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TMR 178

INSTANTANEOUS HEAT TRANSFER, PRESSURE, AND SURFACE
TEMPERATURE CHARACTERISTICS OF SOLID PROPELLANT
ROCKET IGNITERS

U. S. NAVAL PROPELLANT PLANT
Indian Head, Maryland

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POLARIS PROJECT MANAGEMENT OFFICE

Technical Memorandum Report 178

12 April 1960

**INSTANTANEOUS HEAT TRANSFER, PRESSURE, AND SURFACE
TEMPERATURE CHARACTERISTICS OF SOLID PROPELLANT
ROCKET IGNITERS**

By

**J. Nanigian
N. J. Crookston, Jr.
A. Michelson**

**U. S. NAVAL PROPELLANT PLANT
Indian Head, Maryland**

**G. T. ATKINS
Captain, USNavy
Commanding Officer**

**J. E. DODGEN
Commander, USNR
Technical Director**

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ABSTRACT

Equipment was designed to measure both instantaneous heat transfer and pressure characteristics of solid propellant rocket igniters. Results indicate that evaluation of igniters solely on the basis of pressure produced is not valid since igniters differing as much as 150% in total pressure output differed less than 30% in terms of total heat transfer.

INSTANTANEOUS HEAT TRANSFER, PRESSURE, AND SURFACE
TEMPERATURE CHARACTERISTICS OF SOLID PROPELLANT
ROCKET IGNITERS

Ignition failure or improper ignition is one of the most common types of malfunctions experienced in solid-fuel rocket motors. This is not surprising since the ignition process consists of a series of exceedingly rapid, complex, and interdependent reactions which occur in two distinct phases: the transient phase and the steady-state phase. The basic process of transferring energy from the igniter to the propellant grain is time-, temperature-, and pressure-dependent.

During the transient phase of ignition, the rate of instantaneous heat transfer and the total heat transfer from the igniter to the surface of the propellant grain are most important. If the energy supplied by the igniter is not matched to the requirements of the propellant, various abnormalities such as over-ignition, slow-ignition, hang-fires, and chuffing will occur.

During the transition period, from the beginning of ignition to the attainment of steady-state propellant burning, the igniter must supply a minimum threshold pressure. If the pressure is below the minimum threshold value, or if the rate of pressure rise is too slow, ignition delays occur or ignition of the grain may be interrupted. If the rate of pressure rise is too fast, extremely high maximum pressures are built-up quickly with the generation of sufficient force to crack the grain and cause unsteady burning or even explosion of the rocket motor.

From the preceding considerations, it is evident that both pressure and temperature are critical factors in the ignition process. Since both quantities exert their effects simultaneously, it is also desirable to measure both simultaneously. This has not been done, however, because test equipment for the simultaneous and instantaneous measurement of both the pressure and temperature characteristics of the igniters has not been readily available. Consequently, the standard practice has been to assess the igniters primarily by the pressure which they produced since this measurement could be made simply and accurately, and it was assumed that if the pressure characteristics of the igniters were similar, then the thermal characteristics would likewise be similar. The simultaneous pressure and temperature data obtained in this project show the fallacy of this assumption.

TEST EQUIPMENT

A small-caliber aircraft rocket and its black powder-magnesium igniter was the prototype motor used in this work. An igniter test chamber, shown in Figure 1, was designed to simulate this motor. The chamber has the same length and internal free volume as the grain used with the igniter. It is fabricated from stainless steel and consists of three principal sections: a removable head chamber, an instrumented chamber, and a removable nozzle section. The head chamber is easily removable for tests where temperature conditioning of the igniter-head chamber is required. The instrumented chamber has three gage stations, each equipped with a Baldwin HF Series, SR-4 strain gage of 1000 psi capacity and a fast-responding chromel-alumel thermocouple with a response time of 10 microsec-

