A New Approach to Defining Human Touch Temperature Standards

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Abstract

Defining touch temperature limits for skin contact with both hot and cold objects is important to prevent pain and skin damage, which may affect task performance or become a safety concern. Pain and skin damage depend on the skin temperature during contact, which depends on the contact thermal conductance, the object's initial temperature, and its material properties. However, previous spacecraft standards have incorrectly defined touch temperature limits in terms of a single object temperature value for all materials, or have provided limited material-specific values which do not cover the gamut of likely designs. A new approach has been developed for updated NASA standards, which defines touch temperature limits in terms of skin temperature at pain onset for bare skin contact with hot and cold objects. The authors have developed an analytical verification method for safe hot and cold object temperatures for contact times from 1 second to infinity.

Introduction

Correctly defining touch temperature limits for spacecraft equipment protects the crew from pain and physical harm while optimizing crew and system performance. If the touch temperature limits are set too conservatively, the use of operational constraints, such as wearing gloves, may be mandated unnecessarily – increasing the time required to perform tasks. Alternately, thermal coverings may be mandated for powered equipment that would impede their heat transfer to the cabin – decreasing their reliability by causing them to run hotter than is truly required. If the touch temperature limits are set too liberally, the crew may experience pain or skin damage while handling equipment. Therefore, it is important that spacecraft touch temperature limits be defined correctly.

This paper describes the present NASA spacecraft touch temperature limits for the Space Shuttle and the International Space Station, and the limitations and issues with these specifications as written. A new methodology for defining touch temperature limits is presented that includes more recent publications in the literature and that incorporates the physiological effects of touching hot and cold objects. Finally, a new standard for spacecraft touch temperature limits is defined.

Current Spacecraft Touch Temperature Limits

NASA's original hot touch temperature limits were based on human testing with heated aluminum plates. The data showed that pain onset occurred at an aluminum plate temperature of 45°C (113°F).

This temperature was established as the limit for all materials for any contact time from zero to infinity and was the standard until 1995, when two changes were made [1]:

1. Material–specific hot temperature limits were established for times between 1 and 10 seconds.

2. A cold temperature limit of -18°C (0°F) for unlimited contact with all materials was added.

The new hot temperature limits were based on Air Standard 61-39 [2], which in turn was based on Stoll, Chianta, and Piergallini's [3] curve-fit equation to their human testing data. While Stoll et al.'s original data set included touch temperature data up to only 4 seconds, they suggested that the use of their non-physics based curve-fit equation be extended to 5 seconds. However, in the Air Standard it was suggested that the equation could be reliably extended to 10 seconds, which is not appropriate for non-physics-based correlations. Additionally, the current NASA standards can be interpreted to inappropriately allow the use of the equation for indefinite durations.

NASA's cold touch temperature limit of -18°C (0°F) does not trace to any studies or data, and appears to go beyond anecdotal limits for pain[1]. An updated hot and cold touch temperature standard, backed by data, was needed.

The current work results from an effort to:

1. Correct the misinterpretation of Stoll et al.'s work for hot touch temperature limit contact duration.

2. Extend the timescale for material-specific hot touch temperature limits beyond the 5 seconds of Stoll et al.'s correlation - to infinite times if possible.

3. Develop a realistic touch temperature limit for cold objects.

Hot Touch Temperature Limits

When defining touch temperature limits, the question arises as to whether pain or skin damage should be the limiting factor. The danger of allowing skin damage is that it may affect a person's ability to use the affected area, including hands or fingers, which may lead to decreased performance in critical areas such as controlling a vehicle. In fact, the governing International Standard Organization (ISO) standard [4] for human contact with hot surfaces provides a collection of temperature threshold values and assessment methods for skin burns during contact with hot objects.

NASA holds to a higher standard, using the onset of pain as the crew protection limit. Since the ISO Standard [4] does not address the onset of pain, primary sources must be investigated to develop a useable standard. Several experiments beside Stoll et al. have investigated human tolerance to heat pain during contact with the skin. Research by Greene et al. [5] showed that the heat pain threshold is

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[1] Anyone who has tried to select their desired drink from the bottom of an ice-filled cooler has observed that pain results after much less than a minute of immersion in 0°C (32°F) ice water.

reached at 43.7°C (110.7°F) skin temperature. Lloyd-Smith and Mendelssohn [6] found the pain threshold to be 44.6°C (112.3°F). Defrin et al. [7] investigated heat pain threshold across the body and found the lowest level in the chest (42°C or 107.6°F), the highest in the foot (44.5°C or 112.1°F) and the hand was 43.8°C (110.8°F).

