

TECHNICAL REPORT
NATICK/TR-10/022



AD _____

SENSORS, DATA ACQUISITION, AND BURN ALGORITHMS FOR EVALUATING CLOTHING AGAINST BATTLEFIELD, FLAME, AND THERMAL THREATS

by
Jim Reuther*
A.J. Kuhlman*
Alfred Rossi*
Ivan Tomes*
Isaac Zimmer*
and
Carole Winterhalter

*** Battelle Memorial Institute
Columbus, OH 43201**

August 2010

Final Report
August 2007 – April 2010

Approved for public release; distribution is unlimited.

**Prepared for
U.S. Army Natick Soldier Research, Development and Engineering Center
Natick, Massachusetts 01760-5020**

UNCLASSIFIED

DISCLAIMERS

The findings contained in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

Citation of trade names in this report does not constitute an official endorsement or approval of the use of such items.

DESTRUCTION NOTICE

For Classified Documents:

Follow the procedures in DoD 5200.22-M, Industrial Security Manual, Section II-19 or DoD 5200.1-R, Information Security Program Regulation, Chapter IX.

For Unclassified/Limited Distribution Documents:

Destroy by any method that prevents disclosure of contents or reconstruction of the document.

UNCLASSIFIED

REPORT DOCUMENTATION PAGE					Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.						
PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.						
1. REPORT DATE (DD-MM-YYYY) 27-08-2010		2. REPORT TYPE Final		3. DATES COVERED (From - To) August 2007 – April 2010		
4. TITLE AND SUBTITLE SENSORS, DATA ACQUISITION, AND BURN ALGORITHMS FOR EVALUATING CLOTHING AGAINST BATTLEFIELD, FLAME, AND THERMAL THREATS				5a. CONTRACT NUMBER W911QY-07-C-0094		
				5b. GRANT NUMBER		
				5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) Jim Reuther*, A.J. Kuhlman*, Alfred Rossi*, Ivan Tomes*, Isaac Zimmer*, and Carole Winterhalter				5d. PROJECT NUMBER G005881		
				5e. TASK NUMBER		
				5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Battelle Memorial Institute 505 King Avenue Columbus, OH 43201				8. PERFORMING ORGANIZATION REPORT NUMBER		
				G005881-Final Report		
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army Natick Soldier Research, Development and Engineering Center ATTN: RDNS-WSC-M (C. Winterhalter) Kansas Street, Natick, MA 01760-5020				10. SPONSOR/MONITOR'S ACRONYM(S) NSRDEC		
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) NATICK/TR-10/022		
12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.						
13. SUPPLEMENTARY NOTES * Battelle Memorial Institute						
14. ABSTRACT The report summarizes an effort to provide technical guidance to enable the Natick Soldier Research, Development and Engineering Center to make informed decisions and effectively put into practice a thermal-testing facility, which includes an instrumented thermal manikin. This information was obtained by assessing the design, performance, operation, and cost of sensors, data acquisition systems, and burn algorithms used to evaluate thermal protective clothing against battlefield flame and thermal threats. Best-available technical information on test equipment and practices is provided to make reliable, reproducible, expedient, affordable, and safe evaluations of protective clothing. COTS heat-flux sensors and data acquisition systems, as well as state-of-the-art, albeit mature, algorithms for predicting burn injuries are available from more than one source to satisfy the technical requirements.						
15. SUBJECT TERMS						
MODELS	MANIKINS	TEST FACILITIES	THERMAL MANIKINS			
FLAMES	HEAT FLUX	THERMAL TESTS	TEST AND EVALUATION			
SAFETY	STANDARDS	BURNS(INJURIES)	PROTECTIVE CLOTHING			
FABRICS	PROTECTION	FIRE PROTECTION	CONVENTIONAL WARHEADS			
THREATS	PREDICTIONS	SOFTWARE TOOLS	FIRE RESISTANT MATERIALS			
SENSORS	ALGORITHMS	DECISION MAKING	FIRE PROTECTIVE CLOTHING			
BURNSIM	BATTLEFIELDS	DATA ACQUISITION	IED(IMPROVISED EXPLOSIVE DEVICES)			
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON	
a. REPORT	b. ABSTRACT	c. THIS PAGE			Carole Winterhalter	
U	U	U	SAR	36	19b. TELEPHONE NUMBER (include area code) (508) 233-5460	

UNCLASSIFIED

This page intentionally left blank

UNCLASSIFIED

Table of Contents

LIST OF FIGURES	iv
LIST OF TABLES	iv
INTRODUCTION	1
PROJECT OBJECTIVE	1
PROJECT PLAN	1
TASKS AND RESULTS	1
Task 1: Sensors	2
Task 2: Data Acquisition	7
Task 3: Burn Algorithms	8
Task 4: Systems Integration	11
Task 5: Software Template	13
CONCLUSIONS	16
APPENDIX A. BURNSIM INFORMATION	17
APPENDIX B. MetaDAQ USER'S GUIDE	21

LIST OF FIGURES

Figure 1: Three sensors that were evaluated: #1 Copper skin-simulant, NCSU, face not painted black (l); #2 polymeric skin-simulant, Composites USA (c); and #3 calorimetric, Vatel (r).....	3
Figure 2: Response times and measurement errors of Dupont (t) and NCSU (b) sensors.....	4
Figure 3: Copper skin-simulant sensor (l) and polymeric skin-simulant sensor (r).	5
Figure 4: Design specifications of candidate heat-flux sensors.....	5
Figure 5: Solid model drawings of candidate heat-flux sensors.	5
Figure 6: Recommended copper (l in each photo) or polymeric skin-simulant sensors (r in each photo).	7
Figure 7. Recommended data acquisition system hardware and software	8
Figure 8: BURNSIM burn-injury prediction on NSRDEC thermal manikin.	11
Figure 9: Physical view of PyroWeb.	12
Figure 10: PyroWeb processing pipeline.	12
Figure 11: Recommended data acquisition and post-processing systems.	14

LIST OF TABLES

Table 1: Responses to bids for fabricating candidate thermal sensors.	6
Table 2: NSRDEC owned DAQ hardware.	8

ASSESSMENT OF SENSORS, DATA ACQUISITION, AND BURN ALGORITHMS FOR EVALUATING THERMAL PROTECTIVE CLOTHING AGAINST BATTLEFIELD, FLAME, AND THERMAL THREATS

INTRODUCTION

Soldier forces require better protection against the flame and thermal threats from both conventional warheads and improvised explosive devices (IEDs). Current protection against these threats is available in the form of flame-resistant protective clothing.

The report summarizes an effort performed by Battelle Memorial Institute under contract (#W911QY-07-C-0094) to the Natick Soldier Research, Development, and Engineering Center (NSRDEC) to enable NSRDEC staff to make informed decisions and effectively put into practice a thermal-testing facility that includes an instrumented thermal manikin.

Information was obtained by assessing the design, operation, performance, cost, and availability of sensors, data acquisition systems, and burn algorithms used to evaluate thermal protective clothing against battlefield flame and thermal threats.

PROJECT OBJECTIVE

The objective of the project was to assess the design, operation, performance, cost, and availability of sensors, data acquisition systems, and burn algorithms used to evaluate thermal protective clothing against battlefield flame and thermal threats. The problem to be resolved was the lack of understanding of the state-of-the-art of these instruments and models and the lack of details on their associated software. These instruments and models have been employed by industrial, academic, or Government laboratories worldwide for decades without the benefit of a critical comparative assessment.

PROJECT PLAN

The technical approach was for Battelle to act as an honest broker in the collection and comparative assessment of available information on the subject technologies. Metrics for rating the design, operation, and performance of sensors; data acquisition systems; and burn algorithms came from various sources, notably the American Society for Testing and Materials (ASTM). Battelle made use of past and present subject matter experts from NSRDEC, along with information provided in its various technical reports. Once metrics were identified, qualified, and quantified, design and performance data on the subject technologies, along with their cost and availability, were compared. A software template for the overall conversion of sensor data into burn injury predictions was then developed for the preferred integrated system.

TASKS AND RESULTS

The products of this effort are twofold. The first product is best-available technical information on test equipment and practices with which to make reliable, reproducible, expedient, affordable, and safe evaluations of the thermal protection afforded by clothing against battlefield flame and thermal threats. The second product was a software template that utilizes the preferred burn algorithm to translate signals from the preferred sensor(s) into data on the likelihood of first-, second-, and/or third-degree burn injuries to bare or clothed skin.

To develop these products, the following tasks were completed:

Task 1: Sensors;
Task 2: Data Acquisition;
Task 3: Burn Algorithms;
Task 4: Systems Integration; and
Task 5: Software Template.

TASK 1: SENSORS

The objective of Task 1 was to establish, qualify, and quantify the metrics for the design, operation, and performance of available thermal or heat-flux measuring sensors.