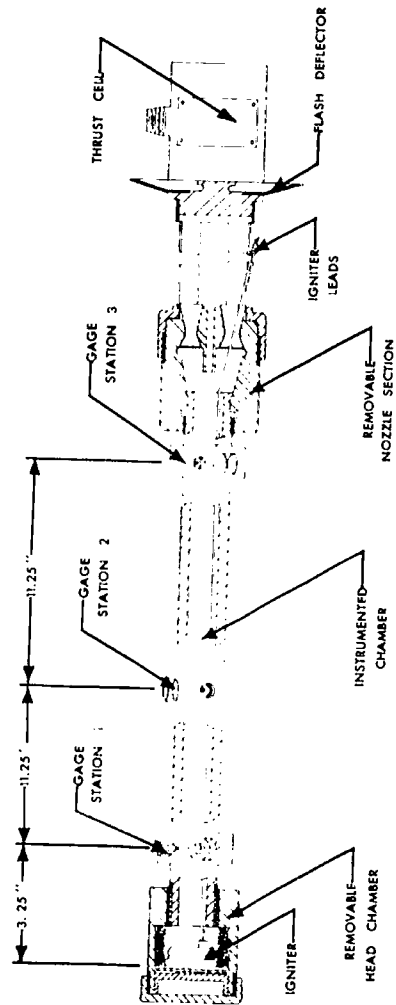


FIGURE 1. IGNITER TEST CHAMBER

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onds manufactured by the NANMAC Corporation. Firing data were recorded on a Consolidated Electrodynamics Corporation Oscillograph recorder. Typical pressure and temperature oscillograms are shown in Figures 2 and 3.

Small-caliber rocket igniters, containing a mixture of black powder and magnesium and having an average charge weight of 8.39 grams, were used in the tests.

TEST PROCEDURES

Test equipment and the mathematical procedures used to calculate the rate and total heat transference were evaluated by firing several igniters with the chamber assembled as a closed bomb. (The nozzle section was sealed shut by a threaded metal cap.) The data obtained were then compared with the mean standard heat-of-explosion values of the igniters. The test chamber was then fitted with a standard nozzle assembly of the type normally used with the igniters and additional firings were conducted. The pressure characteristics of the igniters and the rate of heat transfer and the total heat transfer from the igniter to the wall of the test chamber were calculated from the pressure-temperature oscillograms obtained.

DEVELOPMENT AND APPLICATION OF MATHEMATICAL PROCEDURES

Development of Mathematical Procedures⁽¹⁾

Under the assumptions of unidirectional heat flow in a semi-infinite solid and constant average thermal properties, the rate of

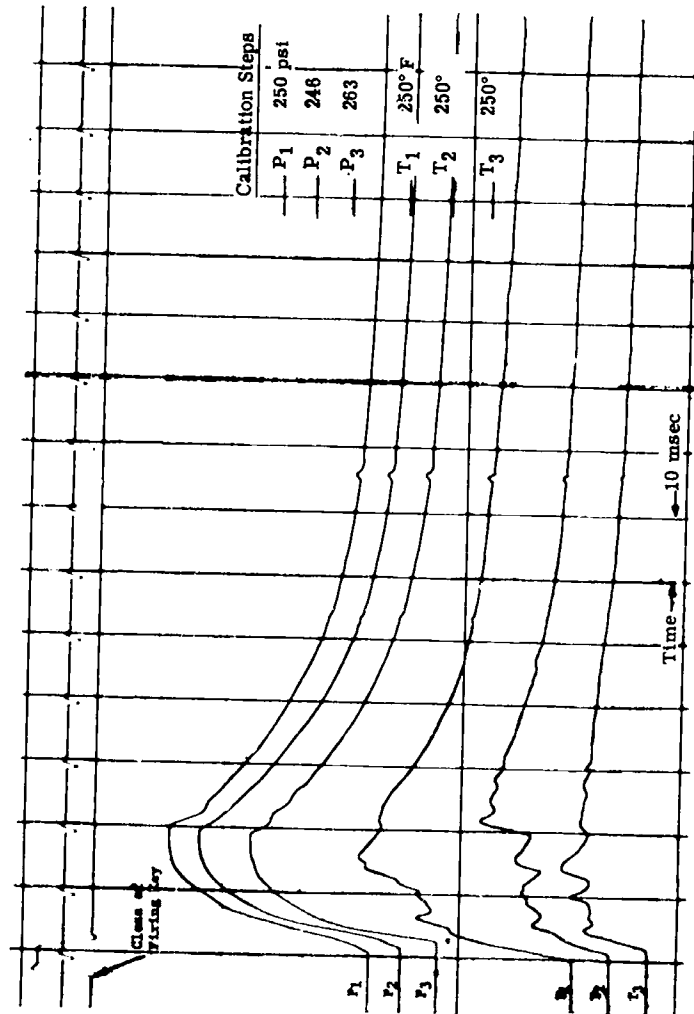


FIGURE 2. PRESSURE AND TEMPERATURE OSCILLOGRAMS AT CORRESPONDING LOCATIONS IN THE IGNITER TEST CHAMBER (ROUND 3)

