SLAC-PUB-731
April 1970
(ACC)

AN IMPROVED TLD READER*

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(Submitted for presentation at the Second International Congress
of the International Radiation Protection Association
to be held in Brighton, U.K., 3-8 May, 1970.)

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*Work supported by the U.S. Atomic Energy Commission, Contract No. AT(04-3)515.

ABSTRACT

Several improvements have been made in a TLD reader using the Conrad readout geometry.

The major improvement is a heating system which utilizes a lead sulfide cell as a temperature sensor. The heating element is heated to a preselected temperature in 3 seconds and that temperature is maintained until readout is complete. The reader has a solid state electrometer and digital readout. Zero drift is virtually nonexistent. About 600 ^{7}LiF loose powder dosimeters have been analyzed in order to establish the readout system's optimum working conditions. For an absorbed dose of ≤0.1 rad the readout temperature is not critical as long as it is above or equal to 240°C.

For higher doses, the best precision is being achieved at a readout temperature between 280°C and 320°C. An analysis is made of the causes of the observed standard deviation (0.6% at 10^2 rad and 0.7% at 0.3 rad), including contributing errors from thermal treatment of ^{7}LiF, background variation and the readout system.

In high precision TLD work, (e.g. 0.6% S.D.), the readout system contributes a significant but not dominant error.

Teflon dosimeters are used for personnel dosimetry at SLAC. The readout cycle for them is 260°C for 15 seconds. This constant temperature cycle prevents the teflon discs from being damaged.

The objective of this study was to develop a TLD reader with the following characteristics:

1. Decreased black body radiation to facilitate the study of spurious emission from the phosphor.
2. Versatile enough to allow the use of all types of thermoluminescent dosimeters except those with built in heaters.
3. A heating cycle capable of reading teflon matrix dosimeters without damaging them.
4. Improved accuracy and speed of reading, especially at lower dose levels.

The basic geometry of the Conrad/Isotopes reader was chosen because the interchangeable planchets allow great versatility in the choice of dosimeters. After considering alternative methods of heating, we also retained the resistive heating method, using the Conrad heater transformer. Except for a few switches and small components, no other part of the Conrad TLD reader was used.

It was desired to heat the planchet as fast as possible to some preselected temperature and then hold that temperature as long as desired. This allows a short readout time, while minimizing the black body signal from the planchet. Although we did not realize it at the time, it also minimizes thermal quenching. The heating circuit was designed to be controlled by the output from a temperature sensor. A magnetic amplifier was used although an SCR circuit should be equally good. The temperature sensor is a lead sulfide cell which is placed underneath the planchet and responds to its infra-red radiation.

This arrangement works quite well. It was calibrated with a fine gauge thermocouple welded to the pan. Observations of the thermocouple output and the current through the magnetic amplifier indicated that the preset temperature was reached in 3 seconds.

The thermocouple response is shown in Figure 1. Between 3 seconds and 6 seconds there is a slow buildup of an additional 25°C, which, however, must be a response phenomenon in the thermocouple rather than indicating a change of planchet temperature.

Figure 2 shows typical glow curves for different readout temperatures.

The area under the curves is the same, and corresponds to an absorbed dose of 10 rad. The shapes of these glow curves are different from those recorded with linear heating rates.

Below 220°C the stability begins to deteriorate and the system is not usable below 180°C. We were concerned that variations in the emissivity of planchets might cause excessive temperature variations. A comparison of results obtained with 20 different planchets indicated that this was not a serious problem. A planchet with a thermocouple attached was read at different heater control settings with and without the bottom of the planchet sprayed with a flat black material. The bright planchet was heated ~50°C hotter at all settings than the blackened planchet. Since this is a much more drastic change than would ever occur in normal planchets, it is expected that in practice we would see only very slight variations in temperature.

The readout of the dosimeters is accomplished by integrating the photomultiplier current on a polystyrene capacitor and measuring the resulting voltage with an electrometer. An electrometer was built using a MOS-FET as the input device. Since the MOS-FET can be damaged or shocked if excessive voltage (>30 volts) is placed on the gate, a protective circuit was added. When full scale for the electrometer (about 500 millivolts) is reached, a reed relay disconnects the electrometer. The reading is not lost since the charge continues to collect on the integrating capacitor. By momentarily connecting a 9X larger capacitor in parallel with the integrating capacitor, its charge can be reduced by a factor of ten until the electrometer is back on scale and can be read. This operation can be performed twice without exceeding the linear range of the photomultiplier. An overload light indicates when this process is necessary. By this means 5 decades of dynamic range can be provided. TLD phosphors may have 8 or more decades dynamic range available, and these can be covered by adjusting the operating range of the reader by varying the photomultiplier high voltage.

The input MOS-FET for the electrometer need not have spectacularly high input impedance, since anything greater than about 10^{10} ohms is satisfactory. Of more importance is the noise level of the device since this can cause an apparent drift in the zero as well as the reading. We are currently using several different types of MOS-FET's including Hughes HRN 1886B and 2N2609. A second generation development of this readout system uses a commercial solid state electrometer amplifier. Typical noise specifications for transistors do not adequately characterize them for electrometer applications. The simplest solution is to select the MOS-FET by actual insertion into the electrometer circuit. With good design and construction techniques, all sources of instability in the electrometer will be caused primarily by the MOS-FET itself. Zero and reading drift have been very good with this system. There is no apparent zero drift caused by overload signals. MOS-FET's are quite susceptible to transients and care should be taken in wiring the circuit to avoid ground loops, pickup, etc.

The readout of the electrometer-amplifier is accomplished by use of a digital voltmeter. There are several inexpensive digital voltmeters on the market that are suitable. We have had good results from both the Fairchild Model 7050 and the Time Systems Corp Model 710. Other similar voltmeters would, no doubt, be equally satisfactory.

Provisions have been made for using either a built-in clock timer or an external electronic timer. The simple clock timers have an inherent inaccuracy in their timing which may be $\frac{1}{2}$ - 1%. This is more than adequate for reading dosimeters since there is virtually no light emitted during the last fraction of a second. It does introduce an error when reading a light source for calibration or diagnostic purposes, however. The reader with an electronic timer is capable of reading a light source (Conrad LSA) with a Standard Deviation of ± 0.1% or better.[1] With the light source currently used (a "filtered" Conrad LSA) we more typically achieve a Standard Deviation of ± 0.2%.

The reader as described is known as the SLAC Mark VI TLD reader.