No endorsement is implied by listing any commercial-off-the-shelf (COTS) or specialty sensor.

Altogether, evaluations were completed on the performance of 12 thermal sensors from:

- 1) Composites USA, MD, commercial vendor of thermal sensors (DuPont technology);
- 2) Concept Engineering, CT, commercial vendor of thermal sensors;
- 3) Cooper Bussman, MO, user of sensors in electric-arc discharge exposure tests;
- 4) Dupont (Thermo-Man), DE, user of sensors in flame tests on “Thermo-Man” manikin;
- 5) Engineering Technology Inc., VA, commercial vendor of thermal sensors;
- 6) Kinetrics, Ontario, Canada, user of sensors in electric-arc discharge exposure tests;
- 7) Lab for Protection and Physiology, St. Gallen, Switzerland, user of sensors in flame tests on “Euro” manikin;
- 8) Medtherm, AL commercial vendor of thermal sensors;
- 9) North Carolina State University (NCSU), NC, user of sensors in flame tests on “PyroMan” manikin;
- 10) Worcester Polytechnic Institute, MA, user of sensors in flame tests on thermal manikin;
- 11) University of Alberta, CAN, user of sensors in flame tests on “Harry Burns” manikin; and
- 12) Vatell, VA, commercial vendor of thermal sensors.

These sensors could be categorized as being the following:

- Made by commercial vendors and sold openly (2, 8, and 12);
- Made by vendors for sale to specific labs (1, 3-7 and 9); or
- Made in-house for internal use only (10-11).

Performance metrics selected for qualification and discrimination were from ASTM F1930, *Standard Test Method for Evaluation of Flame Resistant Clothing and Protection Against Flash Fire Simulations Using an Instrumented Manikin*:

- Minimum response time (≤ 100 milliseconds, ms);
- Heat-flux limits (8.4 to 84 kilowatts per meter squared, kW m^{-2}); and
- Maximum exposure temperature ($\leq 700^\circ \text{K}$).

Other “qualitative” performance metrics assessed were:

- “Robustness” or “durability”;
- Availability (to NSRDEC); and
- Cost per sensor.

To the extent possible, using the open technical and academic literature (MS theses and PhD dissertations), a database was assembled with information on the design, performance, and economic characteristics of each candidate sensor for comparison.

Upon review of sensor design, operation, and performance, two types of heat-flux sensors were preferred: skin-simulant and calorimetric (Figure 1). The skin-simulant sensors were available as both copper and polymeric fixtures. Of the twelve sources identified only three products (shown in Figure 1) were available for evaluation: #1) a copper skin-simulant sensor from NCSU, #2) a polymeric skin-simulant sensor from Composites USA (DuPont technology), and #3) a calorimetric sensor from Vatell.



Figure 1: Three sensors that were evaluated: #1 Copper skin-simulant, NCSU, face not painted black (l); #2 polymeric skin-simulant, Composites USA (c); and #3 calorimetric, Vatell (r).

Both types of sensors were acceptable according to ASTM F1930 requirements. The three products had the following set of relative characteristics:

- Response time: $3 < 1 < 2$ (1 & 2 may be about >100 ms)
- Durability: $3 > 1 > 2$ (2-faced, made of thermosetting epoxy)
- Accuracy: $3 > 1 > 2$ (based on quality standards)
- Estimated Cost: $2 < 1 < 3$ (based on verbal estimates)
- COTS Availability: 3 (1 & 2 are “homemade” or “proprietary”)

Regarding performance, the most-critical requirement (minimum response time) was measured only for COTS sensors. Only qualitative (“fast”) data were available for other sensors.

Regarding estimated costs, anecdotal estimates ranged from \$200 to \$650 per sensor, with the difference being whether the sensor was delivered “as-is” (lower limit), or if specifications (response time and calibration curves) were provided (upper limit). The calorimetric sensor was eliminated from further evaluation because it’s shape and form were not readily compatible with the instrumented manikin.

The key performance metric, minimum response time (≤ 100 ms), was then quantitatively evaluated for the top two sensors identified: 1) Dupont (Thermo-Man manikin) and 2) NCSU (PyroMan manikin).

Data for this evaluation were taken from *Review and Evaluation of Thermal Sensors for Use in Testing Firefighters Protective Clothing*, NIST GCR 99-773, a report from NCSU to the National Institute of Standards and Technology (NIST) in 1999.

The results are presented in Figure 2 for each sensor in terms of apparent response time and measurement error. Response time was defined as the elapsed time required for the sensor to record the target heat flux, $2 \text{ cal/cm}^2\text{-s}$. Measurement error was defined as the percent deviation from this same instantaneous and constant heat flux, which was generated by a “quartz lamp.”

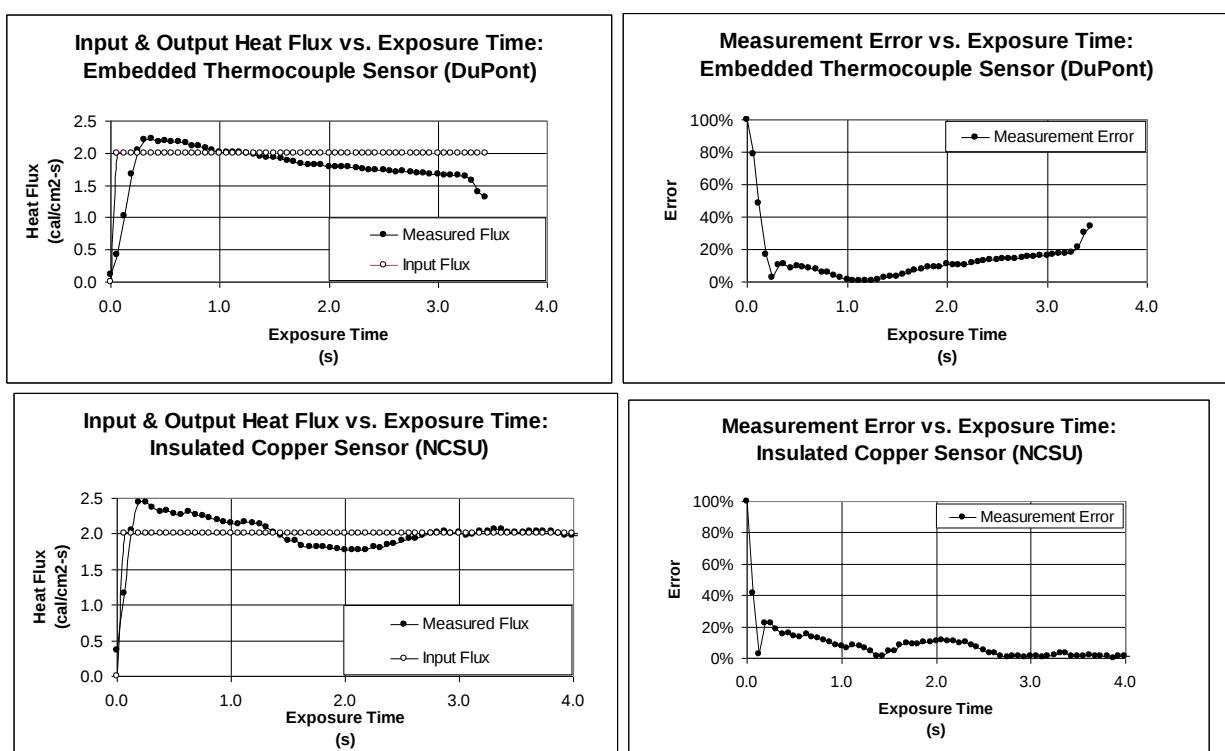


Figure 2: Response times and measurement errors of Dupont (t) and NCSU (b) sensors.

These results, derived from the average of four sets of available data, indicated that response times for the Dupont and NCSU sensors were ~ 200 ms and ~ 130 ms, respectively. This ranking was opposite to that stated in NIST GCR 99-773, wherein the Dupont sensor was described as having a “fast response time” and the NCSU sensor an “adequate response time”. Moreover, these data indicated neither sensor maintained steady-state readings at the $2 \text{ cal-cm}^{-2}\text{-s}$ reference level for much of the interval of 3-4 second exposure.

To better quantify the cost and availability of candidate sensors, detailed drawings were prepared from data in the open technical literature on the thermal sensors identified as best for the ASTM F1930 Thermal Test Facility at the NSRDEC.

Figures 3, 4, and 5 show photographs, design drawings, and solid models, respectively, of both candidate sensors: 1) the copper thin-skin sensor (used in the NCSU PyroMan manikin) and 2) the polymeric skin-simulant sensor (used in Dupont Thermo-Man manikin) with housing removed in Figure 3. The two sensors were somewhat similar in design and dimensions (Figure 4), but were not similar in materials of construction (copper or polymeric).

