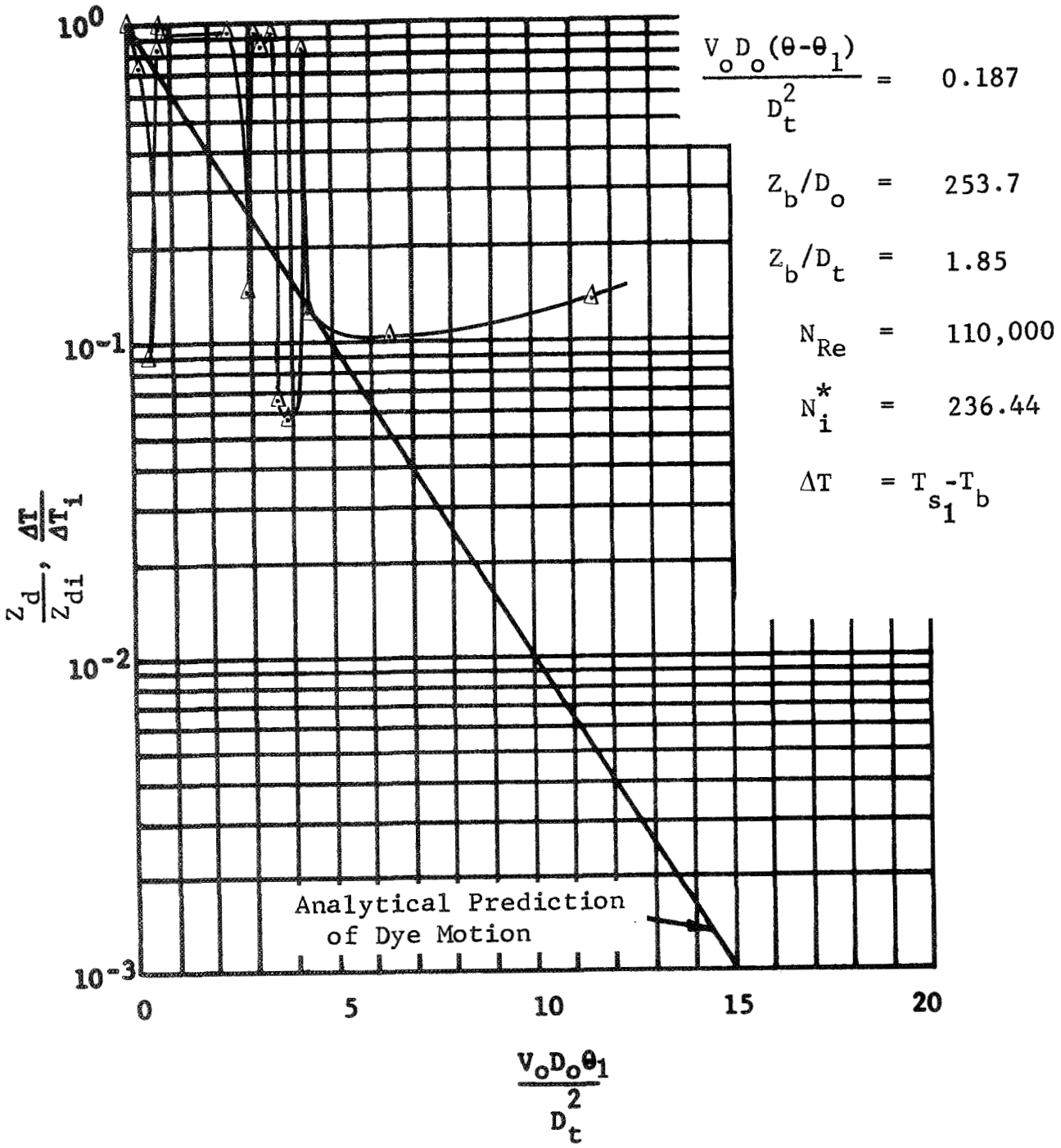

Figure 43 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 11

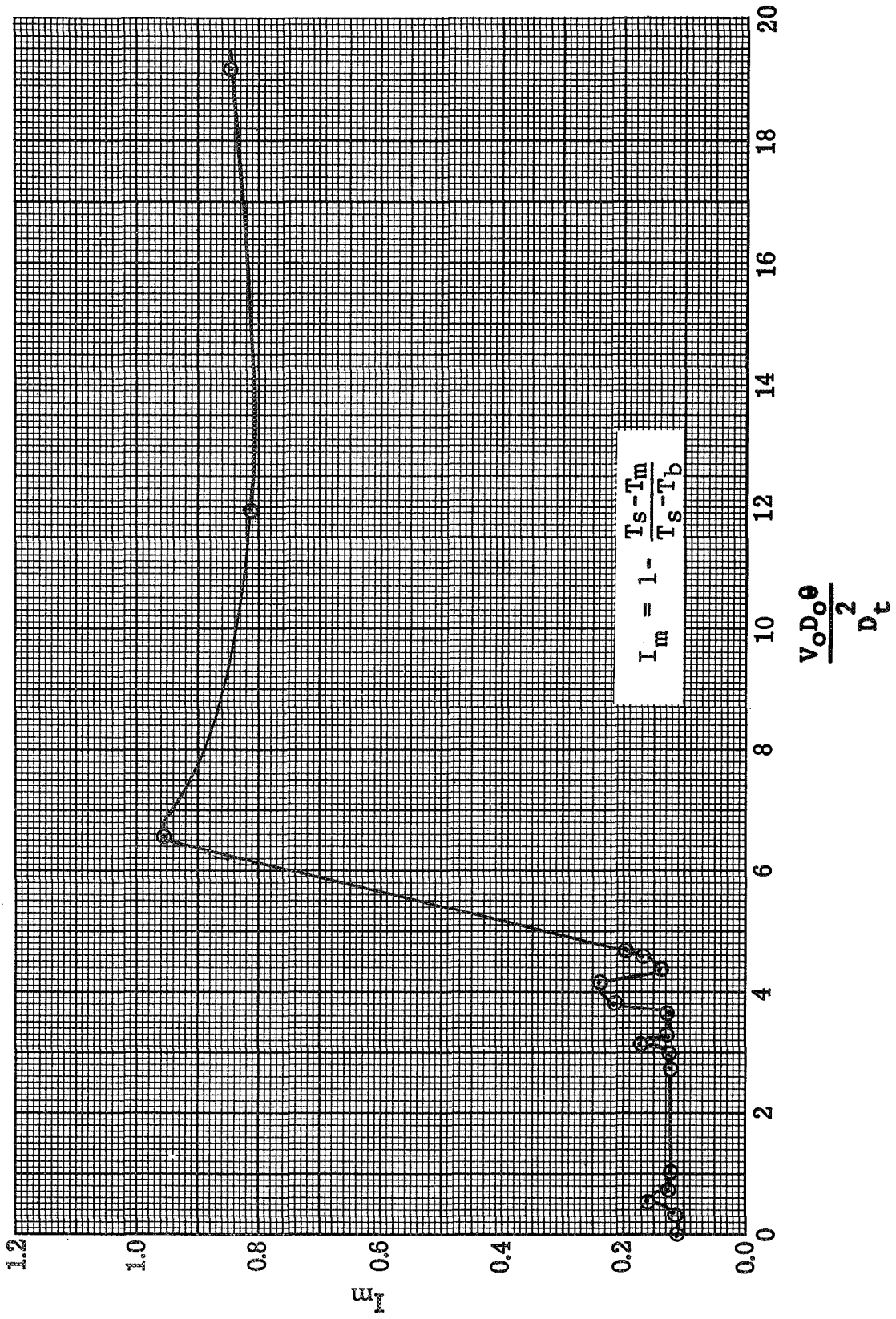

Figure 44 Transient Energy Integral: Run 11

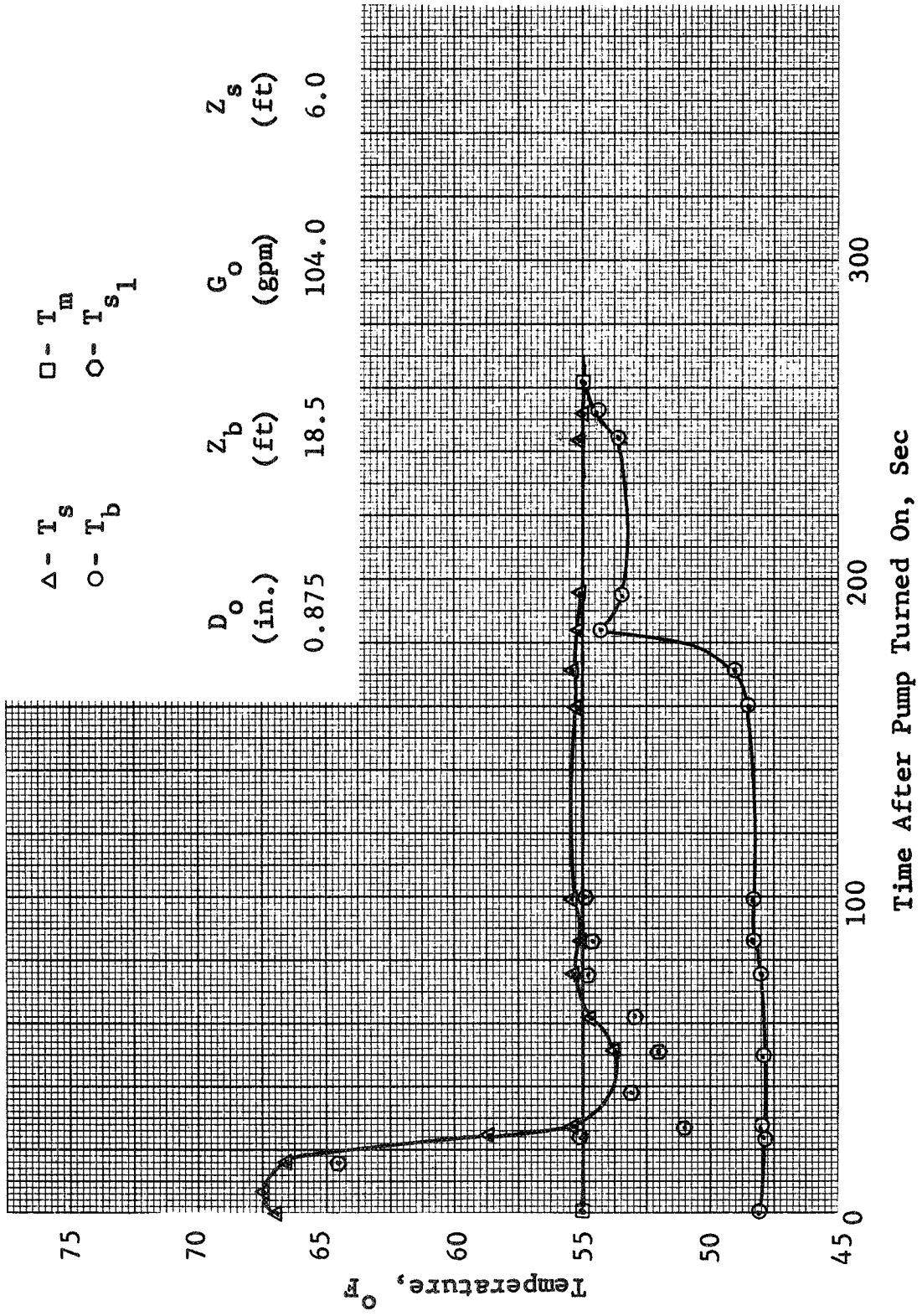

Figure 45 Transient Temperature Destratification : Run 12

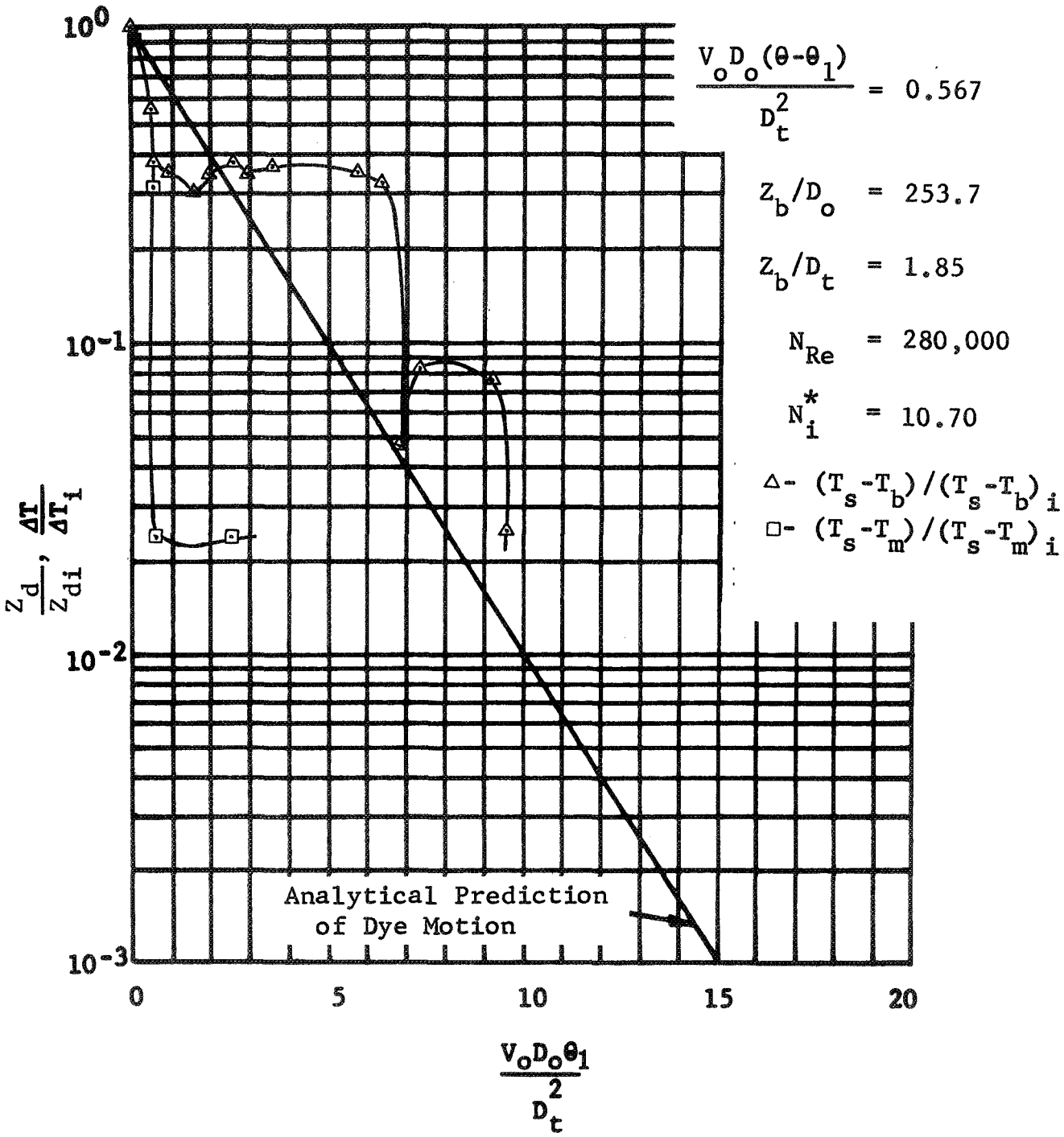

Figure 46 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at $\theta = 0.0$ sec; Average Surface Temperature Drop Starts at $\theta_1 = 0.0$ sec; Run 12

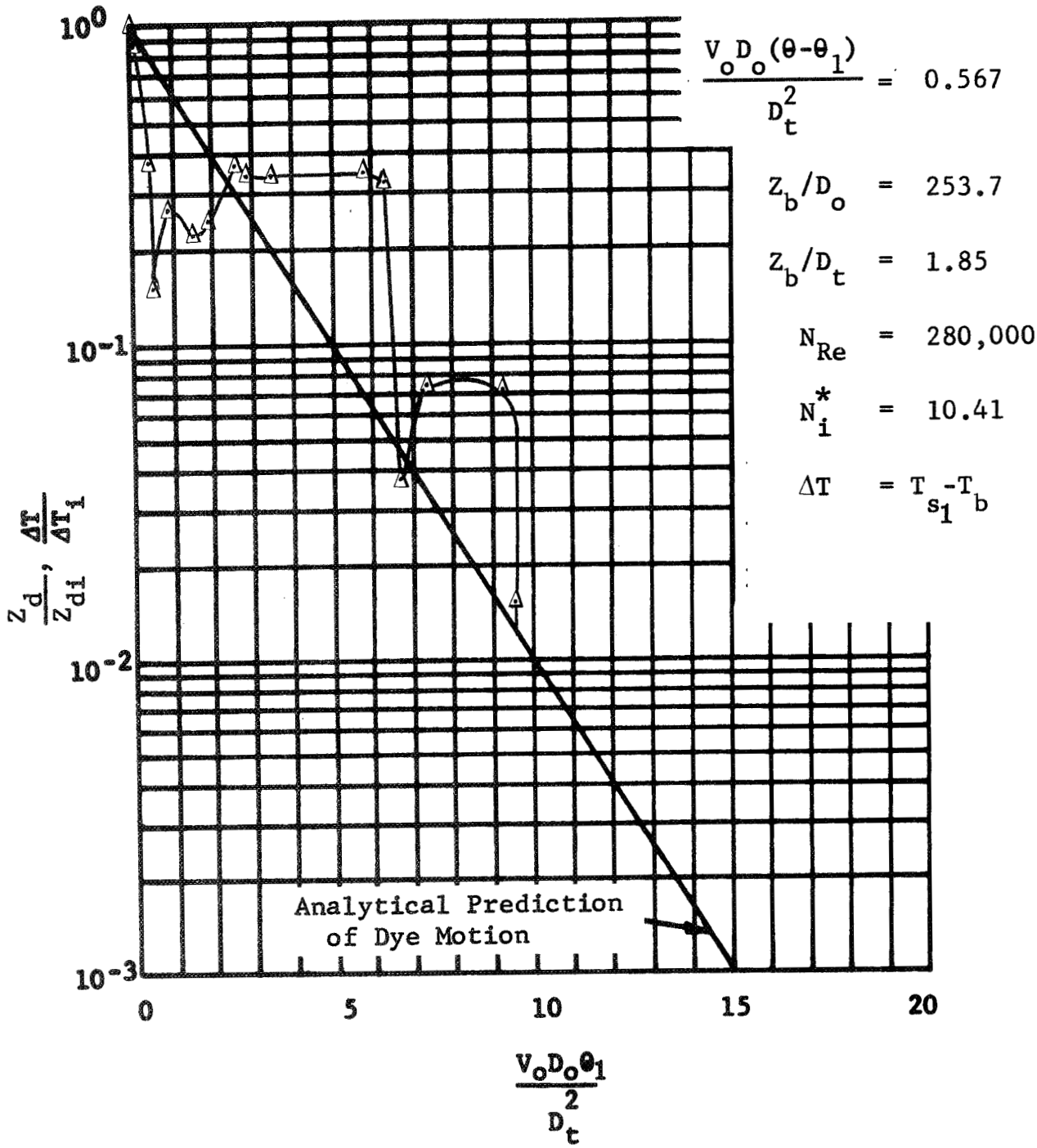

Figure 47 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 12

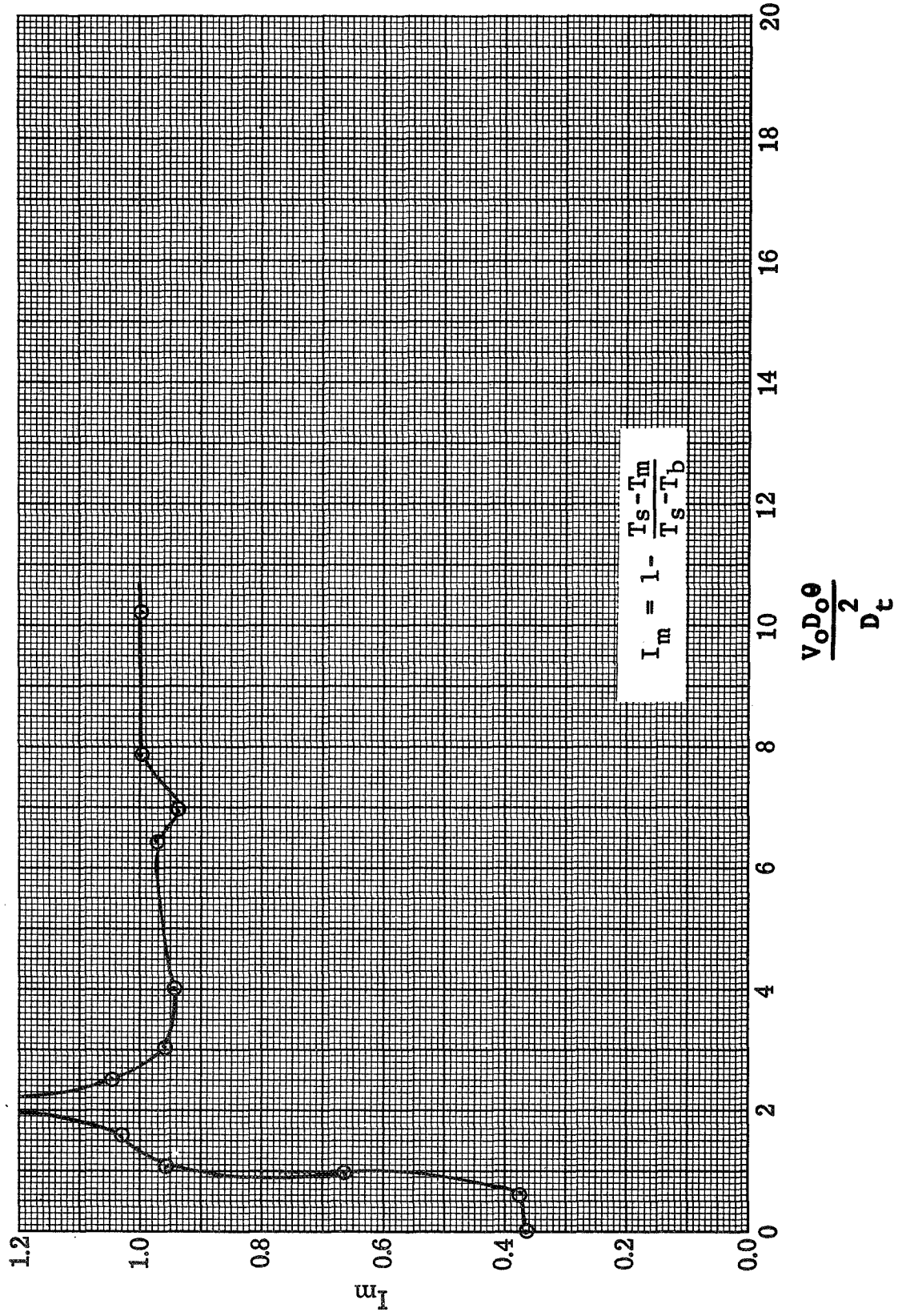

Figure 48 Transient Energy Integral: Run 12

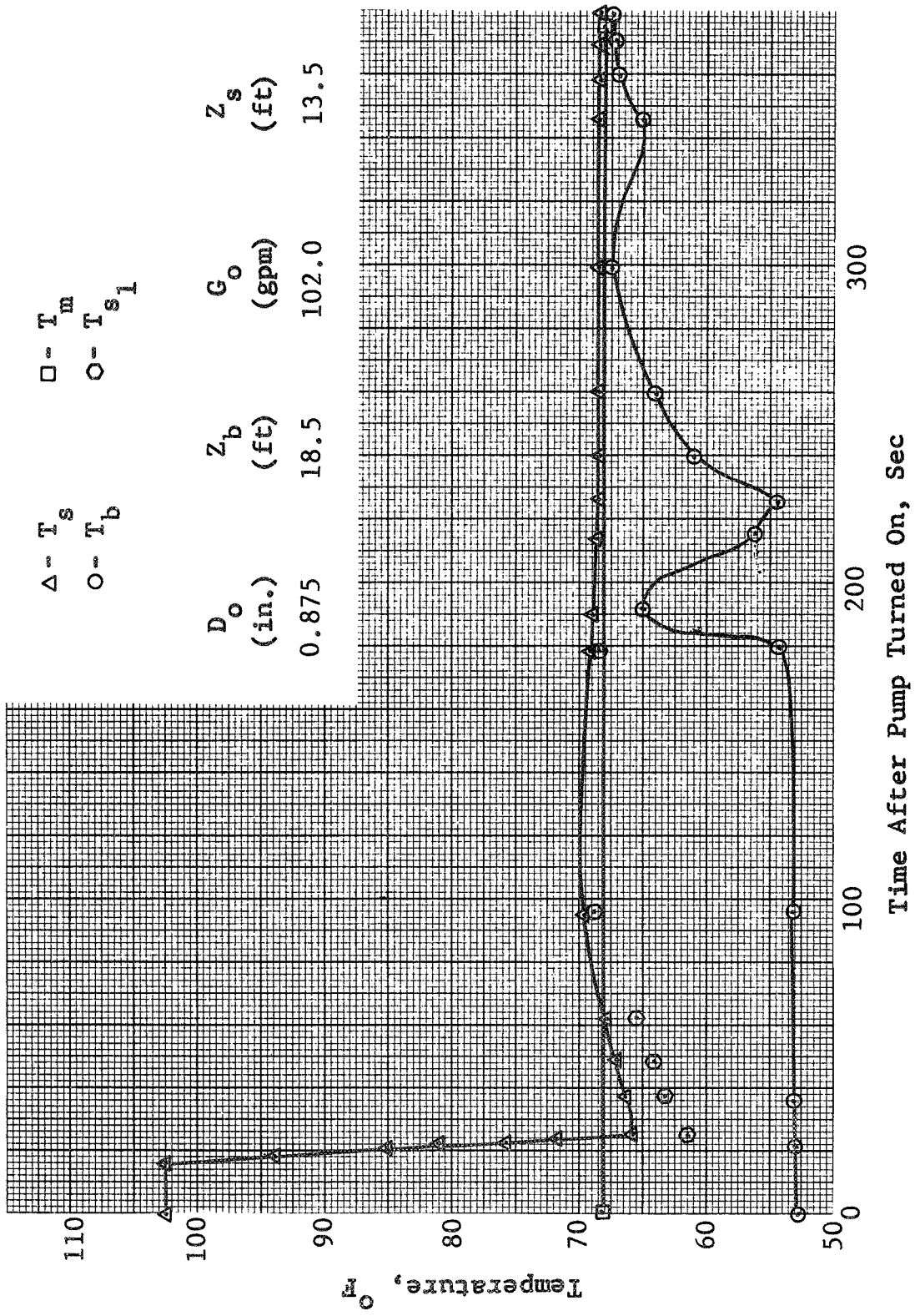

Figure 49 Transient Temperature Destratification : Run 13

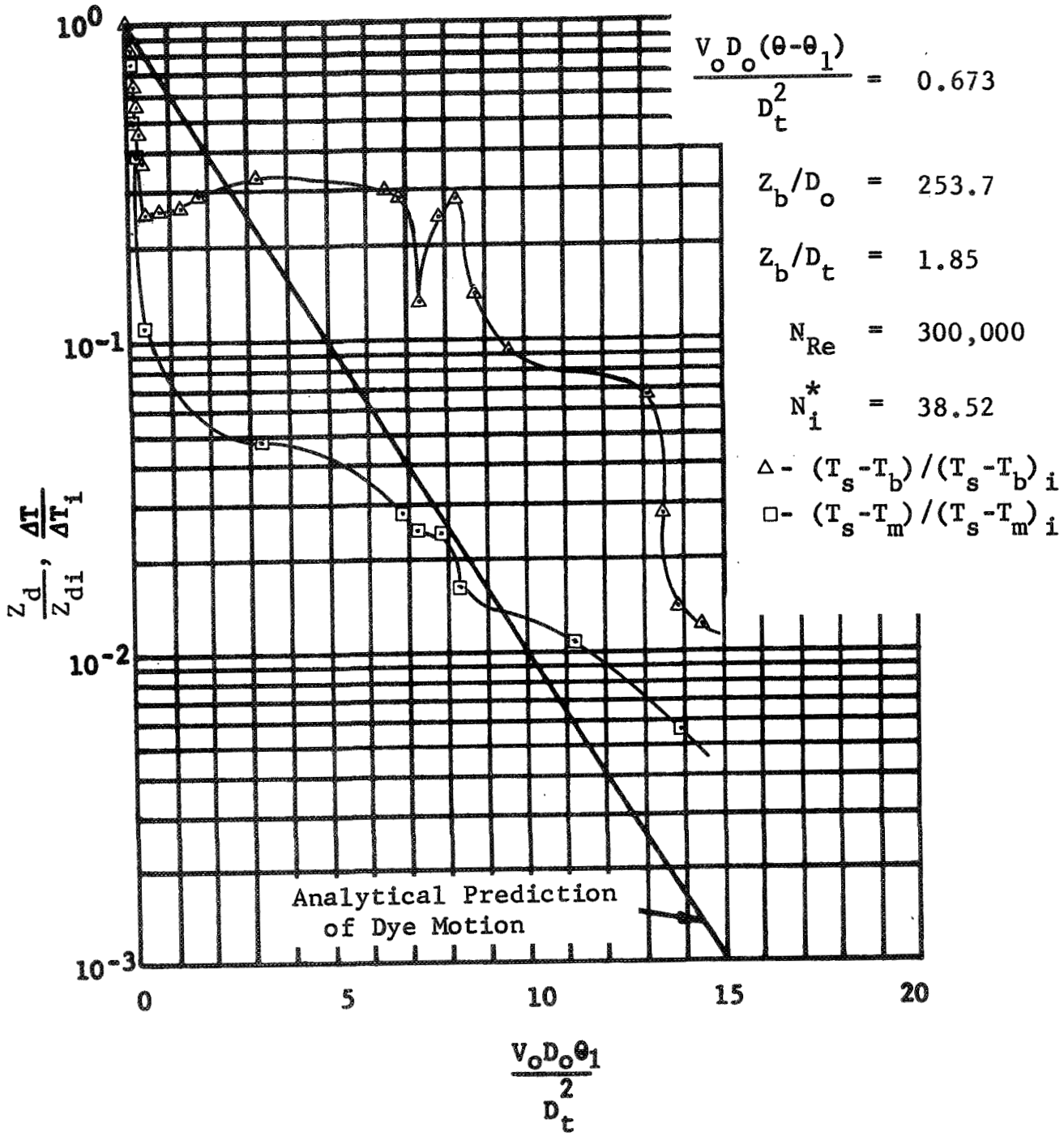

Figure 50 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 13

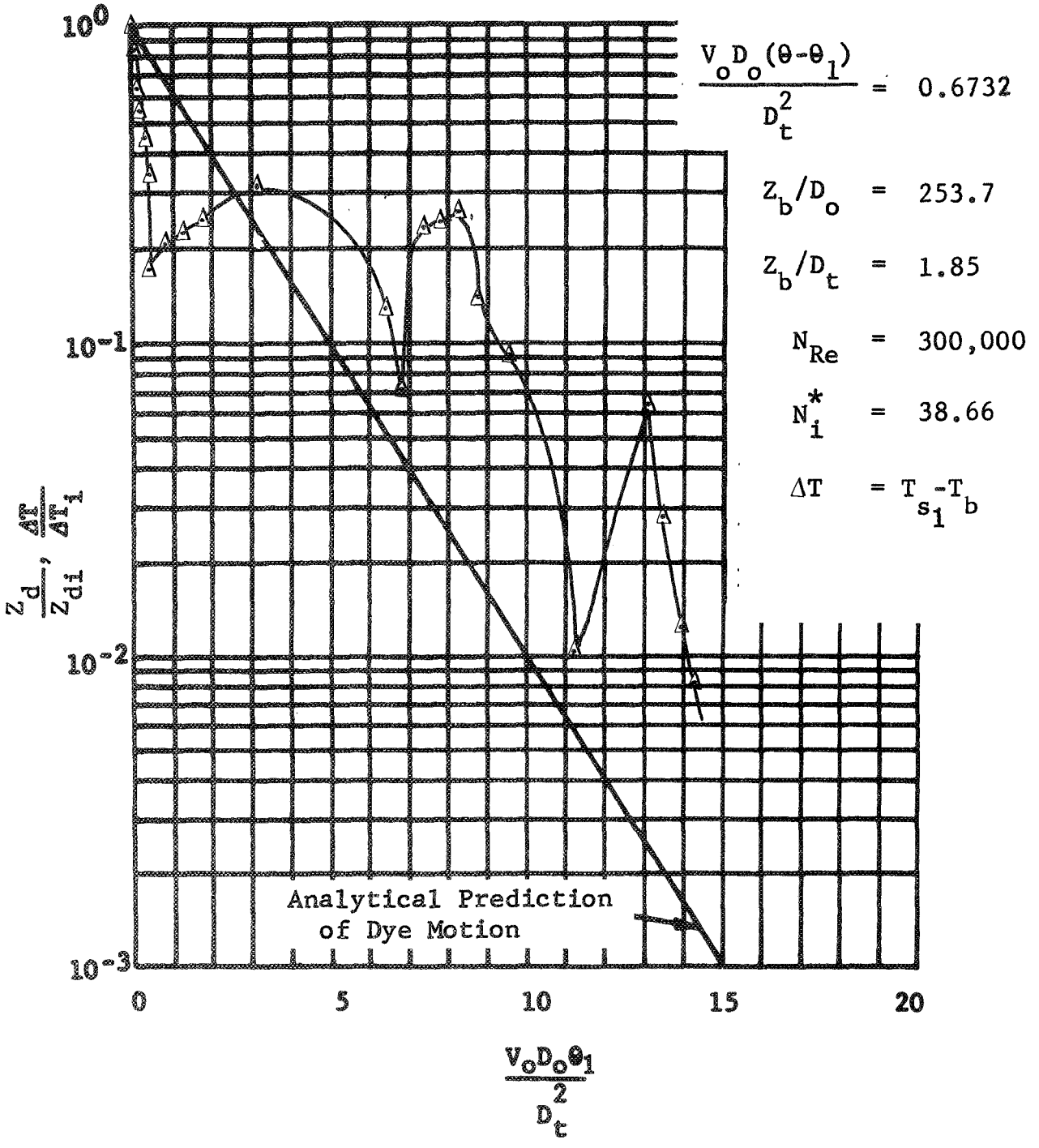

Figure 51 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop; Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 13