Performance

The precision that can be achieved in LiF dosimetry work is dependent on many factors of which four main groups can be distinguished:

1. Uniform and reproducible positioning on the heating element.
2. Performance of the readout system.
3. Background contribution in the low dose region.
4. Thermal history of the dosimeters.

By using the described readout system, we have studied the precision (expressed as relative standard deviation of a single reading) as a function of readout temperature over a wide absorbed dose range.

The annealing before irradiation consists of one hour at 350°C (300°C for teflon dosimeters) and 22 hours at 80°C. A precision oven has been used with a high degree of long-term stability and a temperature uniformity of ± 2%. To achieve a reproducible cooling rate the dosimeters are kept inside the oven when being cooled from 350°C to 80°C and from 80°C to room temperature. Just before reading out irradiated dosimeters they are annealed for 10 minutes at 90°C. This procedure has proved to be especially valuable when working with low dosed teflon discs. Teflon discs that have been exposed to light exhibit a significant TL signal, which, however, is annealed out at 90°C. The results from Carlsson[2] and Martensson[3] indicate that this is not the optimum heating procedure for best precision. For routine use, however, this is the most practical way for us to achieve a reproducible annealing cycle. Reproducible thermal treatment is very important in order to retain the sensitivity in repeated use of LiF dosimeters.

The majority of the dosimeters used in this study were ^{7}LiF loose powder (Harshaw) dispensed in such a way that the average weight is about 29 mg. However, the light output from each dosimeter was normalized to its actual weight which was determined by using a precision balance. The weighing error (0.06% standard deviation in 10 measurements of one sample) is negligible when being propagated with other statistical errors. Each data point is based on 20 powder dosimeters and special care has been taken to level the powder uniformly on the D-20 Conrad planchet.

The first objective was to determine a suitable combination of planchet temperature setting and readout time. The readout time was always determined by means of recording glow curves (see Figure 2). Figure 3 shows the results of 10 sec readouts at different planchet temperatures. The dosimeters were dosed to about 10 rad. The plateau obtained shows that apparently the choice of planchet temperature above 220 C is not critical in order to release the TL signal. However, the criterion of releasing the TL signal is not in itself decisive enough to use in the determination of an optimal readout cycle. Figure 4 shows the relative standard deviation of a single observation as a function of readout temperature. It is clear from this figure that the precision for an absorbed dose of more than 1 rad will be better at higher temperatures. For a dose of 0.1 rad this effect is not seen in our data. For lower doses we therefore pick an optimum readout temperature between 240°C and 280°C and for higher doses a temperature between 280°C and 320°C.

The larger standard deviation at 0.1 rad is not due to variations in the subtracted background; in fact, the error in the background contributes to the total standard deviation by only 10%. It is therefore, likely that the increased standard deviation for lower doses is an inherent dosimetric property of LiF. A calculation based on the model described by Cameron[4] of the number of traps filled at 0.1 rad, gives $1.3\ 10^9$ traps/cm^3. For 29 mg LiF, this corresponds to about $2.6\ 10^7$ traps. For a complete readout cycle, one would, therefore, expect the relative standard deviation of this average to be only about

$$\sqrt{\frac{1}{2.6 \times 10^7}} = 2 \times 10^{-4} \quad \text{or} \quad 0.02\%.$$

For doses $\geq 10^4$ rad it is also important to have a high enough readout temperature (e.g. 280°C) in order to empty the higher temperature traps. This is illustrated in Figure 5 where the normalized light output is plotted as a function of absorbed dose. At this dose level, the curve corresponding to 240°C readout temperature is significantly lower (about 9%) than the two others.

An attempt has been made, in two cases, to analyze the factors mentioned earlier that may contribute to the observed standard deviation.

<u>Case I</u>

In this case, we used the data point in Figure 4 corresponding to 280°C and 10^2 rad. The average of 20 dosimeters is $16.78\ \frac{\text{digit}}{\text{mg}}$, with one standard deviation equal to $\pm\ 0.10\ \frac{\text{digit}}{\text{mg}}$ or 0.60%. The individually weighed dosimeters are about 29 mg each and the digital readout, therefore, reads about 487 ± 2.9 digits. The various contributions to the standard deviation are as follows:

1. Uniform and reproducible positioning on the heating element.

Special care has been taken to level the loose powder. Comparisons have been done with both 10 mg and 29 mg dosimeters; both sizes are small enough to give only one layer of LiF grains on the D-20 planchet. The measurements do not indicate that any significant error can be attributed to this point. This also means that incomplete mixing of the powder has negligible effects.

2. Performance of the readout system has been studied by using a light source with an inherent statistical accuracy of about 0.02%. Under the same conditions as the dosimeters were read out, the light source gave an integrator accuracy of ± 0.28%. With 487 digits in the digital readout this means ± 1.4 digits

3. At 10^2 rad, the background contributes less than 0.01% (10 mrad) and has not been taken into account.

4. The influence of thermal treatment on the precision has been dealt with in accordance with Martensson's[3] analysis. His data indicates that our pre-annealing procedure would contribute about ± 0.4% at this dose level. This gives ± 1.9 digits

The expected standard deviation from these causes is =

$$\sqrt{(1.9)^2 + (1.4)^2} = 2.4 \text{ digits}$$

The observed data give a standard deviation of 2.9 digits.

Case II

This set of data consist of 20 loose powder dosimeters dosed to 0.3 rad. These dosimeters were dispensed, and not weighed, by using a dispenser with a vibrator attached. It can dispense ~30 mg loose powder dosimeters with a standard deviation of ± 0.3%.

The average number of digits displayed on the readout for the 0.3 rad dosimeters are 1323 digits with a standard deviation of ± 9.2 digits (± 0.7%).

The same analysis as above gives:

1. Dispensing inaccuracy = ± 0.3% ± 4.0 digits

2. Performance of the readout system determined by using the light source under the same readout conditions as the dosimeters = ± 0.19% ± 2.5 digits

3. Background contribution is now significant. The standard deviation in the reading due

to background only is ± 6.7% of the average background. ± 2.1 digits

4. There are no data available on how to evaluate the importance of thermal treatment for this dose (0.3 rad). Based on the earlier discussion about the increased statistical inaccuracy for lower doses being an inherent dosimetric property of LiF, we would expect this contribution to be slightly higher than in the case above.

