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**STUDIES ON FLASH BURNS: THE RELATION OF THE TIME AND
INTENSITY OF APPLIED THERMAL ENERGY TO THE SEVERITY OF BURNS**

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**THE UNIVERSITY OF ROCHESTER
ATOMIC ENERGY PROJECT
ROCHESTER, NEW YORK**

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TABLE OF CONTENTS

	<u>Page No.</u>
ABSTRACT	4.
INTRODUCTION	5.
METHODS	6.
Physical	6.
Biological	6.
Statistical	9.
RESULTS	10.
Quantitative Results in the Pig	10.
Qualitative Results in the Pig	18.
Qualitative Results in Man	21.
Quantitative Results in Man	23.
DISCUSSION	26.
SUMMARY AND CONCLUSIONS	30.
BIBLIOGRAPHY	32.
APPENDIX	34.

ABSTRACT

The physical, biological, histological and statistical methods used to produce and to evaluate radiant energy burns are discussed. The influence of variations in the time and intensity of applied radiant energy on severity were studied in a series of 1684 burns in the pig. In general, an inverse relationship exists between the time and the intensity of applied radiant energy in the production of cutaneous burns, although exact reciprocity fails. With increased exposure time, an increased amount of energy is required to cause a similar degree of surface damage. This relationship also exists for burns evaluated microscopically except for "deep dermal" burns where the reverse is true.

Variations in the pathological picture are described and discussed. The demarcation between damaged and undamaged tissue is more abrupt with short than with long exposure times.

A limited number of burns on human volunteers were studied. The amount of energy required to produce an erythematous burn in the pig is approximately equal to that causing a first degree burn in man. At a higher critical energy level the same relationship exists for patchy coagulation in the pig and a second degree burn in man.

A mathematical analysis based on semi-infinite opaque solid theory is appended. This offers possible explanations for the experimental results.

I INTRODUCTION

For several years the work of this laboratory has been directed toward a study of the thermal burn as produced by a pulse from a source of high intensity radiant energy. This method not only has the practical advantage of contributing more knowledge of the flash burn from weapons such as the atomic bomb, but also affords an excellent means of studying the factors governing cutaneous burns. If flame, hot metal or hot liquids are used it is difficult to know the exact amount of heat applied. The intensity and duration of radiant thermal energy, on the other hand, is relatively easy to measure and control. This method has made possible the observations here reported on the effect of the time and intensity of applied energy on the resultant burns.

Experimental burns produced in the dog by flame, hot objects or hot liquids were investigated by Elman and Lischer (5), those from a hot iron in the guinea pig by Leach, Peters and Rossiter (7) and from a hot water regulated burning iron in the dog by Brooks, Robinett, Largen and Evans (1). The most fundamental observations on the time-temperature relation in thermal burns were made by Moritz and Henriques (9) using controlled gradations of hot water on the skin of white pigs. Their results indicated that an inverse relationship existed between the level of temperature and the time of its application.

Experimental study of radiant energy burns has been done by Butterfield and Dixey (2), Sheline, Alpen, Kuhl and Ahokas (14)

and in this laboratory (6, 10, 12, 13). Recently the threshold levels of energy applied for one second were determined (11) for a series of progressively severe lesions. The present experiments were designed to extend these data by a variation in the time of the exposure. In the end this required confirming and adding data to the previous threshold studies in order to attain statistical validity for the whole.

II. METHODS

A. Physical

The equipment used to produce these lesions has been described (4). The thermal source was a 24" Army carbon arc searchlight with an ellipsoidal mirror substituted in place of the parabolic reflector. The intensity of the energy used was regulated by a sliding diaphragm. The time of the exposure was controlled by an electrically activated spring driven shutter. The animal container had a transite shield perforated with circular, counter sunk openings 1.8 cm. in diameter which defined the exposed area. The rate at which known amounts of energy were supplied to the central square centimeter could be varied from 0.7 to 37.5 calories/cm²/sec, which was the range used.

B. Biological

The skin on the side of a Chester White pig has a close structural similarity to that of man and gives a comparable response to quantitatively similar thermal stimuli. Its reflectance of radiant energy appeared to be similar to that

of a fair-skinned human. Pigs of this breed, weighing about 12 kg., were used for the time-intensity study as well as for the comparison with human burns.

All pigs were anesthetized with Dial in urea-urethane (Ciba), 60-75 mg/kg intraperitoneally. The hair was closely clipped, and all areas were avoided which did not show normal reflectance qualities after gentle cleansing with a moist cloth. Room temperatures were fairly stable, though not constant, so skin temperature was not accurately controlled.

The two methods used for evaluating the severity of the lesions were surface appearance and microscopic changes. The mildest surface change of a burn was erythema, while the most severe was carbonization. In between, one could detect, in the pig, only patchy coagulation, uniform coagulation, and the steam bleb. These five conditions gave a basis for grading as tabulated below.

<u>Laboratory</u> <u>Grade</u>	<u>Surface</u> <u>Appearance</u>	<u>Descriptive</u> <u>Term</u>	<u>Human</u> <u>Equivalent</u>
1+	Erythema	Red Burn	1st degree
2+	Patchy coagulation	Spotted white burn	2nd degree
3+	Uniform coagulation	White burn	3rd degree
4+	Steam bleb	Blebbled white burn	3rd degree
5+	Carbonization	Charred burn	3rd degree

It was evident that if uniform increments of thermal energy were applied, the skin would sustain an increasingly severe burn. Yet, the above criteria were the only surface

indication of this. Hence evaluation had to be done in a step-like manner dependent upon the threshold level of energy in a given time which would cause an observable change. Since gradations of each of these major changes were discernible, they were subdivided into mild, moderate and severe in order to have less transition from one to the other.

The biological evaluation was based on the most severe portion of the burn which was usually the central square centimeter. Evaluation was done immediately in the case of steam blebs and carbonization. In the less severe grades assessment was made at 24 hours. Occasionally in 48 hours, when recovery from anesthesia was complete, there was a slight increase in the apparent severity of some burns.

Biopsy for microscopic evaluation was usually done 24 hours after burning. Because of the lack of uniformity of burn depth, each slide was classified by the greatest depth of damage noted. Tissue damage limited to the epidermis, and without separation of the dermal-epidermal interface by edema, was classified as "epidermal". Epidermal burns were subclassified according to whether the type of damage predominating was simple cellular change or acidophilism. When acidophilism predominated it was subclassified as involving part or all of the epidermal depth. All burns showing separation of the dermal-epidermal interface were classified "transepidermal". Those involving the dermal epithelial elements were classified "dermal". The depth of these was more difficult to determine.

The human burns were limited to the dorsal and volar forearm, and the lateral aspect of the calf. They were produced by the same method used for pigs. An exposure of 0.3 seconds was employed in most instances. To obtain normal conditions, no preparation of these surfaces was used. Burns were left exposed without dressing and the characteristics of the healing process were observed.

C. Statistical Methods

A method of systematic randomization of exposure combinations was planned for successive test groups of pigs. With this method, known as the Latin square, each exposure combination appeared once on each pig in the test group, and in each instance it appeared in a different one of the standard positions on the side of a pig. Lesions were evaluated without knowing which exposure combinations caused them. It was felt that this method of systematic randomization would best average out pig-to-pig, and area-to-area differences. A summary of the test groups is given in Table 3.

The 50 per cent probability threshold of any degree of injury was used as one end point for evaluating the result of the time and intensity of applied thermal energy. This gave a value of the 50-50 possibility of the damage occurring at the energy level being studied. A second method of evaluating these data was by determining the average value for a given effect. This was the point at which there were the greatest number of results classed as moderate with smaller numbers of mild and severe on either side.

The results were tabulated by both methods. For example in 1+ burns when threshold levels are given they represent a

50-50 split between no burns and 1+, but when average values are given they are the median level at which 1+ burns occur.

