08:47:11	OCA PAD AME	NDMENT - PRO	DJECT HEADER	INFORMATIO	07/07/	94
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Center # : 10/24-6	-R7796-DA0	Center shr	#:		OCA file #:	
					Work type : RES	
Contract#: DE-FG05	-93ER75879		Mod #: M001		Document : GRANT	•
Prime #:					Contract entity:	GTRC
Subprojects ? : N					CFDA: 81.049	
Main project <b>#</b> :					PE #: N/A	
Project unit:	ME	CH ENGR	Unit code: 0	2.010.126		
Project director(s	):					
WANG C K	ME	CH ENGR	(404)894-371	.9		
			14. · · · · ·			
Sponsor/division n	ames: US DEP	T OF ENERGY		/ DOE OAK	RIDGE - TN	
Sponsor/division c	odes: 141			/ 017		

Sponsor/division codes: 141

to

Total to date

150,000.00

150,000.00

0.00

950430 (performance) 950731 (reports)

Sponsor amount New this change Contract value 0.00 0.00 Funded Cost sharing amount

930415

Does subcontracting plan apply ?: N

Award period:

Title: MIXED FIELD DOSIMETRY USING...LASER HEATING OF THERMOLUMINESCENT MATERIALS

#### PROJECT ADMINISTRATION DATA

OCA contact: E. Faith Gleason	8	94-4820
Sponsor technical contact		Sponsor issuing office
LARRY BAKER		MAURICE A. DAVIS
(202)586-8947		(615)576-7599
U.S. DEPARTMENT OF ENERGY 1000 INDEPENDENCE AVE., N.W. WASHINGTON, D.C. 20585	·	U.S. DEPARTMENT OF ENERGY DOE OAK RIDGE FIELD OFFICE SPECIAL ACQUISITIONS BRANCH, AD-42 P.O. BOX 2001 OAK RIDGE, TN 37831-8757
Security class (U,C,S,TS) : U Defense priority rating : Equipment title vests with:	Sponsor	ONR resident rep. is ACO (Y/N): N DOE supplemental sheet GIT X

Administrative comments -AMENDMENT MOO1 AUTHORIZES: 1) ONE-YEAR EXTENSION; 2) CHANGE IN PI; AND 3) APPROVAL TO SUBCONTRACT W/UNIVERSITY OF MICHIGAN. (NO NEW FUNDING.)

#### GEORGIA INSTITUTE OF TECHNOLOGY OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT

C1	oseout Notice Date 07/28/95
Project No. E-25-W04	Center No. 10/24-6-R7796-DAG
Project Director WANG C K	School/Lab MECH ENGR
Sponsor US DEPT OF ENERGY/DOE OAK RIDGE - TN	
Contract/Grant No. DE-FG05-93ER75879	_ Contract Entity GTRC
Prime Contract No	_
Title MIXED FIELD DOSIMETRY USINGLASER HEATING	G OF THERMOLUMINESCENT MATERIAL
Effective Completion Date 950430 (Performance) 9	50731 (Reports)
Closeout Actions Required:	Date Y/N Submitted
Final Invoice or Copy of Final Invoice	Y
Final Report of Inventions and/or Subcontrac	ts Y
Government Property Inventory & Related Cert:	ificate N
Classified Material Certificate	· · · · · · · · · · · · · · · · · · ·
Other	N
Comments	
**NOTE** USE DOE FORM FOR PATENT	
Subproject Under Main Project No	_
Continues Project No	
Distribution Required:	
Project Director	Y
Administrative Network Representative	Y
GTRI Accounting/Grants and Contracts	Y
Procurement/Supply Services	Y
Research Property Managment	Y
Research Security Services	N
Reports Coordinator (OCA)	Y
GTRC	Y
Project File	Y

NOTE: Final Patent Questionnaire sent to PDPI.

B

(150 characters including spaces)	Mixed Field Dosimetry Heating of Thermolumin	Using Focus escent Mate	sed and Unfocused Laser erials
2. CONTRACT or grant number <u>DE-FG05-93 EA</u>	3.	Performing or number (inter	ganization CONTROL mal)
(GOCO's)	3A	. Budget and F	Reporting code
2B. Responsible PATENT office	ЗВ	Funding YEA 1992	AR for this award
<ul> <li>4. Original contract start date <u>April</u></li> <li>4A. Current contract start date <u>April</u></li> </ul>	<u>15, 1992</u> <u>15, 1992</u> 40	Current cont Anticipated p date	ract close date <u>4/14/94</u> project termination 4/94
5. Work STATUS Proposed Renewal New Terminated	58 5C	. CONGRESSI . STATE or Co performed	IONAL district <u>5</u> <sup>th</sup> buntry where work is being <b>CEORGIA</b> , USA
<ol> <li>Name of PERFORMING organization</li> <li>6A. DEPARTMENT or DIVISION</li> </ol>	Georgia Tech Resear 6B. Street Address	ch Corporat	6C. City, State, Zip Code
	Centennial Research Room 246	h Building	Atlanta, GA 30332
<ul> <li>CU- College, university, or trad</li> <li>FF - Federally funded RD&amp;D construction</li> <li>Government</li> <li>IN - Private industry</li> <li>NP - Foundation or laboratory in</li> <li>ST - Regional, state or local governation</li> <li>TA - Trade or professional organities</li> <li>US - Federal agency</li> <li>XX - Other</li> <li>EG - Electric or gas utility</li> </ul>	e school enters or laboratory operated fo not operated for profit vernment facility nization	or an agency of	the U. S.
8A. Contractor's PRINCIPAL INVESTIG Name/s (Last, First, MI) <u>Kearfo</u>	ATOR/s or project manager ott, Kimberlee J.		-
8B. PHONE/s (in order of PI names with co	ommercial followed by FTS)		

YA.	(full name)	1	Program Office Code
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10.	FUNDING in thousands of dollars (KS). Funds re and capital equipment (FY runs October 1 – Sep	epresent budget obligations for ope otember 30).	erating
	Funding organization(s)	Current FY 99	Next FY
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	Funding organization(s) A. DOE B. C.	Current FY <u>9</u> \$ 150,000	Next FY

 Descriptive SUMMARY of work. Enter a Project Summary using complete sentences limited to 200 words covering the following: Objective(s), state project objectives quantifying where possible (e.g., "The project objective is to demonstrate 95% recovery of sulfur from raw gas with molten salt recycling at a rate of one gallon per minute."); approach, describe the technical approach used (how the work is to be done); expected product/results, describe the final products or results expected from the project and their importance and relevance.

The <u>long-term objective</u> of the proposed research is to develop a unique dosimetry system capable of accurate mixed beta/gamma dosimetry and meaningful shallow/deep dose discrimination using a single-element thermoluminescent detector (TLD) and focused laser readout. The rapid superficial heating of a thick TLD will result in release of the signal due to shallow dose, which will then be followed by the release of the signal due to the deep dose as the deeper portions of the TLD are heated to TL temperatures. Careful analysis of the signal as a function of time should allow quantitative discrimination of the radiation field type. The <u>immediate project objective</u> is to evaluate theoretically the feasibility of laser heating for extracting depth-dose information. The <u>approach</u> will be to use computer models of heat transfer, thermoluminescence and radiation transport to predict TL signal as a function of time (glow curves for different radiation fields, thermoluminescent materials, and heating schemes). An error analysis on these curves will then be completed. The <u>expected results</u> will be 1) an estimate of the anticipated precision of the novel approach for extracting depth dose information and 2) an optimal design of TL detector and spatial/temporal heating scheme.

information you have to complete full bibliographic citation.) Use the back of this form or additional sheets if necessary.

No publications at present (6 months completed to date).

•	KEYWORDS (Listed five terms describing the tech applicable.)	inical aspects of	f the project. List specific cho	emicals and CAS number, if
	radiation			
	dosimetry			
	thermoluminescence			
	radiation detector			
	health physics			
-	RESPONDENT. Name and address of person fillin	a out the Form	538. Give telephone number	, including extension (if vo
	have FTS number, please include it) at which pers	on can be react	hed. Record the date this form	n was completed or update
	The information in Item 14 will not be published.			
	Respondent's Name:		Phone No.:	Date:
	Street:			

Item No.		
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Energy, Office of Scientific and Technical Information, P. O. Box 62, Oak Ridge, TN 37831.

Georgia Tech

E-25-W04 W/a

Office of Grants and Contracts Accounting

**Georgia Institute of Technology** 190 Bobby Dodd Way Atlanta, Georgia 30332-0259 USA 404 • 894 • 4624: 2629 Fax: 404 • 894 • 5519

June 6, 1995

Mr. Maurice Davis, Contract Specialist U. S. Department of Energy **DOE Oak Ridge Field Office** Special Acquisitions Branch, AD-422 Procurement and Contracts Division P. O. Box 2001 Oak Ridge, TN 37831-8757

REFERENCE: Grant #DE-FG05-93ER75879

Dear Mr. Davis,

Enclosed is the original plus (3) copies of the Financial Status Report (SF-269A) for Grant Number DE-FG05-93ER75879 covering the period April 15, 1994 through April 30, 1995.

If you should have questions or need additional information, please contact Geraldine Reese of this office at (404) 894-2629.

