PROJECT MATTERHORN

Princeton University
Princeton, New Jersey

Report completed at
Los Alamos Scientific Laboratory

Report written:
August 31, 1953

PM-B-37

This document consists of 146 pages

No. 7 of 60 copies, Series A

FINAL REPORT OF PROJECT MATTERHORN

Work done by:

All members of Matterhorn staff (names listed in section herein entitled "Matterhorn History") with the collaboration of the members of the Los Alamos Scientific Laboratory, the New York IBM staff, the Washington SEAC group, and the Philadelphia UNIVAC organization.

Report written by:

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PRINCETON

PROJECT M

FINAL

DOE b(3) REPORT PM-B-37 — 31 AUGUST

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However, the yield is quite sensitive to this fineness.

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(Continued on Page 66)

METHODS & RESULTS FULLY DOCUMENTED

The technical documentation of Matterhorn results is of six kinds: (1) Classified Technical reports, a full list of which is given below, together with brief notes about contents. Each such report bears

(Continued on Page 8)

WEAPONS OF 3RD KIND JUDGED UNFEASIBLE

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(Continued on Page 82)

COMPRESSION

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For this purpose a series of simplified and idealized implosion runs were carried out ("Gambit"; Report PM-B-22 by L. Wilets and W. Aron). The primary simplification made throughout is that the pressure is assumed to be given by predetermined, externally applied function. For most of the runs, this function was a crude fit to the pressure which occurred in the

(Continued on Page 77)

SIMPLIFIED ANALYSIS OF BURNING

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Highest priority at Matterhorn went to electronic

(Continued on Page 101)

MATTERHORN HISTORY

EXPERIENCE GAINED ADDS 24 SCIENTISTS TO U. S. NUCLEAR PHYSICS RESERVE FOR CASE OF NATIONAL EMERGENCY. PRESENT POSITIONS LISTED.

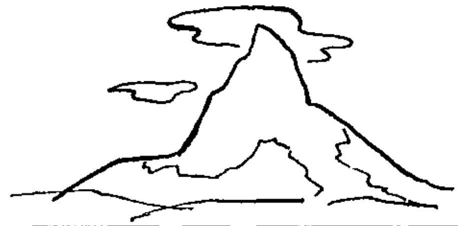
Matterhorn was conceived after President Truman's December 1950 Declaration of Emergency as a project to help Los Alamos overcome shortage of theoretical manpower that hampered the thermonuclear program. By the end of February 1951 informal agreement on plans was reached between Los Alamos and

(Continued on Page 58)

UNIVERSITY

ATTERHORN

REPORT



- 1953

"WOHIN DER WEG? KEIN WEG INS UNBETRETTENE!" - FAUST

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~~WEAPON DATA~~

Distributed: JAN 22 1954 PM-B-37

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Los Alamos Report Library	21 - 60

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Documentation

a PM-B number, under which it can be obtained from the Report Library, Los Alamos Scientific Laboratory, Attention: Report Librarian. Forty to fifty copies of each have been sent to Los Alamos. (2) Unclassified and therefore unnumbered technical reports are also listed below. These bear on their covers a Princeton date line, but in compliance with security requirements carry no Matterhorn or Los Alamos heading. Multiple copies of these again have been or are being sent to the Los Alamos Document Room for whatever future distribution requirements may arise. (3) Classified monthly reports, of which on the average only about five copies were issued, to a small Los Alamos approved distribution list. These also are identified by PM-B numbers as follows: 3, 4, 7, 9, 10, 11, 12, 13, 16, 19, 21, 24, and 25. (4) Print-outs of numerical results obtained in CPC, SEAC, and UNIVAC calculations. The more important of these results are summarized in graphs in the technical reports (Item 1, above).

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To facilitate this reference: (a) All print-outs not destroyed for reasons of obsolescence have been bound up carefully in a number of separate volumes, problem by problem. (b) These volumes are all being sent to Los Alamos Report Library with request that they be kept in a special file as irreplacable reference material. (c) Each volume bears a cover sheet which catalogues the volume according to print-out number (such as PM-PO-13), tells the name of those familiar with the problem, and makes reference to the technical report where further details will be found. (d) A catalogue of these print-out numbers and correlated technical report numbers follows below. (5) In electronic calculations required on the more extensive problems it was necessary to make so-called flow charts, code edits, and sometimes books of instructions for the shift operator who ran the computer. Where it seems possible that Los Alamos may wish to request of UNIVAC or SEAC the running of new versions of these problems, this unclassified material has been prepared in two copies, bound up, labelled with print-out numbers beginning with 1000 (such as PM-PO-1022, copy 1 of 2). In each case copy 1 goes to Los Alamos and copy 2 goes to the computing agency (for UNIVAC, Dr. Eliezer Bromberg and Dr. Eugene Isaacson, Institute of Mechanics and Applied Mathematics, New York University; for SEAC, Dr. Joseph Wegstein and Dr. Ralph Slutz, National Bureau of Standards, Washington). This material is also catalogued below in cross-reference to technical report numbers (PM-B-35, etc). (6) Magnetic tape recording of initial conditions and coded operating instructions for the more important problems, ready for insertion in the UNIVAC. One hundred and seven reels of tapes so prepared and labelled were shipped from Remington Rand, Philadelphia to the New York University UNIVAC, on 15 May 1953 and about the same time two reels

Documentation

of tapes dealing with Problem Macbeth were shipped to the same destination (a total of 109 reels). All this tape material has been prepared in duplicate, with both copies going to New York University, to take care of the possibilities of tape breakage; accidental erasure due to operator error, etc. (7) Classified working notebooks of individual Matterhorn members, returned to Los Alamos for safekeeping (not listed below). There follows the cross reference catalog and then the annotated list of technical report titles, and finally the catalog of magnetic tapes.