TABLE 3
STATISTICAL ARRANGEMENT OF TEST GROUPS

Test Group	No. of Pigs	No. of calorie-exposure time combinations studied	No. of exposures per combination	No. of combinations biopsied	No. of biopsies per combination
A	21	21	21	21	8-11
B	12	12	24	12	11-12
C	16	16	16	4	8-9
D	15	30	12-15	4	9-12
E	7	15	13	13	10-13
F	1	5	5-12	0	0
G	7	2	9	2	9-13
H	5	4	8-10	4	8-12
I	3	3	6-11	1	5
<u>9</u>	<u>87</u>	<u>108</u>		<u>61</u>	

III RESULTS

A. Quantitative Results

1. The Relationship between Flux Density* and Exposure Time

The severity of the lesion as judged by its surface appearance was evaluated in relation to time and intensity of exposure in 1,684 burns. These data are shown in Table 1 where it is seen that the five criteria of severity are each subdivided into the three grades of mild, moderate and severe. There were 648

* The term "Flux Density" was used to indicate the amount of thermal energy flowing in a unit time, i.e. cal/cm²/sec. This could also have been called heat flow, thermal energy flux or irradiance. The latter term would only be applicable when a light was used as a source. Since the burning from the carbon arc light was believed to be due largely to the thermal energy delivered it seemed preferable to use the general term of "Flux Density" which would be applicable to all thermal sources.

TABLE 1

TABULAR SUMMARY OF MACROSCOPIC RESULTS

Group	Time (sec)	Cal cm ²	Cal cm ² Sec	No Burn 0	Erythema (1+)		Partial Coagulation (2+)		Total Coagulation (3+)		Steam Eblb (4+)		Carbonisation (5+)		50 Percent Probability Threshold		Average Values (Mod.)	
					Mid Mod Sev	Mid Mod Sev	Mid Mod Sev	Mid Mod Sev	Mid Mod Sev	Mid Mod Sev	Mid Mod Sev	Total	Cal cm ²	Grade	Cal cm ²	Grade		
A	0.1	0.5	5.0	20	1										21			
	0.1	0.8	8.0	15	6										21			
	0.1	1.0	10	11	10										21	1.0	1+	
	0.1	1.3	13	7	13	1									21			
	0.1	1.5	15	3	14	4									21			
	0.1	2.0	20	1	10	7	2	1							21			2.0
	0.1	2.5	25		3	7	8	3							21			
	0.1	2.5	25		3	3	8	2							15			
	0.1	3.0	30		2	1	6	8							15	3.0	2+	
	0.1	3.8	38		1	1	10	3							15			
	0.2	5.8	58				2	1	8	3	1				15	6.3	3+	
	0.2	7.0	35					5	3	1	3	1			15			7.0
	0.2	7.5	35					5	3	1	3	3			15	7.5	4+	
A	0.3	0.6	8.0	21											21			
	0.3	0.8	2.7	18	3										21			
	0.3	1.1	3.7	10	11										21	1.2	1+	
	0.3	1.1	3.7	9	6										21			
	0.3	1.3	4.3	10	10	1									21			
	0.3	1.6	5.3	3	15	3	3	5							21			
	0.3	2.1	7.7		4	10	3	5							21			
	0.3	2.6	7.7		15	7	12	5							21			
	0.3	3.1	10.3		4	10	7	12							24	3.3	2+	2.3
	0.3	3.5	11.7			10	5	5							24			
B	0.3	3.5	11.7			15	5	5							24			
	0.3	4.0	13.3			11	11	8							24			
	0.3	4.5	15.0			6	8	3							24			4.5
	0.3	4.5	15.0			7	8	3							24			
	0.3	5.0	17				8	3							16			
	0.3	5.5	18				6	2							16			
	0.3	6.0	20				3	6							16	6.3	3+	
	0.3	6.5	22				3	6							16			
	0.3	7.5	25				8	3			2	1			16	8.0	4+	7.5
	0.3	8.5	28.0				1	1			5	2			15			
D	0.3	8.5	28.0							3	5	1			15			
	0.3	8.5	28.0							3	5	1			15			
	0.3	8.5	28.0							1	1	5			16			10.0
	0.3	13.5	38.0										1		15			
I	0.5	14	80									0			6			
	0.5	17	34									3	2		9	17	5+	19.0
H	0.5	19	38									1	2		10			
												5	1	1				
A	1.0	0.7	0.7	21											21			
	1.0	0.9	0.9	18	3										21			
	1.0	1.2	1.2	10	11										21	1.3	1+	
	1.0	1.2	1.2	9	11										21			
	1.0	1.5	1.5	8	11	0	4	2							21			
	1.0	1.7	1.7	4	9	4	2	2							21			
	1.0	2.2	2.2	8	11	5	6	2							21			
	1.0	2.7	2.7	8	8	3	0	4							24			
	1.0	3.2	3.2		1	11	8	5							24			
	1.0	3.7	3.7		1	8	5	9							24			
B	1.0	4.2	4.2					1							24			
	1.0	4.7	4.7					5							24	4.5	2+	
	1.0	4.7	4.7					1							24			
	1.0	5.7	5.7					1							24			
	1.0	6.7	6.7					6							16			
	1.0	7.5	7.5					5							16			
	1.0	7.5	7.5					6							16	7.0	3+	5.7
	1.0	7.7	7.7					1							16			
	1.0	8.7	8.7					1							16			
	1.0	11.0	11												15			
C	1.0	13.5	13.5												15			
	1.0	20	20												15			
	1.0	22	22												11			
	1.0	24	24												12	23	5+	13
															12			
															13			
															13			
															13			
															13			
															13			
E	2.0	1.4	0.7	10	3										13	1.6	1+	
	2.0	1.8	0.9	3	8										13			
B	5.0	3.9	0.8		7	10	4	3							24			3.9
	5.0	4.6	0.9		5	11	8	3							24			
	5.0	5.0	1.0		5	11	3	7							24			
	5.0	5.0	1.0		5	11	3	7							24			
	5.0	5.5	1.1		1	10	2	9							24	5.5	2+	
	5.0	5.5	1.1			2		2							13			
	5.0	5.6	1.1			2		2							13			
	5.0	6.6	1.3			10	2	3							13			
	5.0	6.6	1.3			7	6	9			1				16			
	5.0	7.6	1.5			1	5	1							16			
C	5.0	8.0	1.6					3							13			8.0
	5.0	8.5	1.7					3							16			
	5.0	9.5	1.9					3							16			
	5.0	10.0	2.0					5		1					15	11	3+	14.0
	5.0	12.0	2.4					5		1					15			
	5.0	17.0	3.4					5		1					15	23	4+	24.0
	5.0	26.0	5.2					1		3					15			
	5.0	36.0	7							3					15	42	5+	44.0
	5.0	51.0	10												15			
	E	9.0	6.3	0.7				8	2							15		
9.0		6.3	0.7				5	2							15			
9.0		7.3	0.8		2	6	6	3							15	7.5	2+	
9.0		7.3	0.8		1	0	3	9							13			
9.0		8.5	0.9				6	7							13			
	12.0	8.5	0.7				4	9							13	48.5	2+	
	12.0	10.0	0.8				1	2							13			10.0
C	15	10.5	0.7				1	10							15			
	15	11.8	0.8					3							16			11.8
	15	14.3	1.0					3							15			
	15	16.8	1.1					3							13			
	15	18.0	1.2												15			
	15	23.0	1.5							1					15			18.0
	15	25.0	1.7							1					13			
	15	33.0	2.2												15			
	15	43.0	2.9												15	33	4+	
	15	58.0	3.9							1					15	55	5+	43.0
F	50	33.0	2.2							7					12			
	50	54.0	1.1							4					5	63	4+	
	50	71.0	1.4							1					5			
	100	108.0	1.1							5					5	120	4+	
	100	132.0	1.3							5					5			
Total - 1684																		

This table is a summary of the surface effects produced by increasing the supply of calories (cal/cm^2) and the flux density ($\text{cal/cm}^2/\text{sec}$), within each exposure time investigated. The columns farthest to the right indicate the calorie values that represent the 50 percent probability thresholds and the average values of the burn categories indicated.