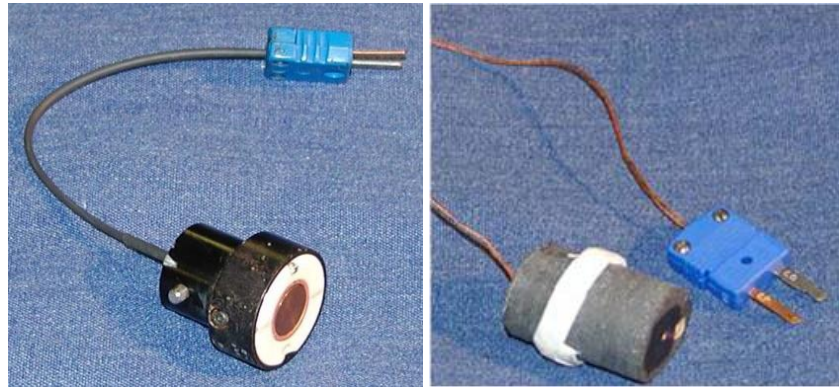


Figure 3: Copper skin-simulant sensor (l) and polymeric skin-simulant sensor (r).

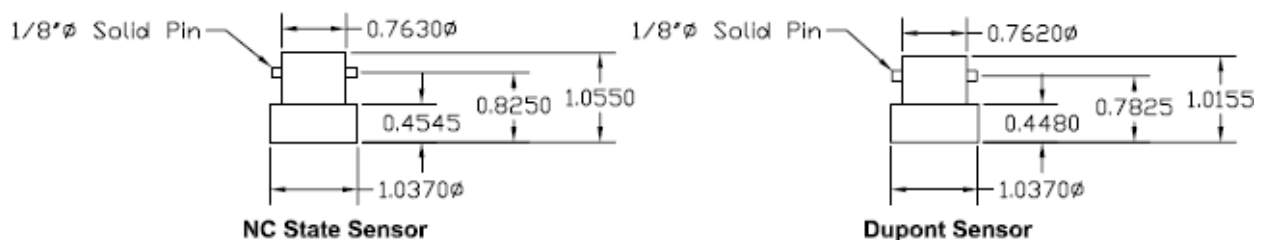


Figure 4: Design specifications of candidate heat-flux sensors.

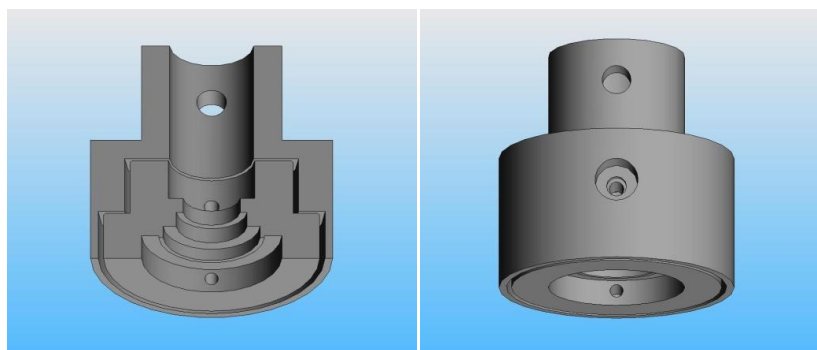


Figure 5: Solid model drawings of candidate heat-flux sensors.

Formal bids were requested from seven vendors to acquire firm price quotes and lead times for the fabrication of these two types of sensors. The request was for 150 to 250 sensors of each type and with as soon as possible delivery. Quotations were requested from the following:

- 1) Acrolab, Ontario, Canada; cbeemer@acrolab.com
- 2) Battelle, Columbus, OH; tolbertb@battelle.org
- 3) Composites USA, North East, MD; jkotch@compositesusa.com
- 4) Concept Engineering, Columbus, OH; conceptinc@aol.com

- 5) Marlin Manufacturing, Parma, OH; sales@marlinMFG.com
- 6) Medtherm Corporation, Huntsville, AL; medtherm@comcast.net; and
- 7) Vatell, Christiansburg, VA MKT@vatell.com.

[No endorsement is implied by listing any manufacturer or vendor.]

The additional information provided on construction was as follows:

- Sensors:
 - Sensing element will be a copper (C101) disk: 0.06 inch thick.
 - Thermocouple wire will be 30 gauge (T-type).
 - Thermocouple wire will be welded to center of copper disk per ASTM E459-05.
 - Thermocouple wire will be 6-inch, with NMP-T male T-type micro connector.
 - Exposed side of the sensing element will be painted a flat black.
- Housing materials:
 - Bids for sensor housing can be made for both casting and machining processes:
 - For cast sensors, supplier is to manufacture a mold to cast the sensor to specifications, as well as to cast completed sensor with specified material.
 - For machined sensors, supplier is to machine housing, and press fit sensor.
 - Material used can be ceramic and high-temperature polymer materials:
 - Castable ceramic to be used is Rescor Silica ceramic 750
 - Machinable ceramic to be used is silicon carbide.
 - Machinable polymer material to be used is mechanical grade polytetrafluoroethylene (PTFE).

Table 1 lists responses to these formal bid requests.

Table 1: Responses to bids for fabricating candidate thermal sensors.

Potential Vendor	Bid Status	Cost Per Sensor	Lead Time	Qualifications
Acrolab	Bid for housing	Unknown	NA	No bid for sensor
Battelle	Bids received	\$167 (150 Type 1) \$156 (250 Type 1)	8-12 weeks	No calibration data
Composites USA	Bids received	\$256 (150 Type 1) \$247 (250 Type 1)	8-12 weeks	No calibration data
Concept	No bid	NA	NA	NA
Marlin	No bid	NA	NA	NA
Medtherm	No bid	NA	NA	NA
Vatell	Bids received	\$197 (150 Type 1) \$186 (250 Type 1)	90-120 days	No calibration data

NA = Not applicable, Type 1 = copper skin stimulant, Type 2 = polymeric skin stimulant

Altogether, there were three complete bids, one partial bid, and three no bids. None of the vendors bid on the Type 2 sensor, probably because it required molding somewhat unique polymeric material (“skin simulant”) requiring specialized equipment. Of the vendors that bid on making Type 1 sensors, only Composites USA had experience doing so, noting in its bid that these “thermocouple sensors fit into manikins we currently manufacture for private, Government (US), and university laboratories around the world”.

After acquiring this information, near the conclusion of the project, NSRDEC became aware of Engineering Technology, Inc (ETI), not included in the original bid list. Because of the growing demand for manikin-mountable thermal sensors for use at Government, industrial, and research laboratories, ETI began manufacture of a copper skin-simulant sensor as a more durable alternative to the polymeric skin-simulant offered by Composites USA; these are shown side-by-side in Figure 6 (ETI on right in each photo). The NSRDEC procured ETI sensors at \$183.50 each, which came with a thicker insulated cable and an additional strain gauge. The ETI sensors performed well in the NSRDEC lab. Because of performance, price, and availability, sensors from both ETI and Composites USA were recommended.



Figure 6: Recommended ceramic (l in each photo) or copper skin-simulant sensors (r in each photo).

Task 1 was completed with the delivery of this information to NSRDEC.

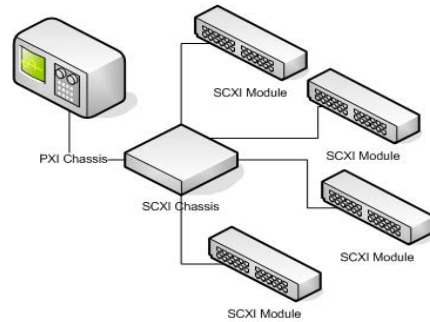
TASK 2: DATA ACQUISITION

The objective of Task 2 was to establish and qualify and quantify the metrics for the performance and cost of data acquisition systems (DAQS). The DAQS evaluated included COTS devices from three candidate COTS vendors that transmitted (wired or wire-less) or processed signals at response times required by sensors and burn algorithms, as follows [no endorsement implied]:

- Fluke;
- meDAQ; and
- National Instruments (NI).

Because of Fluke's limited speed and storage and meDAQ's excessively fast (much faster than ASTM F1930 "once per 0.5 second") sampling speed, NI was identified as the preferred product, in combination with LabView software. This combination had been used by manikin-test labs (NCSU and University of Alberta). Task 2 was completed by recommending the setup shown schematically in Figure 7, consisting of COTS NI hardware and LabView software.

Recommended NI DAQ Set up:



- 1 PXI Chassis w/DAQ card
- 1 SCXI Chassis
- 4 SCXI DAQ Modules (32 channels each)
- Custom LabView program forwards acquired data to centralized database

Figure 7. Recommended data acquisition system hardware and software

Battelle then confirmed that the hardware purchased by the NSRDEC for its ASTM F1930 Thermal Testing Facility was adequate for its needs. This hardware is listed in Table 2, along with its unit costs.

