Certification Testing at Low Temperatures

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Abstract

Regulations governing the transport of radioactive materials require that most hypothetical accident condition tests or analyses consider the effects of the environmental temperature that most challenges package performance. For many packages, the most challenging temperature environment is the cold condition (-29 ºC according to U.S. regulations), primarily because the low temperature causes the highest free drop impact forces due to the higher strength of many energy-absorbing materials at this temperature.

If it is decided to perform low temperature testing, it is only necessary that the relevant parts of the package have the required temperature prior to the drop. However, the details of performing a drop at low temperature can have a large influence on testing cost and technical effectiveness. The selection of the test site, the chamber and type of chilling equipment, instrumentation, and even the time of year are all important. Control of seemingly minor details such as the effect on internal pressure, placement of monitoring thermocouples, the thermal time constant of the test article, and icing of equipment are necessary to ensure a successful low temperature test. This paper will discuss these issues and offer suggestions based on recent experience.

1.0 Introduction

The hypothetical accident condition tests which are required by transport regulations for Type B(U) packages require that the tests be conducted at the ambient temperature condition that is most unfavorable for the package. Usually, only the hot and cold temperature extremes are considered. Once a decision has been made to test at cold temperatures, the selection of the test site, and of the test equipment, will have an important influence on test outcome.

2.0 Choosing a Test Temperature

Since the crush strength of most impact limiting materials increases significantly with a decrease in temperature, the greatest free drop impact magnitude can be expected to occur at low ambient temperature. Conversely, since the crush strength falls with increases in temperature, the risk of impact limiter bottoming (i.e., the utilization of the entire limiter stroke) occurs at high ambient temperature, resulting in an indeterminate impact magnitude. For this reason, impact limiters are designed with reserve capacity at high ambient temperature, and the corresponding impact is generally not bounding. In most cases, then, it is the low ambient temperature condition that represents the greatest impact. In addition, a low temperature impact is the condition under which any gross failure of the impact limiter might be expected to occur, since any deleterious fragmentation of the energy absorbing material or of the adhesives would be more likely.

It should be noted that full prototype testing of a package at extreme temperature conditions does not always need to be performed. The effects of extreme temperatures can frequently be handled using analysis, and even if tests at one extreme temperature are performed, the other extreme can often be evaluated with analysis. Analysis would typically require bench test data on the energy absorbing material at the analysis temperature. Often, room temperature testing is performed with analysis of both extremes. But if this is considered inadequate, the most frequent choice is low ambient testing with analysis of high ambient conditions as required.

A demonstration-by-test approach, in which an elastomer closure seal is expected to remain leak tight after subjection to the maximum impact, might be another reason to perform low temperature testing. However, adequate demonstration of elastomer seal performance can often be obtained using smaller scale bench testing at low temperature, without recourse to a prototype test.

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[1] Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Brittle fracture behavior of the package structures is also typically not a matter for prototype testing. Unless material flaws of the worst-case size, shape, and orientation are present, it would have little meaning. The morphology of the most damaging flaw which could be credibly expected to exist in an actual transport package is usually not known, and if it were, it would be almost impossible to successfully replicate it in a test package. Brittle fracture is avoided in the US by the use of materials whose ductile-to-brittle transition temperature is adequately below the minimum service temperature, as discussed in [1], and which can be demonstrated by bench testing if necessary.

The balance of this discussion will focus on the practical aspects of testing at low ambient temperature. For packages licensed to U.S. regulations (10 CFR 71), the low ambient temperature is -20 °F (-29 °C), and for those licensed to IAEA regulations (TS-R-1), it is -40 °C.

3.0 Facilities and Equipment

Free drop test sites seldom come equipped with convenient facilities to chill a transportation package of any appreciable size. In fact, in a study of such facilities, no U.S. domestic test site featured both a drop pad of proper construction at the same time as a resident chilling facility. For this reason, chilling equipment is typically brought in or constructed as needed.