TABLE 2
SUMMARY OF MICROSCOPIC RESULTS

Group	Time (Sec)	(Cal/cm ²)	(Cal/cm ² /sec)	No Burn	Epidermal			Transepidermal		Dermal				Adipose	No. of Exposures	50 Percent Probability cal/cm ²
					Minimal	Part of Depth	All of Depth	Focal	Complete	Superficial	Mid	Deep	Complete			
A	0.1	0.5	5.0	8	1										9	
	0.1	0.8	8.0	10	0										10	
	0.1	1.0	10.0	6	2	1									9	
	0.1	1.3	12.5	5	1	3									9	1.3 min-ep
	0.1	1.5	15	1	4	5									10	
	0.1	2.0	20	2	3	4	1								10	1.5 part-ep
	0.1	2.5	25	1	0	5	2	2	1						11	2.5 all-ep
A	0.3	0.6	2.0	7	1										8	
	0.3	0.8	2.7	9	0										9	
	0.3	1.1	3.7	8	1										9	
	0.3	1.3	4.3	5	2	3									10	
	0.3	1.6	5.3	8	2	1									11	1.8 min-ep
	0.3	2.1	7.0	4	2	6		1							10	2.1 part-ep
	0.3	2.6	8.7	2	4	4	2	4	1						10	2.7 all-ep
B	0.3	3.1	10.3												11	3.0 c. trans
	0.3	3.5	11.7				1	5	4	1					11	
	0.3	4.0	13.3					1	7						12	
	0.3	4.5	15.0						8						12	4.8 s. dermal
	0.3	5.0	17.0						4						10	
	0.3	6.0	20.0						1						10	7.0 m. dermal
	0.3	8.5	28.0							6	3	1			8	
I	0.5	14.0	28.0							1	3	0	1		5	
	0.5	17.0	34.0							1	9	1	2		13	18 d. dermal
	0.5	19.0	38.0							1	1	4	5	1	12	19 c. dermal
A	1.0	0.7	0.7	10											10	
	1.0	0.9	0.9	8											8	
	1.0	1.2	1.2	9	1										10	
	1.0	1.2	1.2	9	2	1									11	
	1.0	1.5	1.5	6	3										10	
	1.0	1.7	1.7	6	0	2									8	
	1.0	2.2	2.2	6	3	0									9	
B	1.0	2.7	2.7	6	1	1	2	0	3						10	2.8 min-ep
	1.0	3.2	3.2		3	2	4	1	3						12	2.9 part-ep
	1.0	3.7	3.7		0	4	4	1	3						12	3.1 all-ep
	1.0	4.2	4.2		1	4	1	1	5						12	4.2 c. trans
	1.0	4.7	4.7	1	0	1	1	4	3	2	6	2			12	5.5 s. dermal
	1.0	7.5	7.5							2					10	6.5 m. dermal
	1.0	8.5	8.5							1	4	2	1		8	8.5 d. dermal
E	2.0	1.4	0.7	8	5										13	1.6 min-ep
	2.0	1.8	0.9	4	9										13	
	5.0	4.0	0.8	1	4	3	1	0	2						11	
	5.0	4.5	0.9	2	5	4	0	0	1						12	4.8 part-ep
	5.0	5.0	1.0	1	4	2	5	0	0						12	
	5.0	5.0	1.0	4	4	1	3	0	0						12	5.4 all-ep
	5.0	5.5	1.1	5	1	0	1	2	3	1					13	
B	5.0	5.5	1.1	1	2	2	2	4	1						12	5.8 f. trans
	5.0	6.5	1.3	1	0	0	2	1	3						11	6.8 s. dermal
	5.0	8.0	1.6					2	0						12	8.5 m. dermal
	5.0	9.5	1.9							1	3	1	3	1	9	
	5.0	10.0	2.0							3	5	0	1		9	
	5.0	12.0	2.4							1	2	6	1	2	12	11 d. dermal
															12	12 c. dermal
E	9.0	6.5	0.7	5	5	1	0	1		1					12	6.5 min-ep
	9.0	7.0	0.8	2	3	0	3	1	1	1					11	7.0 part-ep
	9.0	8.5	0.9			1	0	1	2	4	1	1			10	8.2 s. dermal
	12.0	8.5	0.7	7	1	0	0	1	2	1					12	8.5 min-ep
	12.0	10.0	0.8	1	0	1	0	0	1	4	2	1			10	10 s. dermal
									1	1	2	3			8	11 m. dermal
											3	3	3		9	11 d. dermal
E	15.0	11.0	0.7												10	12 c. dermal
	15.0	17.0	1.1							1					9	
	15.0	18.0	1.2												10	
	15.0	23.0	1.5												17	
	15.0	24.0	1.6												7	
															6	
															7	
Total - 645																

Table 2 is a summary of the depth of burn, judged by study of microscopic changes, as it was produced by increasing the energy applied (cal/cm²) in each exposure time studied. The column on the right lists the 50% probability of the threshold values in cal/cm² for depth of burn in each time of exposure studied. The abbreviations used refer to the classification of the degrees of depth of injury as they appear at the top of the table.

Figure 1. The flux density required to cause the thresholds of 5 grades of surface change and three levels of penetration in depth is plotted on a linear scale against exposure time. The macroscopic thresholds of 1+ through 5+ are shown in solid lines and the microscopic changes of (A) Epidermal, (B) Transepidermal and (c) Deep Dermal penetration are shown in dotted lines.

of these burns examined microscopically for depth of injury. These microscopic findings are shown in Table 2 where they also are related to time and intensity of exposure. From these data the 50 per cent probability thresholds were calculated for each exposure time as a function of flux density, or $\text{cal}/\text{cm}^2/\text{sec}$. These values, a measure of the rate at which energy was supplied, were plotted against exposure time, using a linear scale as shown in Fig. 1.

This method of expressing the results indicated that, with longer exposure times, very small flux density changes were required to maintain the thresholds, and that only small energy differences existed between thresholds. Consequently, with longer exposure times, small differences in flux density made a considerable difference in burn severity. As the exposure time was extended, the flux density tended to become asymptotic to some small, non-injurious level.

As exposure times became shorter, a rapid increase in the flux density was necessary to maintain the thresholds. With exposures of a fraction of a second the curves of comparable damage approached the vertical. Here the exposure time was far the more critical feature. Small differences in time caused a big difference in burn severity.

2. The Relationship Between Total Energy and Exposure Time

For each exposure time, the 50 per cent probability thresholds and the average (mod.) values of the major grades of burn severity were expressed as a function of the energy applied per unit area. These calorie values were obtained by multiplying the flux density

by the exposure time. For example, an exposure of $25 \text{ cal/cm}^2/\text{sec}$, for a period of 0.1 second would give $2.5 \text{ calories/cm}^2$. These caloric values were then plotted against exposure time using logarithmic scaling to facilitate percentage comparisons of the results. This is shown in Fig. 2 where it is seen that the curves slope upward with increased exposure times. This indicated a greater caloric requirement with longer exposures to give the same surface indication of severity.

As exposure times were reduced, it generally required less energy to maintain the same apparent damage. As the time approached the lower limits available, the rate of fall in the caloric requirement diminished, and most of the lines approached the horizontal.

The data from microscopic evaluation of severity were plotted in the same manner. These curves of microscopic depth of penetration of injury in relation to the time and intensity of application of the thermal energy are shown in Fig 3. In this figure it is evident that as the time of exposure was increased more energy was needed to give the same depth of burn in the epidermis and even to a superficial level in the dermis. This increased caloric requirement with longer exposure times made the curves of superficial penetration slope upward. A different result occurred when the penetration was into the deeper levels of the dermis. Here a longer exposure required fewer calories to cause the same depth of injury so the curve sloped downward. This resulted in all of the curves approaching one another, and indicated that at longer exposure times a very slight change in the amount of energy applied may make a great

Figure 2. The energy required (cal/cm²) to cause the surface damage of the five grades of severity was plotted on a logarithmic scale against exposure time. In the first three the value for the average effect of moderate severity of the lesion was used. In the case of the steam bleb and carbonization only data for the threshold value was obtained.