Table 2: NSRDEC owned DAQ hardware.

Part #	Description	Quantity	Unit Cost	Total Cost
SCXI-1001	12-Slot Chassis	1	\$1,749	\$1,749
SCXI-1102	32-Channel Amplifier & Signal Conditioner	4	\$1,399	\$5,596
SCXI-1600	USB DAQ & Control Module	1	\$1,099	\$1,099
SCXI-1303	32 Channel Isotherm & Terminal Block	4	\$ 299	\$1,196
				\$8,640

List provided by NSRDEC.

TASK 3: BURN ALGORITHMS

The objective of Task 3 was to evaluate burn algorithms, along with the software to convert sensor heat-flux data or hypothetical thermal loads into skin-burn injury predictions. The following metrics were the basis for selection:

- Prerequisite: ASTM F1930 recommendations;
- Precedence: used by other test labs using manikins;
- Applicability: to flame threats of direct interest;
- Versatility: to work with multiple test methods;
- Reliability: extensive burn-prediction database; and
- Availability: source code/documentation.

Programming languages evaluated for use in the software template were COTS (no endorsement):

- C++;
- G (LabVIEW); and
- FlexPro (Microsoft).

Burn algorithms evaluated included those developed by researchers such as:

- Stoll and Chianta (S&C);
- Henriques and Moritz (H&M),
- Torvi, and
- Knox.

To initiate the evaluation, Battelle met with the principal developer of the burn algorithm BURNSIM Dr. Ted Knox, at the Bioscience and Protection Directorate, Air Force Research Laboratory, Wright-Patterson Air Force Base (WPAFB). Dr. Knox provided Battelle with Version 3 of BURNSIM for analysis and equipment algorithm development. Further information regarding BURNSIM, its development, where to obtain it, and how to use it is provided in Appendix A.

Battelle then reviewed reports from the ASTM Technical Committee on Personal Protective Clothing and Equipment (F23), which assessed the Skin Burn Injury Model in ASTM F1930. Overall qualitative findings from evaluating the named algorithms were as follows:

- S&C: Simple to use, but limited to only rectangular thermal pulses and second-degree burns.
- H&M: Endorsed by ASTM F1930, but “confusion and controversy” over Ω factor.
- ***S&C and H&M may predict different burn injuries from the same data set.***
- Torvi: Ongoing development, but focused on long exposures (~30 seconds).
- Knox (BURNSIM): Ongoing development, versatile, recognition, but more complex.

Detailed analysis focused on the aforementioned “confusion and controversy” regarding the H&M model. The burn injury prediction method of H&M can be summarized in two steps. First, the temperature history of the epidermal-dermal interface is estimated. Next, this temperature history is used to compute the value of the damage integral (Equation A1.2 in ASTM F1930). The degree of injury is then determined from the value of Ω : first-degree burns are predicted for $0.5 \leq \Omega \leq 1$, while second-degree burns are indicated by values of Ω that exceed 1. A similar algorithm can be applied at the dermal-subcutaneous boundary for predicting third-degree injuries.

ASTM F1930 provides several constants necessary for the calculation of the temperature history and the damage integral. There is, however, ambiguity in the calculation of the temperature history. The results of this step are dependent on several factors, including the degree to which physiology is taken into account and the exact numerical method used to solve the underlying differential equation. In most cases, these differences are only discussed qualitatively, leaving out crucial details necessary to replicate the results of a given report. Without exact details of these calculations, a meaningful comparison is not possible.

To work around these issues, a version of the H&M algorithm was developed that behaved mathematically and reproduced results using the BURNSIM algorithm, although the temperature histories produced by these two algorithms were not the same (nor should they be). At their core, the H&M and BURNSIM algorithms are essentially the same. The BURNSIM algorithm could

be converted to the H&M algorithm through a judicious choice of constants. This approach would also provide a (somewhat indirect) path to obtain an “H&M-like” algorithm.

There also appears to be some confusion regarding calculating the temperature history of the basal layer. Some favor the Crank-Nicholson algorithm to solve the diffusion equation, though the exact nature of the equation being solved is somewhat fluid. H&M seem to suggest “integrate the Arrhenius equation after determining the temperature history in any manner seen fit.”

These issues need to be resolved. If the H&M model is not employed in exactly the same historical manner, present and future comparisons would be equivocal.

Task 3 was completed with the selection of BURNSIM (Knox) as the preferred burn-injury prediction algorithm and the H&M ASTM F1930 model as the reference burn-injury algorithm.

BURNSIM was preferred as the method for post-processing heat-flux data because it has:

- Modules that allow customization to varying ambient conditions and physiologies;
- Interchangeably to time-to-burn predictions when bare skin is exposed;
- Adaptable to burn-injury predictions from manikin or lab-scale tests;
- Ability to accommodate any form of time history of heat flux;
- Available code documentation in user-friendly format;
- Extensive database using very detailed physiologies;
- Promise of predicting protective effects of clothing; and
- Available source codes.

H&M was selected as reference model only because its use would be the only means to make an “apples-to-apples” comparison of historical data on burn-injury predictions.

The preferred burn algorithm would be used to convert raw heat-flux data into a format that would provide direct data with regard to predicted burn injuries and the extent of protection afforded by clothing, as shown in Figure 8.

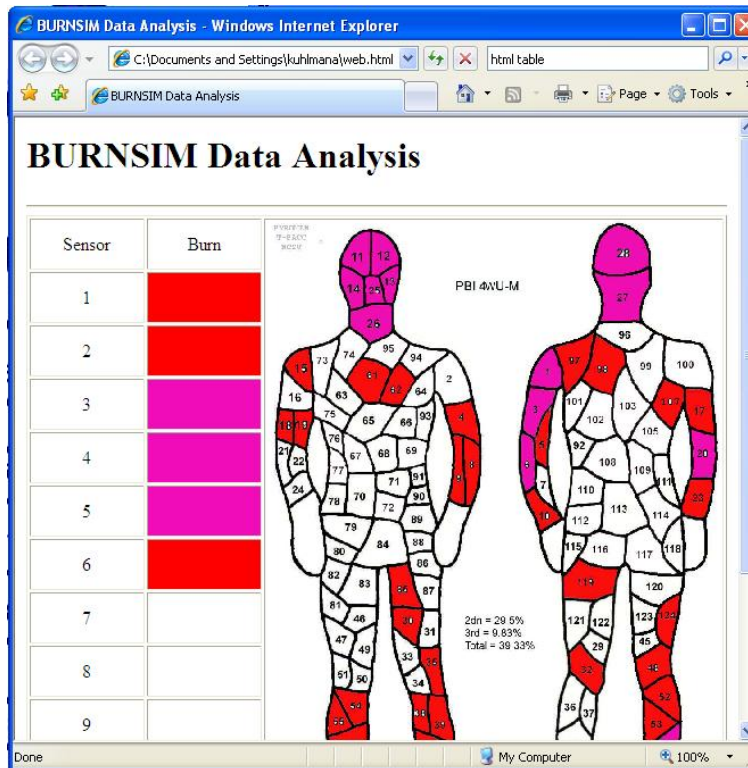


Figure 8: BURNSIM burn-injury prediction on NSRDEC thermal manikin.

TASK 4: SYSTEMS INTEGRATION

The objective of Task 4 was to integrate sensors, data acquisition, and burn algorithms into an operating system in which acquired sensor readings were converted into burn-injury predictions.

To meet this objective, an integration tool was developed called "PyroWeb" (Figures 9 and 10). [This tool has no association to others with similar sounding names, such as NCSU PyroMan]. This "Web" takes streams of raw sensor data from lab instrumentation and associates them to each appropriate parameter, such as sensor location on the manikin or calibration factors. Preliminary transformations are performed and the data passed off to an analysis component (H&M and/or BURNSIM). The results of the analysis sub-problems are then aggregated and combined into a report on burn-injury predictions. As such, this tool is the underlying class model and database schema for automated analysis of data and report generation (Figure 8).

Some of the prerequisite needs for such an integration tool were to be or do the following:

- Inherently graphical, hiding complication by using menus, and navigable using a mouse;
- Configured to automatically handle routine tasks (calculations, and report formatting);
- Use domain-specific language for queries (SQL) common to databases;
- Inherently multiuser, allowing whole teams access;
- Command-line based interfaced; and
- Reduced learning curve.