Hatton and Halfdanarson [8], developed a physically based model that matched Stoll et al.'s results. They found that Stoll et al.'s data for the onset of pain could be well correlated using a one-dimensional semi-infinite model with a constant finite contact conductance. The point where the calculated dermal/epidermal interface (taken as 0.25 mm or 0.010 inches below the surface) reached 44°C (111.2°F) matched very well with the reported onset of pain. The epidermal/dermal interface was chosen as the critical location because only the dermis is sensitive to pain. The epidermis is insensitive to temperature owing to its lack of pain receptors.

Given that the data on pain converge around the same value, the 44°C (111.2°F) epidermal/dermal interface temperature derived by Hatton and Halfdanarson from Stoll et al.'s data should be used as the upper limit for contact with hot objects. A subtle, but important distinction when defining touch temperature limits is that they should be based on the epidermal/dermal interface temperature at pain onset. Some previous standards have incorrectly defined the allowable object temperature as the used the skin temperature limit, which is overly conservative.

Verifying that objects meet touch temperature limits can be performed by test or analysis. However, exploring the limits of pain or skin damage cannot be easily accomplished with live human subjects. Physical models of human skin may be used to evaluate whether skin temperature would exceed given limits when in contact with an object. An example of a physical model is the thermesthesiometer probe, developed by Marzetta [9]. The core of the probe is maintained at a temperature of 33°C (91.4°F). The probe is brought into contact with the hot surface and its temperature response is assessed.

Other possible physical models include dead animal or human skin, and artificial skin, where a thermocouple can be placed subcutaneously to measure the epidermis/dermis interface temperature during contact with a hot object.

A more straightforward and convenient method for verifying touch temperature limits is by analysis.

One validation method is Stoll et al.'s curve fits to their human test data. The pain threshold equation for times between 1 and 5 seconds is:

$$T_{object} = YI \left[(k\rho c)_{object}^{-1/2} + 31.5 \right] + 41$$

(1)

where T_{object} = object temperature in (°C)

$YI = antilog_{10} [YII(a1) + log(YIII)]$

$YII = 1.094 \ t^{-0.184}$

3

YIII=0.490 t$^{-0.412}$

and   kρc is the thermal inertia of the hot material in cal^2/cm^4 °C^2 sec

         k = thermal conductivity

         ρ = density

         c = specific heat

         a1 = epidermal thickness in mm, (Stoll et al. reported an average of 0.25 mm – 0.010 inch)

         t = time of exposure in seconds (limited to between 1 and 5 seconds)

This method allows for evaluation of any material with known thermal properties. However, for times greater than 5 seconds, Stoll et al.'s correlation is not valid and another verification method must be used.

The range of the material-specific hot touch temperature limits can be extended with a methodology based on the work of Hatton and Halfdanarson [8]. They found that Stoll et al.'s data for the onset of pain was well correlated using a one-dimensional semi-infinite model (Eq. 2 and 3) with a constant finite contact conductance[2]:

$$T_{E/D} = \left[T_{skin}(0) + T_{object}(0)\right] \frac{k_{object}/\sqrt{\alpha_{object}}}{k_{object}/\sqrt{\alpha_{hot}} + k_{skin}/\sqrt{\alpha_{skin}}} * \left\{ erfc\left(\frac{|X|}{2\sqrt{\alpha_{skin}t}}\right) - exp\left(h_2|X| + h_2^2\alpha_{skin}t\right) erfc\left(\frac{|X|}{2\sqrt{\alpha_{skin}t}} + h_2\sqrt{\alpha_{skin}t}\right) \right\}$$

(2)

$$h_2 = \frac{H\left(k_{object}/\sqrt{\alpha_{hot}} + k_{skin}/\sqrt{\alpha_{skin}}\right)}{k_{object}k_{skin}/\sqrt{\alpha_{object}}}$$

(3)

where H is the contact conductance, α is the thermal diffusivity (k/ρc), and X is the distance from the interface.

Hatton and Halfdanarson found that using the following parameters with this model yielded an excellent correlation with Stoll et al.'s test data for the onset of pain:

- Initial skin temperature of 32.5°C (90.5°F).
- Skin thermal conductivity of thermal conductivity of 0.54 W/m·K (0.312 BTU/hr ft °F).
- Skin thermal diffusivity of 1.3x10^{-7} m^2/s (1.4x10^{-6} ft^2/s).
- Contact conductance of 1000 W/m^{2}K (173.1 BTU/hr ft^2 °F).
- Pain threshold of 44°C (111.2°F) at the dermal/epidermal interface.
- Dermal/epidermal interface 0.25 mm (0.010 inches) below the surface.