Documentation

Correlation of Reports and Print-Outs

Star * indicates that magnetic tape recordings have been prepared in duplicate.

General Field	Report Numbers & Problem Names	Print-Outs	Flow Charts Code Edits Operator Instructions
DELETED DOE b(3)	PM-B-1 (early summary) PM-B-2 (qualitative theory of steady state flames) PM-B-8 (kinetics of burning)		PM-PO-16 Flow Chart
	PM-B-37 Wh Problem (highly idealized one dimensional problem of approach to steady state	PM-PO-169-173	PM-PO-1040
	DELETED	PM-PO-77-78 PM-PO-164-168 PM-PO-79 DOE b(3)	
	Unclassified: Existence, uniqueness, stability of Steady State (by Layzer)		
	DELETED	PM-PO-81-82 PM-PO-80 DOE b(3)	PM-PO-81
Summary of burning work	PM-B-37 Final Report		

Documentation

Correlation of Reports and Print-Outs
(Continued)

General Field	Report Numbers & Problem Names	Print-Outs	Flow Charts Code Edits Operator Instructions
Steady-state burning (SEAC)		PM-PO-124-139 141 PM-PO-143-145 DOE b(3) CF PM-PO-147-155 157-160-162-3	
Ignition and approach to steady state (UNIVAC)	DELETED	PM-PO-67-74	PM-PO-1020-1031 1036-1038
		PM-PO-67-68	" " " " "
		PM-PO-83-92	PM-PO-1020-1029 1032-1033
		PM-PO-69-74	PM-PO-1020-1031 1036-1038
		PM-PO-107-112	PM-PO-1020-1029 1032-1035
		PM-PO-93-106	PM-PO-1020-1029 1032-1035 1039
Pure radial burning		PM-PO-56-66	PM-PO-1014-1019
Implosion and equation of state		PM-PO-1-30-32-55	PM-PO-1012-1013
		PM-PO-75-76	PM-PO-1010-1011
		PM-PO-113-115	PM-PO-1008-1009

Documentation

Correlation of Reports and Print-Outs
(Continued)

General Field	Report Numbers & Problem Names	Print-Outs	Flow Charts Code Edits Operator Instructions
DELETED		PM-PO-120 DOE b(3)	
	Unclassified: Proposed calculation for compressible fluids (Pennington)		
	DELETED	PM-PO-116-119 DOE b(3)	PM-PO-1001-1007 1041-1042
	Variational Principle (Carter) Approach to Calculation for Co.pressible Fluids (Carter)		
	DELETED	DOE b(3)	
Miscellaneous	PM-B-23 Matterhorn Thermonuclear Conference		
	Sumatrata Opacity	PM-PO-121-122 PM-PO-123	
	Duplicate cover sheets of all sets of Matterhorn printouts, bound together	PM-PO-174 (Compilation)	

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Classified Reports of Project Matterhorn-Division B
(Excluding Monthly Reports)

PM-B-1 DELETED DOE b(3)

Theory of ignition temperature for infinite mass. Same for finite temperature allowing only for radiation loss.

DELETED

DOE b(3)

Theory of appearance of shocks in steady state burning.

PM-B-2 Qualitative Behaviour of Plane Steady State Detonation Waves

Detonation Waves without Losses

1) Solution without losses.
2) Solution with losses.
3) Application to deuterium burning.

Detonation Waves with Losses

1) Solution without losses.
2) Solution with losses.

PM-B-8 The Kinetics of the Burning of Deuterium

Influence of T induction period and n - He^3 reaction on burning of pure D under idealizations.

1) Local deposition of reaction energies to products.
2)

PM-B-14 An Explanation of Chief Listings

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PM-B-15 Swordtail I

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Documentation

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PM-B-15
(Continued)

PM-B-17 Chief I

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Choice of Initial Condition
Results including comparison with steady state calculations of

1) Maximum fuel temperature.
2) Depletion of D fuel.
3) Maximum fuel compression.

PM-B-18 Zephyr

PM-B-22 Gambit.

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Results of calculations including

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Documentation

PM-B-23 Matterhorn Thermonuclear Conference.

General discussion of results of "Ivy" shot

1) Yield estimates from other than radio-chemical sources.
2) Radio-chemical detectors, and predicted yield therefrom.
3) Neutron economy.
4) Radiative yield.
5) Detonation velocity.
6) Tenex results.
7) DELETED
8) Summary of calculated predictions.

DOE b(3)

PM-B-26 Swordtail II

Results of Steady State Burning (PM-B-15) up to September 1952

PM-B-27 Swordtail III - Dressed Swordtail Equations

DELETED

PM-B-28 Swordtail IV - Derivation of "Wardrobe" Equation

PM-B-29 Swordtail V - Results of Steady State Burning

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Documentation

PM-B-29 (Continued) 2) 3)

PM-B-30 Chief III, IV, V.

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DOE b(3)

Burning with extremely poor implosion (Chief IV).

PM-B-31 Zephyr-Tiger Report

PM-B-32 Zip

DELETED

DOE b(3)

Results and detailed summary table of all Zip problems.

PM-B-33 Black Mollie

<u>Documentation</u>

PM-B-34 Critique

Summary and appraisal of results of all work carried out by Project Matterhorn - Division B.

PM-B-35 Shakespeare

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PM-B-36 Tommy

DELETED

DOE b(3)

PM-B-37 Final Report

Self-explanatory.

PM-B-38 Jungfrau-Sonora

Effects included

1)
2)
3)
4)

Effects neglected

1)
2)
3)

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Unclassified Reports

Existence, Uniqueness and Stability of the Steady State in One-Dimensional Flame Propagation - Layzer

Theory of free adiabatic one-dimensional flame propagation in the steady state allowing for diffusion, but limited for simplicity to case of single chemical reaction as heat source.