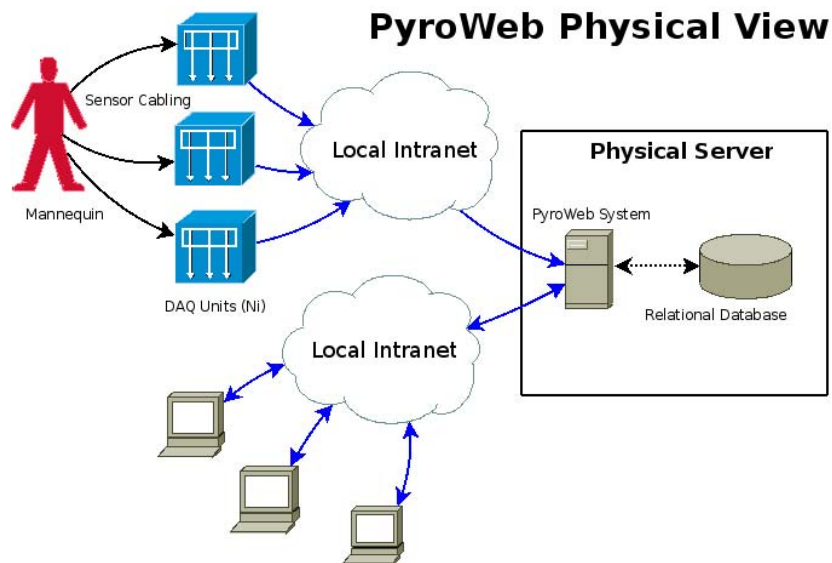


Figure 9: Physical view of PyroWeb.

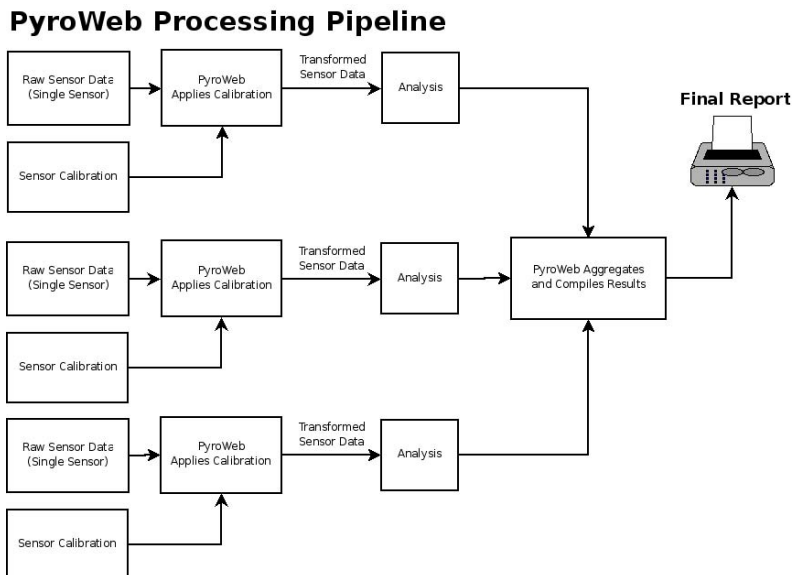


Figure 10: PyroWeb processing pipeline.

Recommended support systems and interconnects for PyroWeb included the following:

- Dedicated central server to host database, webserver, algorithms, and interfacing software;
- Database on server for post-test analysis and storage;
- Human/server interface facilitated with a web-based tool;
- Communication between DAQ/server via Ethernet; and
- Custom DAQ/LabView to forward acquired data to database

The database would have the following functions:

- Organize raw and processed data;
- Simplify information storage, retrieval, and backup;
- Be queryable to ask quantitative questions and get quantitative answers; and
- Be reliable, maintaining integrity between transactions.

The software recommended to do this by Battelle was MySQL, available open source.

No specialized hardware would be required, other than a dedicated PC. Network access could be set up for local (lab) use only. The system could be operated on Linux or some other UNIX variant. The cost would be inexpensive (~\$400).

Task 4 was completed by using the software tool to collect and convert streams of raw data from Battelle HERLA heat-flux sensors, data acquisition equipment, and IED fireballs in real time (minutes) into a report on the actual magnitudes of flame threats (kW/m^2) and predictions for skin-burn injuries using the BURNSIM algorithm. Data conversion was equivalent, whereas burn-injury predictions using BURNSIM were often more severe than those predicted using the H&M model, an issue reported earlier in flame tests in other thermal protection laboratories.

TASK 5: SOFTWARE TEMPLATE

The objective of Task 5 was to provide a template for converting sensor data into burn-injury predictions. The template would incorporate all the hardware and software recommended in Tasks 1-4.

In association with this effort, Battelle analyzed burn-injury predictions in two reports received from NSRDEC: 1) *Thermal Protective Performance (TPP) and the PyroMan Evaluation*, 1999; and 2) *Characterization of Test Garments Using the PyroMan System*, 2003, both published by the Center for Research on Textile Protection and Comfort, NCSU. The objective was to determine the probability of burn injuries as a function of body location on the manikin.

Analysis of the data reported revealed that in all the ensemble tests conducted on the manikin:

- About 11% of sensors (14 of 124) never recorded a second-degree burn, whereas about 29% (36 of 124) never recorded a third-degree burn;
- Only two sensors always reported a 100% probability of a second-degree burn (on the left and right forehead); and
- Only two sensors ever reported any probability of a third-degree burn (again, on the left and right forehead), and in both cases, it was 100%.

Also as part of this task, Battelle continued to interact with Dr. Ted Knox on his efforts to improve and update his BURNSIM algorithm. Current changes included the user being able to:

- Specify blood flow as a function of temperature rather than time;
- Specify the damage rate at which the blood flow stops; and
- Combine the heat flux from different sources including radiant, convection, and conduction.

These revisions were expected to have a dramatic influence on skin-burn injury predictions from the flame threats being evaluated in this program.

The data acquisition and post-processing system recommended for this template comprised an NI DAQ system connected to a centralized server via an Ethernet network. This server could then be accessed from one or more workstations to automatically generate test reports. A diagram of the components of this system and how they interrelate is shown in Figure 11.

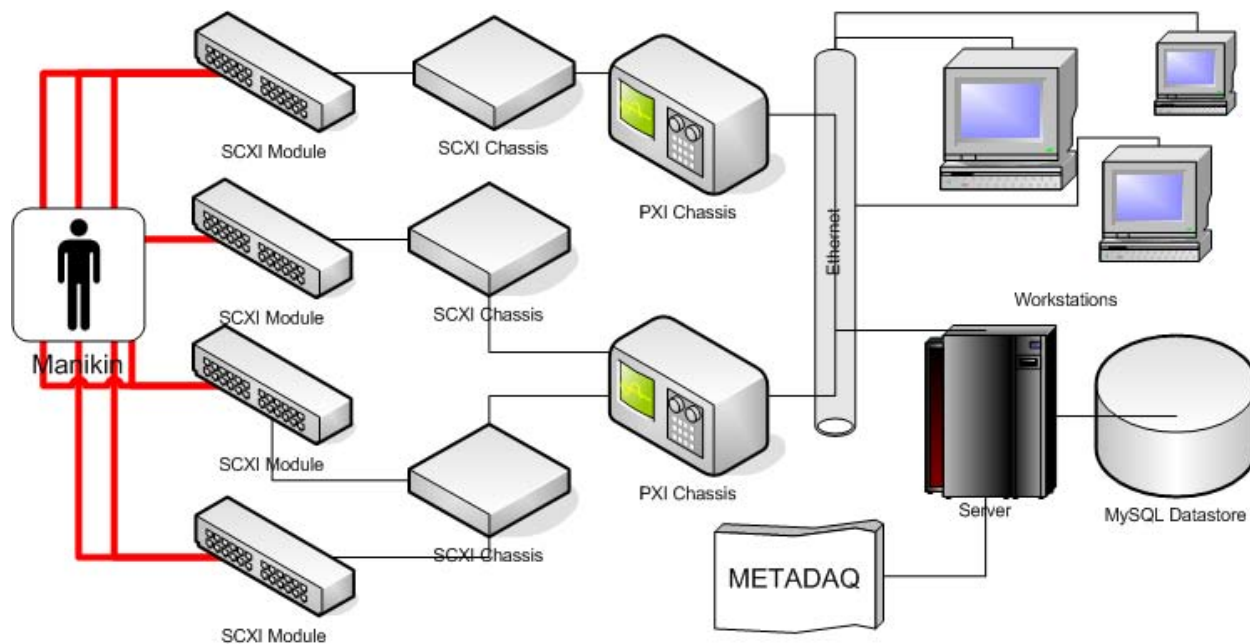


Figure 11: Recommended data acquisition and post-processing systems.

The NI DAQ system would be made up of a number of subcomponents. The manikin would be outfitted with heat-flux sensors that plug directly into an NI Signal Conditioning Extension for Instrumentation (SCXI) module. For this application, Battelle recommended the SCXI-1102b module or equivalent with the SCXI-1303 terminal block. The SCXI-1102 module is adequate to comply with ASTM F1930 specifications. The SCXI-1102 series modules provide signal conditioning that is ideal for the types of sensors under consideration. Each module has 32 differential analog input channels. Therefore, four SCXI modules would be required to account for all 122 heat flux sensors present in a fully instrumented manikin at NSRDEC.