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[2] Which takes into account the imperfect contact of the fingertips with the hot surface.

Hatton and Halfdanarson's methodology was extended in the present work by building a transient one-dimensional heat conduction model for two thermally thick objects. The Fortran model used an implicit finite difference technique. The objects were at different uniform initial temperatures and were coupled through the transient using a constant contact conductance.

Using Hatton and Halfdanarson's recommended initial condition, physical constants, contact conductance, and definition for the onset of pain, the model was run for materials that spanned the range from aluminum to Masonite to define the time and material-specific allowable temperature curves. The time where the epidermal/dermal interface temperature reached 44°C (111.2°F) was taken as the limit and calculated over a range of initial hot object temperatures. The results took the form of

$$T_{object} = a(k \rho c)_{object}^{-1/2} + b \tag{4}$$

where T_{object} is the allowable object temperature in °C, $k\rho c$ is in units of $cal^2/cm^4 \, °C^2$ sec, and a and b are variables that are functions of the time of contact.

The values of a and b for a range of contact times are shown in Table 1. The table also contains the equivalent constants for Stoll et al.'s curve fit for times from 1 to 5 seconds.

Table 1 – Hot Case Constants

contact time (s)	a	b
1	0.920	69.97
2	0.641	61.19
3	0.521	57.42
4	0.451	55.20
5	0.403	53.70
10	0.475	50.07
30	0.459	46.61
60	0.446	45.90
∞	0.422	44.87

In the calculations, 600 seconds was taken to represent unlimited contact time (t= ∞).

The results of the Fortran program along with Stoll et al.'s correlation between 1 and 5 seconds is shown in Figure 1.
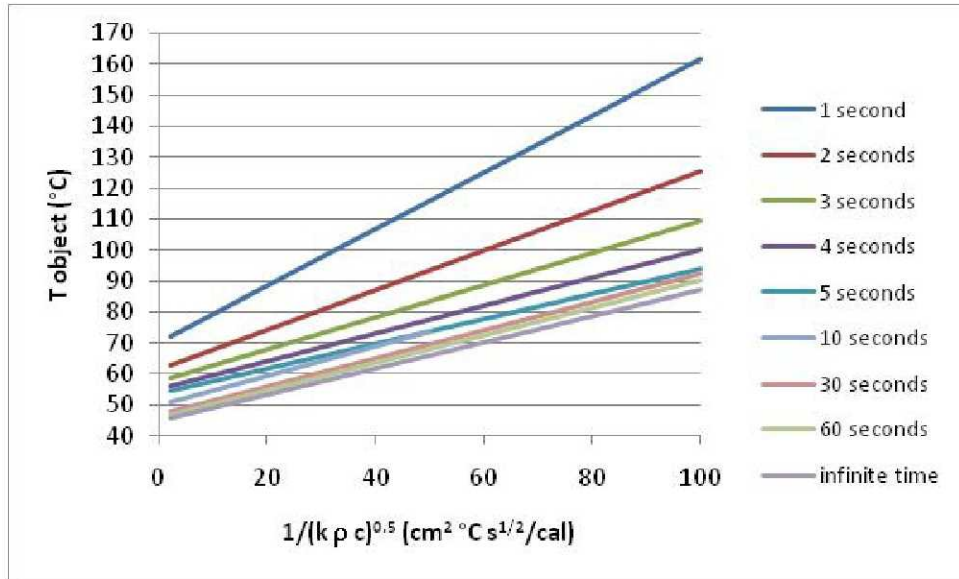
Figure 1 – Hot touch Temperature Limits

Close examination of Figure 1 shows that the curves for 5 seconds (from Stoll et al.) and 10 seconds (from the present work) intersect at a value of inverse square root thermal inertia of 50 $cm^2 \,^\circ C \, sec^{1/2}/cal$. This is caused by the fact that the 5 second and 10 second curves were derived using test data and analysis, respectively. It is recommended that the test data be given precedence and the 10 second curve be considered valid only for $(k\rho c)^{-1/2} < 50 \, cm^2 \,^\circ C \, sec^{1/2}/cal$.

The left hand termini of the lines in the figure correspond to the properties of aluminum. Since none of the lines dip below 45°C (113°F), a material temperature limit of 45°C (113°F) can be used as a first screening point for all commonly used materials. That is, if the temperature of any commonly used material is lower than 45°C (113°F), it will meet the hot touchtemperature requirements for all contact times.