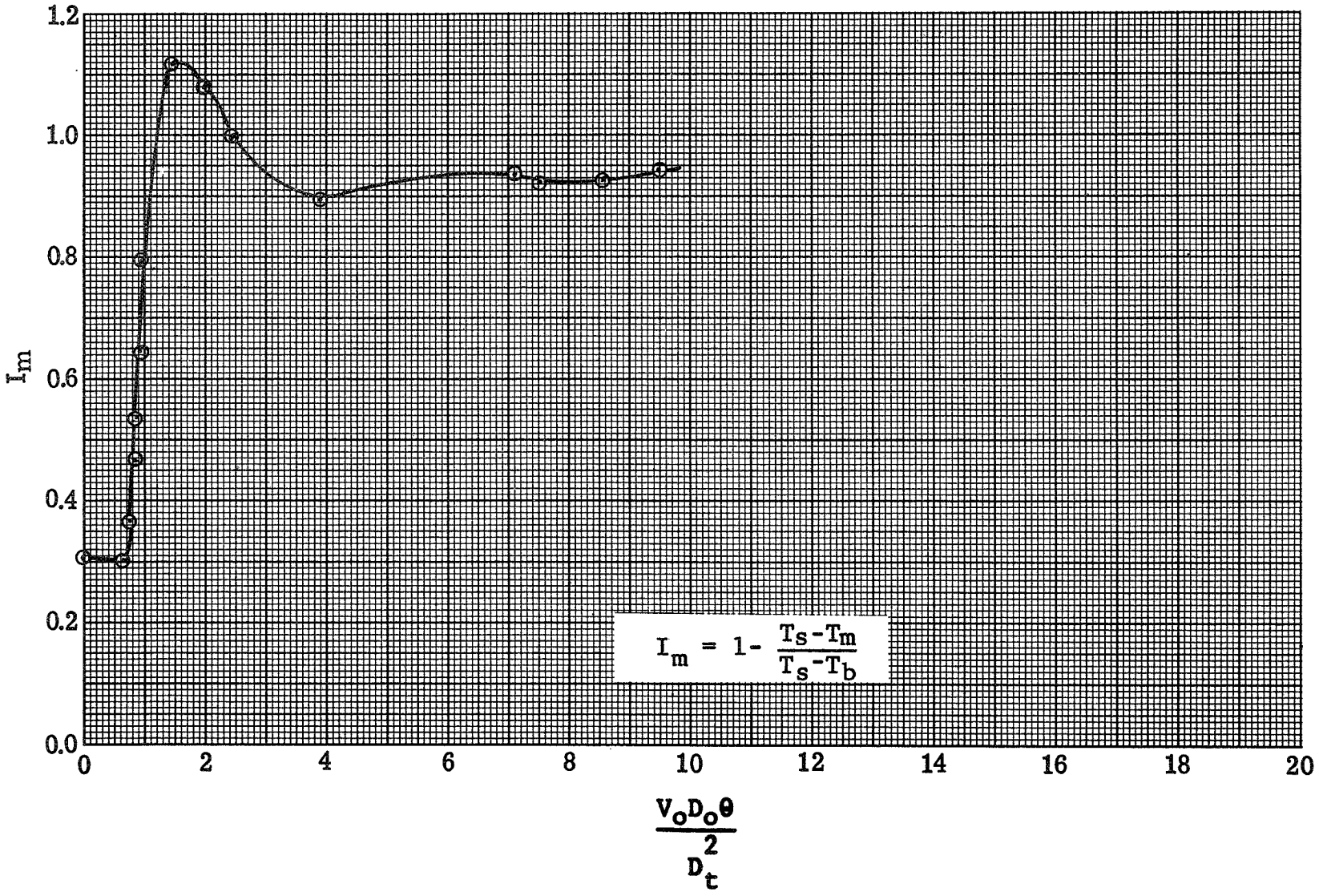

Figure 52 **Transient Energy Integral:** Run 13

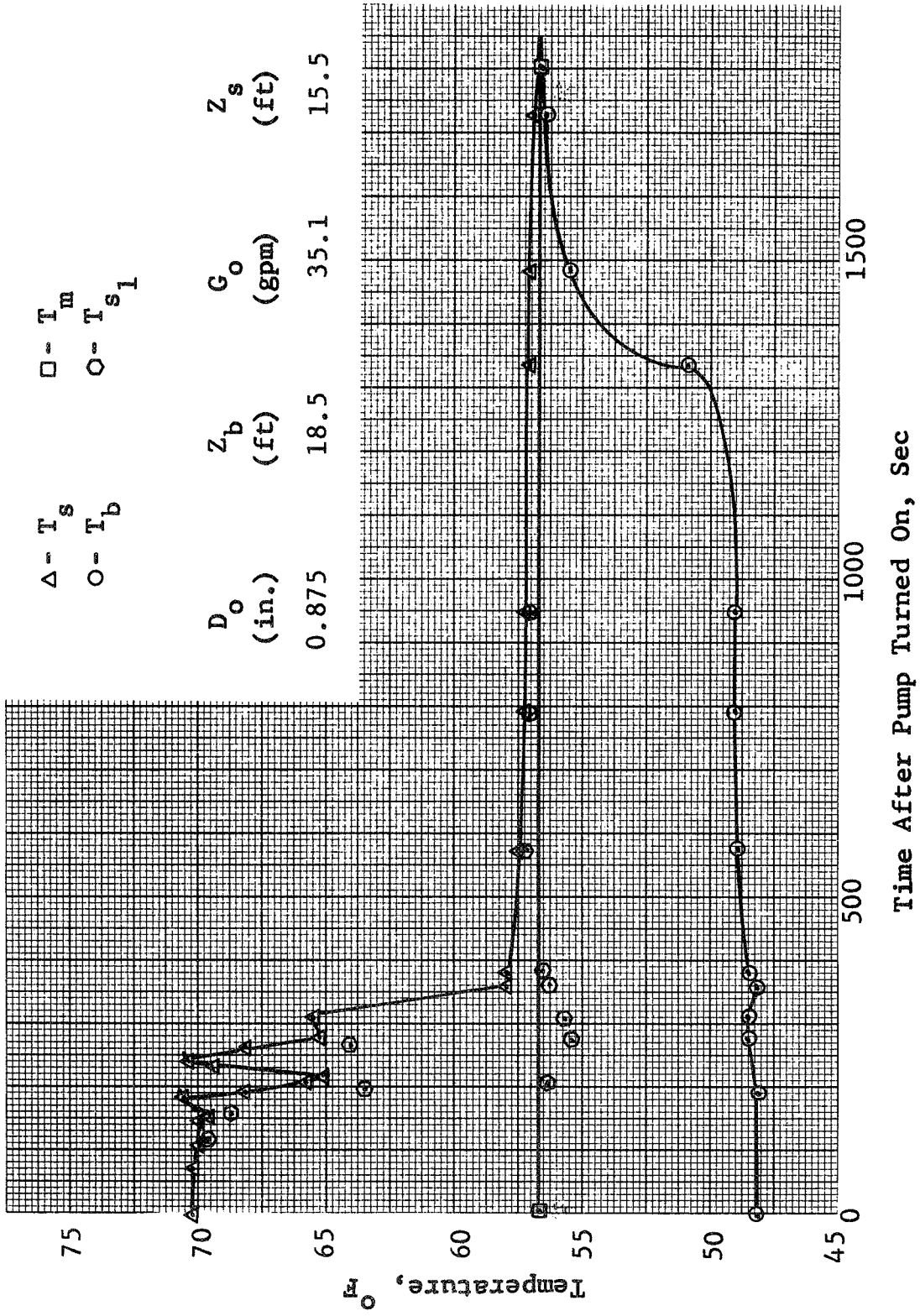

Figure 53 Transient Temperature Destratification: Run 14

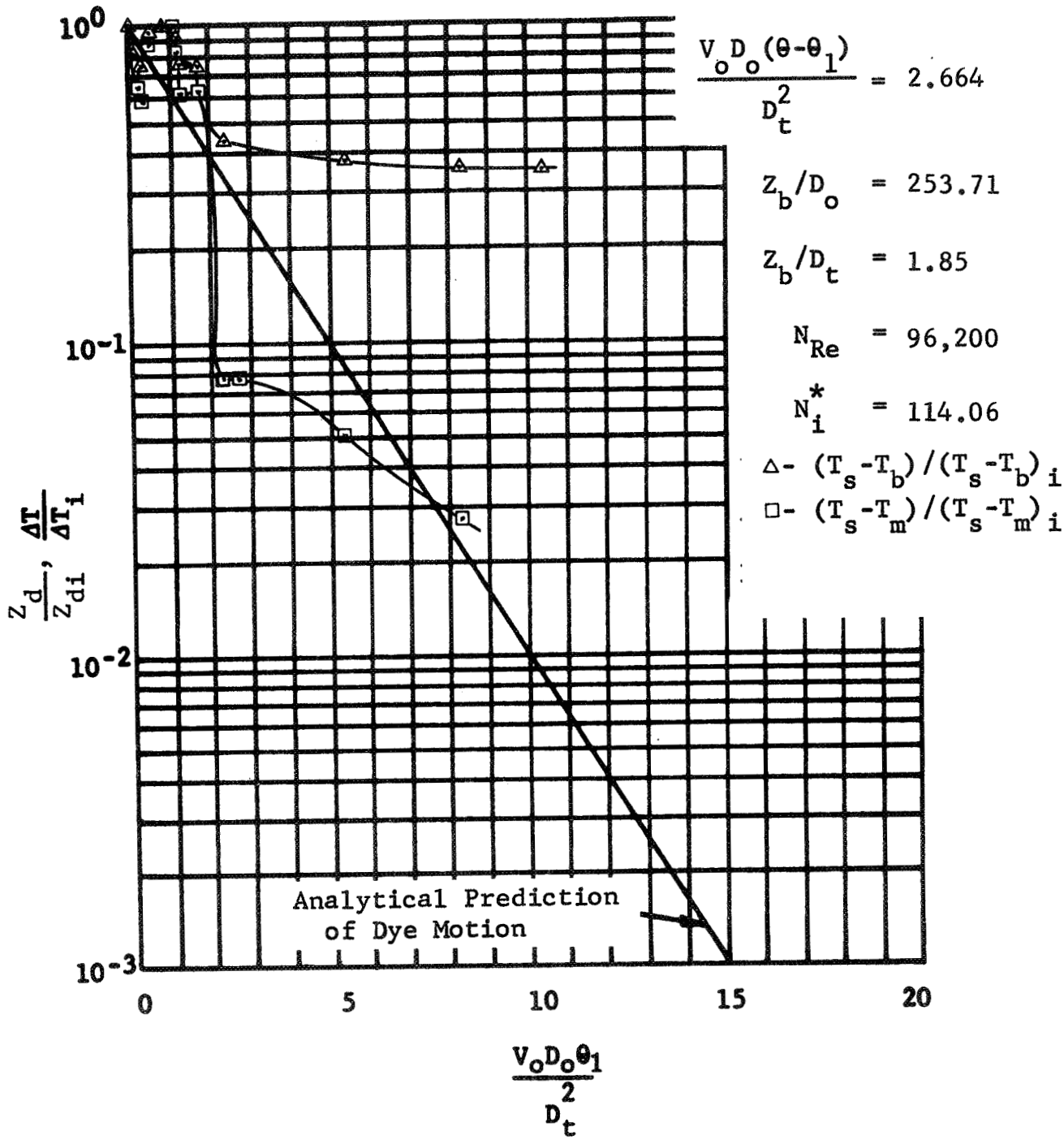

Figure 54 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 14

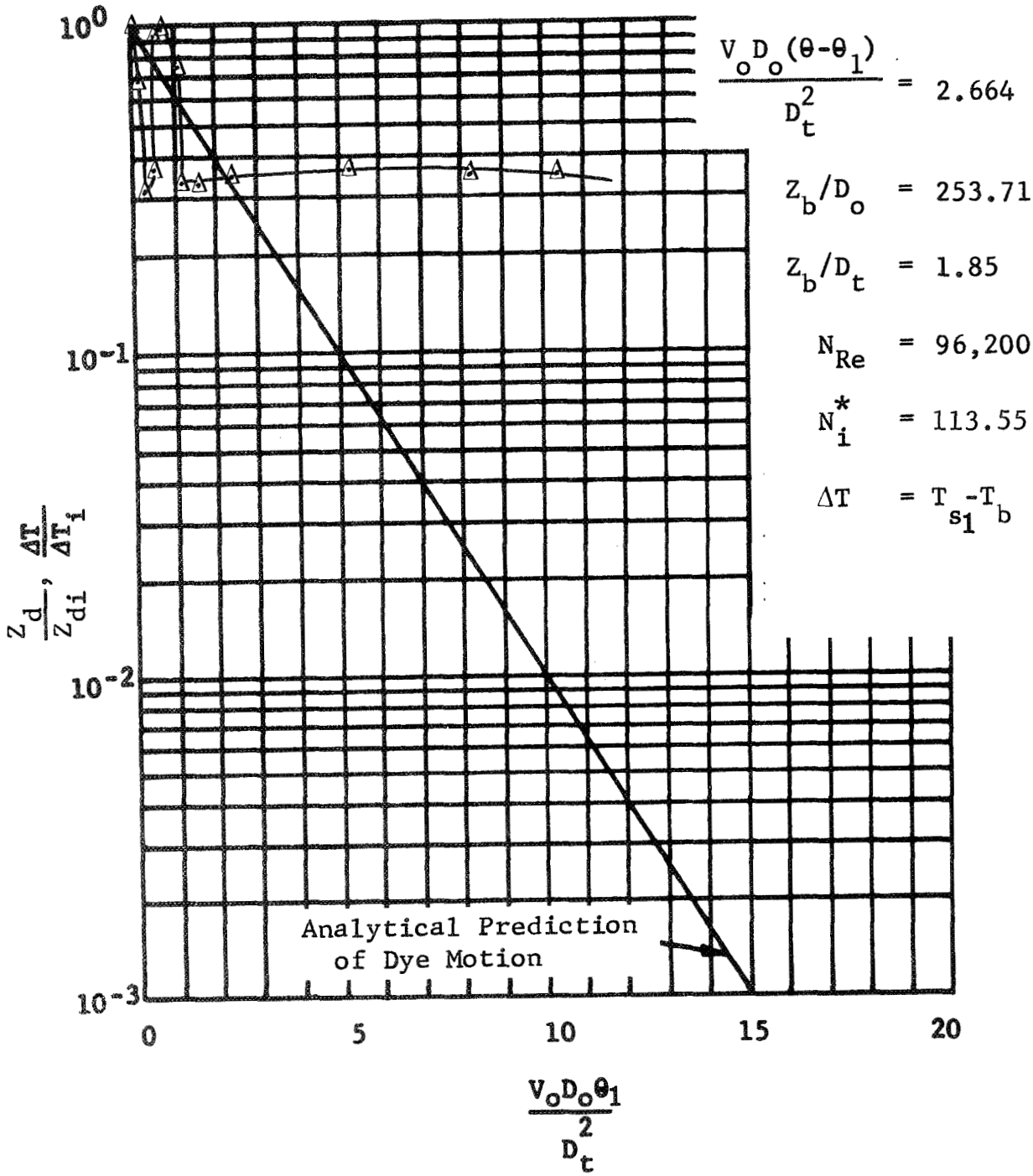

Figure 55 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 14

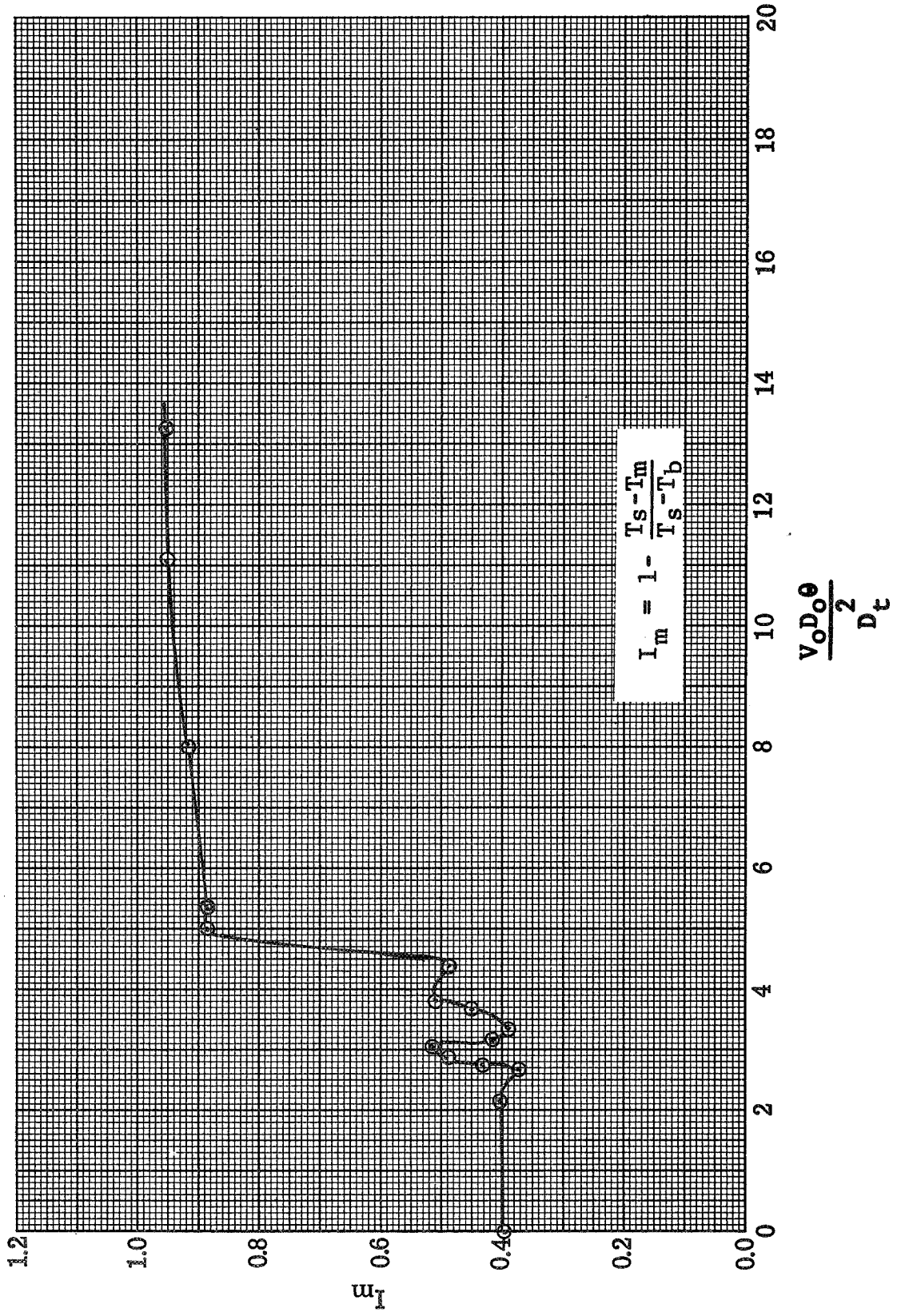

Figure 56 Transient Energy Integral: Run 14

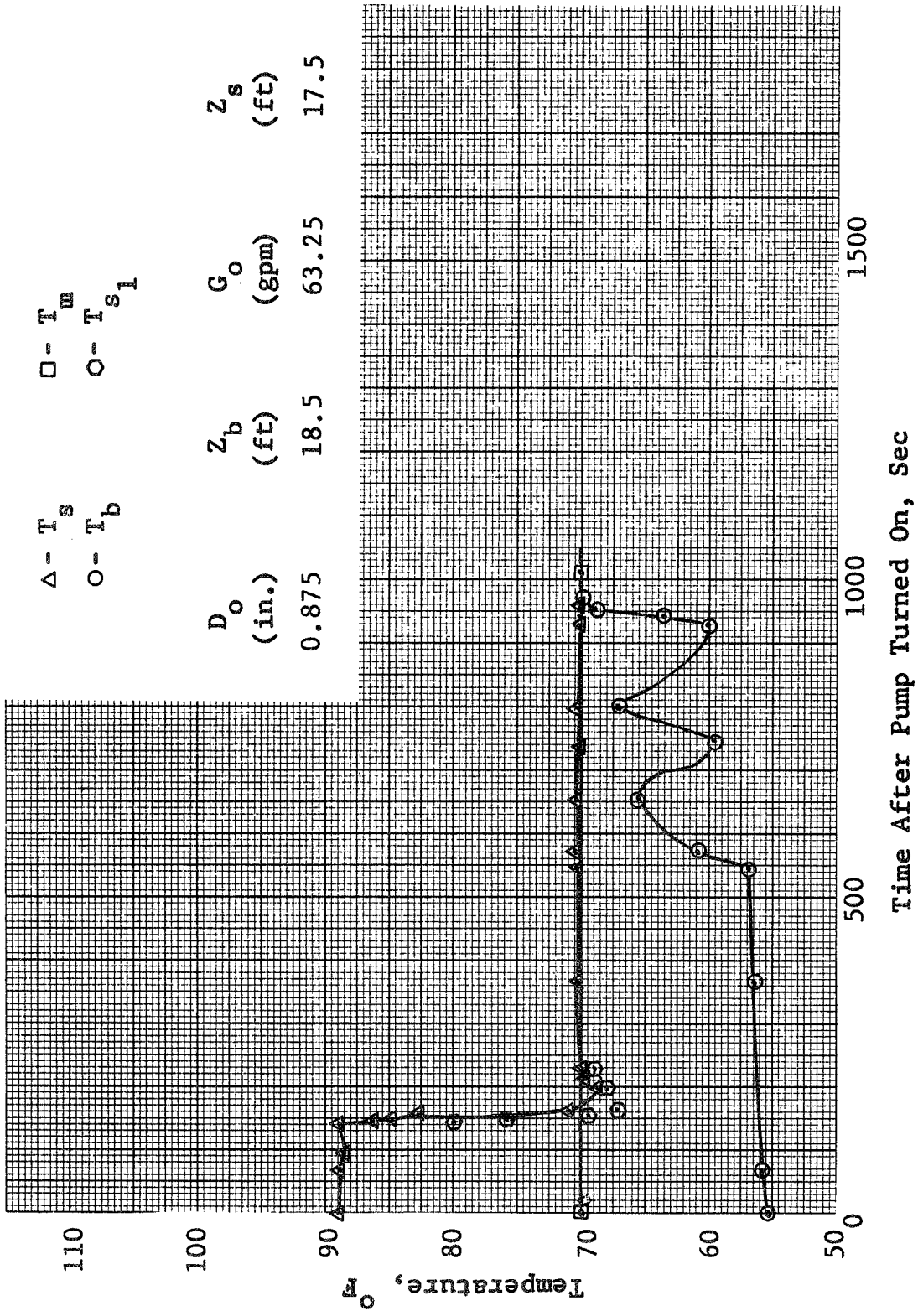

Figure 57 Transient Temperature Destratification: Run 15

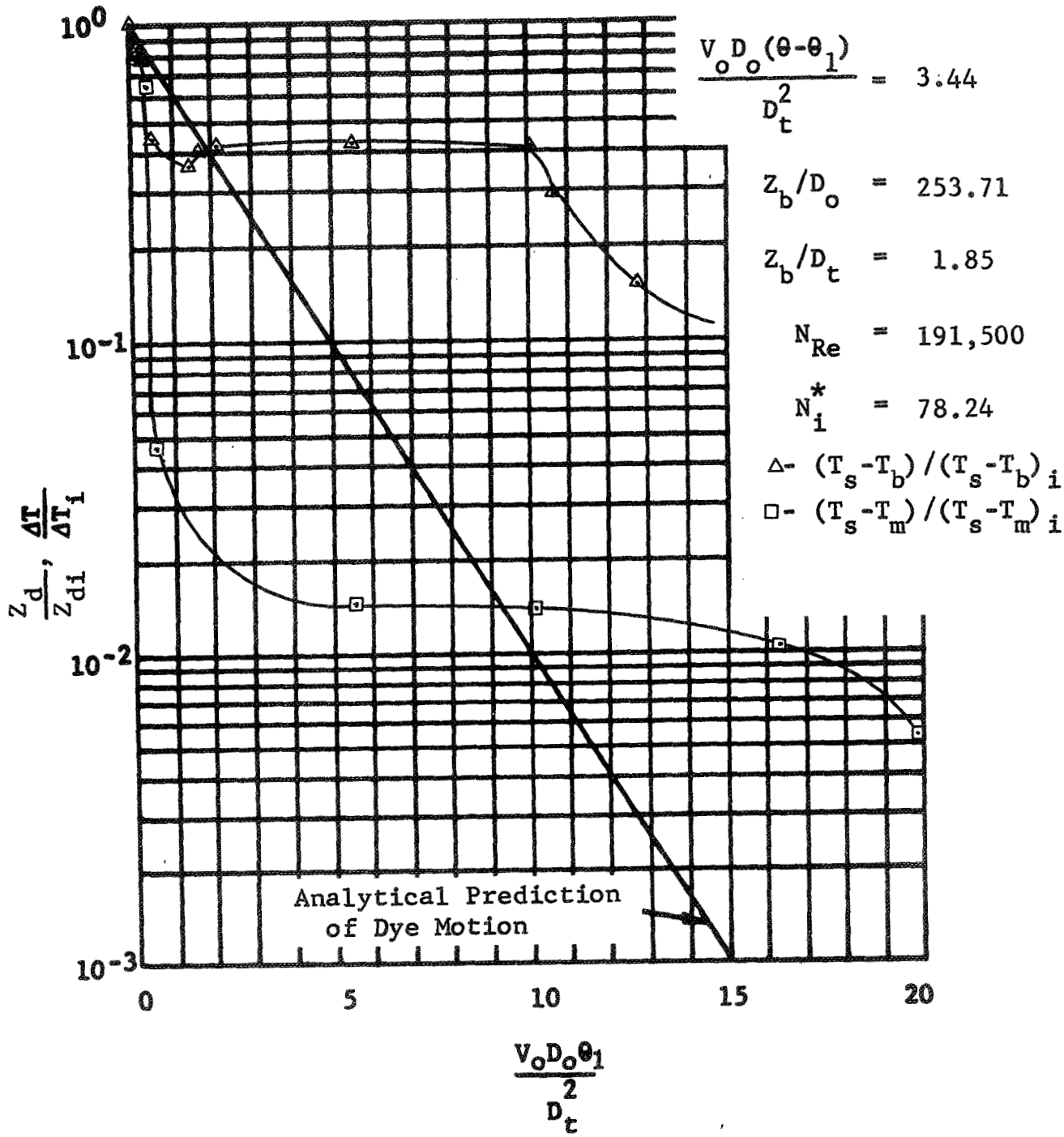

Figure 58 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 15

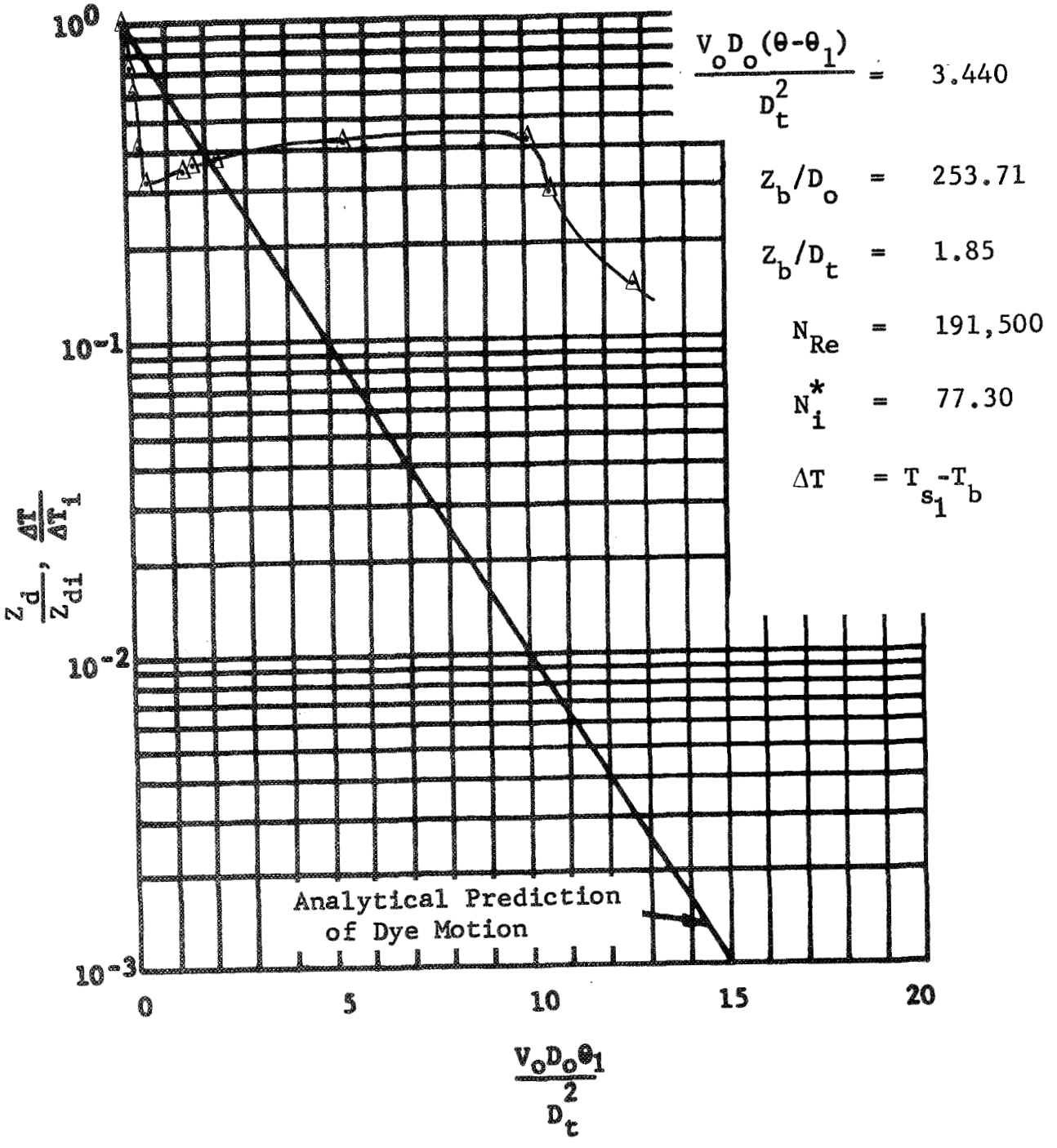

Figure 59 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 15

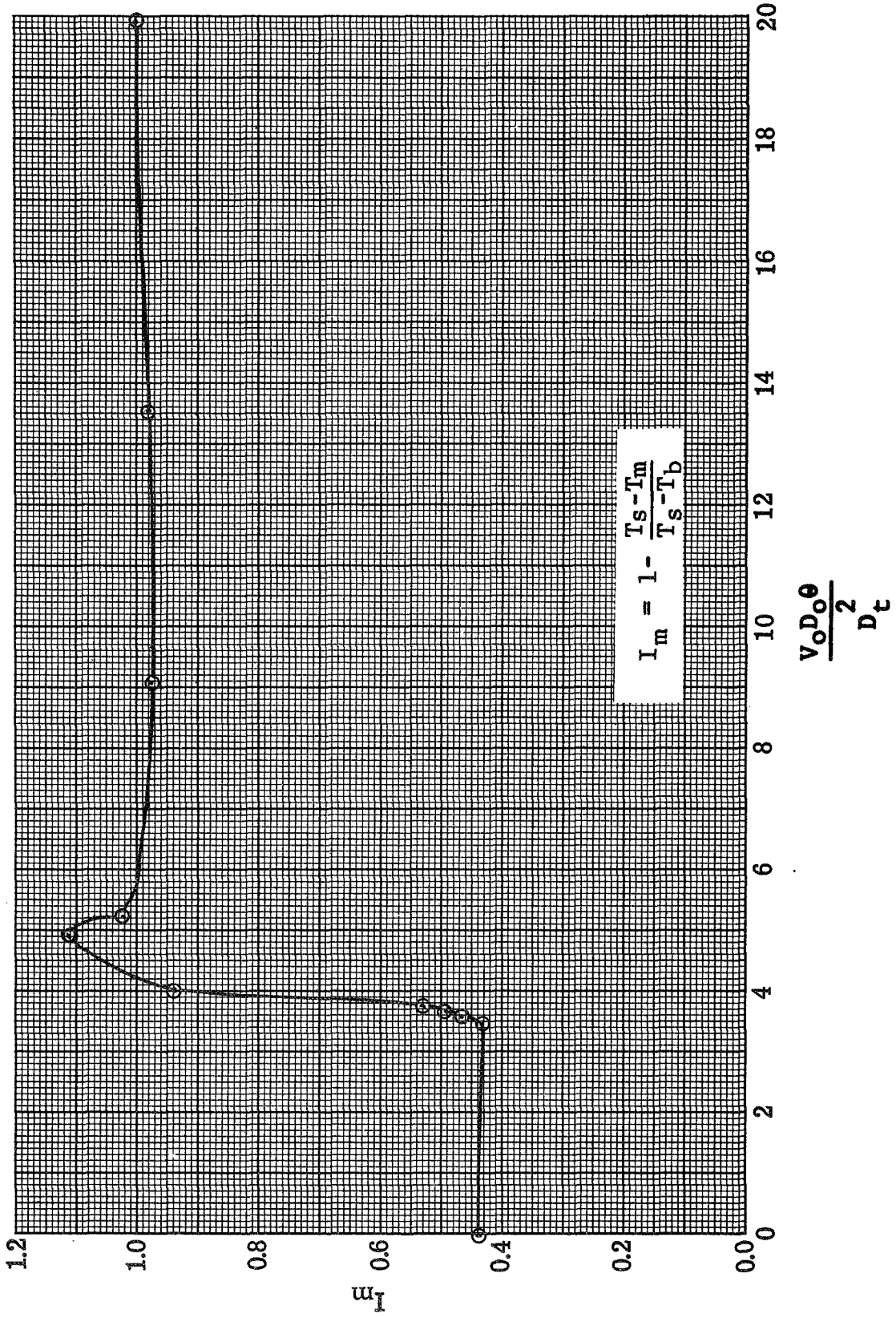

Figure 60 Transient Energy Integral: Run 15

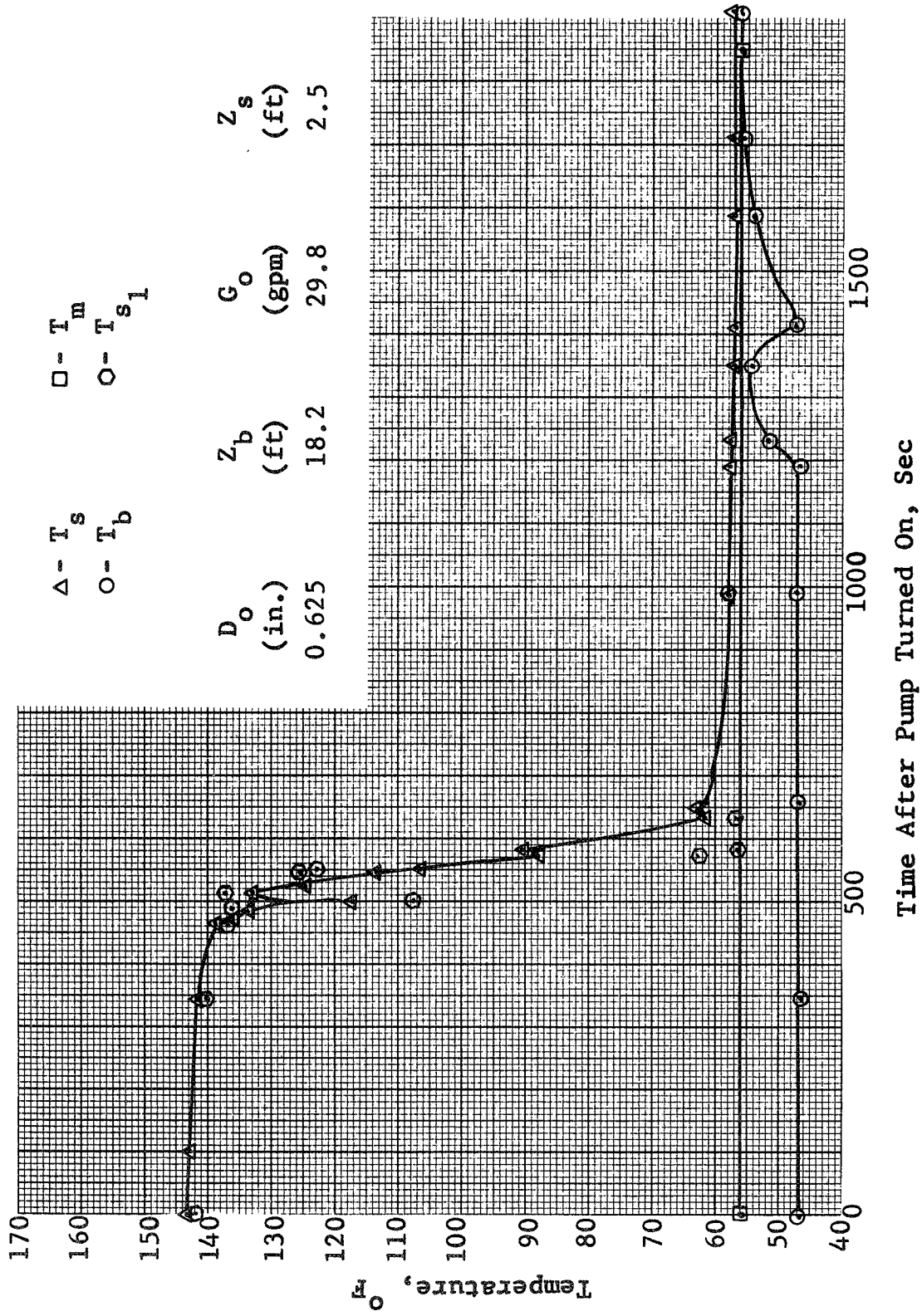

Figure 61 Transient Temperature Destratification Run 16

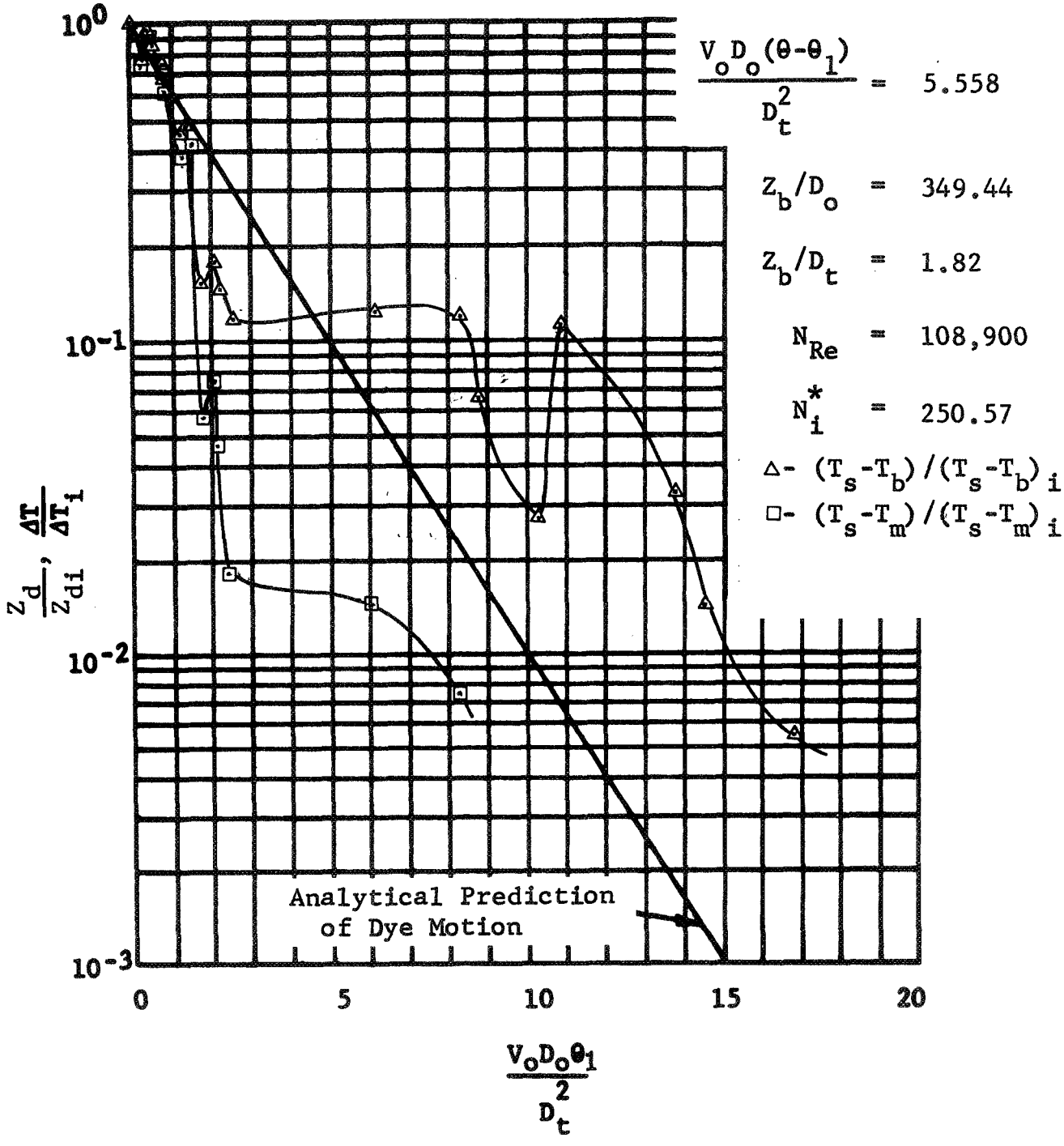

Figure 62 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 16

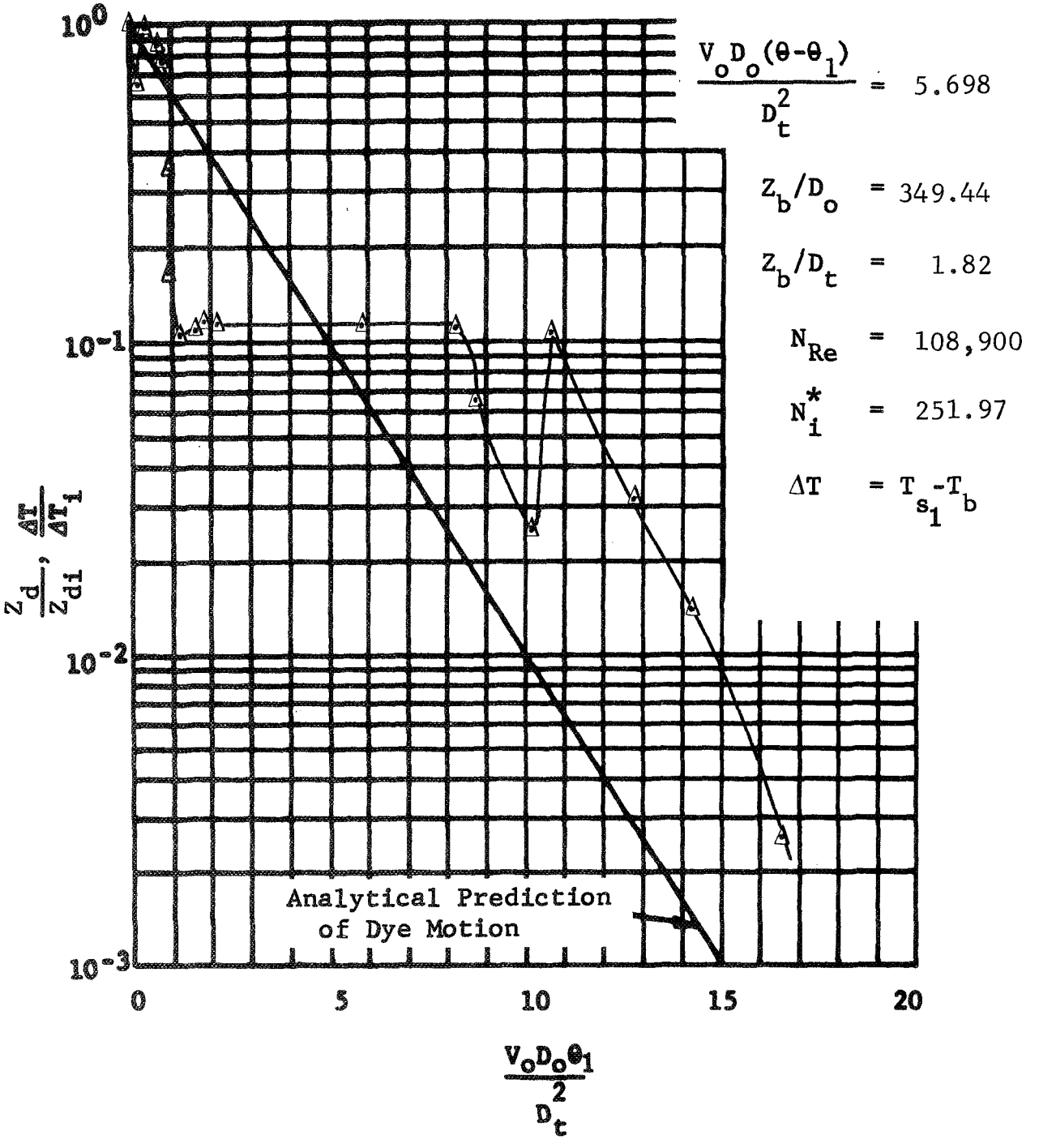

Figure 63 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 16

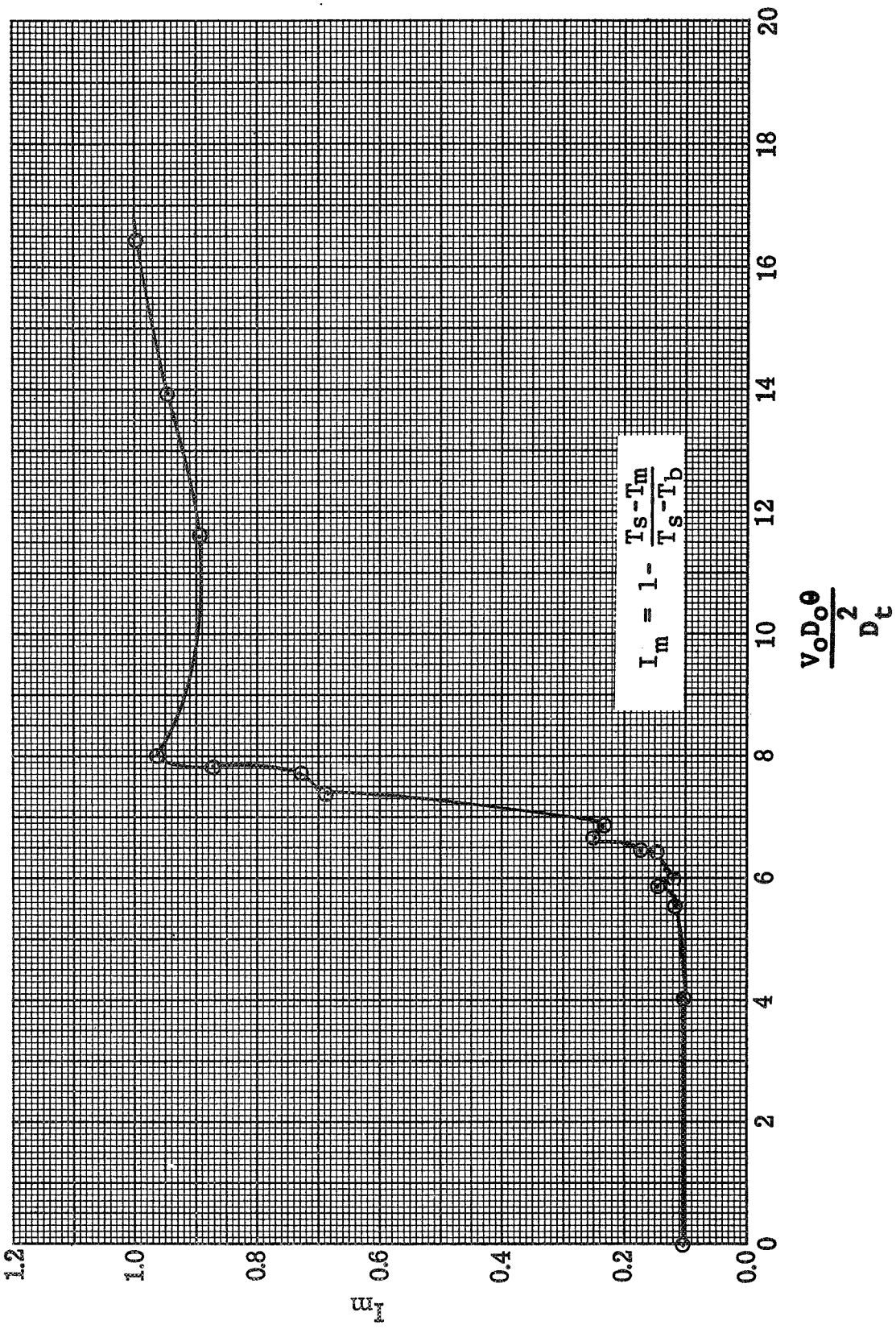

Figure 64 Transient Energy Integral: Run 16

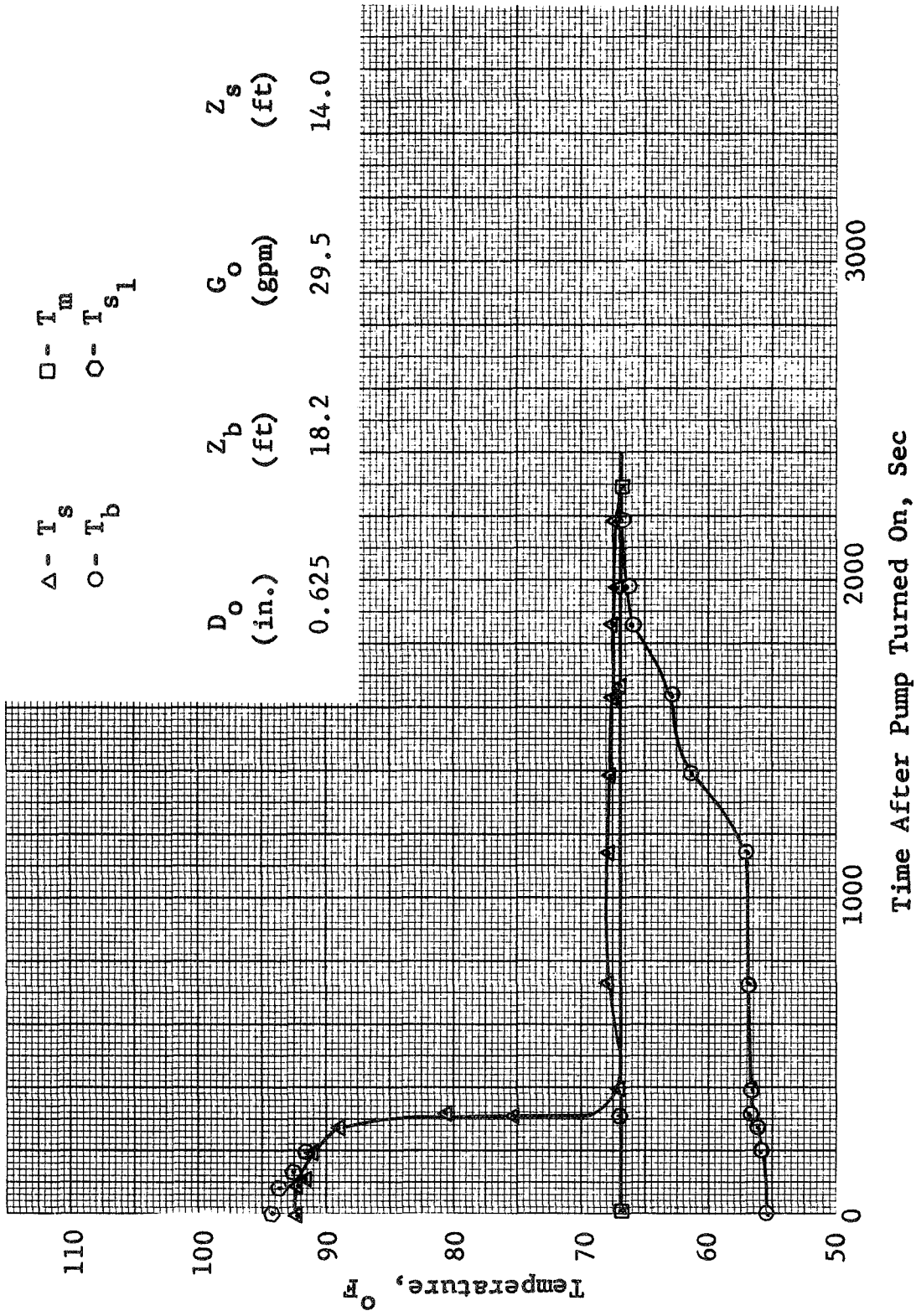

Figure 65 Transient Temperature Destratification: Run 17

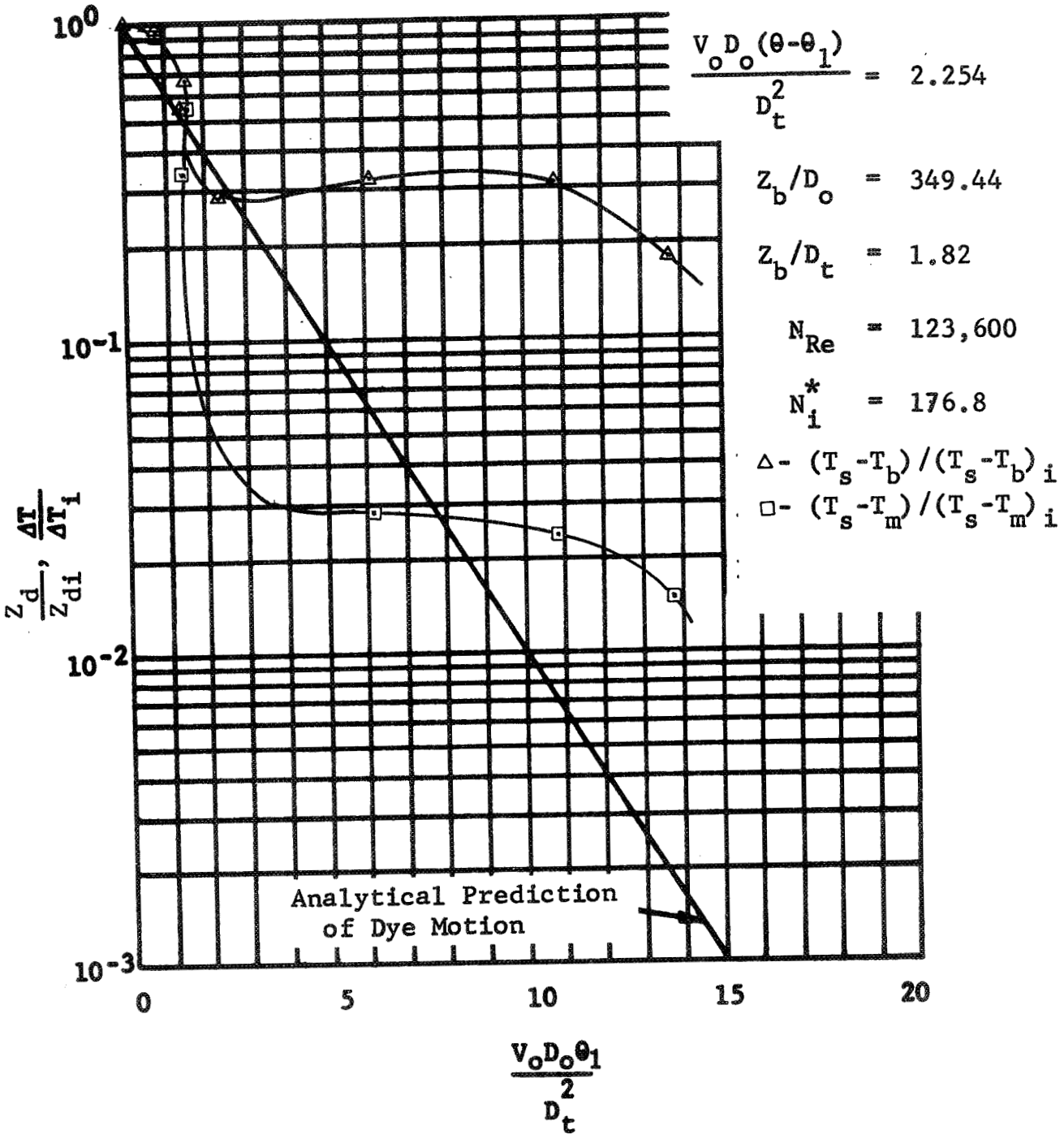

Figure 66 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 17

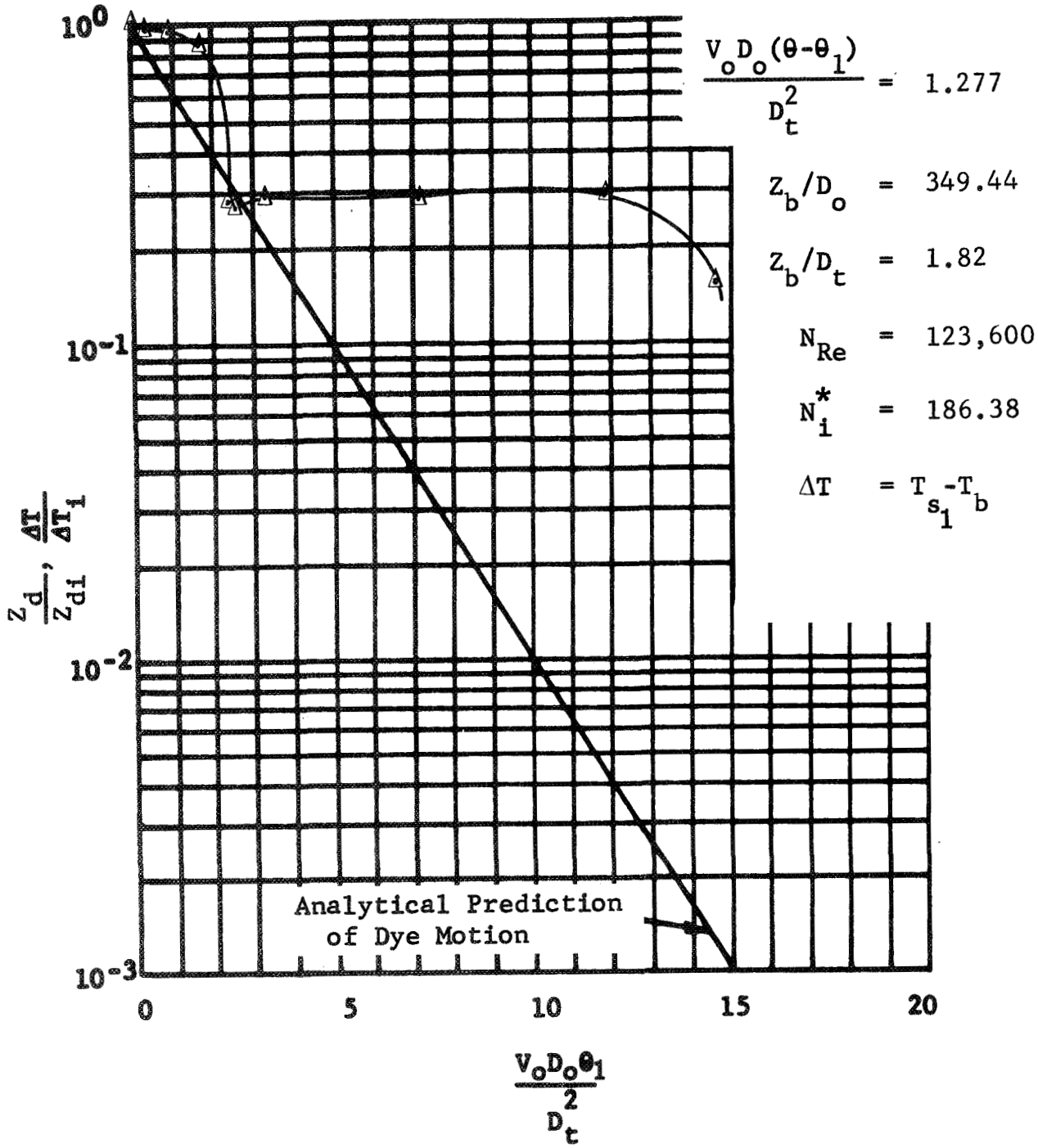

Figure 67 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 17

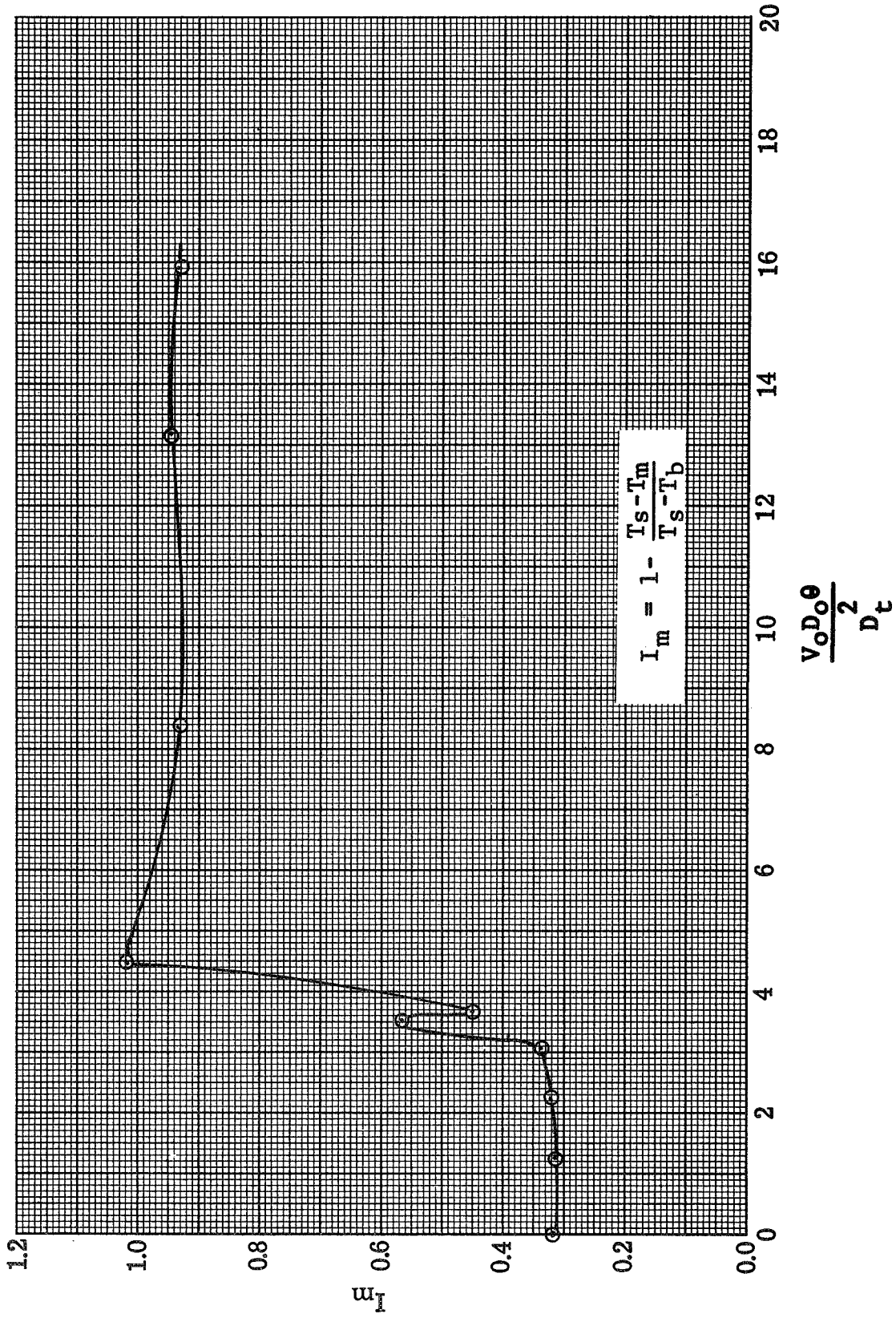

Figure 68 Transient Energy Integral: Run 17

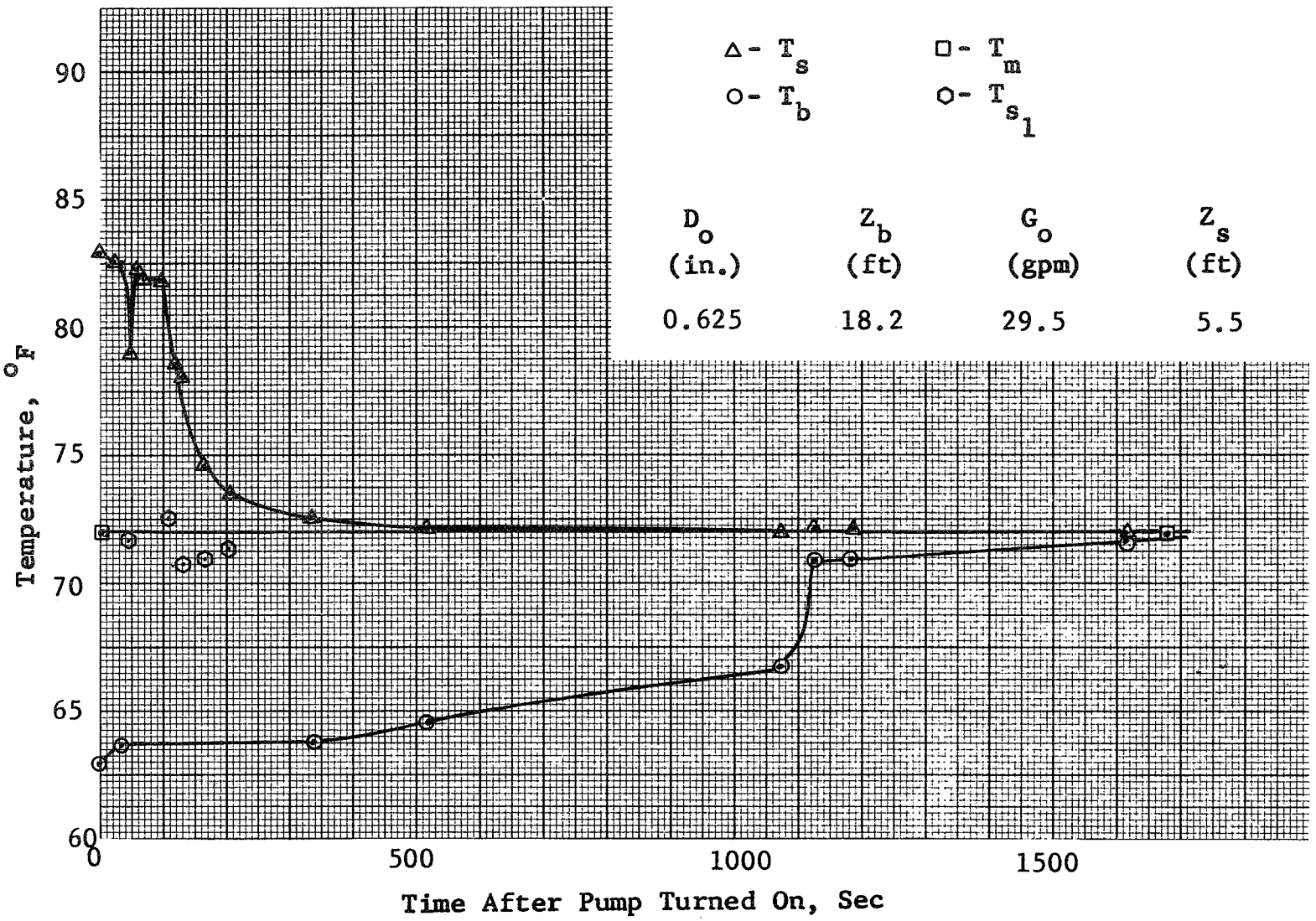

Figure 69 Transient Temperature Destratification : Run 18

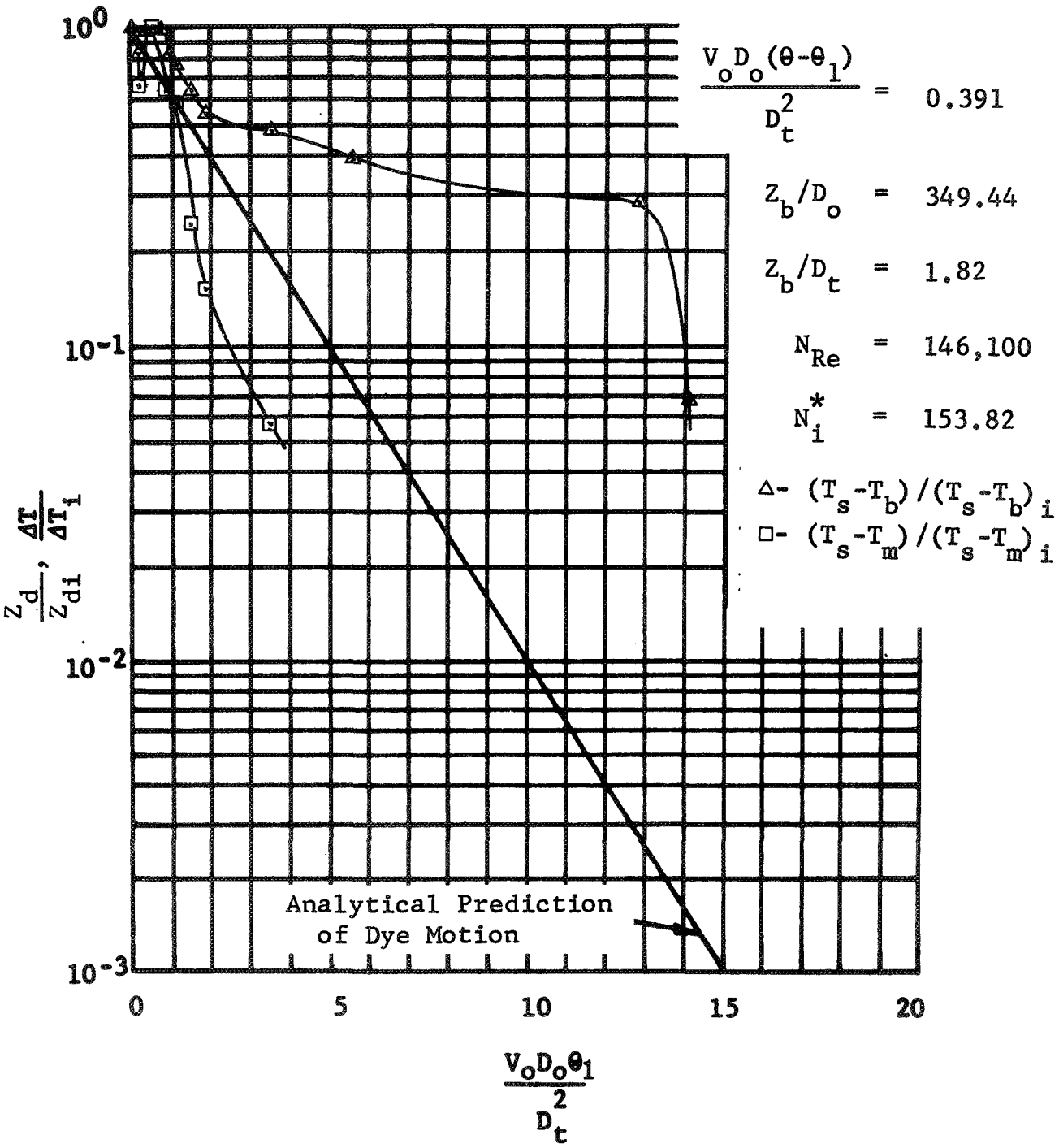

Figure 70 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop; Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 18

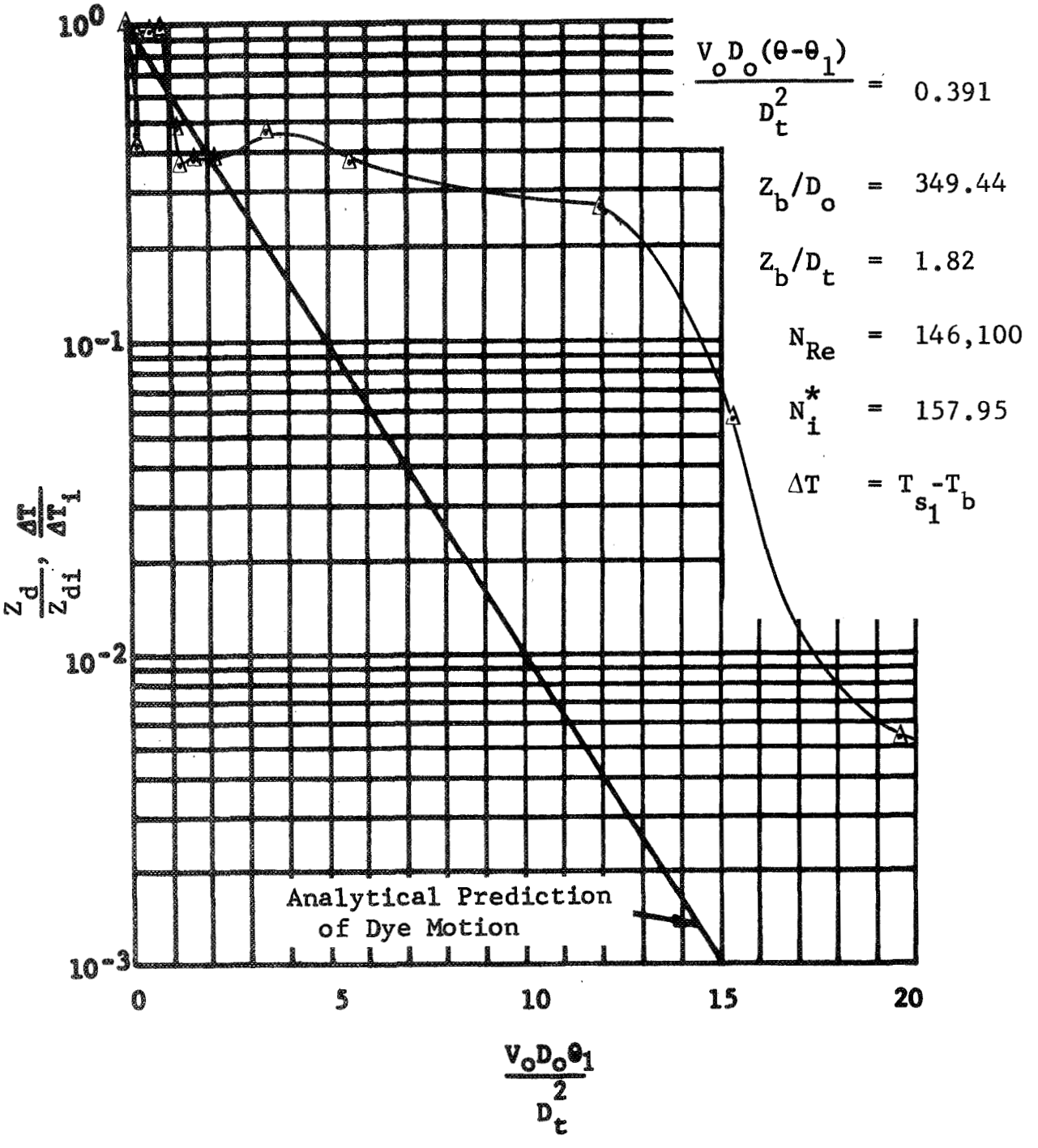

Figure 71 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 18

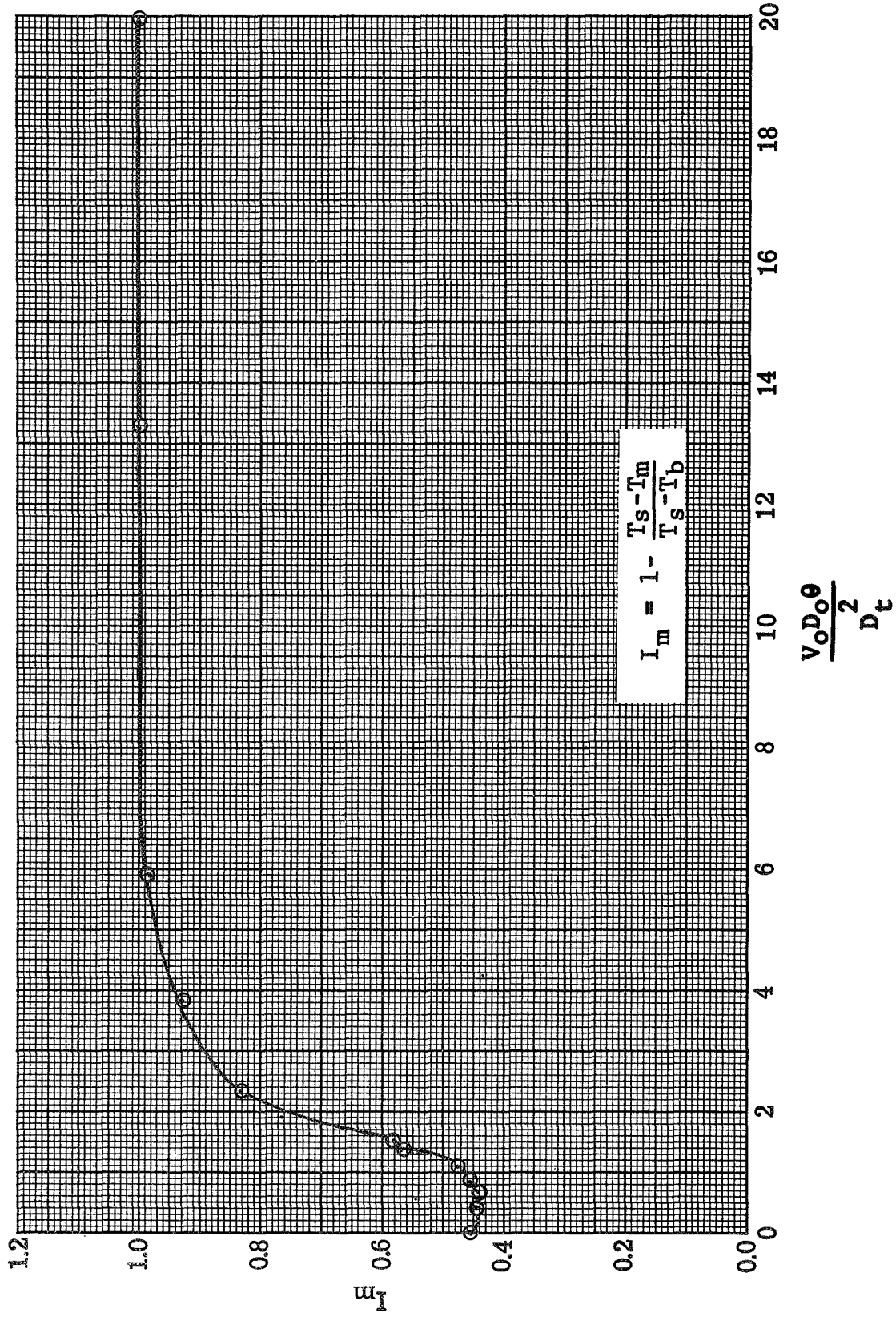

Figure 72 Transient Energy Integral: Run 18

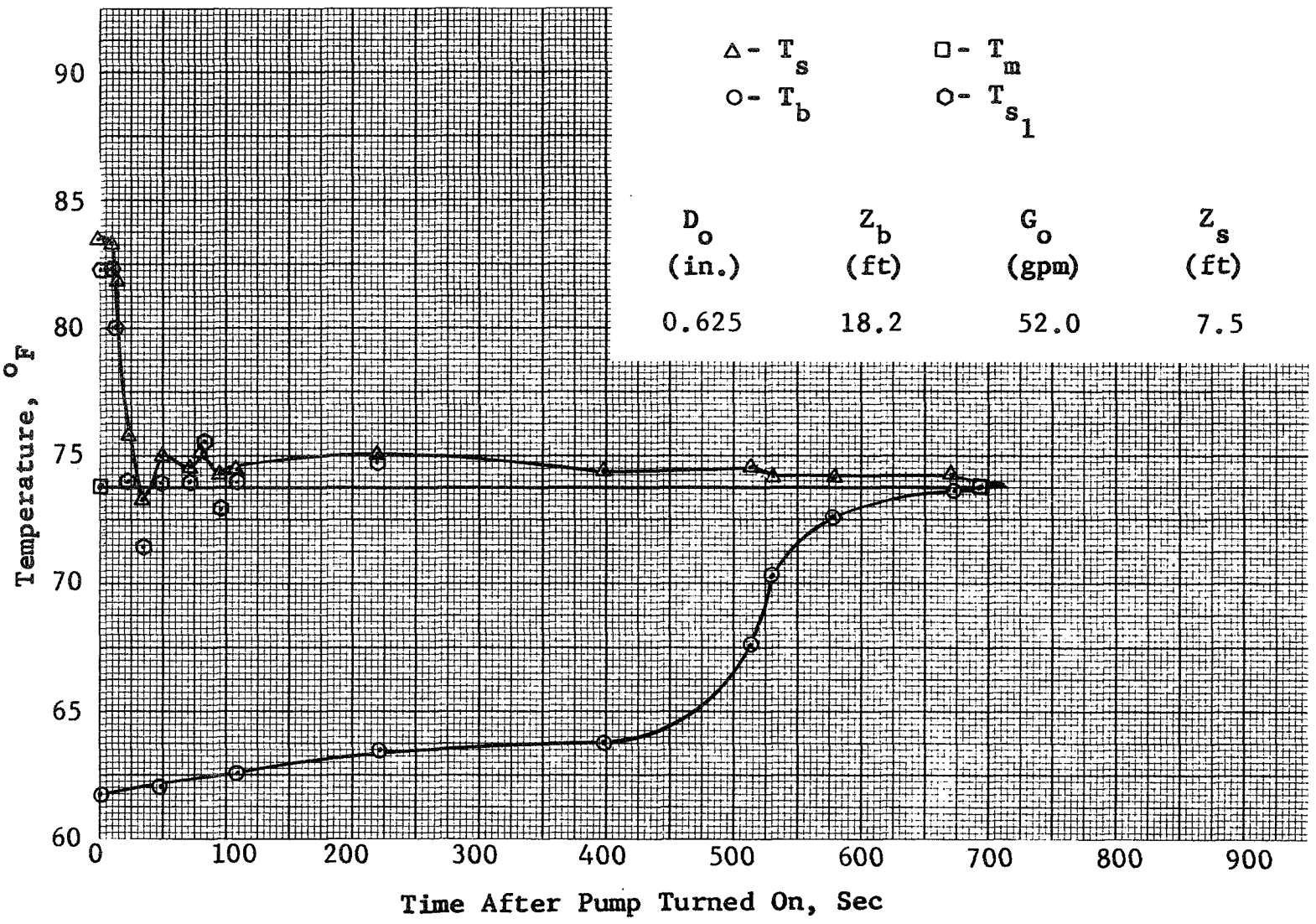

Figure 73 Transient Temperature Destratification: Run 19

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Fort Worth Division

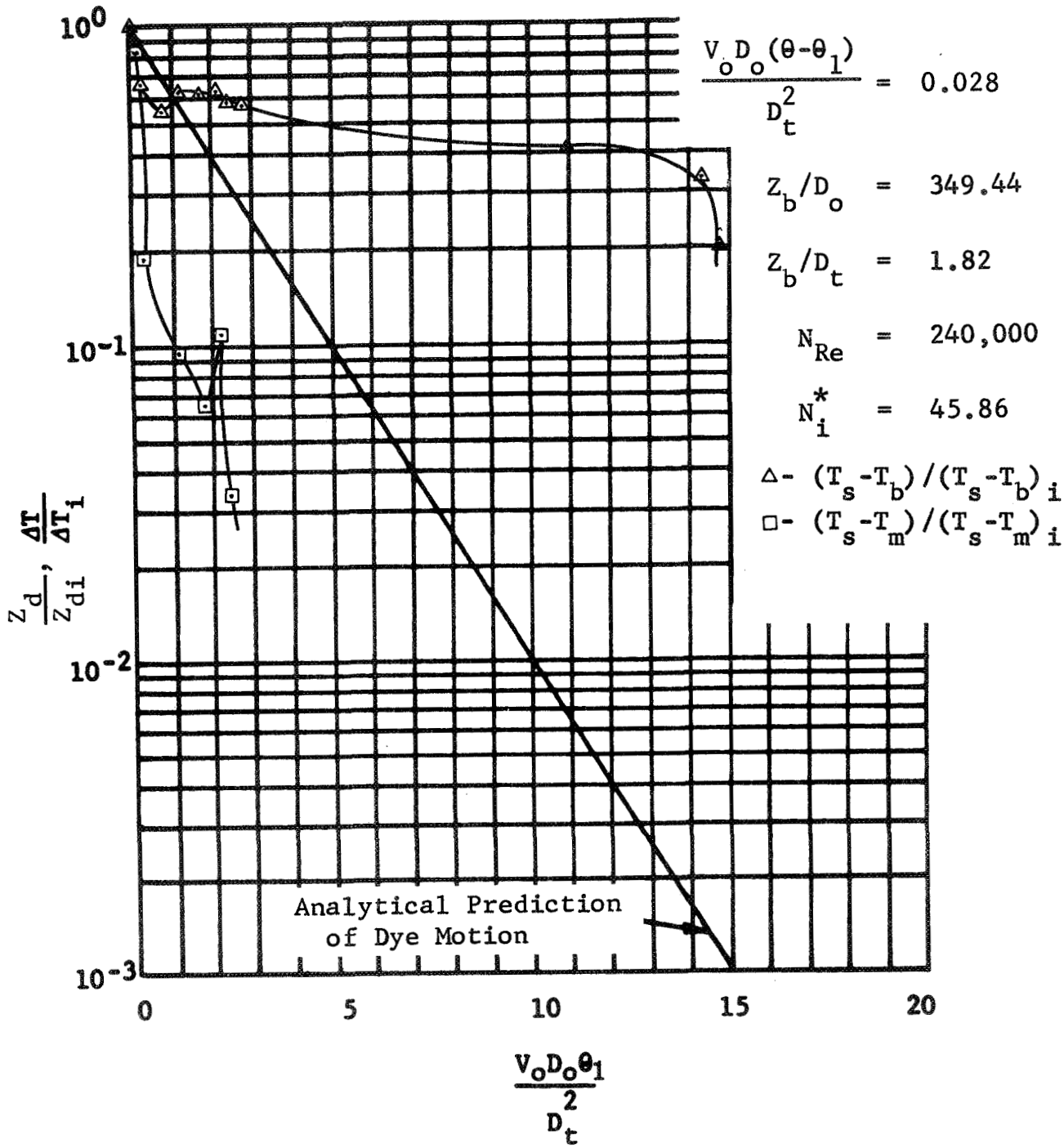

Figure 74 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 19

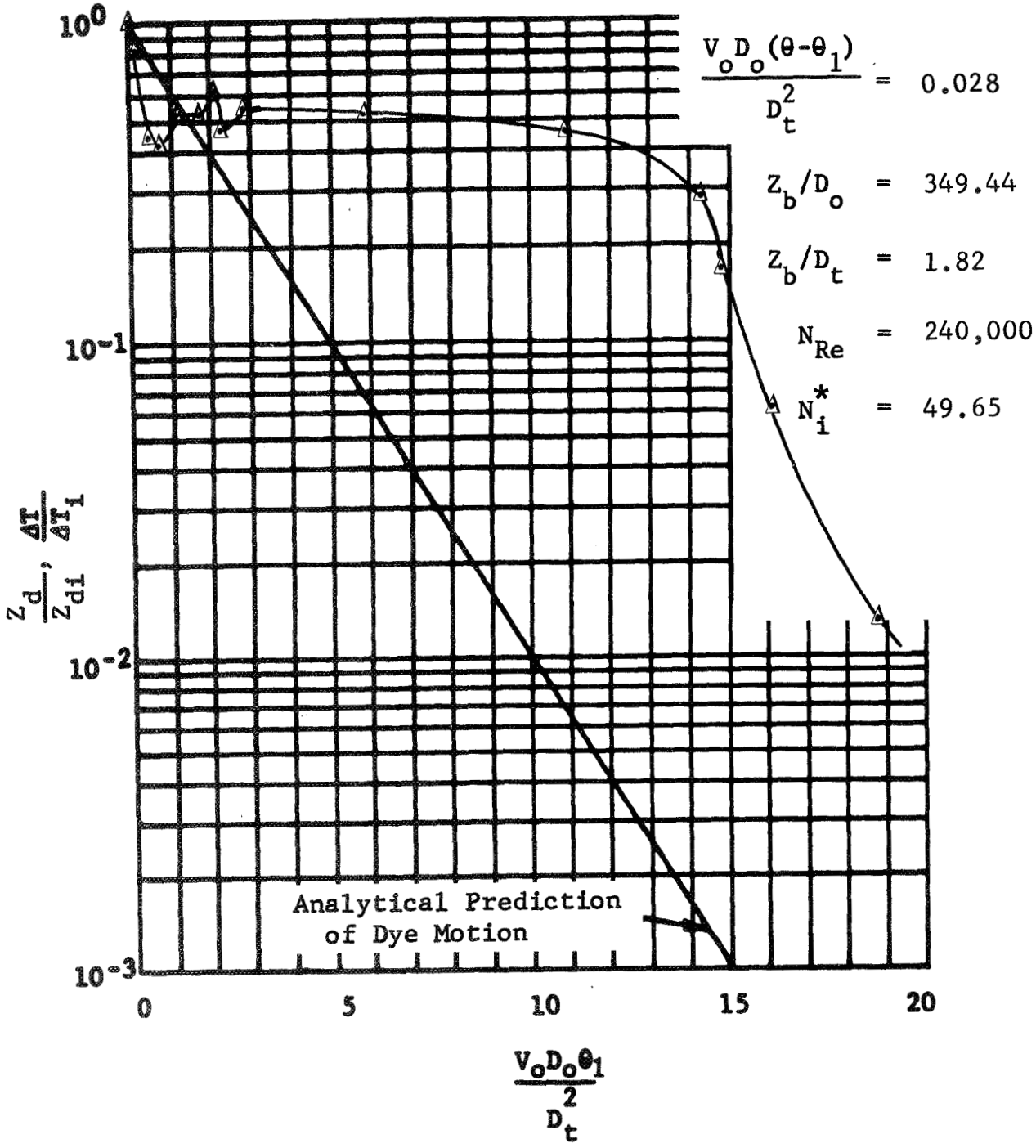

Figure 75 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 19

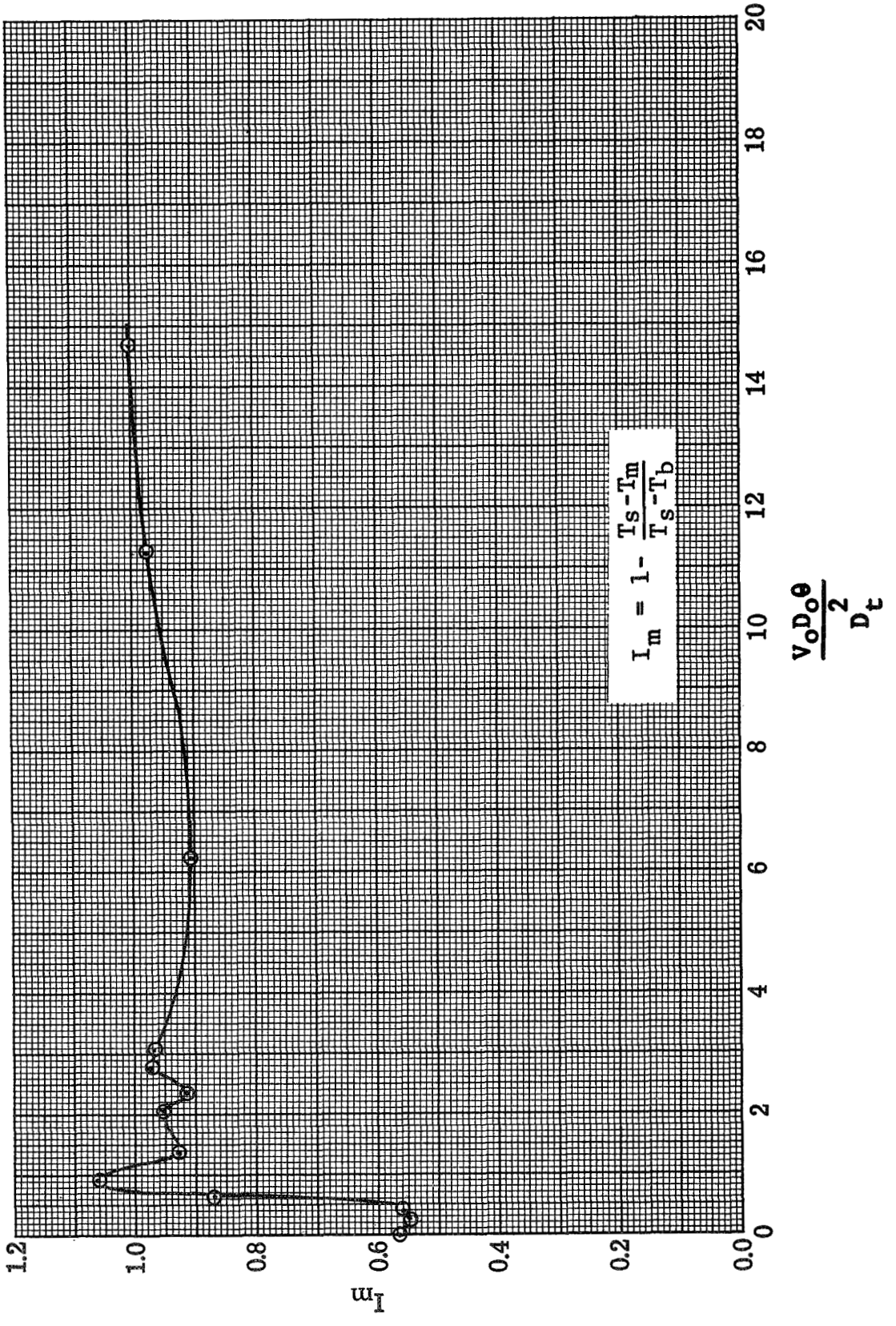

Figure 76 Transient Energy Integral: Run 19

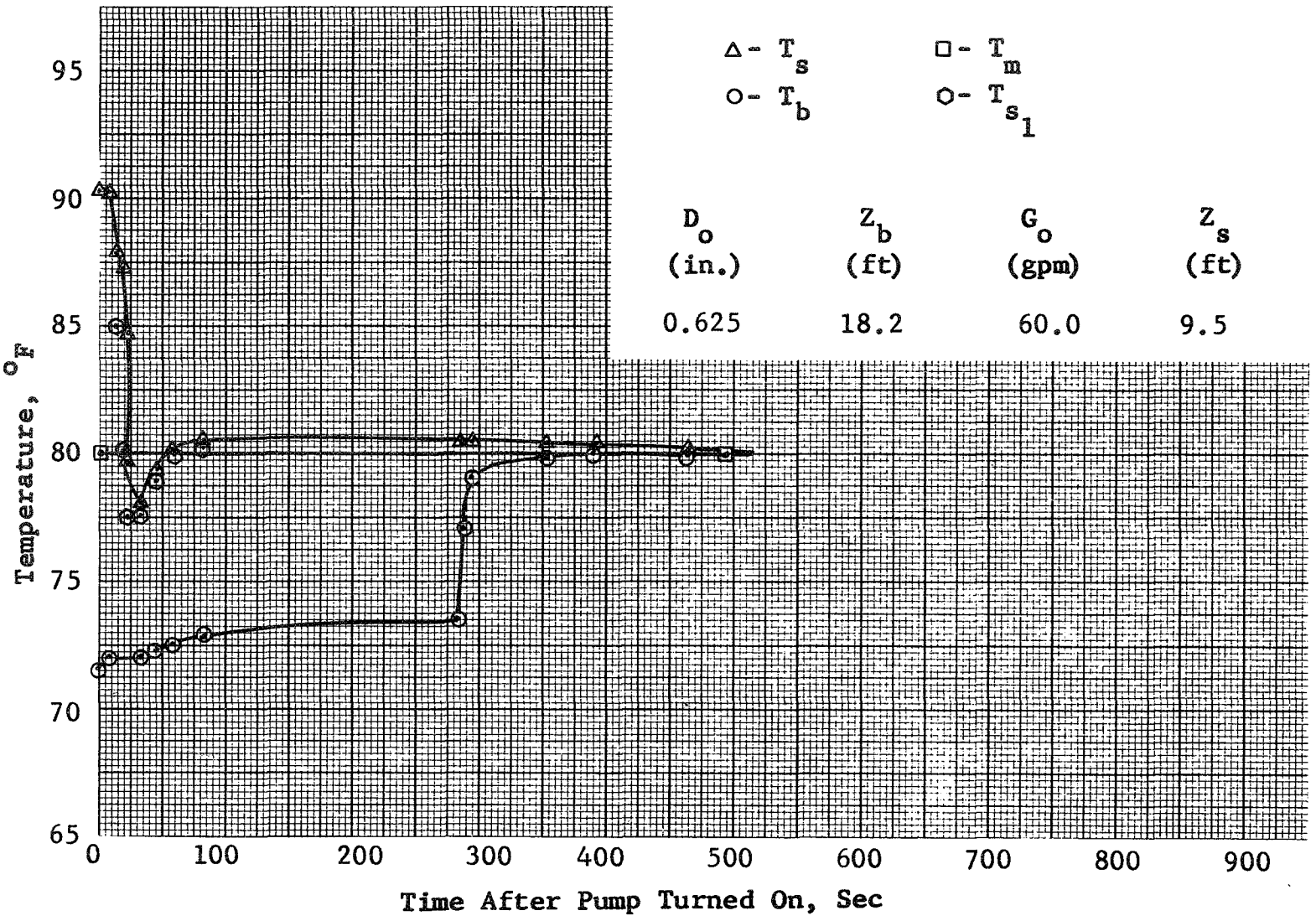

Figure 77 Transient Temperature Destratification: Run 20

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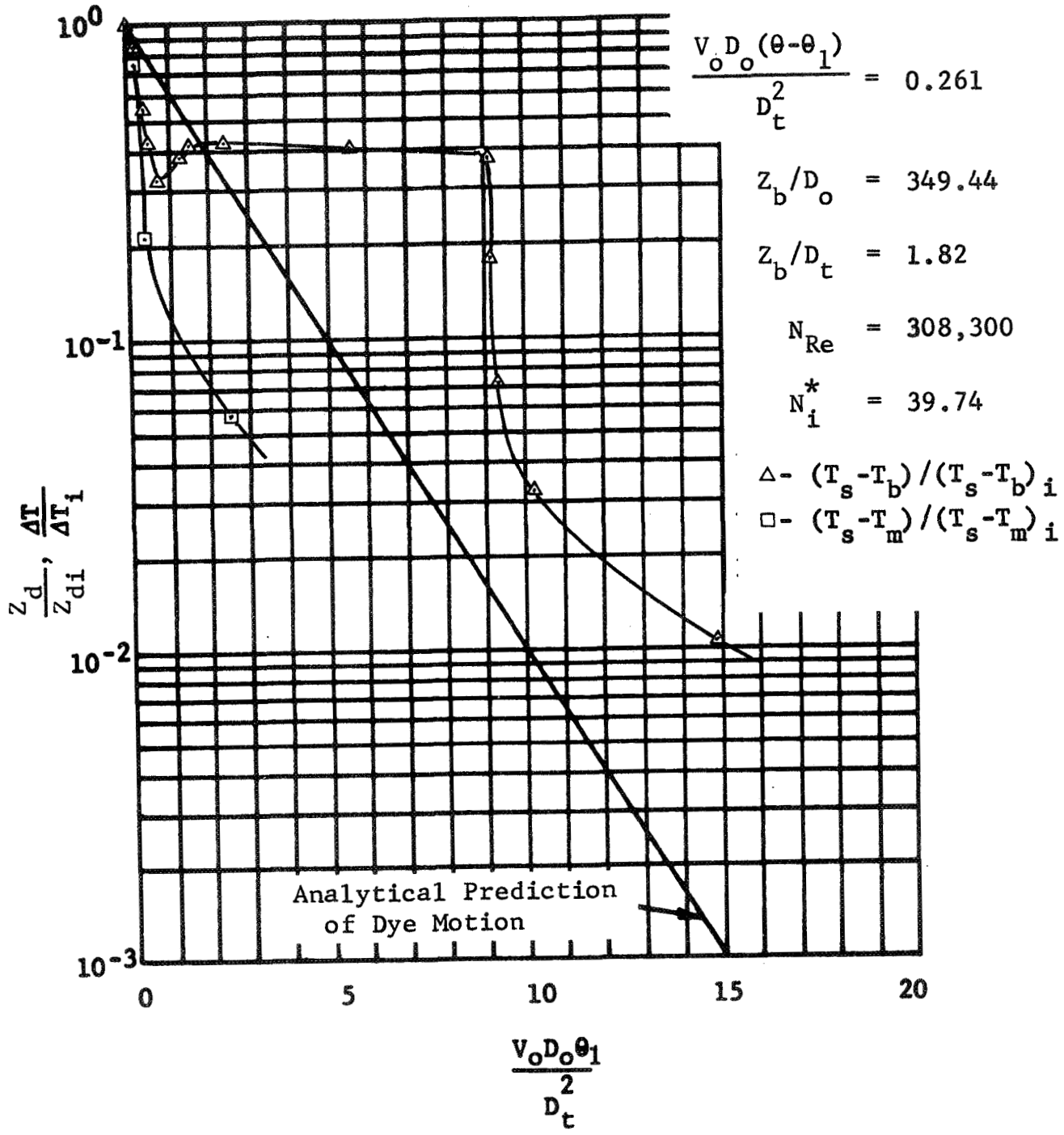

Figure 78 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 20

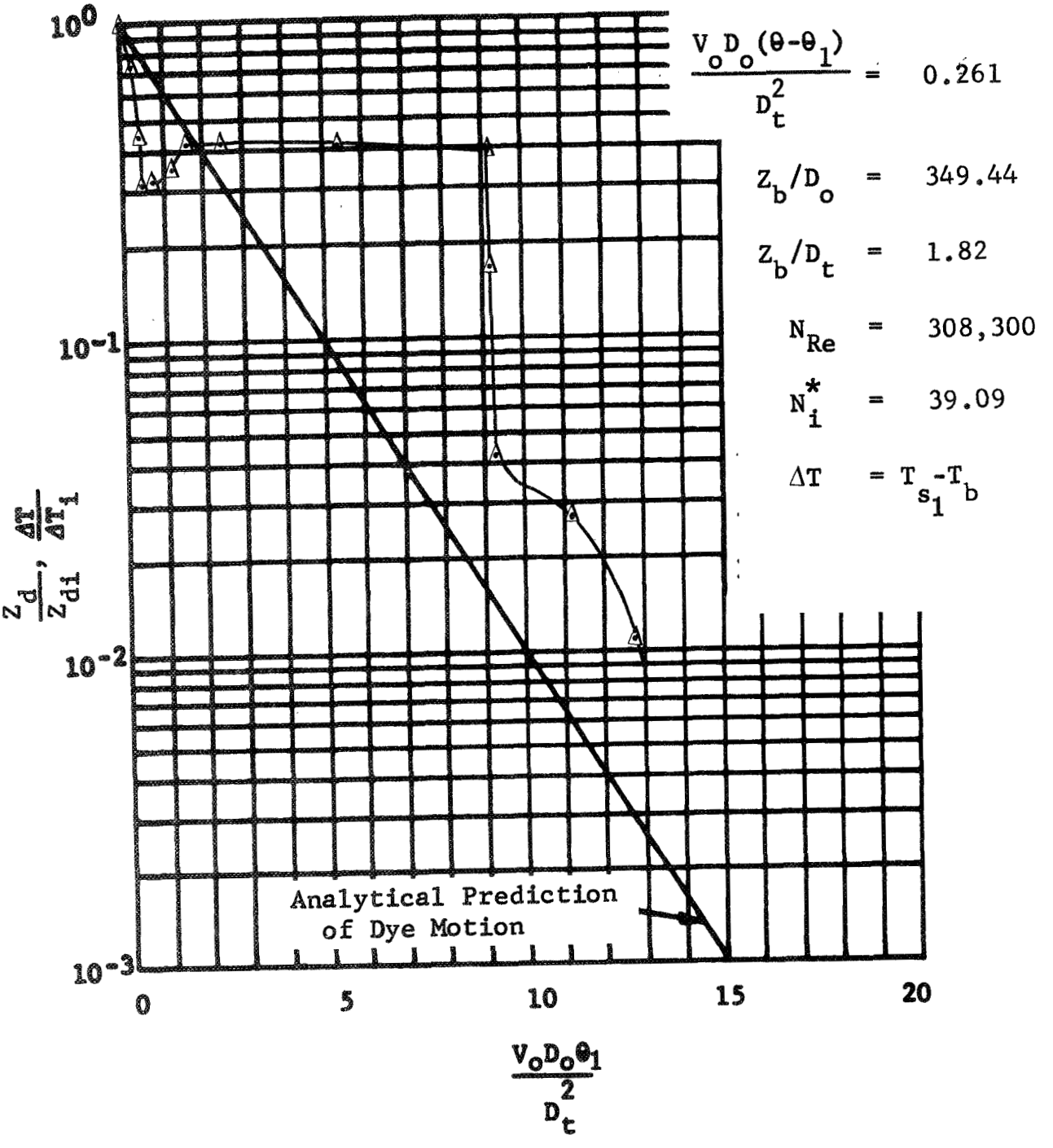

Figure 79 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 20

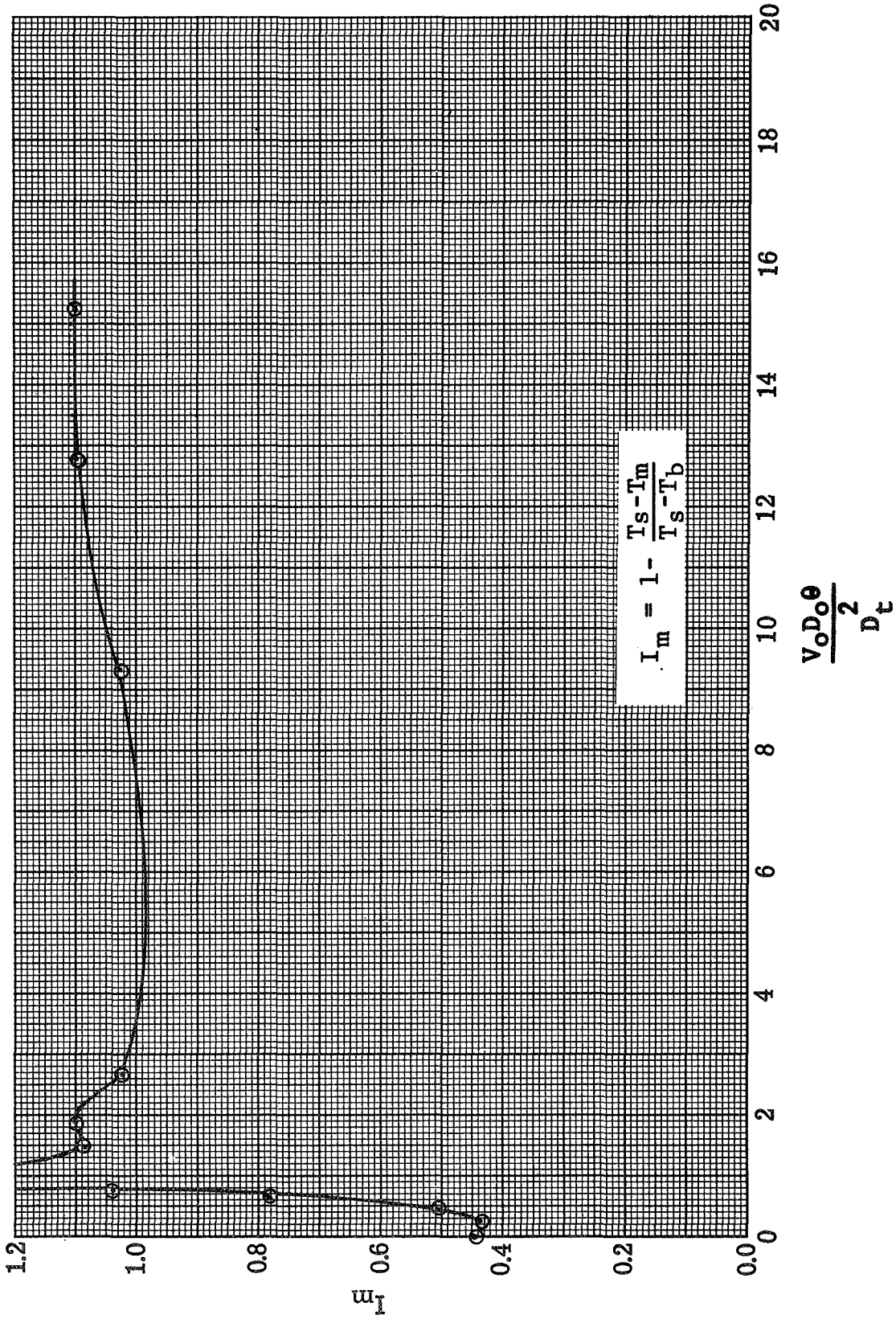

Figure 80 Transient Energy Integral: Run 20

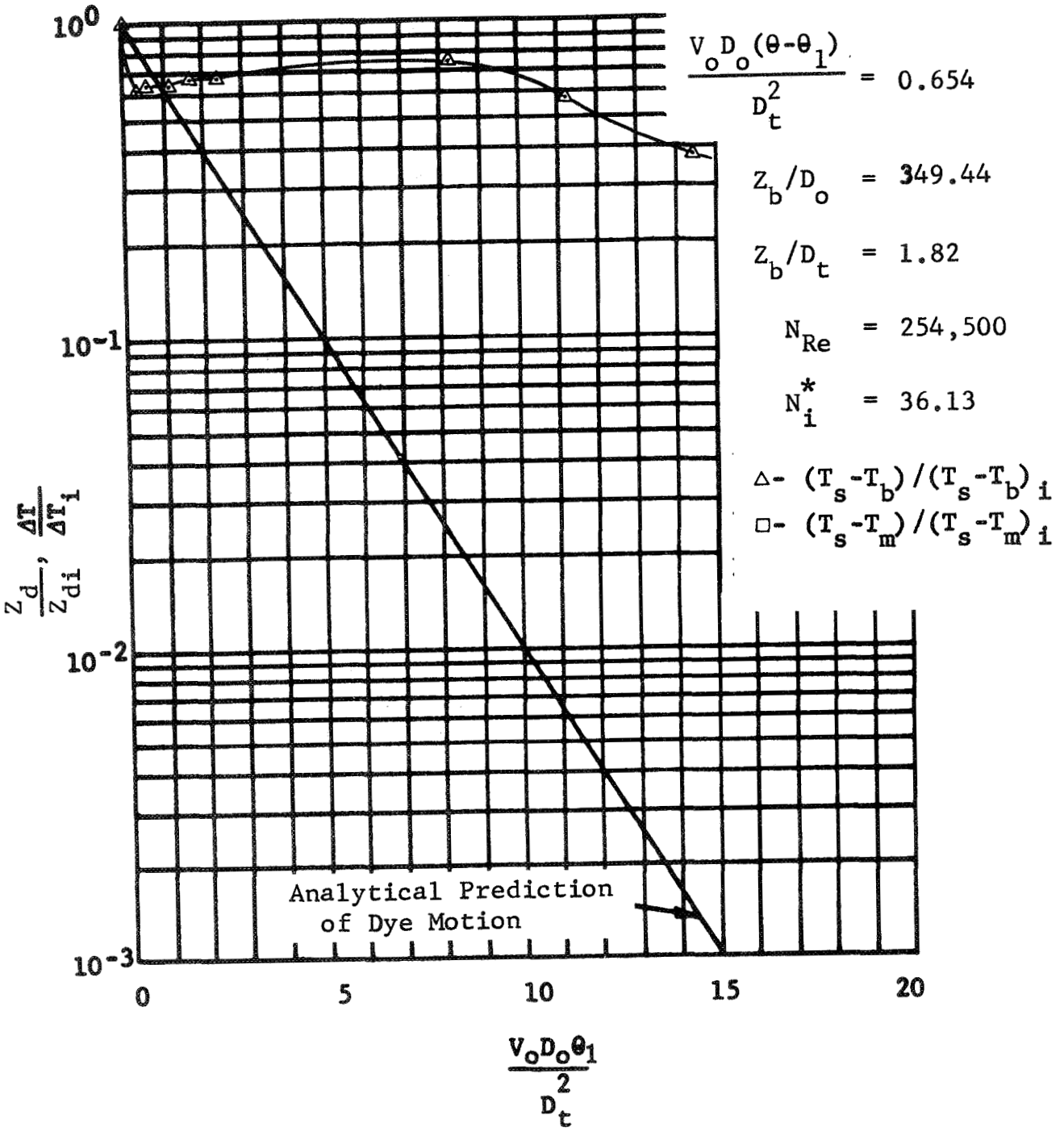

Figure 81 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 21

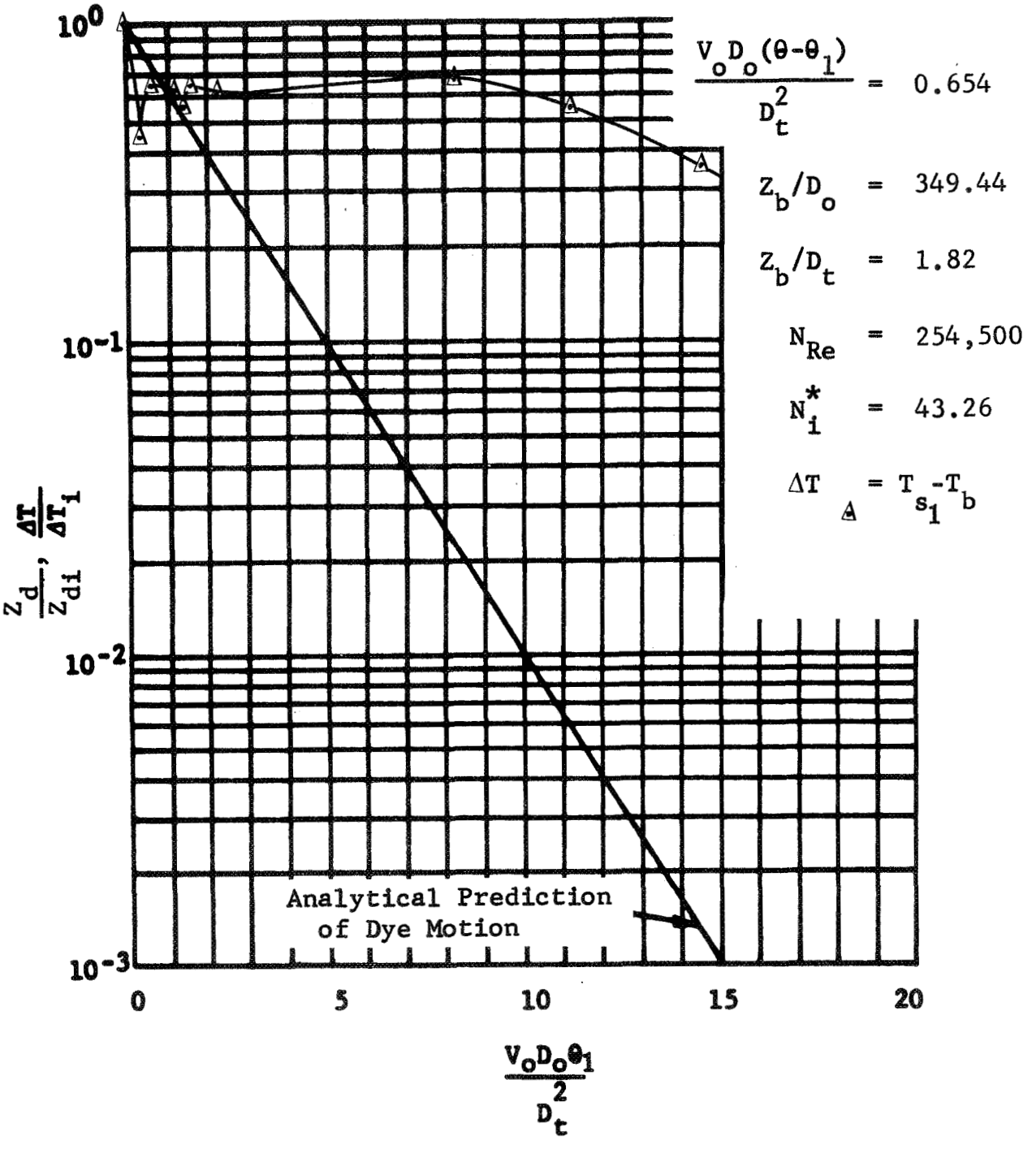

Figure 82 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 21

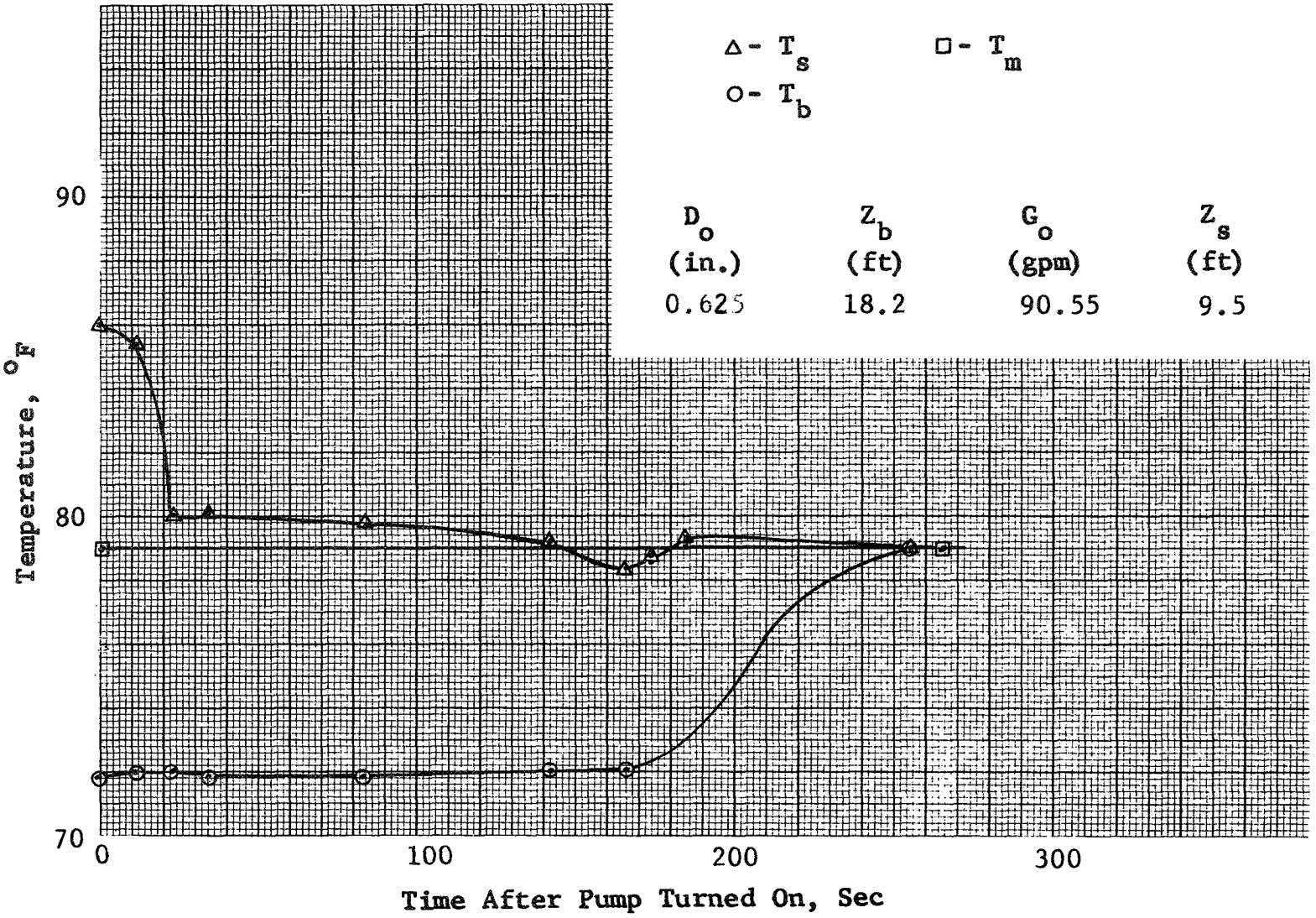

Figure 83 Transient Temperature Destratification: Run 22

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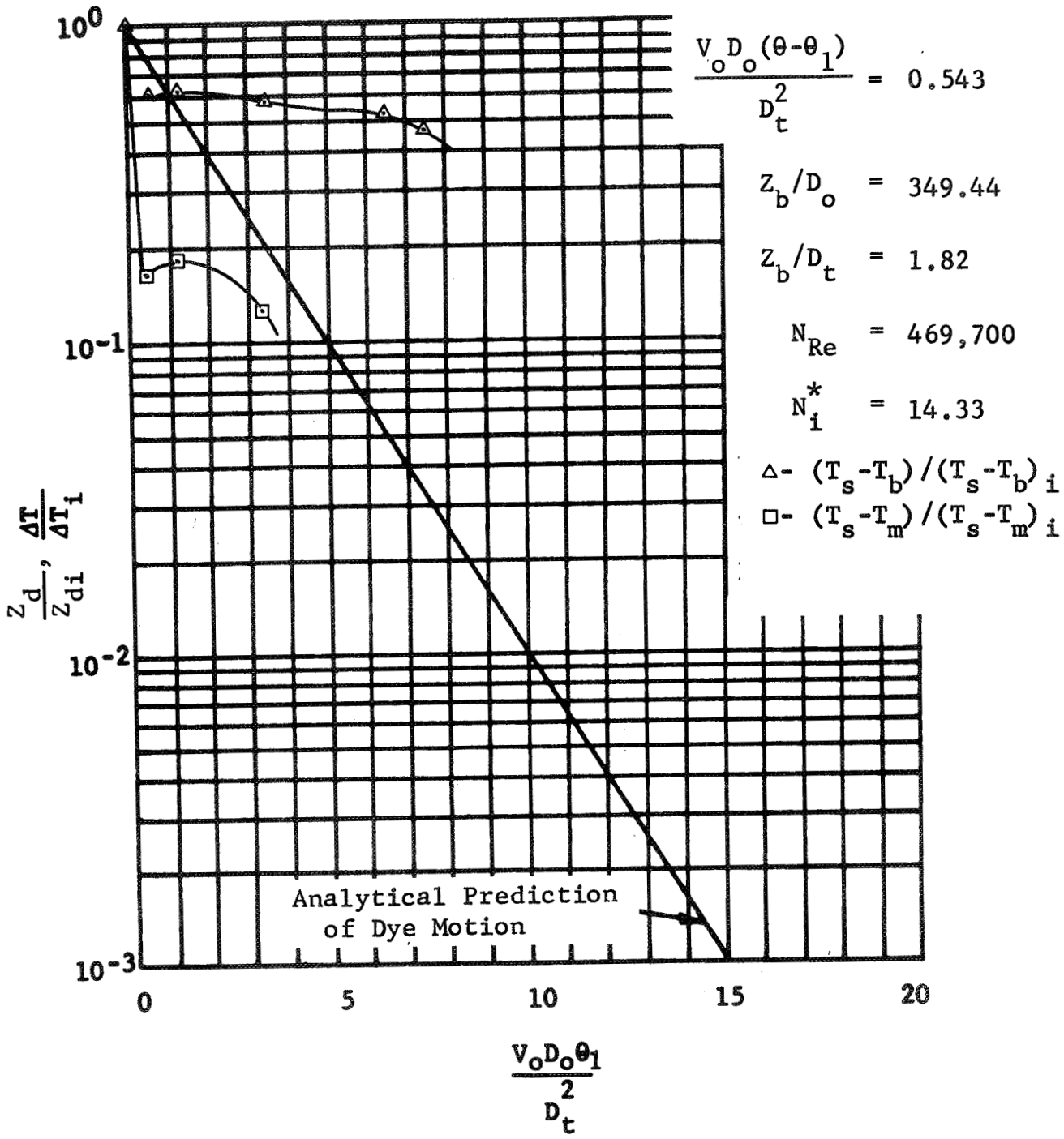