A refrigerated trailer van (“reefer van”) is the most convenient form of cooling device, since it is easily transported to the drop test site, widely available for rent, and since it combines a chilling unit and insulated enclosure in one compact space. The chiller and the container are designed to work together and typically operate unattended. Most vans have an inside width of approximately 8 feet, and would accept all but the largest test packages. However, many older models may have trouble reaching the low temperatures required, and most cooling units are designed only to maintain a low temperature, rather than to remove significant amounts of heat. A margin of 10 degrees or more below the regulatory minimum temperature may be required to ensure that the temperature is low enough at the moment of impact. Fate seems to decree that packages having a rapid thermal response must be tested in the summer. Under severe conditions, only the best and newest units can cool a package to the regulatory minimum temperature for U.S. regulations of -29 °C with any appreciable safety margin. The IAEA minimum temperature of -40 °C could probably not be reached unless the ambient temperature was also low. For this reason, every effort should be made to test in the colder months when using a reefer van.

Flash, or blast, coolers are typically portable units designed to freeze foodstuffs for transport to market. In contrast to reefer vans, they are designed to handle significant heat loads, but are less transportable, and less readily available for rental. They can, however, often cool the interior to as low as -60 °C under severe conditions (see Figure 1). Blast coolers are available with integral insulated chambers, or as separate units designed to duct cold air into a user’s facility. A separate unit may be the most advantageous approach, since the initial investment is lower, and a chamber of appropriate size can be inexpensively constructed as required.

Another method of chilling the package is by the use of liquefied gases, such as liquid nitrogen or CO_2. In this type of system the liquefied gas is introduced into a plenum chamber and a blower is used to distribute the cold gas into the cooling chamber. The amount of liquefied gas required for this method of chilling is generally over one ton. Care must be taken to not over-chill the package, as the boiling point for liquid nitrogen is -196 °C and the sublimation temperature for CO_2 is -79 °C. The extreme cold associated with this chilling method is a safety hazard that must be adequately addressed. Another safety hazard for the CO_2 systems is the refrigeration and pressure necessary to maintain the liquefied gas, which typically operate at a pressure of 20 atm and a temperature of -18°C. For liquid nitrogen systems, evaporative cooling is generally used to maintain the liquefied gas.

The required chilling capacity depends on the size of the test package, the type of chamber and its insulating value, and ambient conditions. If it is assumed that most of the heat in a test package is located in the steel, a 2,500 kg package initially at 30 °C needs to have about 70 MJ removed to cool it to -30 °C. To accomplish this in a reasonable timeframe (say, 12 hours), heat would have to be removed at a minimum rate of 1,600 W in addition to chamber losses. As alluded to above, many reefer vans are only designed for maintenance of temperature, and typically need to handle about 6,000 W just to maintain an internal temperature of -30 °C in a +38 °C environment. Of course, at a lower ambient temperature, the task becomes far easier to accomplish, since both the heat to be removed and the heat losses to the ambient are reduced accordingly. Specific cooling capacity recommendations are beyond the scope of this paper, but the subject is an important one. Calculations, tests, or comparison data should be consulted to ensure adequate capacity. Note that the actual cooling time is heavily influenced by the thermophysical properties of the test package itself, as well as by the cooling system capacity.

A reefer van or blast cooler unit constitutes an enclosure which is well engineered and professionally manufactured. Their advantage is having the right amount of insulation, a robust construction, and doors that are easy to operate and to shut tight. Temporary cooling chambers can also be built at the site for relatively little cost. Some items to consider are as follows:

- Temporary chambers don't necessarily have to be robust in nature. A simple superstructure, made of steel tubing, unistrut, or framing lumber may be adequate. Four inches of Styrofoam or other insulation with an R value of at least 20 will generally be enough.
- Unless the test package is to remain suspended, the floor will need to be strong enough to support the weight of the package. Also consider wind loading, which can be significant with light structures. Keep out any rainwater, which could create problems with ice inside.
- For a fast transfer to a drop-ready condition, consider opening the chamber on the top and leaving the test package suspended while cooling. This may, in fact, be the only option for packages having a rapid thermal response, tested under warm ambient conditions. Pre-orient the package so that only a drop height check is needed. Ensure that the release device is not chilled, to ensure proper function.