Cold Touch Temperature Limits

The origin of NASA's cold temperature limit of -18°C (0°F) for any material for unlimited contact time is unclear, and upon reviewing the literature it was found that this limit is likely to cause both pain and skin damage. Research on human tolerance to cold has shown that onset of pain occurs at 15°C (59°F) skin temperature (Havenith et al. [10]), numbness occurs at 7°C (44.6°F) (Provins and Morton [11]) and risk of frostbite is risked at 0°C (32°F) (Havenith et al. [10]).

As discussed previously, the pain threshold, rather than the damage threshold, should be the limiting factor to maintain performance while using the affected area. Staying above the numbness threshold is also important because numbness may impact performance and can mask skin damage.

The lower skin temperature limit for the standard was defined using the results of human testing of space suit glove thermal performance. The tests showed that a hand skin temperature of 10°C (50°F) was tolerable [12], so this was taken as the skin temperature limit. This limit maximizes the allowable

material temperature envelope while avoiding the risk of numbness. Similar to the hot touch temperature case, the most straightforward and convenient method of verification is by analysis. There is an ISO standard for cold temperatures, ISO-13732-3 [13], but it has several limitations, primarily the limited number of materials - Aluminum, steel, and nylon[3]. .

However, the data of Geng et al. [14] that was the basis of ISO-13732-3 can be used to develop a cold temperature verification method. Geng et al. performed experiments analogous to Stoll et al.'s study, having subjects grasp aluminum, stainless steel, Nylon and wood test articles that had been cooled to between 2 and -40°C (35.6 to -40°F). Geng et al. reported the time required for the subjects' skin temperature (as measured by an externally attached thermocouple) to reach 15°C (59°F), 7°C (44.6°F) , and 0°C (32°F). These temperatures correspond to the previously noted definitions for pain, numbness and skin damage, respectively.

Geng et al.'s data was used to obtain the time and material-specific cold case curves for the chosen skin temperature limit of 10°C (50°F). First, the median data for the both the 15 and 7°C (59 and 44.6°F) cases were curve fit as time to the critical temperature for aluminum, stainless steel and Nylon[4] vs. the difference between the initial skin temperature[5] and the initial object temperature-. The resulting curve fits (Figure 2) allowed calculation of the allowable initial temperature for each of the three materials given a contact time and a target skin temperature of 15 or 7°C (59 and 44.6°F) .
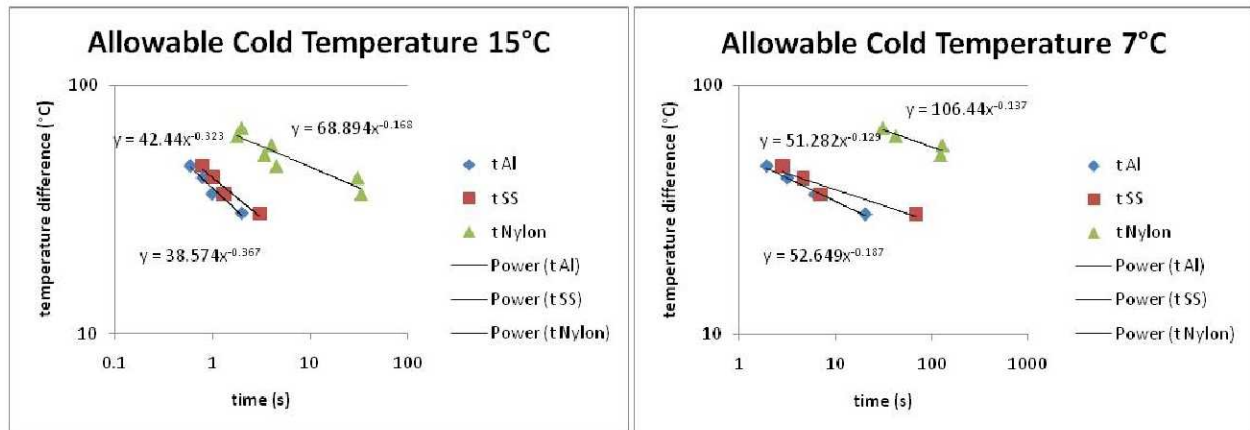

Figure 2 – Curve Fits to Geng et al.'s Data

Using these curve fits, the allowable initial temperature for contact times of 1, 2, 3, 4, 5, 10, 30, 60, and 600[6] seconds were obtained for each of the three materials. Where the calculated initial temperature

[3] Stone and wood are also included, but the specific types of stone and wood are not identified.