Figure 84 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 22

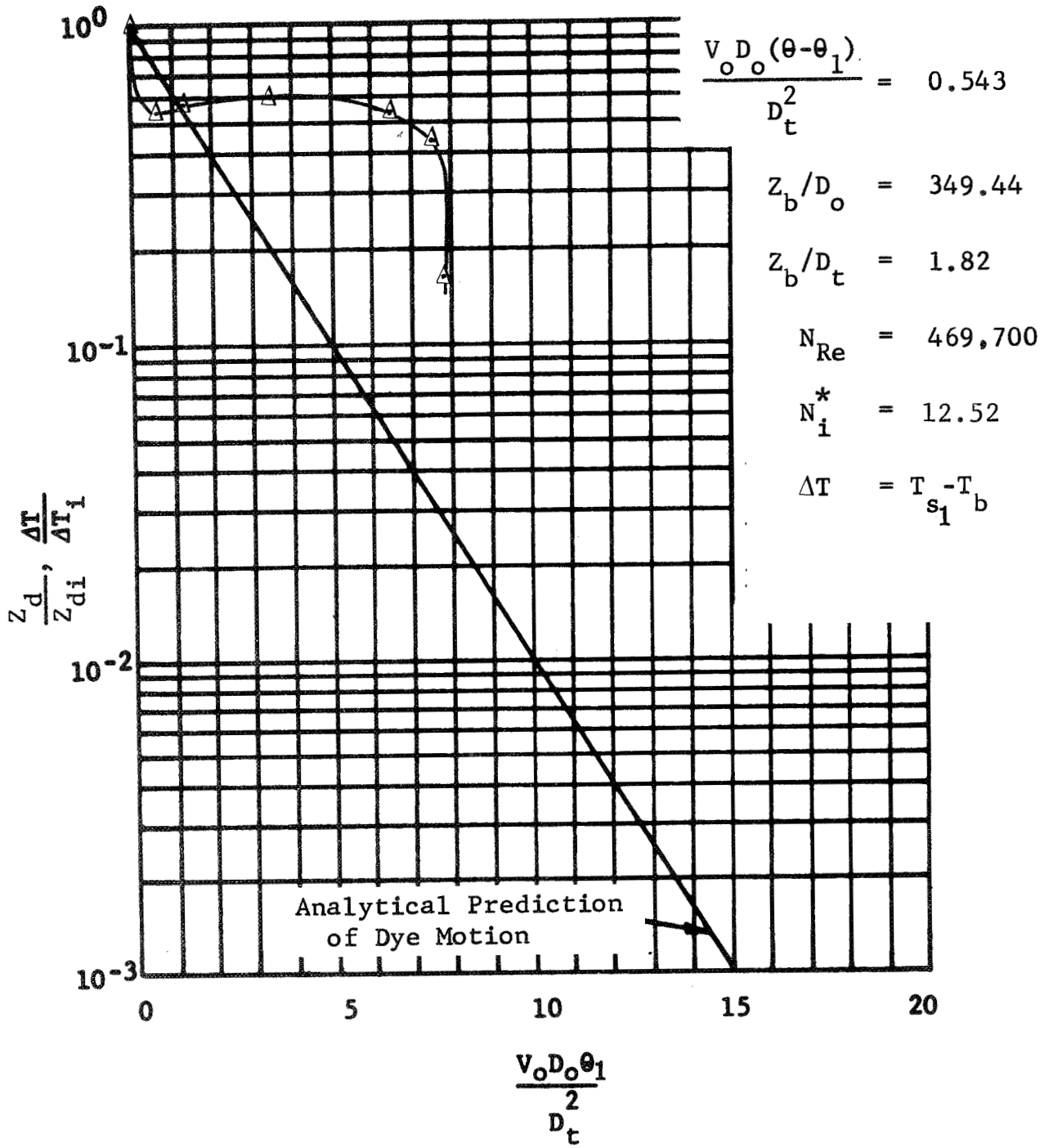

Figure 85 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 22

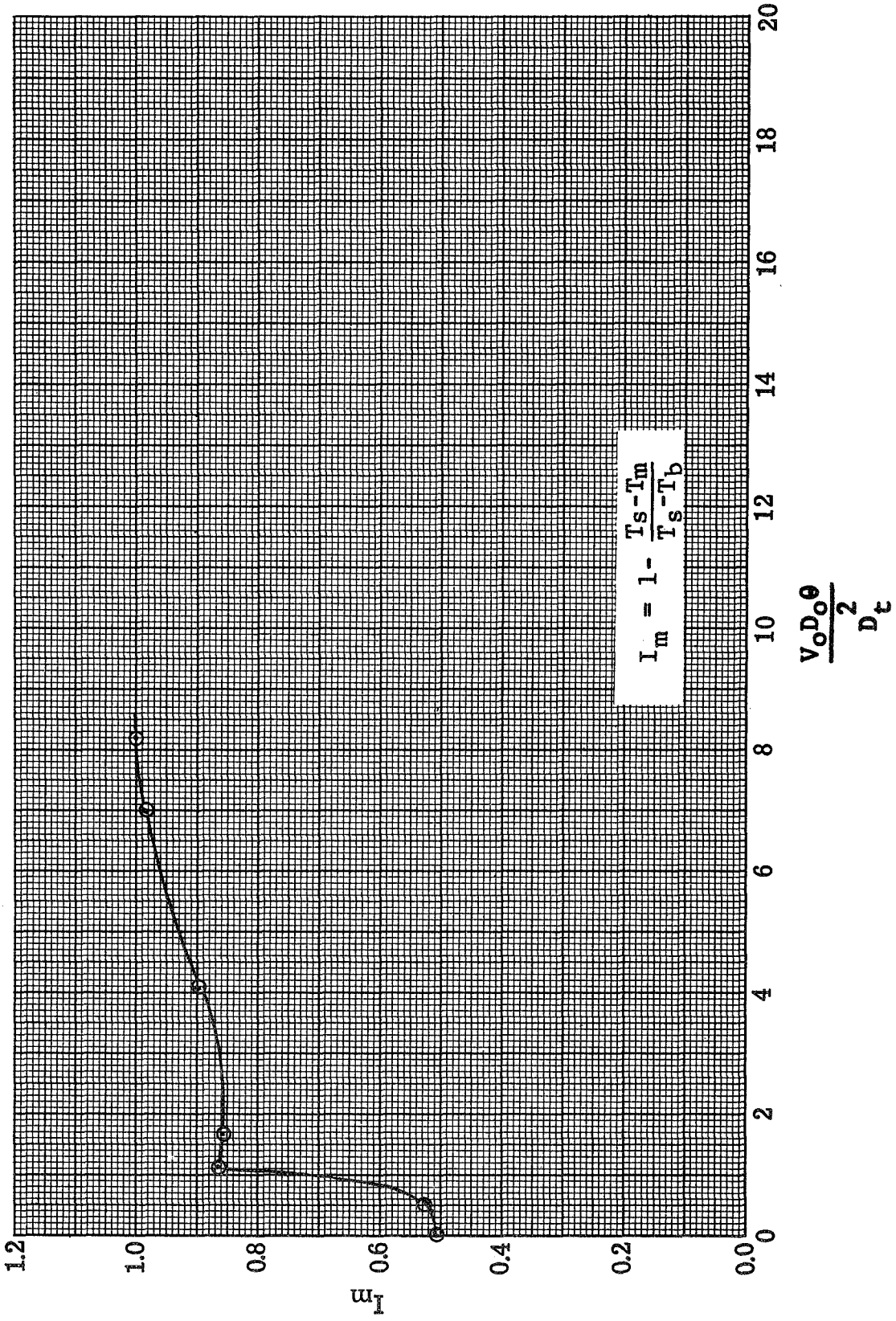

Figure 86 Transient Energy Integral: Run 22

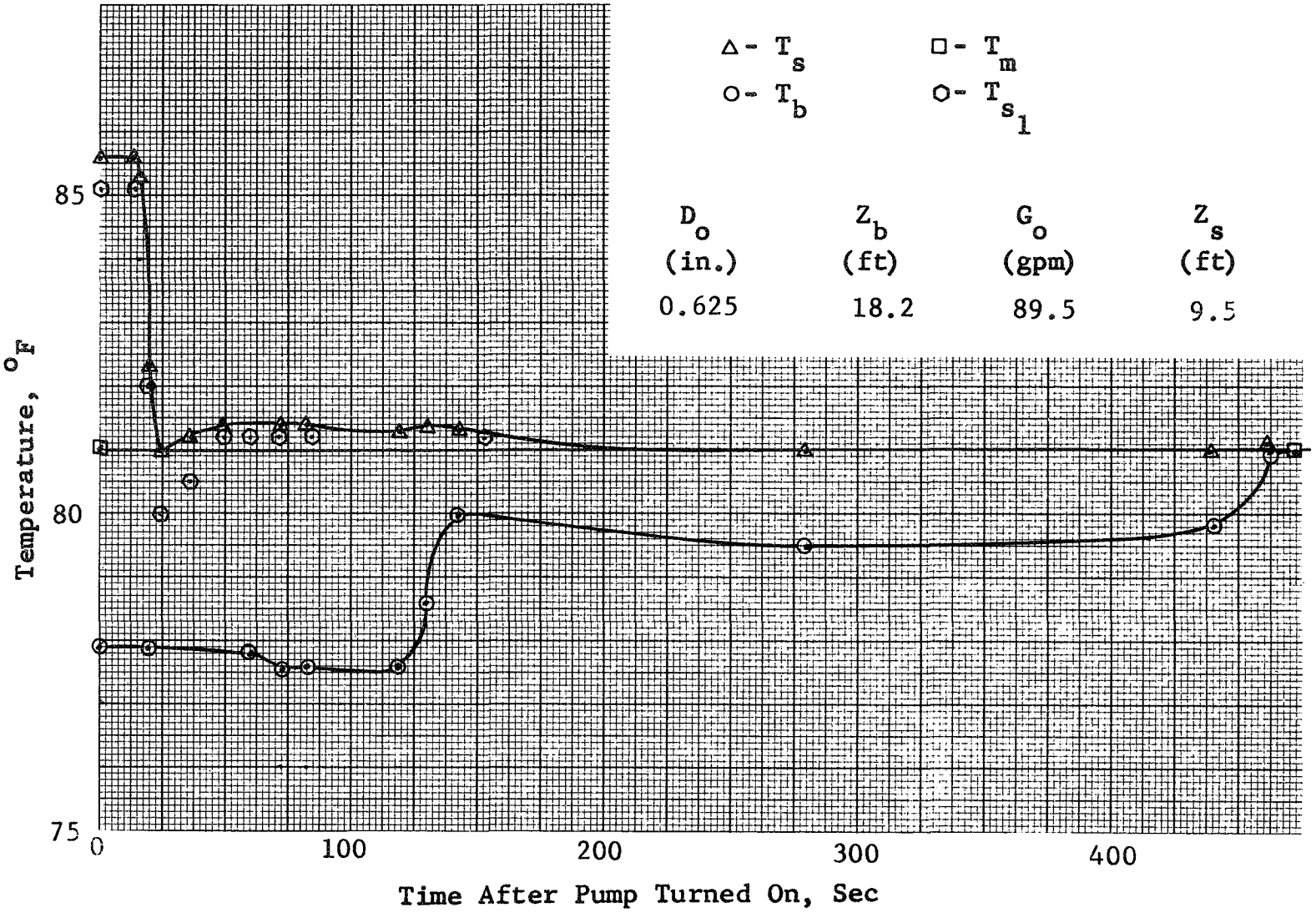

Figure 87 Transient Temperature Destratification: Run 23

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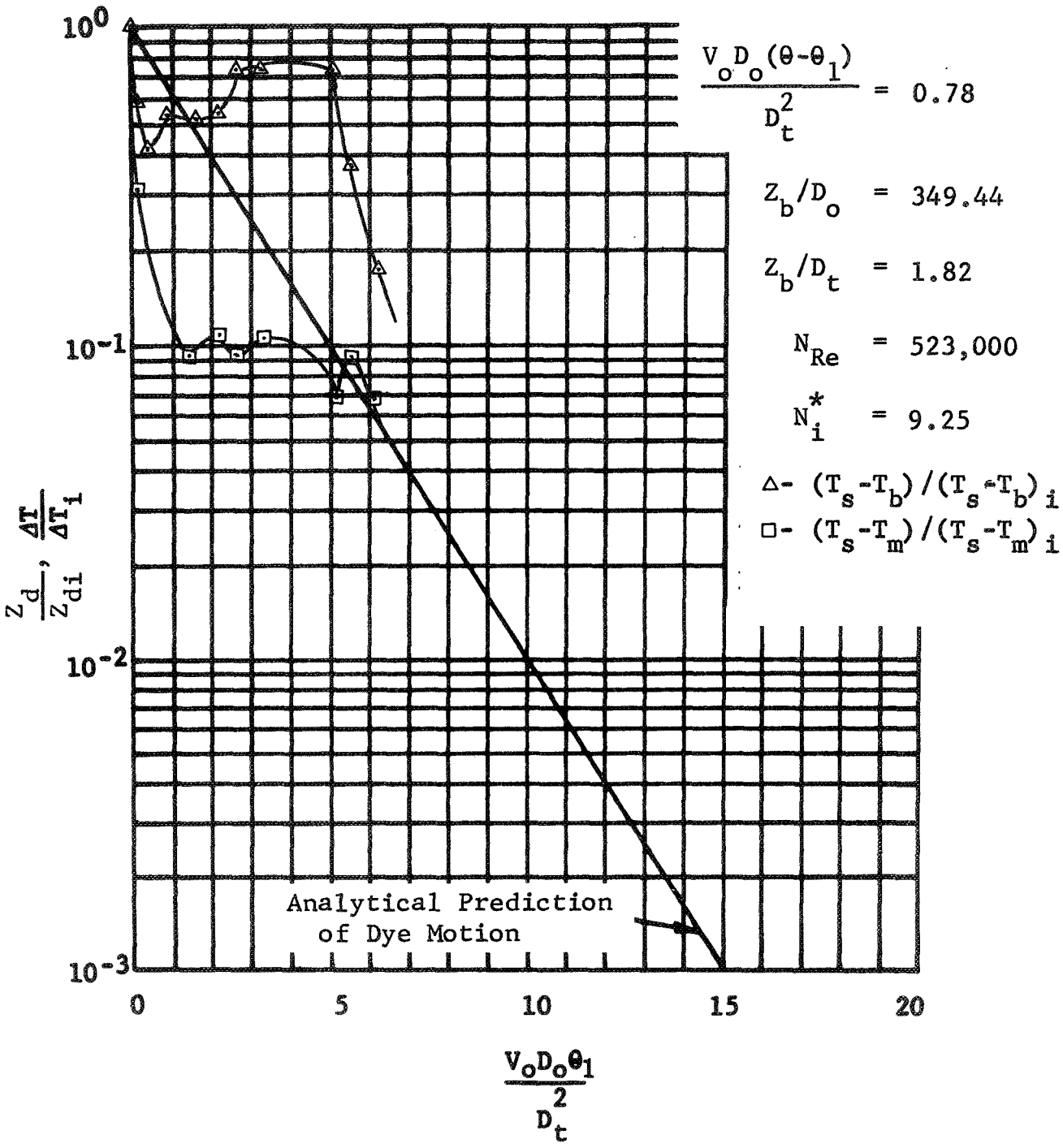