50% PROBABILITY MICROSCOPIC THRESHOLDS
 CALORIES (cm.²) vs. EXPOSURE TIME (sec.)
 (LOGARITHMIC SCALE)

Figure 3. The threshold level of energy required to cause five degrees of depth of microscopic change is plotted on a logarithmic scale.

difference in the depth of its penetration.

The comparison of evaluating burns by surface damage and microscopic depth of injury is shown in Fig. 4. Here it will be seen that the shape and position of the curves were similar for the values of partial coagulation on the surface and for penetration in depth to the superficial level of the dermis. The curves for lesser grades of severity below this level also showed agreement between assessment by surface and microscopic appearance. In contrast the curves of such severe damage as carbonization and deep dermal penetration started from the same level but then diverged. They failed to show correlation between surface and microscopic injury.

B. Pathological Changes

The thermal intensities required to produce burns over a wide range of exposure times caused variations in the pathological characteristics of the lesions. These followed a pattern which was related to the duration of the exposure. A similar type of change in burn characteristics was noted by Moritz in a study of contact burns (8).

1. Macroscopic Changes

The erythematous burn produced by brief exposure to high intensity radiant energy was an elevated, pink unstable lesion characterized by hyperemia. When created by longer exposures to lower intensities it was a flat, bluish-red, stable lesion with congestion and stasis. The latter type became pink after hours or days, depending upon the length of exposure time.

COMPARISON OF SURFACE CHANGES AND DEPTH IN 2 RANGES OF SEVERITY (LOGARITHMIC SCALE)

Figure 4. The energy required to produce two grades of surface injury is compared to that needed for two levels of microscopic depth of penetration at increasing exposure times.

Mild coagulation was spotty and superficial with brief exposures, but was more uniform and centrally penetrating with prolonged exposures. Steam blebs appeared gray, delicate and broad-based with short exposures, but were whiter, thicker, and centralized with longer exposures. These often caused an audible report if they ruptured. Confluent surface carbonization originated from multicentric foci of burned hair stubble in the brief exposures while with longer exposures carbonization often began in the center of a steam bleb which was consumed as charring spread peripherally.

It was noted that brief exposures to high intensity radiant energy resulted in surface effects which were limited to the exposed area. In longer exposures the surface effects of the more severe lesions expanded beyond the area exposed, and the transition to normal tissue was more gradual.

2. Microscopic Changes

Epidermal burns produced by brief exposures resulted in multiple foci of sharply delineated, acidophilic coagulation of the ridges of the skin. The underlying epidermis, and that in the surrounding furrows of the skin appeared normal. Epidermal burns produced by prolonged exposures to lower intensities resulted in a more uniform, less sharply demarcated epidermal damage of the microscopically irregular skin surface. Here, the graduated cytological changes described by Leach, Peters and Rossiter (7) were seen.

With transepidermal burns produced by short exposures there was a moderate amount of focal interface edema, but relatively little

fixed vascular reaction in the capillaries of the dermal papillae. Prolonged exposures resulted in a milder but more diffuse elevation of the irregular basement membrane by interface edema. The underlying vascular reaction was deep, severe, and fixed, as evidenced by distended capillaries packed with hemolyzed red cells.

In the deeper burns, damage to the epithelial elements of the dermis was a more discernible feature than was damage to the body of the dermis. Brief exposures resulted in more severe and sharply limited damage than burns of similar portions of the dermis produced by longer exposures.

In both short and long exposures coagulated tissue usually separated as a sequestrum. Tissue showing other types of damage appeared to undergo autolysis or organization.

C. Human Burns

In order to compare flash burns in human subjects with those described in Chester White pigs, a limited series of 0.3 second exposures were made in eight human volunteers.

1. Qualitative Results

The majority of exposures fell into four groups, classified at 24 hours as follows: no burn; erythema, minor vesiculation, or major vesiculation. Erythema was always pink in color, never cyanotic. Vesiculation presented in several forms. Minor vesiculation occurred in the form of miliary white papules, often over freckles; or as larger, white, slightly elevated plaques with a fine dimpling of the surface which suggested a persistent, multiple anchorage. This type was difficult to distinguish from

superficial coagulation, which occurred obviously in the center of one lesion because in this instance it was encircled by a vesicle. The major, dome-shaped type of vesiculation occurred at slightly higher energy levels. It usually required from 6 to 24 hours to develop fully. These lesions remained moist for 48 hours, then formed a dry eschar.

The healing period of burns showing significant erythema usually lasted for 5 to 12 days. In the more severe ones there was a porky consistency of the skin beneath the superficial dry, brown eschar for 5 to 10 days. Vesiculated burns healed, in most instances, in about 7 to 14 days. Three showed a transient superficial cellulitis after trauma.

There were two types of sequelae of vesiculated burns. If they occurred in tanned surfaces, they usually showed central depigmentation with a surrounding rim of hyper-pigmentation of freckling. If they were on light skinned areas, they showed a deep-seated brownish pigmentation which could be partially blanched. These features were persistent, in some cases for more than 6 months.

One accidentally prolonged exposure caused 8.3 calories to be delivered in one second to a moderately tanned dorsal forearm. This resulted in a typical, large steam bleb. Although the center of the lesion occupied by the collapsed bleb was depressed, the surrounding and underlying tissue showed considerable swelling for 48 to 72 hours. The shriveled, dessicated roof of the steam bleb was desquamated in 7 days. Beneath this was a transparent celluloid-like eschar. This gradually became black, was slowly elevated

from the periphery, and sloughed as a dessicated sequestrum 6 weeks after the exposure.

A few prolonged exposures with a lower flux density were done. Cyanosis was not evident in any of these burns but vesicles formed freely. One 10 second exposure to a total of 8.0 calories resulted in a large vesicle which required 6 weeks to heal, and appeared to have caused deep destruction. This presented quite a different initial surface appearance than did the exposure to 8.3 calories in 1 second.

2. Quantitative Results

The results of 0.3 second exposures to increasing amounts of total energy were tabulated. The threshold and average values were calculated. At each energy level 12 to 15 exposures were made, using 6 or 7 subjects. The results are shown in Table 4 for both fair skinned subjects and for those with more pigmented skin.

Threshold and average values for the production of superficial flash burns in humans were similar to those found in anesthetized pigs. The tendency of humans to form vesicles while the pig did not and the limitation of the human study to gross examination of superficial burns, prevented a complete comparison with the porcine data.

The results of this comparison are shown in Table 5 where it is seen that the threshold of 1.4 cal/cm^2 for the first degree burn in the human was similar to that of 1.2 for a 1+ burn in the pig. Similar threshold values were also found for a second degree burn in fair skinned humans of 3.2 cal/cm^2 and a 2+ burn in the

TABLE 4. Results of 0.3 Second Exposures on Human Subjects

Slightly Pigmented Skin Surfaces

Cal/cm ²	Volar Arm								Outer Calf				Percentage Probability		
	DS	PS	HK	HP	DW	JP	JP	JP	JP	HK	DS	HK	E	v	V
1.0	O	O	O	O	E	O	O	O	E	O	O	O	17	0	0
1.5	E	O	O	O	E	E	O	O	E	E	E	E	58	0	0
2.0	E	E	O	E	E	O	E	E	E	E	E	E	83	0	0
2.5	v	E	E	V	E	v	E	E	E	E	E	E	75	17	8
3.0	V	v	E	V	v	V	v	E	v	E	v	E	33	42	25
3.5	-	v	V	-	V	V	V	-	V	V	V	-	0	11	89

Moderately Pigmented Skin Surfaces

Cal cm ²	Volar Arm			Dorsal Arm								Calf				Percentage Probability		
	CM	LK	HK	PS	LK	DW	HP	CM	JP	JP	JP	PS	CM	DW	LK	E	v	V
1.0	O	O	O	O	O	E	O	E	O	O	O	O	O	E	E	27	0	0
1.5	E	E	O	E	E	E	O	E	E	O	E	O	E	E	E	73	0	0
2.0	E	E	E	E	E	v	E	v	E	E	E	E	E	E	E	87	13	0
2.5	v	E	E	V	V	V	V	v	E	E	V	v	E	E	E	47	20	33
3.0	v	v	V	V	V	V	V	V	V	V	V	V	v	V	V	0	20	80
3.5	-	-	-	Not done on pigmented surfaces										-	-			

E - Erythema (1st degree)

v - Minimal Vesiculation

V - Vesiculation (2nd degree)

TABLE 5. Comparison of 50 Per Cent Probability Thresholds and Average Values in Cal/cm² of Human and Pig Burns at 0.3 Seconds

Grade Surface Change		Subject		Threshold	Average Value
Erythema (E)	1+	Pig		1.2	2.3
	1°	Human Slight Pigment		1.4	2.2
	1°	Human Moderate Pigment		1.3	1.8
Focal Coag Vesicle	2+	Pig		3.3	4.5
	2°	Human Slight Pigment		3.2	4.0
	2°	Human Moderate Pigment		2.8	3.3

white pigs of 3.3 cal/cm^2 . Slightly less energy was needed for a second degree burn in the human with a more pigmented skin.