[4] The wood data was excluded for two reasons: wood is not isentropic as are the other materials and Geng et al's wood data is not self consistent.

[5] Taken as 32.5°C (90.5°F), the same as was measured by Stoll et al.

[6] Taken as infinite time.

was higher than the critical temperature of 15 or 7°C (59 or 44.6°F), the initial object temperature was taken as the critical temperature because that is the true physical limit. The resulting tables of initial temperature vs. time to 15 and 7°C (59 and 44.6°F) were then linearly interpolated for each material to yield the initial temperature for 10°C (50°F) for each time. The results were plotted as a function of the material thermal inertia to yield Figure 3.
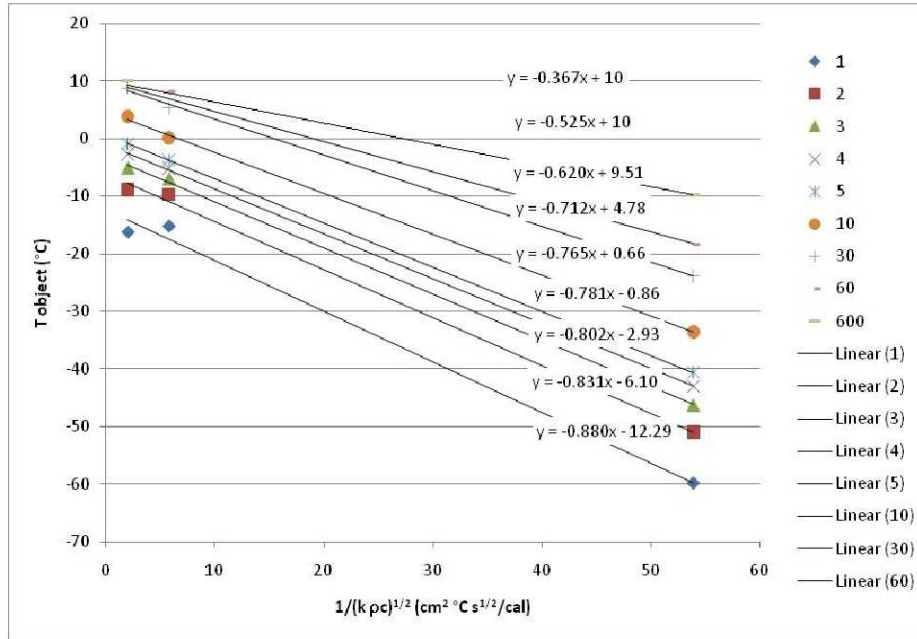

Figure 3 – Initial Object Temperature with Time to 10°C Skin Temperature

– Aluminum, Stainless Steel, and Nylon for 1, 2, 3, 4, 5, 10, 30, 60, and 600 seconds

Linear curve fits[7] to the interpolated data in Figure 3 yielded the recommended cold case values to be used in equation 4. They are listed in Table 2. As for the hot case, 600 seconds is taken as infinite contact time.

Table 2 – Cold Case Constants

contact time (s)	a	b
1	-0.880	-12.29
2	-0.831	-6.10
3	-0.802	-2.93
4	-0.781	-0.86
5	-0.765	0.66

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[7] Where the intersection of the least squares fit was greater than 10°C, the value was set at 10°C and the fit was performed again to yield the final slope. This step was taken to keep the results consistent with the physical limit of a 10°C skin temperature.

10	-0.712	4.78
30	-0.620	9.51
60	-0.525	10
∞	-0.367	10

Conclusion

To prevent pain and ensure optimal task and system performance, it is important to properly define temperature limits and verification methods for touching hot and cold objects. Previous limits for hot objects have often lead to overly conservative designs or operational constraints, while cold limits have been defined at potentially unsafe levels. The proposed limits and verification methods of the present work are founded on a breadth of human research coupled with straightforward analytical methods which are applicable for any material and contact duration. While there is some variability in human perception of pain, these limits are conservative enough to prevent pain in most people during skin contact, but not so conservative as to lead to overdesign or operational constraints. These limits pertain primarily to intentional contact with the hands and fingers, as some parts of the body may be slightly more sensitive to pain owing to their thinner epidermis. However, the hands and fingers are the most likely parts of the body to be unprotected and used for grasping and manipulation of objects. If more precise touch temperature limits are required for other areas of the body, additional testing and analysis would be needed.

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