Figure 2 shows a temporary chamber used at Sandia National Laboratories which was made of cattle gates (steel tubing) and constructional Styrofoam sheets. It was adaptable to two different test packages and several different drop orientations, opening on one long side for horizontal or slapdown orientations, and on the end for vertical orientations. In all cases, the package was pre-oriented and left suspended while cooling. After the package was lifted out of the top of the chamber, the chamber was moved out of the way using a large forklift.

Facility problems that can affect the cooling of a test package include the function of monitor thermocouples, chamber leakage, and icing of the evaporator. First, it is desirable to monitor not only the chamber air temperature, but also the relevant parts of the test package. Most units come equipped to monitor the air, but package temperatures will require a separate system. Thermocouples are delicate, therefore it is good practice to ensure redundancy in their placement. If the package temperature becomes unknown due to thermocouple failure, the drop test cannot proceed. Air leakage, the second concern, may not be much of a problem with permanent or factory-built chambers, but if a temporary chamber is constructed on-site, some thought should be given to the control of the inevitable air leaks. Quantities of foam-in-a-can and duct tape should be available at the test site. Leakage also exacerbates the third problem, evaporator icing, by continually providing a fresh supply of moist air into the cooling circuit. At -60 °C, even desert air can leave a surprising amount of frozen moisture on the evaporator coil, which can severely inhibit its function. This is usually handled by periodically shutting down the evaporator until the ice has melted, and by carefully restricting the introduction of fresh moisture. Ensure that the chilling unit is properly programmed to defrost the evaporator for the specific moisture conditions that will be encountered, and carefully restrict the entry of moist air into the system.

Finally, chilling units consume a lot of power, and many test sites are not equipped with an adequate supply. Placing the chiller near the power instead of near the drop pad introduces difficulties which are discussed in more detail below. Therefore, if the unit is not self-powered, a large generator set may be necessary. A secure supply of uninterrupted power is essential to success of a low temperature test.

4.0 Test Package Considerations

As discussed above, the behavior of the impact limiting structures is typically the primary object of a cold temperature drop test, rather than brittle fracture performance of package materials. The performance of other components of the package, such as internal features or elastomer seals, can frequently be demonstrated more cost-effectively by using smaller-scale bench tests at cold temperature. Most often, therefore, the object is to sufficiently chill the impact limiting structures to ensure that the bulk temperature is at or below the cold test temperature at the moment of impact. For this reason, it may make sense to chill only the impact limiting parts of the package, if possible. This approach would likely allow use of a smaller chiller and possibly a shorter cooling period, but also invokes the following considerations:

- The licensing strategy must ensure that all other temperature-sensitive features of the package are demonstrated using bench tests, analysis, or reasoned argument;
- The package must have removable impact limiters that are readily handled;
- The rate of warming of the impact limiters must be slow enough to allow their removal from the chiller and attachment to the test unit before their temperature rises above the cold test temperature. Contact with the warm test unit will increase the speed of warm-up;
- The differential thermal expansion between the cold impact limiter structure and the relatively warm test unit must not prevent assembly of the limiters onto the test unit;
- It may be difficult to perform more than one drop test on an impact limiter (an efficient and cost-saving test strategy), since removal of the limiter after the first test for re-chilling may not be possible.

In addition, the impact limiters will generally be covered with a film of frost (slippery – a lifting/slinging concern) and too cold to touch with bare hands (a safety concern). When possible, however, this approach is often the best one, and has been successfully used.