Discussion of continuous and discrete solutions for the mass velocity and perturbation of these.

Single Reaction Flames: Approximate Determination of Flame Speeds and Flame Widths - Layzer

DELETED

DOE b(3)

Practical Determination of Flame Speeds with Neglect of Diffusion - Goerss, Layzer

Solution of equation of above report on CPC calculation by Runge-Kutta method, ignoring diffusion.

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Documentation

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On the Weak and Strong Stability of Numerical Solutions of Partial Differential Equations 1-: The Heat Equation - Bellman

Considerations of stability in the approximation of partial differential equations by finite difference equations appropriate for use in electronic calculating machines.

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Documentation

List of Magnetic Tapes for Matterhorn Problems Available in New York

Tape	Prob. Name	Number	Function	Blks	Servo	Date	Comment
3022	gambit	sleepy	Inst	17	1	10-17-52	
2532	"	cornflakes	"	18	1	9-23-52	
X-1724	"	White	"	17	1	8-17-52	
R-413	"	100	"	18	1		
T-198	"	200	"	"	1	12-24-52	
R-417	"	300	"	"	1	12-26-52	
R-414	"	ALL	Edit	2	1		
G-250	"		Input	33		10-17-52	
At 78	Black Mollie	3F	Dump		6		to 3.628
Cal 32	"	2-7	Reader	2	45		
4380	"	7	Start	27	6	2-24-53	start at 1.314
2364	"	"	Dump	27	6		1.414
Q-25	"	"	"	81	6		3.326-3.526
3861	"	3F,G	Edit,Etc	11	3		
4316	"	6	Start	27	6		
3940	"	3	Dump		6		.002-2.006
T-163	"	3D	"		6		to 1.406
2365	"	3G	"		6		to 2.748
2492	"	7	Edit,Etc	11	3		
3360	"	7	Start	27	6		start at 1.314
3921	"	7	Dump		6		2.002-3.226
3814	"	7	"		6		to 2.274
X-193	"	3	Start	27	6		
2471	Rook	1,3	Input	4			Copy 2
3115	"	"	"	"			
2543	"	1	Inst	16			Copy 2
2935	"		"	"			
2130	"		Dump				10.6-10.8
2449	Tommy	1	Inst	40	1	2-25-53	Copy 2
3587	"	"	"	"			
4330	Ileen	1	Inst	8	3		
2179	Gambit-Black Mollie Library			242		12-7-52	See Attached Sheet
2536	" "	" "		"			Copy 2

Documentation

Enclosure Block #	Library-Gambit-Black Mollie Item	Number of blocks
1	Mark VI	1
2-19	Cornflakes Inst	18
20 - 36	Sleepy Inst	17
37 - 53	White Inst	17
54 - 86	Gambit Inputs	33
87 - 122	BMI dump 11.2	36
123 - 147	" Tape 3	25
148 - 149	II Problem Reader	2
150 - 160	" Tape 3	11
161 - 185	" Tape 6	25
186 - 188	" Input B	3
189 - 206	Gambit 100 inst	18
207 - 224	Gambit 200 inst	18
725 - 242	Gambit 300 inst	18

Documentation

TAPES RELEVANT TO MATTERHORN PROBLEMS
Chief, Zephyr, Tiger, Zip series

Tape #	Problem	Contents	#Blocks
00XX	Chief I	Merged tape 2's	1000
1316	"	"	1000
1672	Chief III	Instructions and tape 2's	923
3754	"	"	923
2344	Chief IV	Merged tape 2's	1500
2267	"	"	1400
1923	Chief V	Instructions and tape 2's	936
2483	"	"	936
2315	Zephyr I	"	1514
2421	"	"	1514
CAL 108	Zephyr II	"	1614
T 125	"	"	1614
4347	Zephyr XXII Zephyr XXIII	"	1126
2795	"	"	1126
2714	Zephyr III	Generator and tape 2's	1505
2151	"	"	1505
2918	"	Instructions and tape 2's	1234
2963	"	"	1234

Documentation

TAPES RELEVANT TO MATTERHORN PROBLEMS
Chief, Zephyr, Tiger, Zip series

Tape #	Problem	Contents	#Blocks
X514	Zephyr V	Merged tape 2's	1300
2506	"	"	1300
4599	Zephyr V Zephyr XXV	Instructions and tape 2's	1147
3455	Zephyr V Zephyr XXV	Instructions and tape 2's	1147
2345	Zephyr VI	"	1134
AT 102	"	"	1134
3932	Zip I	Merged tape 2's	1200
2812	"	"	1200
1497	"	"	1500
2506	"	"	1500
5029	Zip XXI	Instructions and tape 2's	934
4836	"	"	934
2619	Zip III	Merged tape 2's	1500
3389	"	"	1500
2682	Zip IV	Instructions and tape 2's	1423
4336	"	"	1423
2469	Tiger I	"	1133
2359	"	"	1133

Documentation

TAPES RELEVANT TO MATTERHORN PROBLEMS
Chief, Zephyr, Tiger, Zip series

Tape #	Problem	Contents	#Blocks
2461	Tiger II	Merged tape 2's	1100
1744	"	"	1100
2370	"	"	1000
3281	"	"	1000
2678	"	Instructions and tape 2's	1233
5346	Tiger II	Instructions and tape 2's	1233
2879	Tiger III	Merged tape 2's	1000
3724	"	"	1000
1767	"	Instructions and tape 2's	1523
3216	"	"	1523
2486	Zip X	Merged tape 2's	1900
4920	"	"	1900
HC495	Zip X, XI	Instructions and tape 2's	568
1868	"	Instructions and tape 2's	568
4346	Zip III	Instructions and tape 2's	1033
2276	"	"	1033
2679	Zip XXIII	Merged tape 2's	500
5044	Zip XXIII	"	500