Sincerely,

David V. Welch Director

DVW/GMR/djt

Enclosures

Dr. W. O. Winer, ME - 0405 C: Dr. Chris Wang, ME - 0405 Ms. Wanda Simon, OCA/CSD 0420 File: E-25-W04/R7796-0A0

*		FINAN (Foll	CIAL STAT (Short Fo	US REPORT				
1. Federal Age to Which U. S. DEP	ency and Organizational Element Report is Submitted	nt 2.   I	2. Federal Grant or Other Identifying Number By Federal Agency DE-FG05-93ER75879			d OMB Approval Page No. 0348-0039 1		of 2 pages
3. Recipient O GEORGIA 400 101 ATLANTA	rganization (Name and complet A TECH RESEARCH COR CH STREET, N.W R A. GA 30332-0415	te address, includi PORATION COM 270	ng ZIP code)					
4. Employer Id 58-0603	entification Number	5. Recipient Act E-25-W04/	count Number of /R7796-0A0	r Identifying Numbe	6. Final Rep	ort I No	7. Basis	Accrual
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Expense	b. Rate See Attached	c. Base	MTDC	d. Total A 15,2	mount 67.63	e. Fee	deral Share 5,267.63	
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Signature of Au	thorized Certifying Official				Date Repo	t Submitter	d 95	
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Prescribed by 10 Attachment page 2 of 2

U. S. Department of Energy Financial Status Report (E-25-W04/R7796-0A0) 06/06/95 Grant No. DE-FG05-93ER75879 Period Covering: 04/15/94 - 04/30/95

	Direct Costs	Indirect Costs		
FY' 93 @ 44.9%	\$ 85.00	\$ 38.17		
FY' 94 @ 37.0%	38,349.46	14,189.31		
FY' 95 @ 40.0%	83,374.45 <sup>(1)</sup>	13,826.18		

<sup>(1)</sup> \$48,809.00 Subcontract costs excluded from Indirect Costs

REPORT PERIOD

	Direct Costs	Indirect Costs
04/15/94 - 06/30/94	\$ 3,895.81	\$ 1,441.45
07/01/94 - 04/30/95	83,374.45	13,826.18

E-25-WO4

Office of Grants and Contracts Accounting

Georgia Institute of Technology 190 Bobby Dodd Way Atlanta, Georgia 30332-0259 USA 404•894•4624; 2629 Fax: 404•894•5519

Na

June 13, 1994

Ms. Melissa Y. Johnson, Contract Specialist U. S. Department of Energy DOE Oak Ridge Field Office Special Acquisitions Branch, AD-422 Procurement and Contracts Division P. O. Box 2001 Oak Ridge, TN 37831-8757

REFERENCE: Grant # DE-FG05-93ER75879

A 1

Dear Ms. Johnson,

Enclosed is the original plus (3) copies of the Financial Status Report (SF-269A) for Grant Number DE-FG05-93ER75879 covering the period April 15, 1993 to April 14, 1994.

If you should have questions or need additional information, please contact Geraldine Reese of this office at (404) 894-2629.

Sincerely,

David V. Welch Director

DVW/GMR/djt

Enclosures

c: Dr. W. O. Winer, Mech. Eng. 0405 Dr. Chris Wang, Mech. Eng. 0405 Ms. Wanda Simon, OCA/CSD 0420 File: E-25-W04/R7796-0A0

	*	FIN	ANCIAL STAT (Short Follow instruction	TUS RE form) s on the ba	PORT					
1. Federal Ag to Which	ency and Organizational Element n Report is Submitted	nt	2. Federal Grant or Other Identifying Number Assigned By Federal Agency DE-FG05-93ER75879			ber Assigned	OMB Approval P No. 0348-0039		ge of	
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4. Employer lo 58-0603	Ventification Number	5. Recipient E-25-WC	Account Number	or Identifying	g Number	6. Final Repo	EX No	7. Basis		
8. Funding/Gra From: (Mon April 15	ant Period (See Instructions) nth, Day, Year) 5, 1993	To: (Month, April 1	Day, Year) .4, 1994	9. Perio From Apri	d Covered (Month, 1 15, 1	by this Repor Day, Year) 993	To: Apr	(Month, 1 i1 14,	D <b>ay. Year)</b> 1994	
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d. Total u	inliquidated obligations							4,	908.49	
e. Recipie	ent share of unliquidated obligati	ions							-0-	
f. Federa	I share of unliquidated obligation	ns						4,	908.49	
g. Total F	ederal share (Sum of lines c a	ind f)							233.17	
h. Total F	ederal funds authorized for this	funding period	I and the second second					150,	000.00	
i. Unoblig	ated balance of Federal funds	(Line h minus	s line g)					97,	766.83	
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13. Certification	I certify to the best of m unliquidated obligation	y knowledge s are for the	and belief that t	his report i th in the aw	is correct a vard docum	nd complete a	and that al	l outlays a	and	
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David V.	Welch, Director, G	rants and	d Contracts	Account	ing	(404) 8	94-2629			
Signature of Au	thorized Certifying Official					Date Report	Submitted			
NSN 7540-01-21	8-4387		269-20	01			Standard F	Form 269A	(REV 4-88)	

#### Attachment

U. S. Department of Energy Financial Status Report (06/13/94) Grant No. DE-FG05-93ER75859 (E-25-W04/R7796-0A0)

	Direct Costs	Indirect Costs
04/15/93 - 06/30/93 @ 44.9%	85.00	38.17
07/01/93 - 04/14/94 @ 37.0%	34,453.65	12,747.86

Mixed Field Dosimetry Using Focused and Unfocused Laser Heating of # 2 Thermoluminescent Materials

E25-604 1

Final Report, Year 1 (Covering Period from April 15, 1992 to June 30, 1993)

#### Prepared: September 27, 1993

This work had as its original goals the theoretical evaluation of a unique method of performing mixed field dosimetry by using focused and unfocused laser heating to extract dose information from the superficial layers, followed by the deeper layers, of a single, thick thermoluminescent detector (TLD). This report will review the original stated goals for this award, then review the results obtained during the first year of the grant. Software tools required to accomplish these goals were completed during the first year of the grant, and preliminary simulated data were obtained. A modification to the approach, utilizing sequential laser heating with different pulse powers and durations and deconvolution of the resulting glow curves was devised as a method for obtaining more complete depth dose information. Optimization and error analysis of the method will be accomplished in detail during Year 2.

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Model	15
Characterize Dose Distributions	15
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2

# Mixed Field Dosimetry Using Focused and Unfocused Laser Heating of Thermoluminescent Materials

# PROJECT OBJECTIVES AND GOALS

The <u>long-term objective</u> of the proposed research is to develop a unique dosimetry system capable of accurate mixed beta/gamma dosimetry and meaningful shallow/deep dose discrimination using a single-element thermoluminescent detector (TLD) and focused laser readout. The rapid superficial heating of a thick TLD will result in release of the signal due to shallow dose, which will then be followed by the release of the signal due to the deep dose as the deeper portions of the TLD are heated to TL temperatures. Careful analysis of the signal as a function of time should allow quantitative discrimination of the radiation field type. The <u>basic hypothesis</u> is that this approach will prove superior to the approaches of employing thin dosimeters, multi-element filtered dosimeters with empirical algorithms, and rapid superficial contact heating. The <u>immediate goal</u> of the research is to explore this basic hypothesis using computer simulations of the laser heating and thermoluminescence processes.

Specific project objectives, presented in the original proposal, are:

1) Theoretical analysis of signal or glow curve production in a TLD undergoing superficial heating with a focused laser;

2) Characterization of the glow curve for TLDs heated by a focused laser followed by unfocused laser heating;

3) Optimal selection of TLD type, dimensions and heating scheme for discrimination of beta and gamma dose;

4) Optimization of the approach for characterizing the depth of penetration of beta fields; and

5) Specification of a prototype system.

Software tools required for accomplishing the above objectives were essentially developed during the first year of the grant. Preliminary simulations obtained suggest a modified approach to the problem, namely the use of a uniform beam and a laser pulse sequence for heating coupled with a deconvolution technique applied to the resulting glow curves in order to determine the depth dose. Error analysis, refinement of the system, and specification of the prototype are the primary remaining tasks for the second year. 4

#### WORK COMPLETED AND PRELIMINARY RESULTS

#### **Development of Computer Models**

General approach: A computer code was developed to model the twodimensional, non-steady state production of thermoluminescence (TL) following laser heating. The heat transfer model used to compute temporal temperature distributions was based upon the thermal diffusion equation implemented for slab geometry. To model the production of TL light, a first-order kinetic model of thermoluminescence (Randall-Wilkins) was employed with the trapping parameters reported for LiF [McKeever 1980]. In order to perform the integrations needed for generating glow curves, the material was subdivided into both the axial and radial dimensions in a cylindrical coordinate system, with symmetry being assumed at any given depth and radius in order to shorten the total number of computations. Computations were performed at the midpoints of each volume element for each time step. Focused and unfocused laser beams were modeled by changing the source term for heat production. The model and its solutions were implemented in Fortran to run on SUN workstations. It should be noted that the problem was completely programmed from scratch since similar work completed 5 years earlier by the Principal Investigator [Grupen and Kearfott 1988] [Grupen-Shemansky et al 1989] was performed for an entirely different problem and was coded for parallel implementation on a minisupercomputer, which is no longer readily available for unlimited use by the PI.