This table also shows that the average values were comparable in the pig and man. The average dose required for a 1° human burn was 2.2 and for a $1+$ pig burn was 2.3 cal/cm^2 . That needed for a 2° human burn was 4.0 and for a $2+$ pig burn was 4.5 cal/cm^2 . These values of the average effective dose will be the ones most useful for interpolation of laboratory or field data on animals into terms of predicted results in humans.

The average values given above for human burns are comparable to those reported by Butterfield and Dixey (2). These authors give the values of 2 cal/cm^2 for 1° burns, 3.5 cal/cm^2 for shallow 2° and 4.6 cal/cm^2 for deep 2° burns.

IV DISCUSSION

There were two main objectives of this work. The first was to study the influence of variations in the time and intensity of applied thermal energy on the severity and character of the burns produced. The second was to obtain a series of standard burns created by a wide range of time and intensity of applied heat to serve as controls for subsequent laboratory and field studies.

Moritz and Henriques (9) advanced the proposition that burns of equal severity resulted from an inverse relationship between temperature and the time of its application. In the present study this factor of time intensity reciprocity was examined in 1,684 burns under controlled conditions including the short exposure times permitted by the technique used. While, within limits, reciprocity existed, prolonging the time of exposure a hundredfold required twice the energy to give the same result. Burns having steam blebs or carbonization on their surface were an exception to this. These criteria of severity required more than double the energy at longer exposure times.

It was found that the application of intense heat for a short time resulted in severe surface damage without deep penetration. There was a sharp line of demarcation laterally and in depth between coagulated and normal tissue. This had previously been demonstrated for flash burns from burning magnesium (6, 13). With the very short exposure times large amounts of energy were needed to alter the degree of burn severity.

If thermal energy of low intensity was applied slowly the surface damage was less striking but the depth of penetration appeared greater. There was a diminishing gradient of damage with irregular margins which eventually tapered off to uninjured tissue. The histological changes created were similar to those described by Leach, Peters and Rossiter (7) and by Moritz (8). It is evident that with long exposure times small differences in the amount of thermal energy applied may make large differences in the depth of the burn.

When microscopic depth of injury was used to judge the severity of burns, the results did not always parallel those from surface appearance. There were 648 burns evaluated by microscopy. When these data were plotted in the same way as those from surface evaluation it was found that the curves of milder degrees of surface damage were similar to those of superficial penetration in depth. This agreement pertained to burns which penetrated into the superficial dermis but did not hold for those deeper than this level. Fewer calories are required to cause a deep dermal burn at longer than at shorter exposure times, whereas the opposite is true for the more severe surface effects. This reverses the slope of the curve for deep dermal burns as compared with the corresponding gross changes. These observations may explain some of the conflicting opinions of previous workers. Moritz and Henriques (9) did not feel that the depth of a burn could be correlated with its surface appearance. Most of their observations were made at longer exposure times. Sheline, Alpen, Kuhl and Ahokas (14) found a "rough proportionality between the degree of superficial and deep damage". The latter used the rat which has a thin dermis which may have reacted as the more

superficial layers of the pig's skin. From the data presented here, it would appear that the defined gross surface changes parallel the depth of damage under the various exposure conditions for mild burns, but, with severe degrees of injury, this relationship does not remain parallel.

It has never been sufficiently emphasized that the depth of a burn was so dependent upon the time the heat was applied. As the length of the exposure was prolonged, the energy required to damage the epidermis and superficial dermis increased while that to penetrate into the deeper dermal layers decreased. This makes the curves of depth of penetration converge as the time of exposure is lengthened. As they approach one another it is evident that very small differences of energy may give large variations in the depth of the burn. Here a calorie or two may mean the difference between a 1° and 3° burn.

The second objective of this study was to create a series of burns over a wide range of time and intensity of applied energy to serve as a standard for comparison with lesions created under other circumstances. These data have already been useful in field and laboratory studies. For example, the thermal burns from two atomic bomb explosions have been evaluated by comparing their severity with that of this series of burns obtained by means of the carbon arc. In this way the atomic bomb burns could be assessed in terms of laboratory standards and a direct comparison made between the thermal energy required to create comparable lesions in the laboratory and in the field.

Another example of the usefulness of these standard burns is their comparison with burns sustained through filters or

fabrics. A study is being made of relative effectiveness of ultra-violet, visible and infrared light in causing thermal burns. This series of standard burns was used as a control for comparing the results with energy from these spectral bands. A similar method was used in a study of the protective effect of fabrics. Since the energy required to cause a burn of any given severity was known from these standards, it was necessary to determine only the amount needed to create an equivalent lesion through a fabric. The difference gave the caloric protection provided by the fabric.

V SUMMARY AND CONCLUSIONS

1) The carbon arc searchlight as it has been modified in this laboratory was an accurate method for causing experimental burns and allowed precise control of the energy applied.

2) A study was made of the surface severity of 1,684 burns on Chester White pigs in relation to the time and amount of thermal energy applied.

3) Surface evidence of injury was divided into five degrees of severity; erythema, patchy coagulation, uniform coagulation, steam blebs and carbonization. These, in turn, were subdivided into mild, moderate and severe. The data obtained were then subjected to statistical analysis in order to show the relation of the degree of damage to the time and intensity of the energy applied.

4) The findings of Moritz and Henriques that burn severity is a function of an inverse relationship between the time and intensity of the applied thermal energy was, in general, confirmed.

5) With long exposure times more energy was required to cause any level of surface damage than was needed for the same degree of injury created by short exposures. But under these conditions small differences in energy may make large differences in the depth of the burn.

6) When large amounts of energy were applied for short times, great variation in surface damage resulted from small differences in the time of the exposure.

7) The severity of 648 burns was appraised by microscopic depth of injury. It was found that surface damage and depth had

a constant relationship in superficial burns, but with deeper injury this relationship varied with the time of the exposure.

8) At longer exposure times the curves of time and intensity of applied energy required for all depths of injury converged toward one another. At a 20 second exposure, two calories may make the difference between a 1° and a 3° burn.

9) Variations in the pathological picture were created by the length of time that the thermal energy was applied. In short exposures of high intensity the appearance was similar to that previously described from this laboratory (6, 13). In longer exposures the changes were similar to those reported by Moritz (8) and by Leach, Peters and Rossiter (7).

10) The severity of 143 burns on humans and those in pigs produced by 0.3 sec. exposures was compared. The average level of energy for a first degree burn in the human was 2.2 cal/cm^2 ; that of a 1+ burn in the pig 2.3 cal/cm^2 . A second degree human burn required an average of 4.0 cal/cm^2 and a 2+ pig burn 4.5 cal/cm^2 . Thus the thermal stimulus causing 1+ and 2+ burns in the pig produced first and second degree burns in the human under similar laboratory conditions.

11) This series of standard burns has been used to assess burns created under other conditions in the laboratory or in the field.

12) The observations here reported give some insight into the mechanism of heat transfer from the skin surface into the sub-surface layers. They point to the need of actual measurements of temperature changes within the skin before this can be completely understood.