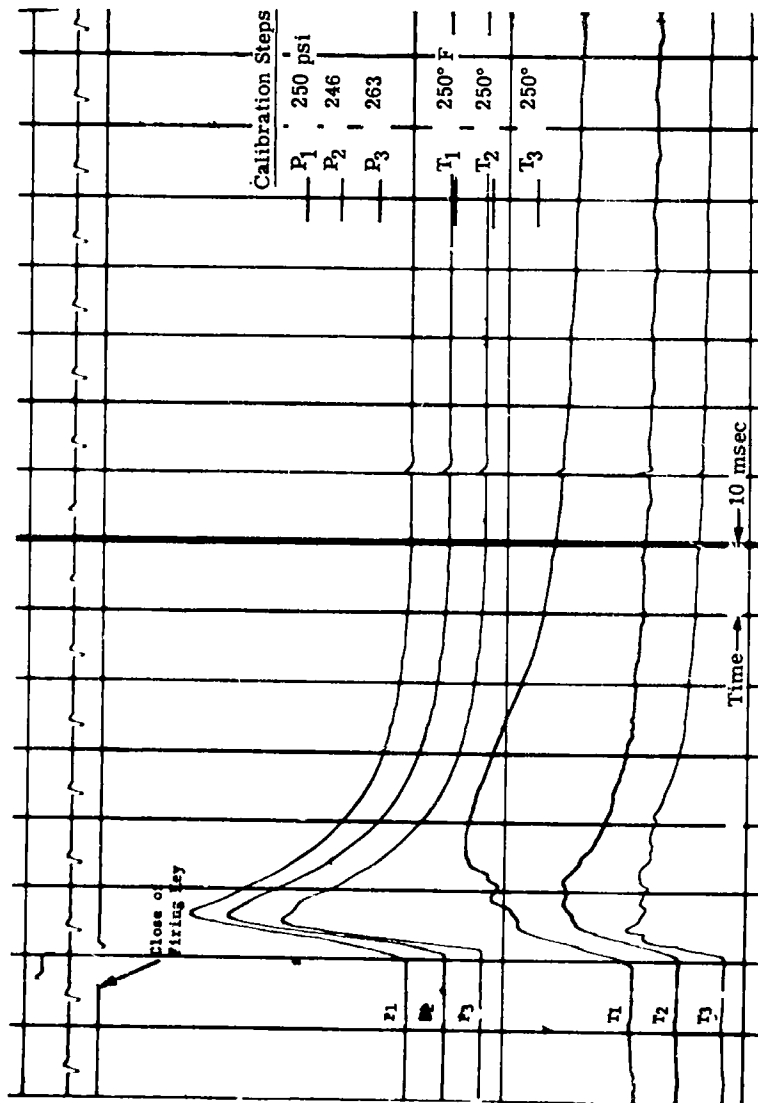


FIGURE 3. PRESSURE AND TEMPERATURE OSCILLOGRAMS AT CORRESPONDING LOCATIONS IN THE IGNITER TEST CHAMBER (ROUND 5)

heat transferred at a gas-metal intersurface may be calculated from the equation:

$$q(t_n) = \frac{K}{\sqrt{\pi\alpha}} \int_0^{t_n} \frac{d\Phi(\lambda)}{d\lambda} \frac{d\lambda}{\sqrt{(t_n - \lambda)}}$$

where

$q(t_n)$ = heat rate at time t_n , cal/sq cm sec

K = thermal conductivity, cal/(sq cm)(sec)(°C/cm)

α = thermal diffusivity, sq cm/sec

t = time, sec

$\Phi(t)$ = function defining the variation of surface temperature with respect to time

λ = variable of integration

T = temperature.