Analytical solution: For an unfocused laser beam as a source term, and assuming a slab geometry with a radial direction large with respect to the laser beam diameter, an analytical solution to the problem of laser heat transfer and TL production is possible [Abtahi et al 1985]. This solution, involving the assumption of a zero temperature gradient at the surfaces of the TLD, was implemented for use in benchmarking purposes. Running a case with this code consumes approximately 10 h of computer time (Sun Sparc1+). The analytical solution could not be readily applied to the case of a focused laser beam.

Numerical solution: It is possible to solve the laser heating problem numerically for layers of material using techniques such as the alternating direction-implicit (ADI) technique [Mansuripur et al 1982]. Such a numerical solution allows the flexibility of easily studying both focused and unfocused laser beams and considering more realistic geometry and boundary conditions. The ADI method [Birkhoff et al 1962] has the advantages of being very stable and saving computing time. This approach was therefore implemented for use as the main tool for studying the extraction of depth-dose information using laser heating of TLDs. The average case studied to date consumes approximately 2 h of computer time (Sun Sparc1+).

## Temperature Profiles and Glow Curves for Uniformly Deposited Dose

As an initial case for study and benchmarking purposes, a 0.09 cm LiF TLD was chosen with an unfocused laser beam diameter of 0.084 cm and a focused beam diameter of 0.032 cm. A 4.93 W continuous wavelength (CW) laser and a uniform deposition of dose throughout the TLD was assumed. The analytical solution included the assumptions of a large radial dimension and a zero temperature gradient at the surfaces. For the numerical solution, which accounts for finite radial dimensions, the TLD was assumed to have a 0.3 cm diameter. The test cases were run assuming boundary conditions of a nitrogen atmosphere and room temperature at the TLD surfaces. Heating times of 300 msec and 50 msec, for unfocused and focused heating, were studied, since longer heating times would result in maximum local TLD temperatures exceeding 700 K, that temperature at which physical damage to the TLD is expected.

Temperature profiles from analytical solution: Figure 1 shows the temperature distribution profile, obtained by analytical solution, at times of a) 100 msec, b) 200 msec, and c) 300 msec following initiation of heating. Each isotherm (383 K, 421 K, 457 K, and 483 K) corresponds to one of the glow peaks (peak numbers 2, 3, 4, and 5) for the LiF:Mg,Ti TLD. These profiles were computed for an unfocused beam, with no heat transfer allowed on the faces of the TLD (zero temperature gradient boundary assumptions) having an infinitely large radial dimension. The case presented in the figure is identical to that studied by other researchers [Abtahi et al 1985]. The excellent agreement between the temperature profiles output from the code developed for this work with those previously reported suggests that the implementation was performed correctly. The increase in temperature at depth as a function of time is apparent in the figure.

<u>Glow curves from analytical solution</u>: Figure 2 shows glow curves, or TL intensity as a function of time, corresponding to the isotherms in Fig. 1. Figures 2a and 2b, which show the glow curve from the entire 0.09 cm TLD, computed using different numbers of radial and axial timesteps, illustrate that a minimum of approximately 50 computational intervals in the radial dimension and >10 intervals in the axial dimension are required to obtain results free from numerical

artifacts. A larger number of axial computational intervals (50) than indicated for reasonable numerical results will be utilized since a greater spatial resolution is desired in this direction. The computed curve is in excellent agreement with previously reported theoretical and experimental results [Abtahi et al 1985]. The portion of the glow curve arising from a depth of 0.09 cm, appearing in Fig 2c, illustrates that the shallow portions of the TLD begin to thermoluminesce very quickly following initiation of heating.

Temperature profiles from numerical solution: Temperature profiles obtained for the numerical solution after 300 msec of heating, using the ADI scheme, are shown in Fig. 3 for unfocused laser heating. Comparing Fig. 3 with the analytical results of Fig. 1c reveal only minor differences. The results from the numerical solution show that heating is less rapid in both the axial and radial directions than predicted by the analytical solution; this undoubtedly results from the differences in the boundary conditions assumed for the two solutions. The numerical solution in Fig. 3 included consideration of heat loss at the surface of the TLD, which was neglected in the analytic solution of Fig. 1c.

The isotherms following 43.5 msec of heating with a focused laser are shown in Fig. 4. The focusing of the beam, which could be accomplished using a germanium lens, results in a much more rapid heating of the TLD than for unfocused heating, with less heating occurring with depth for earlier times. This is expected since focusing the beam result in a much higher beam intensity. Heating to thermoluminescence occurs rapidly within the radial edges of the beam, but there is not as much heating in depth during the initial time period. Heat appears to "dissipate" more rapidly in the radial than in the axial dimension. This result is promising, since use of focused heating would permit the more selective extraction of superficial dose from the TLD. Direct determination of the shallow dose could be done by selection of an appropriate beam power and limited heating time so that primarily shallow dose information is extracted.

Glow curves from numerical solution: Figure 5 shows glow curves using the numerical solution for the unfocused laser heating case. As shown in Fig. 5a, 120 radial increments are needed to avoid numerical oscillations in the solution. In the axial direction, 50 intervals were chosen for the computation. Comparing the glow curve obtained using the numerical solution to those of Fig. 2a, the analytical solution, reveals that the time required for the temperature to increase to thermoluminescent temperatures throughout the TLD is slower than that predicted by the numerical solution, for which heat losses at the surfaces of the TLD were included in the model. The glow arising from a depth of 0.09 cm obtained using the numerical solution is shown in Fig. 5b. This result agrees relatively well the analytical solution of Fig. 2b. However, the more appropriate boundary conditions assumed for the numerical solution result in slower predicted heating and release of TL light. However, the generally good agreement between the analytic and numerical solutions adds confidence to the numerical solution. Since the numerical solution is more flexible in terms of source term and boundary condition selection and approximately 5 times quicker for equivalent cases, it will be used for future analysis related to this grant.

The glow curves for the focused laser case are shown in Figure 6. In Figure 6a, the TL intensity arising from the entire TLD is shown. A mesh size of R/120 in the radial dimension appears to be adequate for modeling purposes. Focused heating tends to not only result in a much more rapid emission of TL light, seen by comparing Fig. 6a with Fig. 5a, but allows the more rapid extraction of dose information from shallower depths. This is illustrated by comparison of Figs. 5b and 6b. These results suggest that the approach of initially heating the TLD using a focused laser for a short time period, followed by longer heating with an

unfocused beam would allow the sequential readout of shallow dose and deep dose.

Intercomparison and benchmarking: Figure 7a shows a plot of glow curves obtained using the numerical and analytical approaches, compared with data extracted from the work of another researcher. Excellent agreement is obtained. Previously reported glow curve data for a 0.38 mm thick TLD and heating with a 4 Watt continuous wavelength CO<sub>2</sub> laser are compared to the modeled data in Figure 7b. Excellent agreement are obtained when a reduction in the model frequency factor is made.

Initial Study of Positional Thermoluminescence (TL) Intensity Curves

Feasibility of using focused and unfocused laser heating of TLDs to extract depth-dose information may be studied by examining the portion of the glow curves arising as a function of depth and radial position in the material. The glow curve arising from a depth of 0.007 cm, obtained using the numerical solution technique, is shown in Fig. 8 as a function of radial position and heating time for a) unfocused laser heating and b) focused laser heating. At very small times, maximum TL emission will occur near the radial center of the TLD; however, very rapidly the signal is depleted from this area. The peak region of thermoluminescent emission progresses out from the center with time for both focused and unfocused laser heating.

The TL intensity, integrated over all radial positions, is shown at various times in Fig. 9 for both unfocused and focused laser heating. As heating time is increased, the total TL signal continues to increase, but a larger portion of the signal begins to arise from positions further from the TLD surface. For unfocused heating, the development of signal deeper in the TLD is more pronounced after 180 msec. For focused laser heating, signal primarily occurs from the most shallow 0.01 cm of the TLD during the first 20 msec of heating.

The glow curves arising from different depth are plotted in Figure 10a for a 0.084 cm diameter unfocused beam and a 0.3 cm x 0.3 cm x 0.09 cm thick LiF detector. Figure 10b illustrates the maximum depth from which signal is obtained as a function of time. These and other data reveal that with time, signal is arising from deeper and deeper portions of the TLD, and there is a distinct relationship between time and the depth from which signal is arising. This supports the utility of laser heating for extracting depth dose.

#### Glow Curves for Nonuniformly Deposited Dose

A simple modification of the glow curve model solved using the numerical method, involving multiplication of the intensity by the depth-dose information and some sensitivity constant, was all that was required to account for nonuniform distribution of dose in the TLD. Coding was completed for accomplishing this (with the exact sensitivity constant yet to be determined). A test case was run using empirical fits of measured data reported in the literature [Turner et al 1988]. The resulting glow curve responses for the <sup>99</sup>Tc and <sup>147</sup>Pm beta sources, normalized to the intensities observed at 300 msec, are shown in Figure 11 for unfocused heating. These glow curves illustrate that the release of light from <sup>99</sup>Tc tends to be slightly more temporally uniform; the betas from <sup>99</sup>Tc (0.292 MeV maximum) are slightly more energetic and penetrating than the betas emitted by <sup>147</sup>Pm (0.225 MeV maximum), resulting in a more uniform depthdose distribution. The fact that noticeable differences in glow curves are computed for a suboptimal heating scheme, laser power, and laser diameter (chosen to match the published work of other investigators, interested in a different problem, for benchmarking purposes) is quite encouraging.