Expected standard deviation based on 1 to 3 =

$$\sqrt{(4.0)^2 + (2.5)^2 + (2.1)^2} = 5.2 \text{ digits}$$

The observed standard deviation was ± 9.2 digits.

If point 4 is the additional source of independent error it would have to contribute with a standard deviation of

$$\sqrt{(9.2)^2 - (5.2)^2} = 7.6 \text{ digits or } 0.57\% .$$

In accordance with our earlier discussions this number seems to be a very reasonable contribution from our pre-annealing procedure.

The difference between the observed and expected standard deviation in Case I corresponds to an independent statistical error of ± 1.6 digits. One possible contribution to this error can be short-term drift in the photomultiplier gain due to the readout process, e.g. heating effects. There may also be some unknown contribution. Of course, this will also affect the conclusion about Case II.

Drift of the electrometer-amplifier-voltmeter combination was measured to be 6 digits out of 1500 over a period of 16 hours. Of these 6 digits, 4 were due to zero drift and 2 due to other sources including the constancy of the input voltage. The drift was slow and steady over this period so it does not appear to be a significant factor.

The implication of this analysis is that whenever LiF dosimetry is being used in high precision relative measurements (e.g. relative spatial distribution of absorbed dose), this TLD reader makes a significant but not dominating contribution to the total error.

In addition to loose powder, we also use many other forms of LiF dosimeters, e.g. teflon matrices and extruded materials. The same high precision cannot be achieved when using these materials, due to nonuniformity within a batch of dosimeters. In such a case, the error contribution from the readout system itself will become unimportant. ^{7}LiF teflon discs (0.4 mm thick; type Conrad) are being used as personnel dosimeters at SLAC. This means that we may cycle more than 1000 per month through the TLD reader. The technician usually operating this reader routinely reads teflon disc dosimeters at a rate of 100/hour. The Mark VI TLD reader has proved especially good for teflon dosimeters. With other readers we were never able to get complete readout without occasionally damaging the dosimeters by overheating. This problem is completely overcome by this heating cycle. A readout temperature of 260°C is being used and Figure 6 shows the integrated light output as a function of readout time.

Each point is the average of several readings. From these data, 15 seconds was chosen as our standard readout time for the teflon disc. It should be noted that these readouts were made with the planchet shown in Figure 7, rather than the standard Conrad disc planchet. It is made from Conrad planchet material (nichrome) with two beryllium copper springs spot welded on. These provide much better thermal contact for the disc and are reusable indefinitely.

Harshaw extruded rods are also used frequently at SLAC. These are LiF (TLD-700) 1 mm diameter by 6 mm long. These are not the new "High Sensitivity" material and are read in the planchet shown in Figure 8. This is a slightly modified Conrad HER planchet (not the current RHE planchet) for teflon rod dosimeters. The current Harshaw rods are more uniform in diameter than these we are using and may fit the Conrad HER planchet without modification. A heating time of 10 seconds at 275°C is used. For Harshaw extruded ribbons (1/8" x 1/8"), a Conrad D-20 planchet is used at 260°C for 15 seconds.

Another solution for heating extruded rod dosimeters is to use a Conrad type RHE planchet with the extruded rod lying on top of the two small bars welded to the planchet. The rods are too rigid to press between these bars as is done for the teflon micro-rods. Some care must be taken in inserting the planchet so that the rods are knocked off but this is not difficult.

Table I lists some characteristics of various LiF dosimeters as measured with the Mark VI TLD reader. The third column contains specifications taken from the manufacturer's literature regarding the uniformity of dosimeters. As has been pointed out before, it is apparent from Table I that the best reproducibility can be obtained with loose powder. The data in Table I were taken with two different Mark VI readers but their performances are nearly identical. The last column of the table is the signal obtained by reading an undosed dosimeter. In all cases, the readout was accomplished in a nitrogen atmosphere. The extruded ribbon data are scanty since we have only a few of these and seldom use them.

We were also interested in the effect of temperature quenching with this type of heating cycle. The results of Gorbics, et al[5] are not applicable since their measurements were all made with a linear heating rate. We made a series of measurements using loose powder TLD-700 at various readout temperatures. The results are shown in Table II. At each temperature either 10 or 20 measurements were made and the results averaged. It appears that over this temperature range, thermal quenching in TLD-700 is not very important with this heating cycle.

ACKNOWLEDGEMENT - The skill and diligence of Miss Deborah Peckham and Mr. Thomas Ginn in performing many of the tests is greatly appreciated.

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TABLE I

Performance of LiF Dosimeters With SLAC Mark VI Reader (%S.D.)

Dosimeter	Relative Light Output	Uniformity According to Manufacturer (%S.D.)	100 mrad	300 mrad	1 rad	10 rad	Total Background (mrad)
Loose Powder (30 mg TLD-700)	13.5	---	1.6 1.8+	1.0 0.8**	0.85 0.70** 0.75+	1.3 0.85** 0.60+	7.9 ± 0.5
Conrad Teflon Discs (13 mm x 0.4 mm)	8.9	3	11.8	11.3	3.9	4.7	15 ± 1.4
Harshaw Extruded Rods (1 mm x 6 mm)	1.0	2-4*	4.1	3.8	2.6	3.1	45 ± 1.3
Harshaw Extruded Ribbon (1/8" x 1/8" x 0.35")	11.7	2-4*	3.0	---	---	2.7‡	---

* Within a single batch.

** Extra care taken to level powder sample.

\+ Extra care taken to level powder sample.
Individual weighing of samples.

‡ Taken at 5 rad.

TABLE II

THERMAL QUENCHING EFFECTS

Readout Temperatures (°C)	Relative Integrated Light Output
220	0.96
240	1.00
260	0.97
280	0.95

FIGURE CAPTIONS

Figure 1 - Thermocouple response during a readout cycle of 15 seconds on the SLAC Mark VI. The thermocouple was welded to a Conrad D-20 planchet.

Figure 2 - Glow curves recorded for different readout temperatures with the SLAC Mark VI readout cycle. The area under the curves is the same and corresponds to an absorbed dose of 10 rad.

Figure 3 - Integrated light signal for different temperatures during 10 second readout cycle. The data are taken for ^{7}LiF loose powder dosimeters and each point consists of several measurements. The crosses and circles are data taken several months apart.

Figure 4 - The relative standard deviation of a single observation as a function of readout temperature. Each point is calculated from measurements of 20 loose powder dosimeters. Glow curves were recorded to assure that the TL signal was completely released.