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APPENDIX

Mathematical Analysis

by

Thomas P. Davis

Introduction

In any discussion of thermal injury to tissue, almost invariably the question of the temperature-time-space history of the damaged tissue, or, more generally, of heat flow is raised. This is, indeed, a central problem of an intelligent understanding of the thermally induced lesion. While an approach to the determination of the temperature gradients can be made by microscopic examination of sections of the damaged tissue itself, this is only descriptive, and is of little use in attempting predictions of damage in dissimilar types of exposures.

A direct approach to this problem would be, of course, the introduction of thermocouples or other fine temperature sensing elements into the tissue to obtain records of temperature vs time for various depths. There are several grave deterrents to this approach, although it offers probably the least questionable results.

A third approach is that of a classical mathematical analysis of the heat flow. The principal disadvantage of this method is that in order to set up a system which is amenable to mathematical solution, rather severe simplifying assumptions must be made. In defense of the method, however, it does yield a clear insight into the mechanism of heat flow, and thus offers the possibility of permitting the investigator to make reasonable guesses as to the

modifications which must be made in applying solutions to the actual, non-idealized system.

In this discussion, the last approach will be employed. A highly idealized system will be set up, with specific assumptions enumerated; the mathematical solution will be presented in the form of families of curves; an attempt will be made to indicate what changes in the solutions should be made for the case of the small area burn on the pig; and the results will be used to offer possible qualitative explanations for certain features observed in the experimental results.

The System to be Analyzed*

One system which allows a direct mathematical solution is the so-called semi-infinite opaque solid. This is a passive receiver which extends infinitely far in both positive and negative y and z directions, and infinitely far in the positive x direction. (Here, x , y , and z refer to the usual coordinate axis system, with the x , y , and z axes mutually perpendicular.) For simplicity, the plane surface of the semi-infinite solid is placed in the y - z plane, or the plane defined by the equation $x = 0$. This solid, initially at a uniform temperature throughout, has thermal conductivity k cal/cm² sec °C/cm density ρ gm/cm³, and heat capacity c cal/gm°C, where k , ρ and c are constant both in position and time.

* This analysis follows that presented in "Temperature Response of Infinite Flat Plates and Slabs to Heat Input of Short Duration at One Surface" by C. D. Coulbert, W. F. MacInnes, et al, of the University of California Department of Engineering, Los Angeles, (April 1951)

Now let the plane surface of the solid be exposed uniformly to an arbitrary pulse of radiant energy. A certain fraction of the radiant pulse will be reflected (it is assumed that the reflectance of the surface is a constant) while the remainder is absorbed at the surface. The temperature of the solid will then rise, and it is the temperature-time-space history which is to be found.

Specifically, then, the system is described as follows:

- 1) The irradiated solid is infinite in lateral extent, and extends infinitely far in the positive x direction, with the exposed surface the plane $x = 0$.
- 2) The solid is entirely uniform throughout.
- 3) The solid is inert; i. e., no changes of phase or composition occur during the thermal incident, and the reflectance of the surface is likewise constant.
- 4) The solid is initially at a uniform temperature throughout.
- 5) An arbitrary pulse of radiation is absorbed uniformly over the surface.
- 6) The radiation is absorbed only at the surface.
- 7) There are no convection or re-radiation losses at the irradiated surface.

With these assumptions, it can be seen that, within the solid, isothermals will be planes parallel to the irradiated surface. Thus, the heat flow is unidirectional (perpendicular to the isotherms) and the general heat flow equation

$$\nabla^2(\Delta T) = \frac{1}{\alpha} \frac{\partial(\Delta T)}{\partial t} \quad (1)$$

reduces to the unidirectional form

$$\frac{\partial^2(\Delta T)}{\partial x^2} = \frac{1}{\alpha} \frac{\partial(\Delta T)}{\partial t} \quad (2)$$

where ΔT is the temperature rise ($^{\circ}\text{C}$),

t is the time (seconds),

x is distance into the solid measured perpendicularly from the irradiated surface (centimeters)

and $\alpha = \frac{k}{\rho c}$ is the thermal diffusivity ($\text{cm}^2/\text{second}$).

Now, with suitable boundary conditions, equation (2) can be solved in a general way for any arbitrary heat input, $q_a(t)$ $\text{cal}/\text{cm}^2 \text{ sec}$. However, for this discussion, the following additional assumption is made:

8) The heat input is a square pulse described by

$$q_a(t) = \begin{cases} 0, & t < 0 \\ Q_a/\eta, & 0 \leq t \leq \eta \\ 0, & t > \eta \end{cases} \quad (3)$$

where Q_a is the total energy absorbed per unit area (cal/cm^2),

and η is the length of exposure time (seconds).

Solution

Under the above assumptions and with suitable boundary conditions, the temperature-time-space history of the irradiated semi-infinite opaque solid may be described by

$$\Delta T = \frac{Q_a}{\eta} \frac{1}{\sqrt{k\rho c}} \left\{ 2\sqrt{\frac{t}{\pi}} \exp\left(-\frac{x^2}{4\alpha t}\right) - \frac{x}{\sqrt{\alpha}} \operatorname{erfc}\left(\frac{x}{\sqrt{4\alpha t}}\right) \right\} \quad (4)$$

$0 \leq t \leq \eta$

where $\exp\left(-\frac{x^2}{4\alpha t}\right) = e^{-\frac{x^2}{4\alpha t}}$,

$$\operatorname{erfc}\left(\frac{x}{\sqrt{4\alpha t}}\right) = 1 - \frac{2}{\sqrt{\pi}} \int_0^{\frac{x}{\sqrt{4\alpha t}}} e^{-v^2} dv,$$

and other symbols are as defined before.

As indicated, equation (4) is valid only for times up to η ,

the exposure time. To obtain the solution for times greater than η , however, is a simple matter of superposition of solutions, and may be given explicitly as

$$\Delta T = \frac{Q_a}{\eta} \frac{1}{\sqrt{k\rho c}} \left\{ 2\sqrt{\frac{t}{\pi}} \exp\left(-\frac{x^2}{4\alpha t}\right) - \frac{x}{\sqrt{\alpha}} \operatorname{erfc}\left(\frac{x}{\sqrt{4\alpha t}}\right) - 2\sqrt{\frac{t-\eta}{\pi}} \exp\left[-\frac{x^2}{4\alpha(t-\eta)}\right] + \frac{x}{\sqrt{\alpha}} \operatorname{erfc}\left(\frac{x}{\sqrt{4\alpha(t-\eta)}}\right) \right\}, \quad t > \eta. \quad (5)$$

Now it is only necessary to substitute numerical values into equation (4) or (5) and plot the temperature-time-space relations. Inasmuch as there are three variables involved, these plots are best made as a series of families of curves. On the following pages, solutions are graphed as $\Delta T/Q_a$ vs time (Figure 5; a, b, and c) with depth, x , as a parameter; and a second set of $\Delta T/Q_a$ vs x (Figure 6; a, b, and c) with time as a parameter. The first set of curves may be thought of as those which would be obtained if a temperature sensing element were buried in the solid at certain depths and direct recordings made of temperature rise vs time. The second set (with time as a parameter) may be thought of as temperature profiles--i.e., temperature gradient curves--observed at particular instants of time.

It will be noted that the curves have been plotted for $\Delta T/Q_a$ rather than ΔT . This simple transformation in a sense normalizes the plots; inasmuch as they apply to any particular value of absorbed energy. Thus, to obtain the temperature rise at a particular depth and time, it is only necessary to multiply the value of $\Delta T/Q_a$ read from the curves by the value of Q_a for that particular exposure.