#### Characterization of Depth-dose Distribution

For the above work, the depth-dose distribution of the field was assumed to be uniform or obtained from empirical data. For meaningful performance of this work, dose distributions as a function of depth are of primary interest and should be well known for the cases of interest. Radiation transport within a thick TLD must be characterized.

EGS4, a code capable of coupled electron-photon transport calculations, was chosen for use in studying the depth-dose distributions of betas and gammas of different energies in a variety of TLD materials. This code was installed on the SUN computers and benchmarked for several test cases of photons and low and high energy betas. Figure 12a. shows the results of depth dose computations for higher energy electrons in LiF, which agrees well with published data (Attix 1986) while Figure 12b shows similar output for lower energy electrons. Figure 13 shows some results, obtained using 100,000 histories, for monoenergetic photons in LiF. Experimental and simulated data readily available to the investigators was utilized for this purpose. The generation of a set of data for depth dose in TLDs for various monoenergetic electron and photon beams is well underway. Software for fitting these data to polynomials and code for generating depth dose for arbitrary spectrum is in progress.

# **Optimization of Heating Approach**

<u>Maximum laser power and pulse duration</u>: Choice of the heating approach is ultimately limited by the maximum surface temperature, 700 K, which may be achieved without thermal damage to the TLDs. Figure 14 shows the temperatures at the surface of the TLD for different power beams. These data indicate the limits for heating. For example, that when a 6 W unfocused beam is utilized, a maximum pulse duration of approximately 0.5 sec. Curves such as this will be consulted in the final design of the heating scheme.

Selection of beam shape: As shown in Figure 15, the isothermals for an unfocused beam spread radially rather than axially as a function of time. This results in a "contamination" of the signal from the deeper layers with signal from

the outer portions of the more superficial layers. Such a problem arises even when the Gaussian beam is the same size or grater than the detector. Usage of a uniform beam, achievable using filters and beam shaping, could avoid such a problem and would be highly desirable. The software was modified for a round, uniform beam and a square uniform beam. The resulting temperature distributions and glow curves are illustrated in Figures 16 and 17. For the square uniform beam, it is assumed that the temperature distribution is essentially flat in the radial direction, which would be the optimal experimental condition for the extraction of depth dose information.

Use of pulsed beam heating sequence: In order to exploit the complete information about depth dose which is contained in the glow curves, it was decided that use of pulsed heating sequence with an unfolding scheme to be applied to the resulting glow curves would be a superior approach to single focused and unfocused pulses. The software was thus modified to enable the study of sequential pulsing, which requires keeping track of those regions of TLD which have already released their signals and tracking temperatures and glow production during the times between pulses. A sample of the output from the code is illustrated in Figure 18 for two sequential pulses. Note that the first pulse, 10 W for 0.5 sec, releases primarily signal from the superficial layer, while the second pulse, 4 W for 0.2 sec, releases signal from deeper layers. This occurs because the material has been preheated and the signal has already been released from the superficial layers by the first pulse at the time of the second pulse. The best situation would appear to be one in which the pulses result in release of signal from distinct depths within the detector.

An improved pulsing scheme is shown in Figure 19, which consists of one 10 W 0.9 sec pulse, a 10 W 1.0 sec pulse, and a 4 W 3.0 sec pulse. The TL intensity

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vs. depth curve reveals an even better coverage and separation of light as a function of depth in the detector.

# Unfolding of depth dose information

For uniform radial and axial dose distribution, the TL light produced as a function of time, F(t), is characteristic for a particular type of heating and TLD geometry. This relationship, which constitutes a type of response function for the system, may be described mathematically by:

$$F(t) = c \int_{0}^{t} \int_{0}^{L} f(z,t) dz dt$$

For some depth dose distribution, D(z), a particular glow curve, P(t), will result, which is given by:

$$P(t) = c \int_{0}^{t} \int_{0}^{L} D(z) f(z,t) dz dt$$

If TL light is emitted during N time intervals denoted i, and light from M finite depth intervals j are considered, then the problem may be restated in a discrete form:

$$P_i = \sum_j D_j f_{ij}$$

where D is a vector of dimension M, corresponding to the depth dose distribution, P is a vector of dimension N, corresponding to measurements of total TL intensity during some time interval, and f is a matrix of dimension NxM, which is characteristic of the TLD and heating scheme.

The vector f could be determined from a known experiment. Then, given an initial guess of  $D_j$ , e.g. for a uniform dose distribution, then P may be computed from:

$$P_{i,computed} = \sum_{j} D_{j} f_{ij}$$

The value of D may then be updated using:

$$D_j^{l+1} = \frac{D_j^l}{\sum_{i=1}^N f_{ij}} \sum_{k=1}^N f_{ij} \frac{P_{k,measured}}{P^l_{k,computed}}$$

Finally, iteration may be performed, checking convergence using:

$$e^{l} = \frac{1}{N} \sum_{k=1}^{N} \left[ \left( \frac{P^{i}_{k,computed} - P_{k,measured}}{P_{k,measured}} \right)^{2} \right]^{\frac{1}{2}}$$

The above scheme was implemented for studying the ability of different heating schemes to allow unfolding of depth dose information. One sample output is included as Figure 20. This shows good agreement at shallow doses between the actual depth dose distribution for Sr/Y-90 beta particles used in the simulation and the depth dose data unfolded using glow curves generated with a three pulse heating scheme. Additional work is underway in an attempt to find a heating scheme which will give better results.

#### **REMAINING WORK**

This section will outline the work remaining for the second year of the project.

# Modify and Implement Heat Transfer and Thermoluminescence (TL) Model

The code has been essentially completed. However, it would be desirable to account for the attenuation of TL light within the detector. A scaling factor, accounting for the efficiency of production and detection of TL signal will must also be determined for various cases and will be used to "calibrate" the computer simulations.

#### **Characterize Dose Distributions**

A variety of radiation fields, corresponding to those fields used for DOELAP or NAVLAP accreditations and including field with low energy betas and photons, must be generated for use in characterizing the performance of the system.

Improve Code for Generating Glow Curves for Nonuniform Dose Distributions

Code for generating any arbitrary depth dose curve from the EGS4 output must be completed and debugged, and the generation of EGS4 output completed. A means for directly reading the depth-dose information contained in files which will be generated by the radiation transport codes and accounting for dose differences in the radial dimension must be devised.

# **Optimize Heating Scheme**

The search for an optimal heating scheme for separating the deep and shallow dose, and obtaining depth dose information requires additional work. Such an approach will most likely require a sequential pulsing scheme.

#### Error Analysis

How well the optimal technique is capable of extract the skin (or shallow) dose and shallow dose from a TLD must be assessed. This will be done for a variety of heating approaches. The problem of extracting depth dose information will also be studied. The analysis will be done for a variety of different depth doses, and include the introduction of uncertainty into the data. Particular attention will be paid to assessing the system's ability to discriminate low energy betas and gammas and perform beta spectroscopy.

#### TIMELINE

Table 1 shows the revised timeline submitted with the grant renewal, which was prepared Oct. 8, 1992. A revision of the estimates of the status of tasks, effected September 27, 1993, is included. The task of applying the heat transfer model for the focused laser case turned out to be more complex than anticipated: this involves a lengthy numerical computation. The code to combine temporal temperature distributions with dose distributions to generate glow curves was far simpler than originally estimated, since it merely involved adding a multiplication in the glow curve computation. Some progress was made on the generation of depth dose distributions over the early summer months, which proceeded rapidly once familiarization with the EGS4 code was obtained.

# SUMMARY

Excellent progress has been made during the first year of this two year effort. The accomplished work has included the development and initial testing of the heat transfer and TL modeling software necessary for analyzing the proposed dosimetry technique, including focused, unfocused and uniform laser source terms. Codes were appropriately modified to simulate the newly proposed pulsed heating method, and software was developed to accommodate the approach of unfolding the glow curves to reveal depth dose information. The generation of appropriate depth-dose information for thick TLDs is underway using EGS4, and software is being developed to generate polynomial description of depth dose in thick TLDs for monoenergetic electrons, with plans to utilize a simple code to obtain data for any spectrum. Several sample cases have been run, indicating an optimal approach of a uniform pulsed beam, possibly involving heating from both sides of the TLD. The primary remaining work for the second year of the grant involves optimization and error analysis of the approach.