Figure 88 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 23

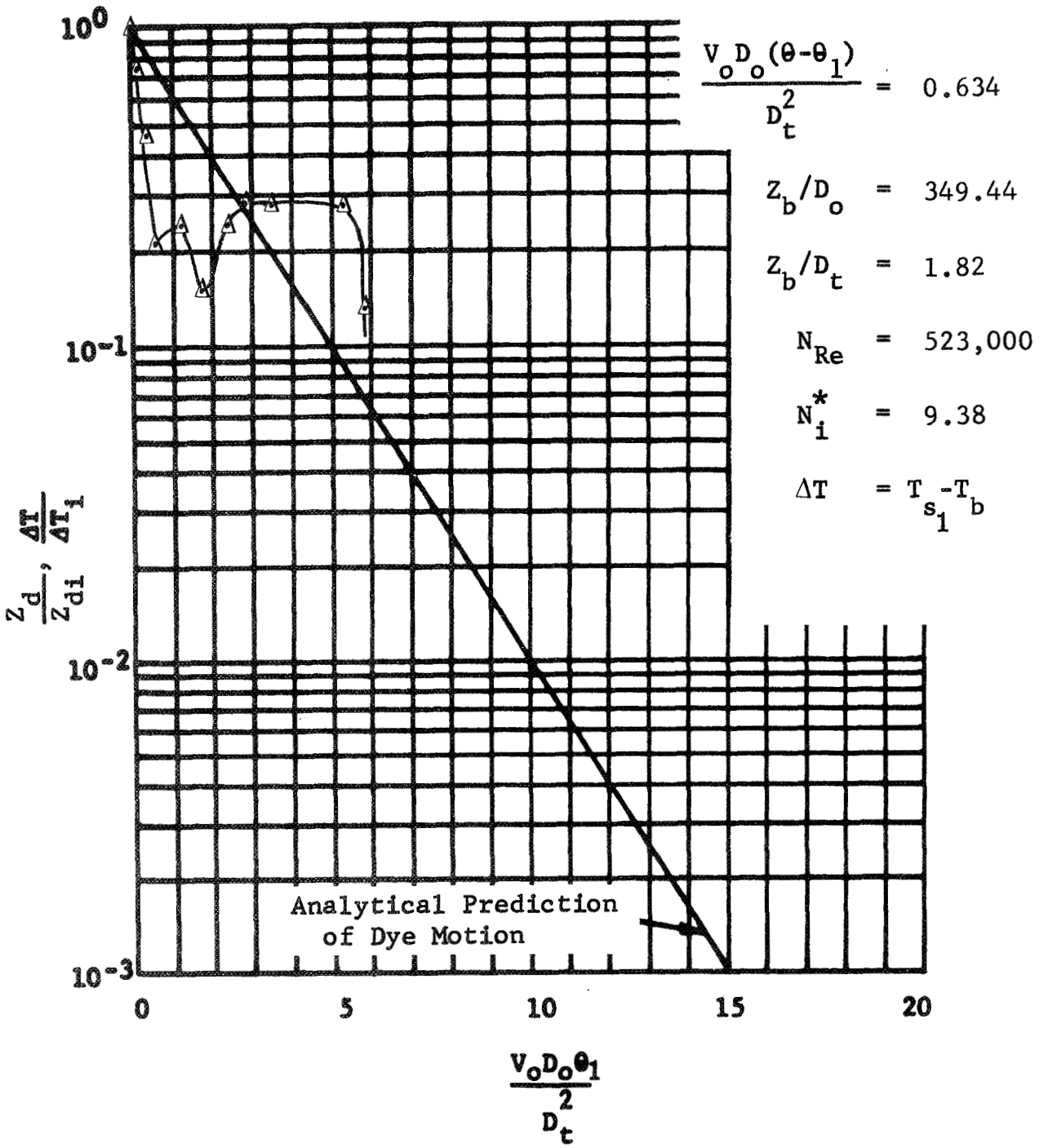

Figure 89 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 23

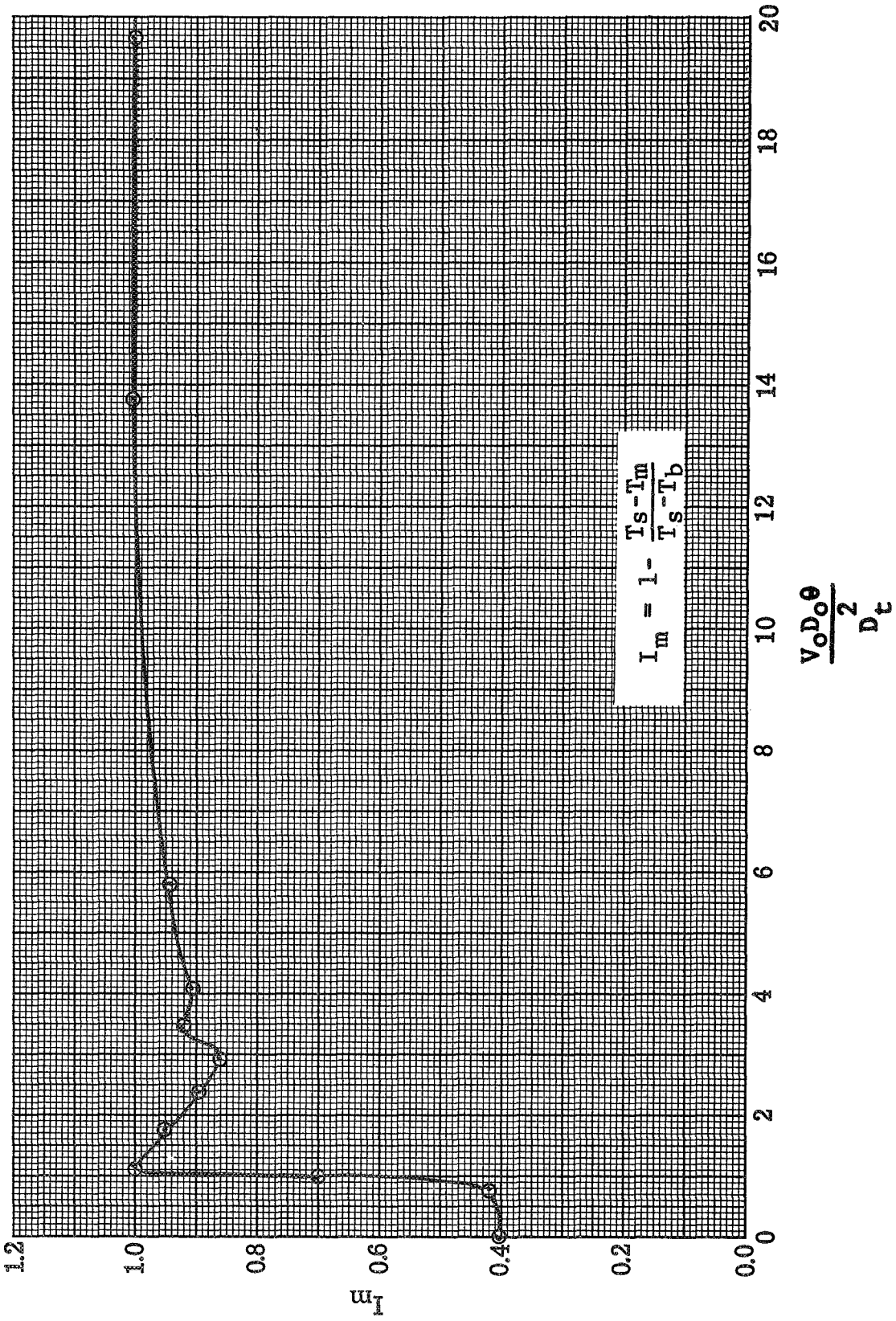

Figure 90 Transient Energy Integral: Run 23

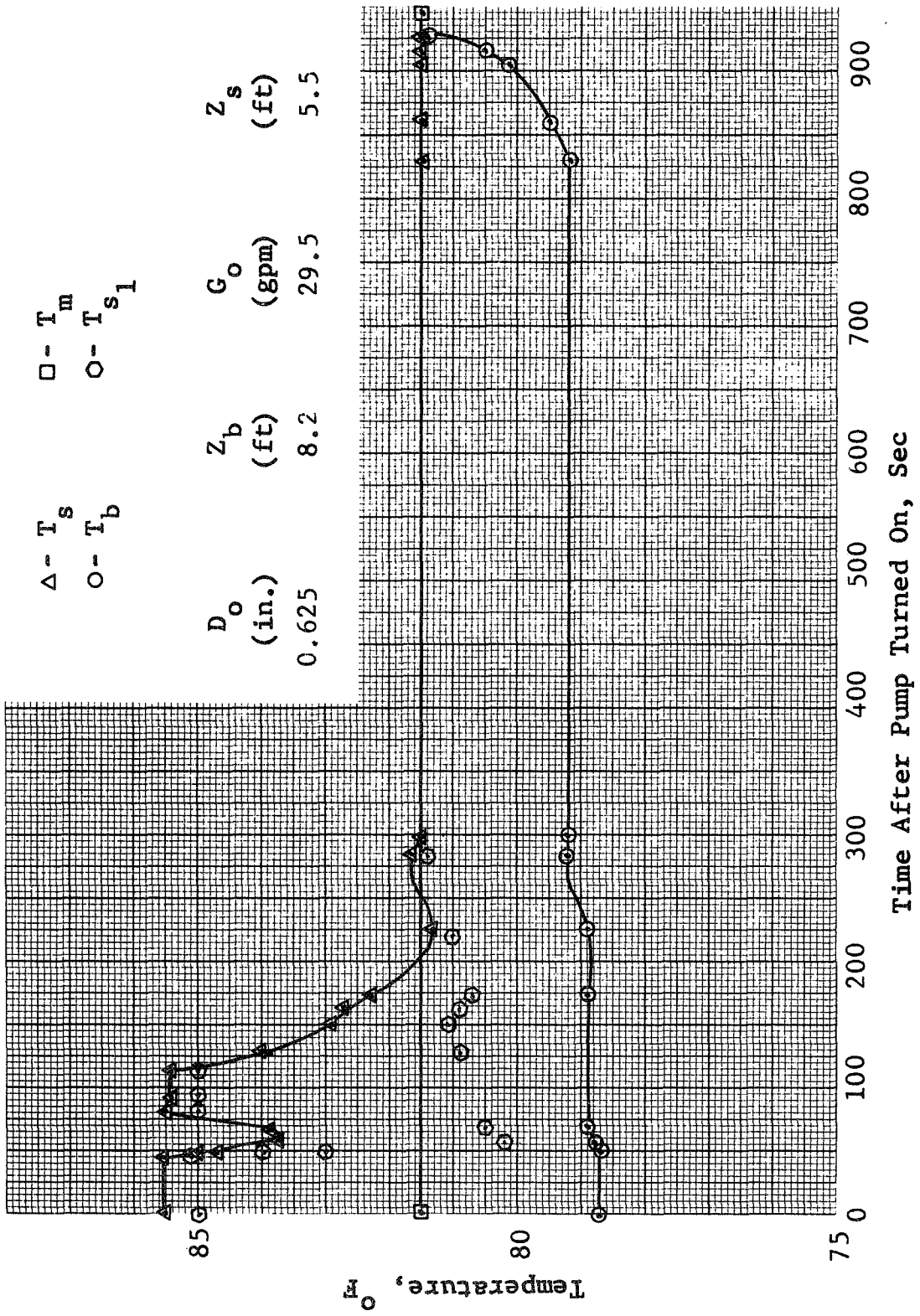

Figure 91 Transient Temperature Destratification: Run 24

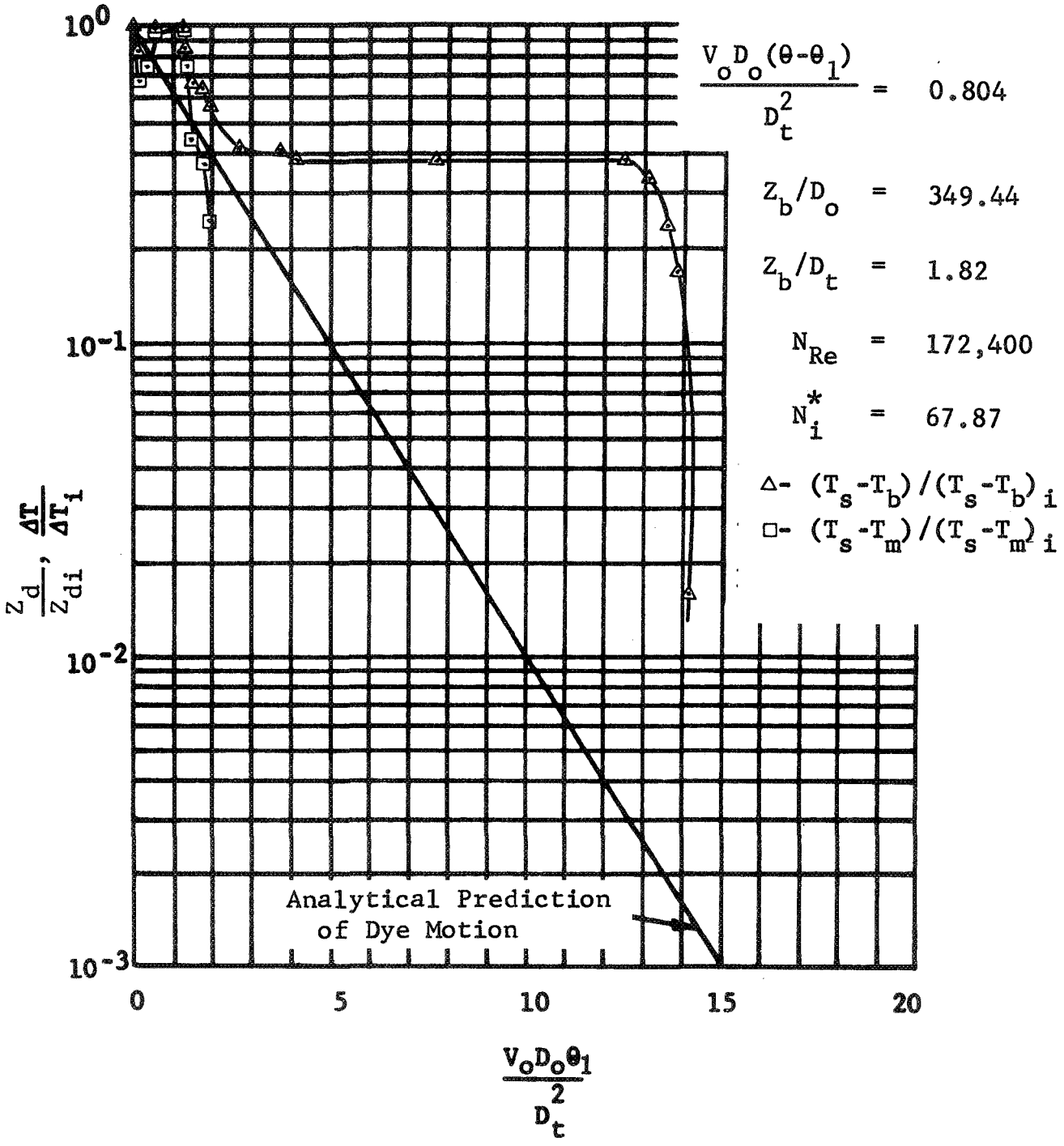

Figure 92 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 24

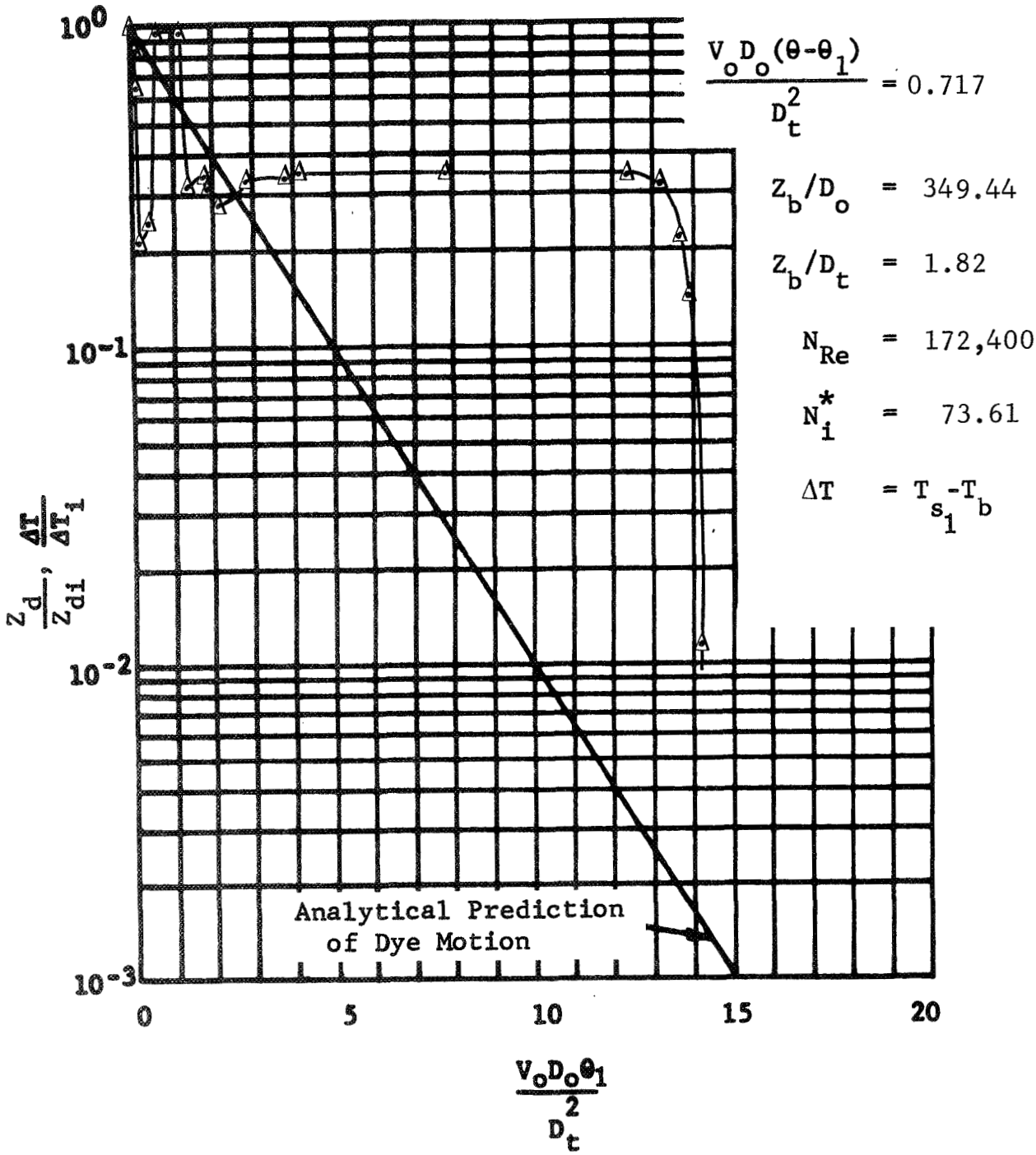

Figure 93 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 24

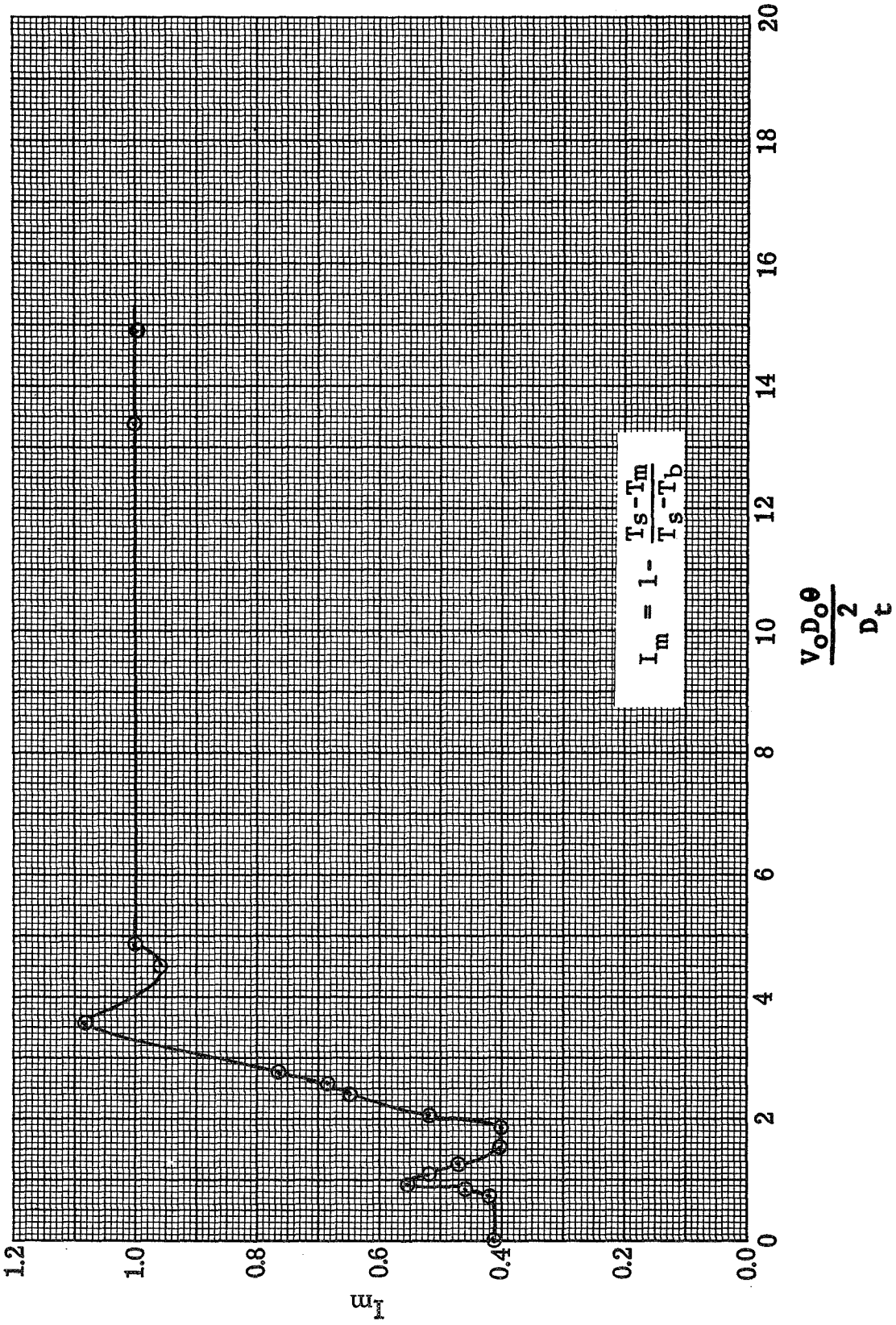

Figure 94 **Transient Energy Integral: Run 24**

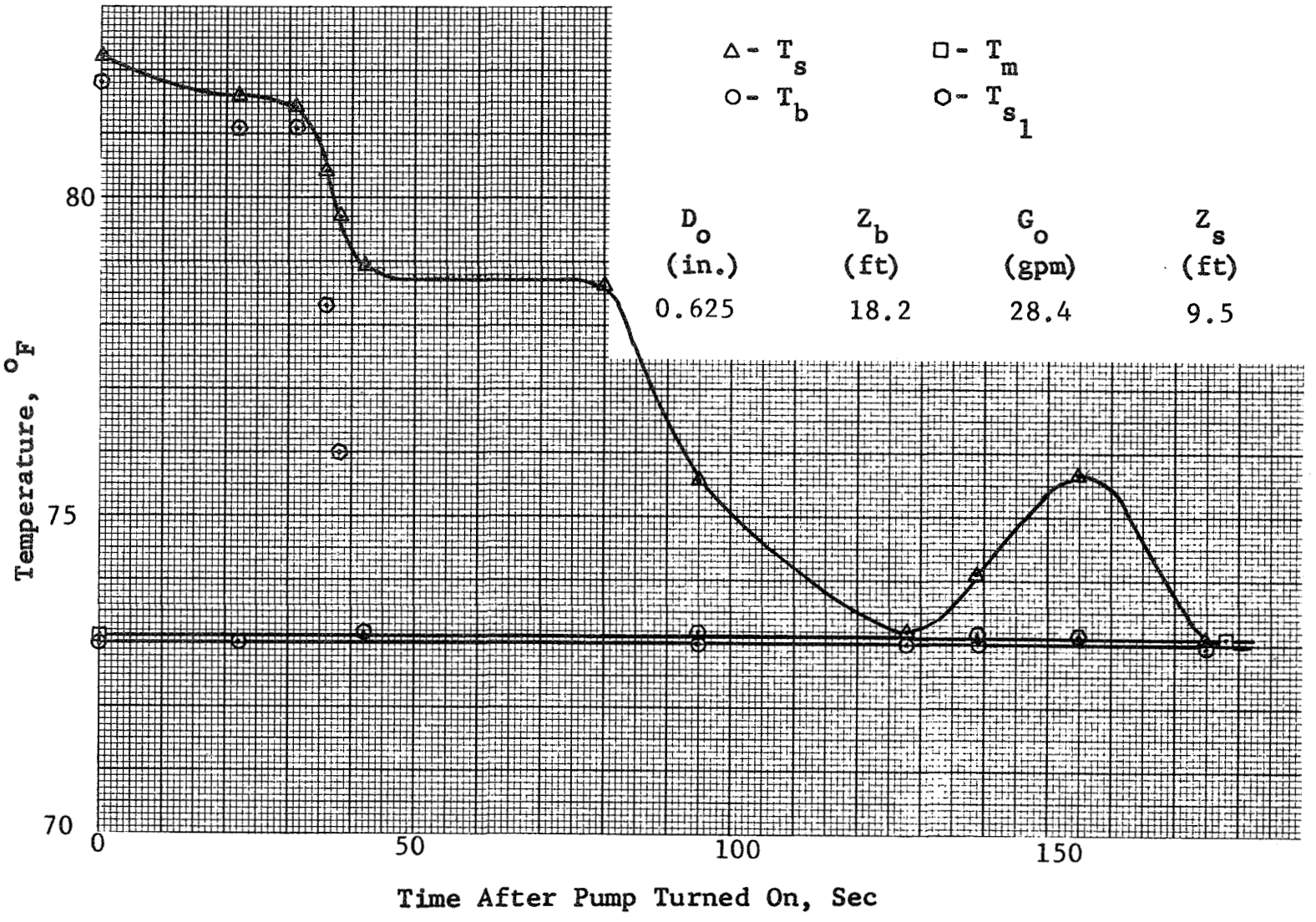

Figure 95 Transient Temperature Destratification: Run 25

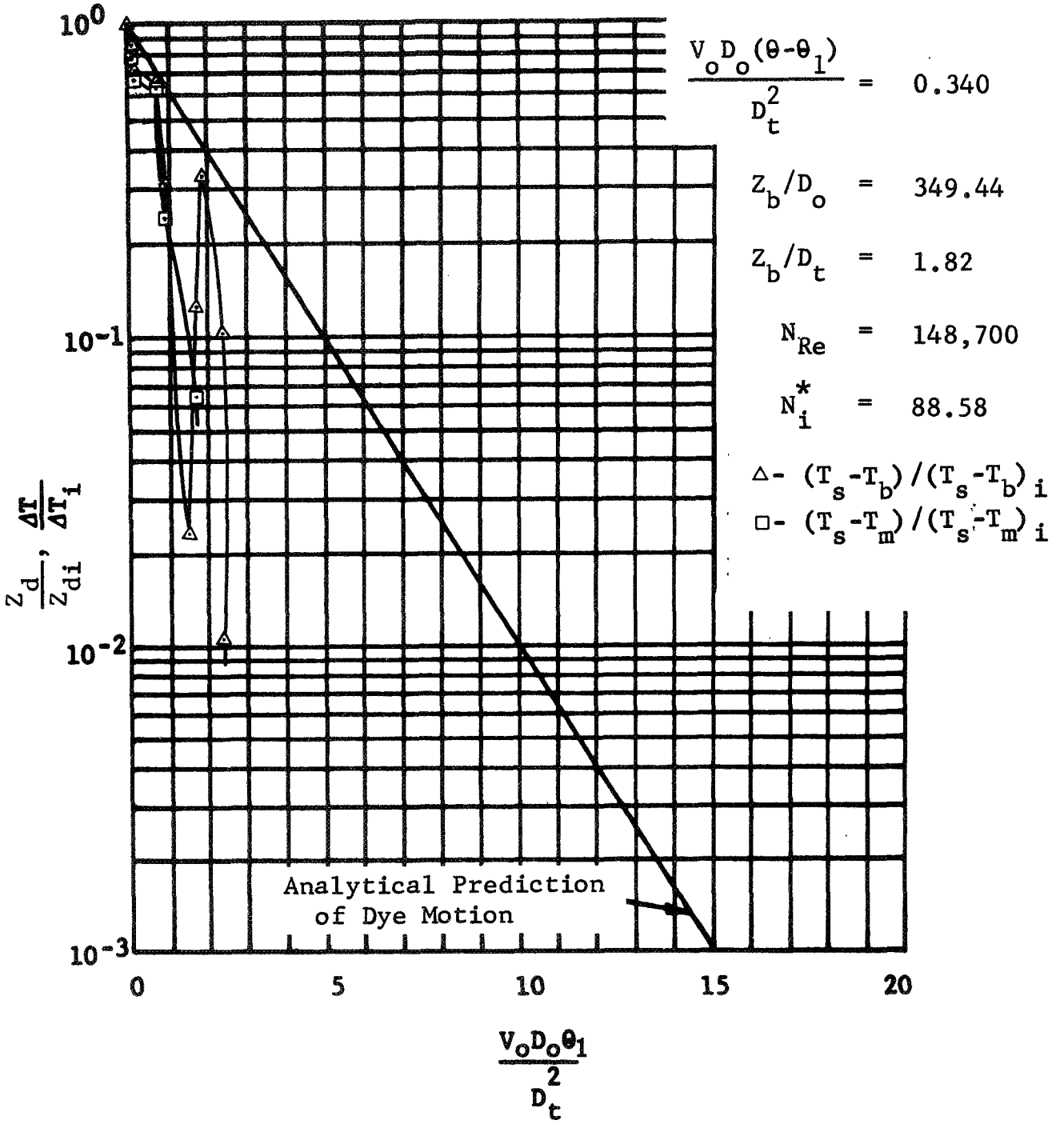

Figure 96 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 25

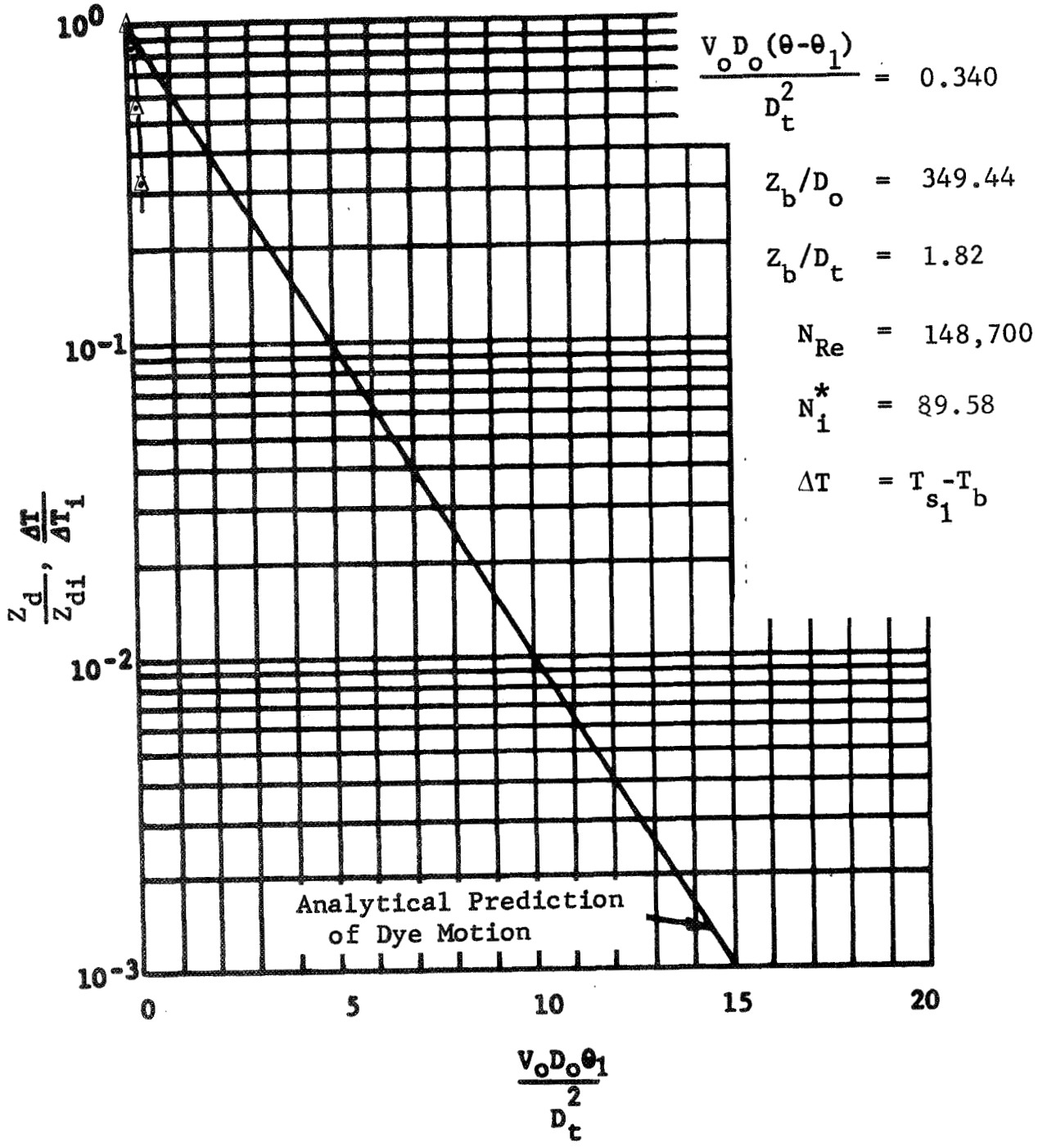

Figure 97 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 25

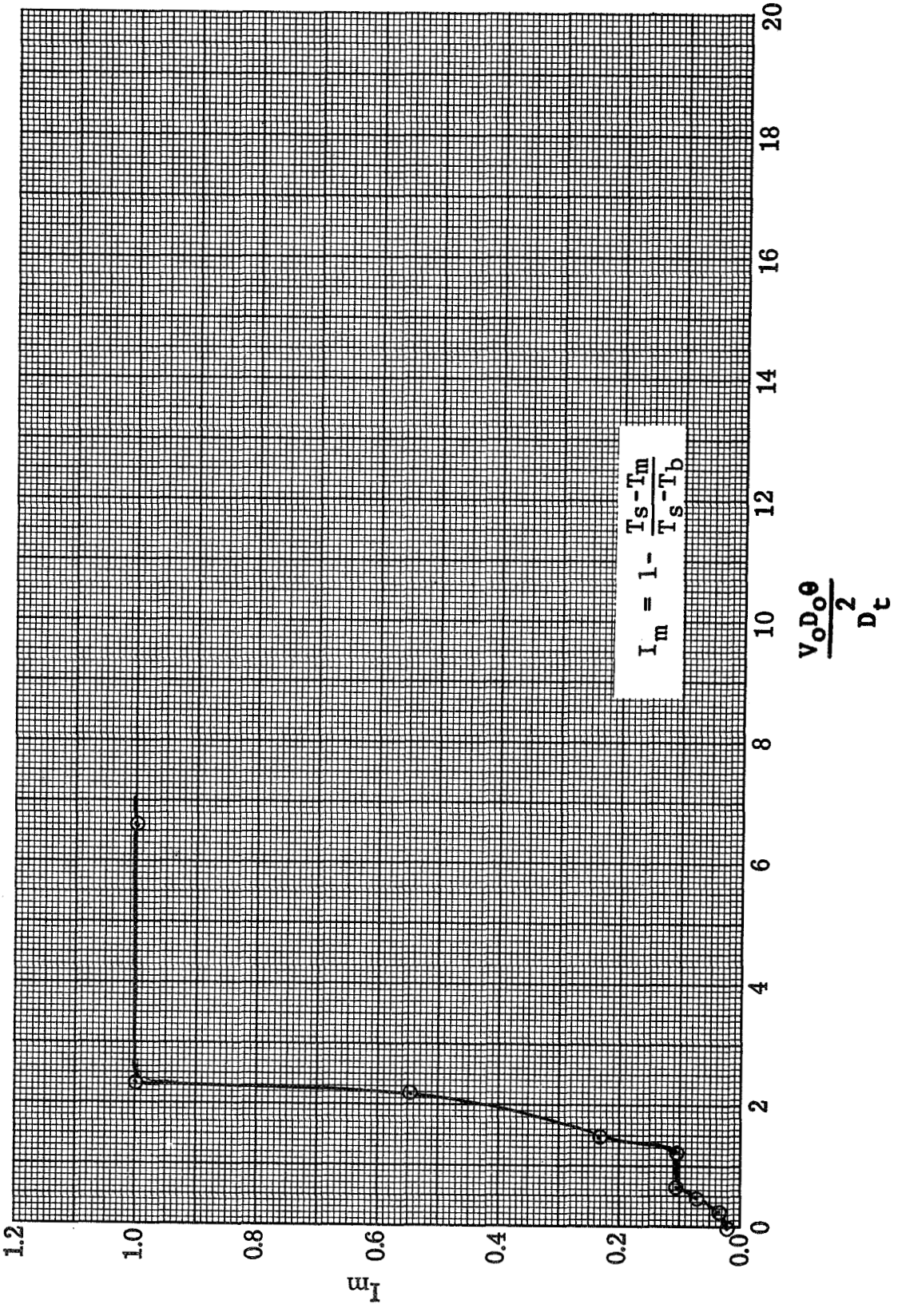

Figure 98 **Transient Energy Integral:** Run 25

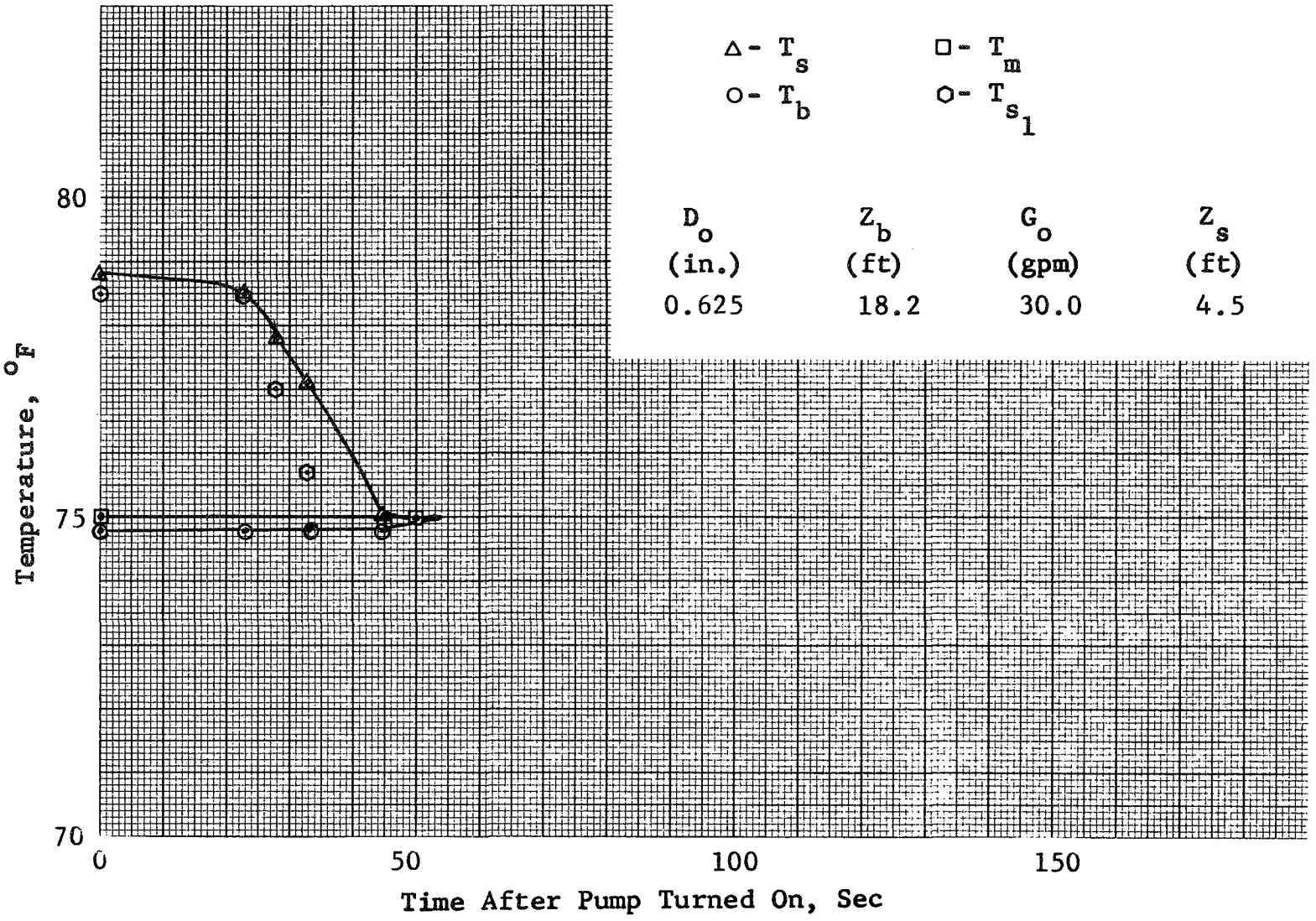

Figure 99 Transient Temperature Destratification: Run 26

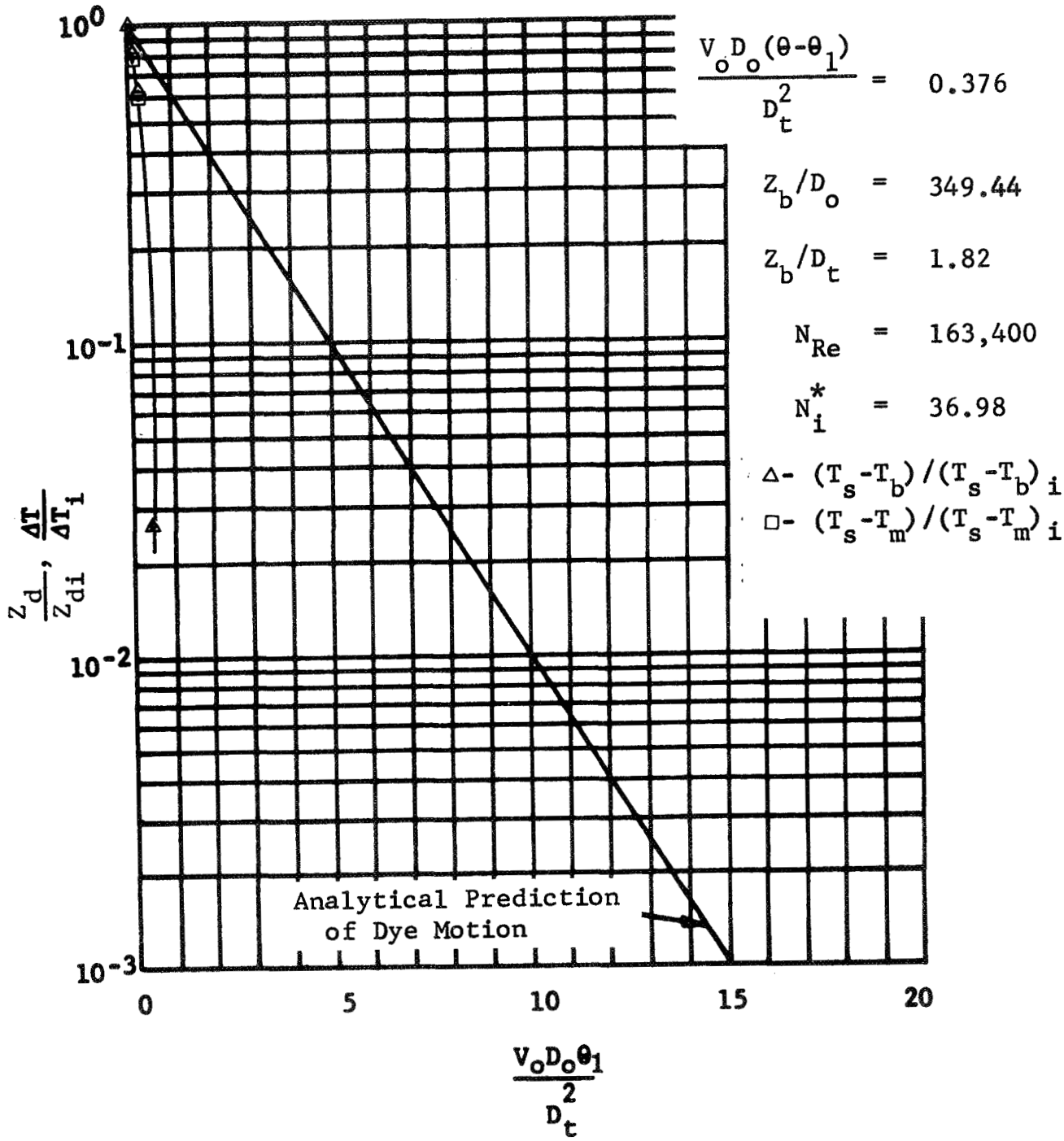

Figure 100 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 26

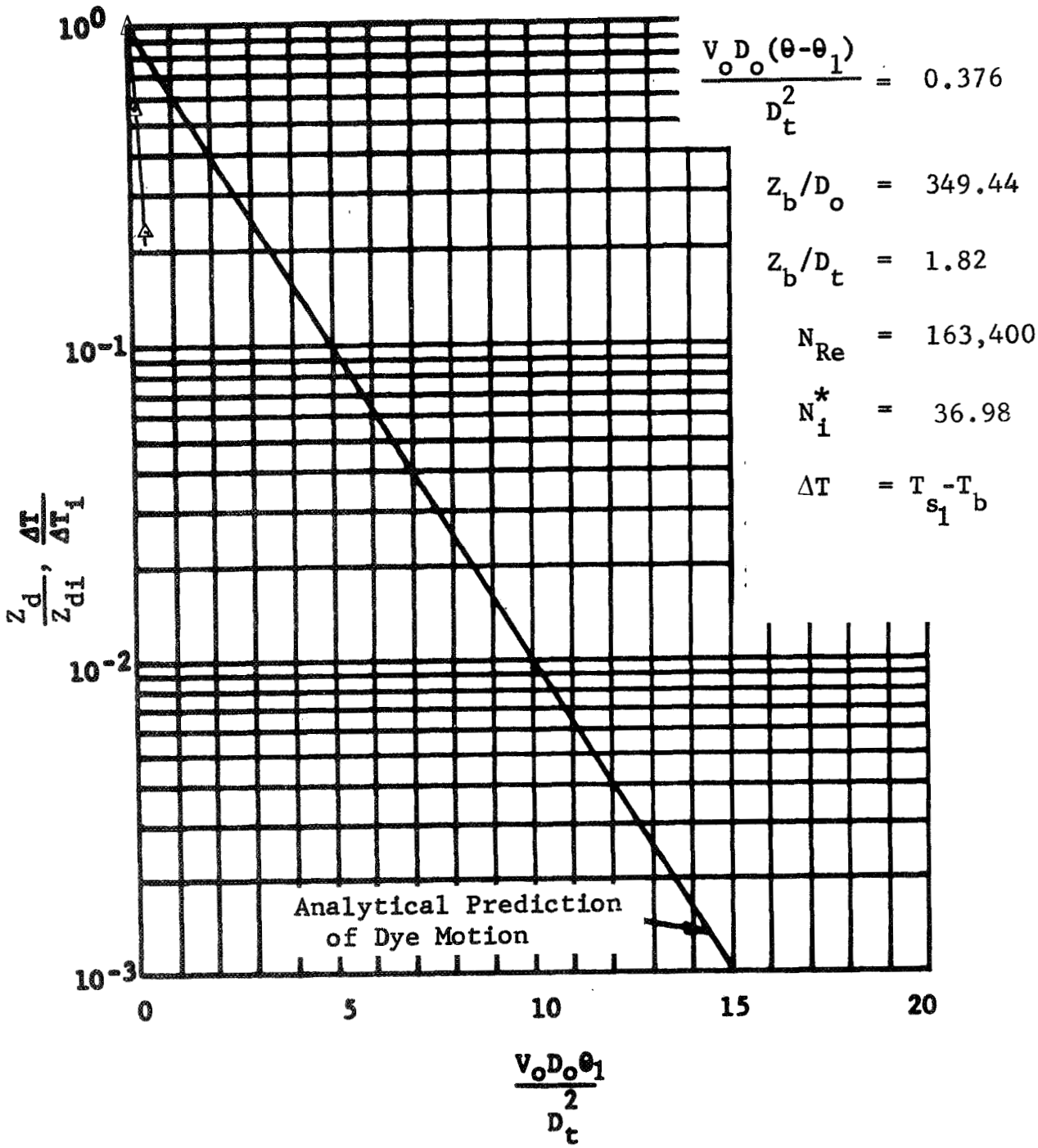

Figure 101 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 26

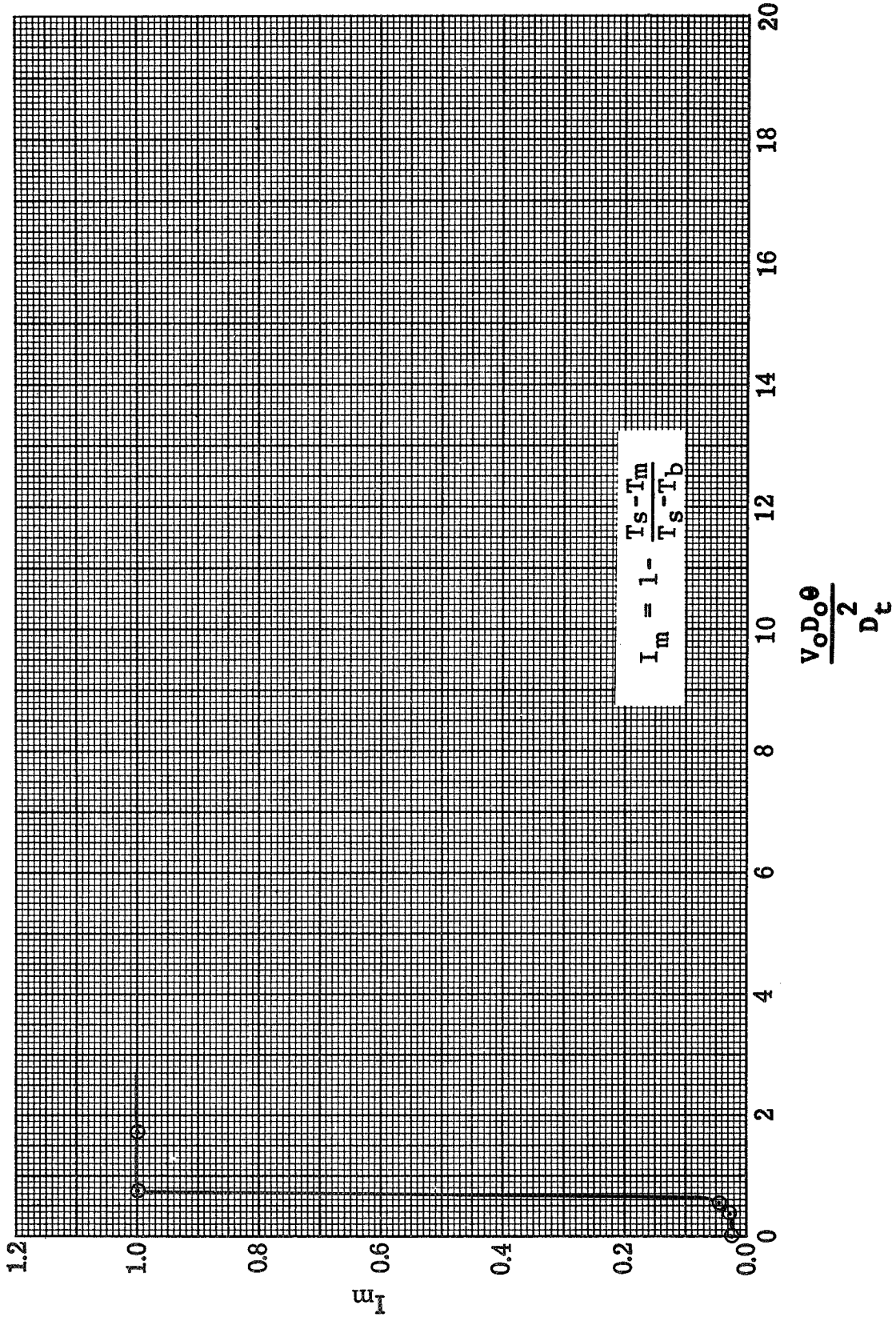

Figure 102 **Transient Energy Integral: Run 26**

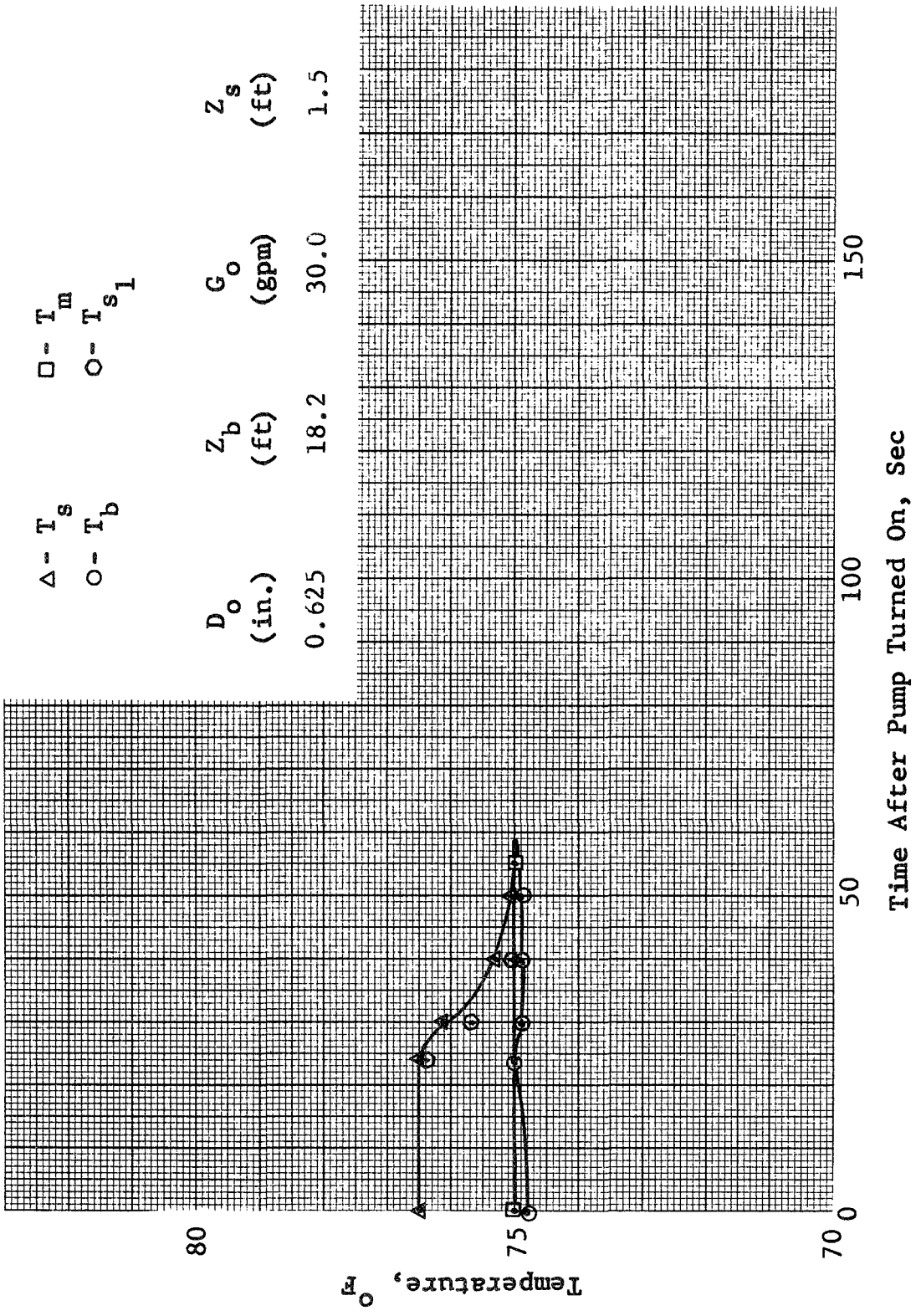

Figure 103 Transient Temperature Destratification: Run 27

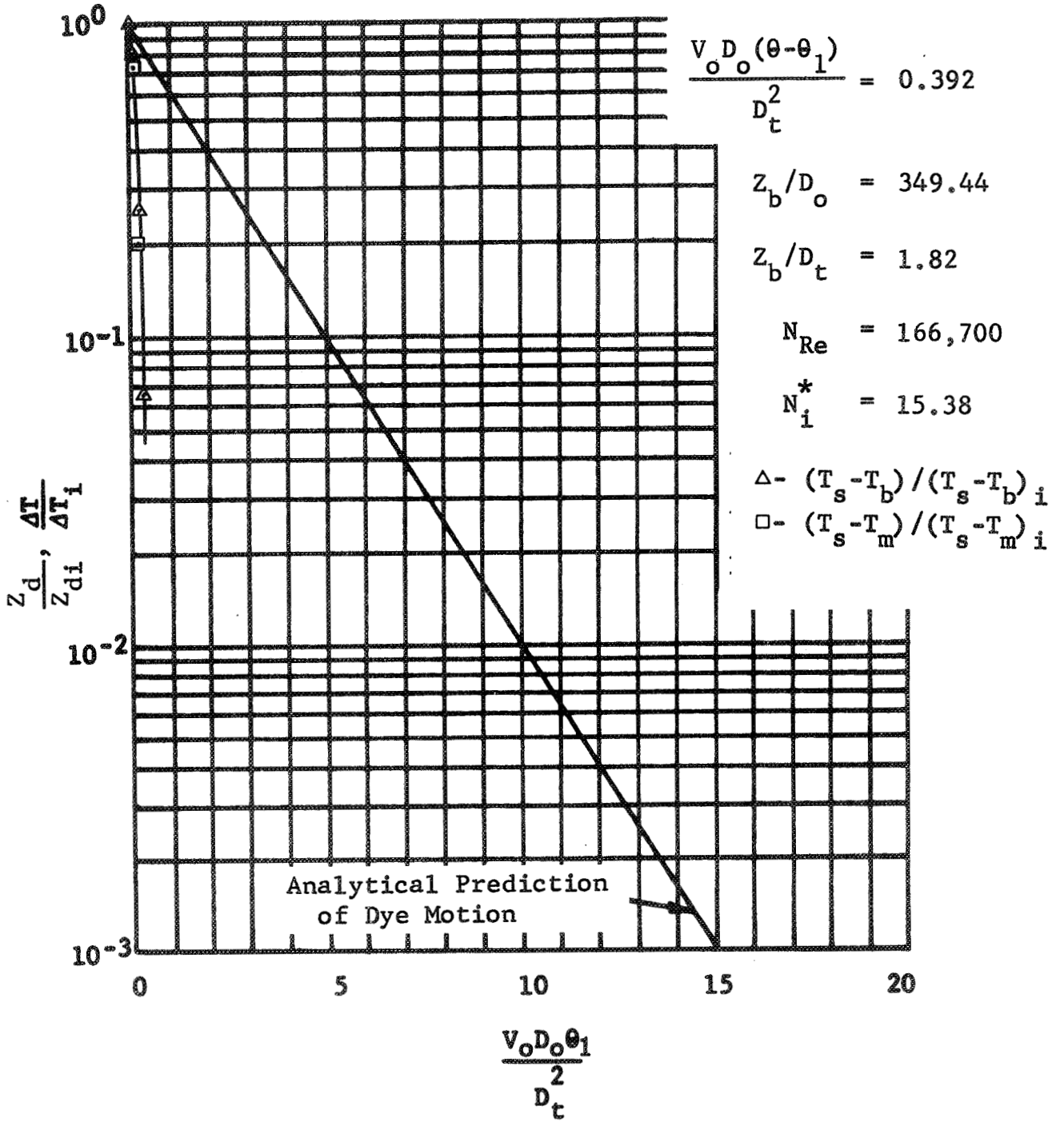

Figure 104 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 27

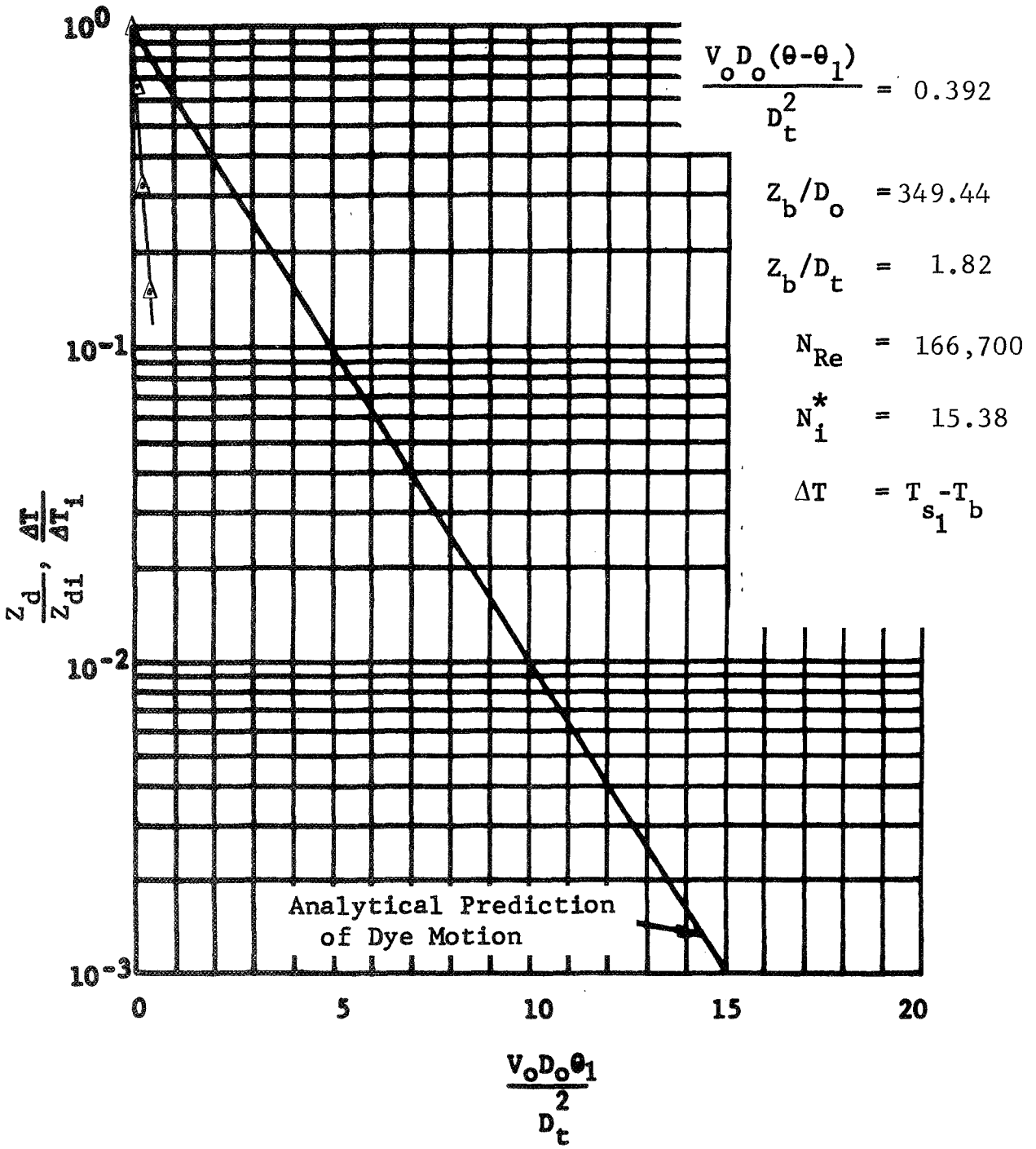

Figure 105 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 27

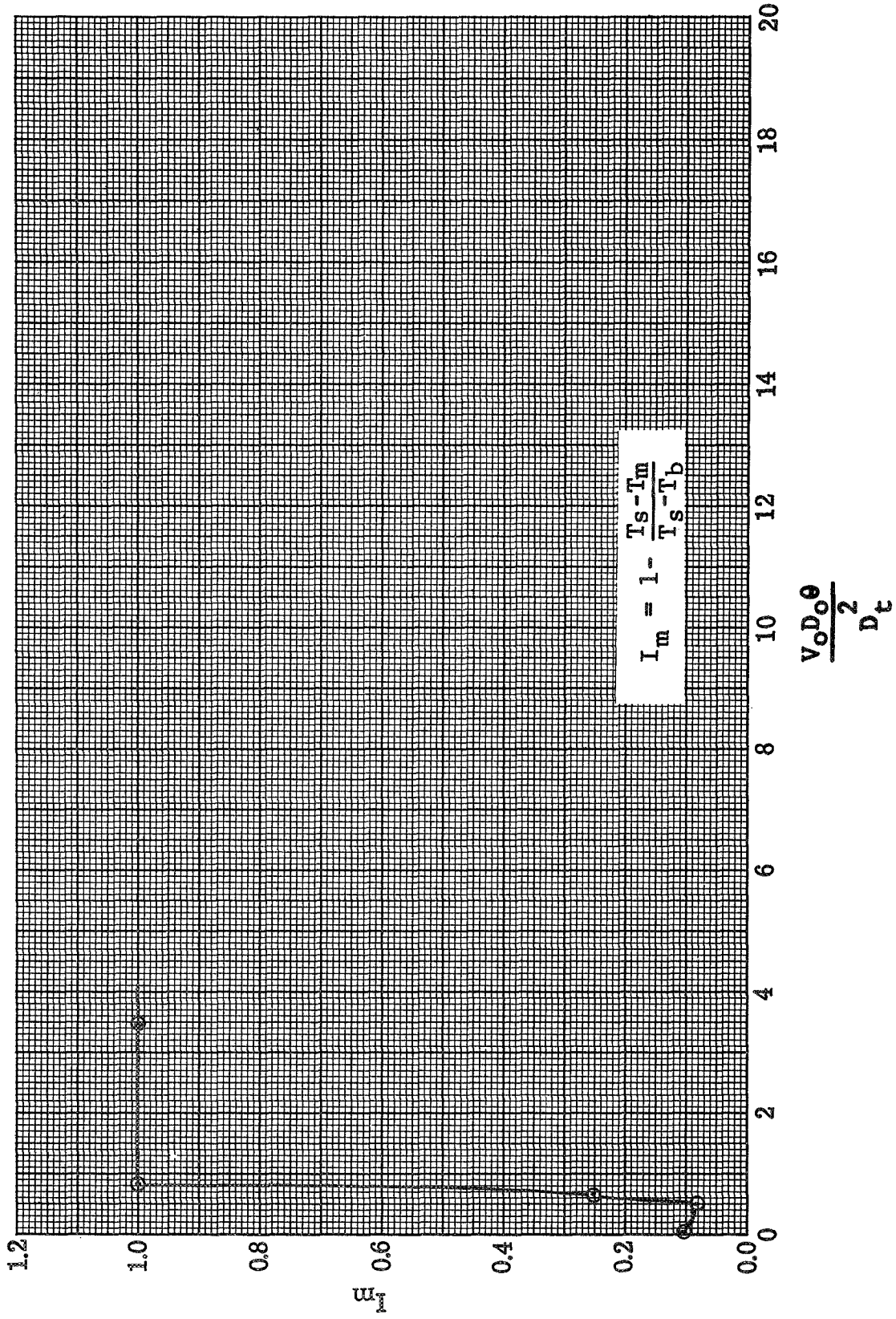

Figure 106 Transient Energy Integral: Run 27

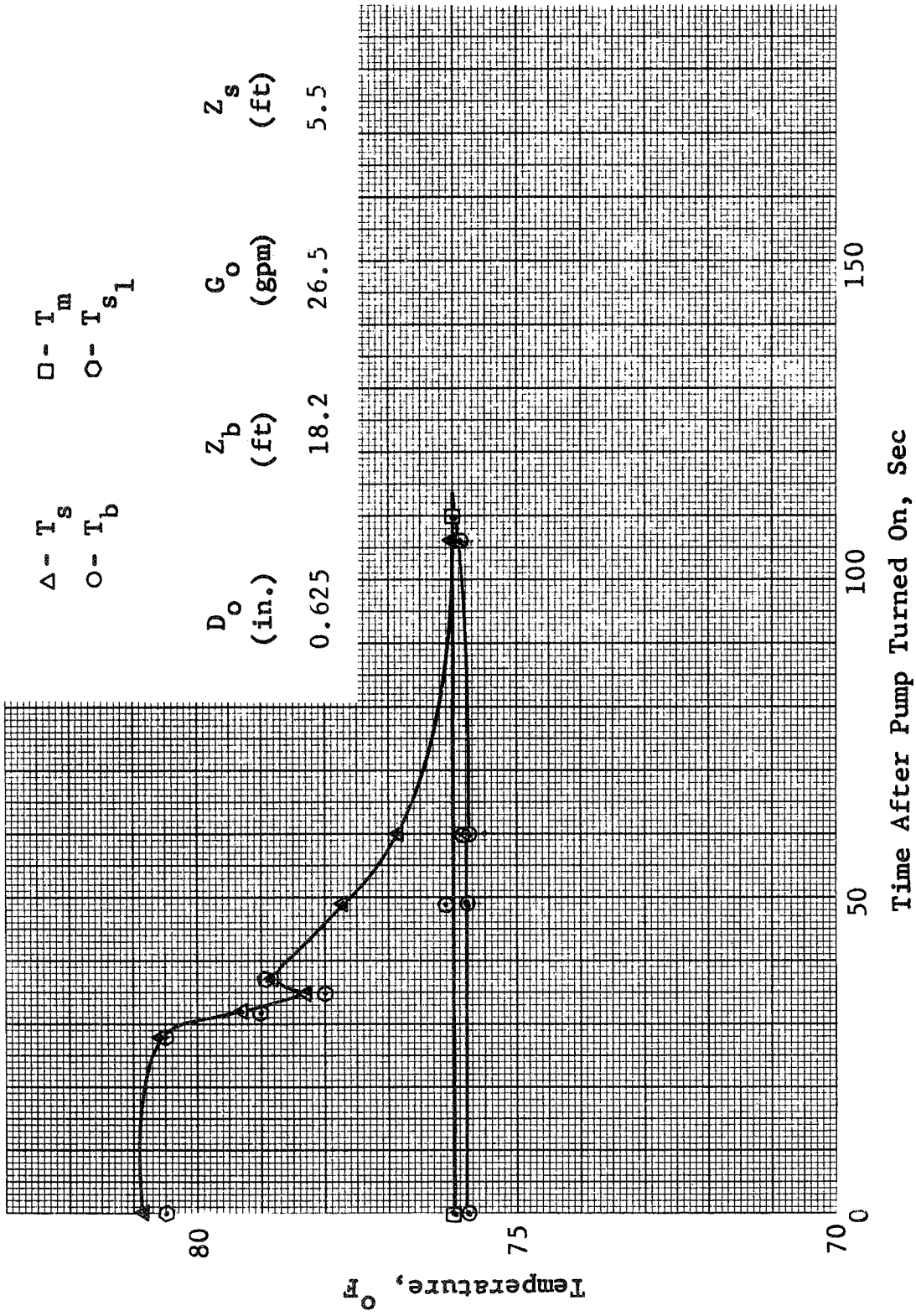

Figure 107 Transient Temperature Destratification: Run 28

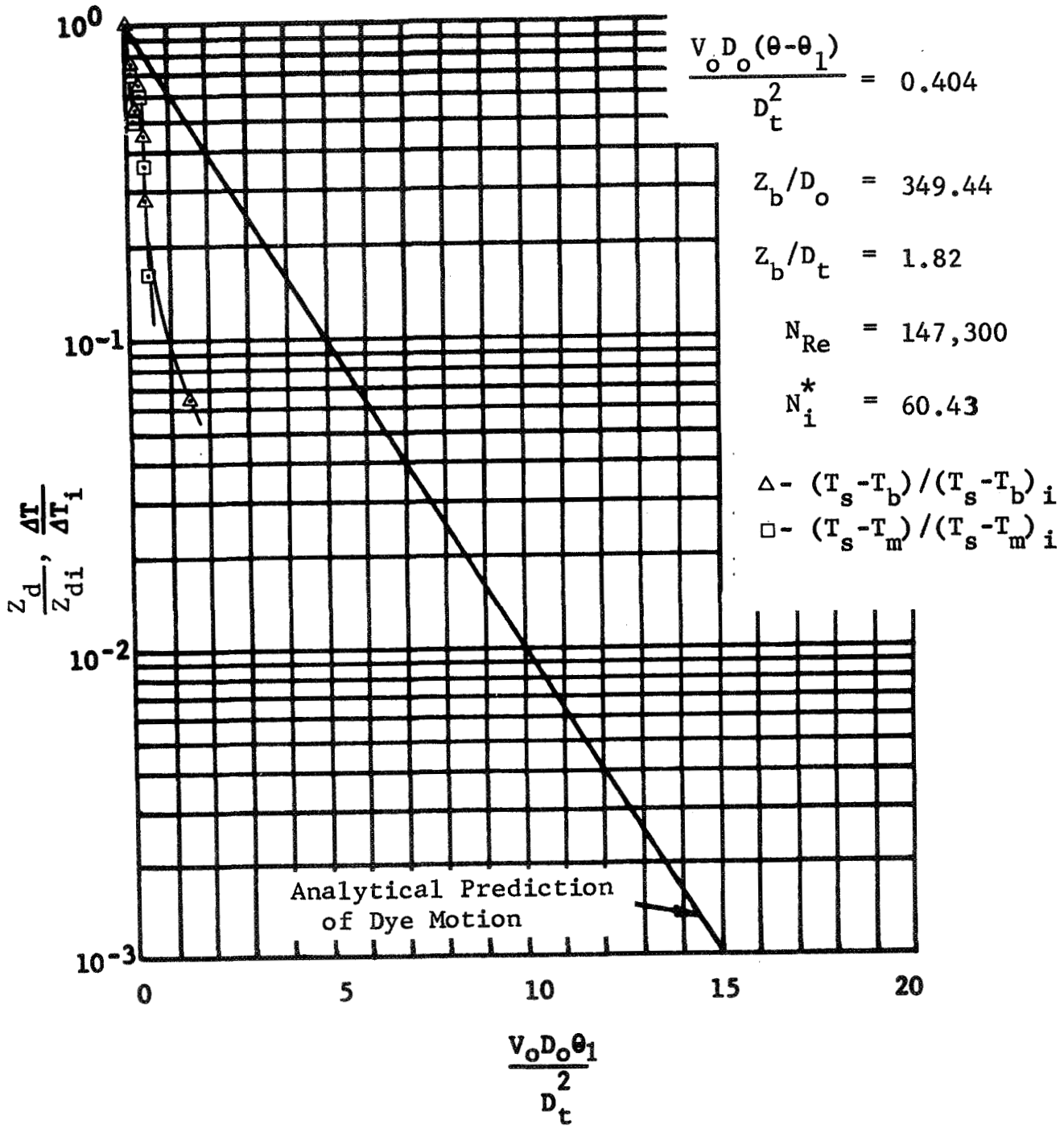

Figure 108 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 28

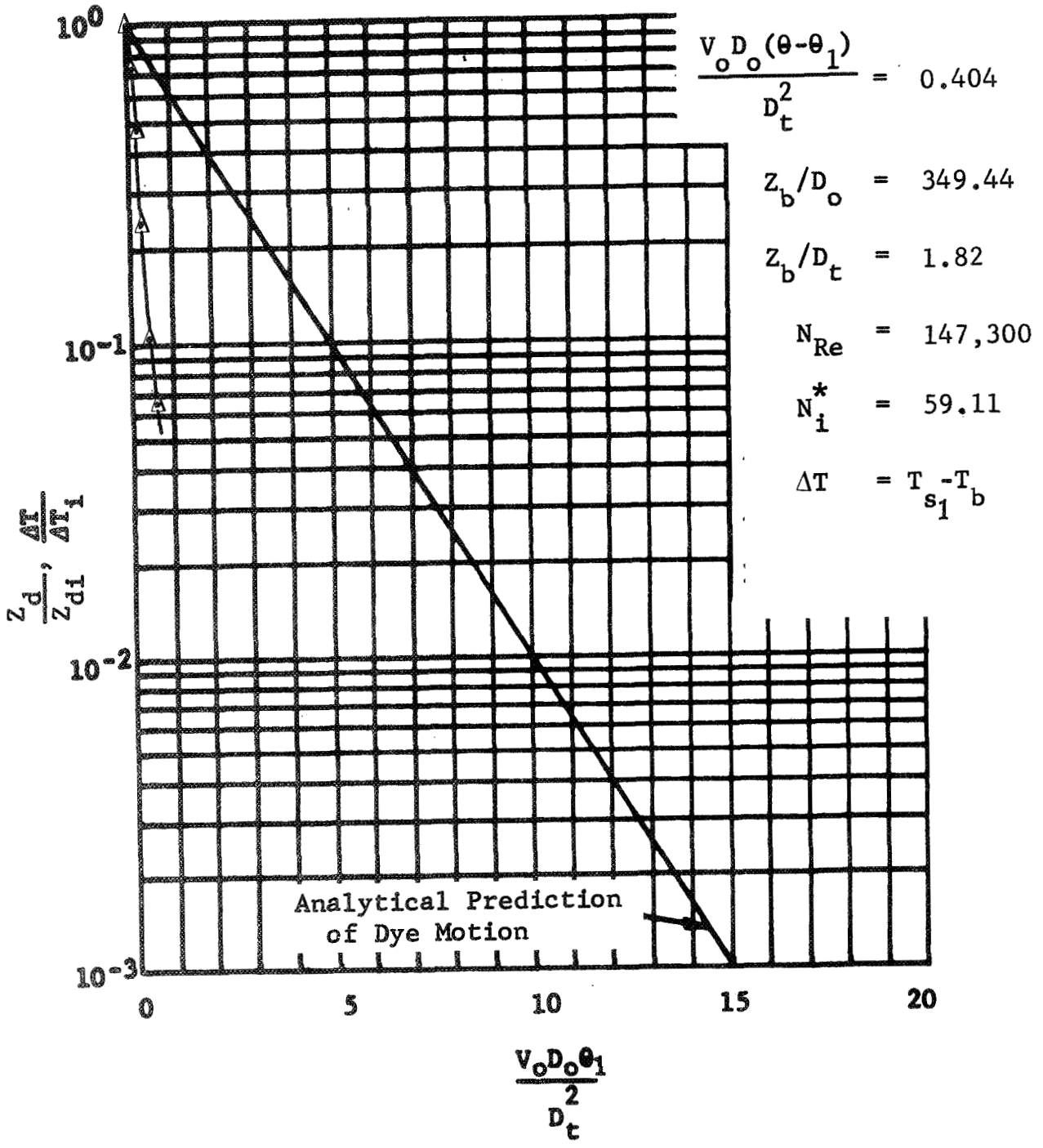

Figure 109 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 28

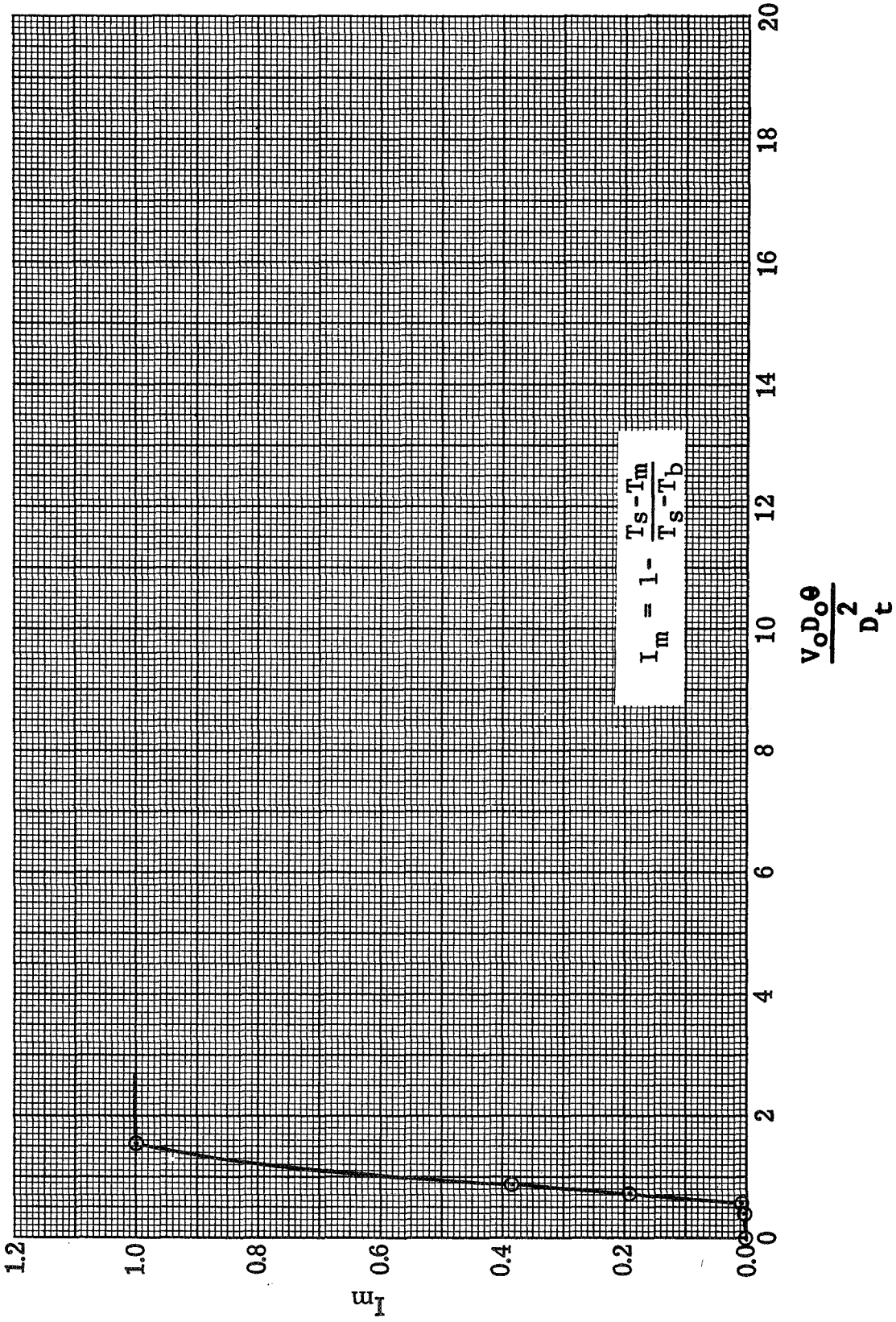

Figure 110 **Transient Energy Integral:** Run 28

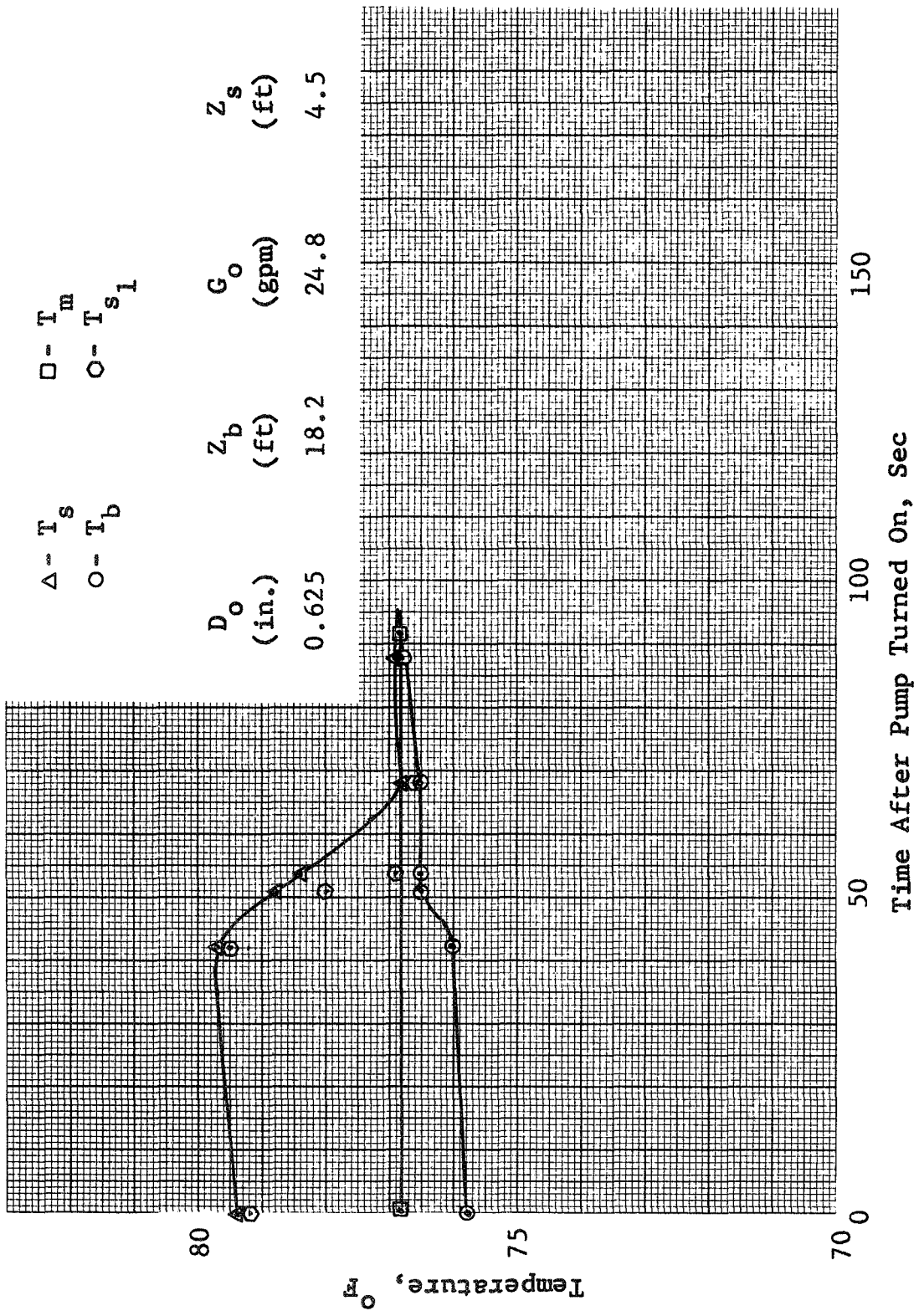

Figure 111 Transient Temperature Destratification: Run 29

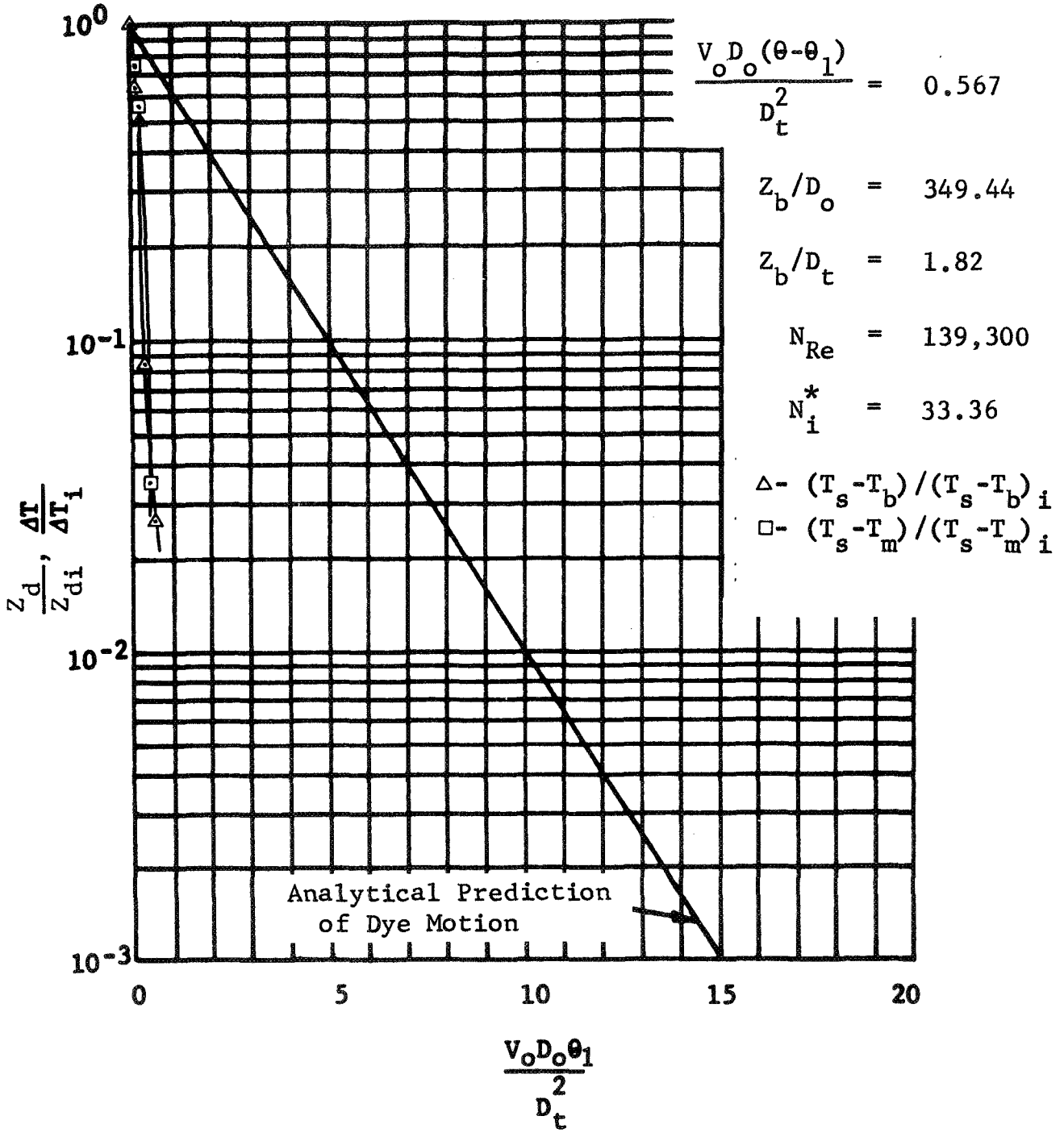

Figure 112 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 29

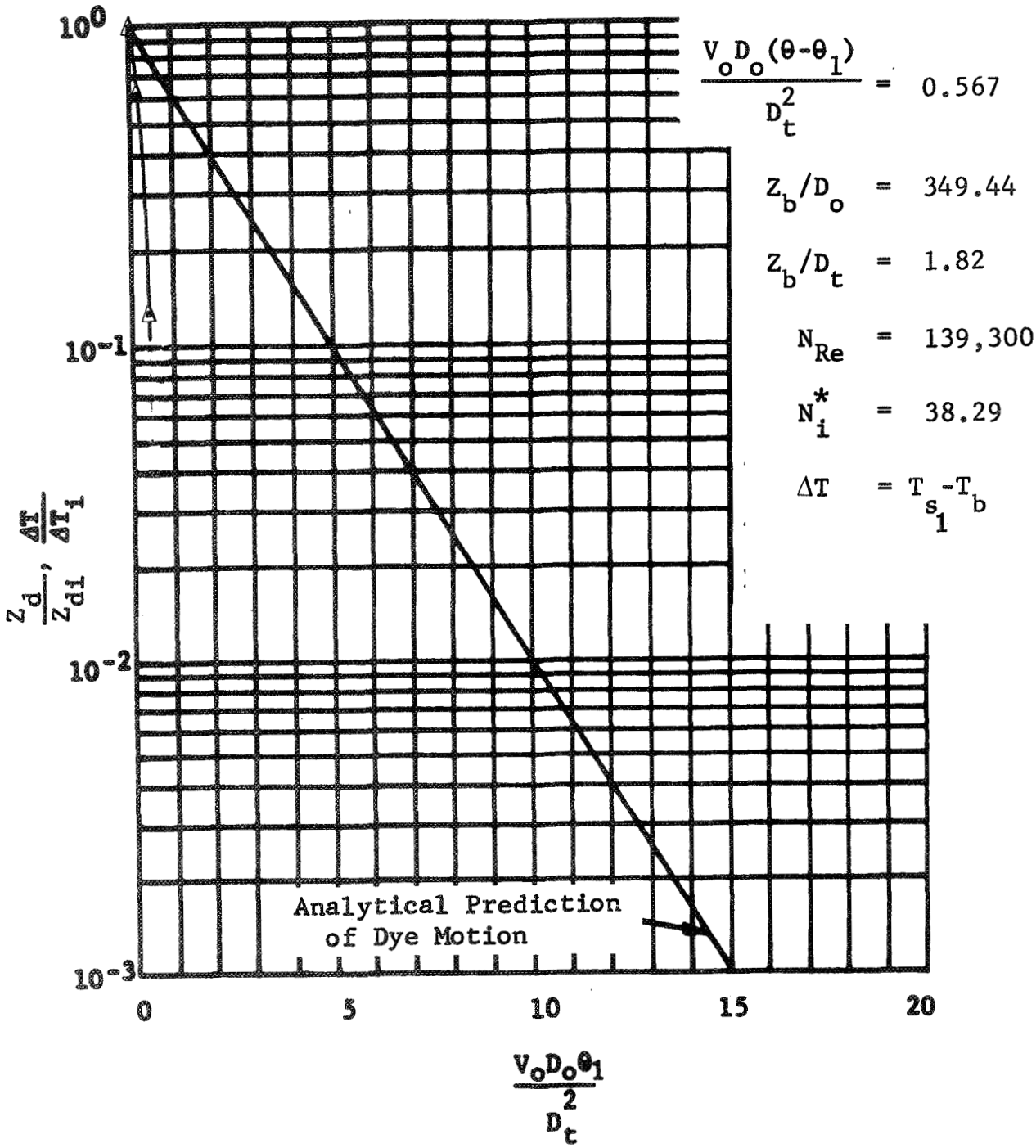

Figure 113 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 29

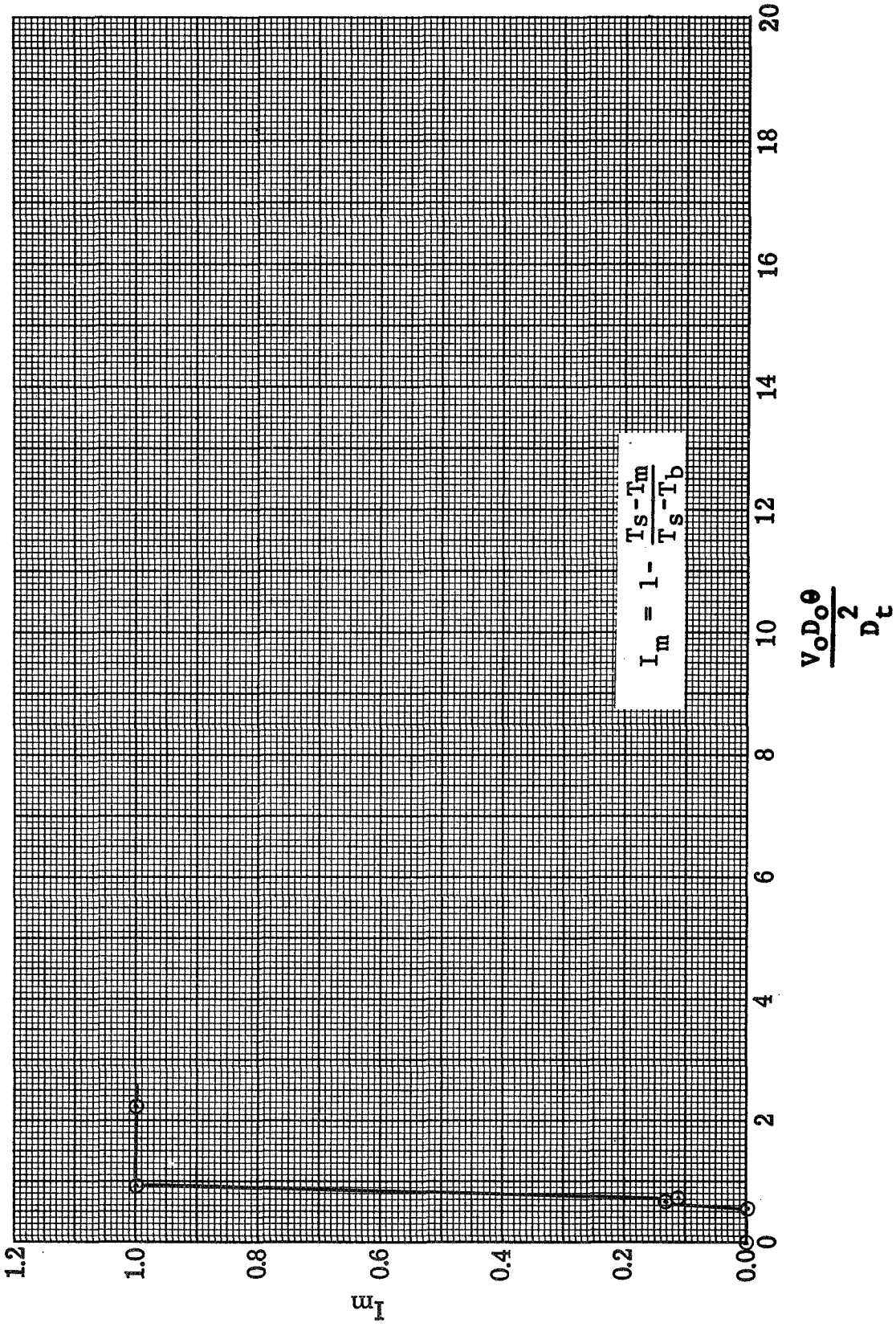

Figure 114 **Transient Energy Integral:** Run 29

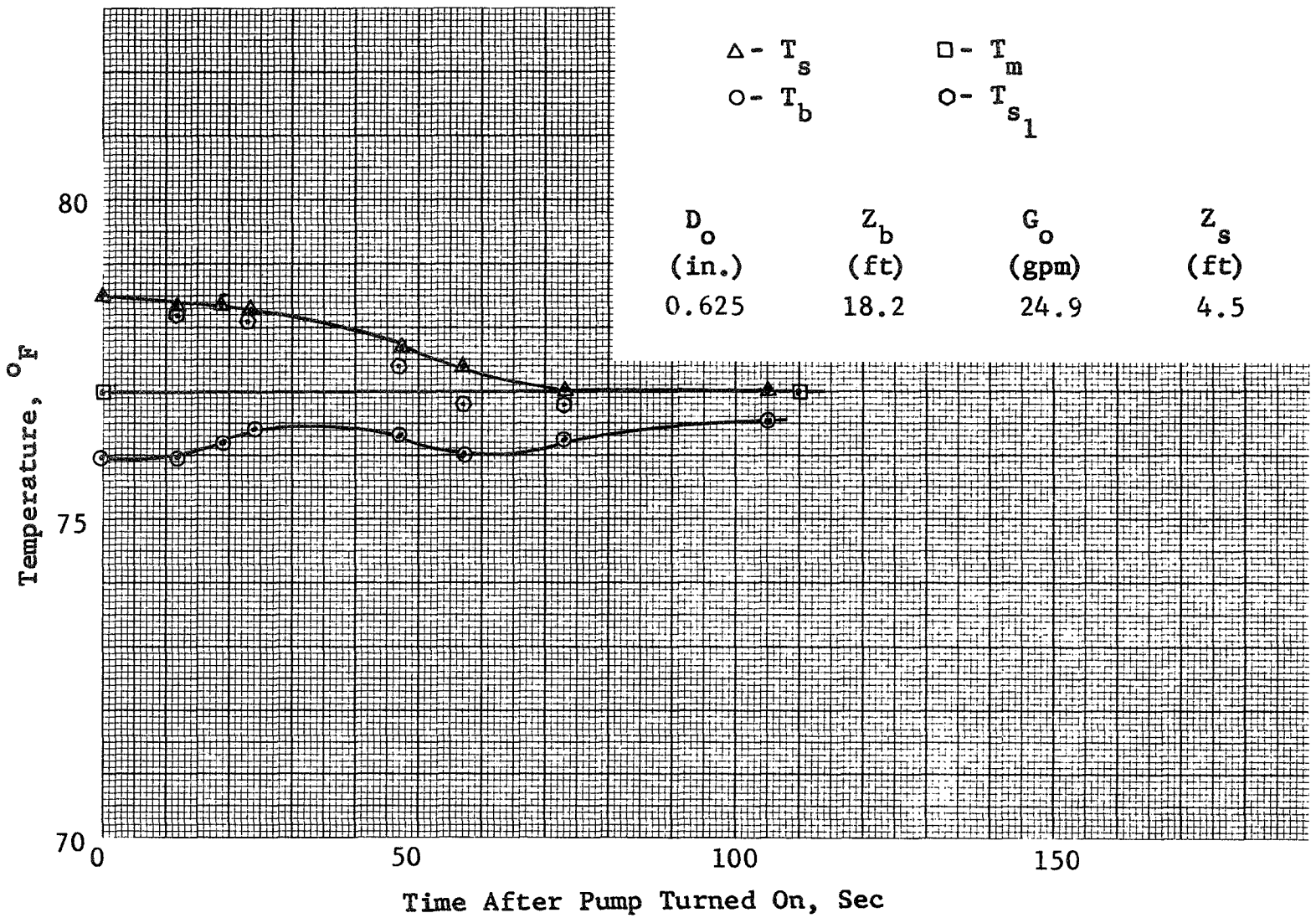

Figure 115 Transient Temperature Destratification: Run 30

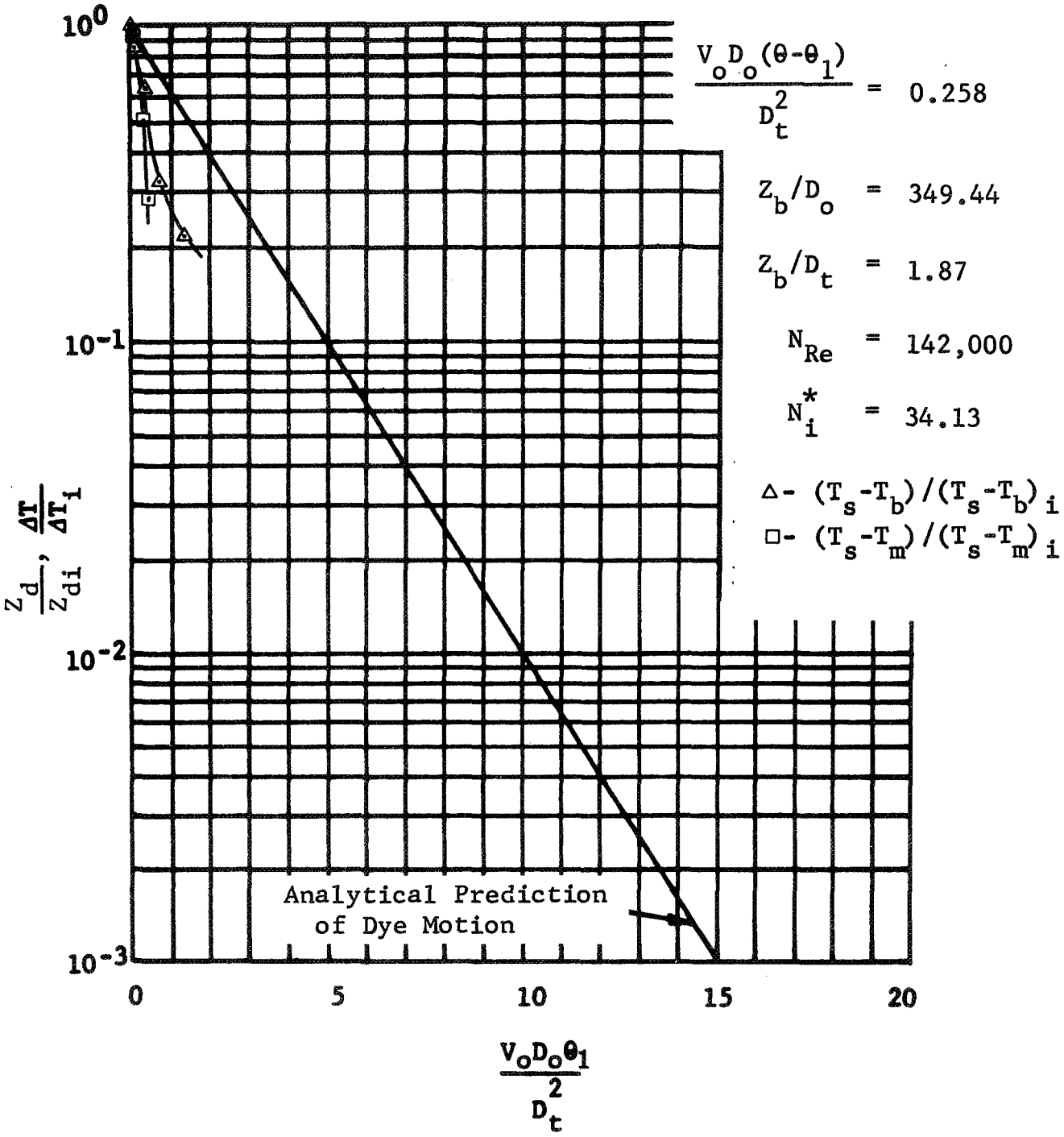

Figure 116 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 30

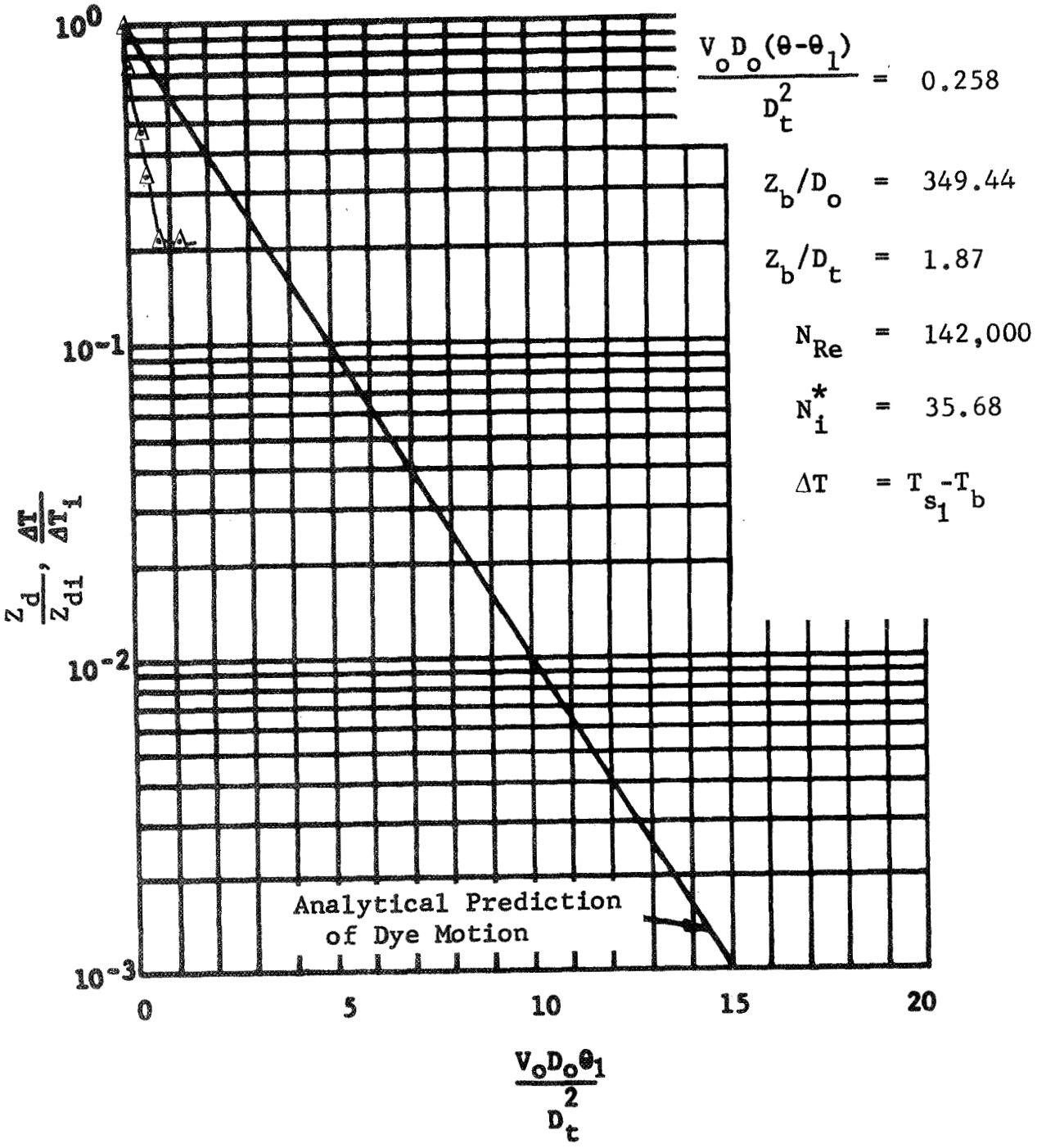

Figure 117 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop : Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 30

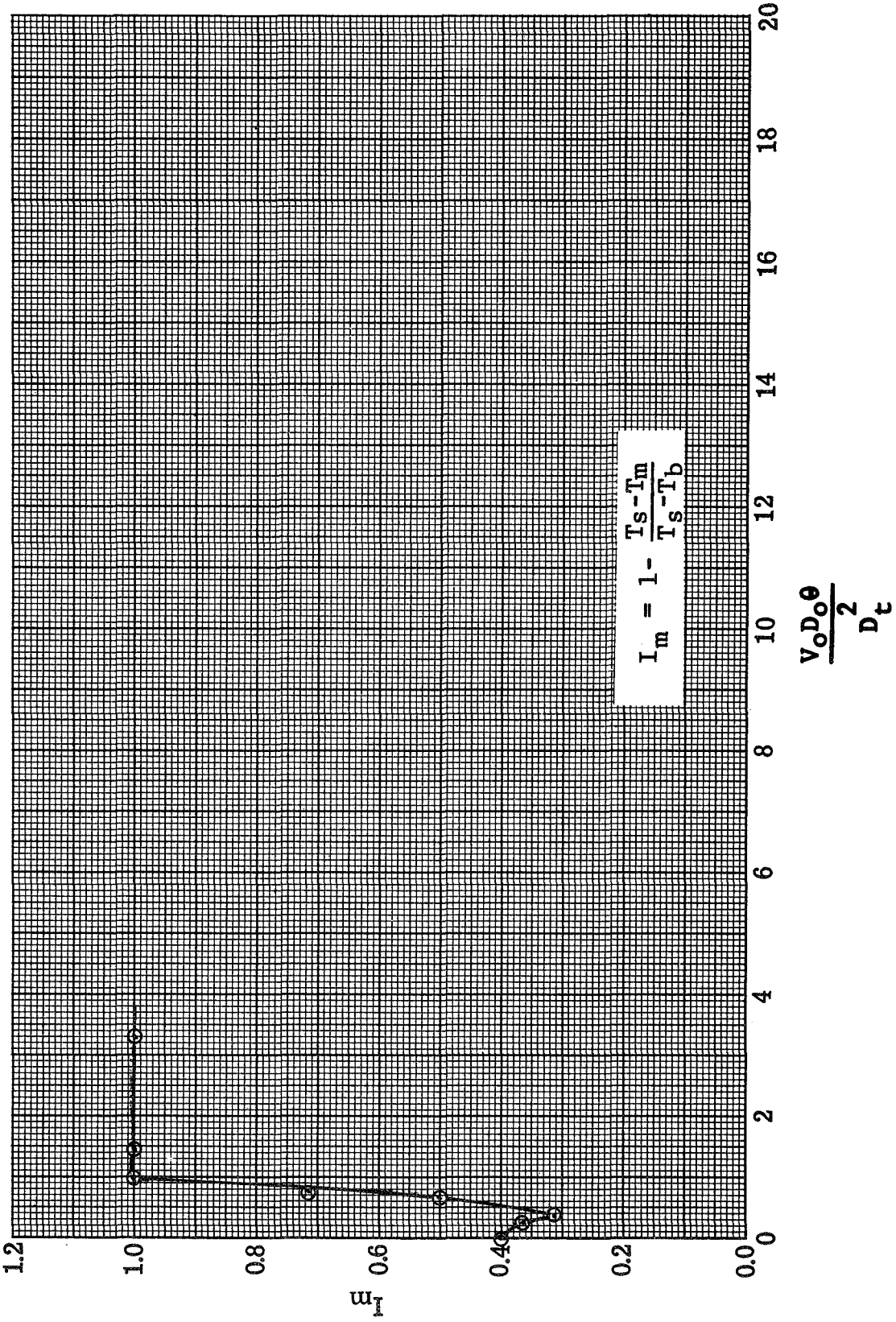

Figure 118 **Transient Energy Integral:** Run 30

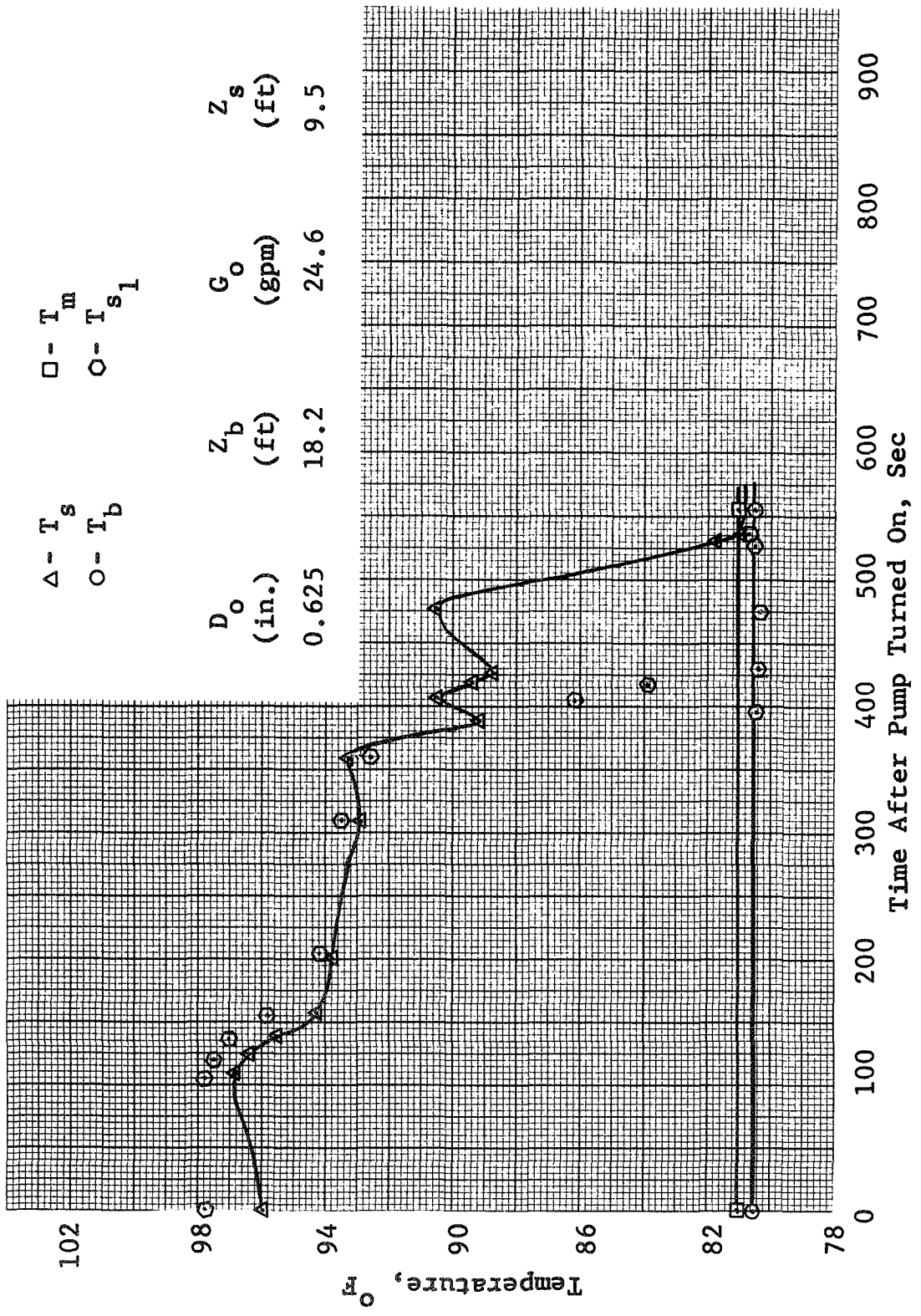

Figure 119 Transient Temperature Destratification: Run 31

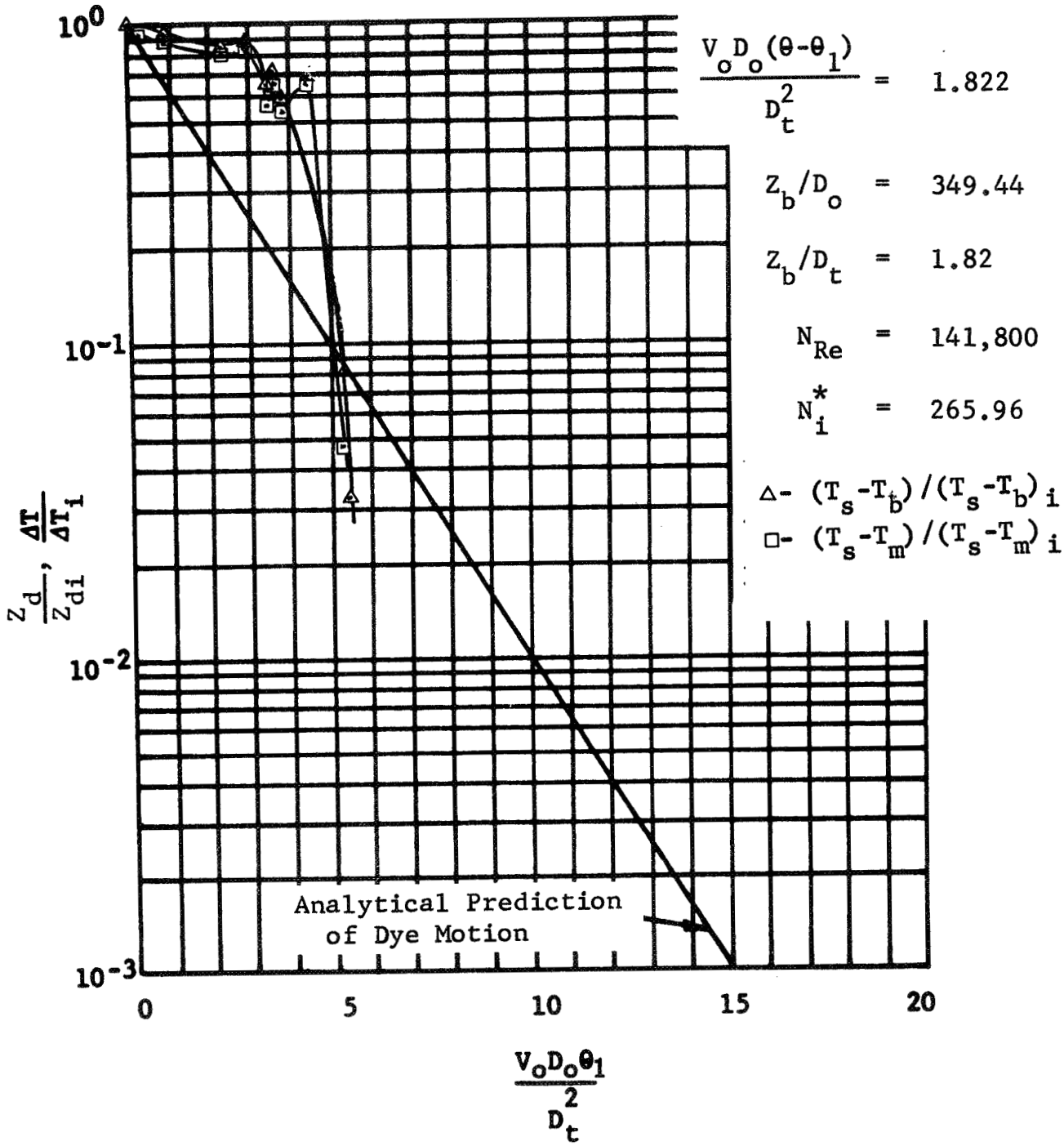

Figure 120 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 31

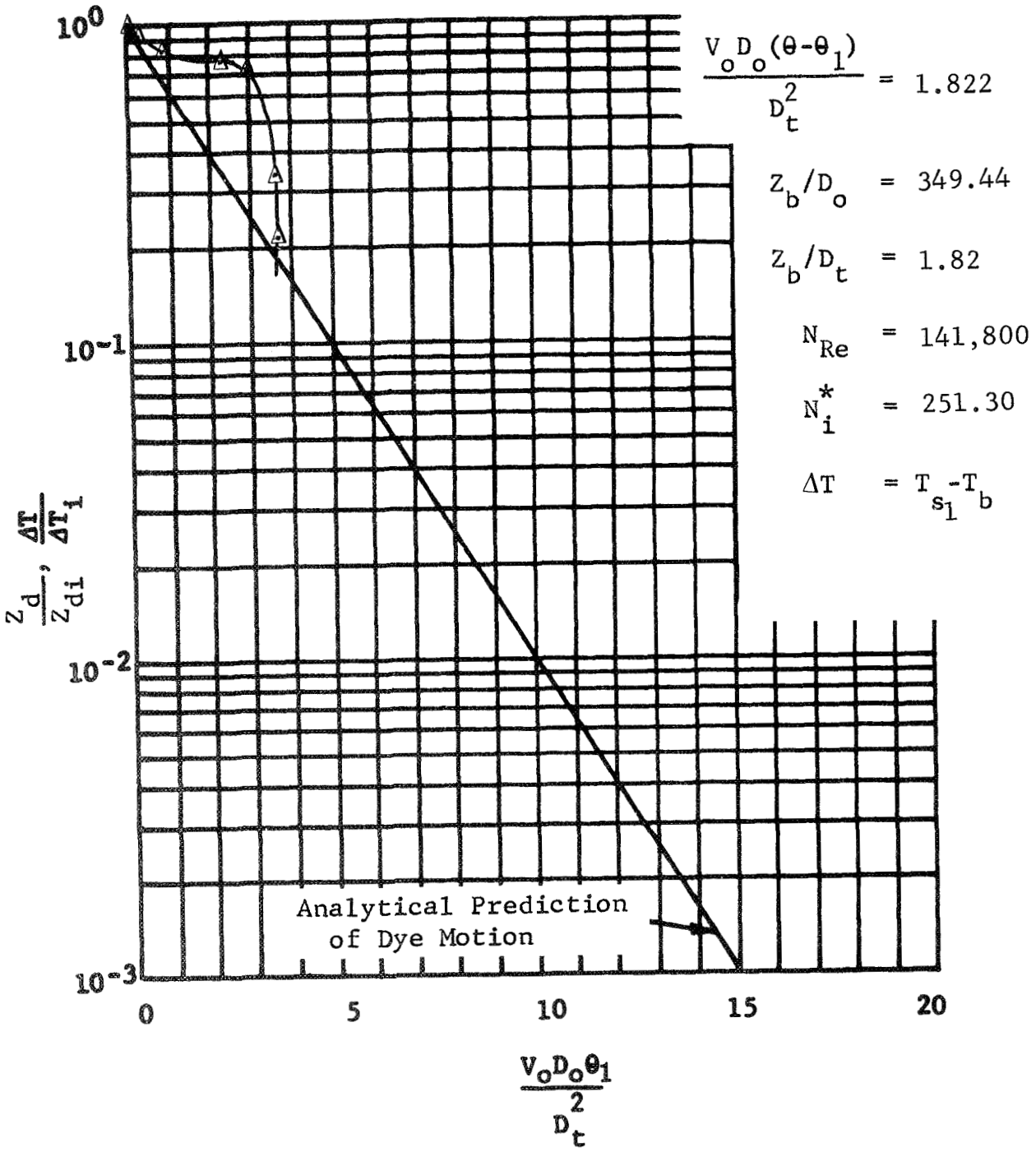

Figure 121 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop
Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 31