Figure 5 - Sensitivity of ^{7}LiF loose powder dosimeters as a function of absorbed dose and readout temperature.

Figure 6 - Integrated light signal for different readout times. Teflon dosimeters were used and the readout temperature was 260°C.

Figure 7 - Nichrome heating element with Be-Cu clips, being used for ^{7}LiF teflon discs.

Figure 8 - Modified Conrad HER Nichrome heating element being used for ^{7}LiF extruded rods.

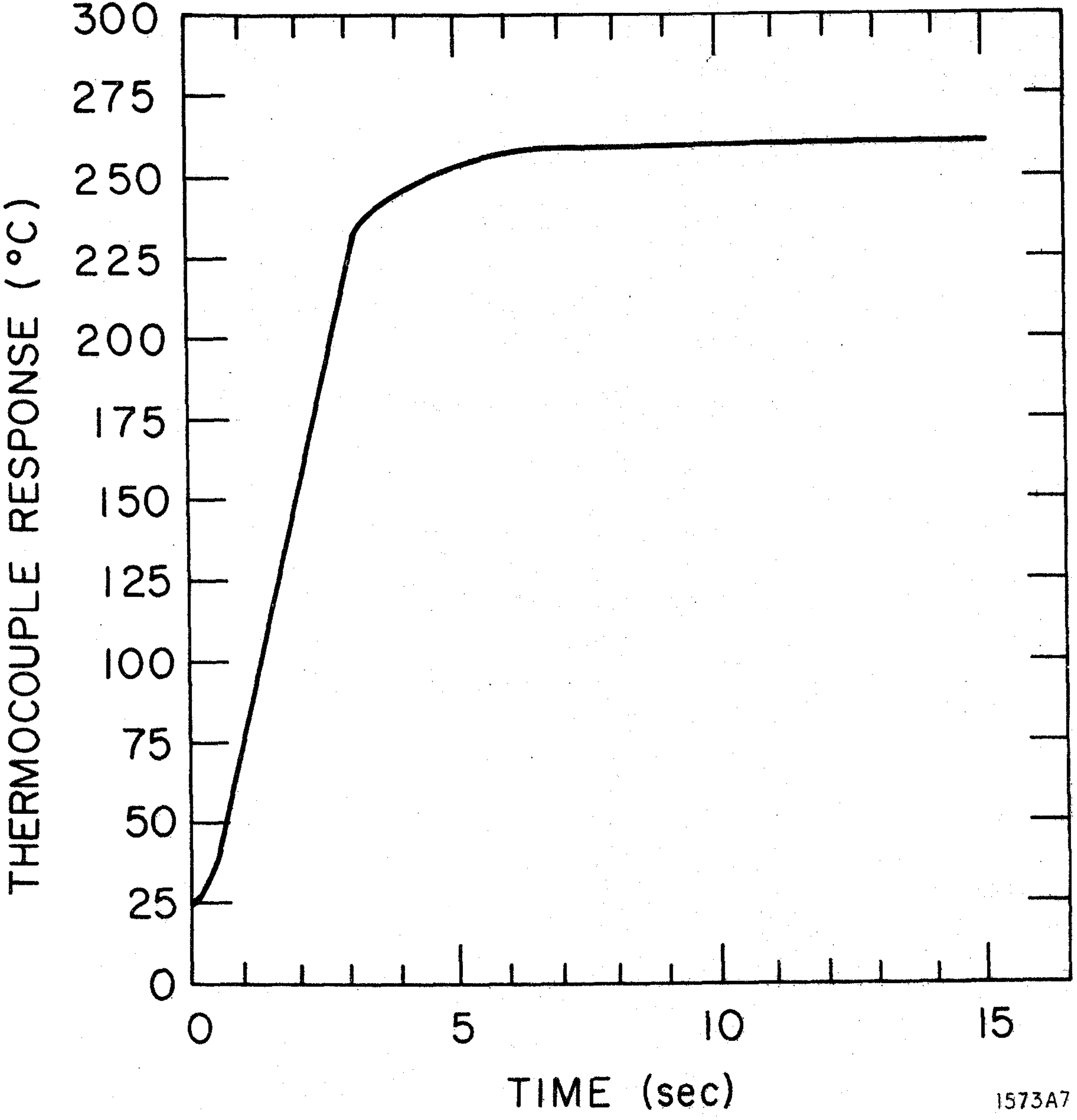
THERMOCOUPLE RESPONSE (°C)
300
275
250
225
200
175
150
125
100
75
50
25
0
0
5
10
15
TIME (sec)
1573A7

Fig. 1

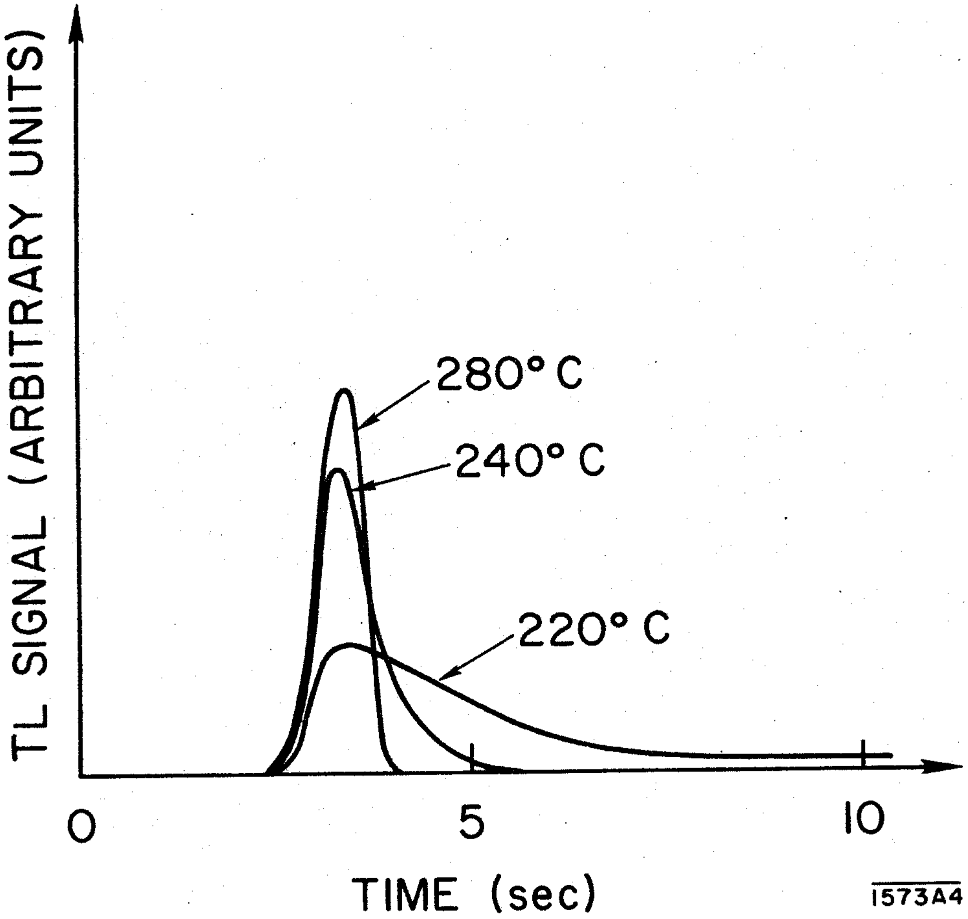
TL SIGNAL (ARBITRARY UNITS)
280° C
240° C
220° C
0
5
10
TIME (sec)
1573A4