The SCXI modules would be connected to a suitable SCXI chassis (-1000 model recommended). This chassis provides four slots for SCXI modules. It would therefore be suitable for the application at hand, allowing for up to 128 sensors. If the number of sensors was increased in future tests, it would then be necessary to purchase an additional SCXI chassis to accommodate more SCXI modules or to acquire a different chassis that would provide more than four slots. The SCXI chassis multiplexes the incoming voltage signals and relays them to an NI PCI Extensions for Instrumentation (PXI) module (-6220 recommended). This module is connected to a PXI chassis (-1042 recommended). The PXI chassis consists of an onboard computer running Windows XP and a custom LabView or LabWindows application connected to a number of slots via a high-performance bus. The incoming voltage signal is digitized by the PXI module

and passed to the onboard computer. The custom LabView or LabWindows application is then responsible for further handling of the data, either storing it locally or uploading it to a centralized database (recommended).

To facilitate the post-processing of the acquired data, a computer, referred to herein as the server, would be connected to an Ethernet network. This computer would run a number of services including, but not limited to, a relational database management system, a web server, and a custom report generation tool known as MetaDAQ.

The server was not meant to be operated locally; instead it is controlled through a series of menus which are accessible via a web browser by an external computer. This server need not be Internet accessible. The only requirement would be that it be made accessible to one or more workstations connected to the server through a local area network.

In this scheme, the PXI chassis would be connected to an Ethernet network. This network connection allows a custom LabView virtual instrument to forward the acquired data to the relational database management system running on the server for further processing.

Automated report generation through the MetaDAQ becomes possible once raw data is available in the database. A user wishing to generate a report connects to the server via a web browser from his or her workstation. From there, the user either specifies an experimental setup or selects one from a pre-existing list. The experimental setup contains information about which components are connected to which channels, the types of components, component specific calibration constants, and any other contextual data needed for report generation (e.g., the location of a particular sensor on the manikin). Once a setup has been selected, additional reporting options can be specified before proceeding with the report generation. These options include digital signal filtering and the application of a particular burn algorithm to the data, as well as more mundane choices such as which plots to include in the final report.

MetaDAQ automates the report generation process. Specifically, MetaDAQ applies channel specific calibration to each channel and then passes the calibrated data through a burn algorithm or other such per-sensor calculation. The results are then re-associated with contextual information about each sensor (e.g., sensor location) before generating the final report. This final report would include descriptive text explaining how the data were handled and transformed. Additionally, various plots, diagrams, tables, and other items could be produced in accordance with user specified options. MetaDAQ compiles these elements into a report and succinctly summarizes the results with a color-coded map relating sensor location and degree of injury. The user is then presented with a comprehensive report that details the results of the test. Final reports are archived for later retrieval through MetaDAQ.

Task 5 was completed by developing a working software template for loading onto NSRDEC hardware and an associated User's Guide, or "flip book", which appears in Appendix B. Battelle also completed a custom report generation tool. The template includes the latest BURNSIM algorithm; the revised source code was provided by Dr. Knox.

CONCLUSIONS

As a result of this effort, the state-of-the-art of these instruments and models, and the details on their associated software are now better characterized and understood. Best-available technical information on test equipment and practices has been provided with which to make reliable, reproducible, expedient, affordable, and safe evaluations of protective clothing using an instrumental thermal manikin.

Commercial-off-the-shelf heat-flux sensors and data acquisition systems, as well as state-of-the-art, albeit mature, algorithms for predicting burn injuries are available now from more than one source to satisfy NSRDEC technical requirements.

APPENDIX A

BURNSIM INFORMATION

Burn CD and Manual BURNSIM Version 3.0.2 24Nov08

Disclaimer

The Government makes no express or implied warranty as to any matter whatsoever including the conditions of the research or any product agreement or of the merchantability, validity, suitability, or fitness for a particular purpose of the research or product developed from the use of the BURNSIM model. In no event will the Government be liable to any other party for compensatory, punitive, exemplary or consequential damages. The Government is neither liable nor responsible for maintenance, updating or correcting any errors in the model or the provided data. The user accepts all risks and responsibilities from the use of this model.

Files on the CD:

Readme First.doc

Folder Burnsim 3.0.2

This folder contains the current version 3.0.2 of the model. The earlier 3.0 version of model was modified during the July-December 2007 time period. The model was first upgraded from VB6 to VB.Net. Then new screens were added to the program for using BURNSIM to predict the burn depth based the TPP value alone, based on a time history of the calorimeter behind the fabric, or based on the time histories of the calorimeter temperature and of the radiant heat flux. The screen for inputting the heat flux according to heat flux type was extensively revised so that the input heat flux could include a combination of heat flux from radiation, conduction and convection. The program was also modified so that the user could input a file containing the blood flow rate as a function of temperature. This allowed the blood flow to be optimized to match the time-to-threshold burn from A. Stoll's empirical data for human skin. The program was then optimized to match the trend line for the deeper burns.

The program assumes that the Microsoft .Net framework version 2 is installed on the computer. The installation file in a subfolder under the Burnsim 3.0.2 folder. Microsoft Excel version 2003 or 2007 is required if the option for creating an Excel plot is used. The program may not run from a network drive under the default permissions for the .Net framework. The user needs to have read and write permissions for the folder where the program is installed.

Folder Setup

The folder contains 6 setup files as examples.

Pig294rf17Dec07.setup

UsaarlBlackened_17Dec07.setup

The Pig294rf17Dec07.setup file contains parameters for the test 294RF burn from the USAARL pig burn data. This setup file can be used as a starting point for the other USAARL tests with burns to bare pig skin. The UsaarlBlackened_17Dec07.setup file is similar to the file for test pig294rf but is intended to be used for USAARL tests involving blackened pig skin. The setup file for the bare pig skin tests is configured for flux penetration of the skin surface although there

is very little penetration for the wavelengths in the spectrum from the JP4 fires of the USAARL tests. The setup file for blackened pig skin assumes that there is no flux penetration of the skin surface.

ASToll01Cal338Sec17Dec07.setup

TPP_17Dec07.setup

The ASToll01Cal338Sec17Dec07.setup file contains parameters for the 0.1 cal/cm²-sec heat flux for Alice Stoll's human time-to-threshold blister data. The setup for the 0.3 cal/cm²-sec heat flux is built into the program as the default. The TPP_17Dec07.setup file is similar except that it assumes an absorptivity of 1 instead of 0.94. The TPP setup file is the setup file for Table 1 in ISO 17492 and ASTM D4108. The file assumes a heat flux of 1.2 cal/cm²-sec but the user can use the TPP Value page under the TPP Test screen to look at other exposure time, heat flux combinations. But the user should be using the TPP_17Dec07.setup file as a starting point when using the TPP test options.

RoUR394_17Dec07.setup

This setup file contains parameters for the Rochester UR-394 bare skin data.

RoUR438Black_17Dec07.setup

This setup file contains parameters for the Rochester UR-438 blackened skin data.

The folder also contains two files that demonstrate the format of the files that are used for calculating the skin reflectivity and linear absorption coefficients in the "Calculate Absorptivity from Spectrum" form. File AbsorptivitySpectrum.csv is a file containing wavelength, reflectivity and linear absorption coefficients. It contains skin properties that can be used for any input spectrum. The values are stored in a file instead of being built into the program so that they can easily be changed without modifying the program itself. File RoCarbonArcSpectrum.csv is an example file containing the spectrum for the University of Rochester carbon arc heat source that was used for UR-394.

The CD also includes several document files containing manuals for the BURNSIM model and other burn related material.

The files are:

Folder Recent Documents

BURNSIM Users Guide v3.0.2, 24Nov08 with added sample runs and documentation of the mathematics underlying the model.

DRAFT Final Report for PM-CIE 4Jan08

Folder Other Documents

This folder contains 27 related documents such as previous versions of the user manual, presentations, technical papers, etc.

It should be noted that improvements have been made to the BURNSIM model that are not discussed in some of the user manuals that are included on the CD. For example, the original

version of the manual describes the model as having 12 nodes in the skin whereas now it has 89 nodes in the skin and 50 nodes in the fat layer. These changes are covered in the help file for the BURNSIM model and in the user manuals. The BURNSIM version 3.0.2 user manual and source code documentation contain the most up-to-date information.

Comparison to Empirical Data

The Comparisons subfolder contains 5 spreadsheets that compare the time-to-pain, time-to-threshold blister and burn depths that are predicted by the BURNSIM model to empirical data. Although the skin properties values in the model were optimized to match the empirical data to the extent that time allowed, the skin property values can probably be improved in the future, especially for very short duration exposures and long duration exposures with low heat flux levels.

AStollTimeToPain_17Dec07.xls : Comparison to A. Stoll, time-to-pain, time-to-threshold blister and surface temperature for blackened human skin.