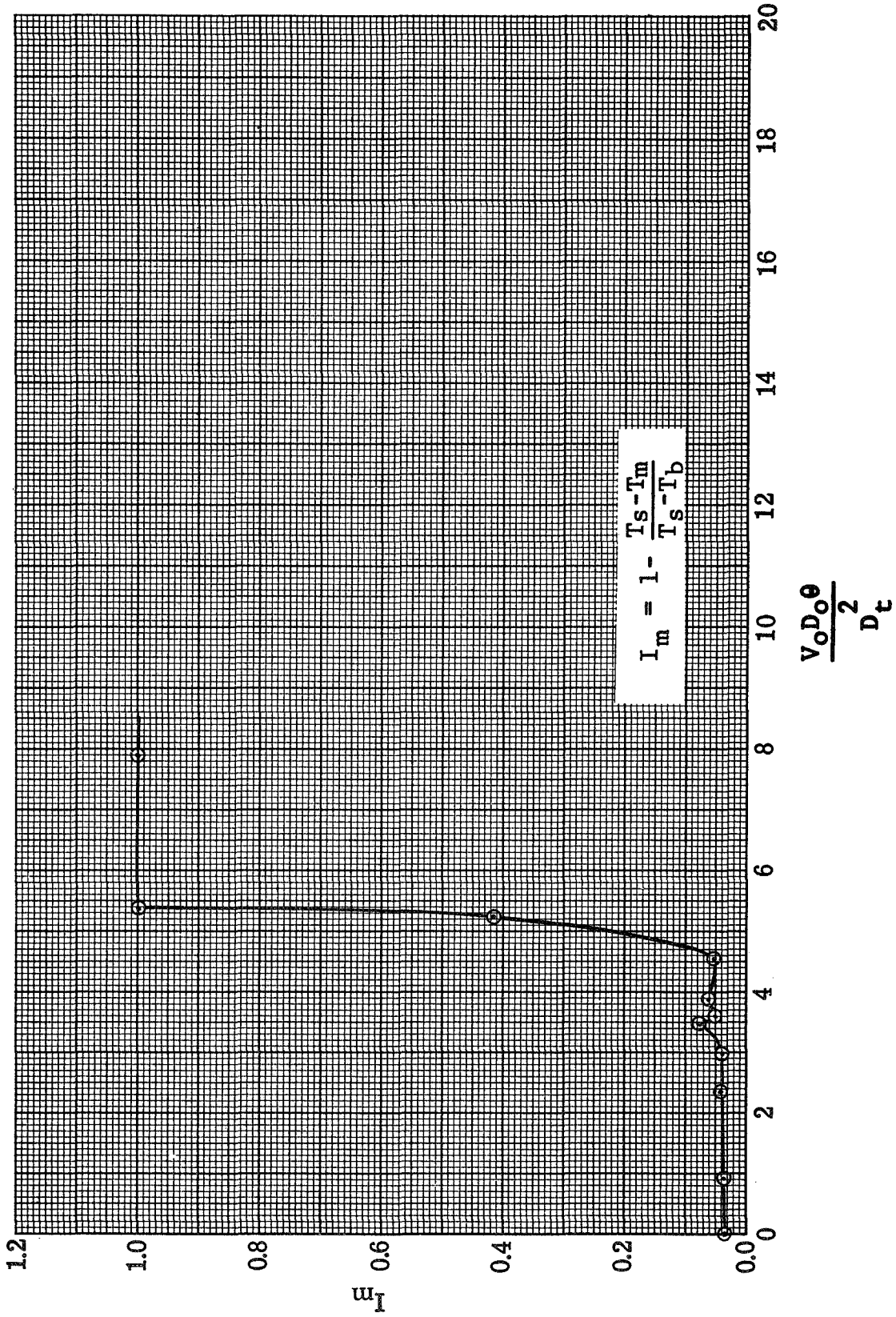

Figure 122 **Transient Energy Integral:** Run 31

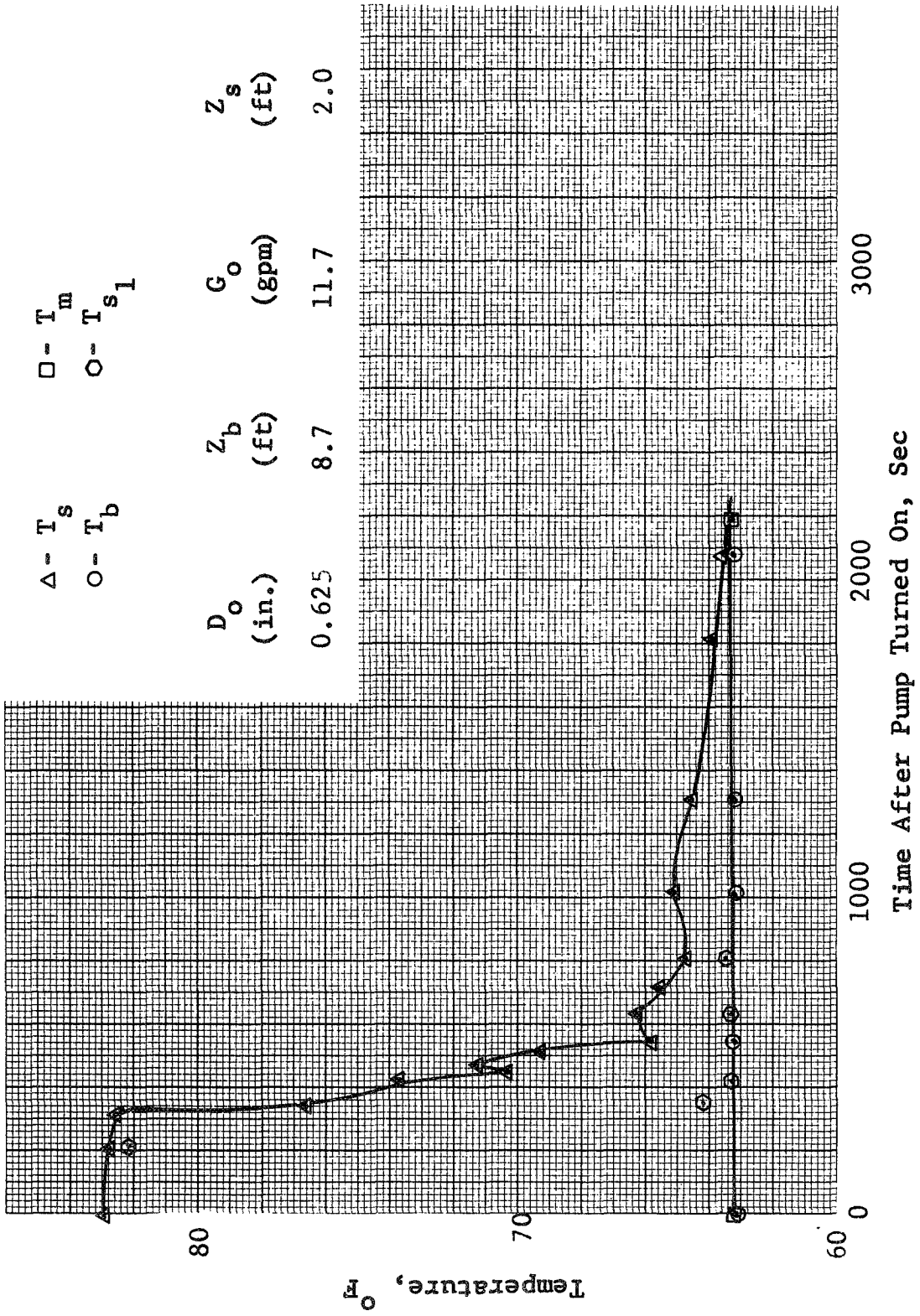

Figure 123 Transient Temperature Destratification : Run 32

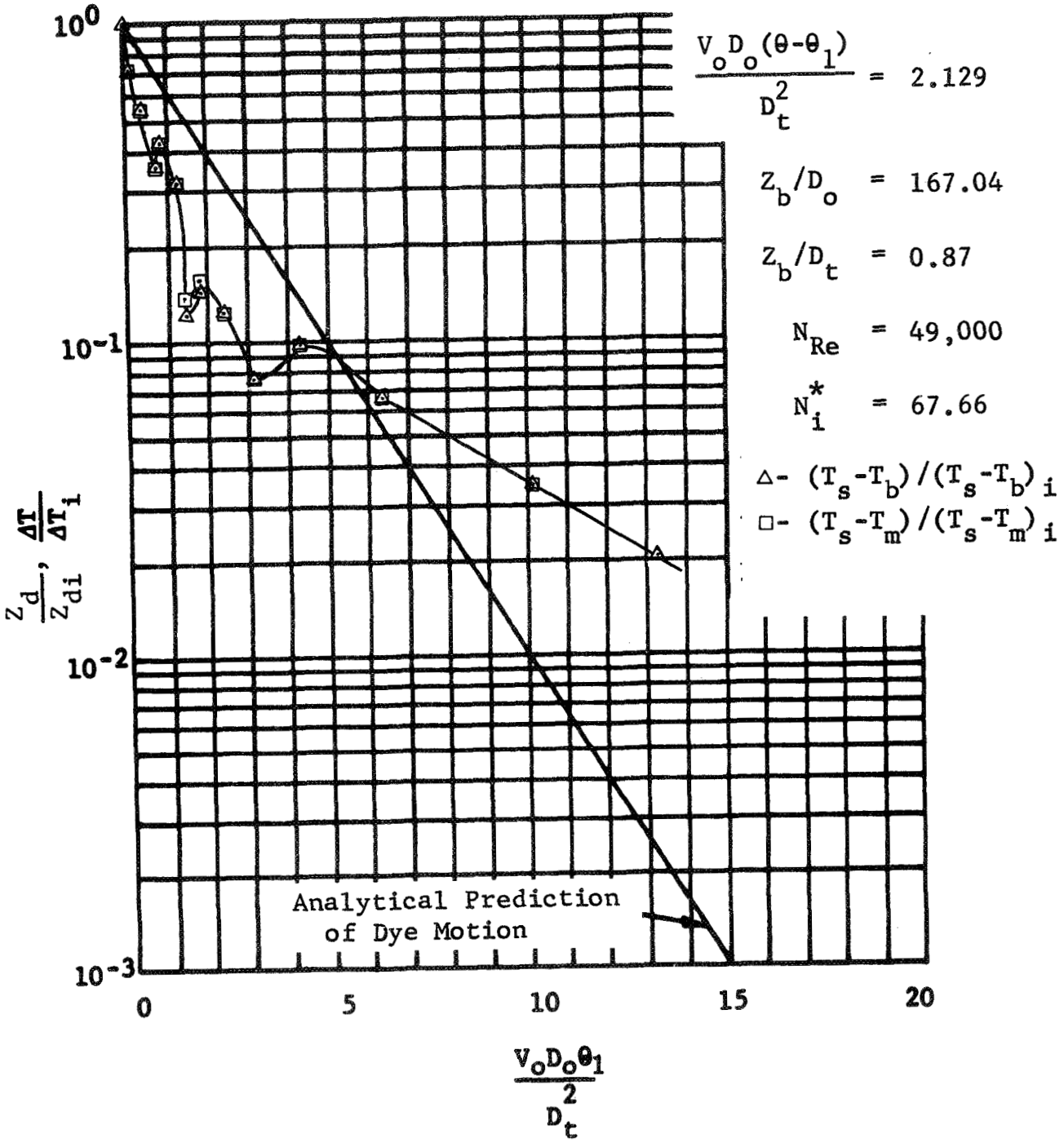

Figure 124 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 32

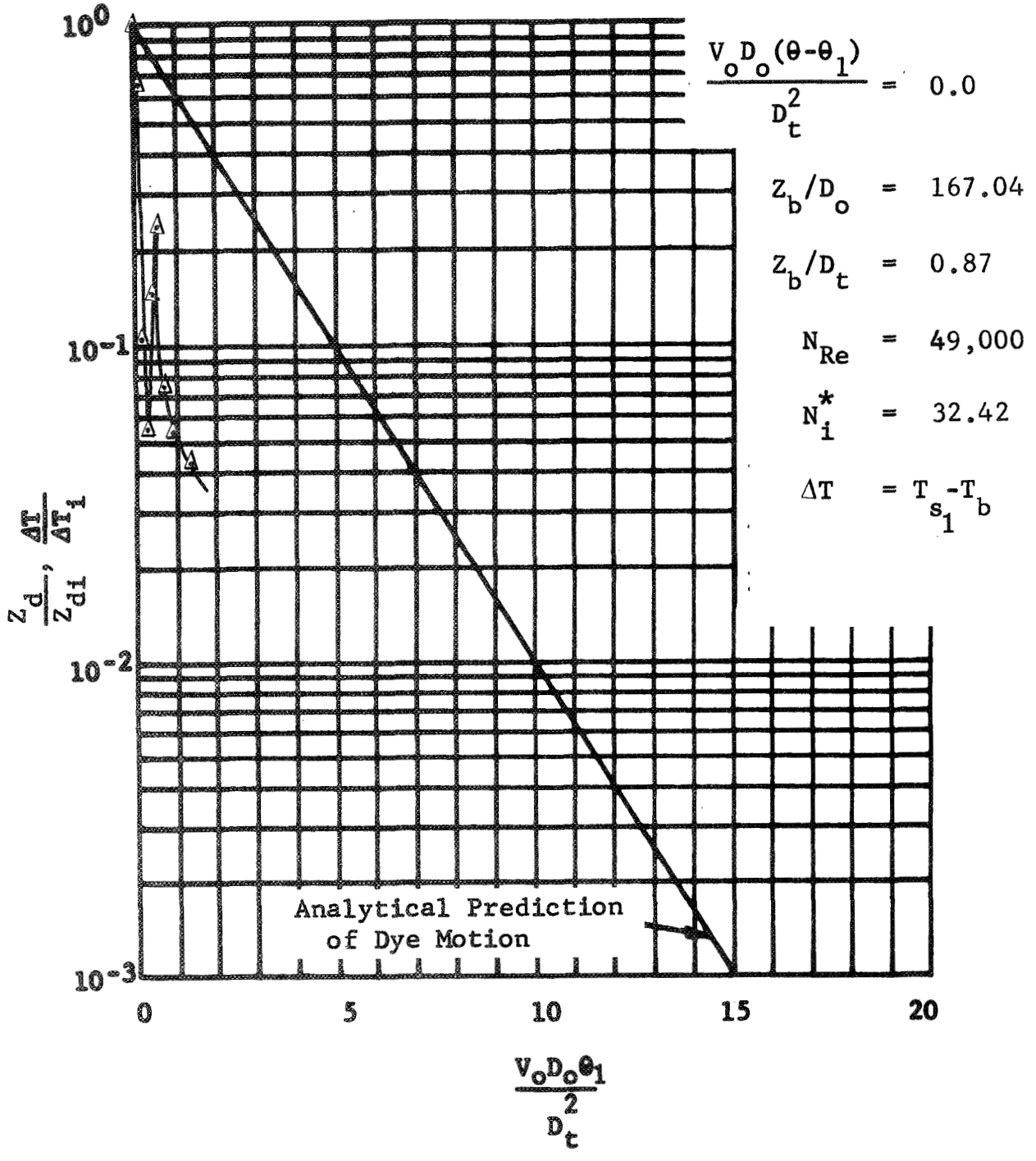

Figure 125 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 32

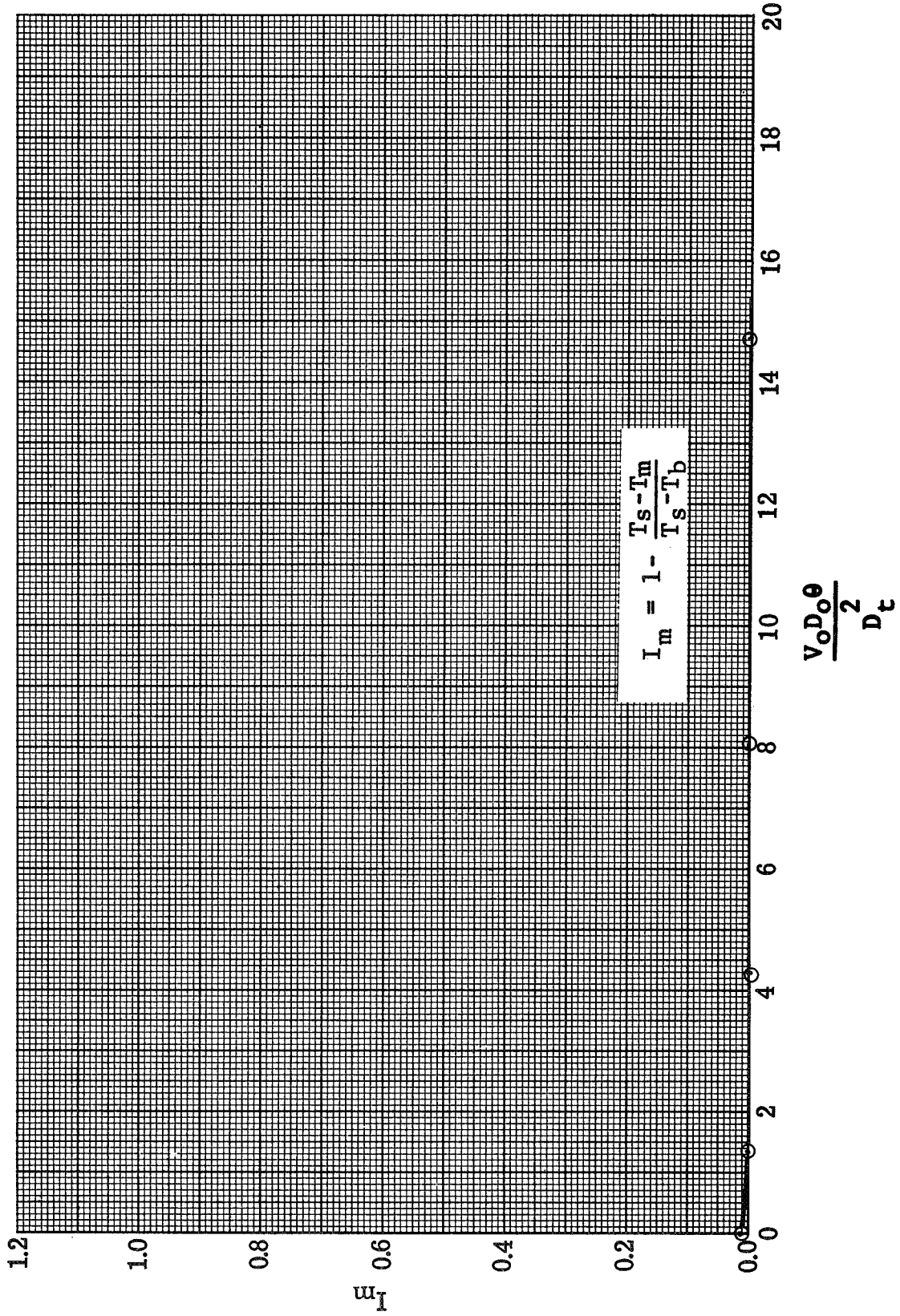

Figure 126 **Transient Energy Integral:** Run 32

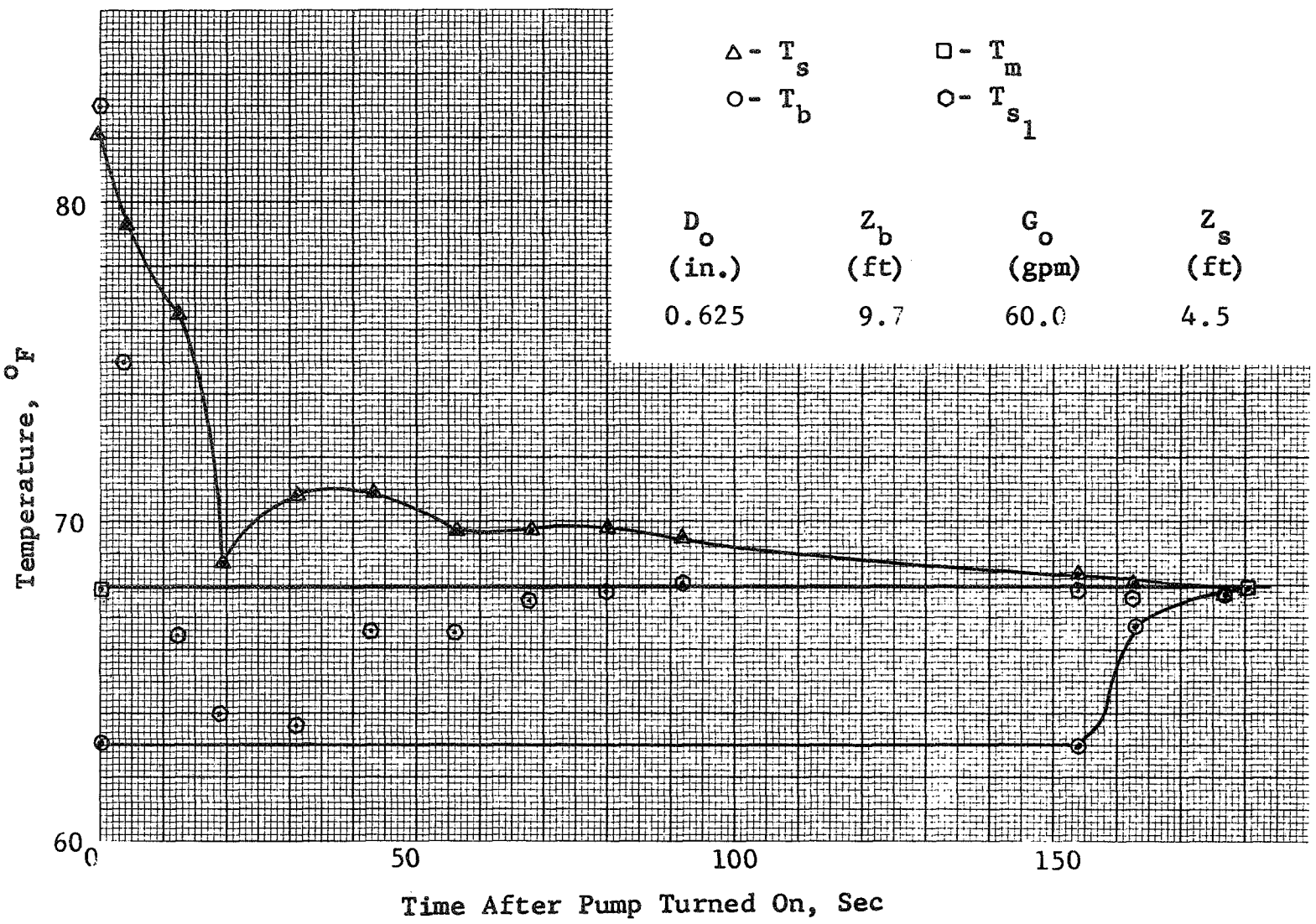

Figure 127 Transient Temperature Destratification: Run 33

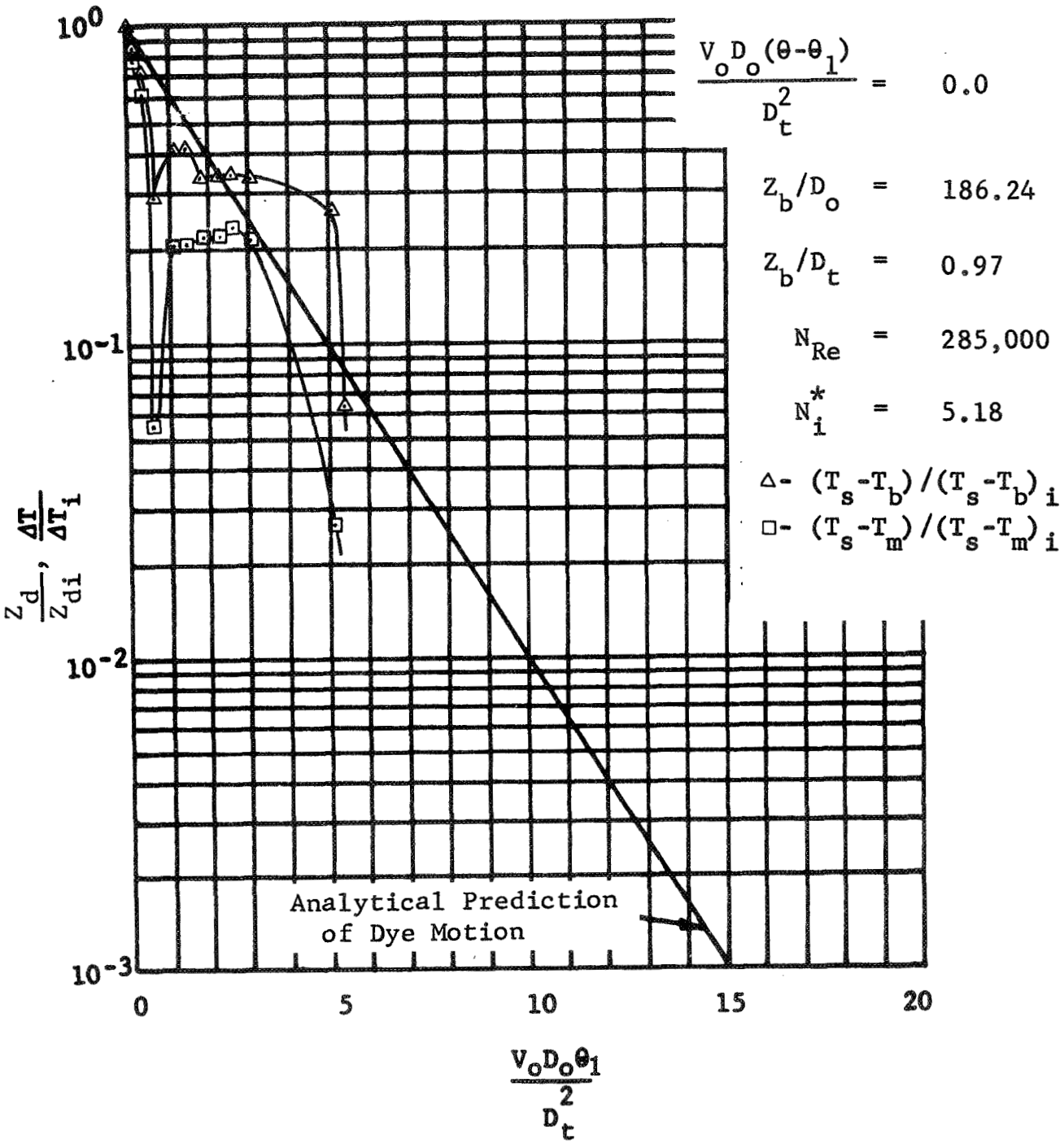

Figure 128 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 33

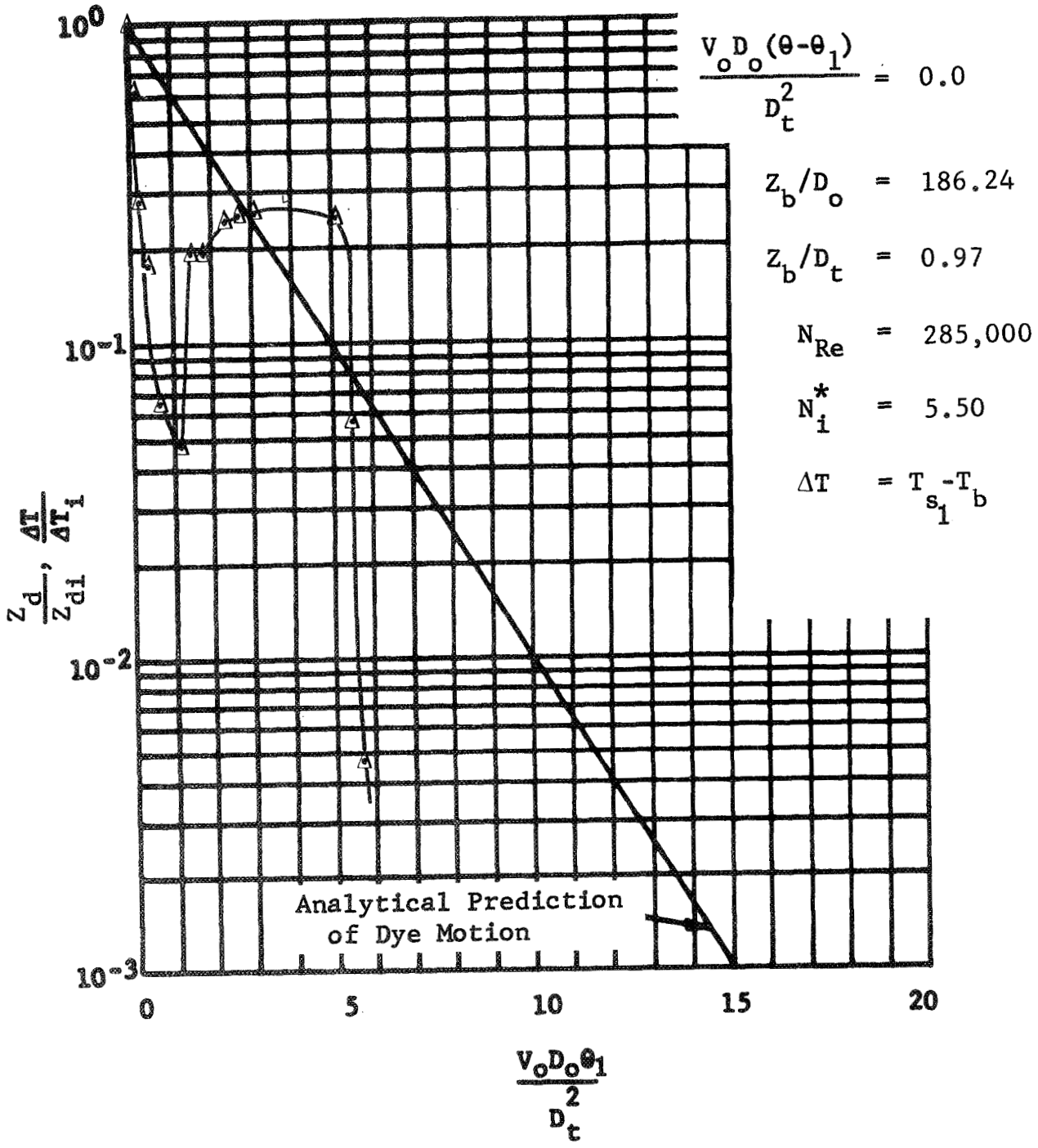

Figure 129 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 33

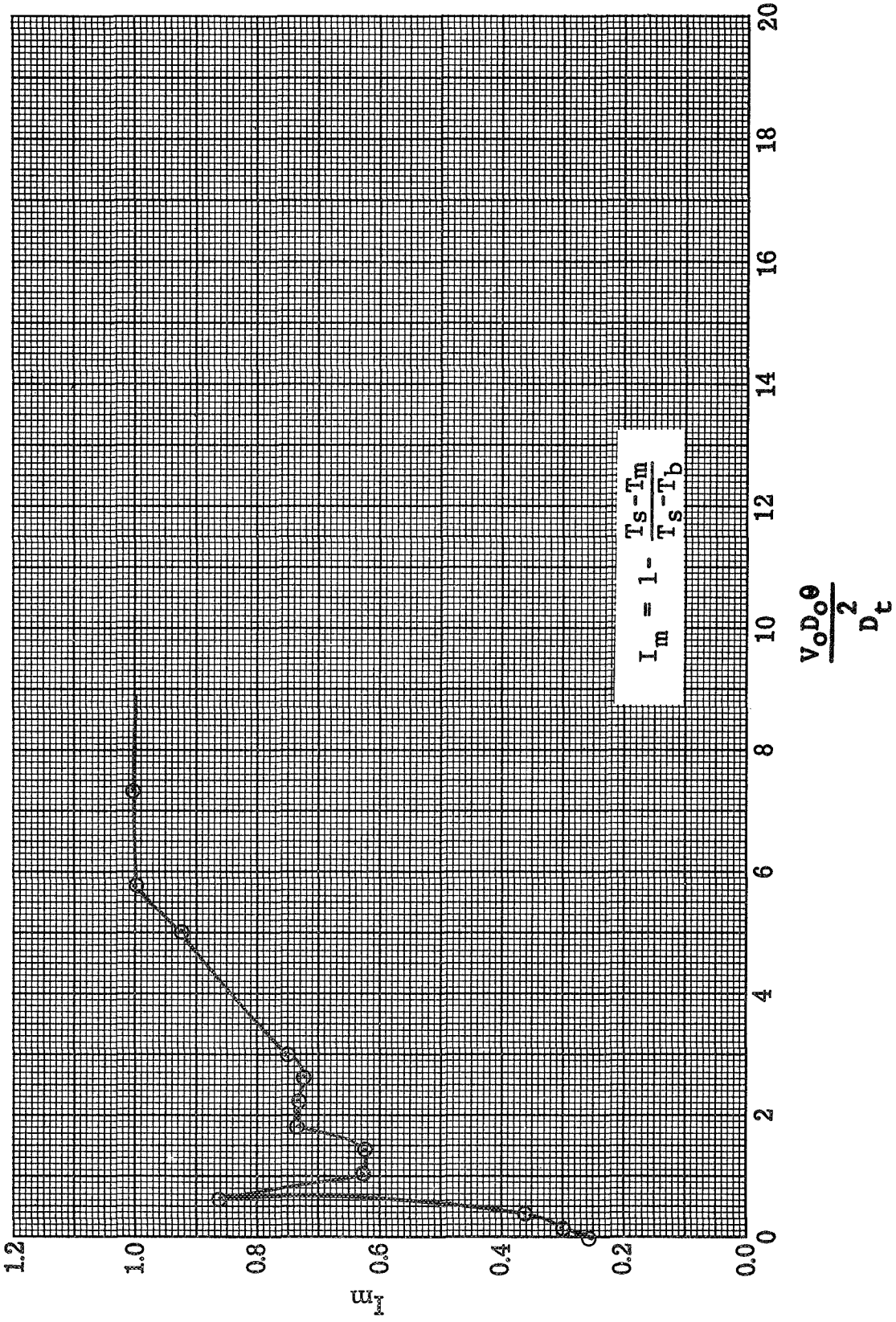

Figure 130 Transient Energy Integral: Run 33

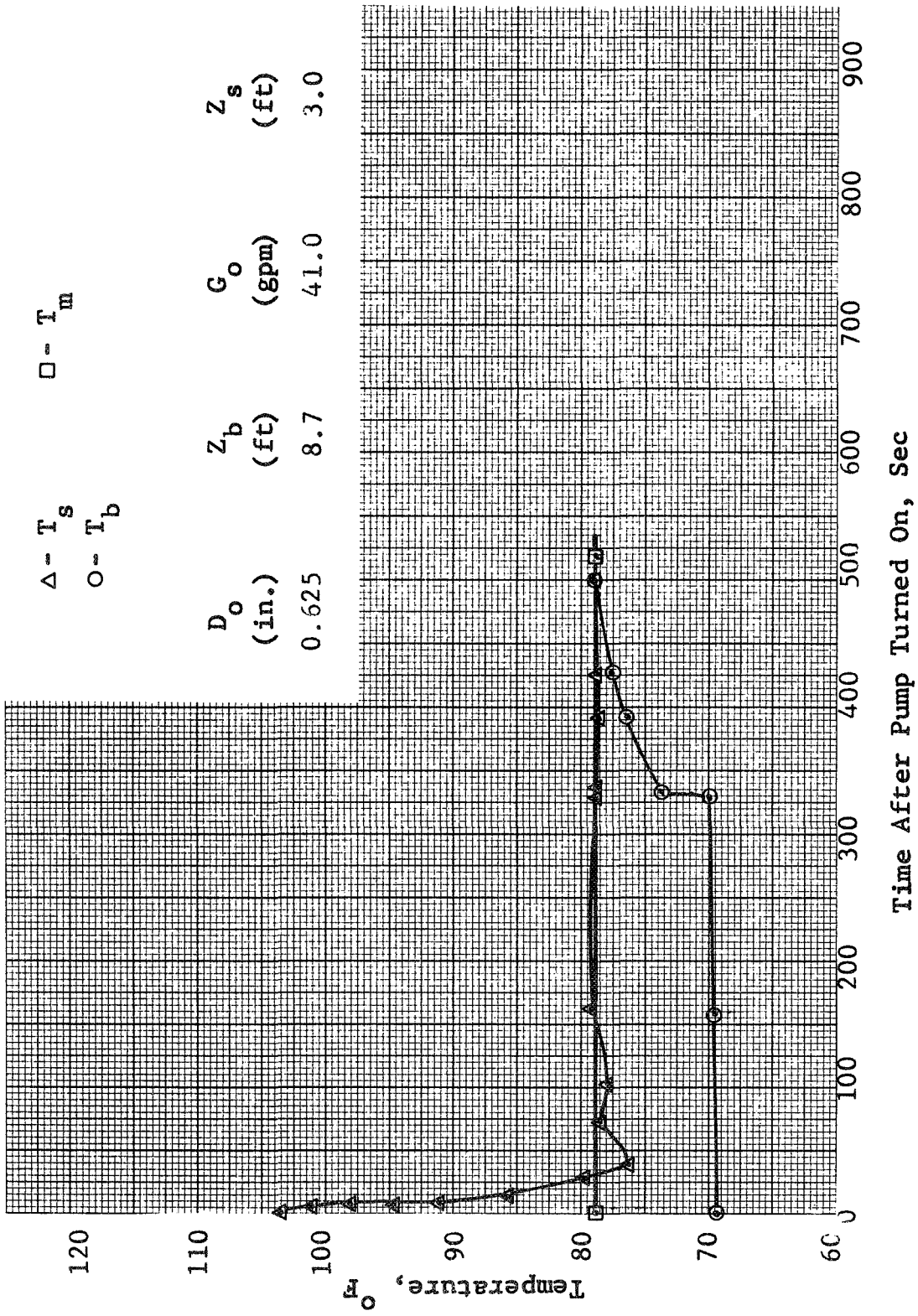

Figure 131 Transient Temperature Destratification: Run 34

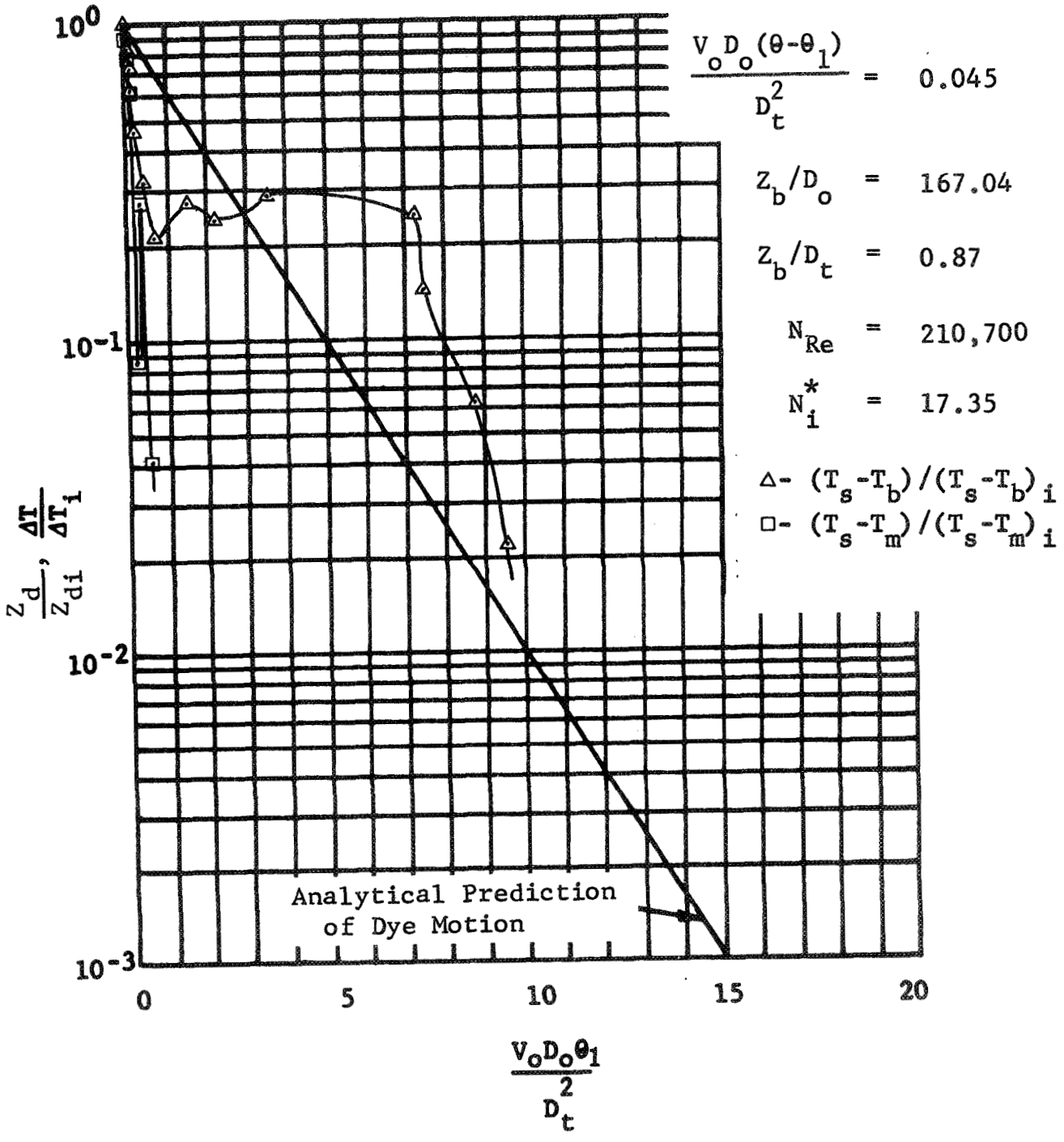

Figure 132 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at $\theta = 0.0$ sec; Average Surface Temperature Drop Starts at $\theta_1 = 0.0$ sec; Run 34

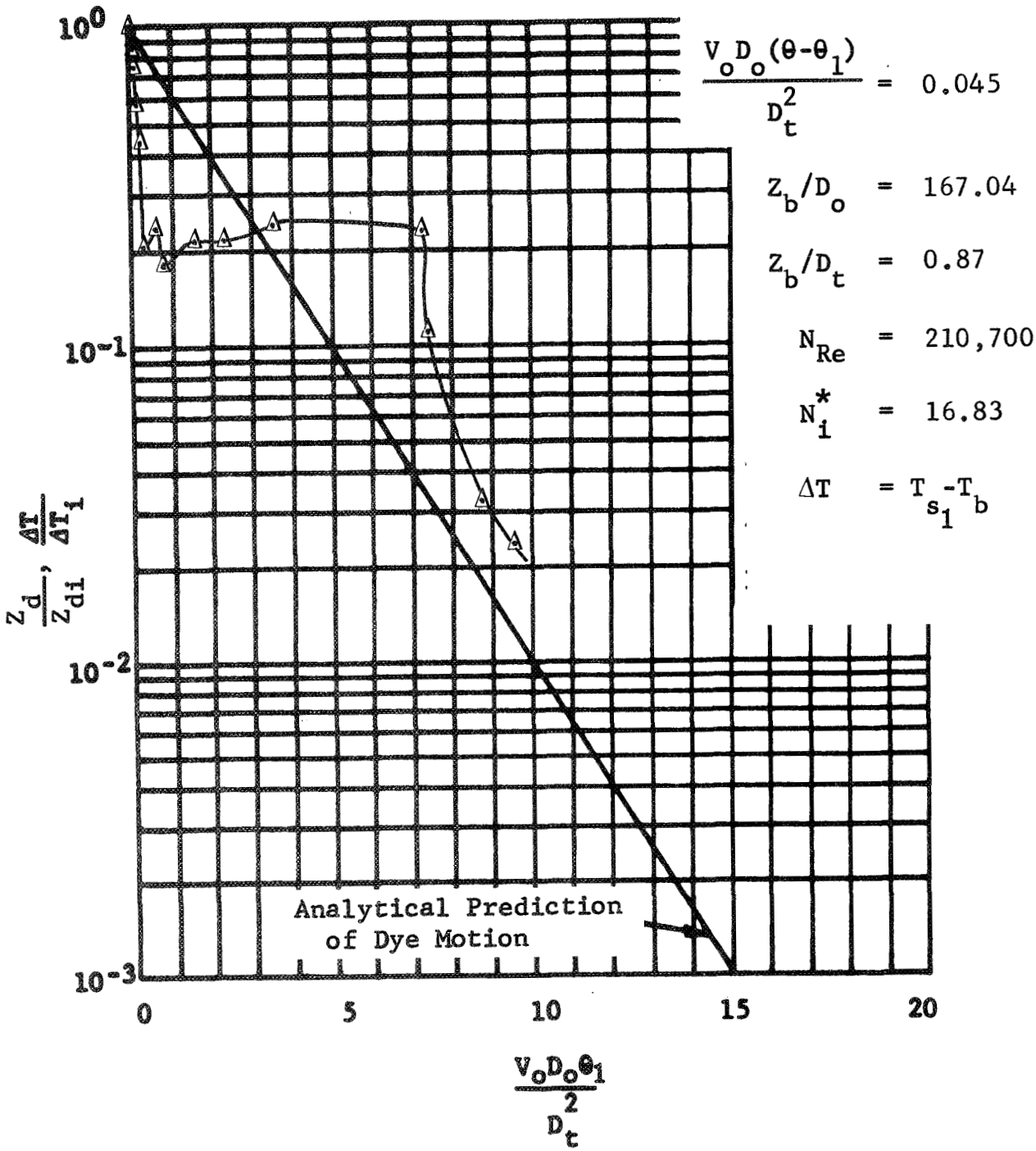

Figure 133 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at $\theta = 0.0$ sec; Centerline Surface Temperature Drop Starts at $\theta_1 = 0.0$ sec; Run 34

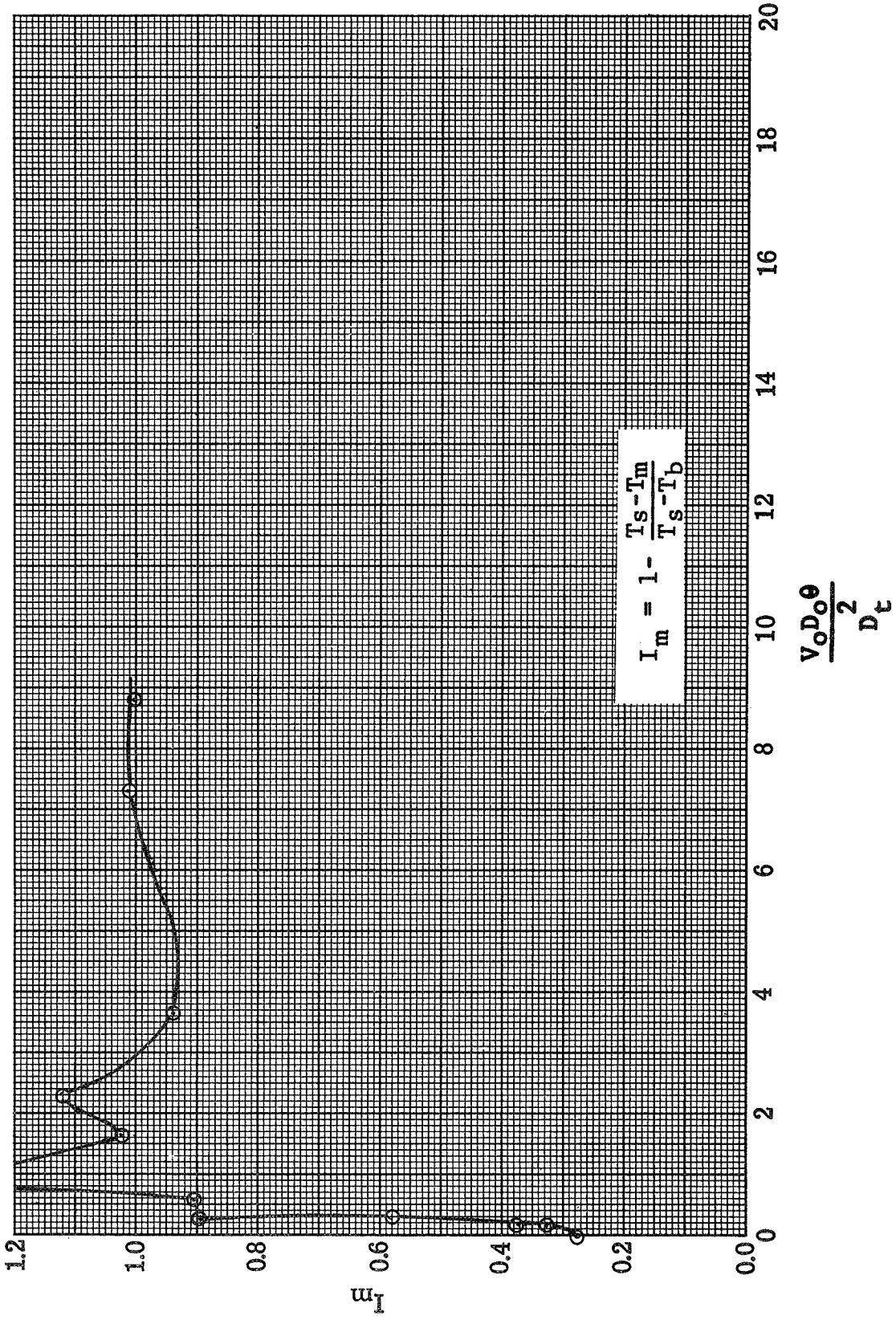

Figure 134 Transient Energy Integral: Run 34

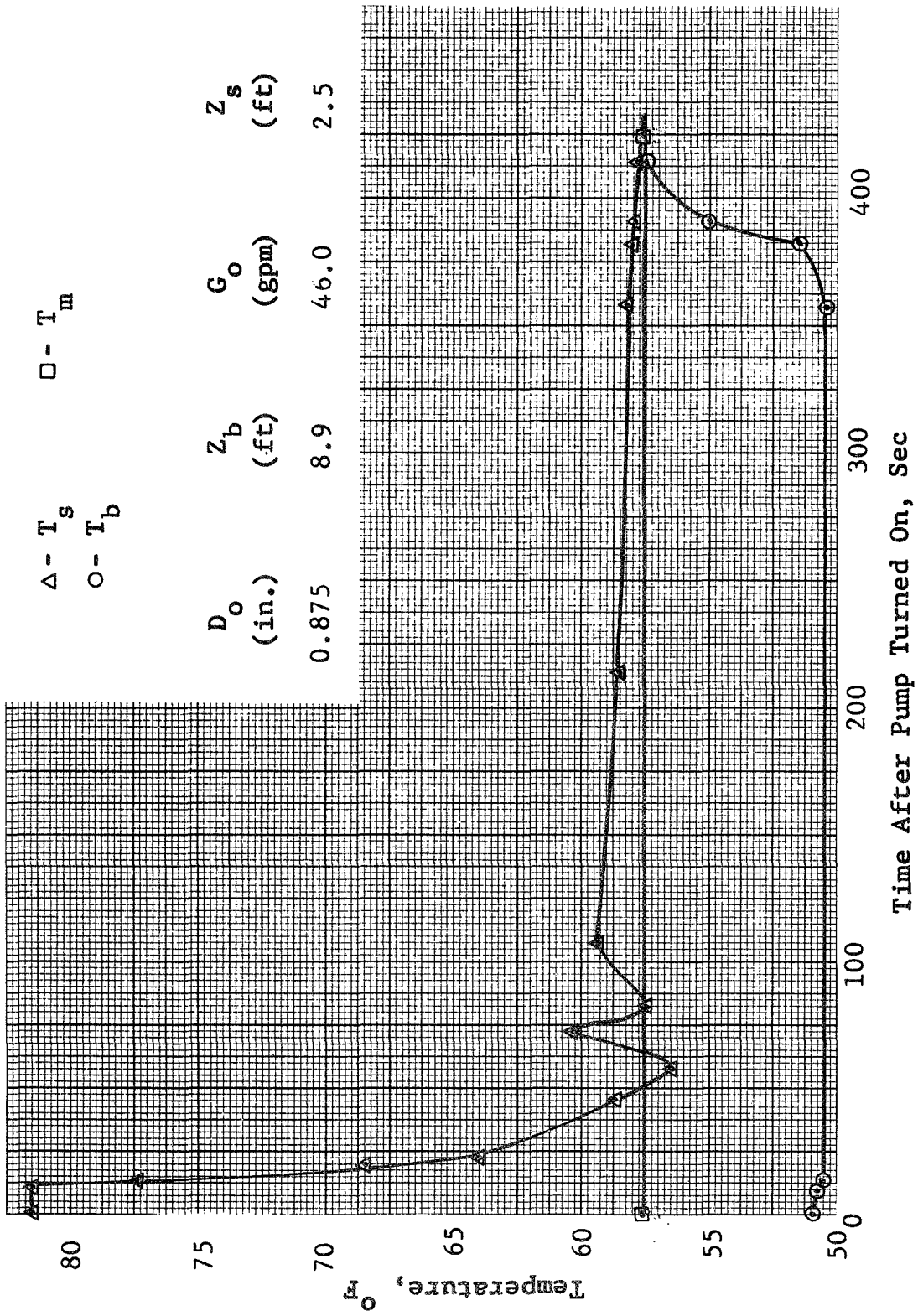

Figure 135 Transient Temperature Destratification: Run 35

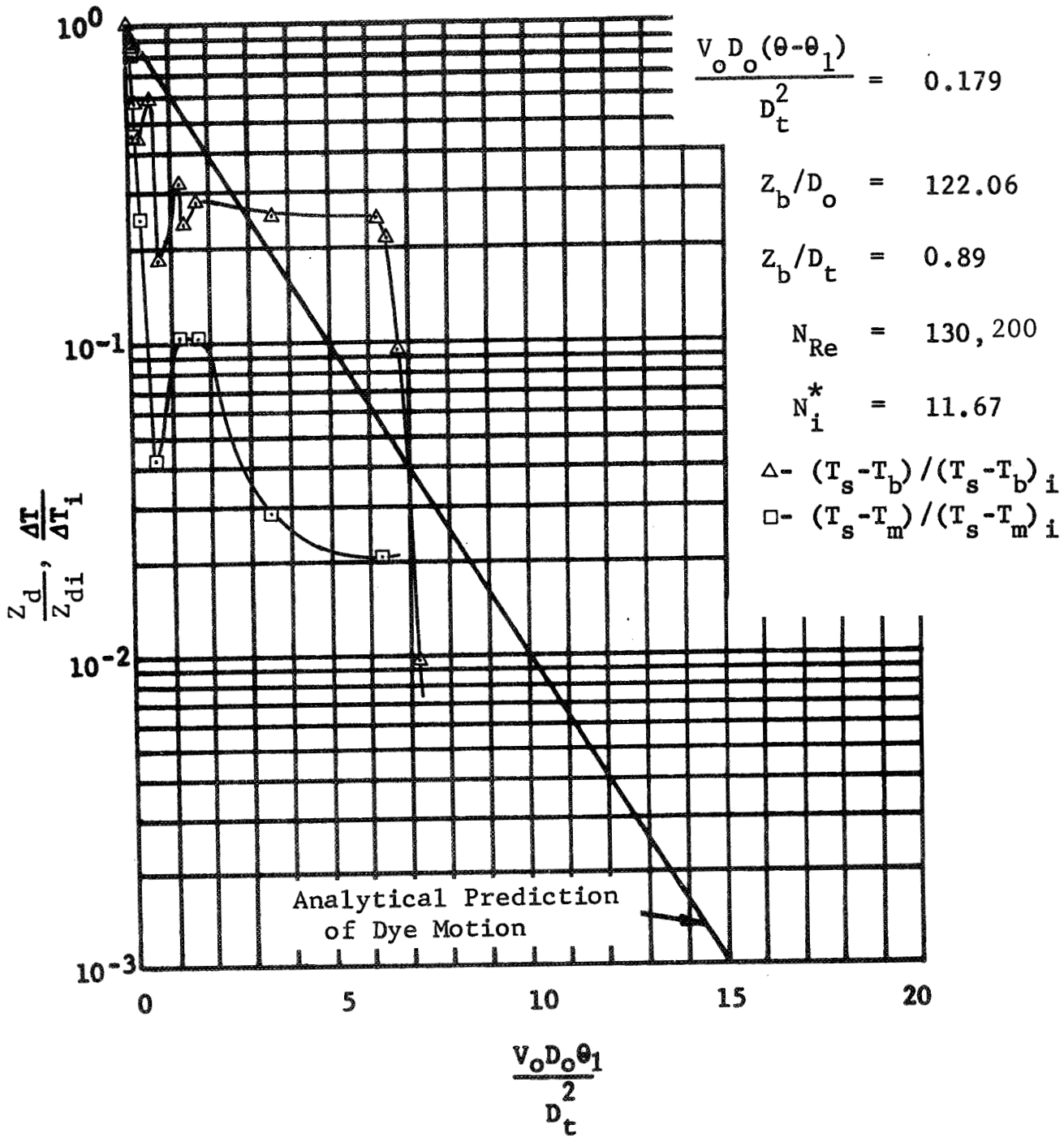

Figure 136 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 35

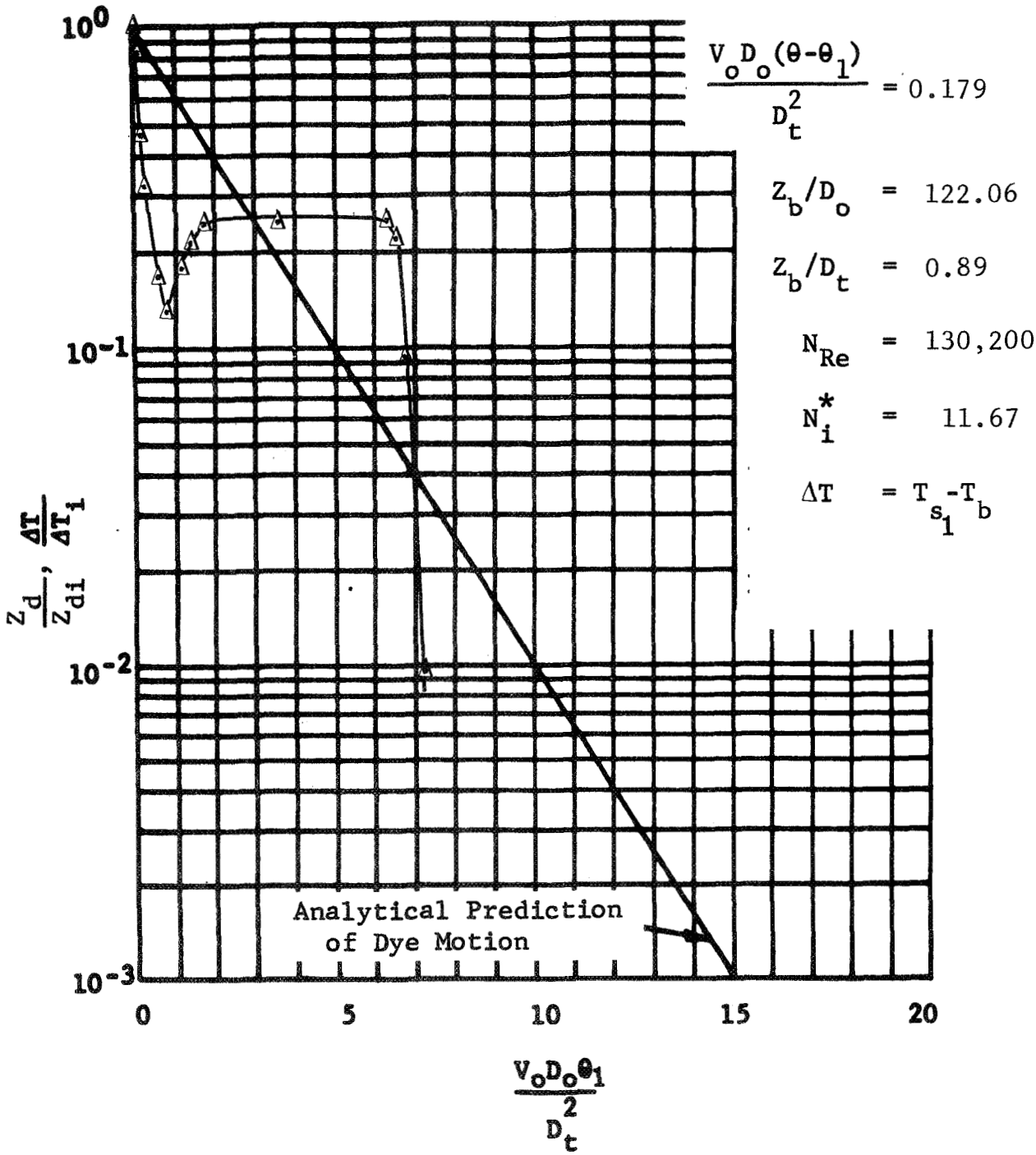

Figure 137 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 35

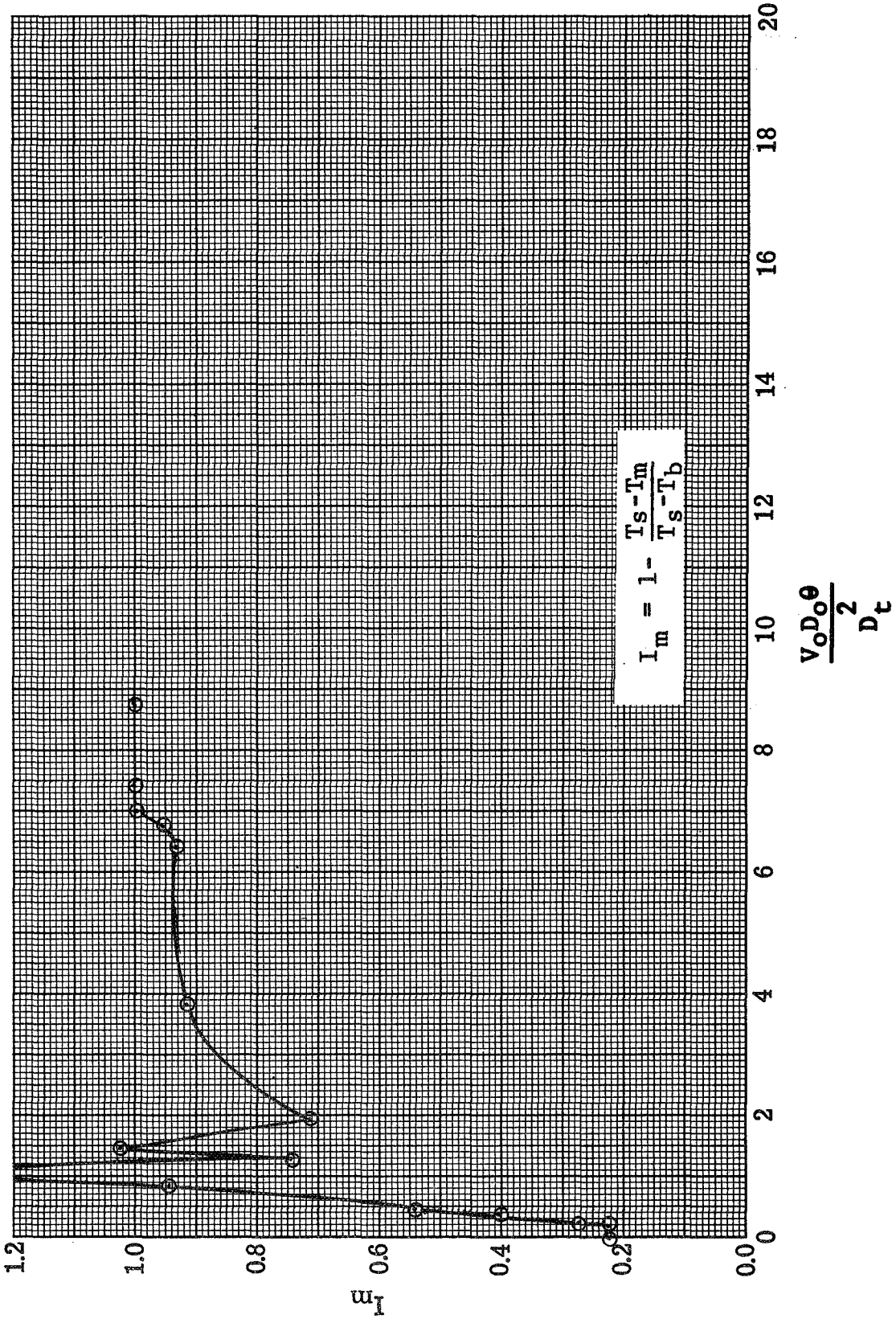

Figure 138 **Transient Energy Integral:** Run 35

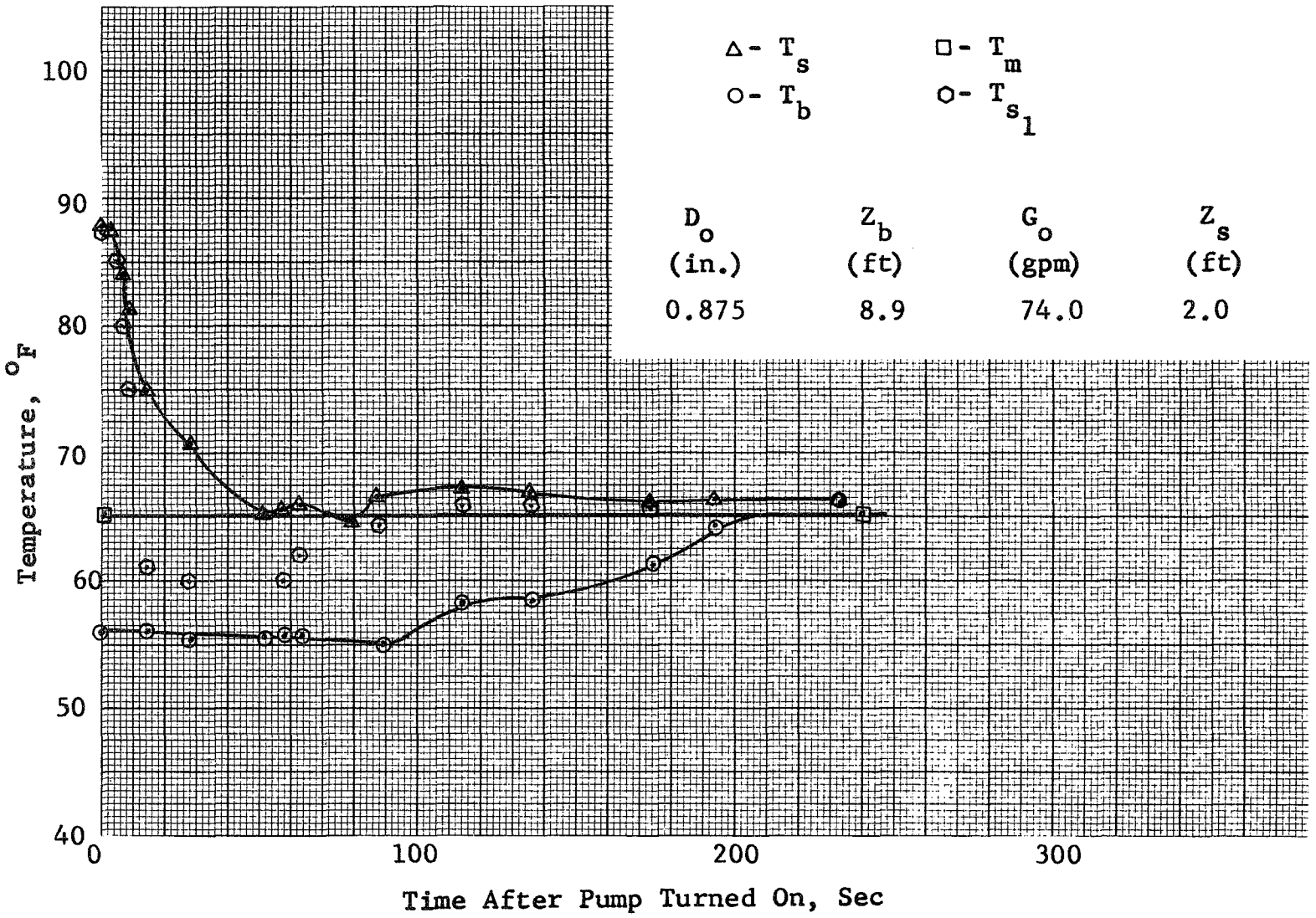

Figure 139 Transient Temperature Destratification: Run 36

GENERAL DYNAMICS
Fort Worth Division

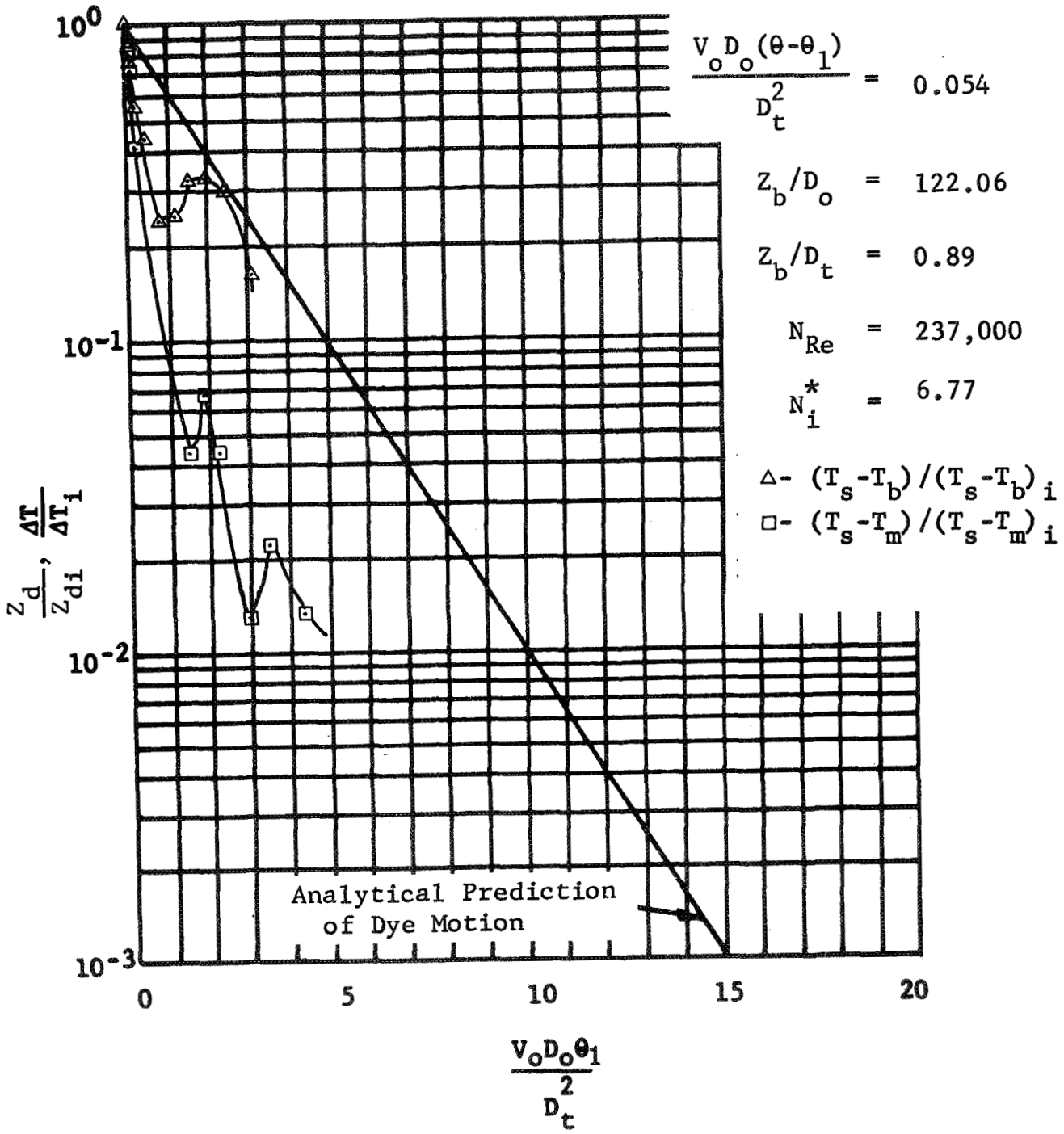

Figure 140 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 36

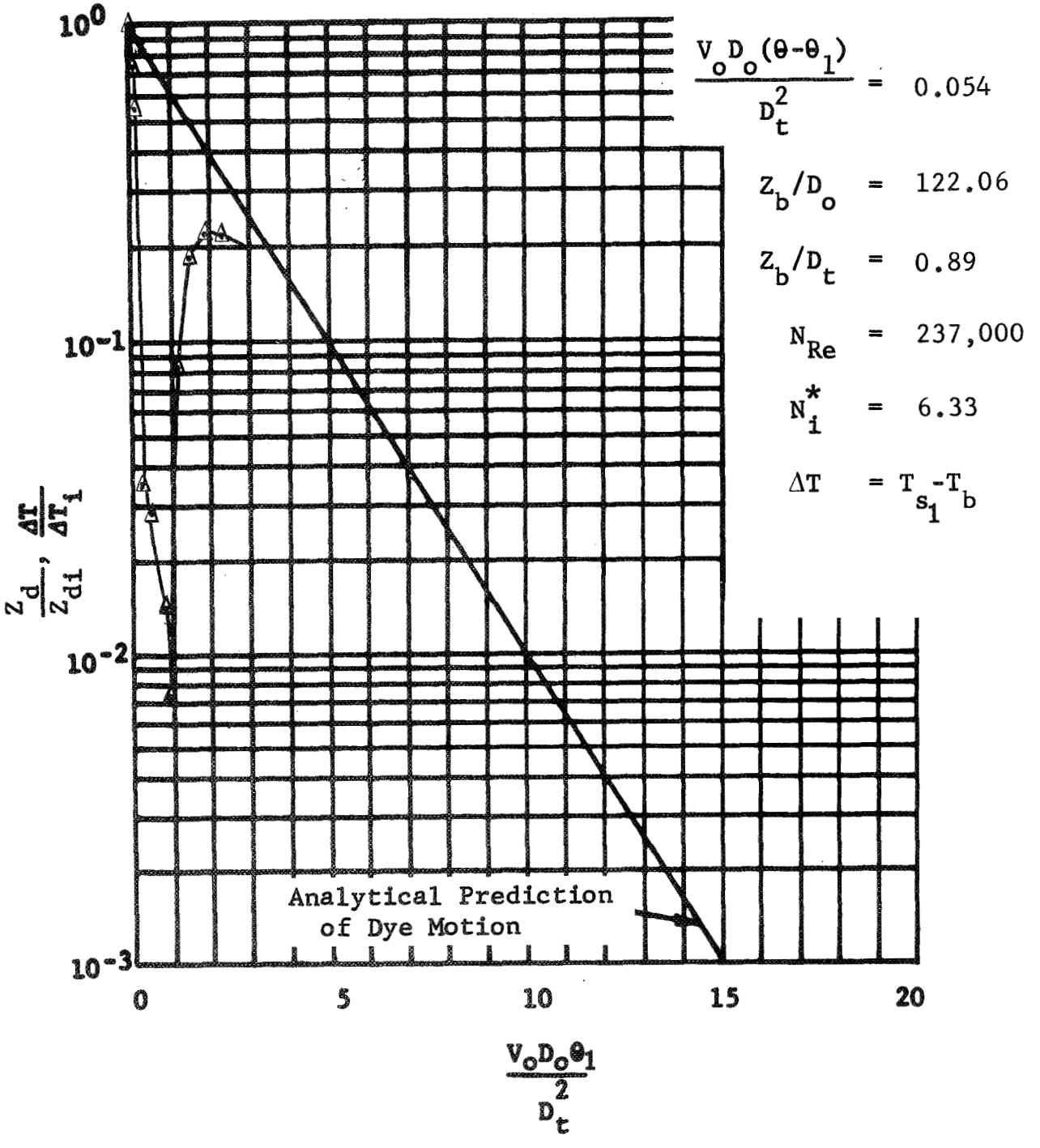

Figure 141 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at $\theta = 0.0$ sec; Centerline Surface Temperature Drop Starts at $\theta_1 = 0.0$ sec; Run 36