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# Table 1: Revised Timeline with Approximate Status ofEach Group of Tasks as of September 27, 1993

# Year 1

- \* Modify and implement heat transfer and TL model: 5 months (Status: 95% complete)
- \* Improve code for generating glow curves for nonuniform dose distributions: 2 months (Status: 90% complete)
- \* Study thick TLDs with both unfocused and focused laser heating: 5 months (Status: 90% complete)

# Year 2

- \* Characterize dose distributions: 3 months (Status: 75% complete)
- \* Generate glow curves for variety of heating schemes, nonuniform dose distributions, and TLDs: 1 month (Status: 50% complete)
- \* Theoretical assessment of system's ability to discriminate low energy betas and gammas: 3 months (Status: 10% complete)
- \* Theoretical assessment of system's ability to perform beta spectroscopy: 3 months (Status: 10% complete)
- \* Design of prototype TLD system: 2 months (Status: 10% complete)

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- Figure 2: Glow curves for a 0.09 cm thick LiF thermoluminescent detector (TLD), predicted using an analytical solution, following heating with a 0.084 cm diameter unfocused 4.93 Watt continuous wavelength (CW) laser beam showing a) effects of radial computation interval on spatially integrated TL intensity, b) effects of axial computation interval on spatially integrated TL intensity, and c) TL intensity arising from a depth of 0.09 cm in the TLD.
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- Figure 7: Comparison of glow curves from a) simulations for numerical and analytic cases compared to published simulation, b) theoretical model with two different frequency factors and experimental data from the literature (Grupen and Kearfott 1988)
- Figure 8: Thermoluminescent intensity produced as a function of radial position at a depth of 0.7 cm in a 0.3 cm x 0.3 cm x 0.09 cm thick LiF thermoluminescent detector (TLD) for different times following commencement of heating with a 4.93 Watt continuous wavelength (CW) laser beam, predicted using a numerical solution method for a) a 0.084 cm diameter unfocused beam and b) a 0.032 cm diameter focused beam.
- Figure 9: Thermoluminescent intensity (integrated over all radial positions) produced as a function of axial position in a 0.3 cm x 0.3 cm x 0.09 cm thick LiF thermoluminescent detector (TLD) for different times following commencement of heating with a 4.93 Watt continuous wavelength (CW) laser beam, predicted using a numerical solution method for a) a 0.084 cm diameter unfocused beam and b) a 0.032 diameter focused beam.
- Figure 10: Signal generated as a function of depth in the TLD, shown as a) different glow curves arising from various depths, b) the maximum depth from which signal is contributed. Data are for a 0.3 cm x 0.3 cm x 0.09 cm thick LiF detector with a 5 Watt CW CO<sub>2</sub> laser.
- Figure 11: Glow curve arising from heating of a 0.3 cm x 0.3 cm x 0.09 cm thick LiF thermoluminescent detector (TLD) with an unfocused 0.084 cm diameter 4.93 Watt continuous wavelength (CW) laser beam for depthdose distributions corresponding to betas from <sup>99</sup>Tc and <sup>147</sup>Pm. Differences between the curves, generated for this non-optimized heating scheme, could be exploited to derive beta spectral information
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- Figure 15: Temperature profile for a 0.38 cm thick LiF TLD, heated for 500 ms with a 0.084 cm diameter unfocused 7 Watt CW CO<sub>2</sub> laser beam.

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- Figure 20: Calculated (unfolded) dose from a thick TLD exposed to Sr/Y-90 beta particles by pulsed heating of a uniform laser beam (10 W, 0.7 sec pulse; 1.9 sec cooling; 4 W, 1.6 sec pulse; 2.0 sec cooling; 2 W, 3.5 sec pulse), compared to actual depth dose curve.







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(a)





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Figure 12b: Depth dose for lower energy electrons in LiF obtained using EGS4 with 10,000 histories









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Mixed Field Dosimetry Using Focused and Unfocused Laser Heating of **Thermoluminescent Materials** 

E-25-W04 #4

**Final Report** (Covering Period from April 15, 1992 to June 30, 1995)

### Grant No. DE-FG05-93ER75879

Prepared by: Dr. C-K Chris Wang

Date: July 24, 1995

This work had as its original goals the theoretical evaluation of a unique method of performing mixed field dosimetry by using focused and unfocused laser heating to extract dose information from the superficial layers, followed by the deeper layers, of a single, thick thermoluminescent detector (TLD). This report will review the original stated goals for this award, then review the results obtained during the three years of grant period.

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## Mixed Field Dosimetry Using Focused and Unfocused Laser Heating of Thermoluminescent Materials

### **Project Objectives and Goals**

The objective of the research project is to develop a unique dosimetry system capable of accurately assessing mixed beta/gamma dosimetry and meaningful shallow/deep dose discrimination using a single-element thermoluminescent detector (TLD) and focused laser readout. The rapid superficial heating of a thick TLD will result in release of the signal due to shallow dose, which will then be followed by the release of the signal due to the deep dose as the deeper portions of the TLD are heated to TL temperatures. The basic hypothesis is that this approach will prove superior to the approaches of employing thin dosimeters, multi-element filtered dosimeters with empirical algorithms, and rapid superficial contact heating. The major goal of the research is to explore this basic hypothesis using computer simulations of the laser heating and thermoluminescent processes.

Specific project objectives, presented in the original proposal, are:

1) Theoretical analysis of signal or glow curve production in a TLD undergoing superficial heating with a focused laser;

2) Characterization of the glow curve for TLDs heated by a focused laser followed by unfocused laser heating;

3) Optimal selection of TLD type, dimensions and heating scheme for discrimination of beta and gamma dose;

4) Optimization of the approach for characterizing the depth of penetration of beta fields; and

5) Specification of a prototype system.

### **Results and Discussion**

Software tools required for accomplishing the specific objectives were essentially developed during the first year of the grant. Preliminary simulations obtained suggested a modified approach to the problem, namely the use of a uniform laser beam and a laser pulse sequence for heating coupled with a deconvolution technique applied to the resulting glow curves in order to determine the depth dose. All five goals have been achieved. The detailed description of the modified approach and the simulated results are provided in <u>Attachment A</u>. In summary, the modified approach appears to be novel and feasible. However, the deconvoluted depth-dose result may contain large uncertainties due to the uncertainties associated with the thermal parameters of TLD, namely absorption coefficient of laser beam, thermal conductivity, and specific heat. To thoroughly address this issue, an experimental study must be conducted.

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Prepared by: Dr. C-K Chris Wang

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This work had as its original goals the theoretical evaluation of a unique method of performing mixed field dosimetry by using focused and unfocused laser heating to extract dose information from the superficial layers, followed by the deeper layers, of a single, thick thermoluminescent detector (TLD). This report will review the original stated goals for this award, then review the results obtained during the three years of grant period.

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## Mixed Field Dosimetry Using Focused and Unfocused Laser Heating of Thermoluminescent Materials

### **Project Objectives and Goals**

The objective of the research project is to develop a unique dosimetry system capable of accurately assessing mixed beta/gamma dosimetry and meaningful shallow/deep dose discrimination using a single-element thermoluminescent detector (TLD) and focused laser readout. The rapid superficial heating of a thick TLD will result in release of the signal due to shallow dose, which will then be followed by the release of the signal due to the deep dose as the deeper portions of the TLD are heated to TL temperatures. The basic hypothesis is that this approach will prove superior to the approaches of employing thin dosimeters, multi-element filtered dosimeters with empirical algorithms, and rapid superficial contact heating. The major goal of the research is to explore this basic hypothesis using computer simulations of the laser heating and thermoluminescent processes.

Specific project objectives, presented in the original proposal, are:

1) Theoretical analysis of signal or glow curve production in a TLD undergoing superficial heating with a focused laser;

2) Characterization of the glow curve for TLDs heated by a focused laser followed by unfocused laser heating;

3) Optimal selection of TLD type, dimensions and heating scheme for discrimination of beta and gamma dose;

4) Optimization of the approach for characterizing the depth of penetration of beta fields; and

5) Specification of a prototype system.

### **Results and Discussion**

Software tools required for accomplishing the specific objectives were essentially developed during the first year of the grant. Preliminary simulations obtained suggested a modified approach to the problem, namely the use of a uniform laser beam and a laser pulse sequence for heating coupled with a deconvolution technique applied to the resulting glow curves in order to determine the depth dose. All five goals have been achieved. The detailed description of the modified approach and the simulated results are provided in <u>Attachment A</u>. In summary, the modified approach appears to be novel and feasible. However, the deconvoluted depth-dose result may contain large uncertainties due to the uncertainties associated with the thermal parameters of TLD, namely absorption coefficient of laser beam, thermal conductivity, and specific heat. To thoroughly address this issue, an experimental study must be conducted.

# THEORETICAL EVALUATION OF MIXED BETA/GAMMA FIELD DOSIMETRY USING PULSED LASER HEATING OF THERMOLUMINESCENT MATERIALS

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> Short Title: Pulsed Laser heating of TLDs

## THEORETICAL EVALUATION OF MIXED BETA/GAMMA FIELD DOSIMETRY USING PULSED LASER HEATING OF THERMOLUMINESCENT MATERIALS

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Abstract -- This paper described a detailed computational study of a new method for mixed beta/gamma radiation field dosimetry using single-element thermoluminescent dosemeters (TLD) with pulsed laser heating schemes. The main objective of this study was to obtain an optimum heating scheme so that the depth-dose distribution in a thick TLD could be determined. The major parts of the study include: (1) heat conduction calculations for TLDs with various heating schemes, (2) glow curve calculations for TLDs, (3) unfolding of the depth-dose distribution based on the glow curve data, and (4) estimation of shallow and deep dose from the unfolded depth-dose distribution. An optimum heating scheme based on a sequence of laser pulses were obtained in this study for a uniform laser beam. The resulting glow curves were successfully used to unfold the depth-dose distribution in the TLD. The unfolded depth-dose distribution correctly predicts the shallow and deep doses with relative errors less than 20% in various pure and mixed beta/gamma radiation fields.