The numerical values used for the physical constants of the solid were selected as the best current estimates of living skin,

and are

$$k \rho c = 1.47 \times 10^{-3} \text{ cal}^2/\text{cm}^4 \text{ sec } (^\circ\text{C})^2$$

and

$$\rho c = 0.8 \text{ cal/cm}^3 \text{ } ^\circ\text{C}.$$

Thus, $k = 1.84 \times 10^{-3} \text{ cal/cm}^2 \text{ sec } ^\circ\text{C/cm}$

$$\alpha = \frac{k}{\rho c} = 2.30 \times 10^{-3} \text{ cm}^2/\text{sec}.$$

As indicated, equations (4) and (5) were solved for values of x from 0 to 0.20 cm, and values of time from 0 to 3 seconds.

The Actual System

Although the above solutions are exact for the idealized system as described, when they are applied to such a complex event as a radiant exposure of porcine skin, it is obvious that they fall short of a close approximation to the actual system. However, as indicated in the introduction, it should now be possible to make reasonable guesses as to the alteration of the solutions necessary for their application to the non-idealized system.

Consider the description of the system as enumerated above:

- 1) The irradiated solid is infinite in lateral extent and extends infinitely far in the positive direction.

Considering the small range of depth considered ($x = 0.2$ cm, maximum) the pig is certainly an infinite body, and the exposed surface is reasonably plane.

- 2) The solid is entirely uniform throughout.

This assumption is very poor, indeed, as the skin is a most complex structure, stratified both laterally and in depth. Within the range of depth considered, probably the most marked change is that from the epidermis to the dermis, although there are substrata

in both of these layers, and, in fact, the change from epidermis to dermis is not completely abrupt. Hair follicles and sebaceous glands further complicate the picture, although these points are of considerable interest since thermal damage here has a marked effect on re-epithelialization.

One approach to this problem is to ignore the epidermis, and consider that the solutions apply only to the more uniform dermis. The plane $x = 0$ is then the dermal-epidermal interface. Justification for this approach is that the epidermis is quite thin (circa 0.006 cm), and from the temperature rise vs time curves it can be seen that the curve for $x = 0.006$ cm would be quite close to that for $x = 0$. Further, the epidermis is relatively transparent, while a pigmented layer occurs at the dermal-epidermal interface; thus, much of the radiation is absorbed at this interface rather than at the true surface of the skin. This approach still does not help in resolving the question of the temperature rise of the hair follicle bases, and, in general, it must be admitted that no mathematical analysis or armchair philosophizing can properly take into account the extreme complexity of living skin.

3) The solid is inert and the reflectance of the surface is constant. Here again, the complexity of the burn process in living skin makes the evaluation of the assumption difficult. Certainly the skin is not inert, and many changes do occur, the changes depending upon the severity of damage.

For the 1+ burn, the most evident manifestation is increased blood flow (vasodilatation). It is probable, however, that blood

flow, even at the maximum depth considered, is not sufficient to alter appreciably the temperature response. At the 2+ and 3+ levels, dermal collagen has been thermally altered ("coagulated") which, as a phase change, will abstract heat from the heat flow process, resulting in smaller temperature rises than would be predicted on the idealized system basis. By the time that the steam bleb level (4+) is reached it is obvious that liquid water must have been converted into steam, with the consequent removal of the large heat of vaporization. This heat may be regained for damage purposes if the steam condenses without bursting out from the bleb, but should the bleb break, then the steam will carry away its heat of vaporization. In any event the temperature at any point might be expected to level off when it reaches 100°C until all water at that point has been changed to steam. Thus, while the curves predict a maximum surface temperature of 247°C for the 50% threshold level for a 4+ burn at one second it is doubtful if such a high temperature is actually reached.

At the carbonization, or 5+ level, one might expect a gain of heat if this carbonization does, indeed, represent an exothermic reaction. This effect may well take place but in all likelihood it is masked by the rather violent eruption of material from the exposed area, such material probably being destructive distillation products and steam. This efflux of heated material undoubtedly serves to abstract considerable heat from that producing a temperature rise in the skin; hence again, the temperature should not rise as high as predicted.

At the carbonization level, this heat loss is somewhat counter-balanced by the blackening of the surface and consequent decrease in

skin reflectance. Thus, a larger fraction of incident energy is absorbed, although the cloud of material issuing from the burned area probably attenuates this incident energy. Undoubtedly, the overall effect will be the lowering of the expected temperature rise.

- 4) The solid is initially at a uniform temperature throughout.

A gradient does exist in the skin prior to the exposure, although over the range of depth considered, this gradient is quite small. In any event, this constant gradient represents a steady-state heat flow, and superposition allows the simple addition of temperature rises from the steady-state flow and the transient heat flow from the radiant exposure. Thus, if the initial temperature at a given depth is known, the predicted temperature at any time is the sum of this initial temperature and the predicted temperature rise.

- 5) The radiation is uniform over the surface.

In the actual system, an aperture limits the exposed area to a disk of 1.7 cm diameter. Further, the radiant power delivered by the arc lamp drops to approximately 70% of the central maximum at the edges of the exposed area. However, the curves of temperature rise vs time (Figure 5) indicate that at only 0.2 cm from the surface the temperature displays a marked insensitivity to the surface temperature, and considering the situation of lateral conduction, it follows that the temperature along the center line of the burned volume will be relatively unaffected by the "sink" of unheated tissue surrounding the volume. In other words, the iso-thermals will be very nearly plane surfaces near the center line of the burned volume, hence, the heat flow will be practically perpendicular to the exposed surface through the central area of the burn.

Just how large this central area might be is rather difficult to estimate, but it is felt that over the central circular area of one square centimeter (diameter of 1.13 cm) the temperature should be sensibly independent of the surrounding cold tissue. At lower depths, of course, the area of uniformity will be decreased, but for depths of only 0.2 cm, this same 1.13 cm diameter circle would seem reasonable. Further, over this area, the irradiance from the arc lamp has a spatial variation of only about 10%, so as long as this central area is considered, the system is probably a good approximation to the uniformly irradiated semi-infinite solid system.

6) The radiation is absorbed only at the surface.

It is obvious that radiation can penetrate the skin, that is, the skin demonstrates the property of diathermancy. This effect can be accounted for in a more involved mathematical analysis, although for the latter it is necessary to assume uniform diathermancy through the skin, which is a poor assumption. Another difficulty with such an analysis is that it is difficult to obtain good values for the transmission coefficient in living skin.

The general effect of diathermancy is to lower the surface temperature rise, and increase the rise in depth; thus, the temperature rise vs depth curves will not be as steep as predicted on the opaque solid theory.

7) There are no convection or re-radiation losses at the irradiated surface.

An extreme estimate of the re-radiation losses from the surface can be made by taking the maximum surface temperature achieved during exposure, assuming that the surface was at that temperature for the

entire exposure time, and calculating the re-radiation losses from the surface, assuming an emissivity of unity. Such a calculation yields a value of about 0.18 cal/cm^2 loss for an absorbed energy of 10 cal/cm^2 in a one second exposure. This figure is much larger than would actually be expected, yet it is still negligible.

Convection losses will likewise be quite small, unless the losses due to transport of heated material (see discussion under (3) above) is counted as convective loss. In this case, at high values of absorbed energy, the "convection" losses could be quite large and difficult to evaluate.

8) The heat input is a square pulse.

The shutter used for this burn study has an opening and closing time of about 25 milliseconds, with exposure time based on the half-open to half-closed period. For exposure times of one-half second and longer the approximation to a square pulse is excellent, but for times shorter than this the approximation is not so good, with the exposure approaching a triangular form at the 0.1 second time. A slightly more involved mathematical treatment can account for this variation, but for the present discussion, the solutions are not applied to exposure times of less than 0.5 second.

Application to Experimental Results

One of the striking features of the flash burn is the sharp line of demarcation between normal and damaged tissue, both laterally and in depth. In the present study this sharp line was observed for those burns produced at the shorter times, but at longer exposure times this line became much less distinct with the histological picture being a more or less gradual change from injured to normal cells. The curves

of temperature rise vs depth (temperature profiles) indicate an explanation for this result.