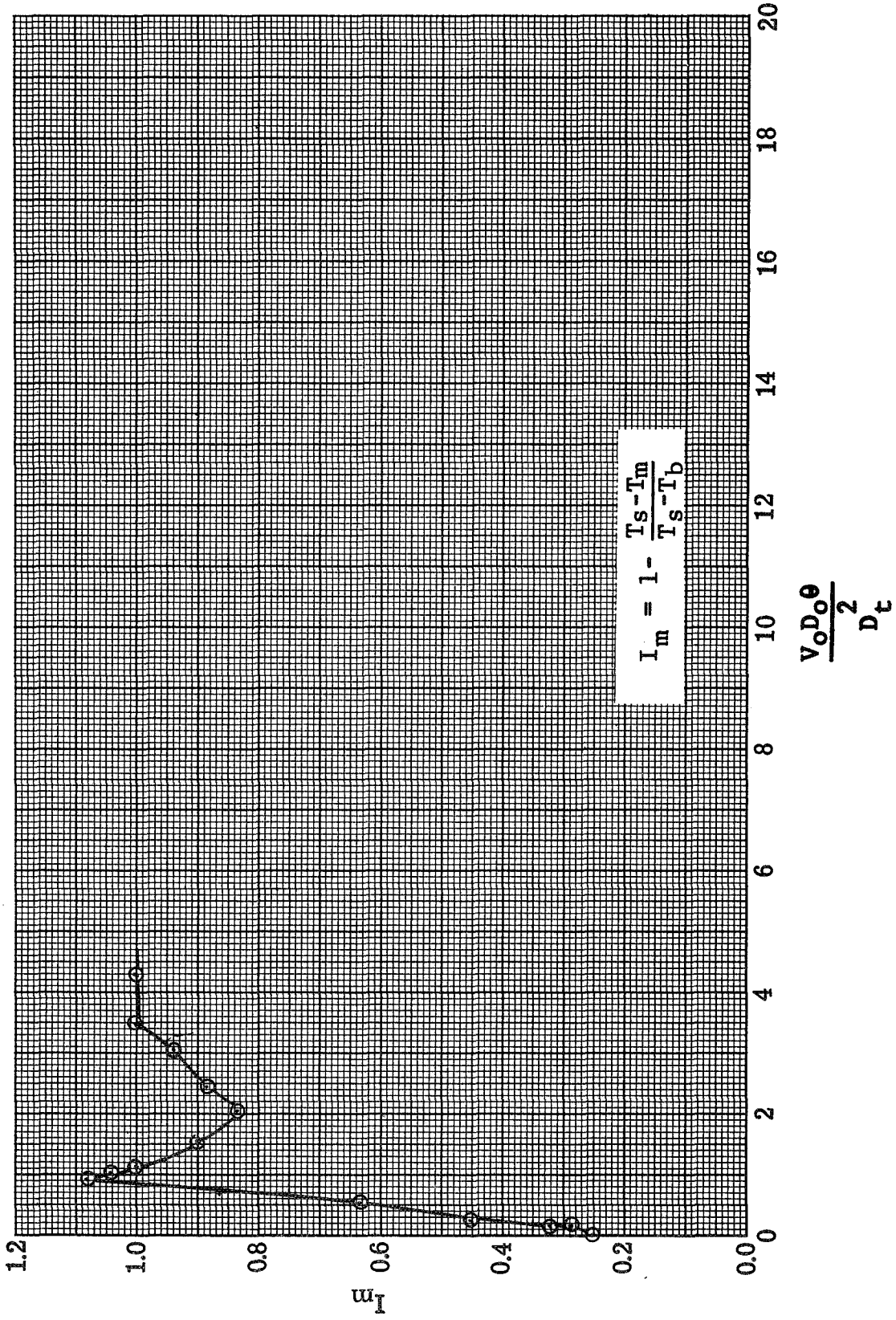

Figure 142 **Transient Energy Integral:** Run 36

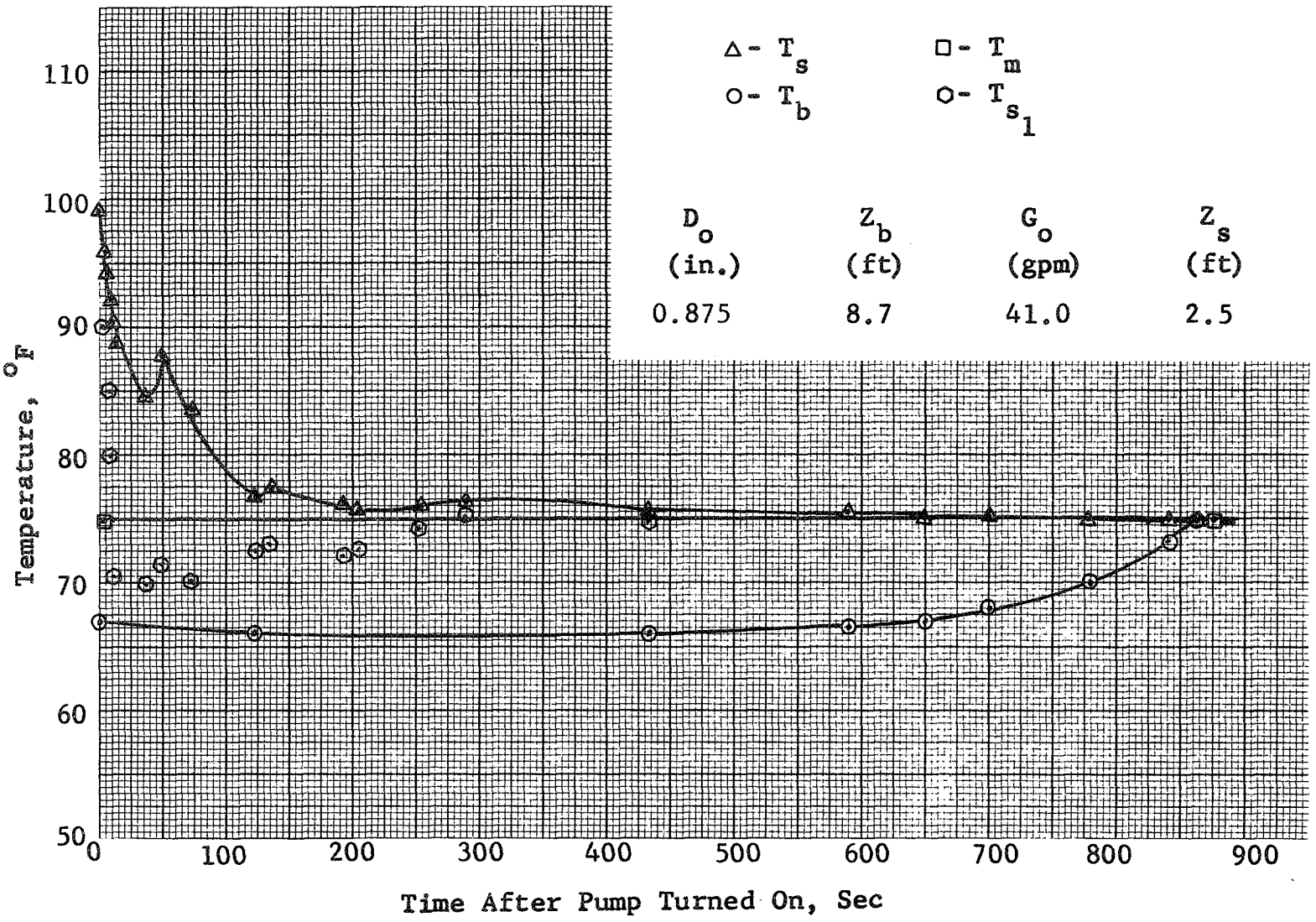

Figure 143 Transient Temperature Destratification: Run 37

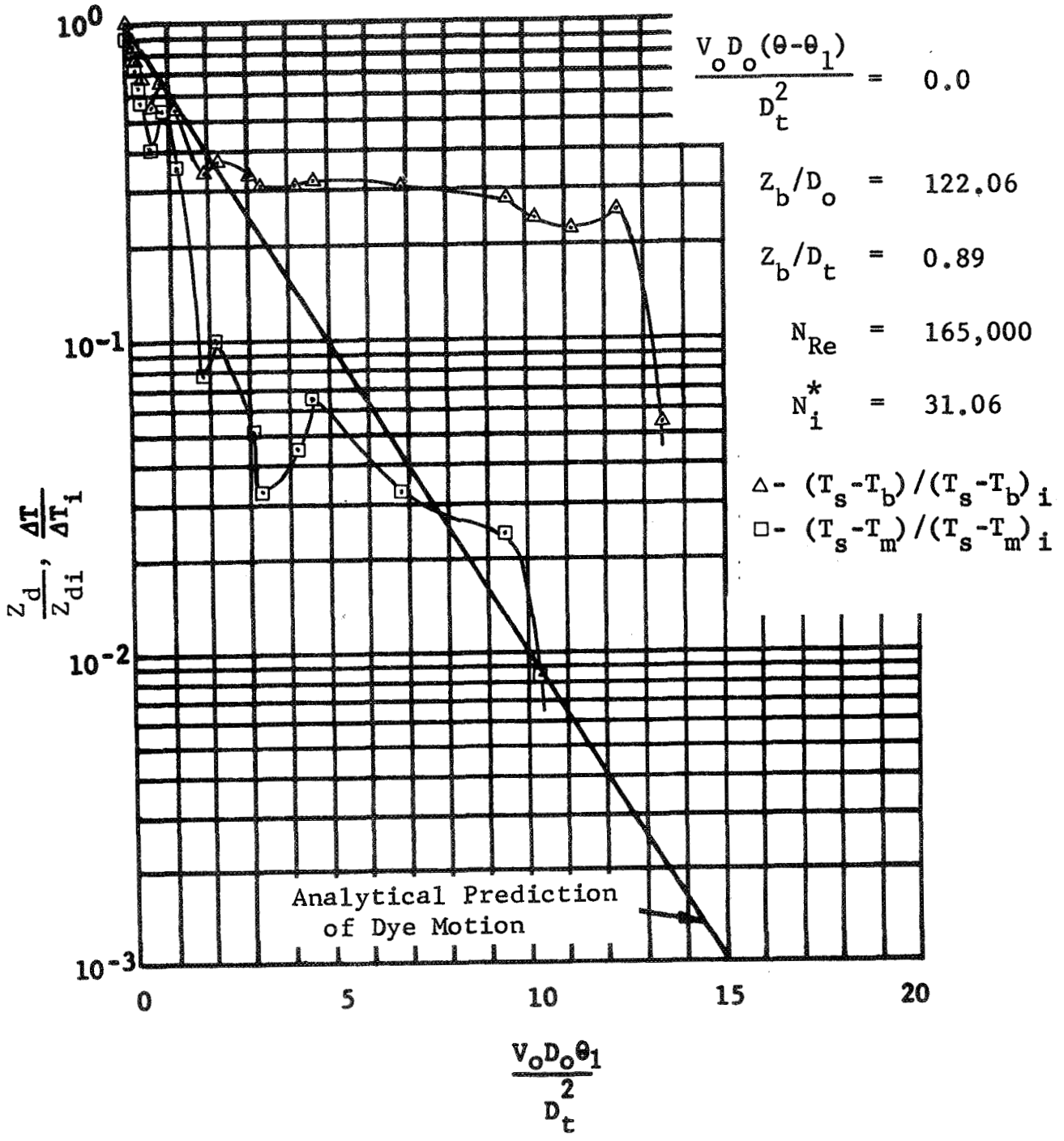

Figure 144 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 37

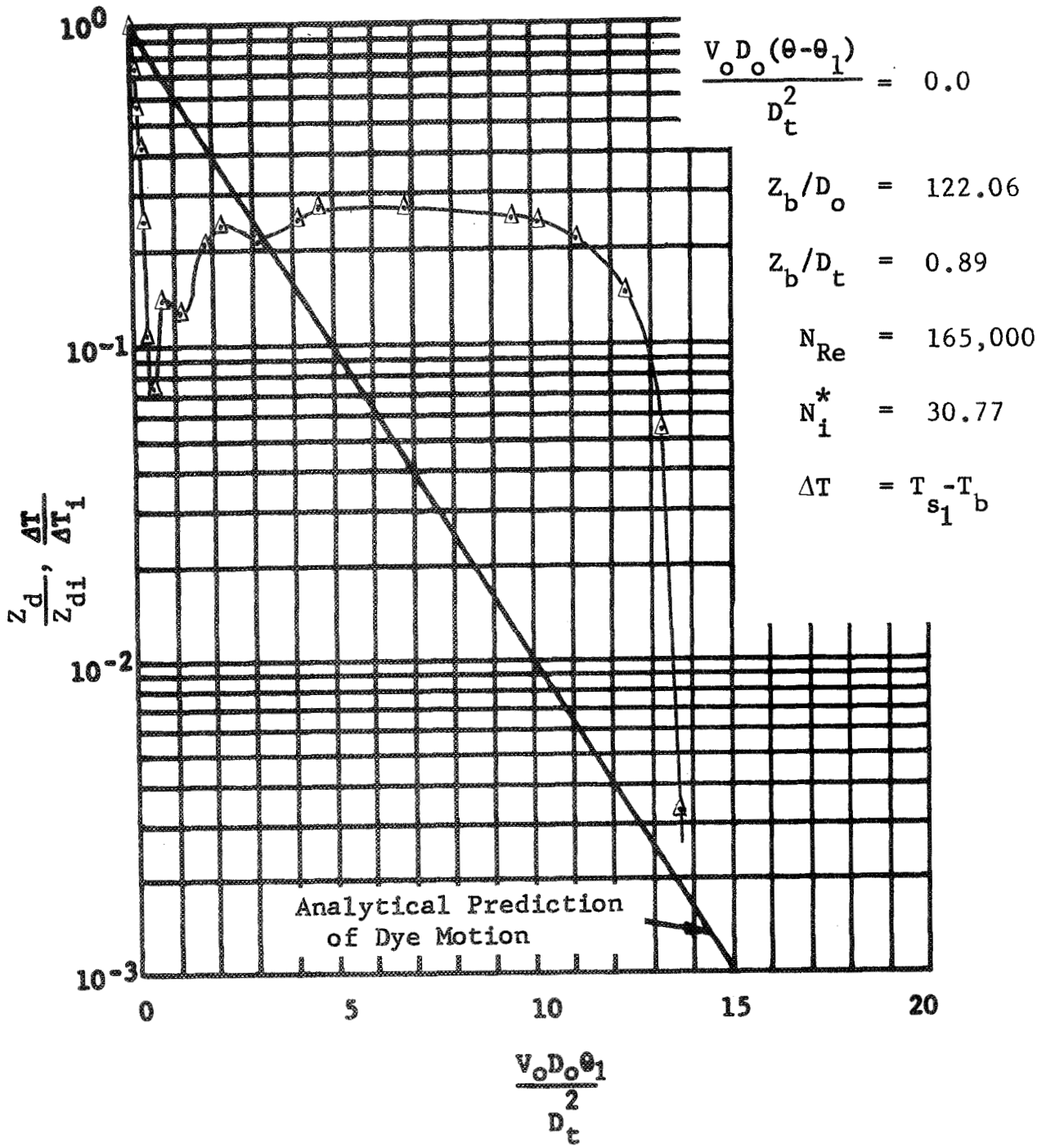

Figure 145 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 37

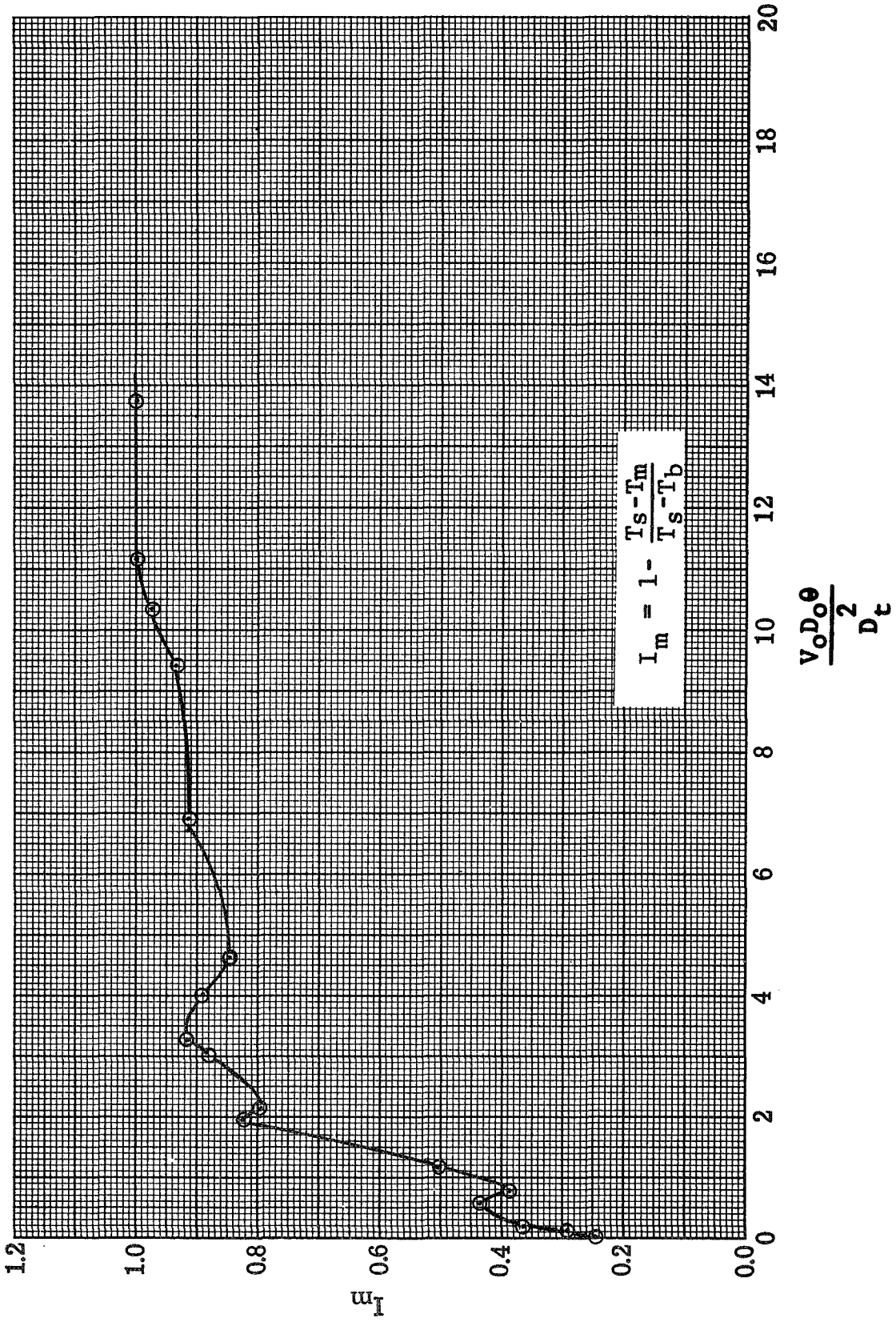

Figure 146 **Transient Energy Integral:** Run 37

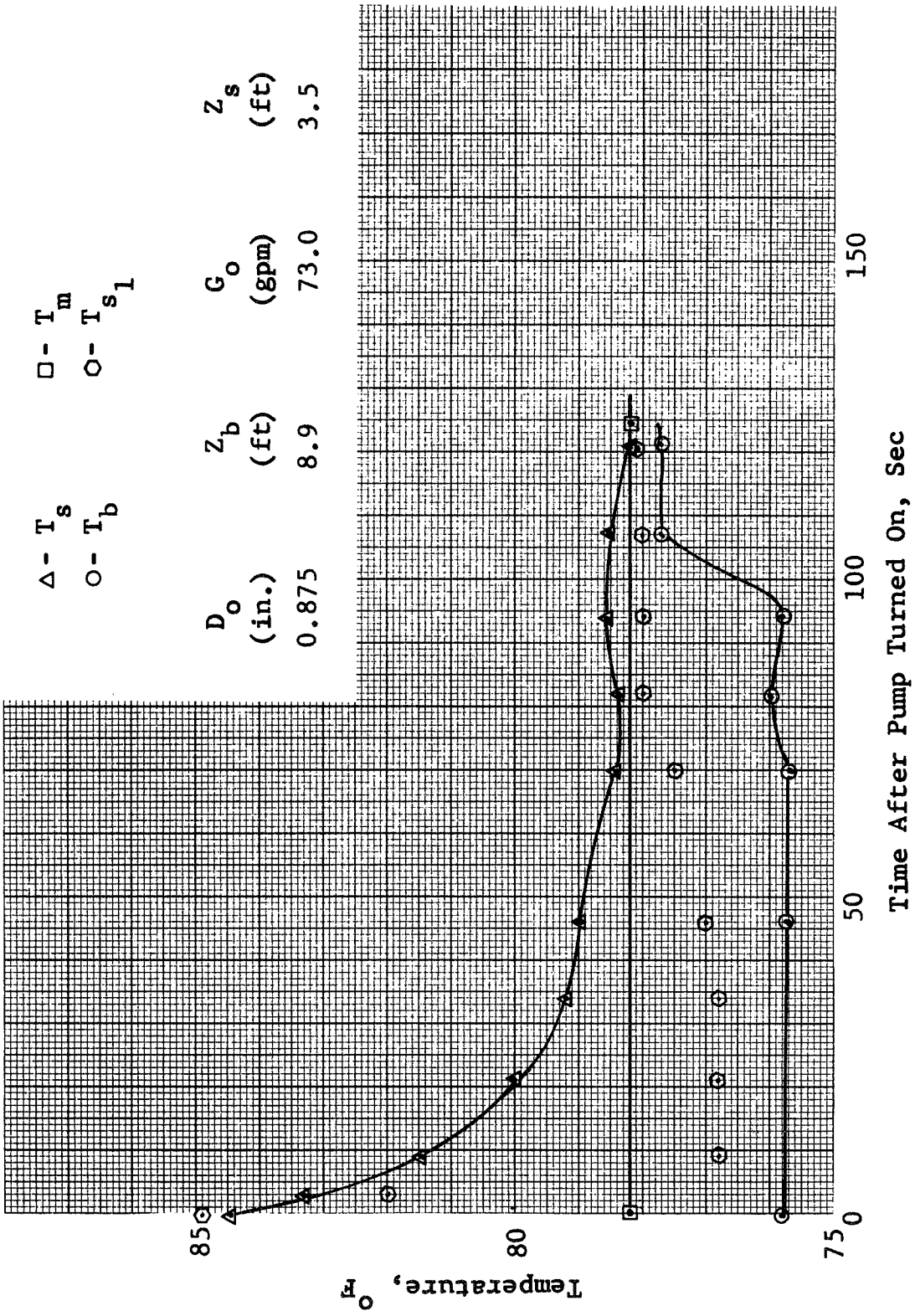

Figure 147 Transient Temperature Destratification: Run 38

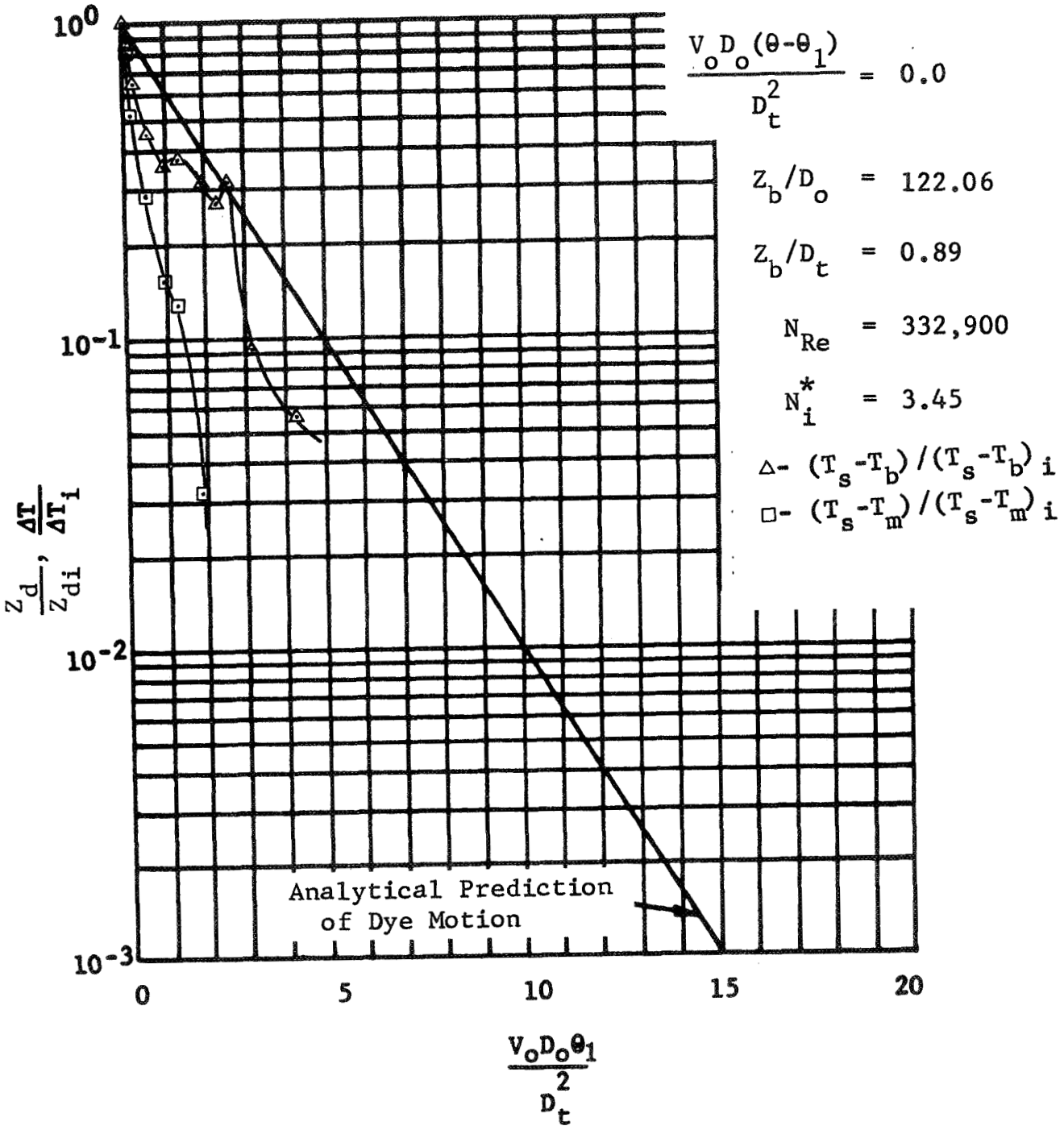

Figure 148 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop; Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 38

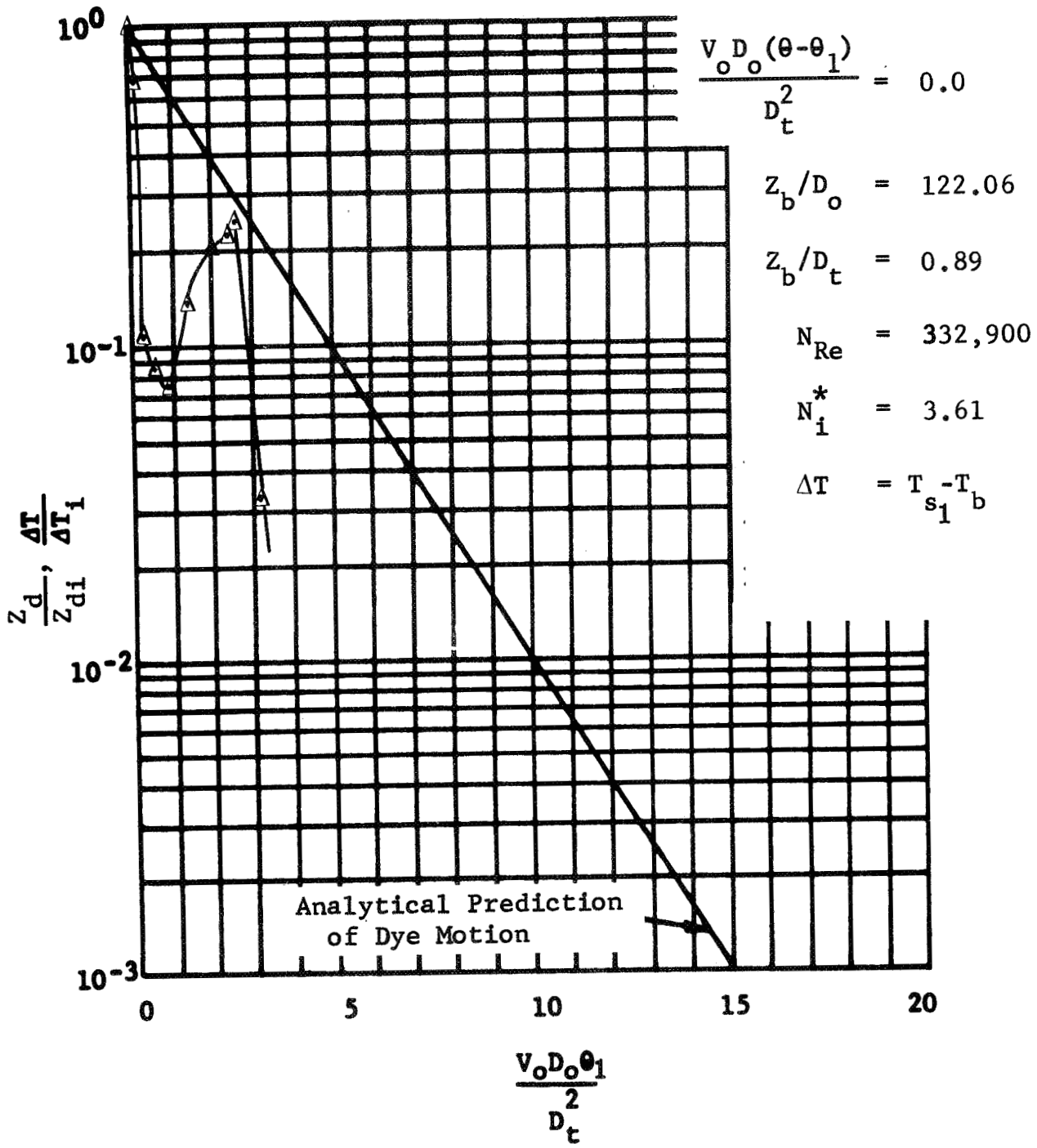

Figure 149 **Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop:** Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 38