### INTRODUCTION

Mixed beta/gamma dosimetry typically involves determining the shallow (or skin) dose and deep dose for human body exposed to mixed beta/gamma radiation fields. The International Commission on Radiological Protection (ICRP)<sup>(1)</sup> has recommended that an appropriate measurement of skin dose is that integrated between tissue depths of 5 and 10 mg.cm<sup>-2</sup> (i.e. 50-100  $\mu$ m) which corresponds to the depth of cells in the basal layer of the More recently, the International Commission on Radiological Units and body. Measurement (ICRU)<sup>(2)</sup> prescribed two new operational quantities intended for application to individual monitoring: the individual dose equivalent penetrating,  $H_{p}(d)$ , and individual dose equivalent superficial, H<sub>s</sub>(d). They are defined as the dose equivalent in soft tissue below a specified point on the body at depths of 10.0 and 0.07 mm, respectively. Two major techniques have been attempted to measure these quantities using thermoluminescent dosimeters (TLDs). They include using thin detectors and multielement dosimeters.

A thin TLD typically has a thickness of approximately 5 mg.cm<sup>-2</sup>. To measure  $H_s(d)$  and  $H_p(d)$ , tissue-equivalent filters with thicknesses of 7 mg.cm<sup>-2</sup> and 1.0 g.cm<sup>-2</sup> must be used respectively. Several types of thin TLDs have been developed<sup>(3,4)</sup>. The materials include CaSO<sub>4</sub>(Tm), MgB<sub>4</sub>O<sub>7</sub>(Tm), and LiF(Mg,Cu,P). The first two materials are regarded as ceramic TLDs, and their sensitivity to mixed beta/gamma radiation are higher than that of the LiF(Mg,Cu,P). The ceramic TLDs are less tissue-equivalent, however, and require corrections of the over-response at low photon energies.

In the multi-element approach, a minimum of three detectors, two for shallow dose and one for deep dose, are placed behind different thickness of filters. The resulting readings for the various detectors are then analyzed to evaluate shallow dose and deep dose equivalents<sup>(5,6)</sup>. The ultimate limitations of this approach are discontinuities and instabilities of the computational algorithms, the system energy dependence, the low limit for the measurable maximum beta energy, the high lower limit of detectability, and added cost due to the use of multiple detectors<sup>(7,8)</sup>. In addition, dosimeter-to-dosimeter variation introduces a source of random error to the method which may be amplified by the computational algorithm<sup>(9)</sup>. Energy range and energy dependence can be improved by using a larger number of elements or thinner detectors at the expense of greater complexity and higher random error<sup>(7)</sup>.

The two techniques discussed above use conventional heating in which a TLD chip was brought into mechanical contact with a heated metal plate or immersed in a hot gas or fluid. Heating rates were limited to about 10 K.s<sup>-1</sup>. In recent years the use of laser beams to heat TLD chips has been studied as a direct, rapid and noncontact heating method<sup>(10,11,12)</sup>, providing a high heating rate of about 10<sup>4</sup> K.s<sup>-1</sup>. Laser heating has been recognized as a promising technique to increase the signal-to-noise ratio<sup>(13)</sup>, because the dark current background noise reduces proportionally to the reduction in time achieved over conventional heating. This paper presents a computational study of a new method of extracting depth-dose distribution (between the surface and the depth at 1.0 g.cm<sup>-2</sup>) from a thick TLD chip using pulsed laser heating schemes. This depth-dose distribution provides not only the information about shallow (or skin) and deep doses, but also the dose at the depth of  $300 \text{ mg.cm}^{-2}$  (the depth of the lens).

### **METHODS**

The original hypothesis of this study was that a thick TLD (>0.1 cm) may be used to determine shallow and deep doses in mixed radiation dosimetry using the differential heating technique<sup>(14)</sup>, which employs a focused laser beam to selectively heat the superficial and the deep portions of the TLD. This approach was then extended to the pulsed laser heating technique, in which a sequence of laser pulses with various powers and durations is applied to a TLD. The resulted temporal output of TL signal contains depth-dose information, which can be extracted by iterative unfolding techniques.

Figure 1 describes the conceptual thick TLD, which is a parallelepiped LiF chip measuring 0.3 cm on its sides and 0.38 cm on its height. The main feature of this dosemeter is that the shallow and deep doses correspond to the thicknesses of 0.0027 cm (7 mg.cm<sup>-2</sup>) and 0.38 cm (1000 mg.cm<sup>-2</sup>), respectively. The computational study includes various numerical and analytical methods used to simulate and optimize the performance of the proposed TLD system. Figure 2 provides the logistics of the computational study. The idea is based on the fact that the depth-dose distribution in a TLD may be unfolded from a collection of TL light emissions following the heating with a sequence of laser pulses. The unfolding is possible because one may select a particular heating scheme (i.e. a sequence of laser pulses, each with a specific power, duration, and cooling period) so that each pulse preferentially extracts TL light from a certain depth in a TLD. As illustrated in Figure 2, the temperature profile of a TLD was first obtained by solving the

heat conduction equation with a specific heating scheme. The TL light intensity vs. time (or the glow curve) was then calculated using a first-order kinetic model and an initially guessed depth-dose distribution. The TL light thus obtained was then used with the response function matrix of the TLD to update the depth-dose distribution. This iterative procedure continues until the depth-dose distributions between two consecutive iterations converges to a preset deviation criterion. Several computer programs were developed based on the computational methods. In order to computationally evaluate the performance of various pulsed laser heating schemes, depth-dose distributions for all the DOELAP radiation fields<sup>(15)</sup> for dosemeter calibration were calculated by the Monte Carlo electron/photon transport code EGS4<sup>(16)</sup>. These depth-dose distributions were then used to generate TL light (or the glow curve) for each heating scheme. Many pulsed laser heating schemes were studied for all the DOELAP radiation fields, and the resulting unfolding depth-dose distributions were then compared with that obtained by the EGS4. The judgment for the optimal heating scheme was based on how good the agreement is between the unfolded depth-dose distributions and the distributions obtained by EGS4. Another requirement for an optimal heating scheme is that it should be fairly simple to More detailed calculational methods are described in the following implement. subsections.

### **Heat Conduction Calculations**

The transient temperature profiles of the thick TLD during and after an uniform surface heating by a laser pulse was calculated by numerically solving the following heat conduction equation:

$$\rho C_p \frac{\partial T}{\partial t} = k(T) \nabla^2 T + \frac{\partial k}{\partial T} \left[ \left( \frac{\partial T}{\partial x} \right)^2 + \left( \frac{\partial T}{\partial y} \right)^2 + \left( \frac{\partial T}{\partial z} \right)^2 \right] + S \tag{1}$$

where  $\rho$  is the density,  $C_p$  is the specific heat capacity, k is the thermal conductivity, and S is the heat source function, i.e. the power per unit volume present at a depth z during laser heating. Correcting for reflective loss on the front surface at z=0, the heat source function becomes

$$S(z) = \mu (1 - R_f) I_0 e^{-\mu z}$$
<sup>(2)</sup>

where z is the depth in TLD,  $R_f$  is the reflectivity,  $\mu$  is the absorption coefficient of laser beam, and  $I_0$  is the beam power density. The expression of Equation (1) specifically considers the temperature dependencies of thermal conductivity, i.e. k(T), which varies considerably for temperatures between 0° and 500° C. The temperature dependence of the thermal conductivity was assumed to follow T<sup>-1</sup> relationship<sup>(17)</sup>. With a uniform heating at the TLD surface (i.e. at z=0) and a zero-heat-flux condition at the side boundaries, Equation (1) can be simplified to a 1-dimensional problem. The solution of Equation (1) was obtained numerically using the explicit technique<sup>(18)</sup> in which the entire TLD was discretized into a large number of depth intervals.

### **Calculation of Depth-Dose Distributions by EGS4**

Depth-dose distributions for all the DOELAP radiation fields (listed on Table 1) for dosemeter calibration were calculated by the Monte Carlo code EGS4. The TL material used in EGS4 is LiF, and the all incident particles were assumed to be perpendicular to the front surface of the TLD. 50,000 particles were run for every EGS4 calculation for every DOELAP radiation field. For the mixed fields listed on Table 1, a 1:1 mixing ratio was applied. The calculated depth-dose distributions were then used with the temperature profiles (provided by heat conduction calculations) to generate glow curves.