Fig. 2

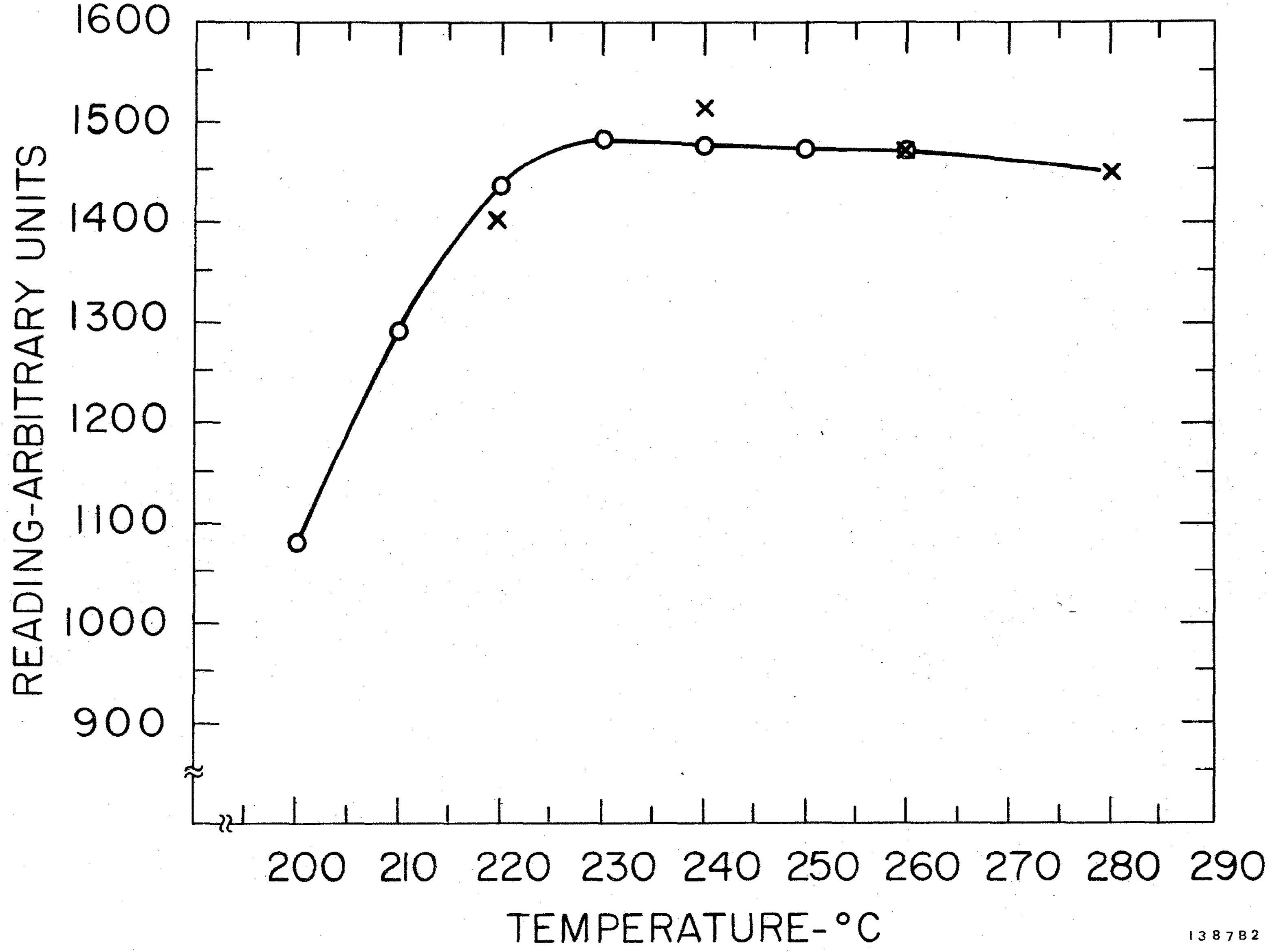
1600
1500
1400
1300
1200
1100
1000
900
READING-ARBITRARY UNITS
200
210
220
230
240
250
260
270
280
290
TEMPERATURE-°C
138782