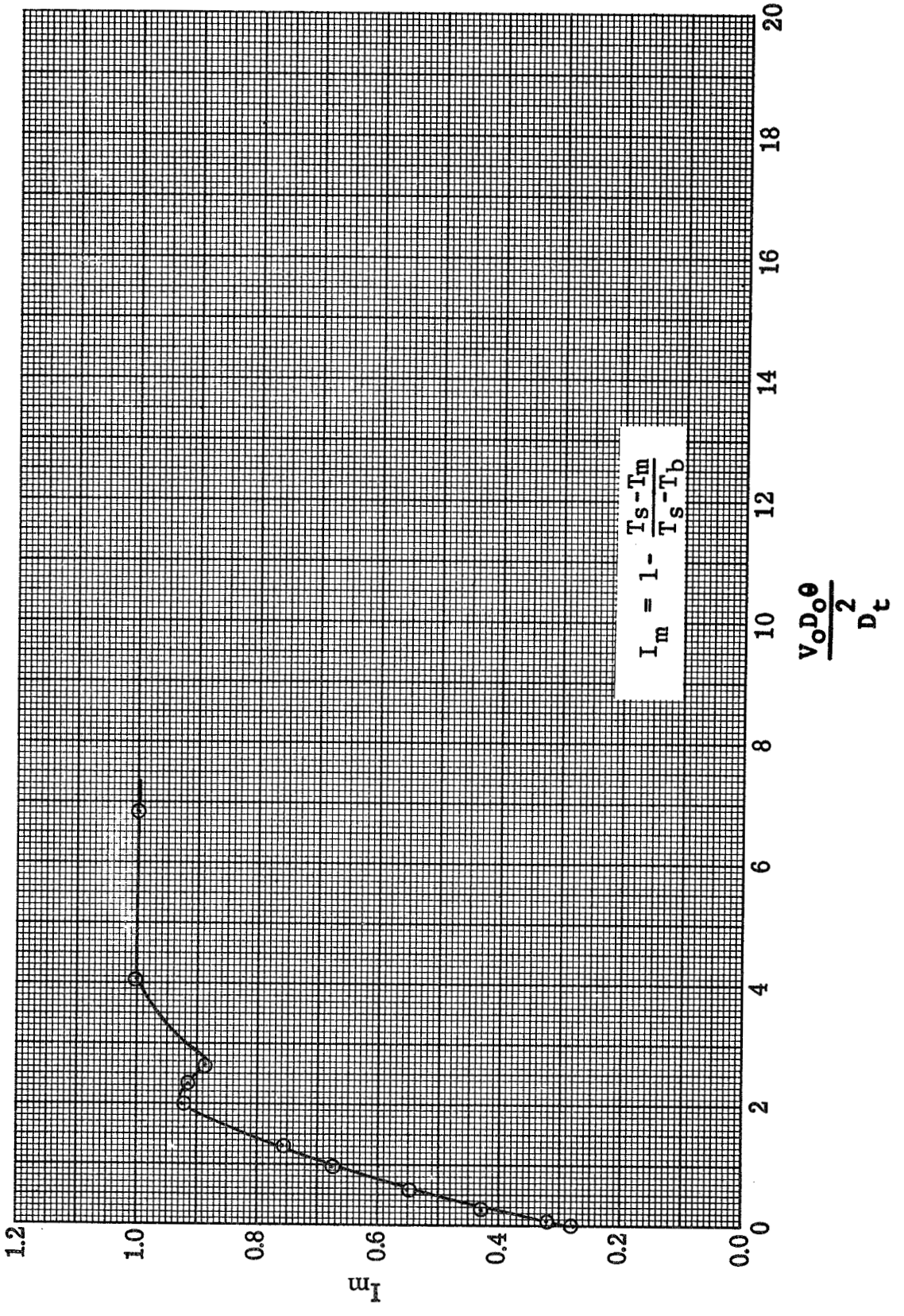

Figure 150 **Transient Energy Integral:** Run 38

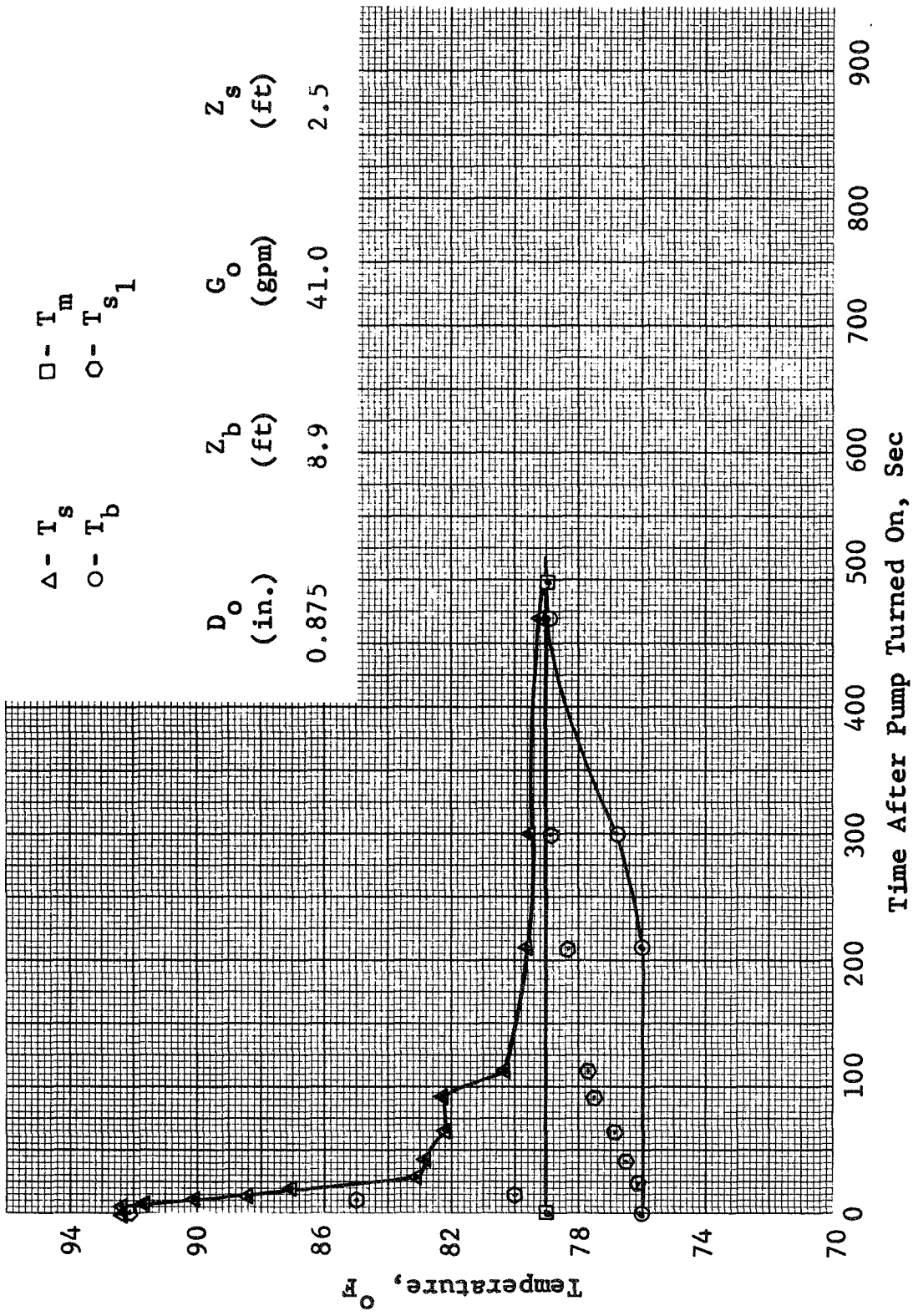

Figure 151 Transient Temperature Destratification: Run 39

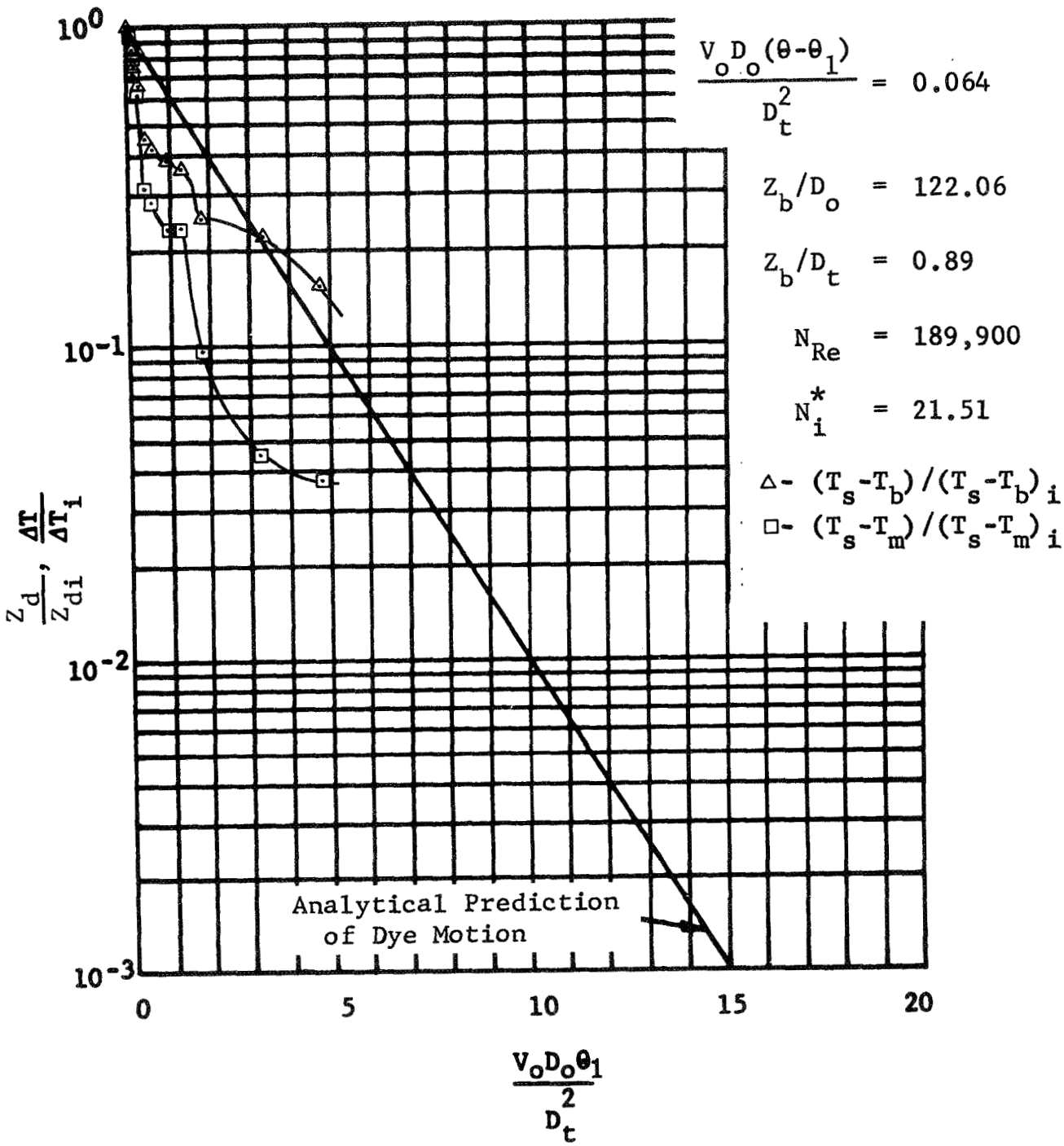

Figure 152 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 39

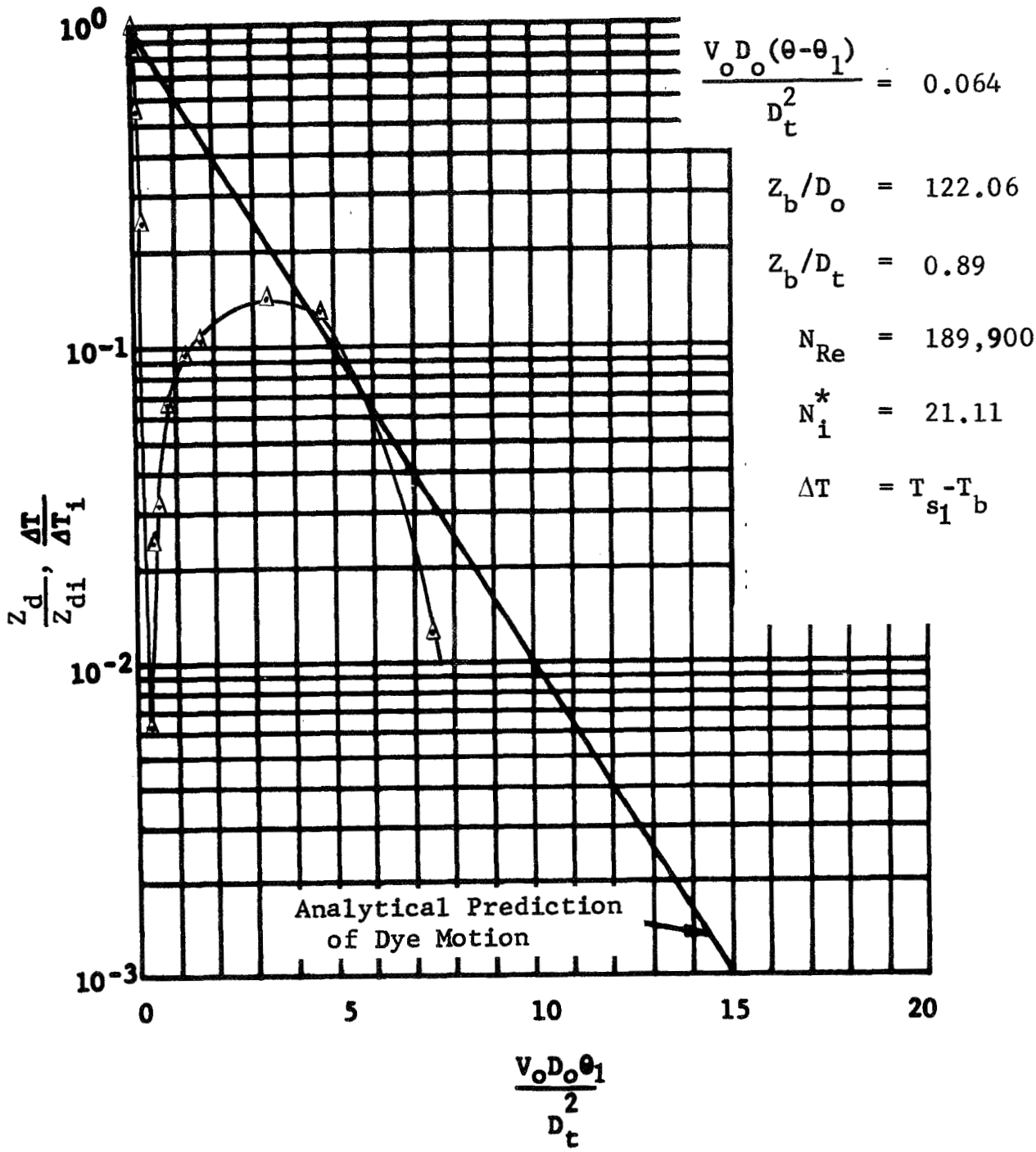

Figure 153 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 39

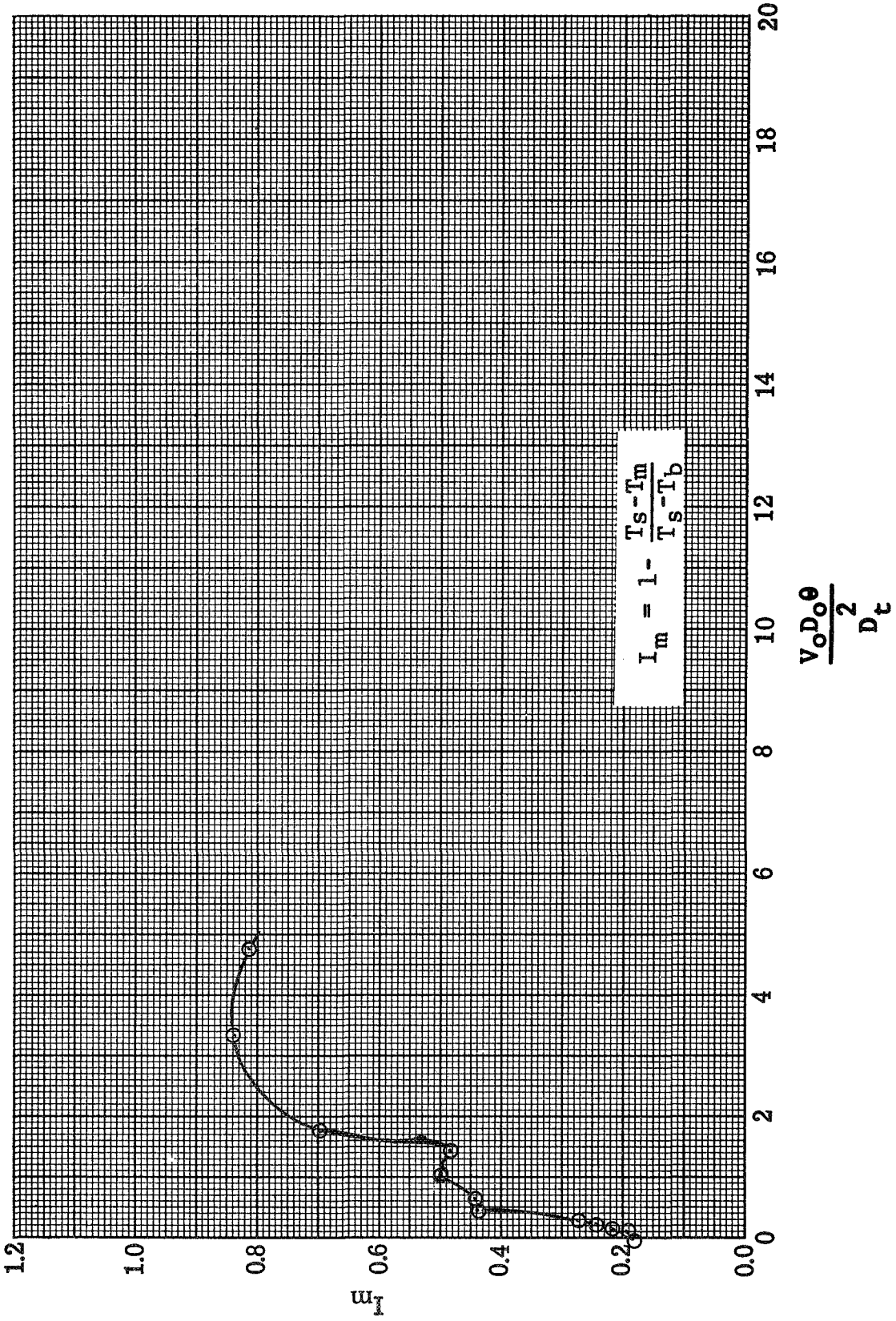

Figure 154 **Transient Energy Integral:** Run 39

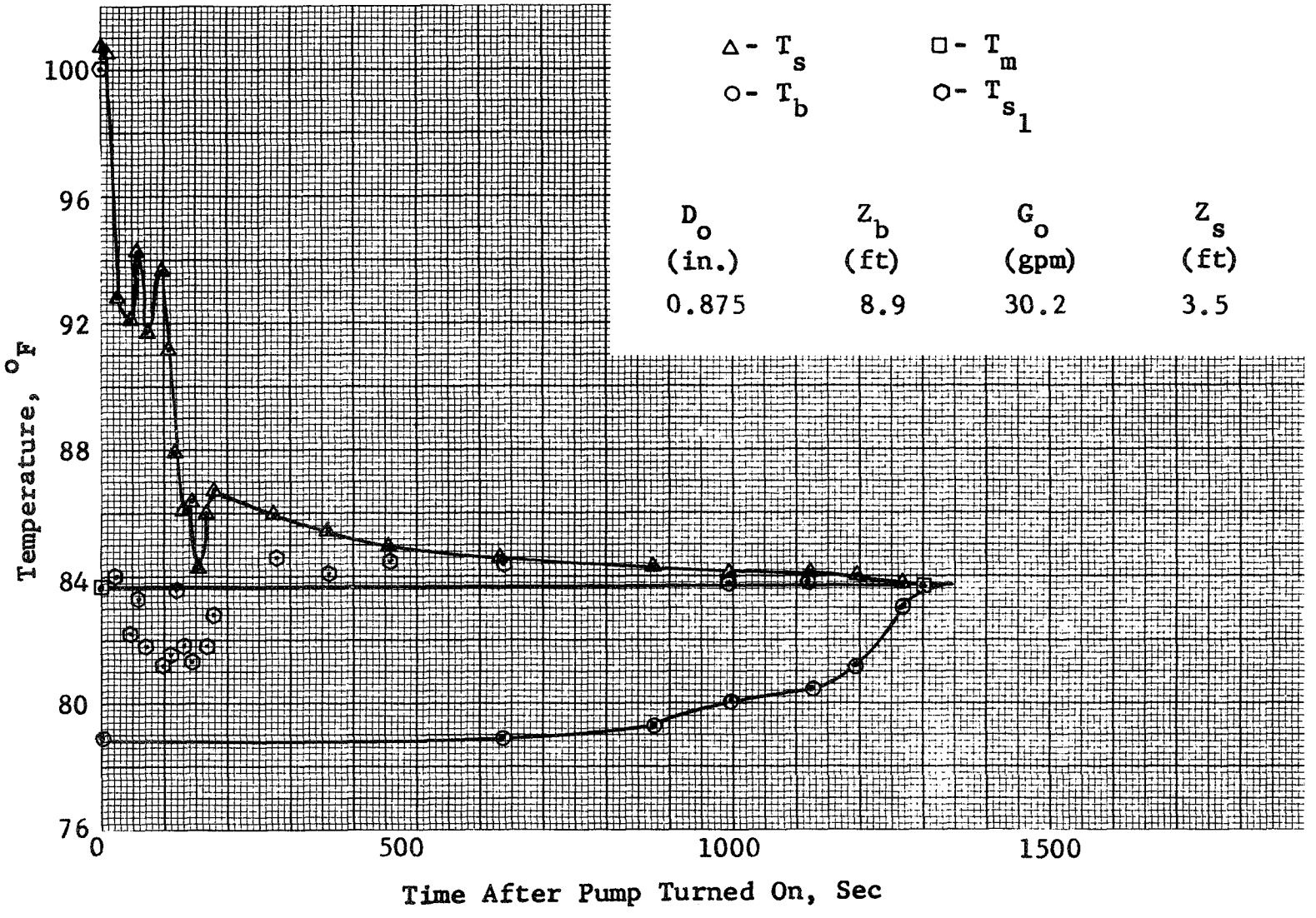

Figure 155 Transient Temperature Destratification: Run 40

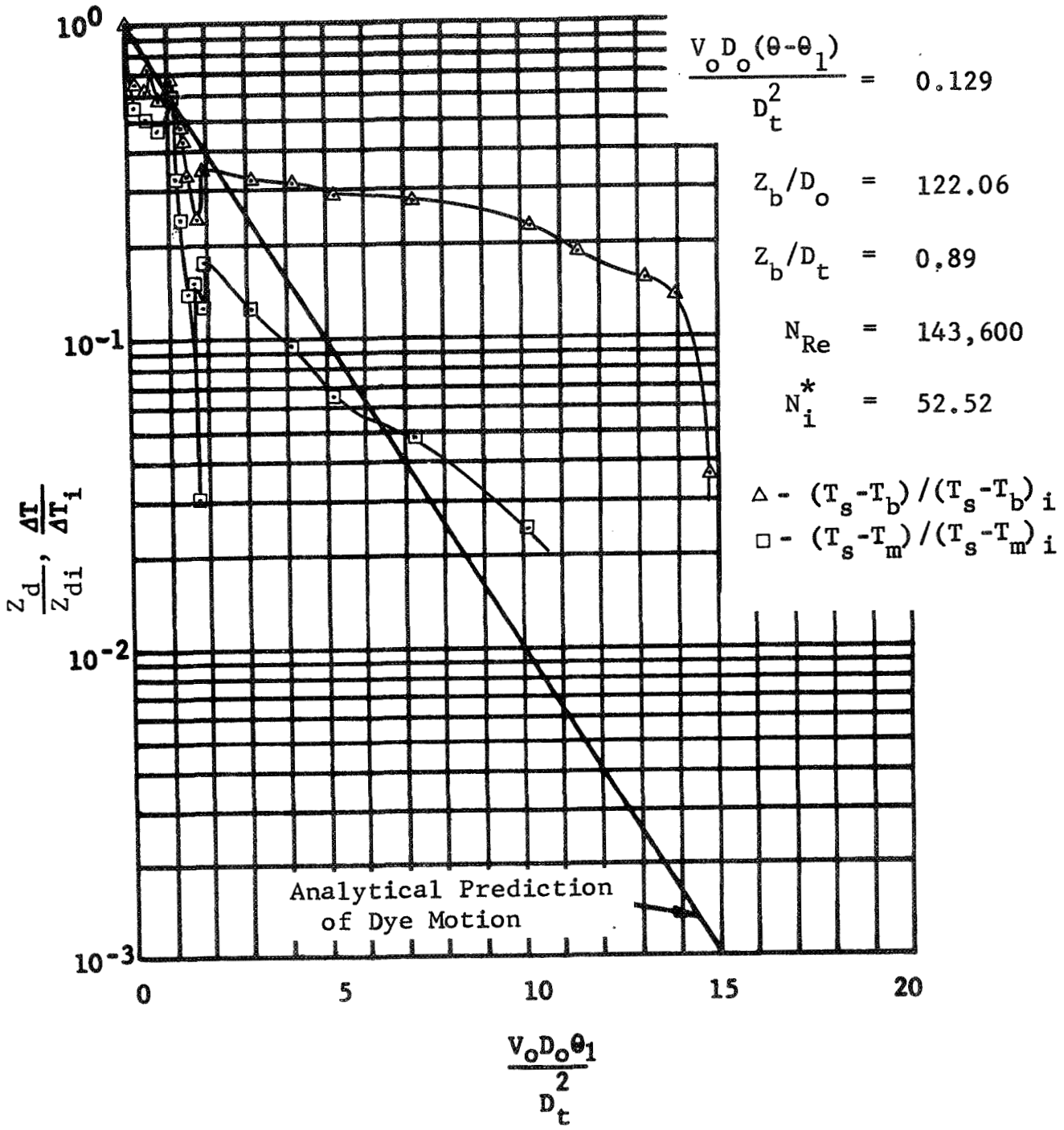

Figure 156 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 40

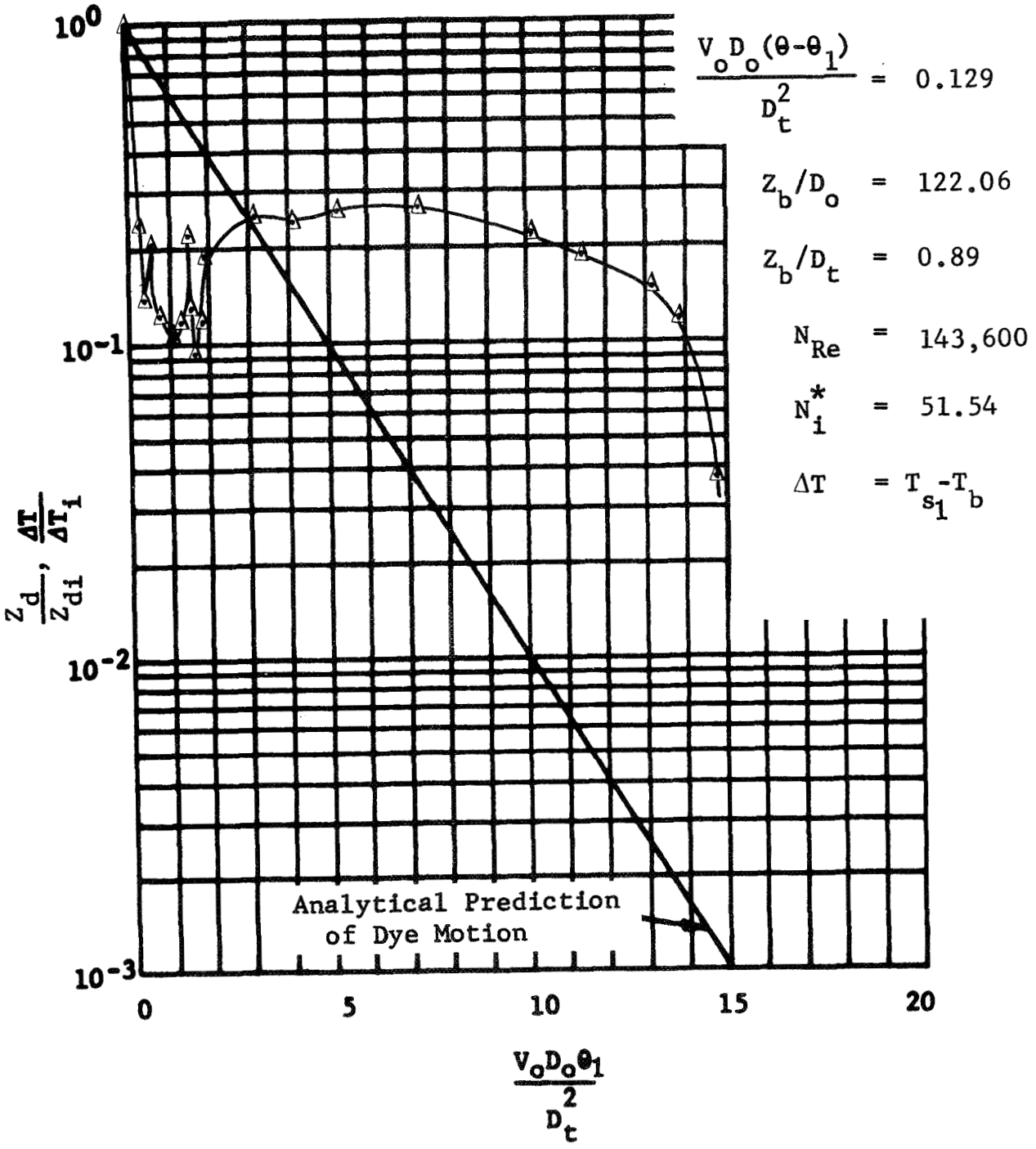

Figure 157 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 40

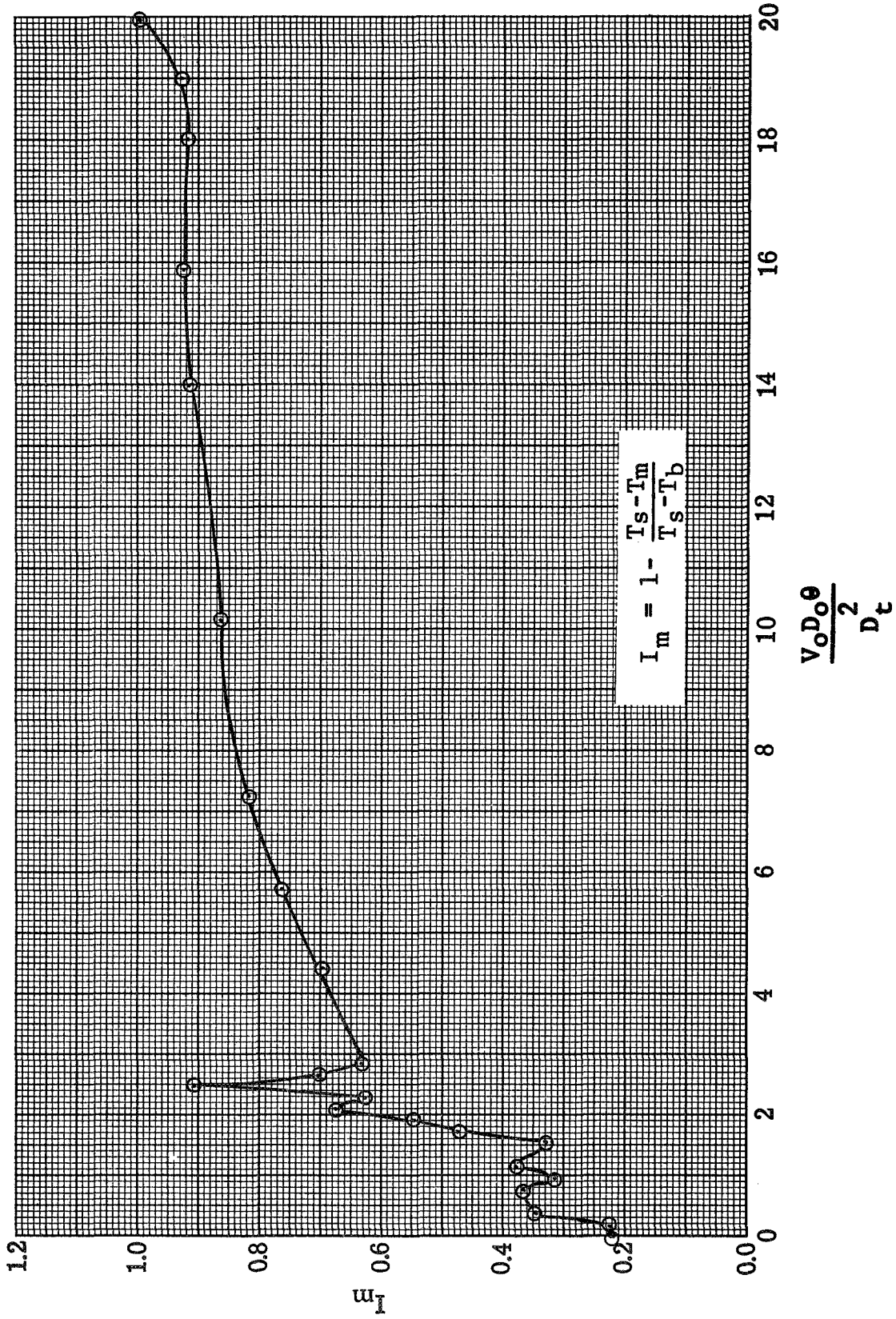

Figure 158 **Transient Energy Integral:** Run 40

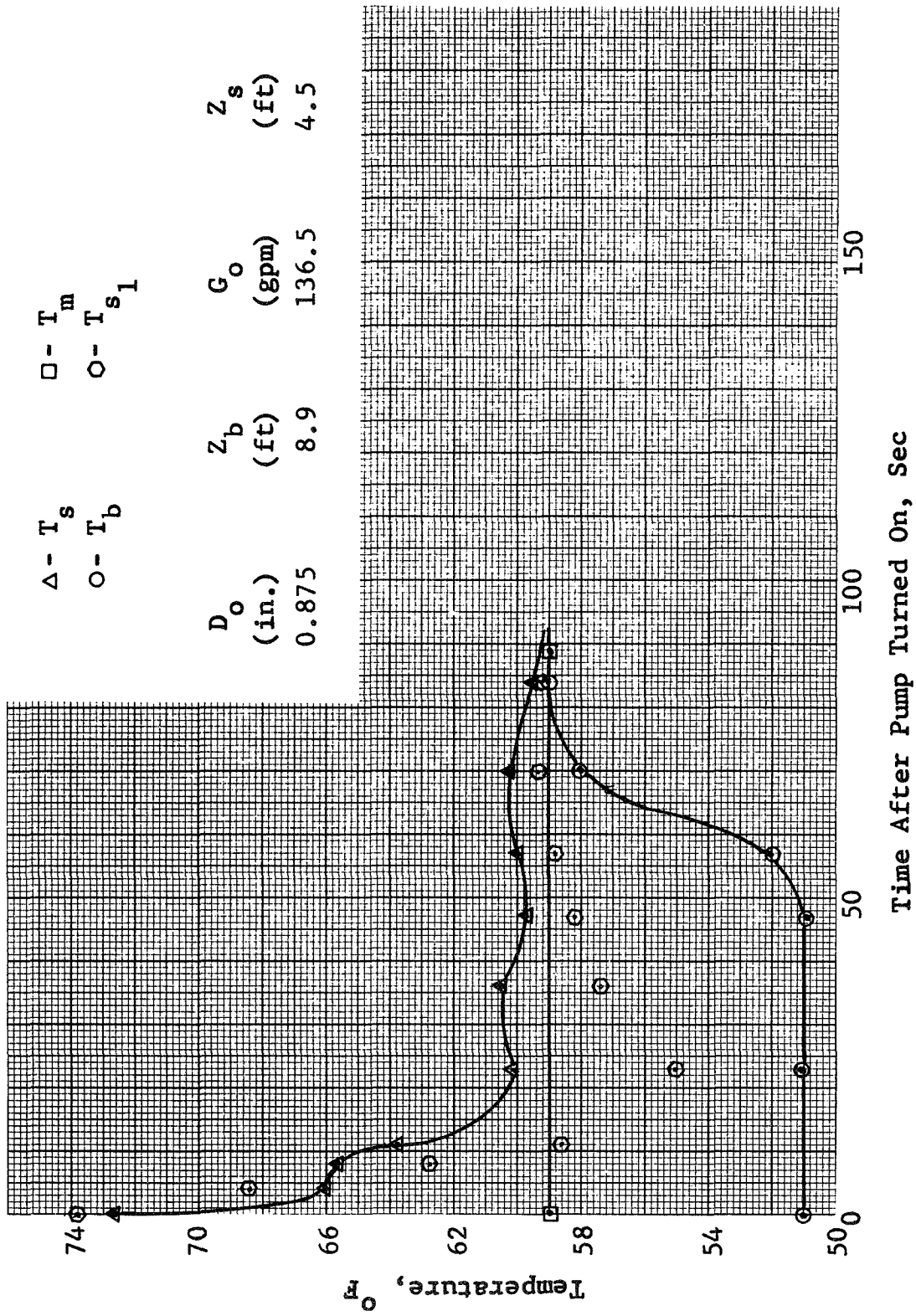

Figure 159 Transient Temperature Destratification: Run 41

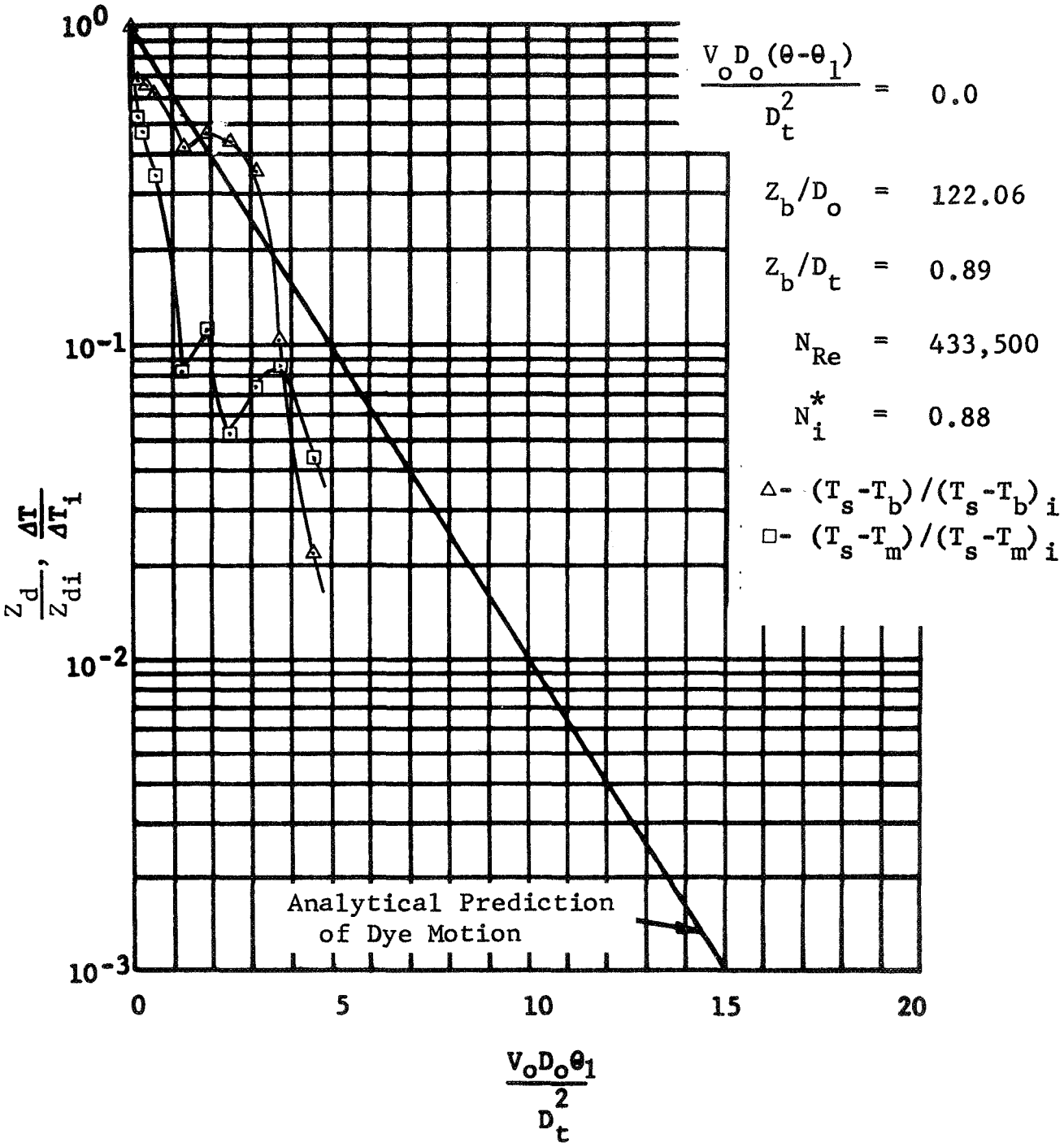

Figure 160 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 41

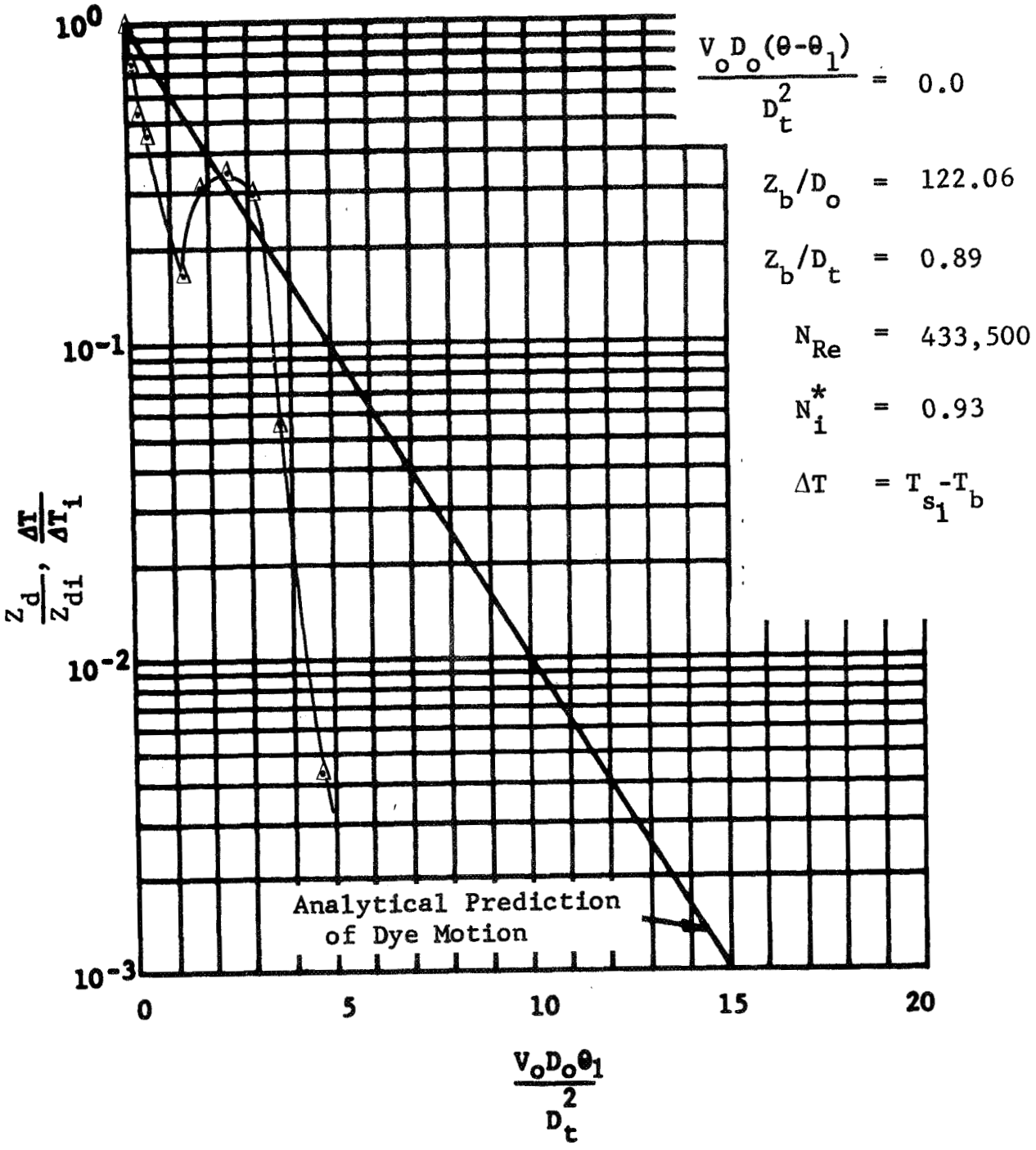

Figure 161 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 41

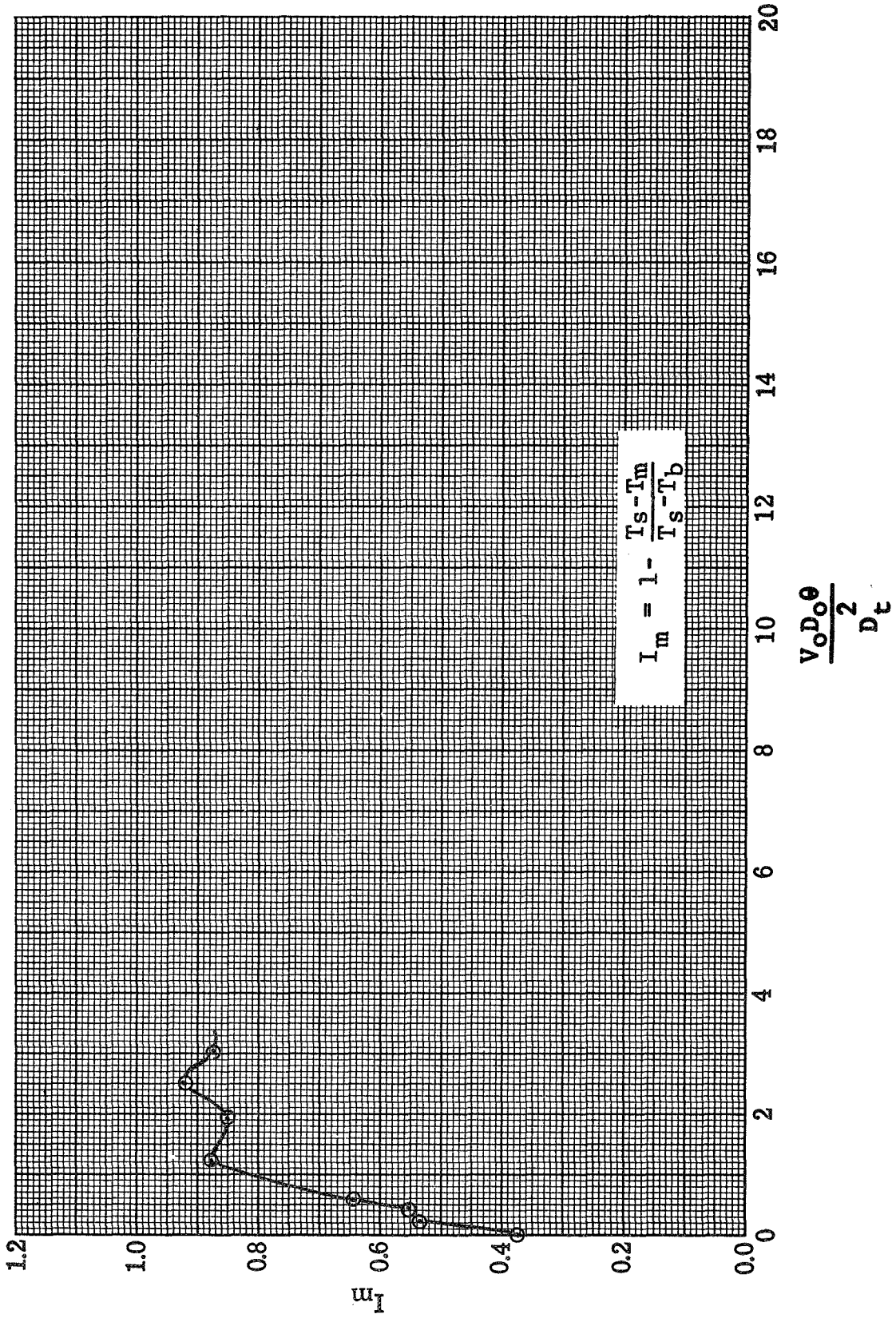

Figure 162 **Transient Energy Integral:** Run 41

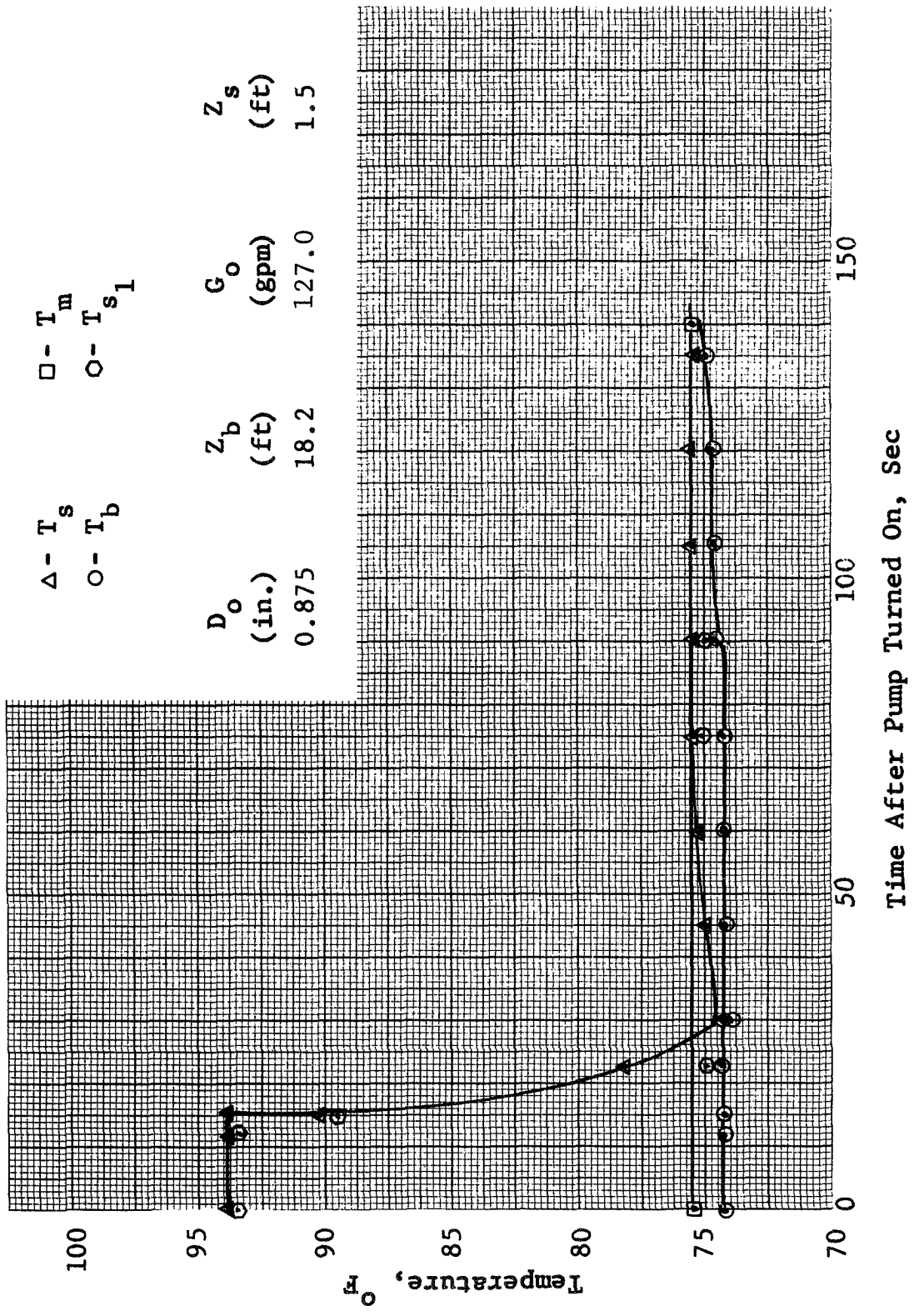

Figure 163 Transient Temperature Destratification: Run 43

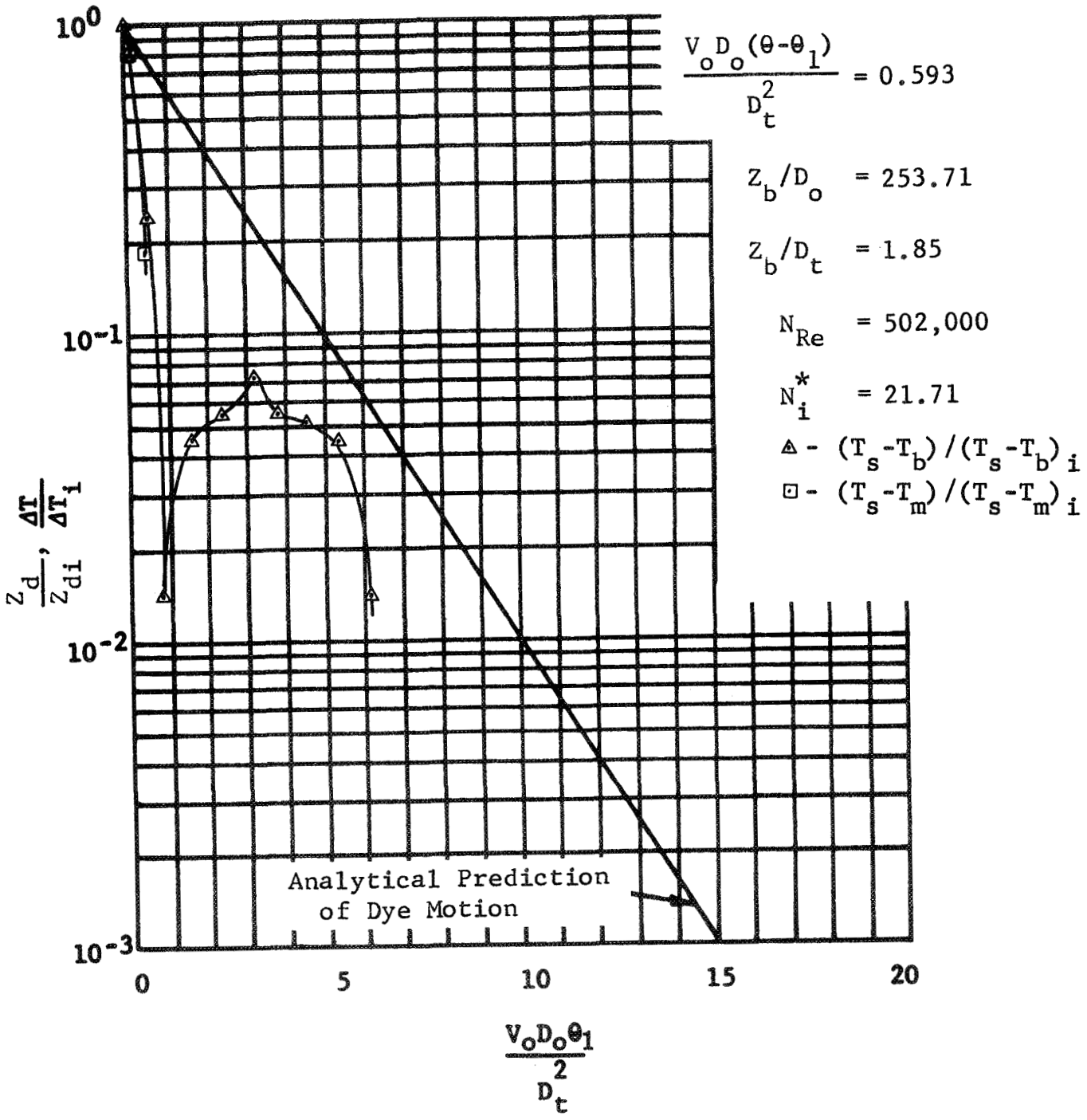

Figure 164 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 43

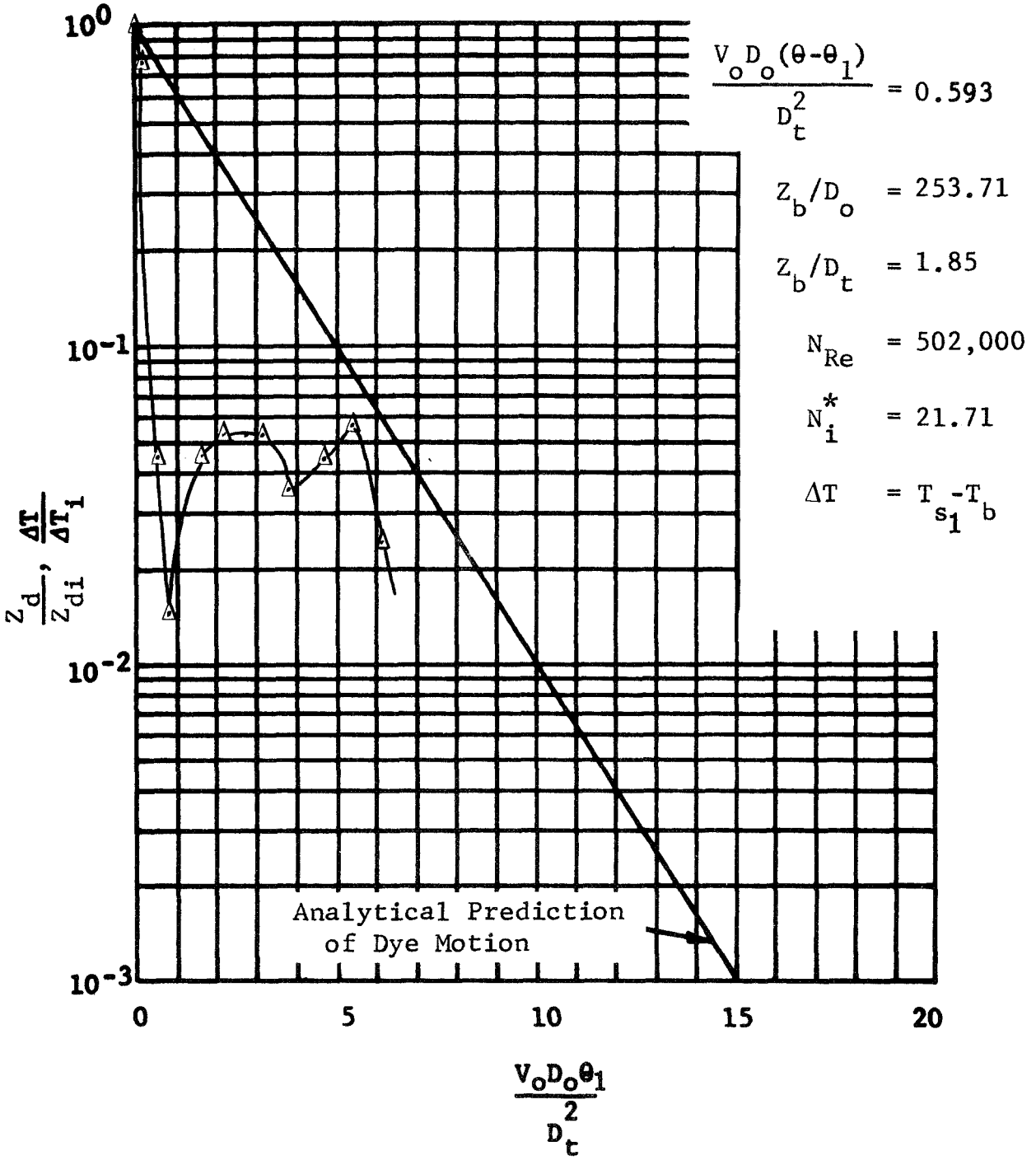

Figure 165 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 43

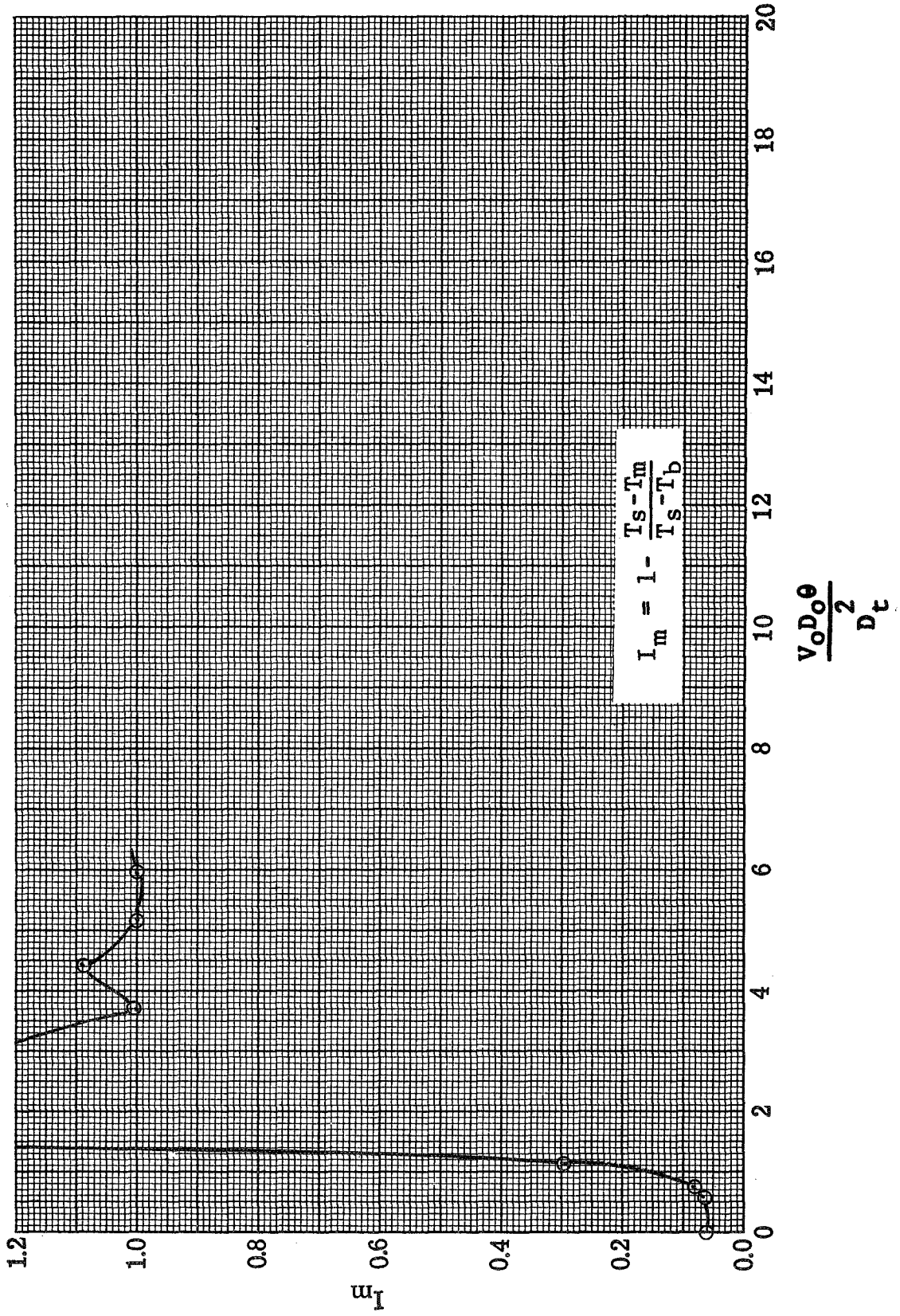

Figure 166 **Transient Energy Integral:** Run 43

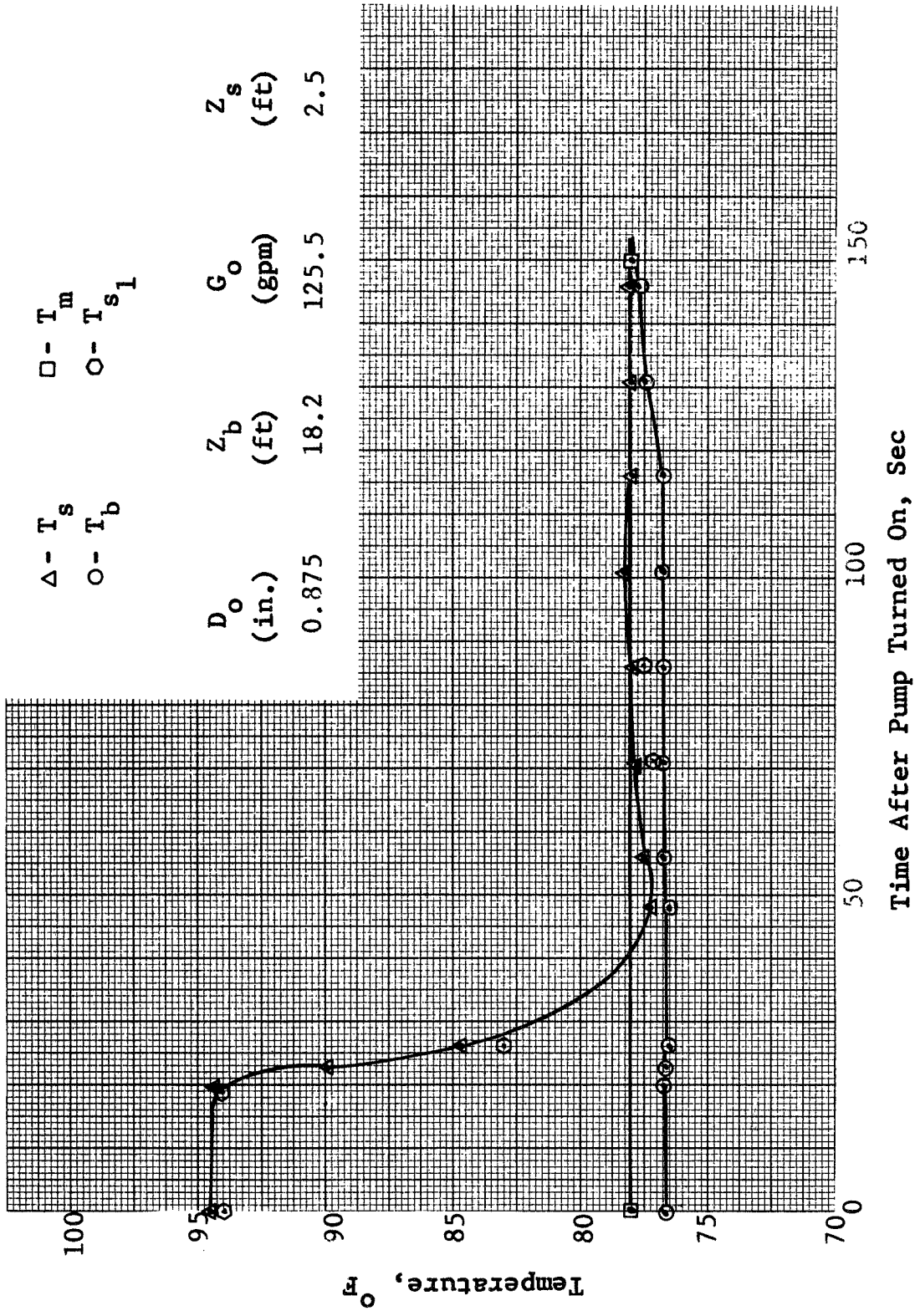

Figure 167 Transient Temperature Destratification: Run 44

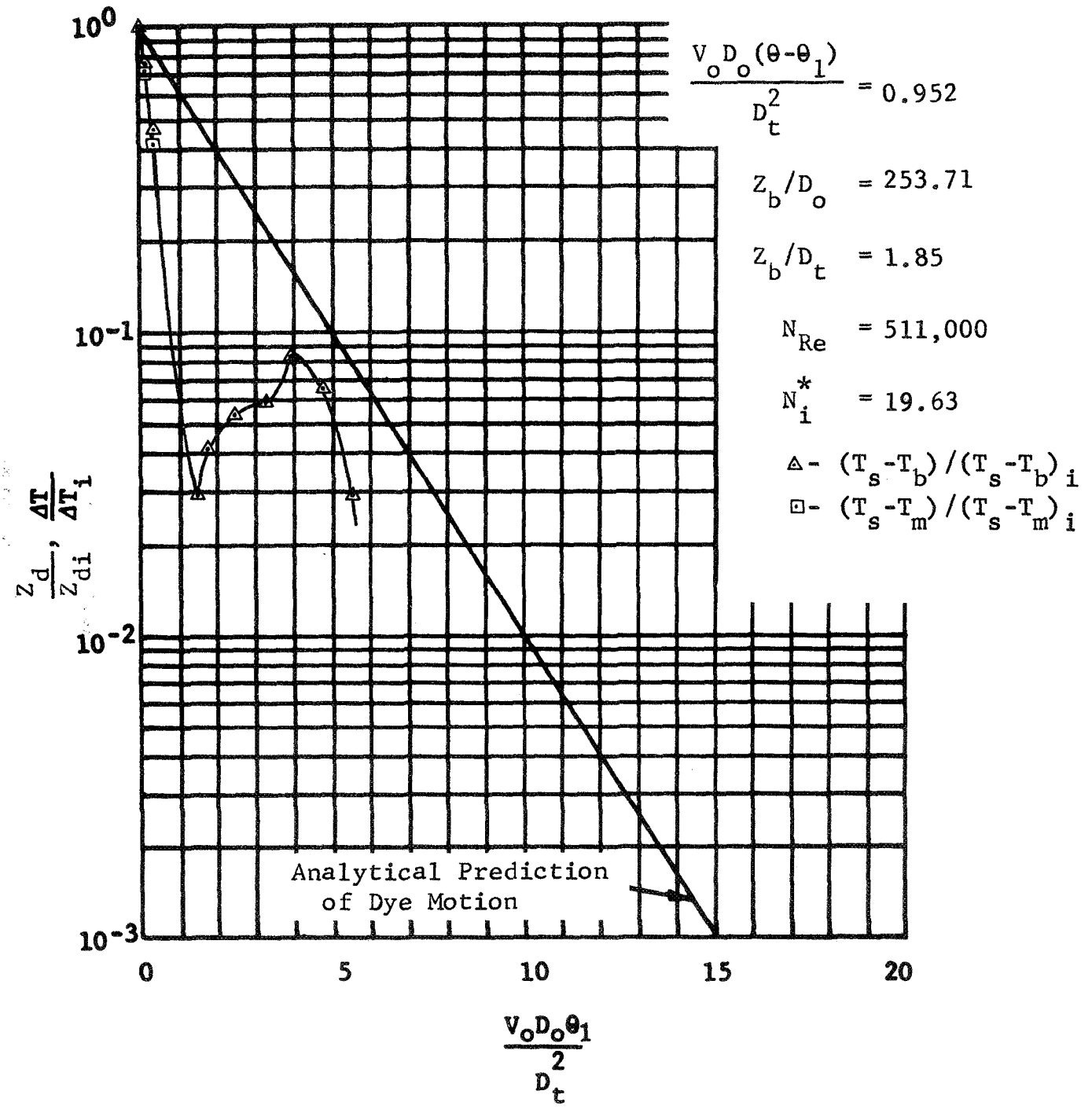

Figure 168 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 44

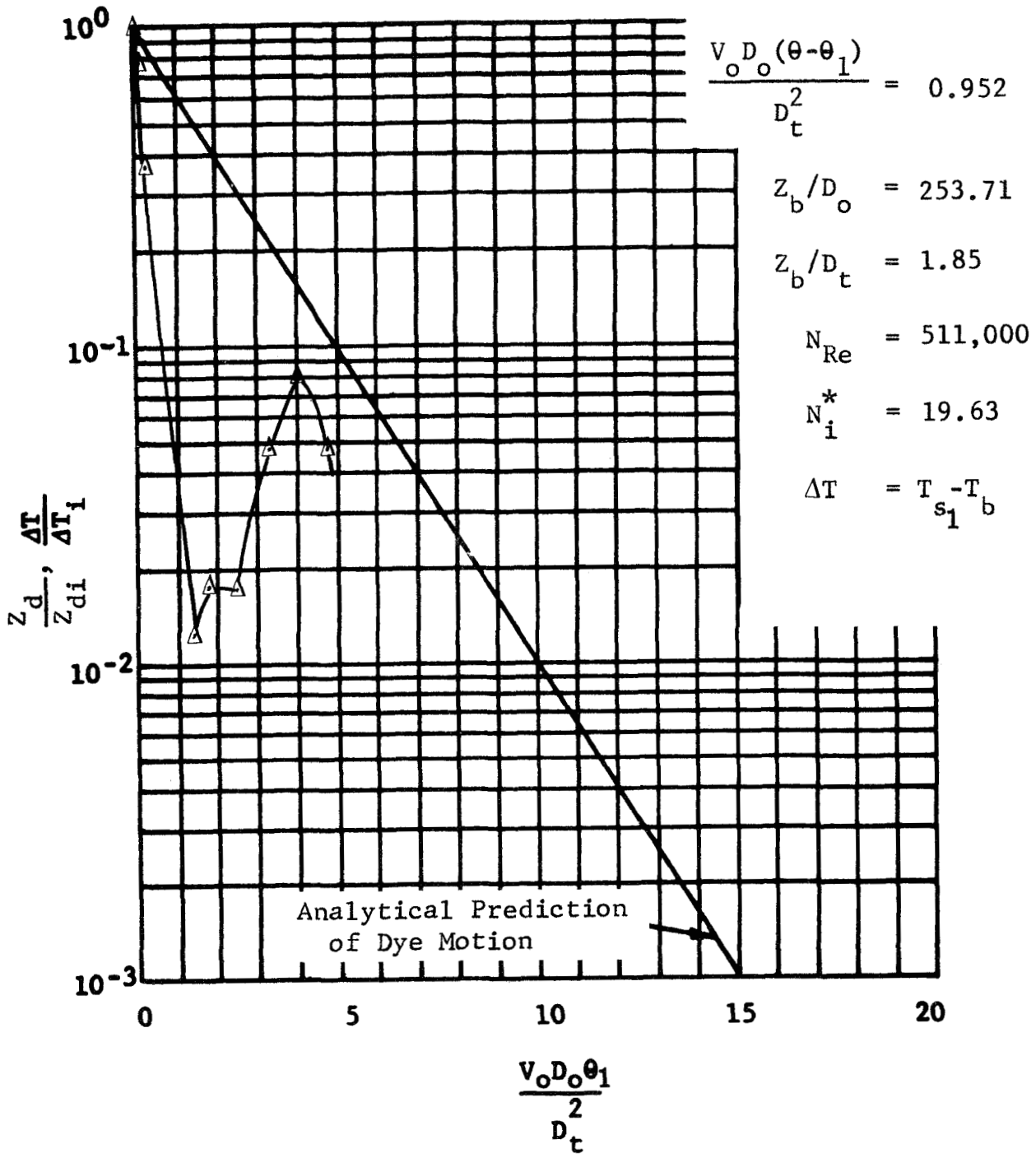

Figure 169 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 44

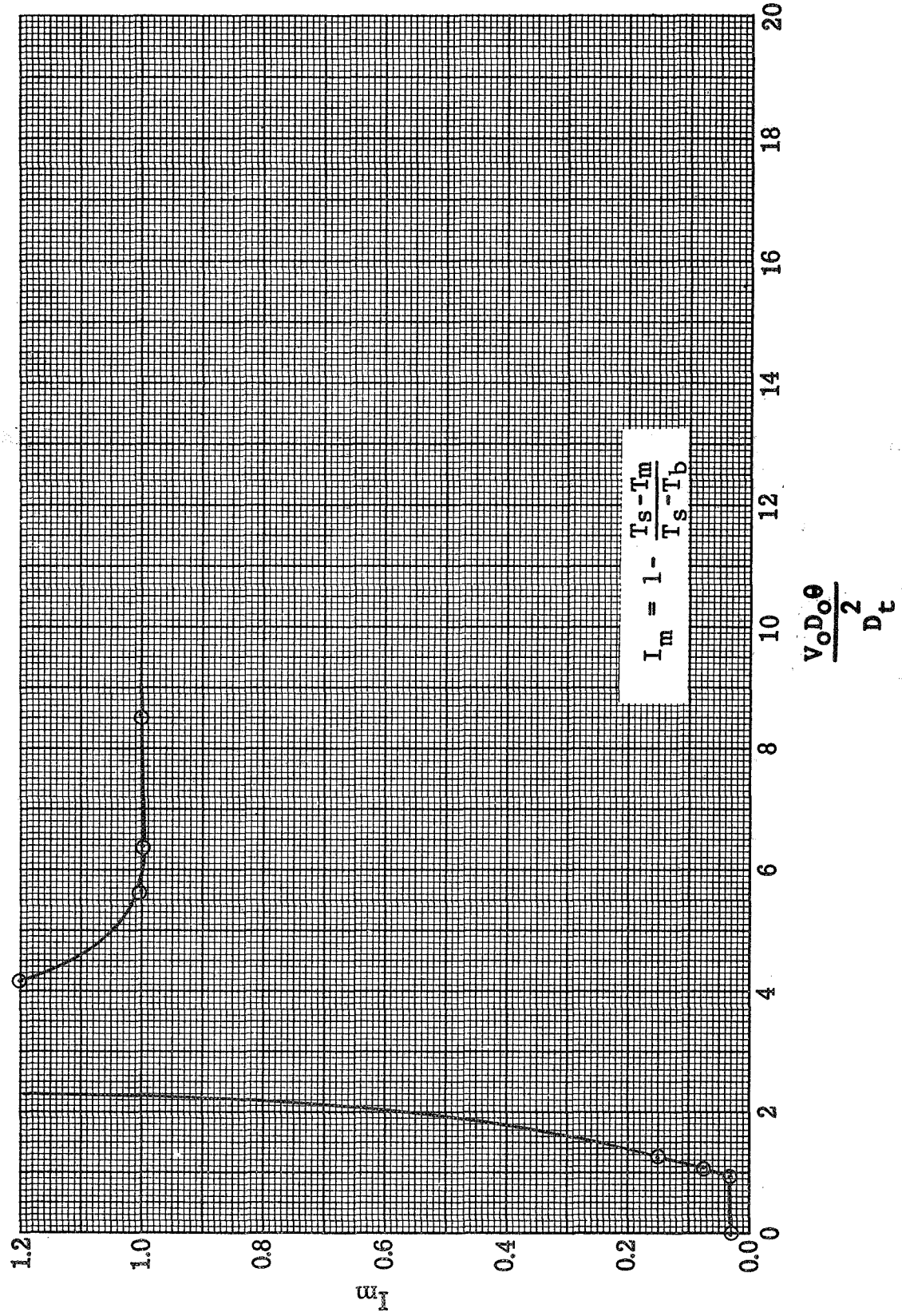

Figure 170 **Transient Energy Integral:** Run 44

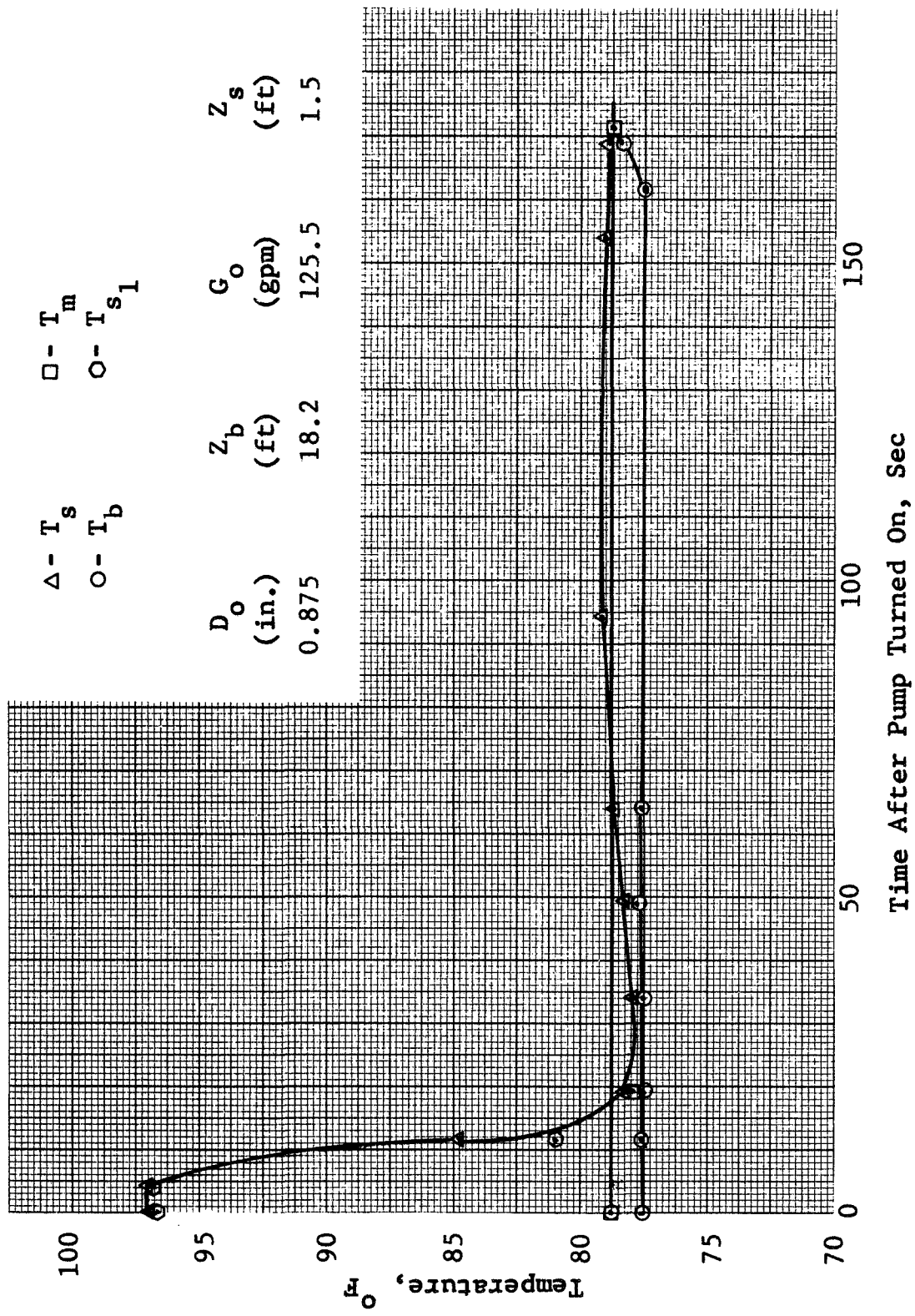

Figure 171 Transient Temperature Destratification : Run 45

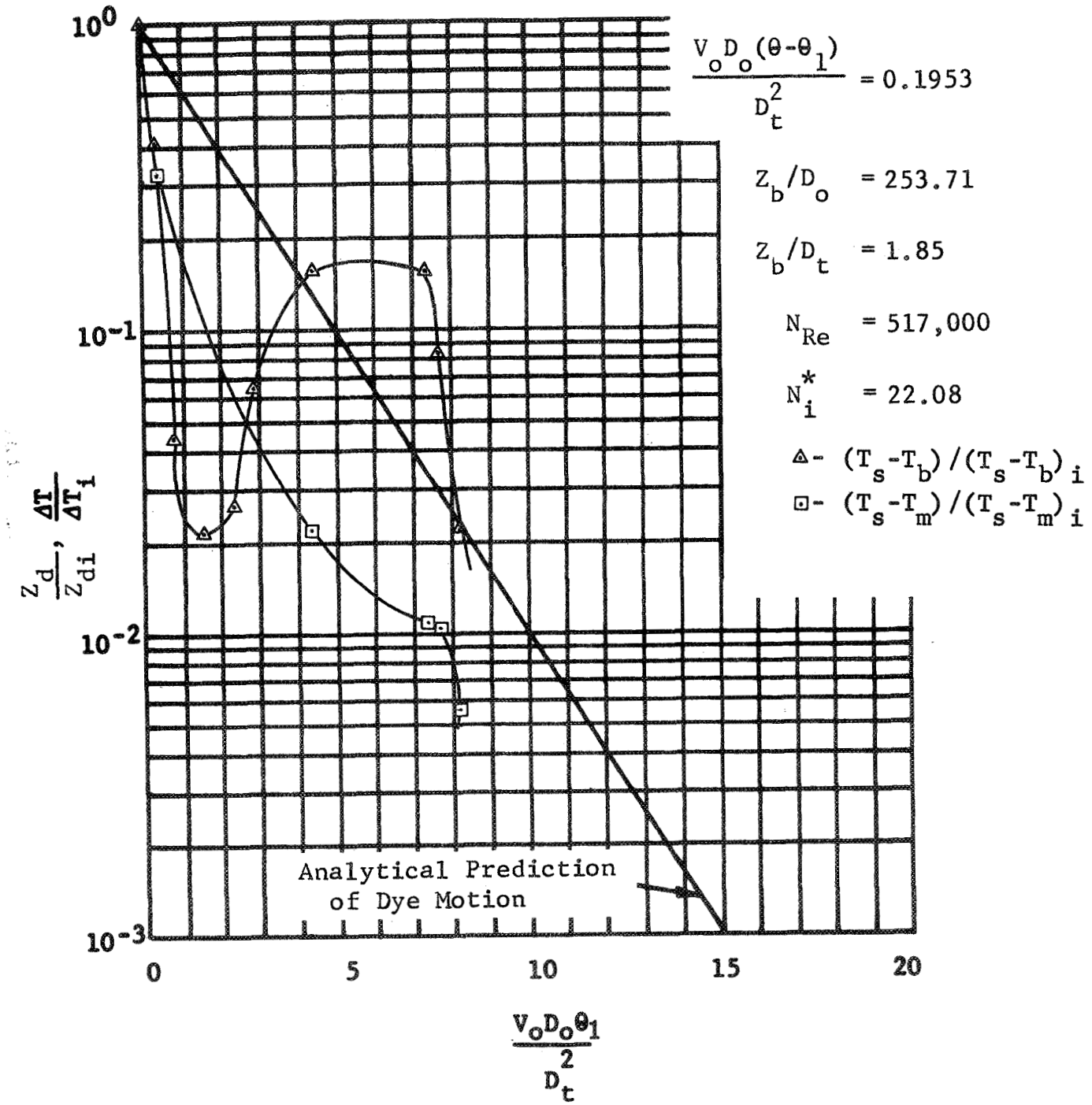

Figure 172 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at $\theta = 0.0$ sec; Average Surface Temperature Drop Starts at $\theta_1 = 0.0$ sec; Run 45