CompareTppBurnsim17Dec07.xls : Graphs showing the comparison of the BURNSIM results to the time-to-second degree burn in Table 1 of ISO 17492 and ASTM D4108.

RoU438BlackenedComparison17Dec07.xls : Comparison to University of Rochester UR-438 blackened pig skin burn depths.

RochesterU394ComparisonPen17Dec07.xls : Comparison to University of Rochester UR-394 bare pig skin burn depths. The heat flux source was a carbon arc and spectrum contained ultraviolet, visible and infrared light with wavelengths mainly below 1.2 micrometers. About 40% of the incident heat flux was reflected and some of the heat flux penetrated the skin beyond the epidermis.

UsaarlGroup1Comparison17Dec07.xls : Comparison to USAARL bare and blackened pig skin burn depths. The heat flux source was a JP4 fire and the spectrum was in the infrared with wavelengths mainly above 1.2 micrometers. It is estimated that about 10% of the heat flux was due to convection. At these longer infrared wavelengths, it is estimated that only about 10% of the incident heat flux was reflected and almost all of the heat flux was absorbed in the epidermis.

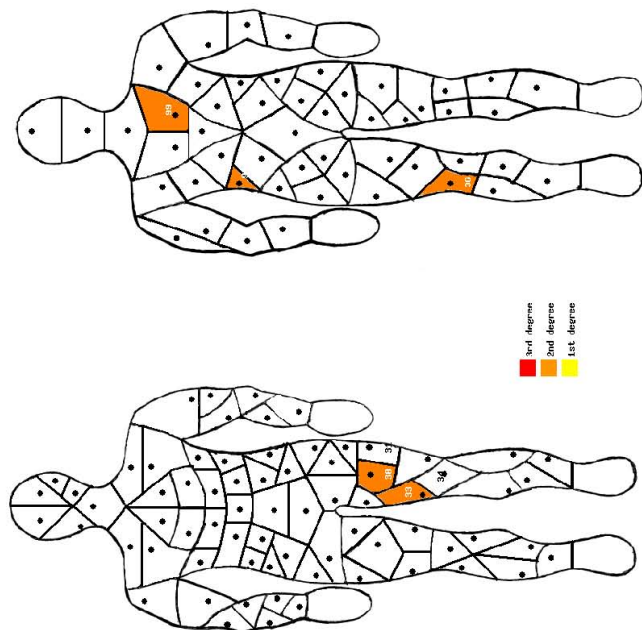
Contact information:

Ted Knox, Ph.D.
Principal Scientist
AFRL/HEPA
2800 Q. Street, Bldg. 824
WPAQFB OH 45433-7947
937-255-0410
Ted.Knox@wpafb.af.mil

Steve Mosher
General Dynamics

AFRL/HEPA
2800 Q. Street, Bldg. 824
WPAQFB OH 45433-7947
937-904-7091
Steve.Mosher@wpafb.af.mil

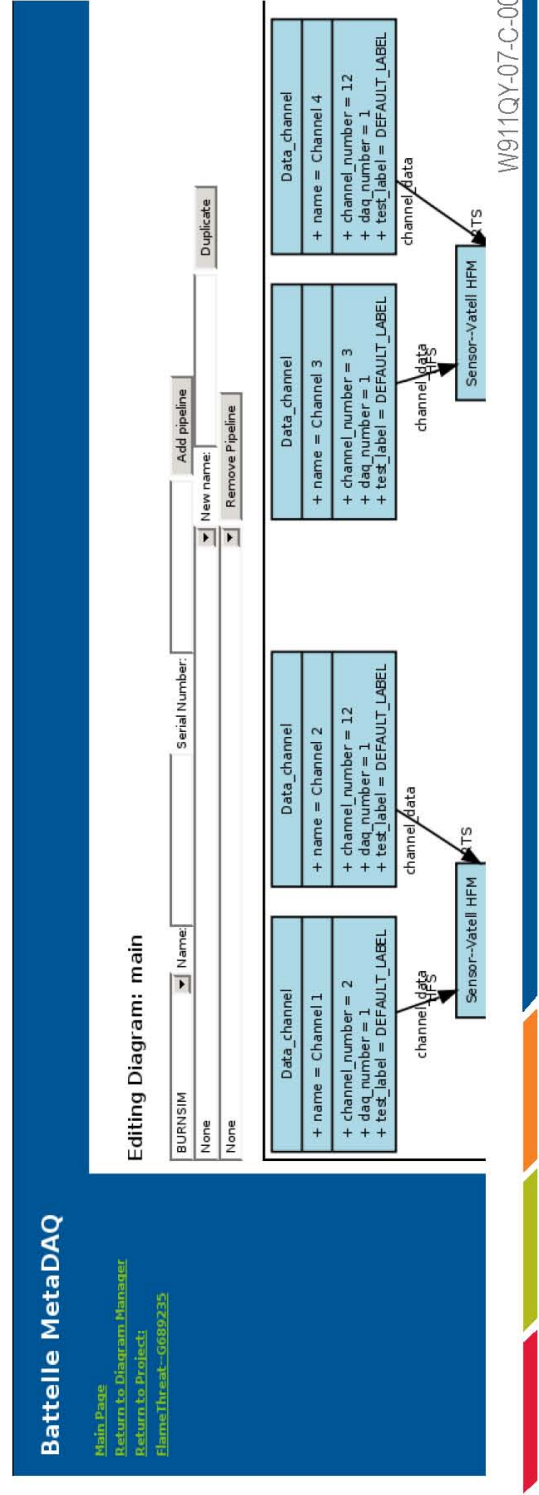
Task 5: Software Template: MetaDAQ, as applied to Thermal Protective Testing



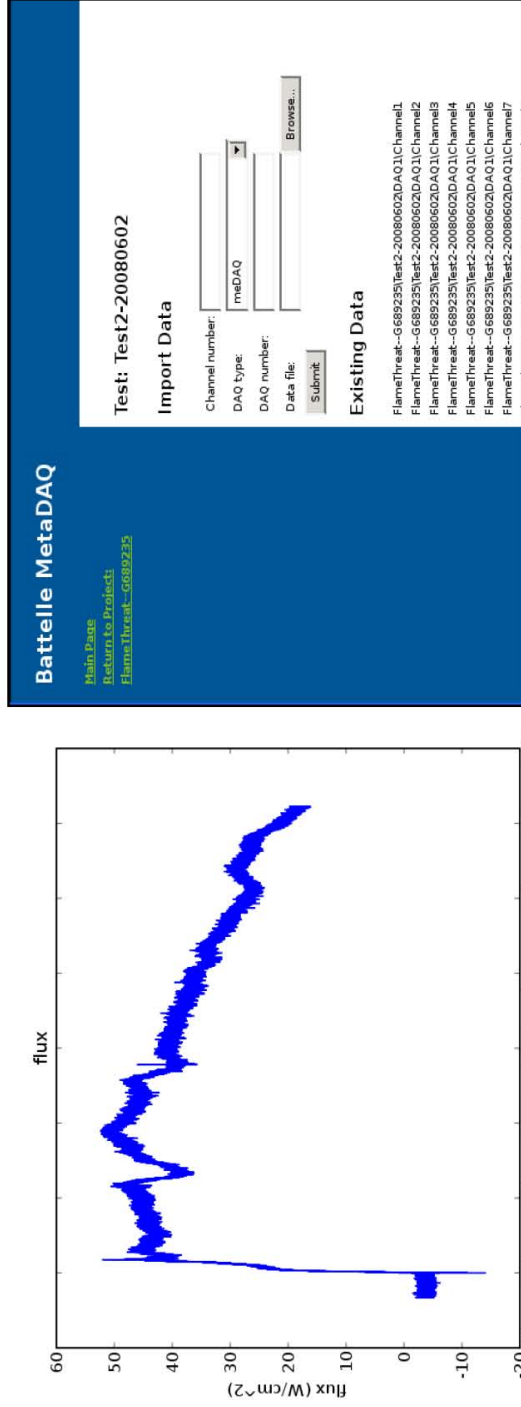
ASTM F1930

MetaDAQ

All projects performing testing require the ability to post-process data. Since the type of data acquired can vary from task-to-task, processing these data can be a time-consuming and costly process. Time spent manipulating data by applying the same transformations repeatedly to every data channel is not an efficient use of staff time and is often a source of error. MetaDAQ streamlines this process, thereby removing this potential for human error, adding accountability and reducing post processing time and cost.