Documentation

TAPES RELEVANT TO MATTERHORN PROBLEMS
Chief, Zephyr, Tiger, Zip series

Tape #	Problem	Contents	#Blocks
3813	Zip XI	Tape 2:N 400	100
OXOX	"	Tape 2:N 450	100
4845	"	Merged tape 2's	1400
4821	"	"	1400
2597	Zephyr XXV Zip II Tiger	Instructions	200
4627	"	"	200
4633	Zip II	Initial Data	100
2499	"	Tape 2: N 050	100
2466	"	Tape 2: N 100	100
2388	"	Tape 2: N 140	100
2427	"	"	100
R 153	Chief-Zephyr	Generators	11
R 443	Zip	"	11
4592	Zip IV, XXI	Final instructions	67
4344	"	"	67
5031	Zip and Tiger	Generators, Graph Edit	52
5066	"	"	52
2618	Graph edit	10 F-8	14
2748	Zephyr IV	K cycle instructions	13
2043	Chief	Consolidated instructions	91

Documentation

The following booklets were sent to New York UNIVAC from Philadelphia, Remington Rand, relative to the above magnetic tapes and problems:

1. Chief I
   Problem constants and Printouts to N 360 $\Delta\rho$ .02

2. Chief III
   Problem constants, Initial Data and scattered Printouts to N 220 $\Delta\rho$ .02

3. Chief IV
   Problem constants, Initial Data Generator, and Printouts to N 495 $\Delta\rho$ .02

4. Chief V
   Problem constants, Initial Data Generator, and Printouts to N 360 $\Delta\rho$ .02

5. Zephyr I
   Problem constants, Initial Data Generator Zephyr I and II, and Printouts to N 320 $\Delta\rho$ .02

6. Zephyr II and XXII
   Problem constants, Printouts Zephyr II to N 450 $\Delta\rho$ .02, and Printouts Zephyr XXII to N 020 $\Delta\rho$ .02 (For Initial Data see Tiger III)

7. Zephyr III and XXIII
   Problem constants, Initial Data, Printouts Zephyr III to N 850 $\Delta\rho$ .02, and Printouts Zephyr XXIII to N 350 $\Delta\rho$ .02

8. Zephyr IV
   Problem constants and scattered Printouts

9. Zephyr V and XXV
   Problem constants, Printouts Zephyr V to N 300 $\Delta\rho$ .02, and Printouts Zephyr XXV to N 260 $\Delta\rho$ .02

10. Zephyr VI
    Problem constants, Auto Comparison of Zephyr VI and Tiger I Initial Data, and Printouts to N 390 $\Delta\rho$ .02

11. Tiger I
    Problem constants, Initial Data, and Printouts to N 400 $\Delta\rho$ .02

12. Tiger II
    Printouts to N 790 $\Delta\rho$ .02
    (For Initial Data see Zephyr III)

Documentation

13. Tiger III
    Initial Data and Printouts to N 850 $\Delta\rho$ .02

14. Zip I and XXI
    Handwritten Problem Constants, Two blocks of Initial Data used in Taper Generator, Printouts Zip I to N 480 $\Delta\rho$ .02, and Printouts Zip XXI to N 330 $\Delta\rho$ .02

15. Zip II
    Printouts to N 140 $\Delta\rho$ .005

16. Zip III and XXIII
    Two block Initial Data used in Taper Generator, Printouts Zip III to N 650 $\Delta\rho$ .02, and Printouts Zip XXIII from N 650 to N 770 $\Delta\rho$ .02

17. Zip IV
    Handwritten Problem Constants and Printouts to N 380 $\Delta\rho$ .02

18. Zip X
    Problem constants, Initial Data, and Printouts to N 670 $\Delta\rho$ .02

19. Zip XI
    Problem constants, Initial Data, and Printouts to N 470 $\Delta\rho$ .02

20. Duplicate Copy Chief Instructions - unannotated

21. Duplicate Copy Zephyr and Zip I Series Instructions - unannotated

22. Duplicate Copy Tiger and Zip X Series Instructions - unannotated

23. Duplicate Copy Main Edit Instructions - unannotated

24. Duplicate Copy Taper Generator Instructions

25. Code Check of Zip I Series Instructions

26. Duplicate Copy of Operating Instructions and Routine Description

27. Ozalid Masters of Flow Charts and Tape Layout
    a. J Cycle Chief (same for all problems except for equations)
    b. Old K Cycle Chief
    c. New K Cycle Chief (same for all problems except for equations)
    d. Main Edit Chief (same for all problems)
    e. Tape Layout Chief (slight changes for other problems)

28. Photostatic Negatives of Problem Constants - 47 pages

Documentation

The following table summarizes the status of Matterhorn problems insofar as recorded on the preceding magnetic tapes (a guide for anyone wishing to run a problem to a later time to secure more detail about progress of burning, etc., in any of the listed types of thermonuclear devices).

1.	Chief I	Finished at N 400 K 066	delta rho .02
2.	Chief III	Finished at N 220	delta rho .02
3.	Chief IV	Finished at N 540 K 100	delta rho .02
4.	Chief V	Generated from end point of Chief IV Finished at N 360 K 100	delta rho .02
5.	Zephyr I	Finished at N 320	delta rho .02
6.	Zephyr II	Finished at N 450	delta rho .02
7.	Zephyr XXII	Generated from Zephyr II at N 450, X3, and X9 changes Run to N 090 If this is to be continued, the Taper Generator must be used to cut off the first 20 zones and taper the t's for the next 5 zones. This is to be run until K active equals 40 or quantities stabilize.	delta rho .02
8.	Zephyr III	Finished at N 850 K 049	delta rho .02
9.	Zephyr XXIII	Generated from Zephyr III at N 850, X3, and X9 changed Run to N 350 K 049 To be run until K active equals 52 or quantities stabilize	delta rho .02
10.	Zephyr IV	Generated from Zephyr III at N 400 Experiment with z formula Finished at N 250	delta rho .01 delta rho .02
11.	Zephyr V	Finished at N 300	delta rho .02
12.	Zephyr XXV	Generated from Zephyr V at N 300, X3, and X9 changed Finished at N 260 K 040	delta rho .02
13.	Zephyr VI	Finished at N 390	delta rho .02
14.	Tiger I	Finished at N 400	delta rho .02