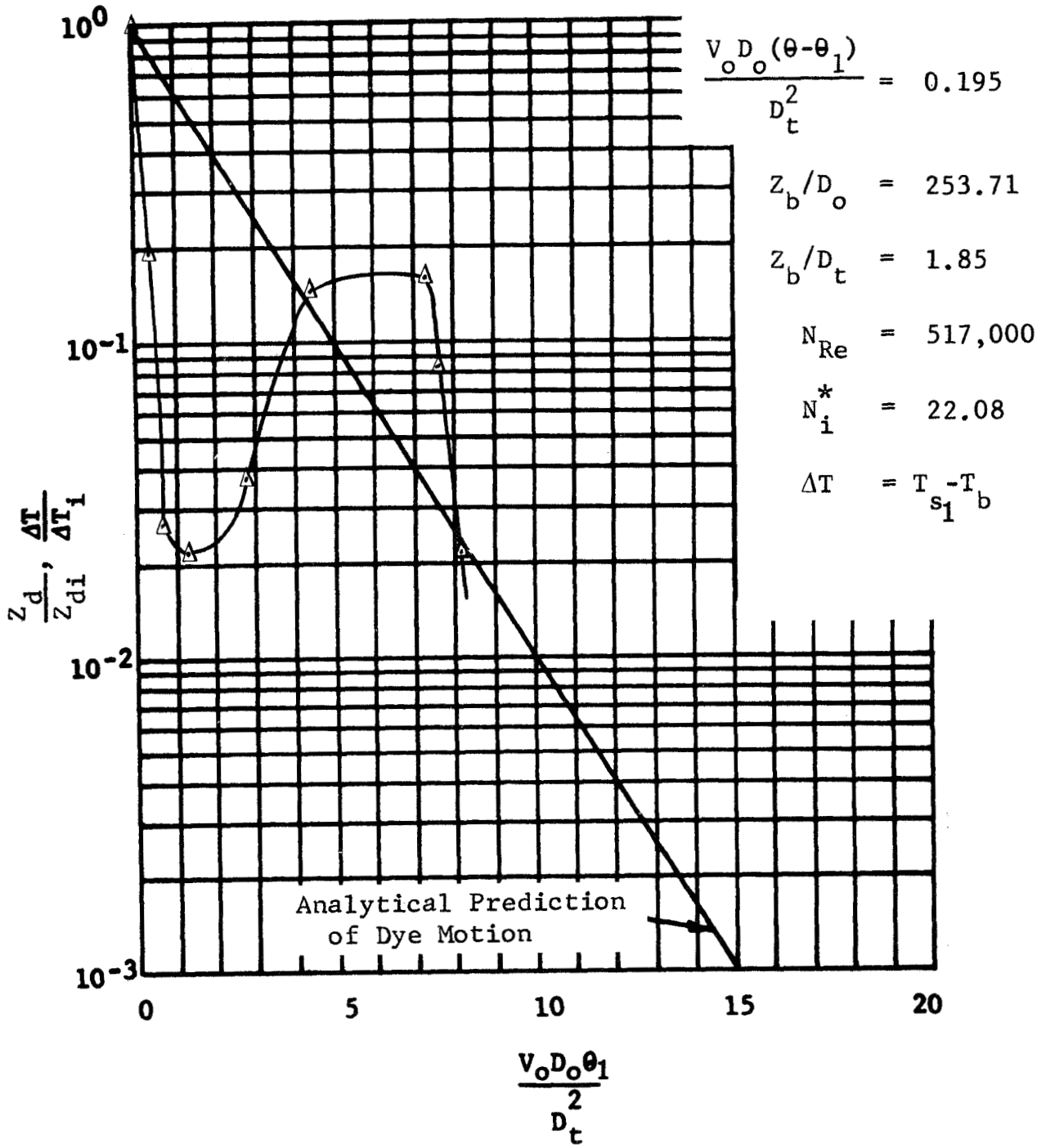

Figure 173 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 45

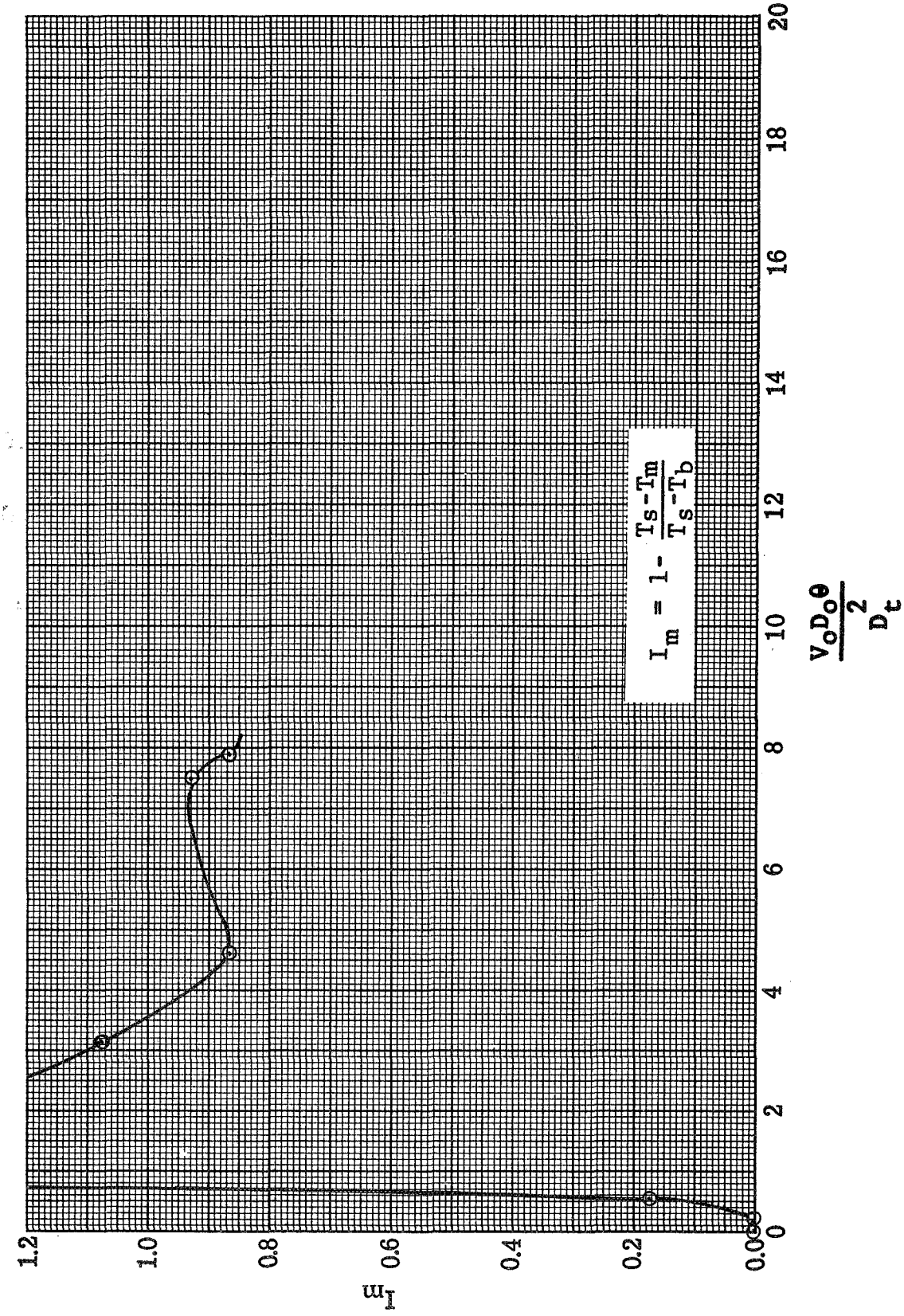

Figure 174 Transient Energy Integral: Run 45

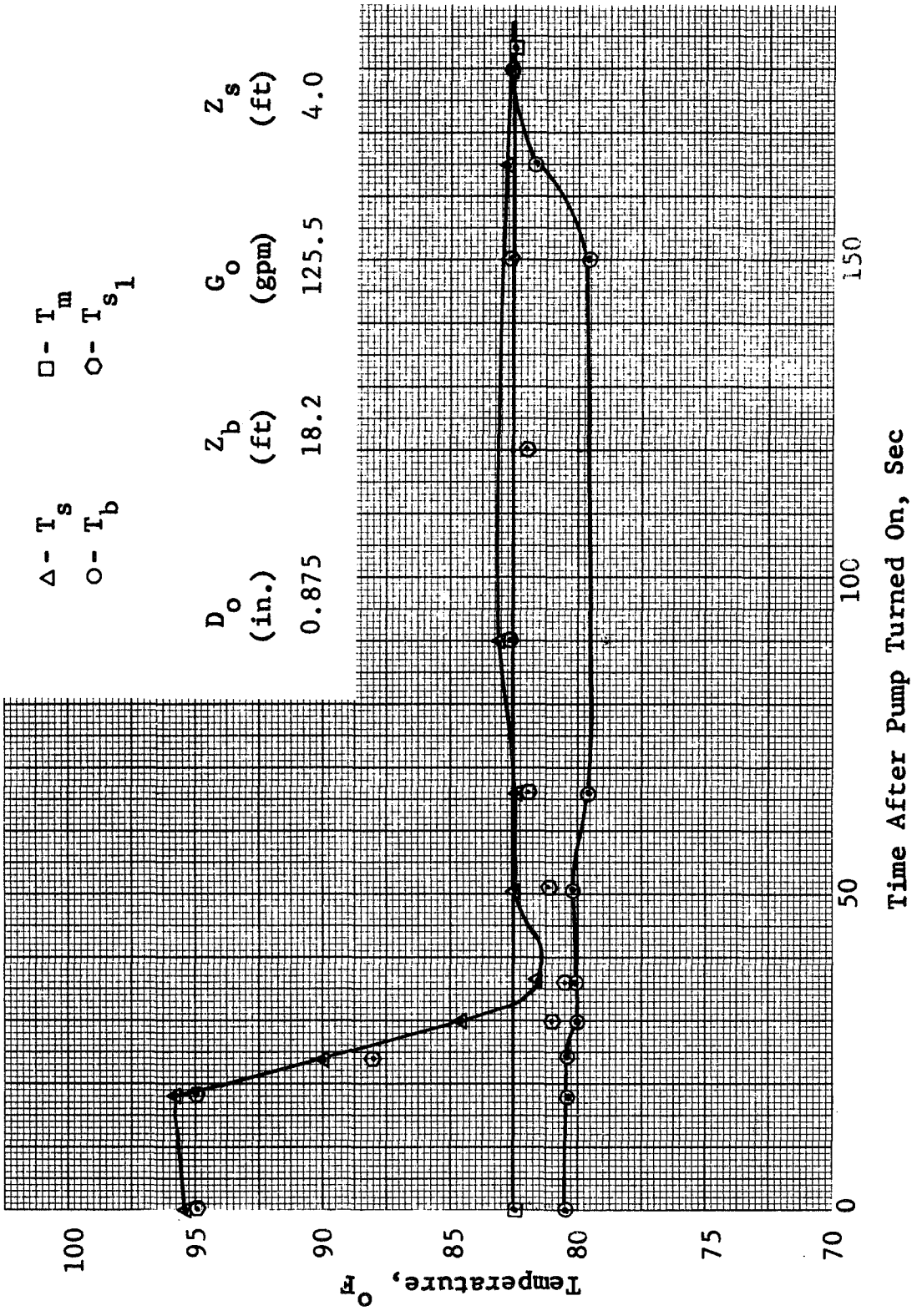

Figure 175 Transient Temperature Destratification: Run 46

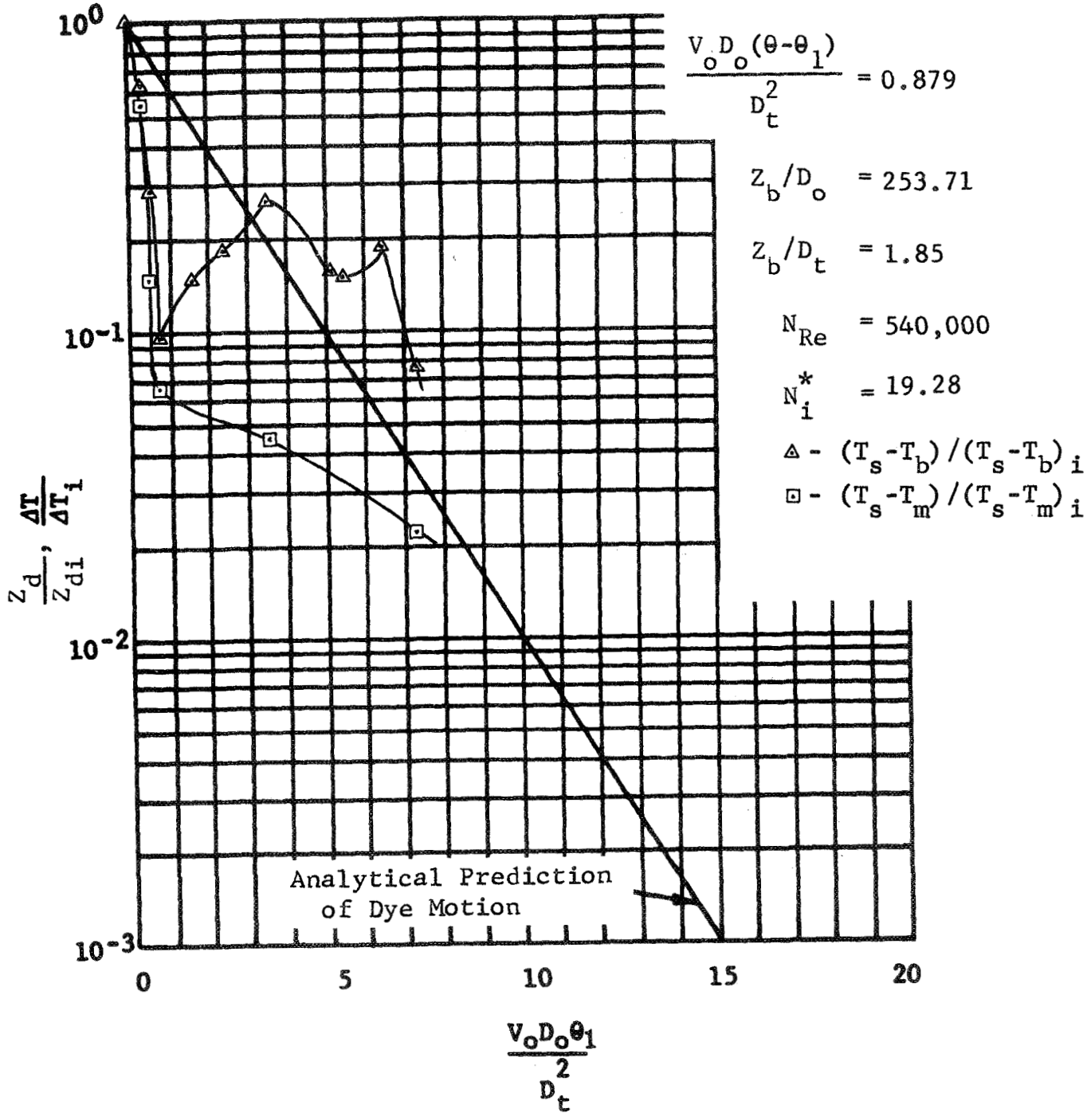

Figure 176 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 46

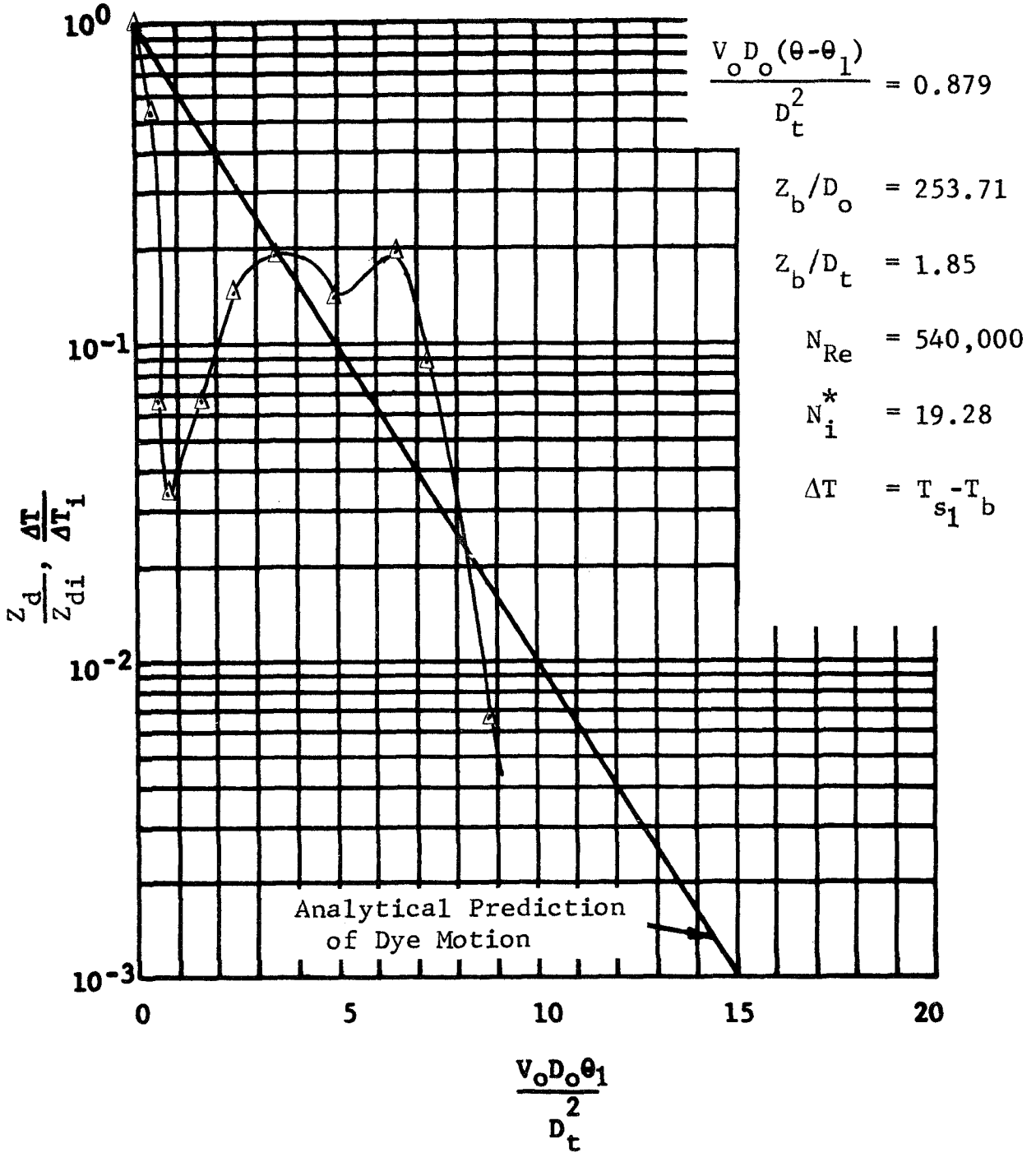

Figure 177 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 46

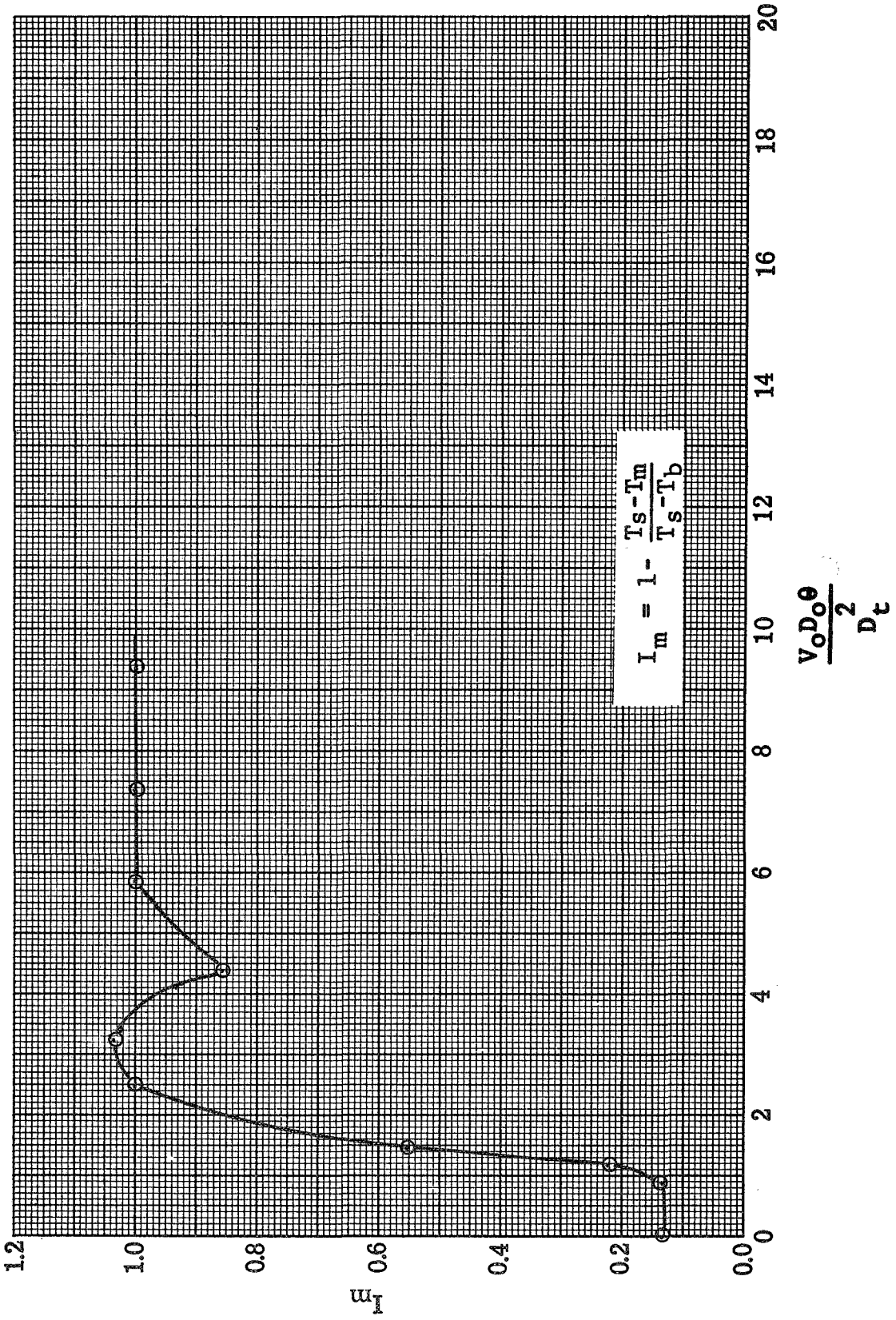

Figure 178 **Transient Energy Integral:** Run 46

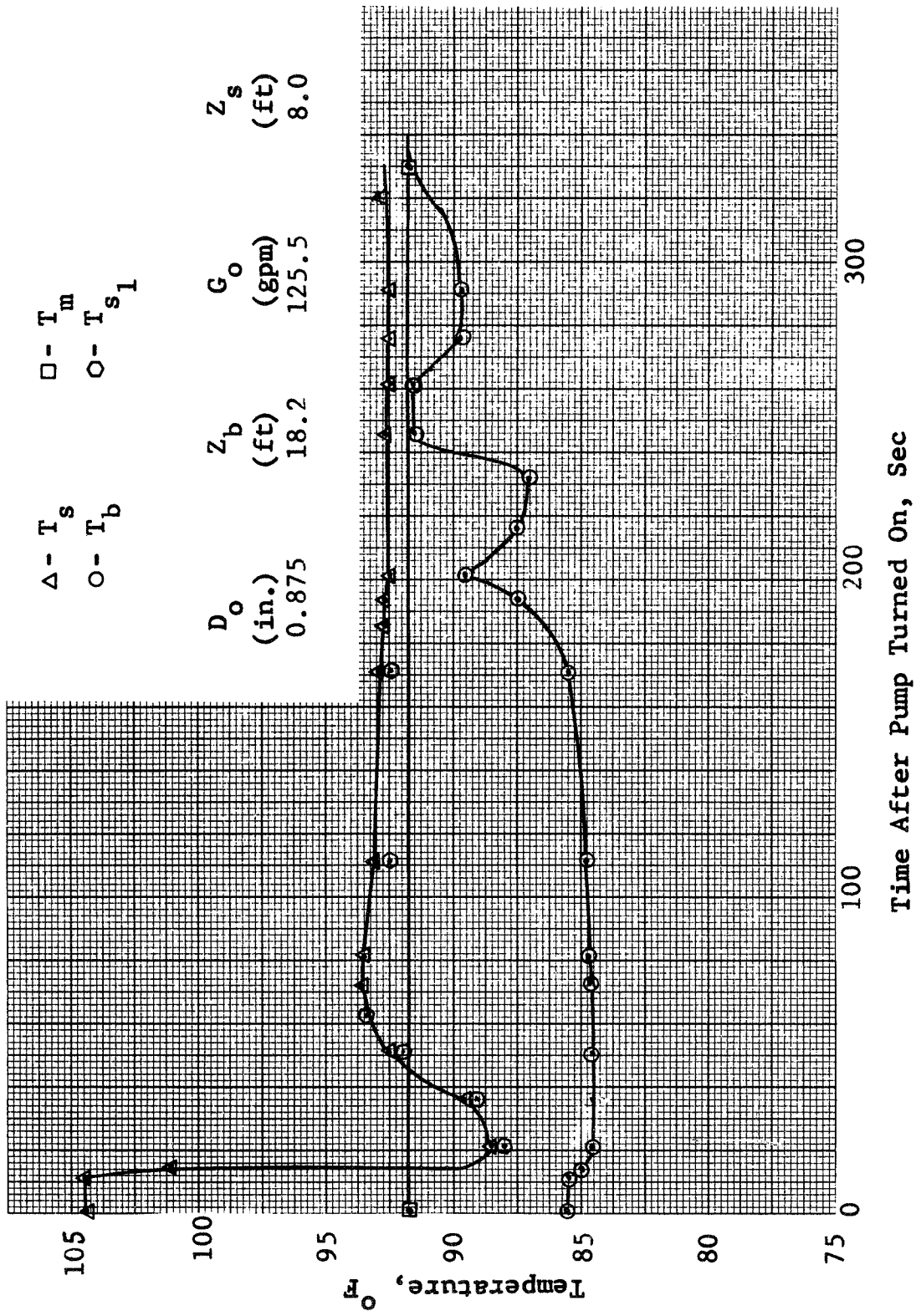

Figure 179 **Transient Temperature Destratification :** Run 47

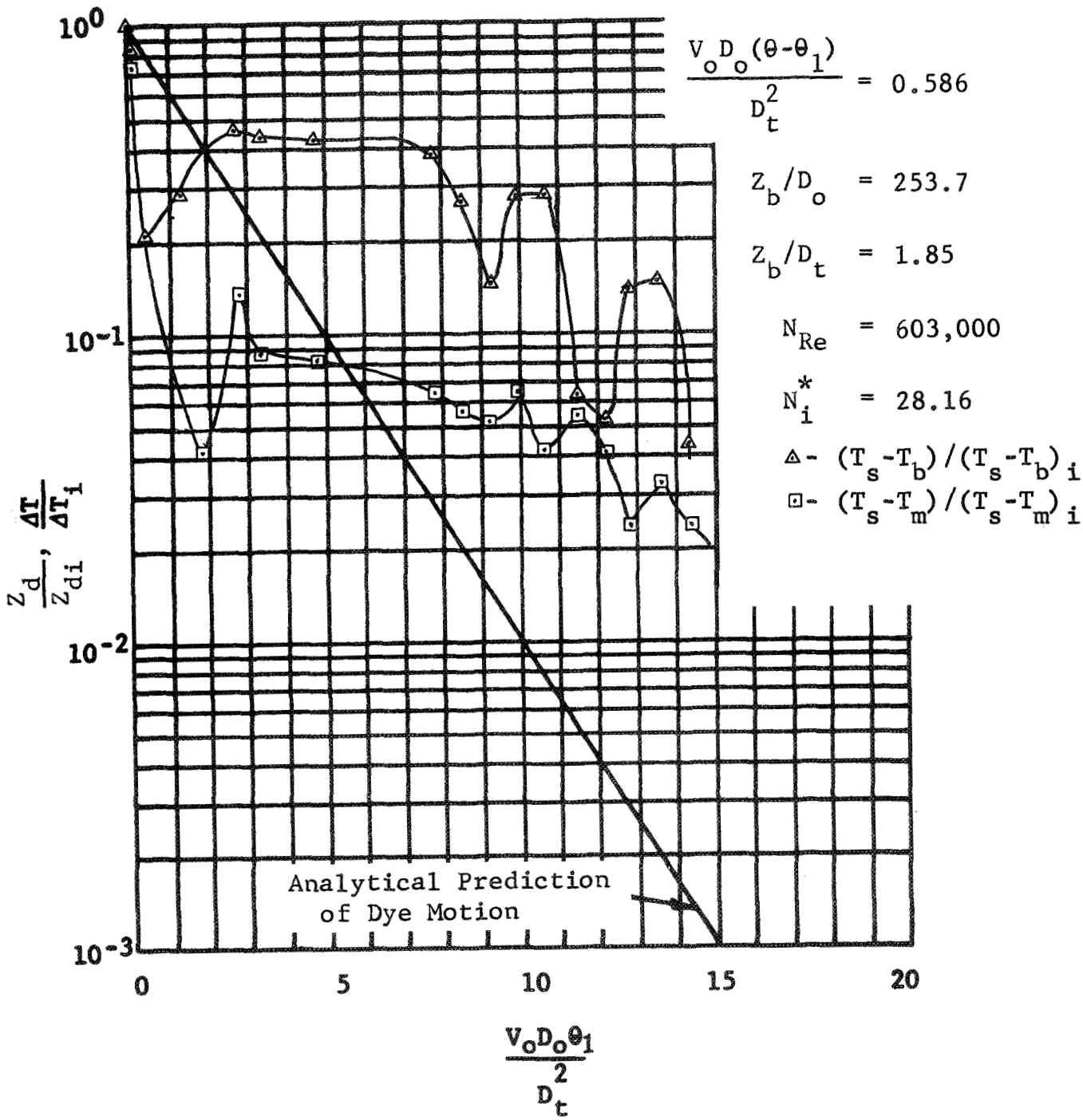

Figure 180 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 47

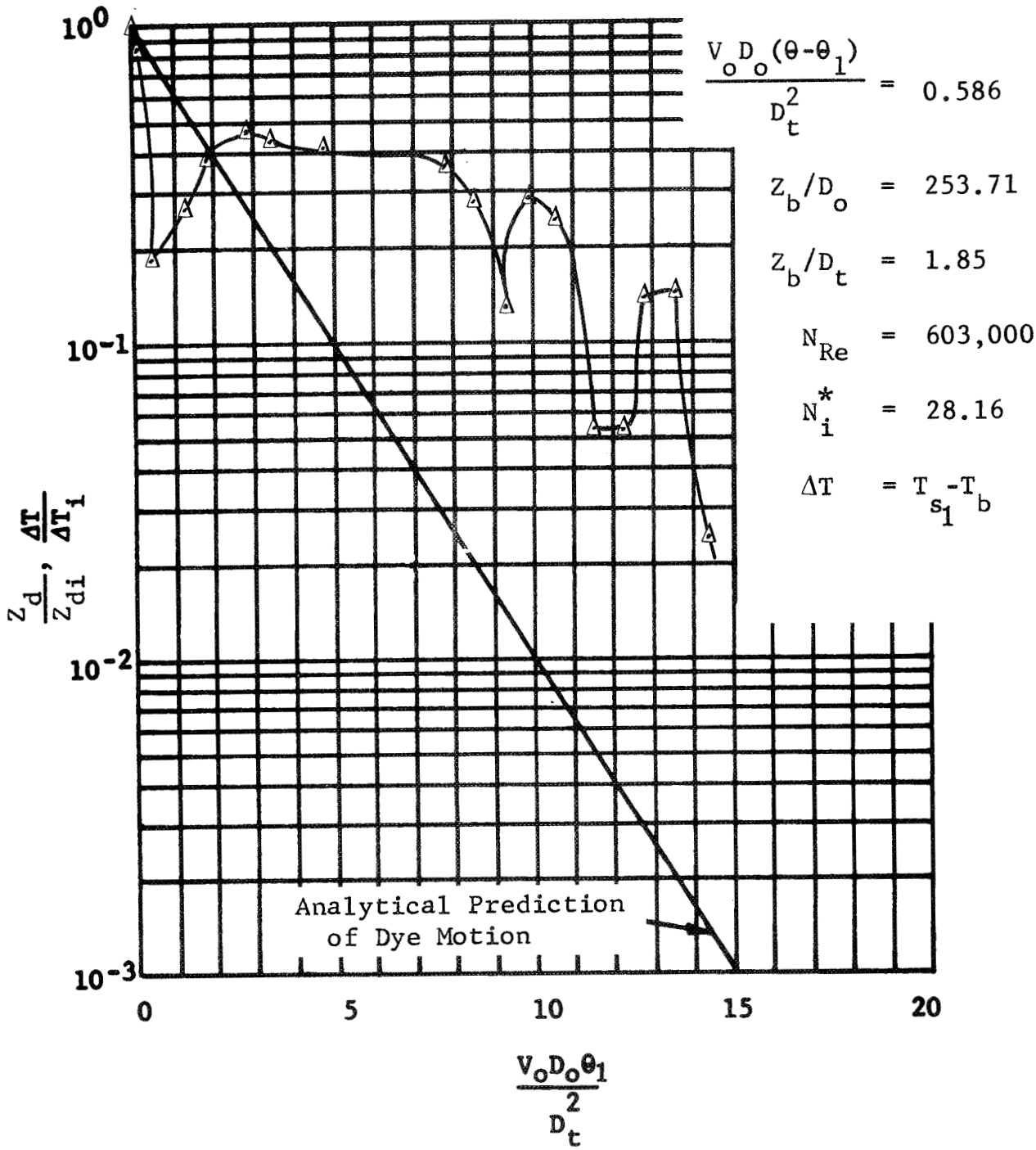

Figure 181 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 47

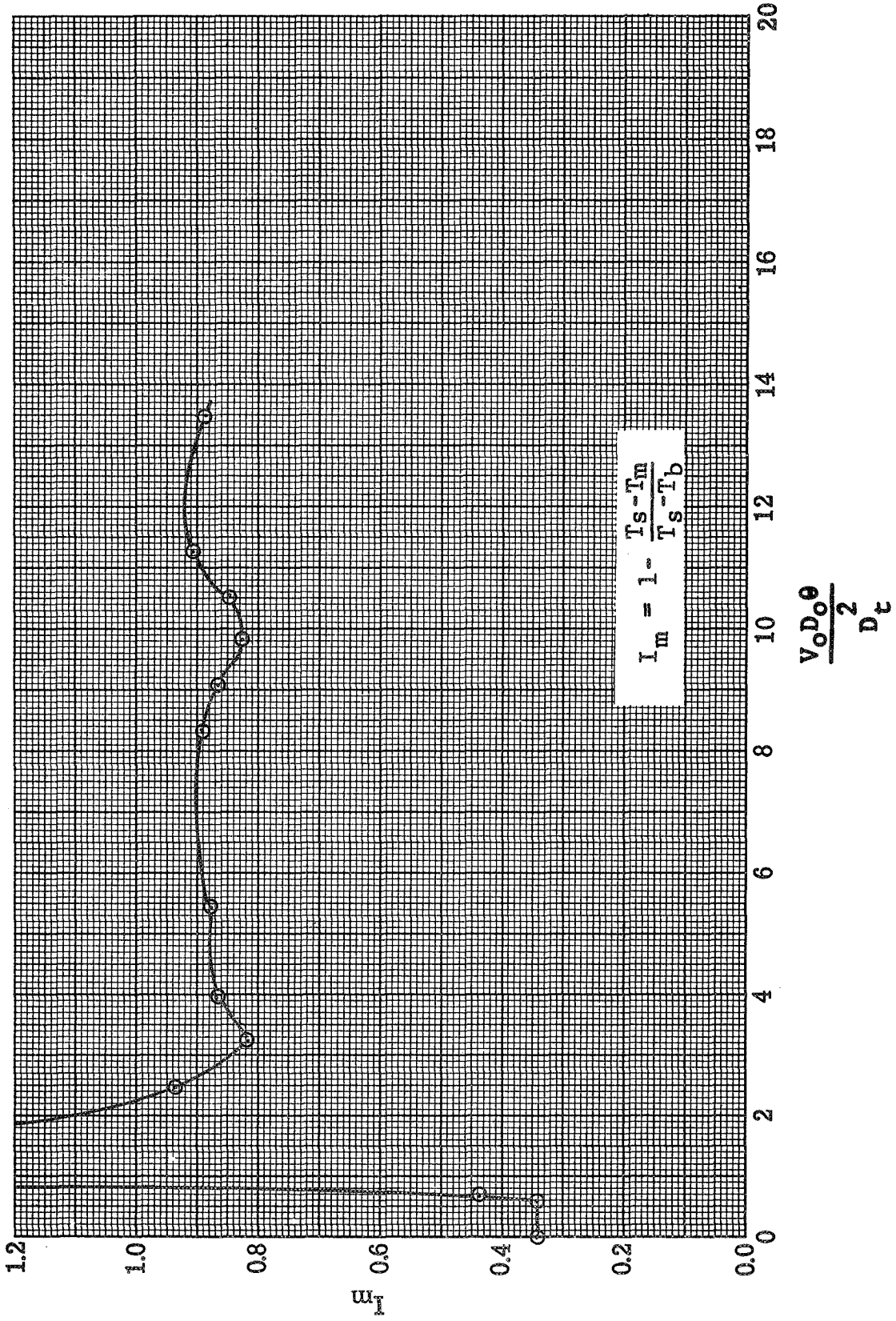

Figure 182 **Transient Energy Integral:** Run 47

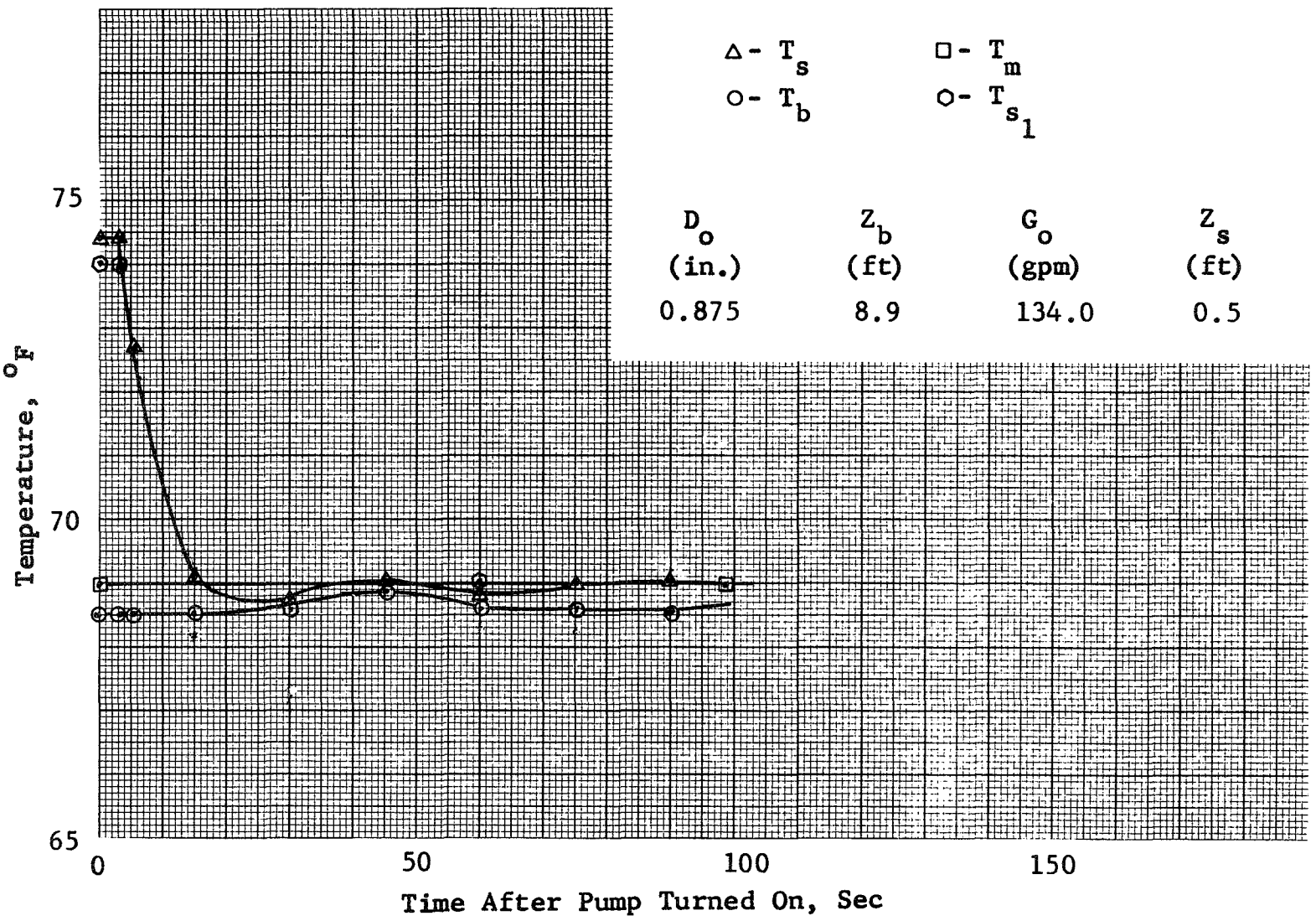

Figure 183 Transient Temperature Destratification: Run 48

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Fort Worth Division

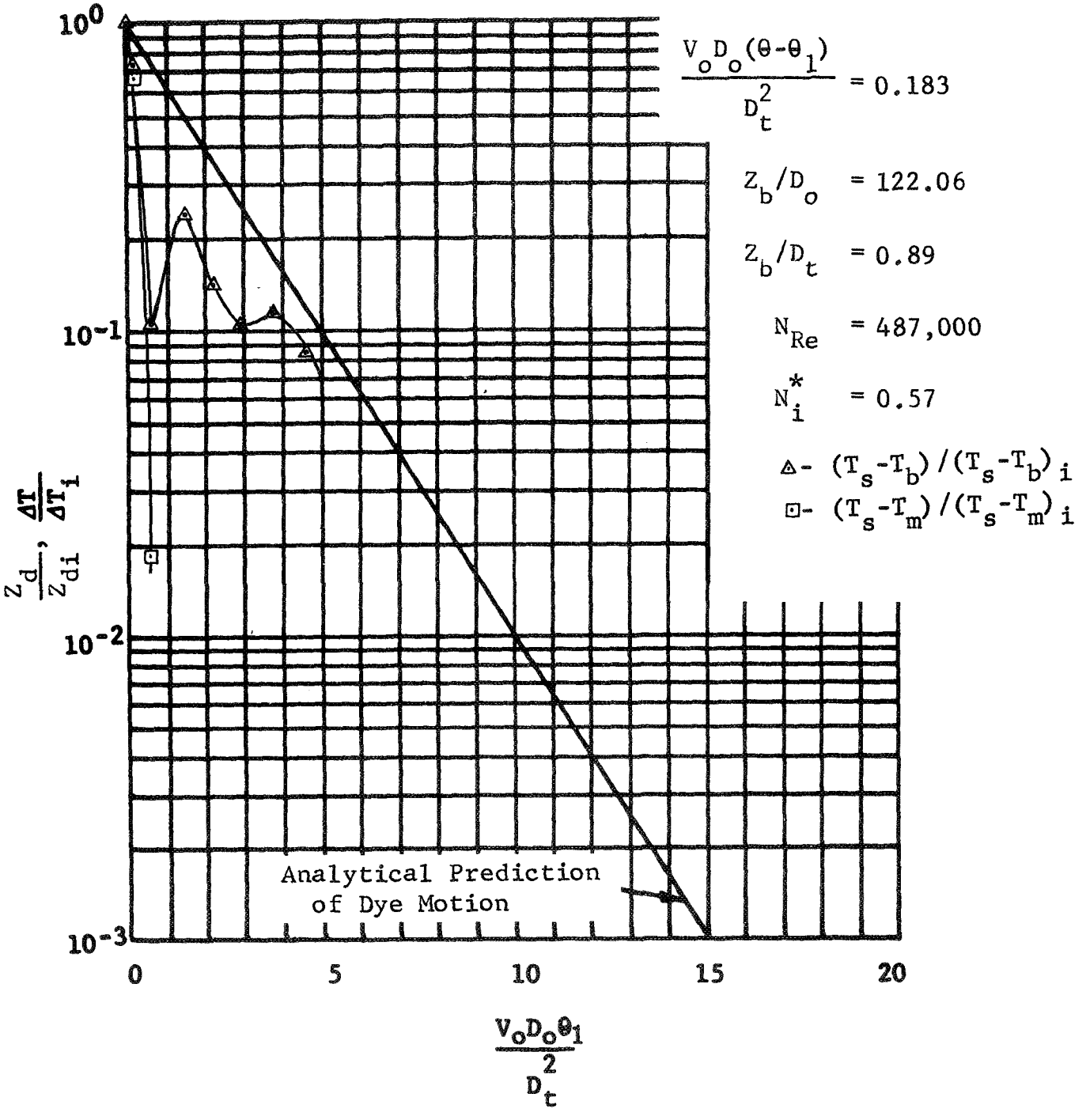

Figure 184 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 48

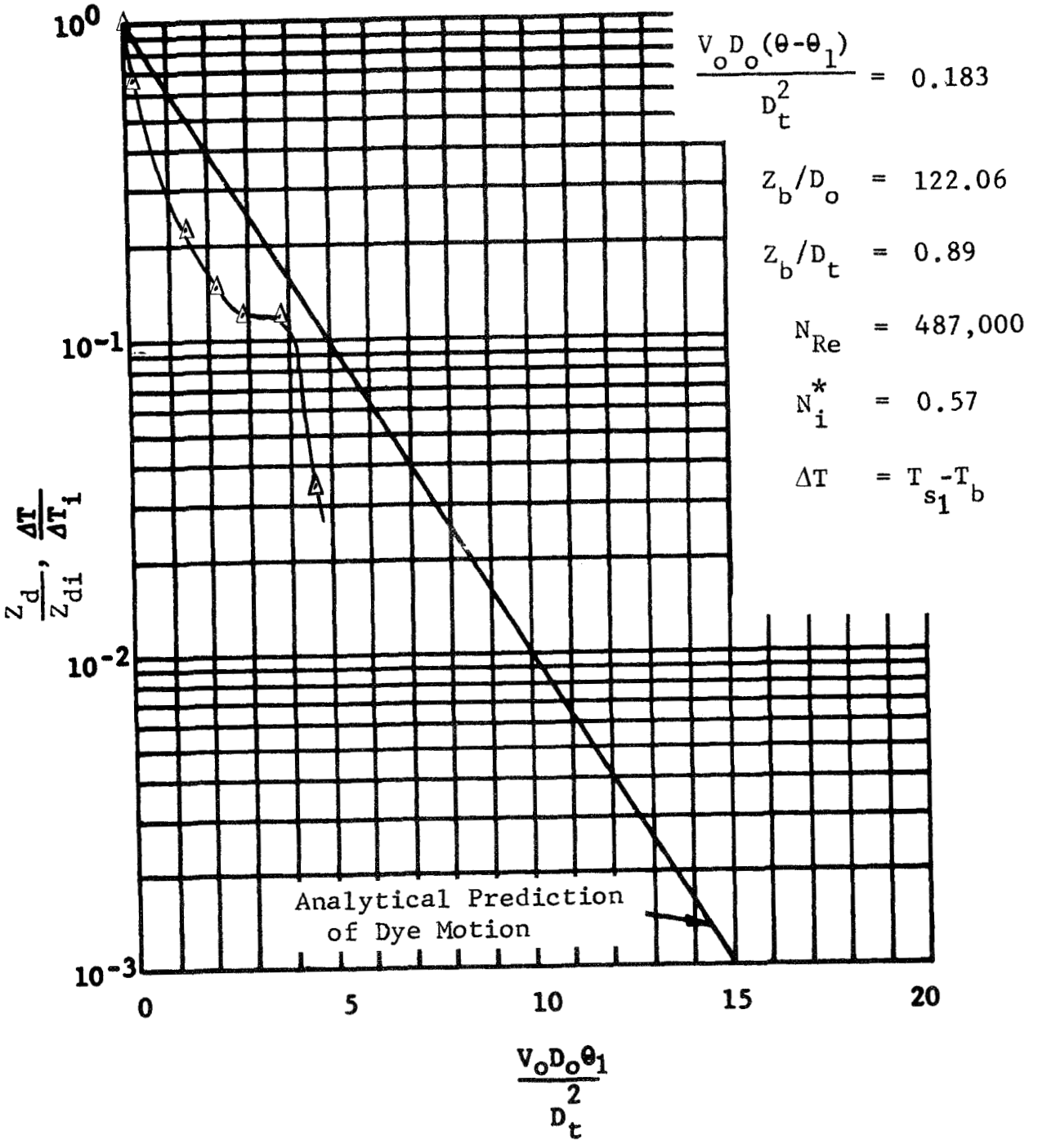

Figure 185 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 48

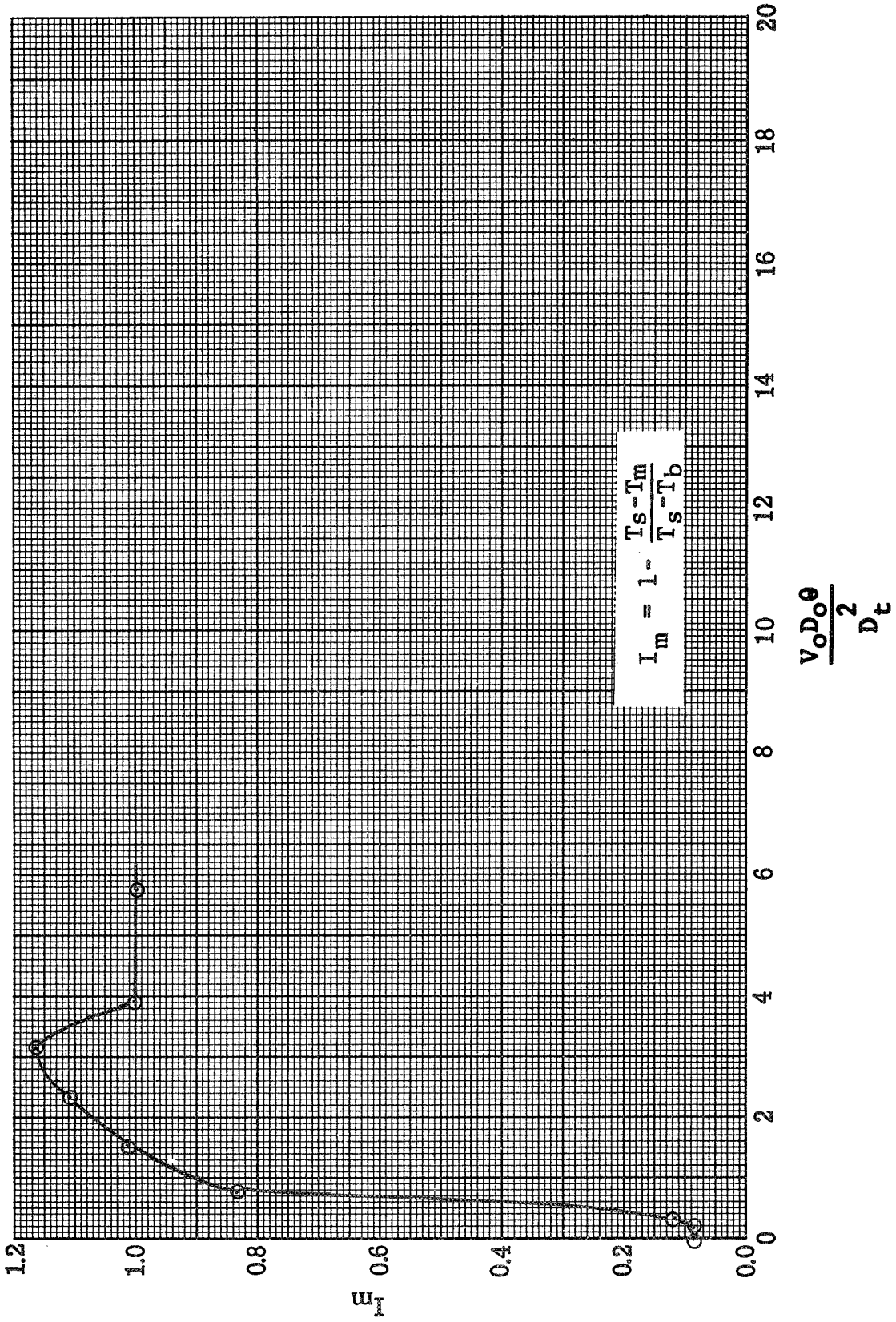

Figure 186 **Transient Energy Integral:** Run 48

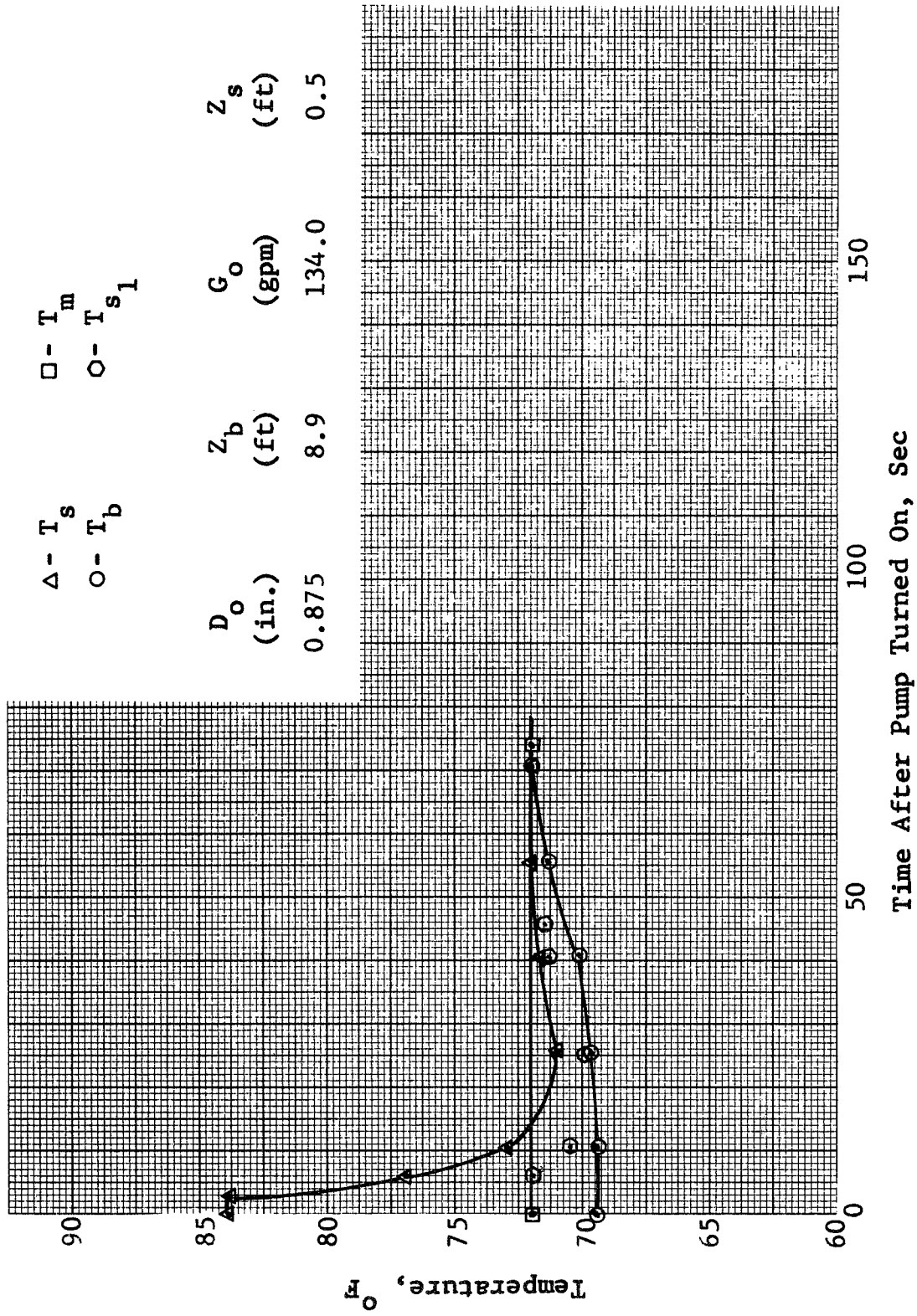

Figure 187 Transient Temperature Destratification : Run 49

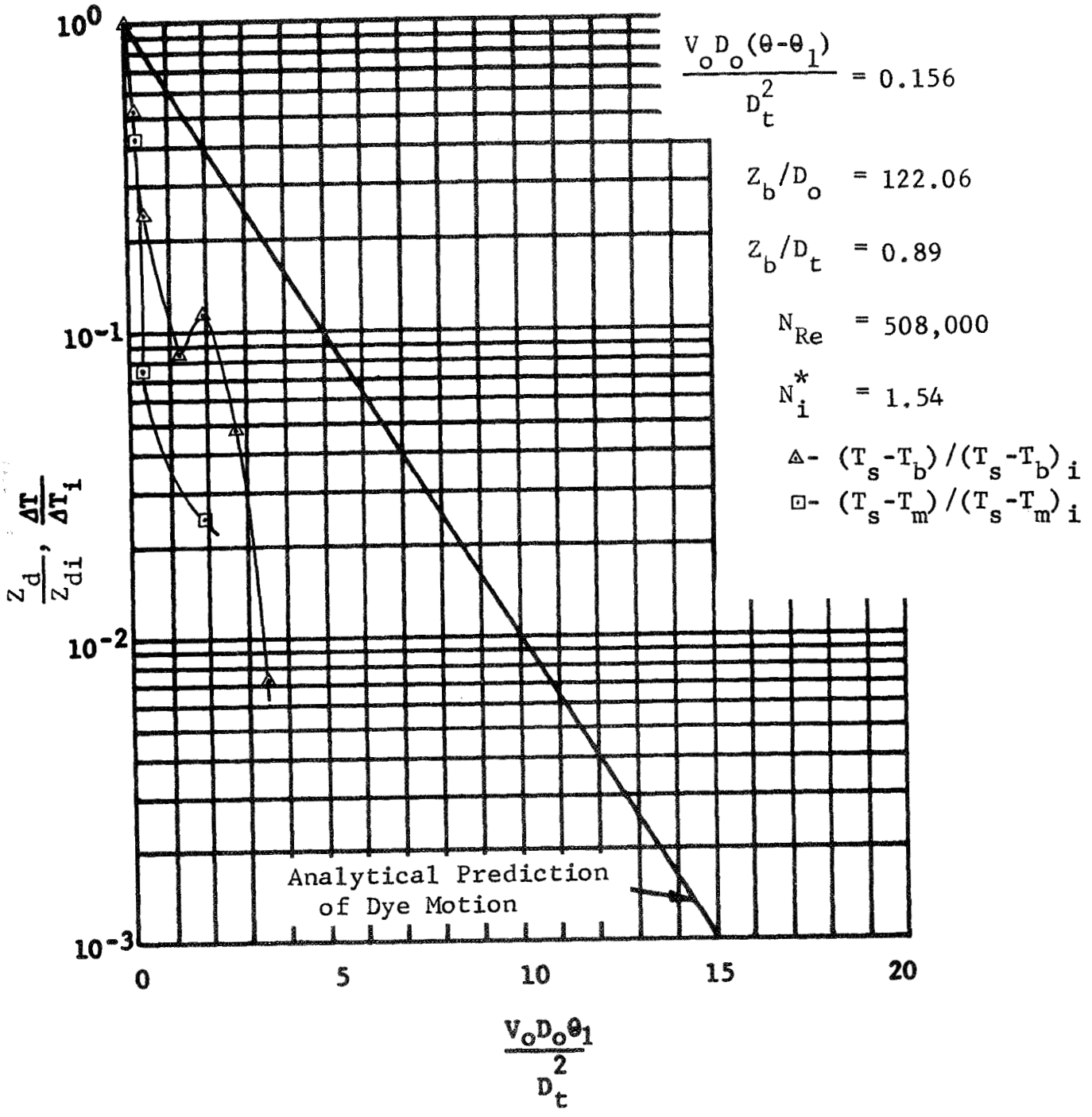

Figure 188 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 49

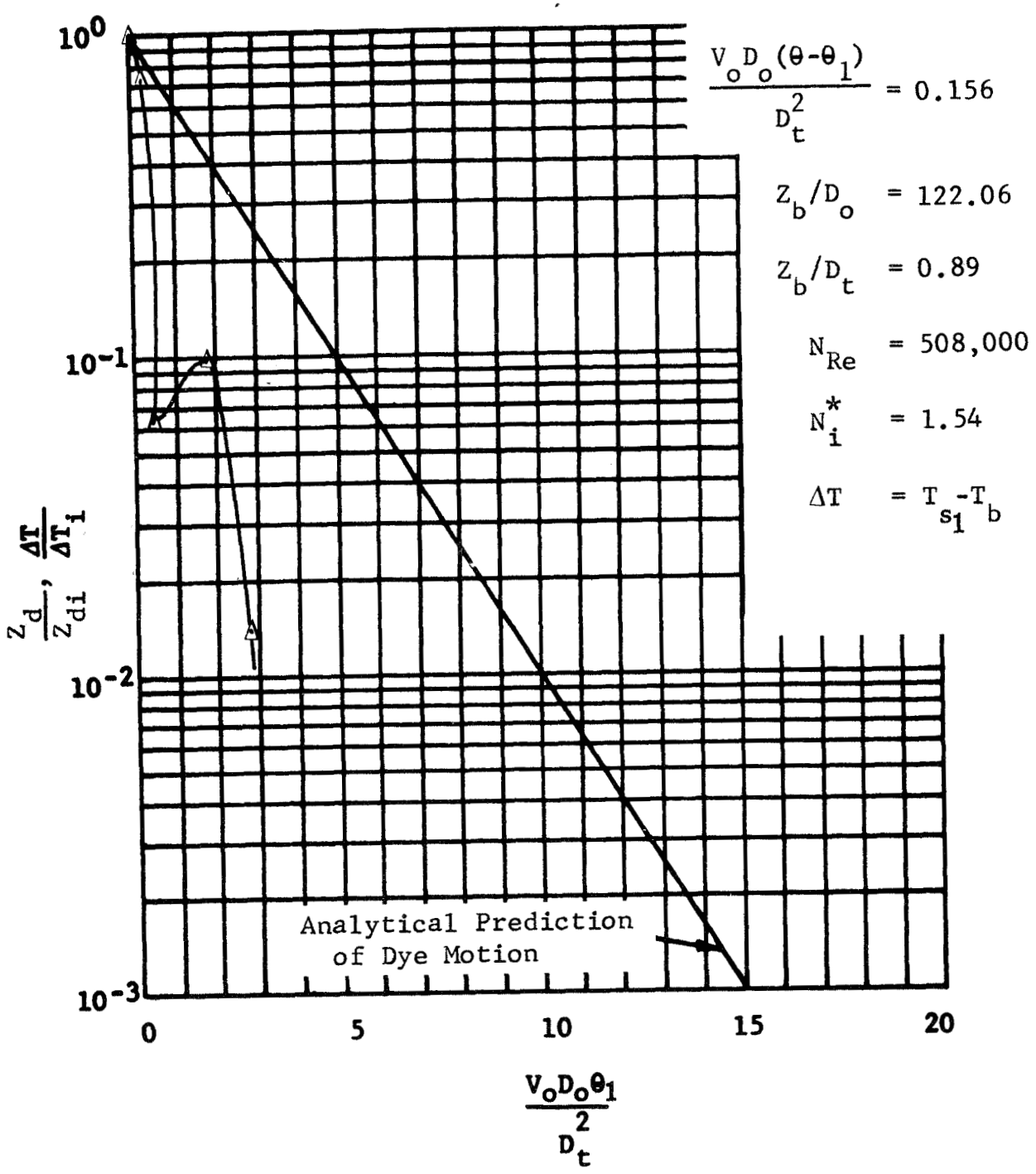

Figure 189 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 49

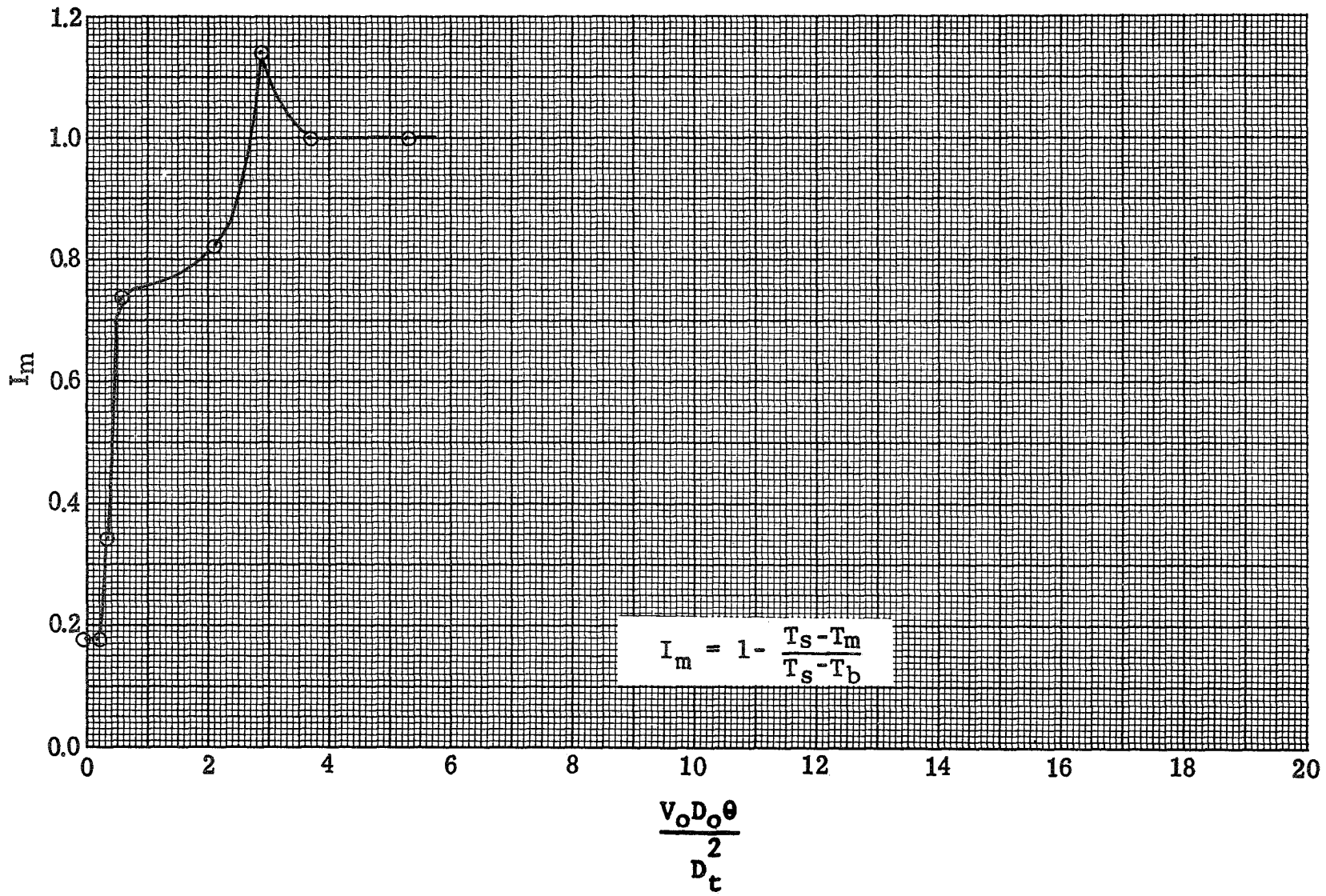

Figure 190 **Transient Energy Integral:** Run 49

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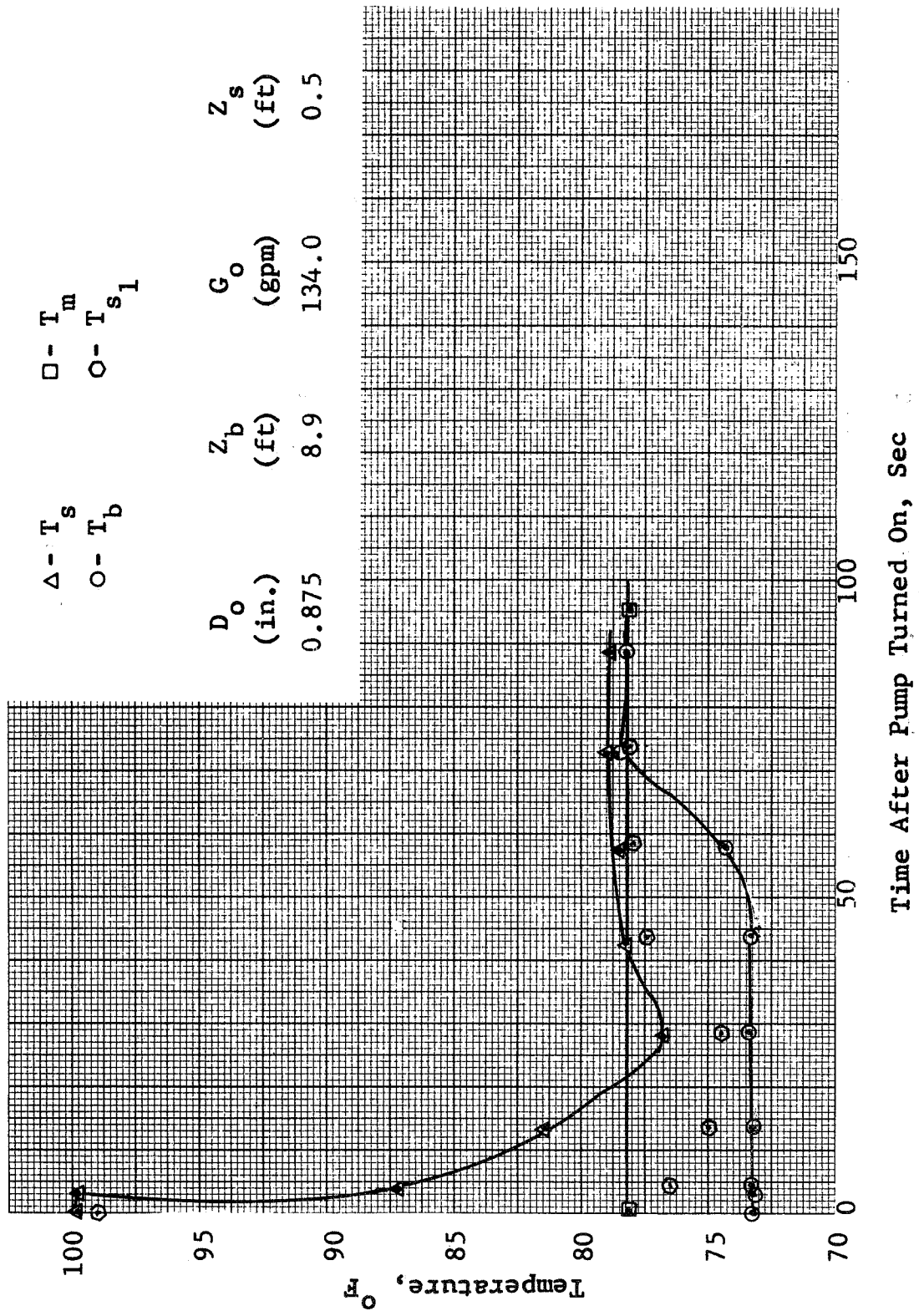

Figure 191 Transient Temperature Destratification: Run 50

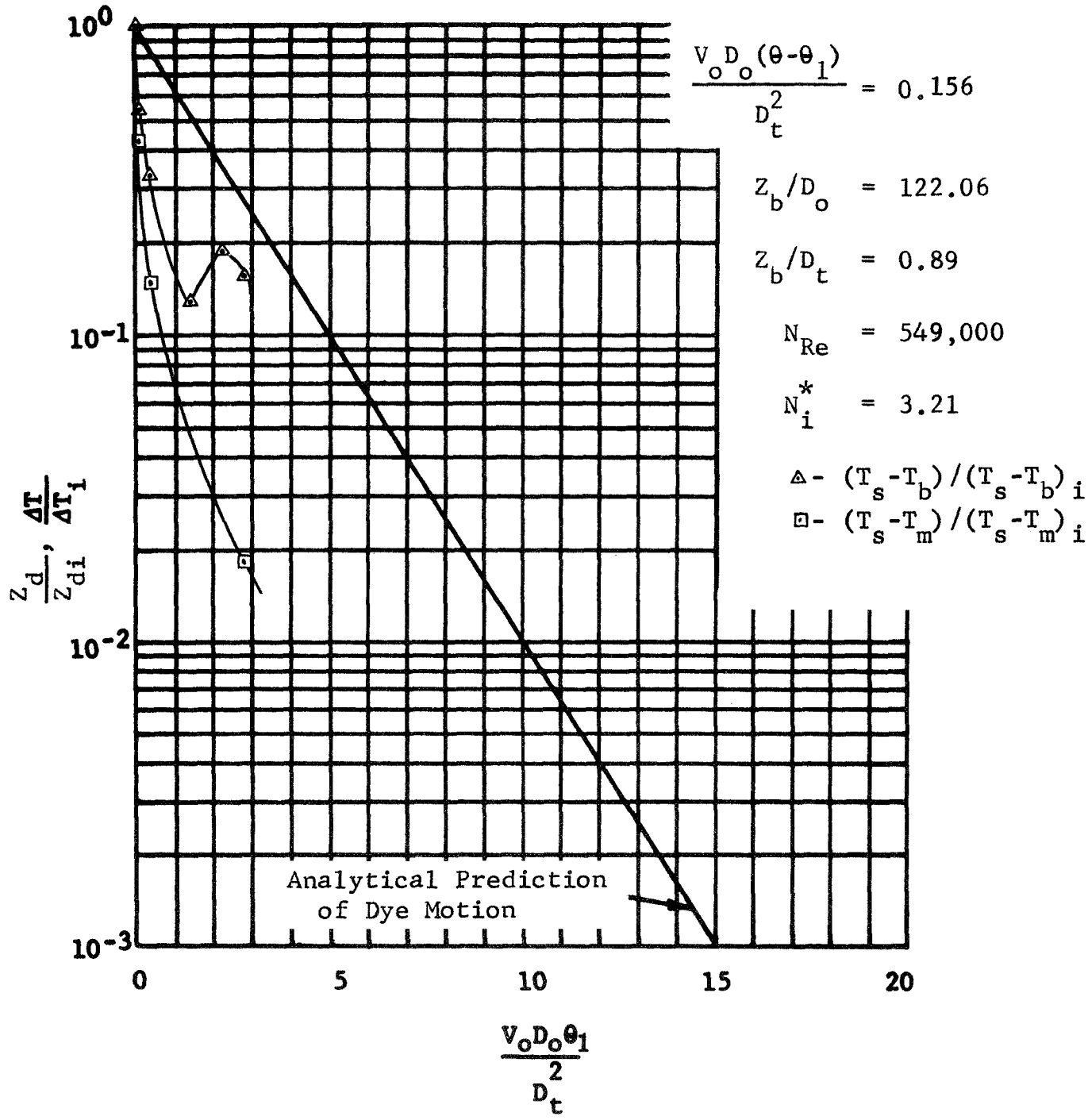

Figure 192 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 50

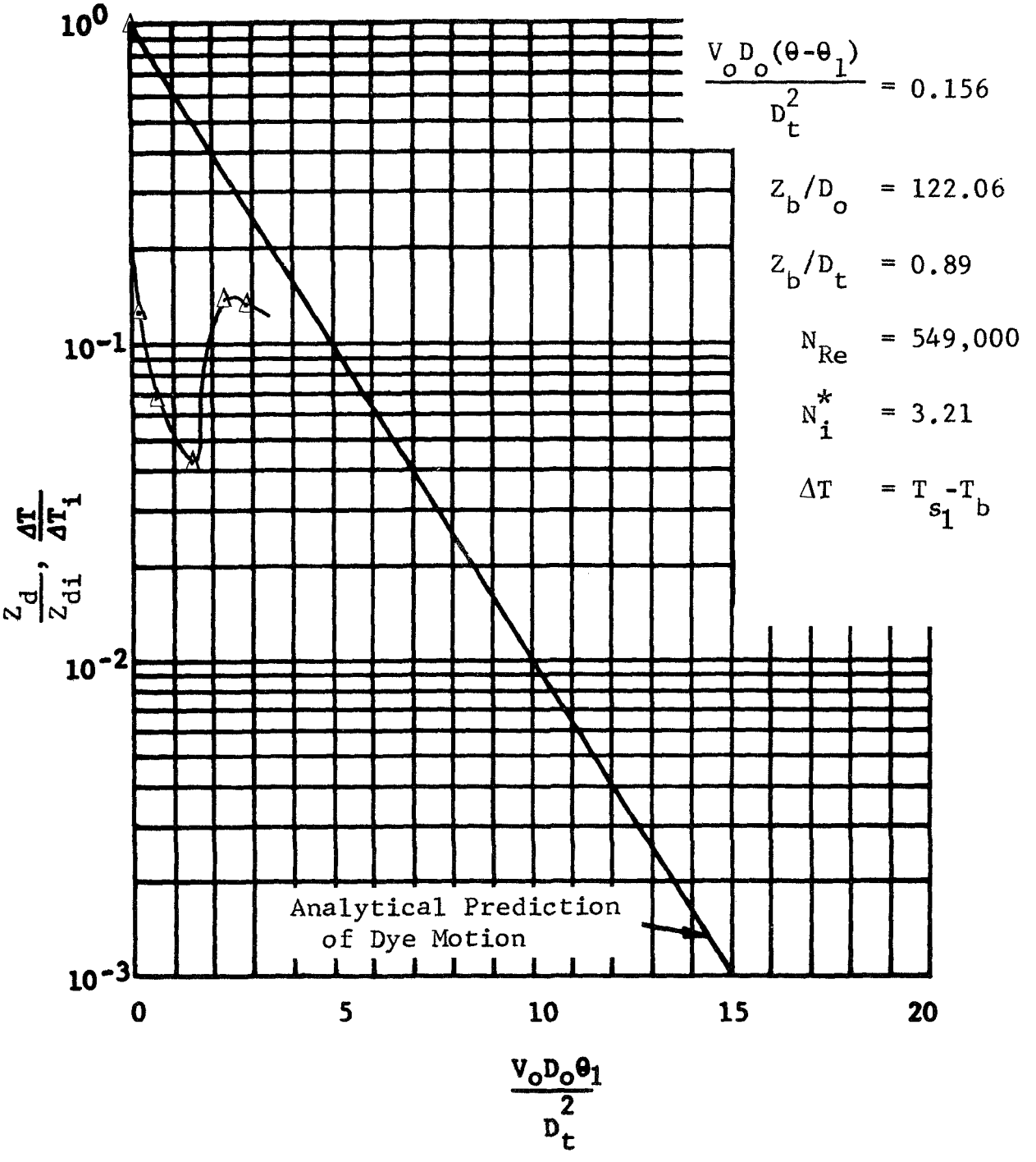

Figure 193 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 50

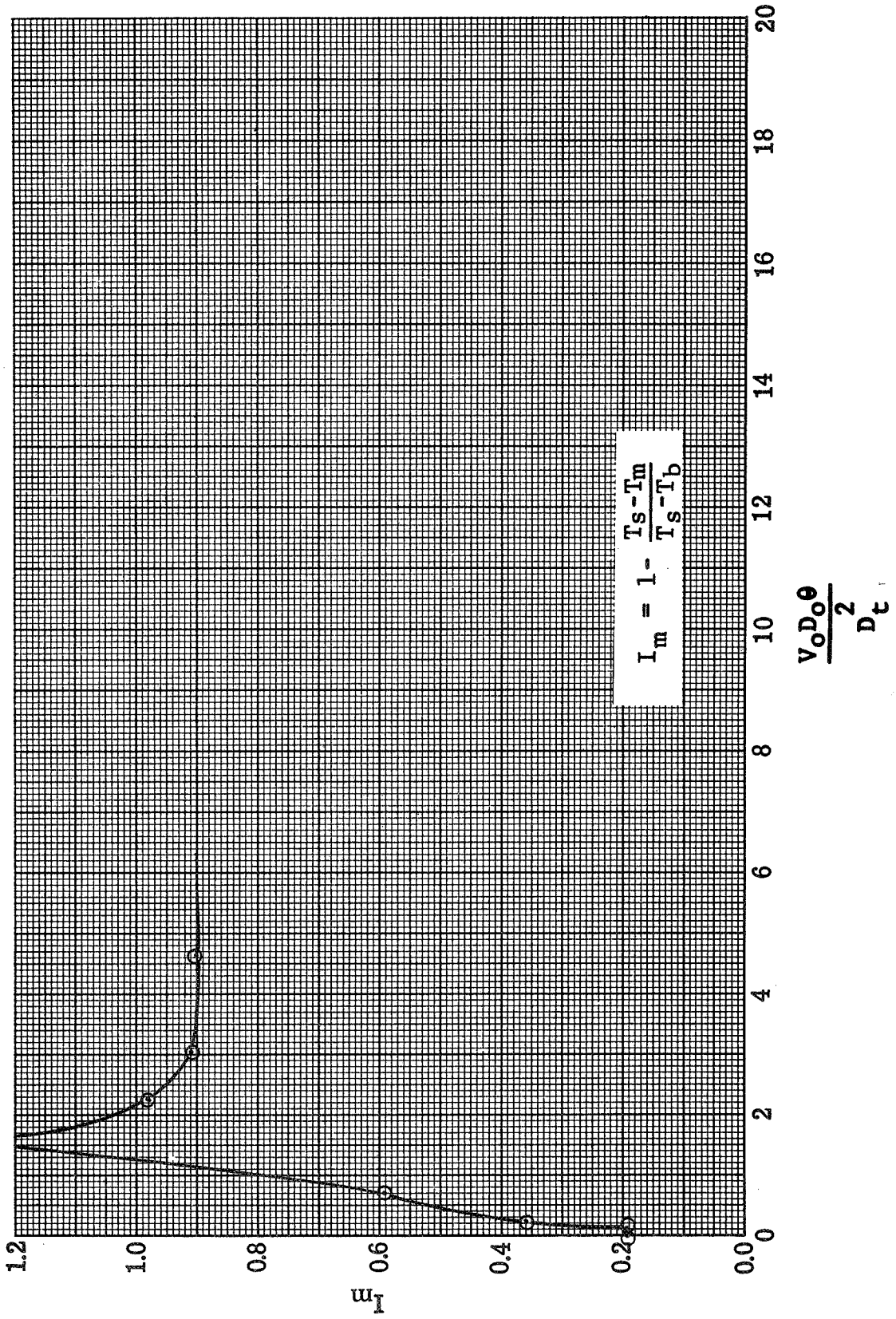

Figure 194 **Transient Energy Integral:** Run 50

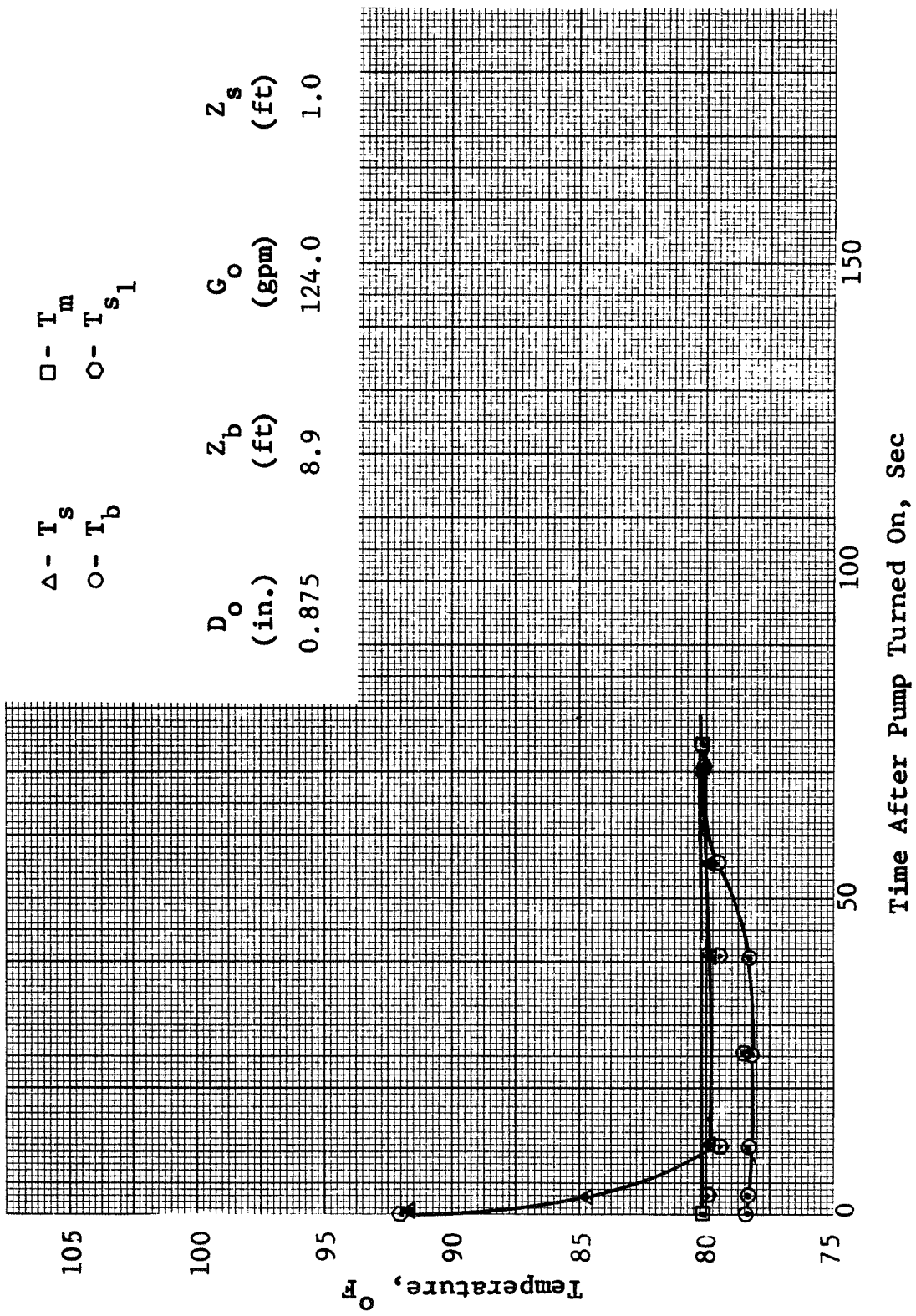

Figure 195 Transient Temperature Destratification : Run 51

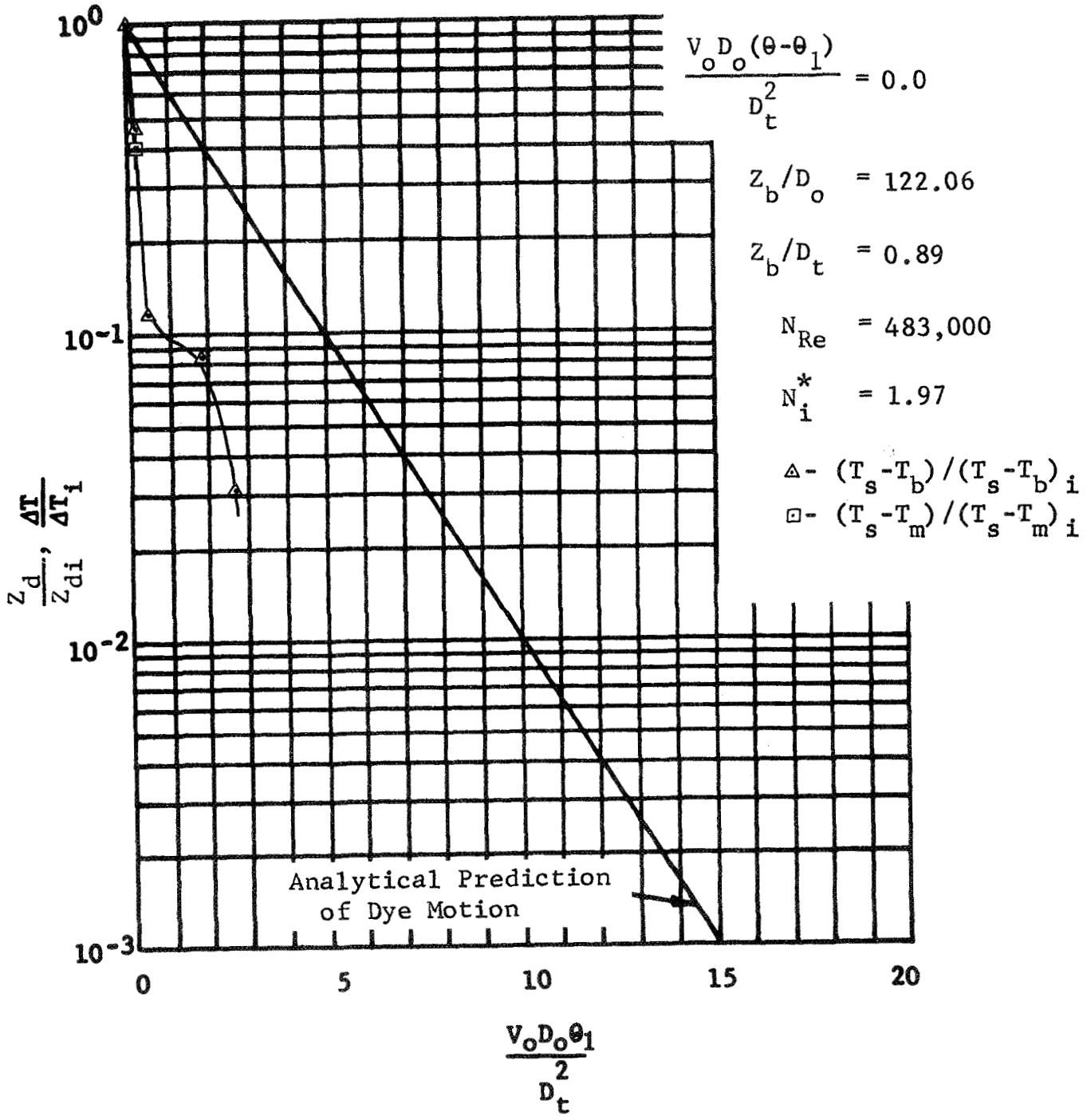

Figure 196 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 51

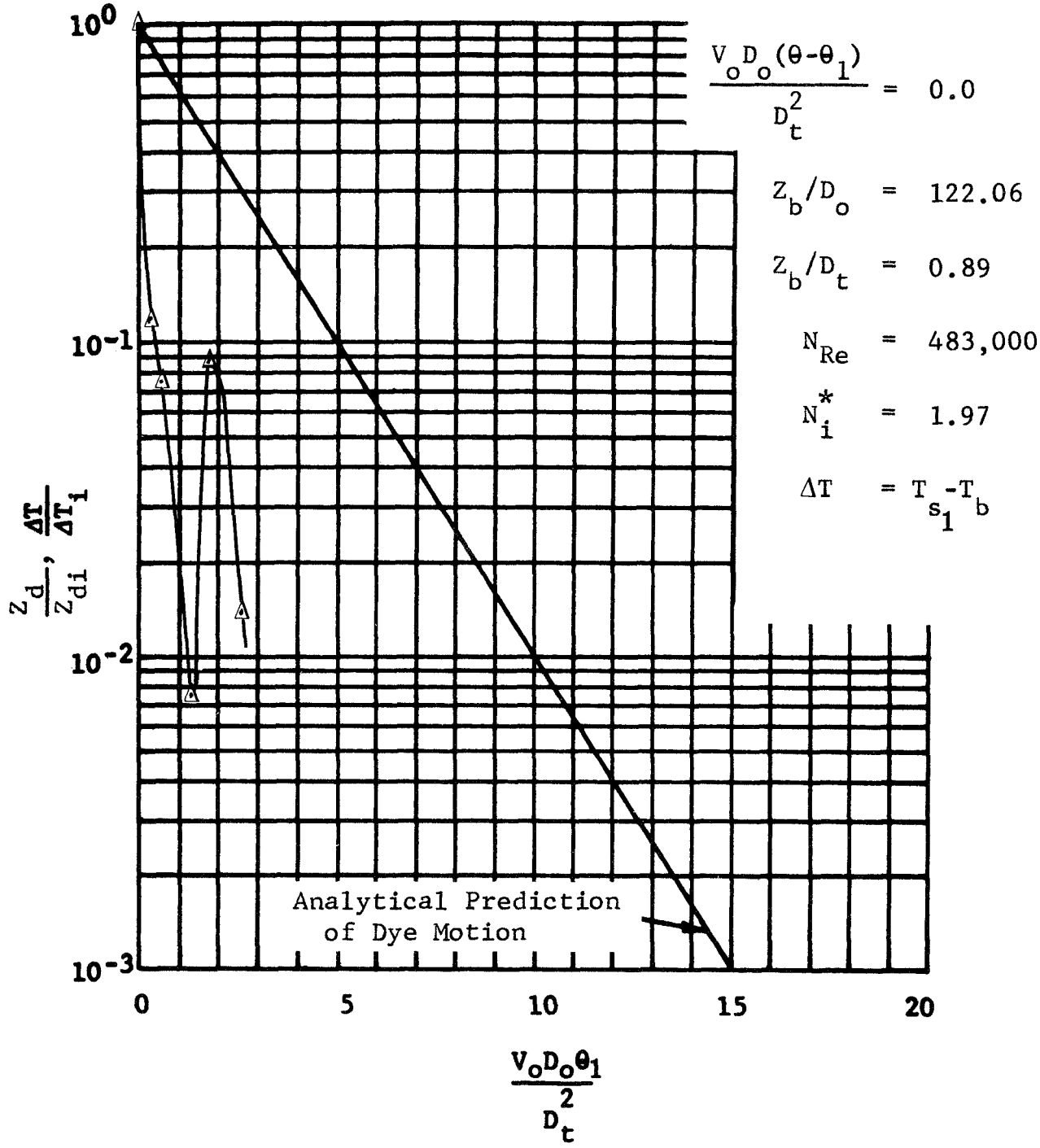

Figure 197 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 51

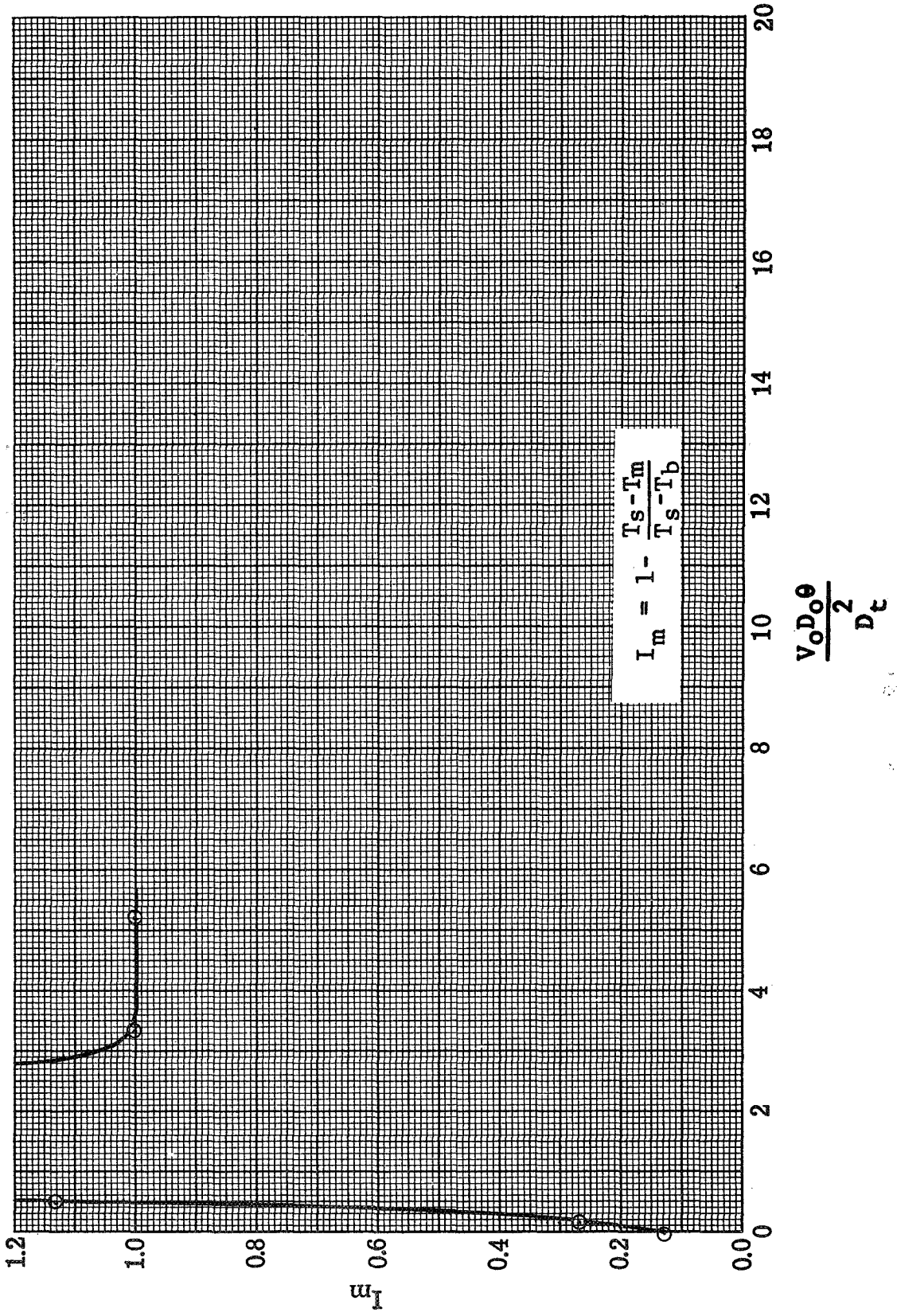

Figure 198 **Transient Energy Integral:** Run 51

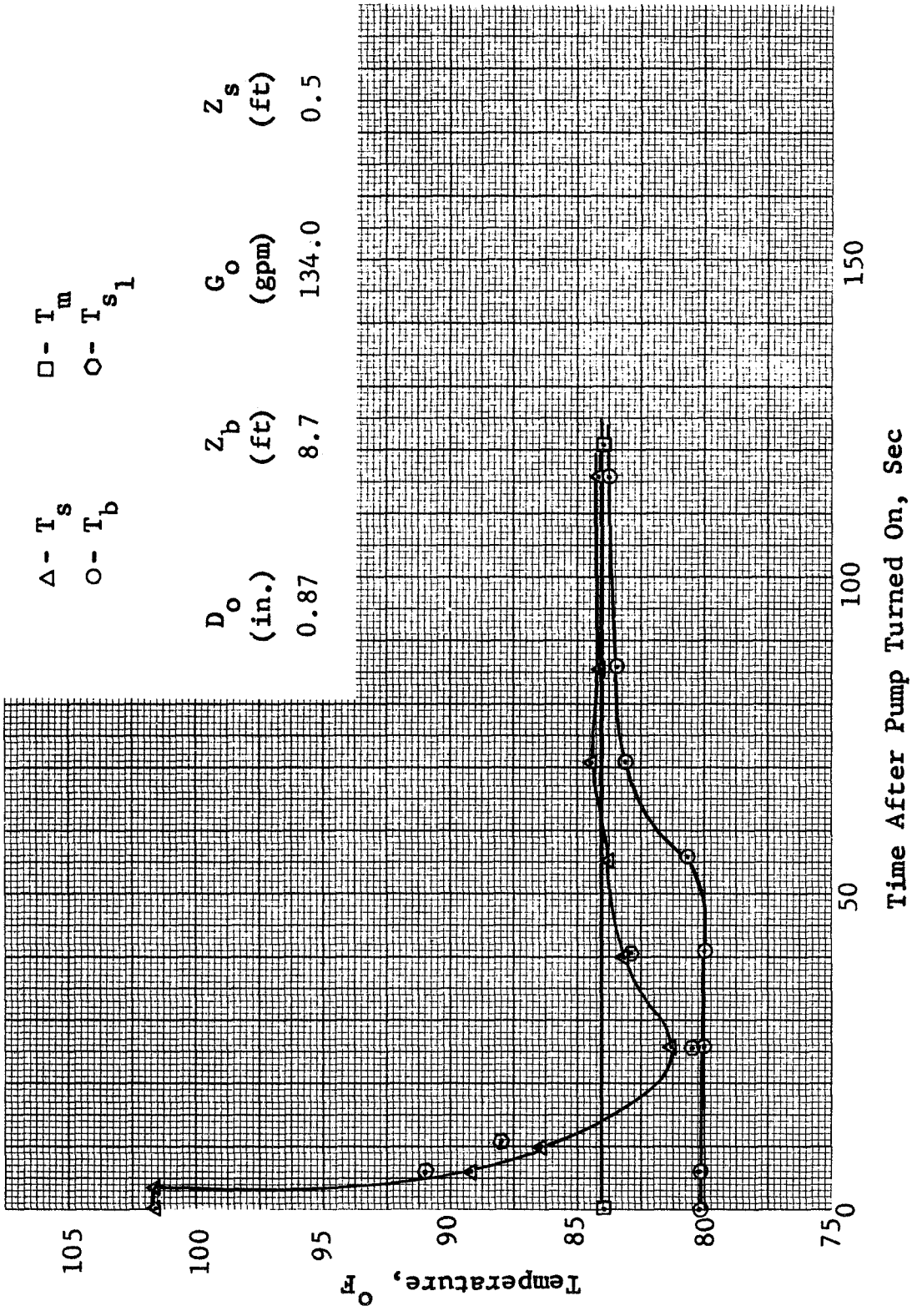

Figure 199 **Transient Temperature Destratification :** Run 52

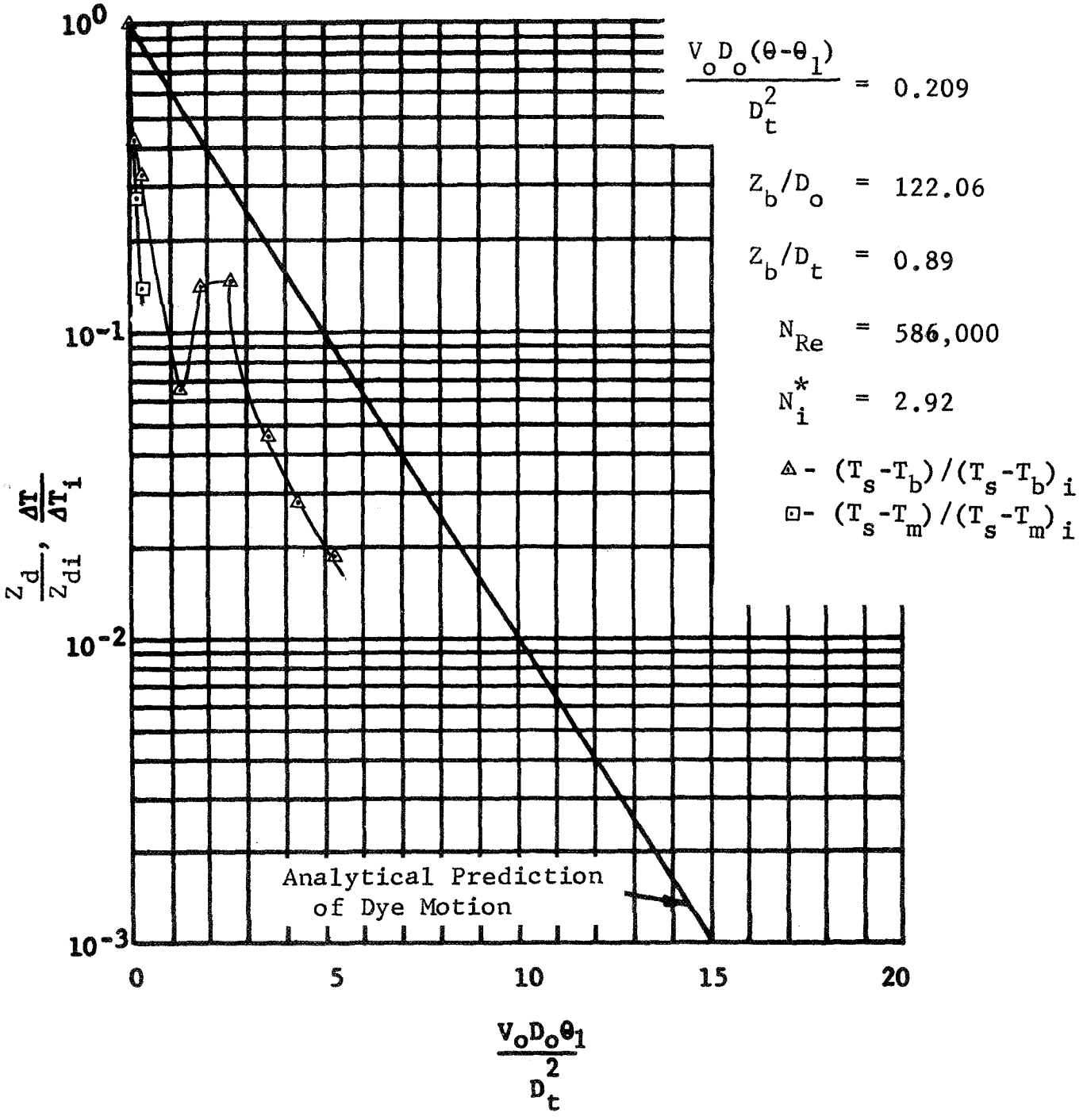

Figure 200 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 52

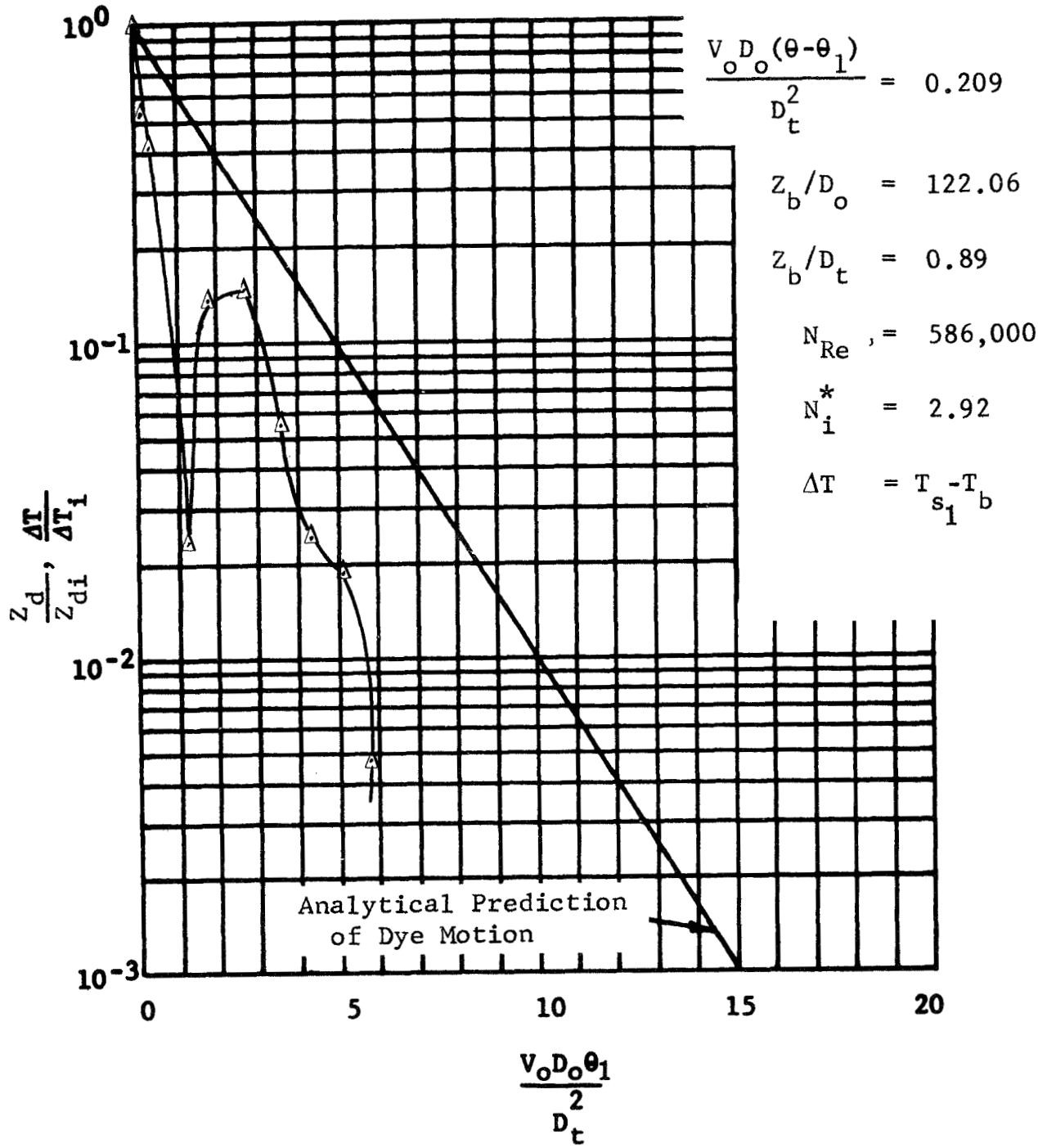

Figure 201 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 52

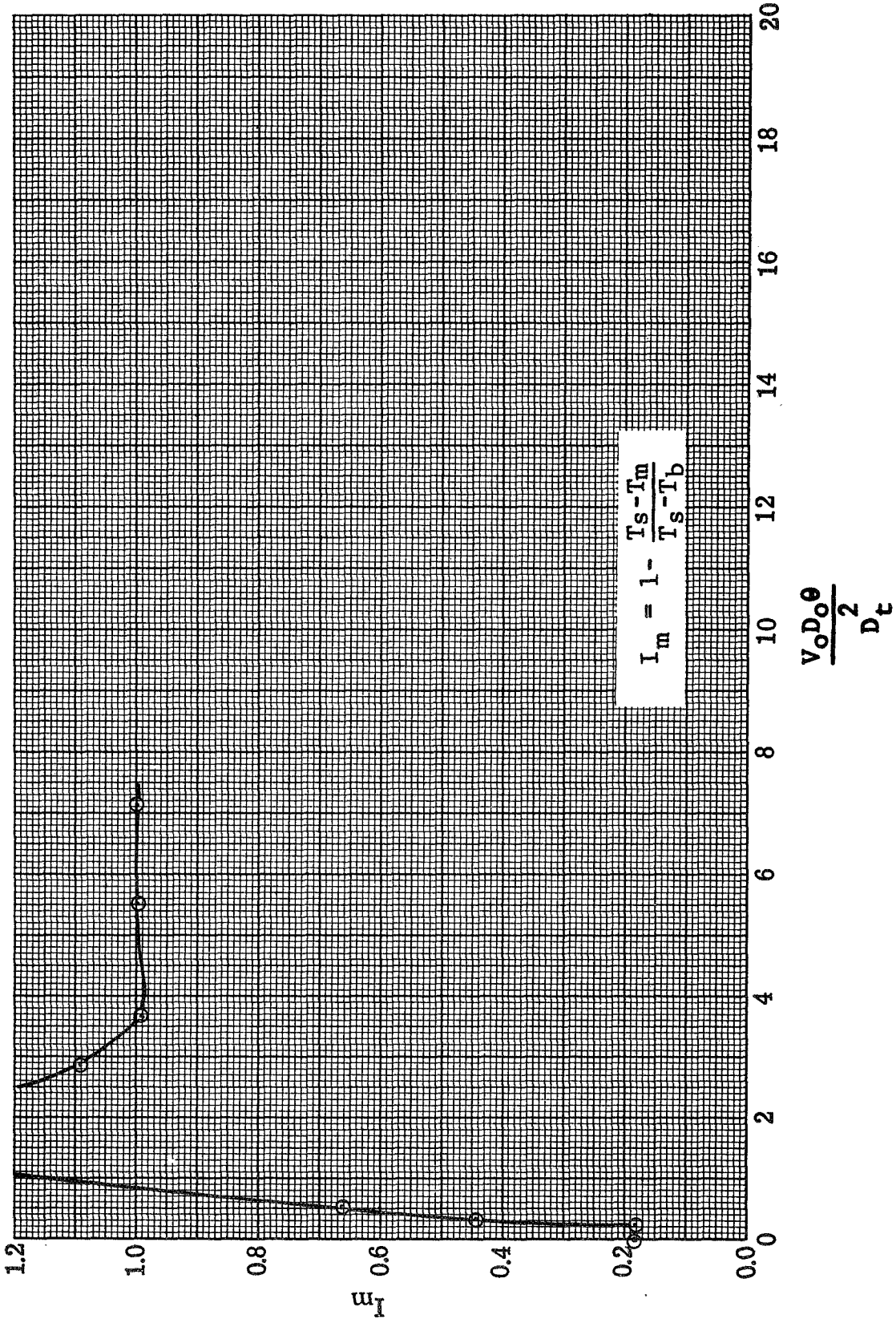

Figure 202 **Transient Energy Integral:** Run 52

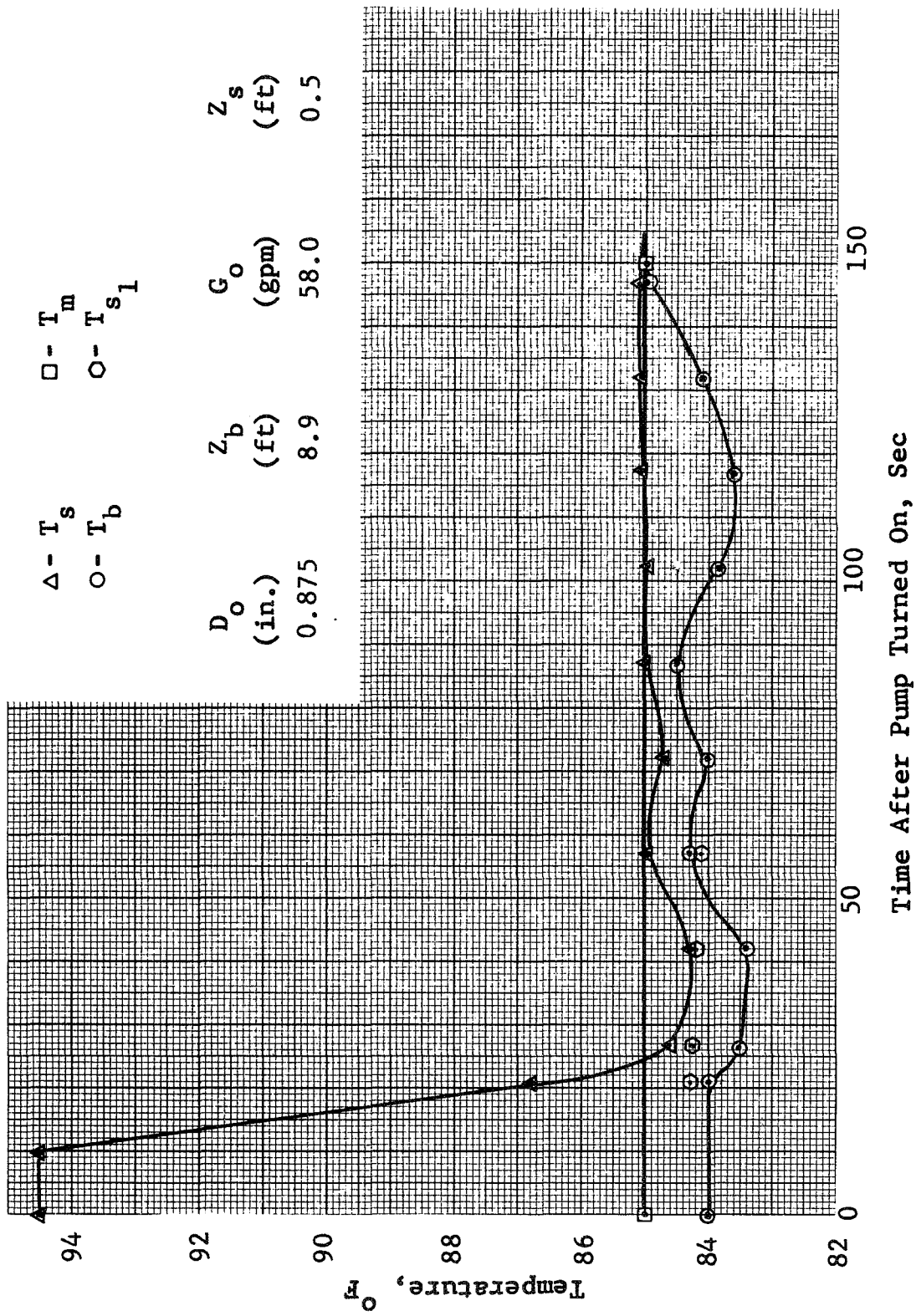

Figure 203 Transient Temperature Destratification : Run 53

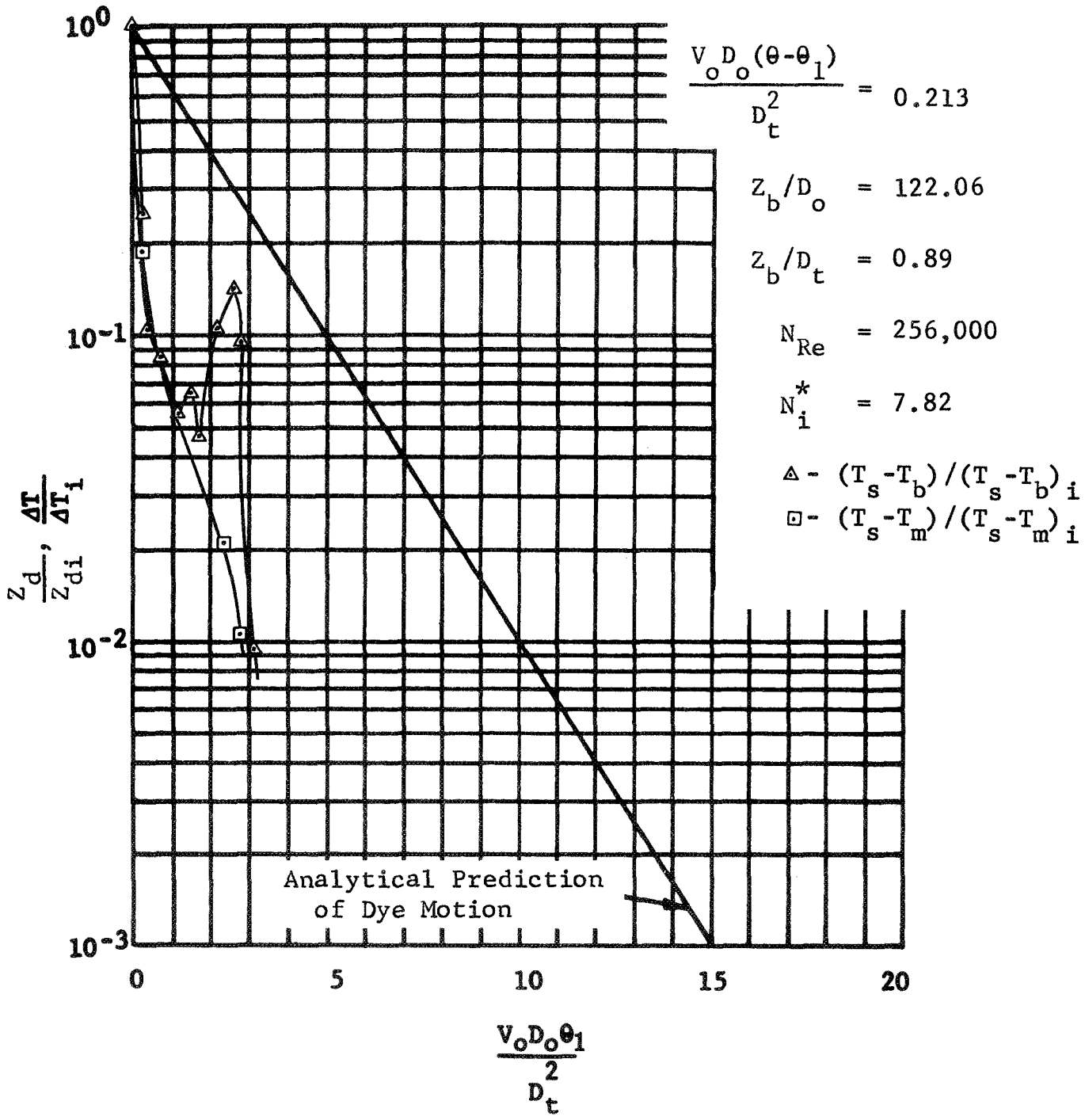

Figure 204 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Average Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 53

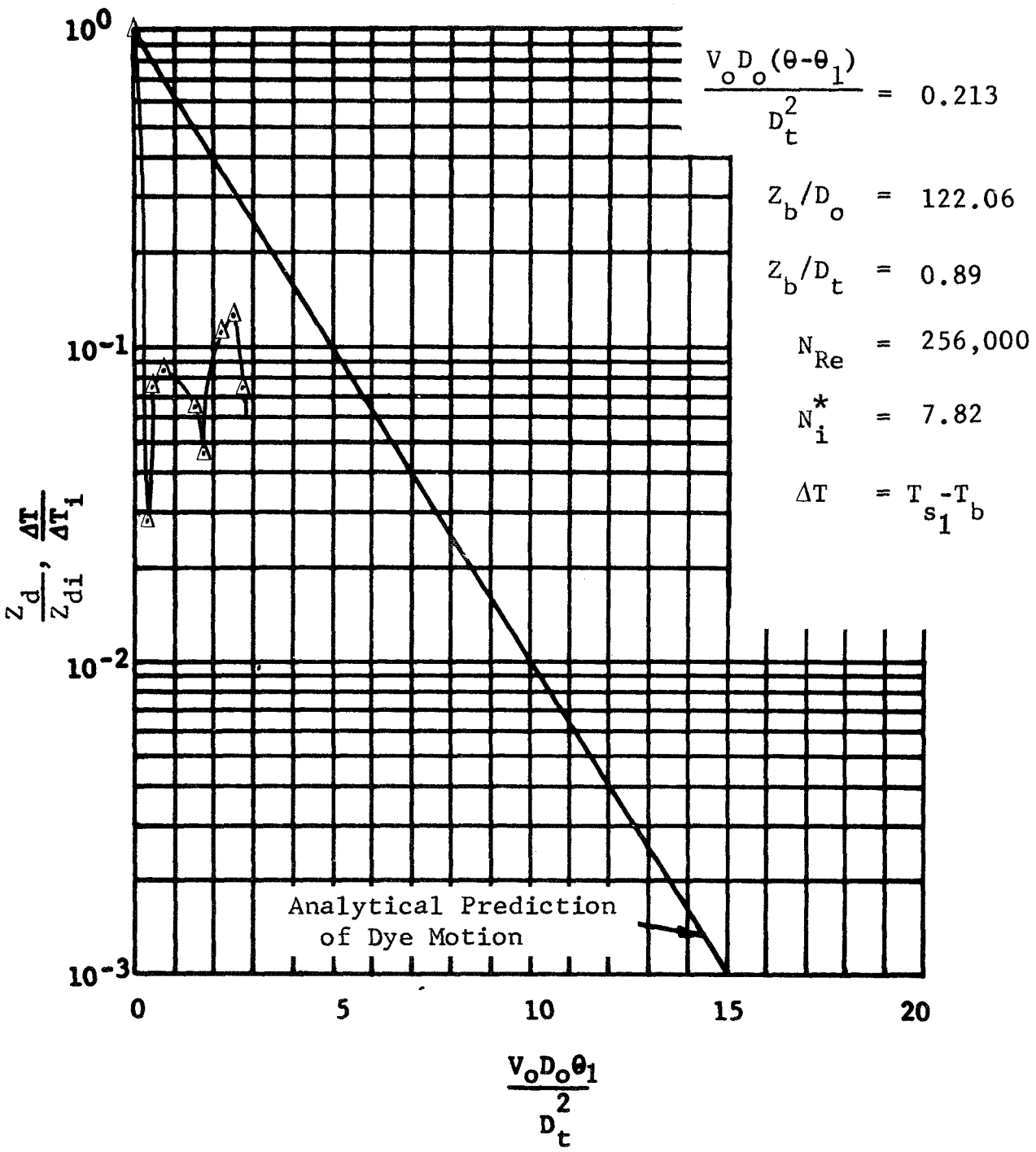

Figure 205 Fraction of Initial Temperature Difference After Surface Temperature Starts to Drop: Pump Starts at θ = 0.0 sec; Centerline Surface Temperature Drop Starts at θ_1 = 0.0 sec; Run 53

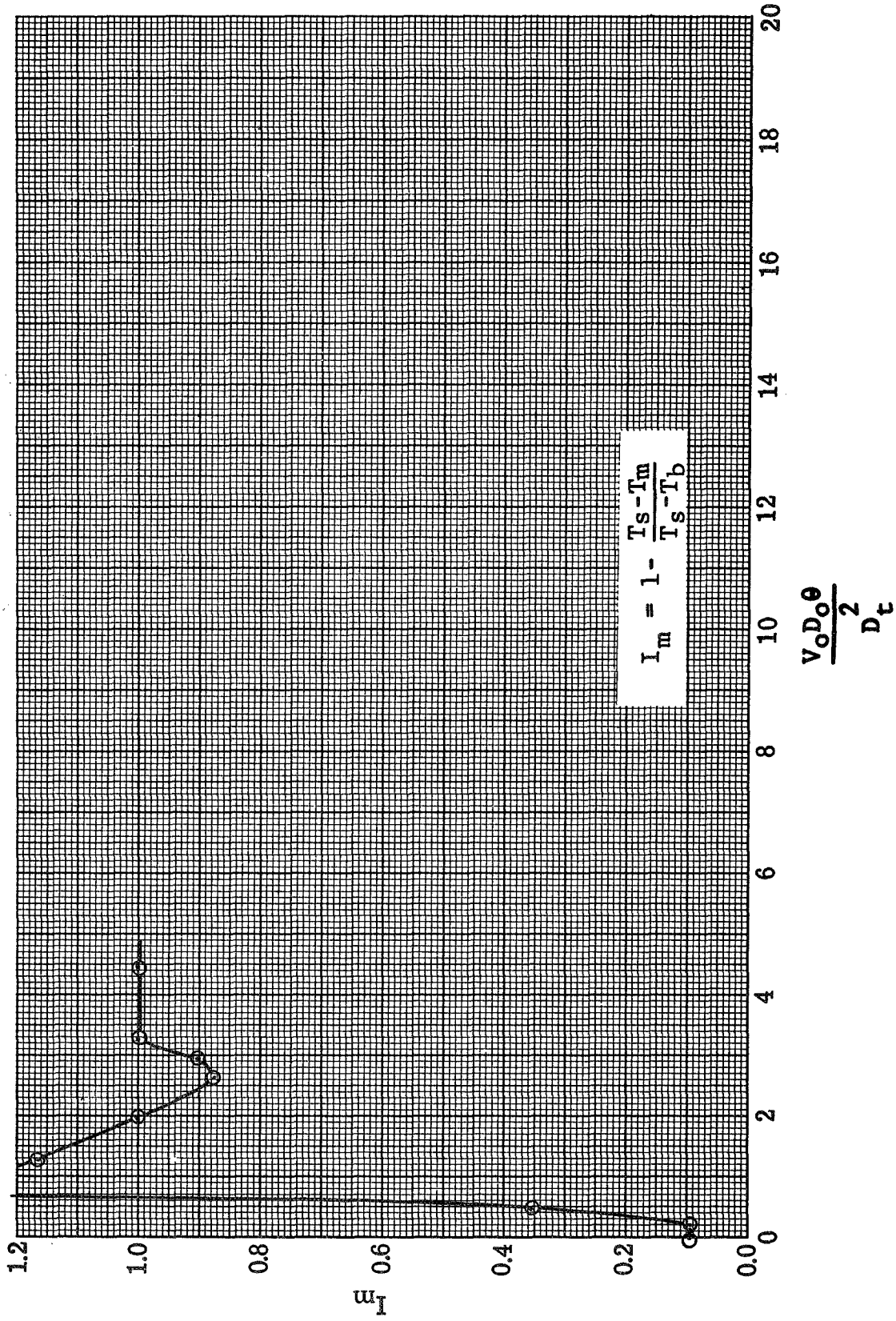

Figure 206 **Transient Energy Integral:** Run 53

R E F E R E N C E S

1. Poth, L. J., et al., A Study of Cryogenic Propellant Mixing Techniques, Final Report, General Dynamics Fort Worth Division Report FZA-439-1, 1 November 1968.

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