MetaDAQ



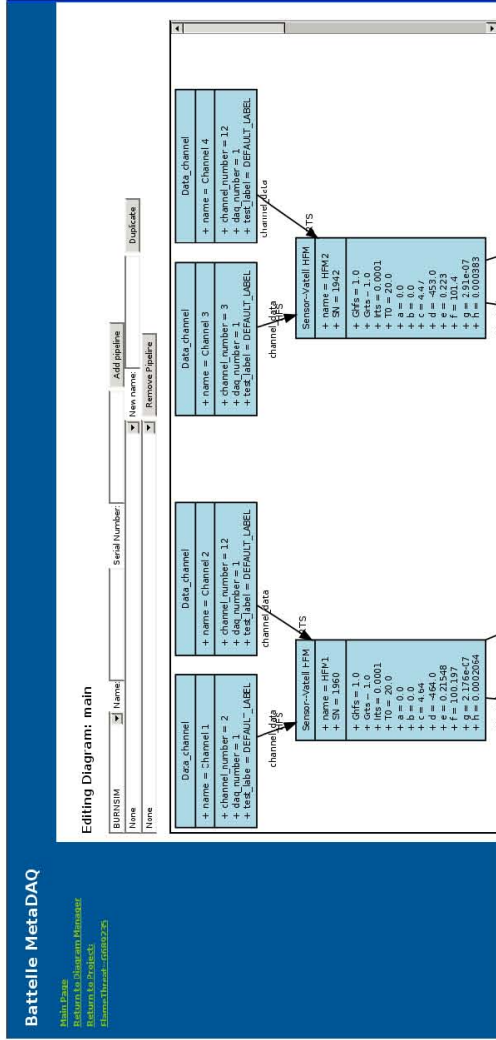
MetaDAQ features a centralized repository, providing an always-on, shared, and collaborative working environment for data analysis. This tool mitigates the effects of incompatibilities between a wide range of data-acquisition systems and specialized laboratory equipment and automates the processing of data and the report generation process.

Features

- Database connectivity provides network accessible, collaborative environment for your data processing team
- Test data and reports are easily organized by project, simplifying archiving and retrieval
- Test reports are stored in a central repository allowing for on-demand access

The image displays two screenshots of the Battelle MetaDAQ web application interface. Both screenshots have a blue header with the Battelle logo and the tagline 'The Business of Innovation'. The left screenshot shows the 'Existing Projects' page, which includes a table with project details and a 'Go' button. The right screenshot shows the 'Create New Project' page, which includes input fields for 'Project Name' and 'Charge Number', and a 'Submit' button.

Features



- Has intuitive, graphical representation of data processing
- Incorporates Knox BURNSIM v3.0 burn-injury prediction algorithm for conversion of measured heat flux by the sensor into an injury prediction in terms of 2nd and 3rd degree burns
- Allows wide variety of transformations
- Extendable to new transformations and sensor types

Workflow

The first step when working with MetaDAQ is the creation of a new project. This project will store all future data and reports generated for the test series.

[Main Page](#)

[Return to Project: FlameThreat--G689235](#)

Battelle MetaDAQ

Existing Projects

New Project

Create New Project

Project Name: FlameThreat

Charge Number: 77193-2

Submit

Test: Test2-20080602

Import Data

Channel number:

DAQ type:

DAQ number:

Data file:

Submit

Browse...

Existing Data

FlameThreat--G689235Test2-20080602DAQ11Channel1

FlameThreat--G689235Test2-20080602DAQ11Channel2

FlameThreat--G689235Test2-20080602DAQ11Channel3

FlameThreat--G689235Test2-20080602DAQ11Channel4

FlameThreat--G689235Test2-20080602DAQ11Channel5

FlameThreat--G689235Test2-20080602DAQ11Channel6

FlameThreat--G689235Test2-20080602DAQ11Channel7

FlameThreat--G689235Test2-20080602DAQ11Channel9

FlameThreat--G689235Test2-20080602DAQ11Channel8

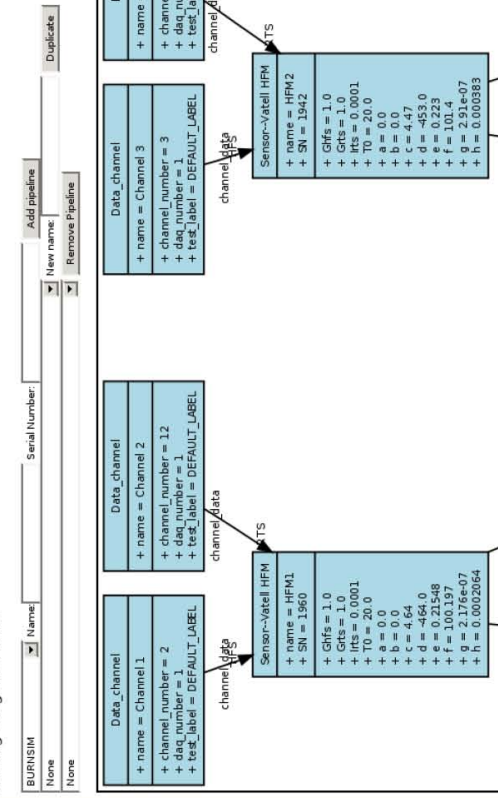
FlameThreat--G689235Test2-20080602DAQ11Channel10

FlameThreat--G689235Test2-20080602DAQ11Channel11

FlameThreat--G689235Test2-20080602DAQ11Channel12

After creating the project, it is possible to import data from individual tests into the database. Alternatively, data can be directly uploaded from the DAQ system into the MetaDAQ database.

[Main Page](#)
[Return to Diagram Manager](#)
[Return to Project](#)
[Flame Threat - G689235](#)



W911QY-07-C-0094

Workflow

The preprocessor feeds a number of *report generation units* (RGU). RGUs represent individual elements of a finished report, *i.e.*, plots, images, tables, *etc.* RGUs can be selected in any desired order, allowing complete freedom in designing the final report.

The final step of report generation is to assign the outputs of the preprocessor to the available inputs of the RGUs. Again, it is only necessary to complete this step once. Subsequent tests are able to reuse preexisting report generator setups.

[Main Page](#)
[Return to Project:](#)
[ElansThreat_0609235](#)

Battelle MetaDAQ

Editing Report Generator: generator-20080702

Available Preprocessors

Report Generation Units

Add a Report Generation Unit

Burned Manikin Map Name:

Existing Report Generation Units

[fluxplot1](#)

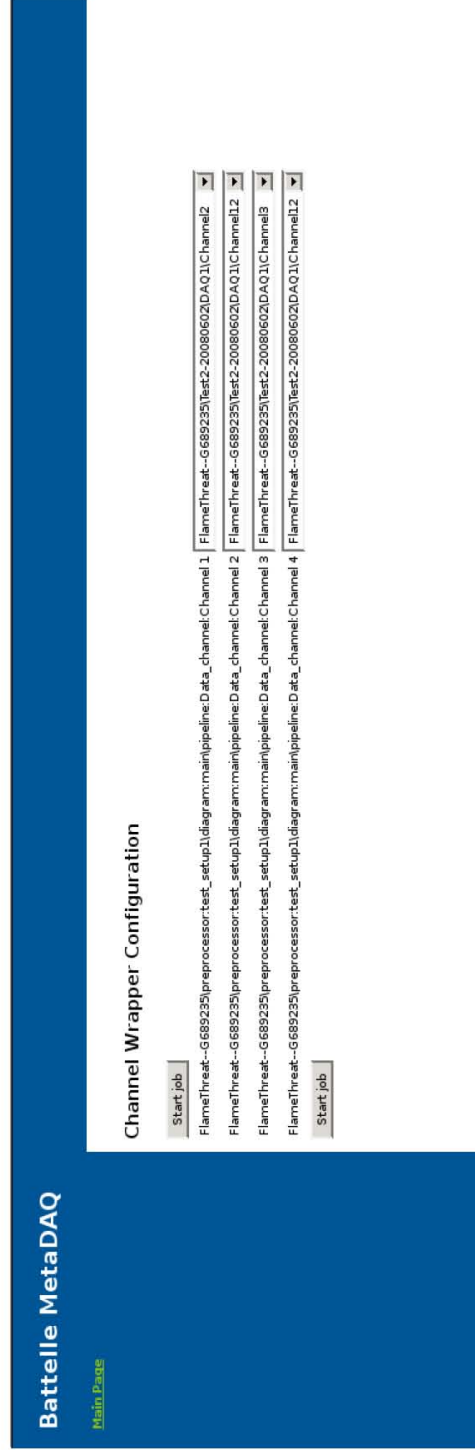
[fluxplot2](#)

[ManikinMap](#)

[ManikinTable](#)

Workflow

Creation of the preprocessor and report generation units establishes the format of the final report. A test report is obtained by selecting a data set to act on. A correspondence between the test data channels and the input channels of the preprocessor is determined. In most cases, this process is automatic, though it can be overridden if necessary.



Workflow



Finally, a request for report is submitted to a background process which preprocesses the data and aggregates the result of each RGU, producing a copy of the report in both .html and .pdf formats. The use of common formats makes it easy to extract images and text from a report for use in other documents. Additionally, reports are archived within MetaDAQ, allowing for easy archival and on demand retrieval.