Let it be assumed that cell death is dependent on the maximum temperature reached by that cell, and that each cell has a certain critical temperature necessary for its destruction. It would be reasonable to expect that the critical temperature of one cell would be approximately but not exactly equal to that of another similar cell, so that the destruction of a group of cells could be predicted only in a statistical way, as is true for many other biological processes. It then follows that on the ordinate of a set of temperature profiles a band could be drawn covering the range of critical temperatures of a large group of cells; at the lower edge of this band the most susceptible cells would be destroyed, while if the temperature increased to the upper edge of the band, the hardest cells would be killed.

Now, considering the temperature profiles for an exposure time of 0.5 second (Figure 5 c), the curves are quite steep for times up to 0.5 second and will pass through this "cell injury band" within a short distance along the depth scale. The temperature profile for the 2 second exposure, being much less steep, will cover a considerably longer range on the depth scale in passing through the same width band. Thus, in the first case, one would predict a sharp demarcation between normal and damaged cells, while in the latter situation, one would expect a more diffuse area of partial cell injury shading outward from the zone of total destruction. Further, it would seem reasonable that these same considerations would also apply to lateral conduction. Thus, the mathematical

analysis offers a most reasonable explanation for this microscopic observation.

A second feature of interest in this study is the character of the curves of 50% probability levels of surface manifestations as related to time of exposure (Figure 2). These curves all display a positive slope; i.e., more energy is required to produce a given surface effect at longer exposure times than at shorter. The temperature rise vs time curves (Figure 5) clearly indicate that the maximum surface temperature achieved for a given absorbed energy increases as the length of exposure time decreases. In fact, it can be readily derived from equation (4), that for the idealized system this maximum temperature, which is always reached at the end of the exposure period ($t = \eta$), is given by

$$\Delta T_{\max} = \frac{2Q_a}{\sqrt{\pi k \rho c}} \cdot \frac{1}{\sqrt{\eta}} \quad , \quad (x=0, t=\eta) \quad (6)$$

where, as before, η is the exposure time (seconds) and the other symbols are as previously defined.

Thus, assuming that the surface damage is related to the maximum surface temperature achieved, one would expect that, for a given value of absorbed energy, damage would be more severe at the shorter exposure times, or, conversely, that it would require less energy to produce a given level of damage at the shorter exposure times. To indicate the degree of agreement between theory and observation, the data of actual experimental results (Table 1) have been plotted with curves of constant maximum surface temperature added

(Figure 7). For each damage level, the temperature was calculated from equation (6) for the incident energy per unit area obtaining at the one second exposure time, assuming a reflectance of 40% and an initial surface temperature of 35°C. The dashed lines then indicate the incident energy necessary to produce this same maximum surface temperature at any other exposure time. While the agreement is not too good, particularly at the lower damage levels, it does indicate that surface appearance can be approximately related to predicted maximum surface temperatures, and offers a reasonable explanation for the slope of the macroscopic threshold curves.

A rather interesting and significant explanation may be offered for this poor agreement between theory and experiment at the less severe levels of damage. It must be realized that for the first three levels of damage, at least, macroscopic observations are in reality observations of depth phenomena. The redness of the 1+ burn is due to a suffusion of blood which occurs in the dermis, and, similarly, the 2+ and 3+ burns are characterized by a white appearance which is due to coagulation of dermal collagen. Thus, these "surface appearances" actually represent depth changes, and one would not expect good correlation with surface temperatures. In Figure 7, for the 1+ level, the curve for a constant maximum predicted temperature at a depth of 0.05 cm is added as a dotted line, with the same assumptions used as in calculating the predicted surface temperatures. The agreement with actual results is much better than is the case for predicted surface temperatures.

Turning to the 50% threshold levels of constant damage as determined microscopically (Figure 3), it can be seen that while

the curves for the less severe lesions are similar to the macroscopic curves, the levels for the severe burns display a negative slope. Further, in contrast to the approximately parallel macroscopic thresholds, the microscopic curves tend to converge at long exposure times.

The curves of temperature rise vs time offer a possible explanation for the apparent anomaly of the negative slopes of the deep dermal and -- at the shortest exposure times -- the mid-dermal thresholds. Comparison of Figures 5a, 5b, and 5c shows that the curves of temperature rise at a depth of 0.2 cm are, for the three times considered, remarkably similar; i.e., the temperature rise in depth is virtually independent of the length of time of exposure -- over a reasonable range of time -- and depends only upon the total energy absorbed. Thus it might be predicted that damage in depth would also be a function only of absorbed energy, and hence, iso-damage curves would have zero slope on an incident energy vs exposure time plot, such as Figure 3.

However, recalling the violence of the surface reaction at these severe burns, with consequent abstraction of heat from that producing a temperature rise in the tissue, it would appear reasonable that at the shorter exposure times, where the surface reaction is more violent due to the higher surface temperatures achieved, more heat would be required to produce a given level of depth damage than would obtain at the longer exposure times. This, then, would explain the negative slopes of the curves of deep dermal injury and -- at the short exposure times -- of mid-dermal damage.

The convergence of the microscopic threshold curves at long exposure times (Figure 3) may be explained if it be postulated that

all the cells in the tissue are destroyed within a rather narrow range of temperatures; i.e., the cells all have about the same critical temperature. The curves of temperature rise vs depth (Figure 6) indicate that at long exposure times, the temperature gradient through the skin becomes rather flat. Hence, once the absorbed energy is sufficient to produce a destructive temperature in, say, the superficial dermis, it is also very nearly sufficient to destroy the deep dermis, and a slight increase in absorbed energy will produce a marked increase in depth of damage.

While the temperature profile curves have been used in explaining the convergence of the microscopic threshold curves, the explanation is obvious on purely intuitive grounds. As the rate of delivery of thermal energy is reduced and the exposure time increased, it is clear that the temperature gradients through the skin will become less and less steep and the threshold curves will continue to converge. As this process is continued, steady-state conditions will be reached and, finally, all the microscopic threshold curves will turn upward to a 45° slope to become asymptotic to some small non-injurious value of incident radiant power.

The final point to be discussed concerns the situation depicted in Figure 4, comparing the 2+ and 5+ levels of surface injury with the focal transepidermal and deep dermal levels of depth injury. The good agreement between macroscopic and microscopic evaluation at the less severe level is probably due largely to the methods of assessment. As discussed above, at the 2+ level, the "surface" appearance in reality reflects depth phenomena, and is observable grossly only because of the transparency of the epidermis. Thus

the macroscopic criterion is coagulation of dermal collagen while the microscopic criterion is focal transepidermal necrosis; generally the same level of damage is being observed in both cases, and one would expect good agreement between the two methods of assessment.

In the case of the higher levels of damage in Figure 4 the gross criterion is carbonization -- a true surface phenomenon -- while the microscopic level is characterized by deep dermal injury. Clearly, these criteria are quite different, and the possibility of failure of agreement exists. The suggested explanations for the character of these two curves have been presented in the preceding paragraphs, and, it is believed, adequately cover the possible reasons for the observed failure of agreement.

Conclusion

The above discussion of a few of the features of the experimental results of this burn study indicates a reasonably satisfactory application of the mathematical approach to the problem of heat flow in thermally irradiated tissue. The section dealing with the application of the idealized system solutions to the actual system points out the tremendous difficulties involved in attempting to get at better approximations to the actual system through a straight mathematical treatment, and should provide justification for the introductory statement that direct measurement by fine temperature sensing elements in the skin probably offers less questionable results. Certainly this direct approach is indicated, if only to check mathematical analyses, and would undoubtedly prove useful in attempting a truly quantitative explanation of the thermally induced lesion.

A major assumption implied in this discussion is that the thermal damage can be predicted on a "maximum temperature attainment" criterion. It is generally agreed that this is not a good criterion for quantitative results, a much better one being the punishment integral, which, unfortunately, requires a quite involved analysis. The success of the qualitative explanations based on the maximum temperature criterion justified its use in this paper, inasmuch as a quantitative discussion was not attempted.

Figure 5a

Figure 5b

Figure 5c

Normalized Temperature Rise vs Depth

Opaque, Semi-Infinite Solid

Exposure Time - 2.0 sec.

Figure 6a

Figure 6b

Figure 6c

50% Threshold Values for Constant Surface Appearance

Figure 7