An observation of the temperature-time curve reveals that $\Phi(t)$ is a high order polynomial. Equations of this nature are difficult to fit and would, at best, be a close approximation to the true curve. However, small segments of the curve can be closely approximated by linear equations. If we let $\psi_i(t)$ represent the linear equation for approximating $\Phi(t)$ over an interval ΔT_i , the derivative of $\psi_i(t)$ is the slope, m_i , of the line. If the temperature change over the i^{th} interval is represented by ΔT_i , then the slope $m_i = \Delta T_i / \Delta t_i$. The linear slope over a small interval is then the best approximation for $d\Phi(\lambda)/d\lambda$. Thus, we can rewrite $q(t_n)$ as follows:

$$q(t_n) \approx \frac{K}{\sqrt{\pi\alpha}} \sum_{i=1}^n m_i \int_{t_{i-1}}^{t_i} \frac{d\lambda}{\sqrt{(t_n - \lambda)}}$$

$$q(t_n) \approx \frac{2K}{\sqrt{\pi\alpha}} \sum_{i=1}^n m_i \left[(t_n - t_{i-1})^{1/2} - (t_n - t_i)^{1/2} \right].$$

Experimentation with different time intervals led to the conclusion that 1-millisecond intervals provide a sufficiently accurate approximation for this particular problem.

Application of Mathematical Procedures

An example will illustrate the actual procedure used to calculate the heat transfer rate. To facilitate computation, the temperature oscillogram is traced on graph paper so that ordinate and abscissa values can be readily obtained. This introduces the necessity for a constant, c , to define the relationship between graphic blocks and °C/millisecond which represents the true slope m . The graphic slope m' is obtained as $(y_i - y_{i-1}') / (x_i' - x_{i-1}')$ for the i^{th} interval, where x_i' and y_i' are the time and temperature elements respectively in terms of graphic units. Therefore $m = cm'$ where c is the constant mentioned above. The number 2 developed through the integration of

$$\int \frac{d\lambda}{\sqrt{t_n - \lambda}}$$

is then combined with the thermal constant

$$\frac{K}{\sqrt{\pi\alpha}}$$

and c to provide a total constant,

$$C = \frac{2cK}{\sqrt{\pi\alpha}},$$

for each $\Phi(\lambda)$. (C may change for each $\Phi(\lambda)$ depending on the calibration of that curve.)

Computation is simplified by the use of a table set up for each $\Phi(\lambda)$ similar to Table I in the Appendix on which is calculated the

$$m_i' \left[\left(t_n - t_{i-1} \right)^{1/2} - \left(t_n - t_i \right)^{1/2} \right]$$

for each required interval. It will be seen that the expression

$$\left[\left(t_n - t_{i-1} \right)^{1/2} - \left(t_n - t_i \right)^{1/2} \right]$$

is the difference between consecutive square roots and can be readily computed.

To obtain the heat transfer rate for a specific time, t_n , it is first necessary to compute the cross-products for each interval from t_0 to t_n . It is then necessary to sum the diagonals for each interval $i=1, 2, 3, \dots$ thereby obtaining the

$$\sum m_i' \left[\left(t_n - t_{i-1} \right)^{1/2} - \left(t_n - t_i \right)^{1/2} \right].$$

This sum is then multiplied by the constant C to obtain the heat rate for time t_n . For example, using the tabulation below, we wish to find the heat rate when $n=5$. For time t_5 we have:

Time t_i (msec)	Slope m_i	Time Element $\left[\left(t_n - t_{i-1} \right)^{1/2} - \left(t_n - t_i \right)^{1/2} \right]$	Temperature- Time Element
1	5.75	(0.2361)	= 1.3576
2	5.00	(0.2679)	= 1.3395
3	5.25	(0.3179)	= 1.6690
4	3.75	(0.4142)	= 1.5532
5	1.00	(1.000)	= <u>1.0000</u>
			6.9193

For this temperature curve,

$$c = \frac{^{\circ}\text{C/block}}{\text{msec/block}} = 4.9164$$

and

$$C = \frac{2cK}{\sqrt{\pi\alpha}} = 0.06224.$$

Therefore, at t_5 the rate of heat transfer $q(t_5)$ is $\approx (0.06224)(6.9193)$
 $= 0.43066 \text{ cal/sq cm sec.}$

To obtain the heat input $Q(t)$, for a specific $d(\lambda)$, it is necessary to obtain the heat rate $q(t)$ for each interval over the required time. (This may be the total burning time or some smaller period within the limitations imposed by the assumptions.) The integral of the heat rate curve $q(t)$ is the required quantity, $Q(t)$, the total heat input of the rocket igniter.