Documentation

15.	Tiger II	Finished at N 790	delta rho .02
16.	Tiger III	Finished at N 850	delta rho .02
17.	Zip I	Finished at N 500 K 049	delta rho .02
18.	Zip XXI	Generated from Zip I at N 500, a_{31} & a_{32} changed Finished at N 330 K 070	delta rho .02
19.	Zip II	Run to N 140 a_{31} & a_{32} to be changed and problem to be continued	delta rho .005
20.	Zip III	Finished at N 650	delta rho .02
21.	Zip XXIII	Continued from Zip III, a_{31} & a_{32} changed Run to N 769 If this is to be continued, N 769 should be changed to N 119. To be run until quantities stabilize.	delta rho .02
22.	Zip IV	Finished at N 380 K 035	delta rho .02
23.	Zip X	Run to N 670 If this is to be continued, overflow must be corrected. To be run to N 700 or until quantities stabilize.	delta rho .02
24.	Zip XI	Run to N 470 If this is to be continued, overflow must be corrected. To be run until N 520 or quantities stabilize.	delta rho .02

Ivy Shot

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In addition the shot may be said to give a reasonable order of magnitude verification of burning theory.

Burnability Summary

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Burnability Summary

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Burnability Summary

The factors a, b, and c were varied and considered in some detail. Factors d and e were generally standardized at values which other calculations had shown to be reasonable.

The principal factors considered in the burning calculations are the following:

(a)
(b)
(c)
(d)
(e)
(f)
(g)

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Details of these calculations are presented in the critique report PM-B-34 and the other reports to which it makes reference.

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Thus quantities to a number of the order of 15000 were taken into account, each being calculated for a number of times of the order of 1000 during the burning process.

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Burnability Summary

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In this diagram the horizontal scale gives distance in cm and the vertically plotted numbers, multiplied by 20, give temperatures in kev; and the curves are labelled by the times at which they were calculated, expressed in shakes (10^{-8} sec).

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Once a steady state is attained, evidently the state of affairs at any one point is identical with that at any other point, except for a difference in the time at which things start. To study this condition there is consequently no need to deal with a 100 slice problem; one slice is enough. The problem then becomes sufficiently simple to handle on the Washington SEAC. The nature of the problem is now changed. Instead of the problem being started off in any one of a number of ways, all of which lead to the same steady state conditions, the temperature - regarded as a function of time - takes off from zero in a perfectly well prescribed way, once an assumption is made about the speed of the steady state flame. But the further course of the calculation leads to unreasonable results - such as a temperature curve rising to infinity as time progresses - because the assumed value of the flame velocity was incorrectly

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Burnability Summary

chosen. Physically, the flame will burn that fast, but only if a great additional source of heat follows along some distance behind to keep it going that fast. The necessity for such an extraneous source (or sink) for heat is only avoided for one particular choice of the flame velocity. Its value is found by rerunning the problem repeatedly, using a procedure of trial and error.

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The UNIVAC ignition calculation in such a case shows a flame front which, starting with the moment of ignition, grows steeper and steeper as it moves forward, and approaches as close to a shock as permitted by the finite grid of the calculations. Some progress has been made in finding a way to analyze the shock type of burning (see item "Flameson" under the section of this report called "Simplified Analysis of Burning") but as yet this method of analysis has not been applied to burning calculations of the completeness and complexity of Swordtail. To do so will be an important item for the future evaluation of low compression, low yield devices.

Typical results of a steady state burning problem are collected in Figs 2 - 7, taken from the Swordtail Report PM-B-26 of Kenneth Ford and John Toll.

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Burnability Summary

This brief resume of the main features of burning opens the way to a more detailed discussion (largely based on the work of K. W. Ford) of the influence of each factor in turn upon output. For this purpose it is appropriate to compare problems in which other factors are as nearly as possible alike.

1. Comparison of two different ways of doing the same problem (steady state on SEAC; ignition and approach to steady state on UNIVAC.

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The SEAC problem has the designation SWORDTAIL 112 (report PM-B-26) and the UNIVAC problem is CHIEF I (report PM-B-17). A bird's-eye view of the results of the ignition version is provided by Figs 8, 9, and 10, taken from the CHIEF report. The formulations of the two problems had nearly the same basis, except for a slight difference in formulae used to represent the D-D cross section:

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For high temperatures the Swordtail values are always higher than the chief values and this leads to a faster DD burn up.

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It is concluded that the comparison gives reason to believe in the

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Figure 8

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Figure 9

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Figure 10

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essential identity of results obtained in two different ways.

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This being the case, one cannot call the comparison unreasonable. These two problems are believed to give the best approximation of any problems so far run to the actual behavior of IVY MIKE.

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Fig. 12 shows the results of the undoable

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Figure 11

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Figure 12

SEAC problem, as far as they went, for comparison. There is a qualitative agreement, except that the SEAC problem, with its effectively finer mesh, goes higher on temperature and fuel velocity.

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SEAC and UNIVAC having been thus compared, it is appropriate to compare SEAC problems with each other to study the effect of individual factors.