### **Glow Curve Calculation**

Glow curves of a TLD following pulsed laser beam heating were calculated numerically by integrating the TL light intensities of all the depth intervals. For a depth-dose distribution, D(z), the resulting TL light intensity corresponding to the i<sup>th</sup> pulse of a heating scheme can be expressed as

$$I_i = \int_i \int_0^L D(z) R_i(z,t) dz dt$$
(3)

where  $t_i$  is the duration of the i<sup>th</sup> pulse, L is the TLD thickness, and  $R_i(z,t)$  is the response function converting the depth-dose distribution to TL light intensity. In this study,  $R_i(z,t)$  was calculated based on the uniform depth-dose distribution. The glow curve peaks considered in this study are commonly called peaks 2,3,4, and 5 (as shown in Figure 3), corresponding to the trap depths of 1.13, 1.23, 1.54, and 2.17 eV and frequency factors of  $6.1 \times 10^{13}$ ,  $4.0 \times 10^{13}$ ,  $7.3 \times 10^{15}$ , and  $4.0 \times 10^{21}$  sec<sup>-1</sup> via a fit of experimental curves to first-order kinetics described by MeKeever<sup>(19)</sup>. Laser heating generates a time-dependent temperature profile in the TLD. The TL light intensity is a function of temperature T, and it was calculated by the first-order kinetic expression

$$I(T) = cn_0 s_0 \exp[-\frac{E}{k_b T}] \exp\{-\frac{s_0}{b} \int_{T_0}^T \exp[-\frac{E}{k_b T}] dT\}$$
(4)

where T is the absolute temperature,  $n_0$  is the concentration of initially trapped charges,  $s_0$  is the frequency factor, E is the activation energy (or trap depth),  $k_b$  is the Boltzmann's constant, and b is the heating rate (i.e. dT/dt, assuming it is linear).

Because it was speculated<sup>(20)</sup> that the frequency factors decrease in proportion to the increase of heating rate, and because the heating rate with the laser beam is approximately 100 times that used by McKeever<sup>(19)</sup>, the glow curves in this study were calculated with the afforementioned frequency factors reduced by a factor of 100. Figure 4 shows the comparison between the calculated glow curve and the experimentally measured glow curve<sup>(21)</sup> for a 0.038 cm thick LiF (TLD-100) Harshaw chip with a 10 W laser of uniform beam profile. As shown, there is a general agreement between the two curves characteristically. The difference between the absolute thermoluminescent light intensities is attributed to the fact that the experimentally measured glow curve was obtained based on the TLD mounted on a glass substrate, whereas the calculated glow curve did not include this condition

### **Unfolding of Depth-Dose Distribution**

Since in practice both  $I_i$  and  $R_i(z,t)$  are known in Equation (3), the depth-dose distribution, D(z), can be obtained by solving the inverse problem of Equation (3). The method used to solve this inverse problem is based on an iterative algorithm developed by Doroshenko<sup>(22)</sup>. In order to numerically carry out the iterative algorithm, Equation (3) was first converted to the matrix form:

$$I_i = \sum_{j}^{M} D_j R_{ij} \tag{5}$$
where  $D_j$  is the absorbed dose at j<sup>th</sup> depth interval, M is the total number of discretized depth intervals in the TLD, and  $R_{ij}$  is the response function matrix which converts dose at j<sup>th</sup> depth interval to TL light intensity following the heating by the i<sup>th</sup> pulse. The iterative procedure follows the steps below:

(1) give an initial guess of D<sub>j</sub> (e.g., an uniform depth-dose distribution),

(2) calculate  $I_i$  using Equation (5) for all the laser pulses in a heating scheme,

(3) update  $D_j$  with the measured  $I_i$  using:

$$D_{j}^{l+1} = \frac{D_{j}^{l}}{\sum_{i=1}^{N} R_{ij}} \sum_{j=1}^{M} R_{ij} \frac{I_{i,measured}}{I_{i,calculated}}$$
(6)

where  $D_j^l$  is the depth-dose distribution for the l<sup>th</sup> iteration, and N is the total number of laser pulses, and

(4) iterate steps (2)-(4) until either a specified number of iterations is exceeded or a specified convergence criterion is met. The convergence criterion is based on the deviation of the calculated TL light intensities and the measured TL light intensities for all the laser pulses in a heating scheme. The deviation is defined by the following equation:

$$\varepsilon' = \frac{1}{N} \sum_{k=1}^{N} \left[ \left( \frac{I_{k,calculated}^{l} - I_{k,measured}}{I_{k,measured}} \right)^{2} \right]^{1/2}$$
(7)

Due to the nature of this iterative algorithm, the final solution does vary slightly with the initial guesses of  $D_j$ . The initial guesses of  $D_j$  used for all cases in the study were an

uniform depth-dose distribution (i.e.  $D_j = 1.0$ ), because it is most reasonable to assume such a distribution when a radiation field is practically unknown.

## **RESULTS AND DISCUSSION**

To obtain the optimum pulsed heating schemes, a large number of heating schemes were investigated in this study<sup>(14)</sup>. These heating schemes mainly consist of combinations of various laser powers, pulse durations, and cooling periods between two consecutive pulses. Because the results for all the heating schemes are too voluminous to be presented, this section only presents the results for the optimum heating scheme. The optimum heating scheme consists of a total of 6 laser pulses. The pulse sequence started with a set of 3 pulses heating the front surface of the TLD, and then followed by another set of 3 pulses heating the back surface of the TLD. The laser powers and durations associated with each pulse, and cooling periods between two consecutive pulses are shown in Figure 5. As shown, the first pulse of a three-pulse set is always high-power and short-duration so that it preferentially heats the superficial layer of the TLD. The second and the third pulses of the three-pulse set are less-power and longer-duration so that the temperature at inner portion of the TLD can be elevated without overheating the surface. Figure 6 and Figure 7 show the calculated temperature profiles and glow curves produced by each set of three pulses, respectively, and the calculations were based on a depth-dose distribution produced by a <sup>90</sup>Sr/<sup>90</sup>Y beta source.

Figure 8 (a)-(d) shows the unfolded depth-dose distribution and the distributions calculated by EGS4 for the TLD irradiated with various DOELAP radiation fields. All four figures show good agreements between the unfolded depth-dose distributions and the

distributions calculated by EGS4. Shallow doses, doses at 300 mg.cm<sup>-2</sup>, and deep doses obtained from the unfolded depth-dose distributions were all quantitatively examined, and compared with those obtained from EGS4 calculations. The unfolded results and the EGS4-calculated results for doses at the depth of 300 mg.cm<sup>-2</sup> were found to agree within 10% for all the DOELAP radiation fields. The comparison for shallow doses and deep doses are summarized in Table 2 and Table 3, respectively. Table 2 indicates that except for the fields containing <sup>137</sup>Cs, the unfolded depth-dose distribution based on the optimum pulsed laser heating scheme predicts well the shallow doses (i.e. <20% of error) for the DOELAP radiation fields. Table 3 indicates that the unfolded depth-dose distribution based on the optimum pulsed laser heating scheme predicts well the deep doses (i.e. <10% of error) for all the DOELAP radiation fields. The fields which contain <sup>204</sup>Tl shown in Table 2 are not included in Table 3 because <sup>204</sup>Tl has no contribution to deep doses. The lack of agreement of shallow doses for the fields containing <sup>137</sup>Cs is due to the sharp gradient of dose distribution on the superficial layer. The sharp gradient cannot be accurately resolved by the few more-or-less smoothly distributed response functions. The lack of agreement of shallow doses, however, should not be thought as a drawback for the proposed technique, because deep dose (which is accurately predicted) is usually the limiting factor for the fields containing <sup>137</sup>Cs.

Due to the uncertainties associated with the response functions and the experimental data, the unfolded results are subjected to variations. The variations of unfolded depth-dose distributions due to the uncertainties associated with TLD thermal parameters (i.e., absorption coefficient, thermal conductivity, and specific heat) were systematically

studied<sup>(14)</sup>. As examples, Figure 9 (a) and (b) show the variations of unfolded depth-dose distribution in the TLD due to 5% variations of thermal conductivity and specific heat, repectively. The TLD was exposed to a 20 keV x-rays. Table 4 shows the relative errors (%) of shallow and deep doses unfolded from the thick TLD with respect to  $\pm 2\%$  and  $\pm 5\%$  variations of the three thermal parameters. The corresponding errors of unfolded doses are between 4.3% and 50.9%. In addition, shallow doses are significantly more sensitive to the variations of thermal parameters than are the deep doses. Among the three thermal parameters, the unfolded doses are most sensitive to the specific heat.

The low dose threshold for the thick TLD were not included in this computational study. Due to the larger quantity of TL material, one may expect the thick TLD to have lower dose threshold than that of thin TLDs. The thermal quenching effect caused by the high laser heating rate, however, may diminish this claim. To thoroughly address this issue, an experimental study must be conducted.

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## **Table Captions**

- Table 1. DOELAP radiation fields for dosemeter calibration<sup>(15)</sup>. These radiation fields were used to calculate the depth-dose distributions within the thick TLD by EGS4 code.
- Table 2.Comparison of the unfolded results of shallow doses based on the optimum<br/>pulsed laser heating scheme and the results calculated by EGS4<sup>(16)</sup> for various<br/>DOELAP radiation fields<sup>(15)</sup>.
- Table 3. Comparison of the unfolded results of deep doses based on the optimum pulsed laser heating scheme and the results calculated by EGS4<sup>(16)</sup> for various DOELAP radiation fields<sup>(15)</sup>.
- Table 4. The relative errors (%) of shallow and deep doses unfolded from the thick TLD with respect to  $\pm 2\%$  and  $\pm 5\%$  variations of the three thermal parameters.