DISCUSSION OF RESULTS

Test equipment and mathematical procedures used to calculate the rate and total heat-transfer data were evaluated by firing several randomly chosen igniters in the chamber after it had been assembled as a closed bomb by sealing off the nozzle section with a threaded metal cap. A comparison of the total heat thus measured with the mean standard heat-of-explosion values of similar igniters showed that there was no statistically significant difference between the data obtained by the two different methods. Once this had been established, the test chamber was fitted with standard nozzle assemblies, and additional data were obtained. In these tests the igniters were subjected to the various nozzle closure effects normally experienced in actual use. The usual ballistic characteristics

such as ignition delay, burning time, maximum pressure, and pressure-time integrals were determined from the pressure oscillograms. The rate of heat transfer and the total heat transfer from the igniter to the wall of the test chamber were calculated from the temperature oscillograms.

A summary of ballistic and heat-transfer data for one series of igniters tested is presented in Table II of the Appendix. It is evident that the ballistic characteristics of the igniters vary widely, particularly with respect to rates of pressure rise and, in the case of Rounds 3 and 5, with respect to burning time and pressure-time integrals. The large difference in the pressure-time integrals of Rounds 3 and 5 indicates that these rounds may differ in total energy output by over 150%. However, the difference between the two rounds in terms of total heat transfer is actually slightly less than 30%. The heat-transfer data for Rounds 3 and 5 also indicate that an average of 3453 calories was transferred from the igniter to the chamber. Since standard closed bomb measurements revealed that an average of 7764 calories was available from the igniters, it is apparent that 4311 calories were lost via the nozzle. Therefore, slightly over 55% of the total energy output of the igniters was actually not available to the grain for ignition. Hence, instantaneous heat-transfer measurements provide valuable data for the design of nozzle assemblies and seals which deliver the maximum quantity of energy from the igniter to the grain.

Heat-transfer data from these and other rounds also indicate that the distribution of heat energy throughout the chamber has a fairly consistent, although nonuniform, distribution pattern from round to round (even for rounds whose total heat transfer was

greatly different from Rounds 3 and 5). For example, the average percentage of the total heat input measured at Gage Stations 1, 2, and 3 respectively was 45%, 30%, and 25%. The stations were located 3.25, 14.50, and 25.75 inches distant from the blowout plug of the igniter. Typical heat-transfer curves and the resultant composite total heat transfer curve are shown in Figure 4. Data of this type are particularly useful in studying the process of ignition since it is generally conceded that the surface of the grain is raised to its ignition temperature by the energy which it receives from the reaction products of the main igniter charge. Igniter test chamber data not only show the distribution pattern of this energy but also permit its quantitative measurement quite accurately. The advantages of the test chamber's measuring both heat transfer and pressure are quite obvious.

The equipment used in this work is rugged, inexpensive, and simple to fabricate. The mathematical procedures are straightforward and can be performed by technicians using desk calculators. The Naval Propellant Plant plans to use this procedure as a routine surveillance tool. Although the present application deals only with small-caliber rocket igniters, the procedure has numerous applications in the study of propellant burning rates and can be of assistance in evaluating propellant formulations, in securing heat transfer and pressure data for motor and nozzle design studies, and in other circumstances where it is desirable to isolate and measure pressure and temperature effects simultaneously.