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Burnability Summary

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Burnability Summary

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Further details of the burning process, and tabulations of results, will be found in the reports cited in the Documentation section of the present report. DELETED

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Also reference should be made--in connection with the start-off of initiation-type burning calculations--to PM-B-33, "Black Mollie - Zombie

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Burnability Summary

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Burnability Summary

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Princeton University, and on June 28, 1951, Subcontract SC-6 of Contract W-7405 Eng. 36 was signed between the Regents of the University of California and Princeton University. Work began on May 25, 1951 in the Matterhorn premises, a guarded steel building 2 miles from the University campus at the newly acquired James Forrestal Research Center.

Personnel Recruiting

Beginning early in March 1951 letters were written to all known suitable U. S. theoretical physicists and applied mathematicians - a total of over 140 people.-- requesting participation in a program of assessment and primordial design work on thermonuclear weapons. Reasons cited for the request were: (1) The difficult world situation and the need for assuring "peace through strength." (2) The importance of atomic weapons — and therefore of conceivable thermonuclear improvements — in the overall picture of U. S. war potential, relative to all other means of exerting power. "At peak production during War II we turned out about 4 kilotons a day in conventional high explosives. In the crude and highly arbitrary measure of total energy release this output means one fifth conventional atomic bomb per day, or in 700 days, 140 old fashioned atomic bombs. For comparison take any newspaper guess as to atomic bomb output." (3) Dismaying shortage of people on the idea assessment and primordial design end. "You would make percentage-wise more difference there than anywhere else in the national picture."

Matterhorn recruiting was cleared through Los Alamos to avoid interference. The following is a passage from a typical recruiting letter: "By carbon copy of this letter to Dr. Carson Mark, head of the Theoretical Division of the Los Alamos Scientific Laboratory, I am notifying him of our request for help in our program of assistance to the Los Alamos Laboratory. It is conceivable that Dr. Mark, or some other member of the Los Alamos Laboratory, may approach you with a request that you assist directly at Los Alamos itself. In this case I would like to advise you to consider such a request more seriously. The program of experimental and theoretical work going on at Los Alamos, in connection with which we are assisting on the theoretical end, is so important that anyone who is willing to assist, whether there or here, especially at this time, will be doing a great service."

Typical of the great number of "No" replies were:

- B: "Unwilling to give up University work for this type of defense work."
- C: Refused, working at Brookhaven, would get lower salary at Princeton.
- E: "Recently accepted position at Hughes Aircraft."
- F: "I do not wish to take part in the project you mention. The expectation value of the usefulness of my work is greatest on the hypothesis that I stick to my teaching job here."
- F: Continuing post-Ph. D. study abroad.
- G: Going to position with higher salary at Applied Physics Laboratory.
- K: "I believe that my development into an accomplished physicist would best be served by continuing here at H. in my present capacity."

History and Personnel

N: Desires to continue academic work.
S: "I cannot possibly come. I am unwilling to consider at this time contributing directly to our war potential."

Numerous responsible men were impressed by the national need and took part - some for six months, some for a year, and some for the whole 25 May 1951 - Spring 1953 period of the project. Th se who did come fell into two groups - young men who had just recently received their Ph. D's (or were in some cases in process of getting them; and a few older men with established positions who could secure leave of absence for the work. No one who was already well started on the early part of his career took part, except H. Pierre Noyes, whose help was much appreciated. In a number of cases better paying offers elsewhere were given up because of the feeling of urgency and patriotic obligation connected with the Matterhorn work. The membership of the project averaged 13 physicists, document custodian, secretary, three computers, and an IBM electronic computer staff of two. The associated computing facilities (IBM, New York and Princeton; UNIVAC, Philadelphia; and SEAC, Washington) greatly multiplied the working power of this group.

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This work was conducted in separate premises at the Forrestal Research Center. Adding a man to the staff at the date he could make, instead of at the uncertain date of his clearance, made the difference in several cases between getting the man and not getting him.

Within Princeton University, Project Matterhorn operated on a non-departmental basis under the jurisdiction of a management committee drawn from several divisions of the University, with Professor Lyman Spitzer, Jr., as chairman. Professor John A. Wheeler was scientific director of the project, and the associate director was Dr. John S. Toll. Though thermonuclear weapons or "burning" work (Division B) in the Matterhorn building at Princeton's Forrestal Research Center comes to an end in the spring of 1953, there will continue in the same building an entirely distinct project, under the scientific direction of Professor Spitzer, and under the auspices of the AEC Division of Research (Matterhorn, Division S), concerned with the desgin of a "Stellarator", or controlled thermonuclear reactor.

Computing Facilities

Before IBM equipment was available in Princeton, use was made of IBM facilities in New York. Later on even more extensive use was made of AEC-arranged computing facilities on SEAC in Washington and UNIVAC in Philadelphia. The staffs at these locations, under the direction of John Sheldon, Joseph Wegstein, Herbert Mitchell, Edward Cushen and Paul Chinitz, multiplied the effectiveness of Matterhorn personnel.