Fig. 3

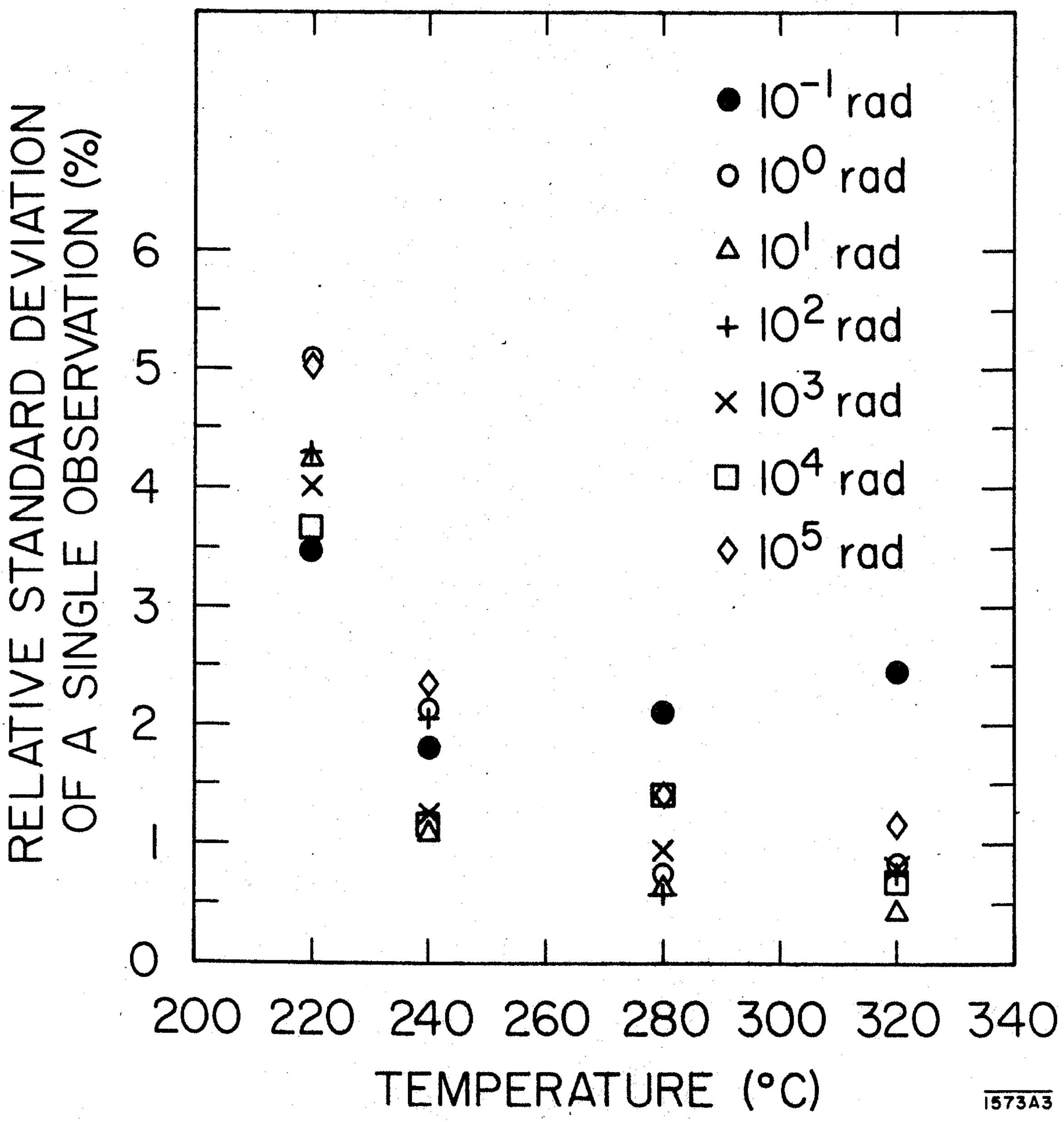
RELATIVE STANDARD DEVIATION OF A SINGLE OBSERVATION (%)
0
1
2
3
4
5
6
200
220
240
260
280
300
320
340
TEMPERATURE (°C)
● 10^{-1} rad
○ 10^{0} rad
△ 10^{1} rad
+ 10^{2} rad
× 10^{3} rad
□ 10^{4} rad
◇ 10^{5} rad
1573A3

Fig. 4

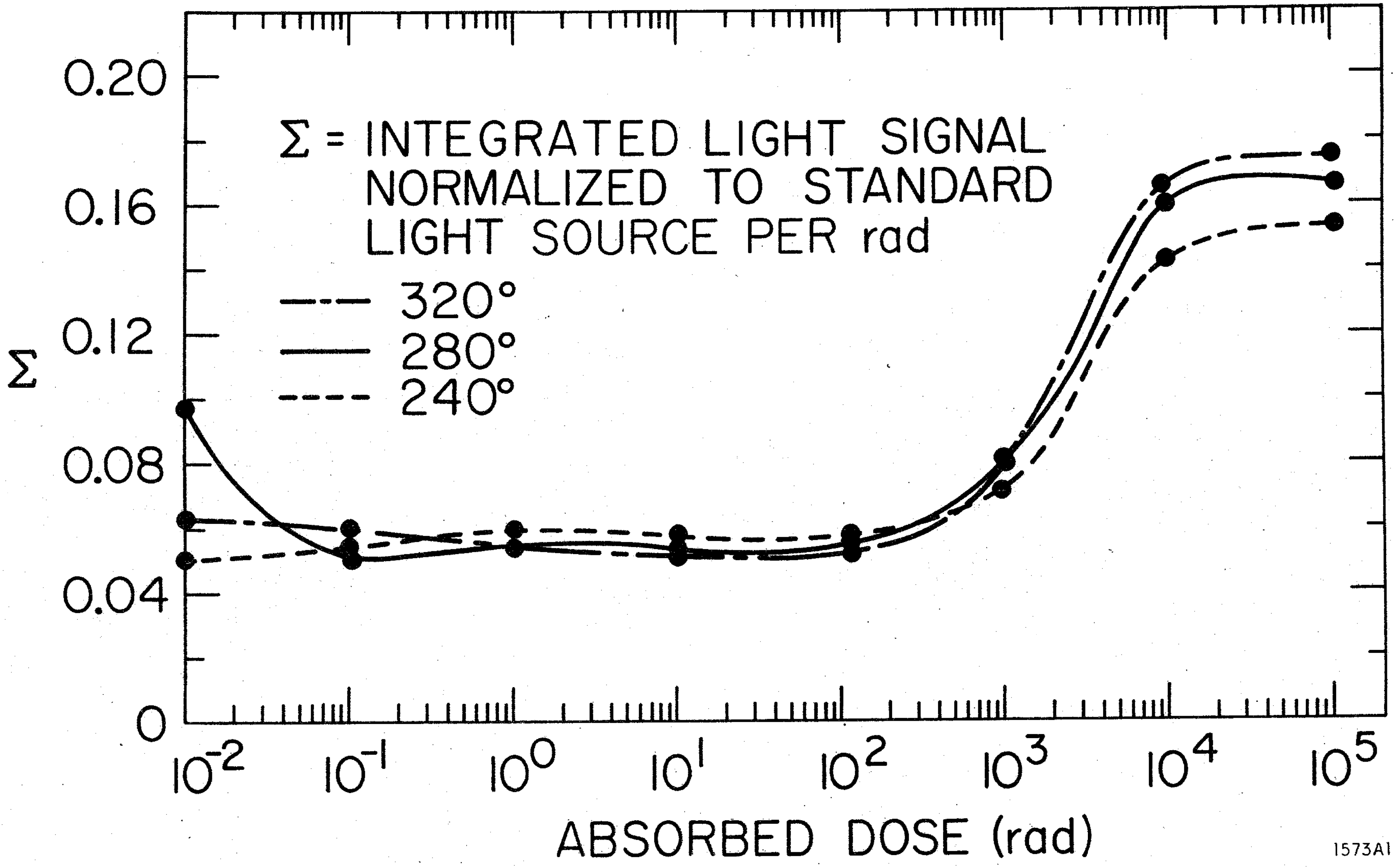
Σ = INTEGRATED LIGHT SIGNAL NORMALIZED TO STANDARD LIGHT SOURCE PER rad
320°
280°
240°
Σ
0.20
0.16
0.12
0.08
0.04
0
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
ABSORBED DOSE (rad)
1573A1