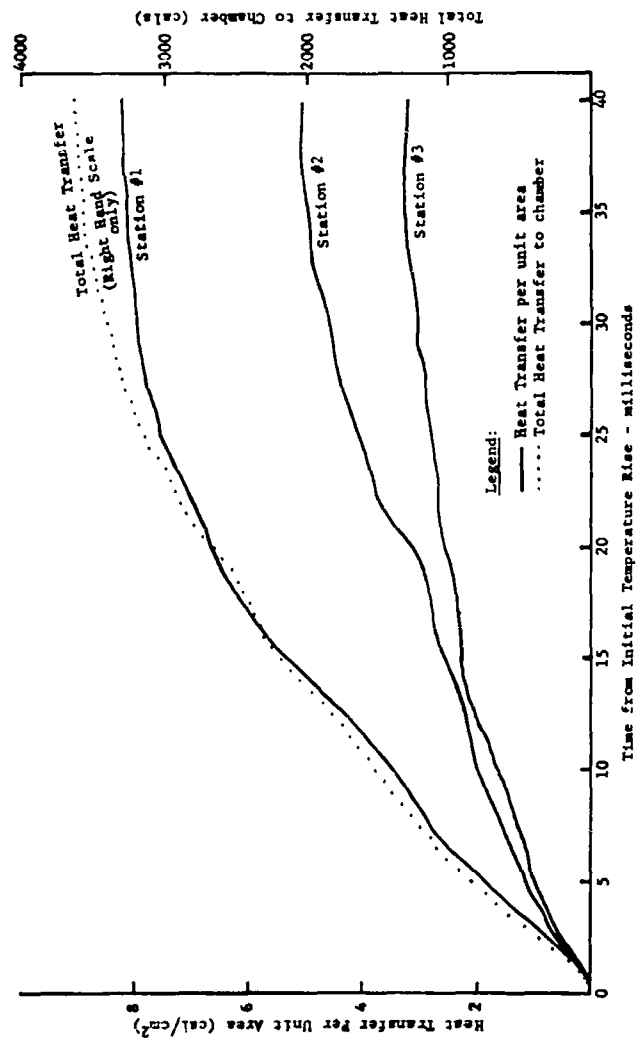


FIGURE 4. INSTANTANEOUS HEAT TRANSFER CURVES

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REFERENCE

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APPENDIX

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Table I
APPLICATION OF TEST DATA FOR ROUND 3, GAGE STATION 1

Time t_i (msec)	Graphic Slope m_i	t_i						
		1	2	3	4	5	6	7
		$t_i^{1/2}$						
1.0000		1.4142	1.7321	2.0000	2.2361	2.4495	2.6458	
$t_i^{1/2} - t_{i-1}^{1/2}$								
1.0000		0.4142	0.3179	0.2679	0.2361	0.2134	0.1963	
5.75		2.3816	1.8279	1.5404	1.3576	1.2270	1.1287	
5.00		2.0710	1.5895	1.3395	1.1805	1.0670		
5.25		2.1745	1.6690	1.4065	1.2395			
3.75		1.5532	1.1921	1.0046				
1.00		0.4142	0.3179					
3.50		1.4497						
1.75								

Table II
SUMMARY OF BALLISTIC AND HEAT TRANSFER DATA

Ballistic Parameter	Round 1			Round 2			Round 3			Round 4			Round 5		
	Gage Station			Gage Station			Gage Station			Gage Station			Gage Station		
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Ignition delay (msec)	5.72			6.03			5.84			5.87			5.42		
Burning time (sec)	>0.1050	>0.1000	>0.1000	>0.0950	>0.0950	>0.0930	0.1091	0.1026	0.1038	0.1050	0.0980	0.0940	0.0450	0.0443	0.0470
Pressure curve slope (psi/sec)	4000	6000	8000	2833	4250	5730	3800	4600	6667	2556	2727	2286	6000	8000	8000
Maximum pressure (psig)	480	490	473	380	374	354	498	515	507	440	443	431	500	489	488
Average pressure (psig)							165	176	175				161	159	150
Pressure time integral (lb sec/sq in.)							18.02	18.08	18.14				7.25	7.06	7.07
Maximum temperature (°C)	98	65	55	98	65	41	151	93	62	37	70	39	118	77	68
Propagation velocity (fps)															
$P_1 \rightarrow P_3$		1181			987			1132			924			1181	
$T_1 \rightarrow T_3$		1162			1258			1132			637			1257	
Heat transfer (cals)															
(cal/sq cm)							8.32	5.21	3.39				7.16	3.28	2.87
(cals)							1637	1336	911				1407	842	772
Total heat transfer (cals) ¹								3884							3021

¹Completion time - 40 milliseconds. Completion time taken at point where the heat transferred-versus-time curve had a slope essentially equal to zero.

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