History and Personnel

Nature of Work

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Later work made the models more and more complicated -- but at the same time more accurate -- by taking into account simultaneously the maximum number of physical processes known to influence the burning significance. Further description of the way of work at Matterhorn is extracted from a letter written to an applied mathematician who wanted to know enough to decide whether to join: "There is then the problem of writing down the equations to describe that model. Some of the quantities which enter these equations are empirical functions. Various among us here have specialized in one or another aspect of the physics of our own problems, so that we are fairly well equipped with the empirical functions that we need for a wide class of problems. The equations once formulated, we would like to see how to get analytic solutions for them when possible. Usually this is not possible, and we have to set our equations up in a difference form suitable for electronic computation. There are people here who have had enough experience in this end so that they can take part of the burden in this respect. However, one has to pitch in on this to some extent himself in most cases in order to make progress at a reasonable rate and not to load up too heavily the ones among us who have had most experience with the electronic computer. Usually the most productive manner of participation, from the point of view of the Project, amounts to carrying on perhaps two things at the same time, one a project that may take from a few days to two weeks, and the other a longer term proposition which may take two weeks to two months. We hold regular Monday meetings to discuss the overall status of progress and to have everyone put forward his ideas, suggestions, and proposals for what ought to be done next. This democratic way of working puts on everyone a heavy responsibility to decide for himself whether he is working on the most important part of the whole thing within his reach. For this reason it is important that each of us barge in on the others for discussions, questions, and for the formulation of new ideas by discussion and argument. Of course, there are also special services that a mathematician can perform in our group: translation of an integral equation into a differential equation, suggestions how to 'solve' an otherwise complicated algebraic relation by a suitable parametric representation of the variables; advice about different methods of integration of differential equations as regards relative stability for large interval size. Here is a typical question of the service variety: .... But to pay attention to only such service questions would very greatly decrease one's usefulness. It is awareness of larger issues of the work and concern - - expressed by discussion with others and attempts to formulate and carry through idealized problems - - which make all the difference."

History and Personnel

"Briefly put, the work has in it lots of sweat and effort; there may very well be unclassified work coming out of it which you could publish; but this is to be considered purely incidental, accidental, and very much subsidiary to the main line effort; any major contact with one's normal scientific work is pretty much a nights and Sundays matter. Security restrictions are no bar to one's discussions about other matters or publications along purely scientific lines. If you are willing to face these rather heavy responsibilities, we would be very happy indeed to have you."

Three Phases of Work

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Ending of Project Matterhorn

The establishment of Project Whitney at Berkeley in the summer of 1952 created another center for work in the weapons field. This step, and requests from that new project for any theoretical talent willing to go to Livermore, forced reconsideration of the Matterhorn program. It was also apparent that Project Matterhorn had had since its beginning an emergency character which could not be continued indefinitely within the university set-up under peacetime conditions (heavy demands for overtime; work dead-lines; lack of opportunity for research; $100/month or more short of salary for comparable work elsewhere). No solution for these difficulties being in sight, and a well defined phase of the thermonuclear assessment and primordial design work having been completed, it was concluded to terminate Project Matterhorn about 1 March 1953 despite the continuing need in the AEC program for some such center of analysis of long range weapon possibilities and of assessment of advantages of one weapon compared to another. This date was fixed as a compromise between the late 1952 date when Livermore wished to secure interested Matterhorn personnel, and the spring 1953 date for the freezing of the basic theoretical design of the Castle shots.

Nuclear Physics Reserve

The results obtained by Matterhorn are summarized in reports listed elsewhere in these pages. There follows a list of who made up the scientific staff of Matterhorn, and who by their experience and clearability now constitute in effect members of a U. S.

Nuclear Physics Reserve (some of them still on active duty!):

Aron, Walter: A. B. University of Illinois 1942, M. A. 1944; Ph. D. University of California 1951; Matterhorn, June 1951 to March 1, 1953; DOE b(3) DELETED Since March 1, 1953 with high energy accelerator project, Physics Department, Princeton University.

Bellman, Richard: B. S. Brooklyn College 1941; Ph. D. Princeton University 1946, Professor Mathematics on leave of absence from Stanford University for Project Matterhorn, October 1, 1951 to April 8, 1952. DOE b(3) DELETED Following July 1952 permanently with Rand Corporation, Santa Monica, California.

Berger, Jay M.: B. S. University of Michigan 1947, A. M. Columbia University 1948, Ph. D. Case Institute of Technology 1952. Project Matterhorn, October 21, 1952 to February 28, 1953. DELETED DOE b(3) With Stellarator controlled thermonuclear project, Princeton University, following March 1, 1953.

Brown, Harold Dean: On loan from Argonne Laboratory - Savannah River Project, E. I. duPont de Nemours and Company, December 1952 to February 1953. DELETED DOE b(3)

Carter, David: B. A. University of British Columbia 1946, M. A. 1948, Ph. D. Princeton University 1952. Project Matterhorn, July 1951 to November 30, 1952. DOE b(3) DELETED With T Division, Los Alamos, following December 1, 1952.

Clendenin, William W.: B. A. Swarthmore College 1948, M. S. Yale University 1949, Ph. D. 1952. Project Matterhorn, July 1952 to February 28, 1953. DELETED DOE b(3) With high energy accelerator project, Physics Department, Princeton University, after March 1, 1953.

Driggers, Frank: On leave from Argonne Laboratory - Savannah River Project, E. I. duPont de Nemours and Company, October to December 1952. DOE b(3) DELETED

Ford, Kenneth W.: B. A. Harvard University 1948, Ph. D. Princeton University 1953. Project Matterhorn August 1951 to February 28, 1953. At different intervals during this period Dr. Ford worked only part-time, using the remaining portion of his time for work on his doctoral thesis. Analysis of all phases of thermonuclear burning. Los Alamos Scientific Laboratory July 1950 to July 1951. After March 1953 with high energy accelerator

History and Personnel

project, Physics Department, Princeton, part time and part time consultant to Los Alamos on SEAC calculations. After September 1953, staff, Physics Department, University of Indiana, Bloomington.

Frieman, Edward A.: B. S. Columbia University 1946, M. S. Polytechnic Institute 1948, Ph. D. 1951. Project Matterhorn, January 1952 to February 28, 1953. DELETED With Stellarator controlled thermonuclear project, Princeton University, following March 1, 1953. DOE b(3)

Goldgraber, Howard D.: B. M. E. The Cooper Union 1943, M. S. University of Pennsylvania 1946, Ph. D. 1952. Project Matterhorn, October 1952 to February 28, 1953. Hydrodynamic instability. With Project Whitney, Livermore, California, following March 1, 1953 with duty station at AEC UNIVAC, New York University.