Fig. 5

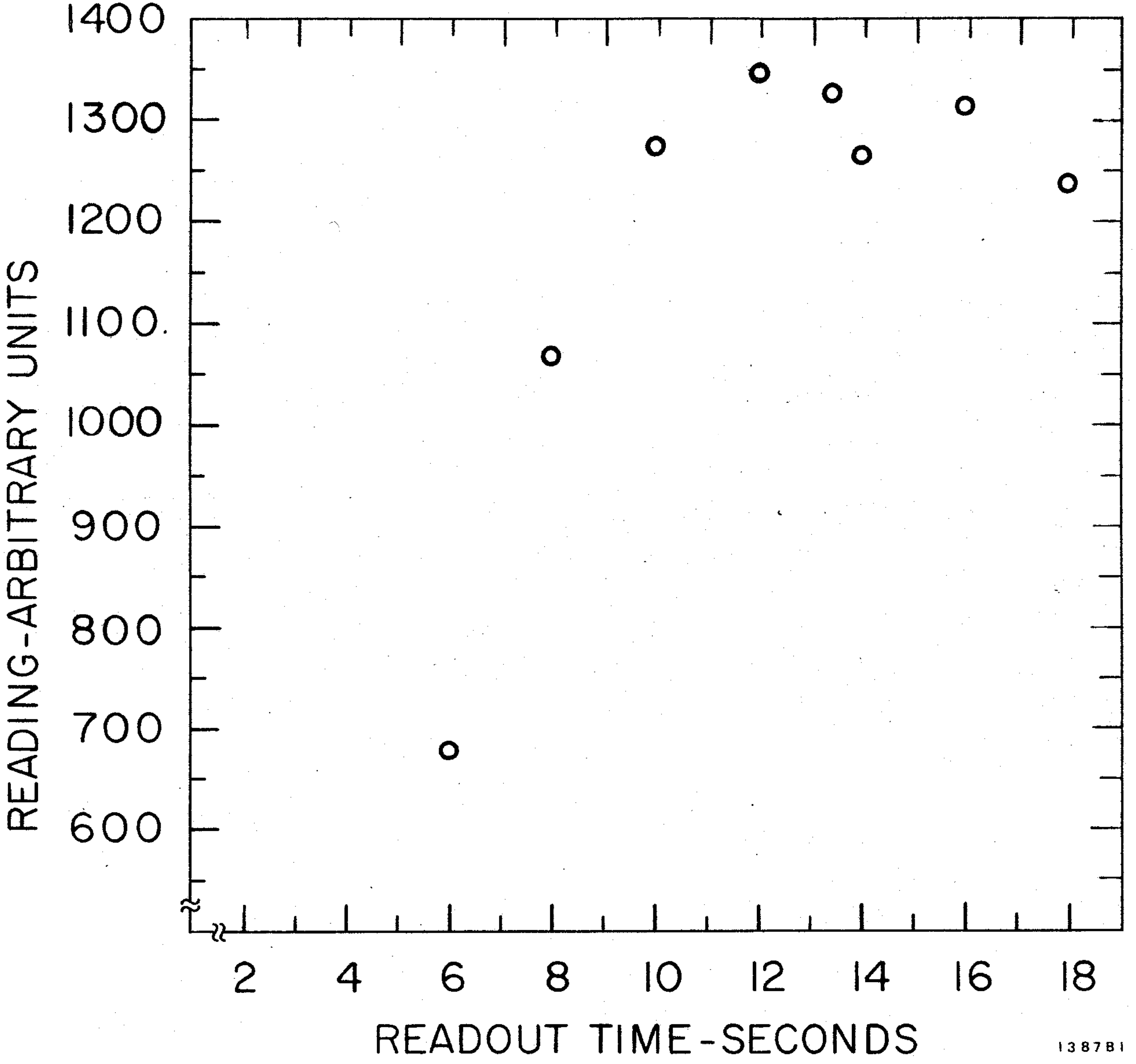
1400
1300
1200
1100
1000
900
800
700
600
READING-ARBITRARY UNITS
2
4
6
8
10
12
14
16
18
READOUT TIME-SECONDS
138781