# **Figure Captions**

- Figure 1. The configuration of the thick LiF thermoluminescent dosimeter used in the pulsed laser heating study.
- Figure 2. The schematic diagram of the logistics of the computational study.
- Figure 3. Thermoluminescence glow curves of LiF (TLD-100) analyzed by McKeever<sup>(19)</sup>. The curves were obtained by experimental fits of LiF glow peaks (i.e. peaks 2-5), notably the trap depths of 1.13, 1.23, 1.54, and 2.17 eV and frequency factors of 6.1x10<sup>13</sup>, 4.0x 10<sup>13</sup>, 7.3x10<sup>15</sup>, and 4.0 x 10<sup>21</sup> sec<sup>-1</sup>.
- Figure 4. A comparison between the calculated glow curve (solid line) and the experimentally measured glow curve (dotted line) for a 0.038 cm thick LiF (TLD-100) Harshaw chip heated by a 10 W laser of uniform beam profile. The measured glow curve was obtained from Braunlich<sup>(21)</sup>.
- Figure 5. Description of the optimum pulsed laser heating scheme. It consists of two sets of sequential laser pulses. (a): the first set of three laser pulses heating the front surface of the TLD, and (b): the second set of three laser pulses heating the back surface the TLD.
- Figure 6. The calculated temperature profiles of the thick TLD following the optimum pulsed laser heating. (a) corresponds to the temperature profiles immediately following each of the first three laser pulses heating the front surface of the TLD, and (b) corresponds to the temperature profiles immediately following each of the second three laser pulses heating the back surface of the TLD.
- Figure 7. The calculated glow curves of the thick TLD exposed with <sup>90</sup>Sr/<sup>90</sup>Y beta particles based on the optimum pulsed laser heating scheme. (a) corresponds to the glow curve based on the first three laser pulses heating the front surface of the TLD, and (b) corresponds to the glow curve based on the second three laser pulses heating the back surface of the TLD.
- Figure 8. Comparison of the depth-dose distributions in the TLD obtained from the unfolding method and that obtained by EGS4<sup>(16)</sup> for various DOELAP radiation fields<sup>(15)</sup>: (a) <sup>90</sup>Sr/<sup>90</sup>Y beta particles, (b) <sup>137</sup>Cs photons, (c) M150 + <sup>204</sup>Tl mixed field, and (d) M30 + <sup>137</sup>Cs mixed field. The particles were assumed to be perpendicularly incident upon the front surface of the TLD.
- Figure 9. The variations of unfolded depth-dose distribution in the TLD due to 5% variations of: (a) thermal conductivity and (b) specific heat. The TLD was exposed to a 20 keV x-rays.

Radiation Field	Description	
K16	16 keV monoenergetic x-rays	
M30	20 keV NBS filtered x-rays	
S60	36 keV NBS filtered x-rays	
M150	70 keV NBS filtered x-rays	
H150	120 keV NBS filtered x-rays	
K59	59 keV monoenergetic x-rays	
<sup>13</sup> ′Cs	662 keV Cs-137 gammas	
<sup>90</sup> Sr/ <sup>90</sup> Y	2300 keV (max) Sr/Y-90 betas	
<sup>204</sup> Tl	760 keV (max) Tl-204 betas	
$M30 + {}^{204}T\ell$	20 keV x-rays + 760 keV (max) betas	
$S60 + {}^{204}T\ell$	36 keV x-rays + 760 keV (max) betas	
$M150 + {}^{204}T\ell$	70 keV x-rays + 760 keV (max) betas	
$H150 + {}^{204}T\ell$	120 keV x-rays + 760 keV (max) betas	
$^{137}Cs + {}^{204}T\ell$	662 keV gammas + 760 keV (max ) betas	
$M30 + {}^{137}Cs$	20 keV x-rays + 662 keV gammas	
$S60 + {}^{137}Cs$	36 keV x-rays + 662 keV gammas	
$M150 + {}^{137}Cs$	70 keV x-rays + 662 keV gammas	
$H150 + {}^{137}Cs$	120 keV x-rays + 662 keV gammas	
$M30 + {}^{90}Sr/{}^{90}Y$	20 keV x-rays + 2300 keV (max) betas	
$S60 + {}^{90}Sr/{}^{90}Y$	36 keV x-rays + 2300 keV (max) betas	
$M150 + {}^{90}Sr/{}^{90}Y$	70 keV x-rays + 2300 keV (max) betas	
$H150 + {}^{90}Sr/{}^{90}Y$	120 keV x-rays + 2300 keV (max) betas	
$^{137}Cs + {}^{90}Sr/{}^{90}Y$	662 keV gammas + 2300 keV (max) betas	

Radiation Field <sup>†</sup>	EGS4 <sup>‡</sup> Results	Unfolded Results	Relative Error <sup>*</sup> (%)	
K16	2 73**	2.77***	1.47	
M30	1.86	1.84	1.08	
S60	0.57	0.55	3.51	
M150	0.27	0.32	18.50	
H150	0.44	0.37	15.90	
K59	0.27	0.29	7.41	
<sup>137</sup> Cs	0.38	0.67	81.50	
<sup>90</sup> Sr/ <sup>90</sup> Y	291.0	247.4	14.98	
<sup>204</sup> Tℓ	422.9	365.9	13.48	
$M30 + {}^{204}T\ell$	424.7	364.8	14.10	
$S60 + {}^{204}T\ell$	423.4	364.6	13.89	
M150 keV + $^{204}T\ell$	423.2	364.9	13.78	
H150 keV + $^{204}T\ell$	423.3	364.5	13.89	
$^{137}Cs + {}^{204}T\ell$	423.3	364.2	13.96	
$M30 + {}^{137}Cs$	2.23	2.45	9.87	
$S60 + {}^{137}Cs$	. 0.87	1.20	37.93	
$M150 + {}^{137}Cs$	0.65	0.98	50.77	
H150 keV + $^{137}$ Cs	0.78	1.02	30.77	
$M30 + {}^{90}Sr/{}^{90}Y$	292.9	249.0	14.99	
$S60 + {}^{90}Sr/{}^{90}Y$	291.5	247.6	15.06	
$M150 + {}^{90}Sr/{}^{90}Y$	291.3	247.3	15.10	
$H150 + {}^{90}Sr/{}^{90}Y$	291.4	247.3	15.13	
$^{137}Cs + {}^{90}Sr/{}^{90}Y$	291.4	247.9	14.93	

<sup>†</sup> These radiation fields are described in Table 1.

<sup>‡</sup> These results are based on the smoothed depth-dose distributions calculated by EGS4 and, therefore, contain no uncertainty information.

(Unfolded result - EGS4 result)/EGS4 result.
The results correspond to the energy deposited between the depths of 5 mg/cm<sup>2</sup> and 10 mg/cm<sup>2</sup> with the unit of MeV per 0.001 cm of LiF.

Radiation Field <sup>†</sup>	EGS4 <sup>‡</sup> Results	<b>Unfolded Results</b>	Relative Error <sup>*</sup> (%)
K16	0.82**	0.79**	3.7
M30	0.80	0.82	2.5
S60	0.37	0.40	8.1
M150	0.21	0.23	9.5
H150	0.37	0.36	2.7
K90	0.45	0.46	2.2
<sup>137</sup> Cs	2.01	1.99	1.0
<sup>90</sup> Sr/ <sup>90</sup> Y	0.11	0.10	9.1
$M30 + {}^{137}Cs$	1.4	1.41	0.71
$S60 + {}^{137}Cs$	1.18	1.21	2.5
$M150 + {}^{137}Cs$	1.1	1.12	1.8
$H150 + {}^{137}Cs$	1.18	1.16	1.7
$M30 + {}^{90}Sr/{}^{90}Y$	0.45	0.42	6.7
$S60 + {}^{90}Sr/{}^{90}Y$	0.24	0.23	4.2
$M150 + {}^{90}Sr/{}^{90}Y$	0.16	0.15	6.3
$H150 + {}^{90}Sr/{}^{90}Y$	0.24	0.22	8.3
$^{137}Cs + {}^{90}Sr/{}^{90}Y$	1.05	1.0	4.8

<sup>†</sup> These radiation fields are described in Table 1.

\* These results are based on the smoothed depth-dose distributions calculated by EGS4 and, therefore, contain no uncertainty information.

\* (Unfolded result - EGS4 result)/EGS4 result.

"The results correspond to the energy deposited at the depth of 1.0 g/cm<sup>2</sup> with the unit of MeV per 0.001 cm of LIF.

% Variation of Thermal Parameters		Relative errors (%) of the Unfolded Results		
		Shallow Dose	Deep Dose	
Absorption	+2	9.8	2.8	
Coefficient	-2	-8.2	-2.4	
	+5	24.5	6.8	
	-5	-20.3	-6.2	
Thermal	+2	-4.3	-0.9	
Conductivity	-2	5.7	1.4	
	+5	-11.1	-2.7	
	-5	14.1	2.9	
Specific	+2	-14.2	-6.3	
Heat	-2	18.1	7.1	
	+5	-32.1	-15.1	
	-5	50.9	19.1	







Temperature (°K)





Time (seconds)