Grasberger, William H.: A. B. University of California, 1950, M. A. 1951. Project Matterhorn September 12, 1951 to July 10, 1952. Opacity analysis; implosion and burning problems. Since August 1952 completing graduate work in astronomy, University of California, Berkeley.

Haefner, Richard: On loan from Argonne National Laboratory - Savannah River Project, E. I. duPont de Nemours and Company October 1952 to February 1953. DELETED DOE b(3)

Haussman, Capt. Alfred C.: Project Matterhorn, September 1, 1952 to February 28, 1953. DELETED With Project Whitney, Livermore, California following March 1, 1953. DOE b(3)

Heller, Jack: BaeE Brooklyn Polytechnic Institute 1946, MAeE 1946, Ph. D. 1950. University of Manchester, England, 1950-1951, University of Cambridge, England 1951-1952. Project Matterhorn May 1952 to March 11, 1953. DELETED Following March 11, 1953 with UNIVAC Center, Institute of Mechanics and Applied Mathematics, New York University. DOE b(3)

Henyey, Louis G.: Professor of Astrophysics, University of California, Berkeley, on leave with Matterhorn from August 1, 1951 to August 31, 1952. DELETED DOE b(3)

History and Personnel

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Layzer, David R.: A. B. Harvard College 1947, Ph. D. Harvard University 1950. Project Matterhorn July 1952 to February 28, 1953. DELETED DOE b(3) Following March 1, 1953 with Solar Physics Project, Harvard College Observatory.

Levee, Richard D.: A. B. University of California at Los Angeles, M. A. University of California (Berkeley) 1951, Ph. D. 1951. Project Matterhorn October 22, 1951 to October 2, 1952. Opacity; steady state burning of deuterium and ignition thereof. Following October 1952 Assistant Professor of Astronomy, University of Missouri, Columbia.

McIntosh, John S.: B. S. Yale University 1948, M. S. 1949, Ph. D. 1952. Project Matterhorn, July 1952 to April 1, 1953. DELETED DOE b(3) Equation of state of deuterium compounds. Consultant to AEC thermonuclear work following April 1, 1953. Los Alamos (Summer 1953). After September 1953, staff, Physics Department, Princeton University.

Osborn, Howard A.: B. A. Princeton University, 1949. Project Matterhorn, September 11, 1951 to June 21, 1952. DELETED DOE b(3) Following June 1952 completing graduate work in mathematics, Stanford University.

Pennington, Capt. Ralph H.: Project Matterhorn, September 14, 1951 to December 20, 1952. DELETED DOE b(3) Following January 1, 1953 with Project Whitney, Livermore, California.

St. John, Daniel S.: On loan from Argonne National Laboratory - Savannah River Project, E. I. duPont de Nemours and Company, part-time October 1952 to February 28, 1953. DELETED DOE b(3) Assessment of design feasibility.

Toll, John S.: B. S. Yale University, 1944, M. S. Princeton University 1948, Ph.D. 1952. Los Alamos Scientific Laboratory June 1950 to August 1951. Project Matterhorn, February 1952 to March 1953. Associate Director of the Project from August 1, 1952 to March 1953. All phases of burning analysis and overall assessment. Following March 1, 1953 Chairman, Physics Department, University of Maryland, College Park, Maryland.

Wheeler, John A.: On leave of absence from Princeton University at Los Alamos, March 1950 - May 1951. Matterhorn, May 25, 1951 - April 1, 1953. DELETED After April 1, 1953, Physics Department, Princeton University. DOE b(3)

Wilets, Lawrence: B. S. University of Wisconsin 1948, M. A. Princeton University 1950, Ph. D. 1952. Project Matterhorn, November 1951 to February 28, 1953. DELETED Following March 1, 1953 with Project Whitney, Livermore, California. DOE b(3)

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Further theoretical work may be expected to lead to revisions of more or less extent in these numbers.

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Table III

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Compression

Los Alamos Maniac IV Implosion Run. The pressures assumed and the range of validity of the equations of state are applicable for radiation implosions only.

It is not presumed that these calculations should play the same role as the more detailed Los Alamos SEAC or Maniac implosion calculations, but rather it was hoped that, because they are essentially simpler and machine-wise faster, they could be used to survey the field and obtain an understanding of the implosion process as well as to acquire semi-quantitative information that could be used in optimizing design features. All calculations were carried out on the Eckert-Mauchly UNIVACs in Philadelphia.

The results of a number of problems are summarized in the following Table I.

In Table II are listed our best estimates of implosions attainable with standard Ivy geometry.

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TABLE II

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Compression

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Weapons of Third Kind

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Consequently it was concluded that this version of a weapon of the third kind is unfeasible. The following account of the analysis that led to this conclusion is due to Noyes, and is quoted verbatim from his notebook:

I. Introduction

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Weapons of the Third Kind

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Weapons of the Third Kind

Table I

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Simplified Burning Analysis

calculations of burning that included all effects for which one knew how to make allowance, in order to make more or less justified predictions as to appropriate values of design parameters. However, there was always in mind the hope--not yet justified--that one might in addition construct (a) a simplified mock-up of the burning process and (b) from this mock-up derive a not too complicated formula for the yield of thermonuclear devices. It would be very desirable to have an equation analogous to the Bethe-Feynman equation for the yield of fission weapons. It is obvious such a formula must be considerably more involved in the thermonuclear case.

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For this reason it is perhaps understandable why it has not been possible up to now to construct such a yield formula.

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The six idealized problems that have been considered--though short of the kind of mock-up that is desired--do succeed in bringing out some of the factors important in burning.

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Simplified Burning Analysis

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Figure 1

Simplified Burning Analysis

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Simplified Burning Analysis

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Simplified Burning Analysis

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Figure 2

Simplified Burning Analysis

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Simplified Burning Analysis

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