Fig. 6

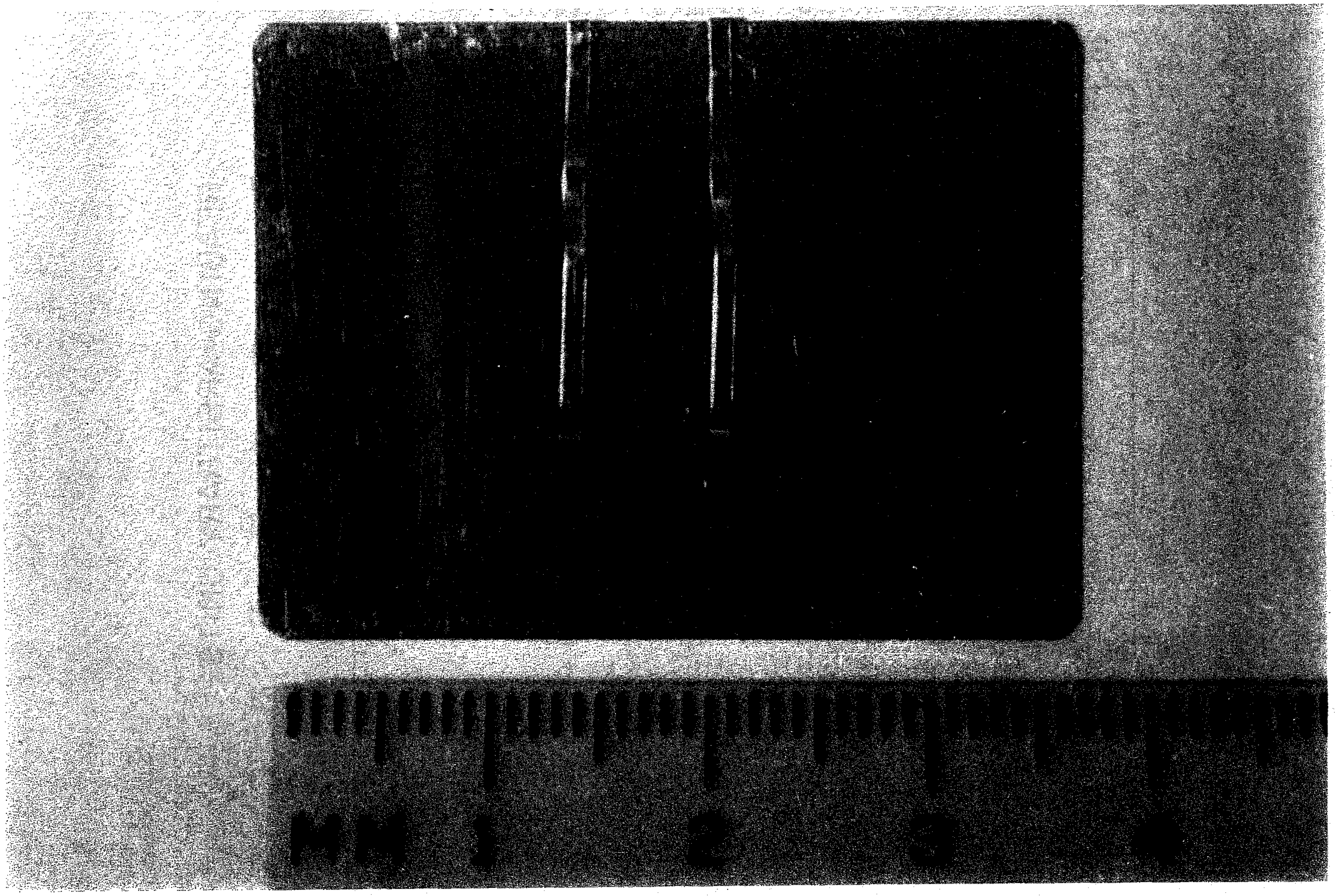

Fig. 7

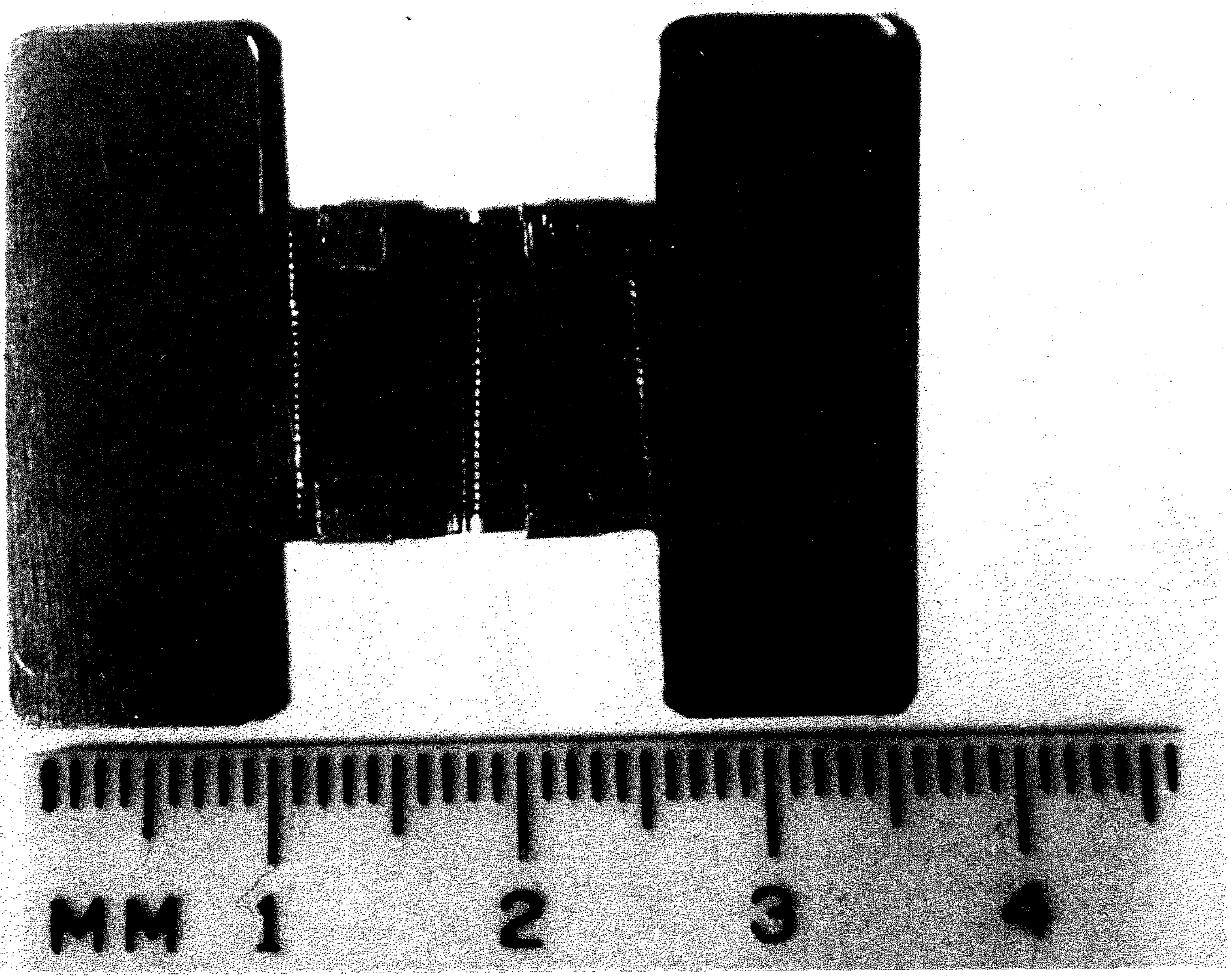

Fig. 8