The chiller air temperature, the test unit surface temperature, or thermal calculations alone should not be relied upon to establish the temperature of the impact limiting material. Instead, thermocouples which penetrate through the structure into the material should be used to monitor the temperature. Strictly speaking, it is only necessary to cool the material which will actually undergo crush, which may be only a relatively small region of the package. Note, however, that the less mass that is cooled, the more difficult it will be to maintain the cold temperature until the moment of impact. For this reason, thoroughly cooling the impact absorbing material, monitoring the point of slowest cooling, is advised. Due to temperature gradients during warm-up, monitoring the center of the expected crush region is also encouraged. The thermocouples can be inserted to the bottom of a small hole supplied in the wood, foam, or other material. Some degree of redundancy is advisable, and they should be easily pulled out so that they don't interfere with hoisting the package, or be damaged at impact.

If the entire test unit is chilled, and if it features measurement devices such as accelerometers, strain gages, pressure transducers, etc., ensure that they will function and remain in calibration under cold conditions, and that their attachments will not fail in a brittle mode. Note that if the test unit is pressurized at ambient temperature, the pressure will be somewhat less after chilling. While this is generally perfectly acceptable, if the pressure is to be reconfirmed or monitored in the cold state, it will require a compensation in acceptance criteria. This can be done using a straightforward application of the perfect gas law. Alternately, establish the pressure prior to chilling, and confirm it only after the return to ambient temperature.

Depending on the chamber configuration and the type of chiller used, the temperatures within the chamber may be significantly stratified, warmer on top and colder on the bottom. This would be more pronounced for tall configurations (such as a package oriented vertically in a correspondingly tall chamber). This is another reason for pre-orienting the test unit in the planned free drop orientation, since the region of impact at the bottom of the package will also be the coldest. Consideration must be given, however, to any secondary impact (if important), which may be on an impact limiter which was located in an upper portion of the chamber and therefore not be as cold.

One of the most important considerations in low temperature testing, and often the most difficult, is the ability to maintain the cold temperature until the moment of impact. This is governed by four factors:

- The thermal properties of the package;
- The ambient temperature and solar conditions at the test site;
- The amount of sub-cooling used;
- The elapsed time between removal from the chamber and impact.

The properties of the package important for assessing the thermal response are established by the design, and include such factors as the surface area and weight of the impact limiting structures, the specific heat and conductivity of the materials, and the gap resistance between the internal components. A rough estimate of the thermal response of the test unit can be obtained from:

$$\mathrm{T} = \mathrm{T}_{\mathrm{amb}} + \left(\mathrm{T}_{\mathrm{o}} - \mathrm{T}_{\mathrm{amb}}\right)\mathrm{e}^{-(\mathrm{hA}/\mathrm{cW})\theta} \qquad [2]$$

where:

T = temperature response of a relatively shallow thermocouple
T_{amb} = ambient temperature
T_o = initial temperature
θ = elapsed time
h = convective heat transfer coefficient
A = surface area of the impact limiting region (including the part contacting the package, a rule of thumb that accounts for chilling at the package interface)
c = weight-averaged specific heat
W = weight of impact limiting region

This formula strictly applies only to bodies where the internal thermal resistance is negligible compared to the external resistance. This is generally not true for impact limiters, but as an approximation, this may be helpful if the region of applicability is restricted to a shallow depth near the surface. It does not apply to the center of the region. Figure 3 shows the comparison between a prediction using this formula to data collected for a package with an integral overpack using redwood as the impact limiting material, encased by stainless steel. The curve shows the cool-down period, where T_o was warm, and T_{amb} was cold. Since, upon removal of the package from the chamber, T_o and T_{amb} switch places, the curve can be inverted to estimate the warm-up behavior. The important period for warm-up is the first half- to one hour after removal from the cooling chamber, where the temperature rise is linear and fairly steep. In this example, the temperature rose at the rate of approximately 20 °C per hour. Since ambient temperature and insolation have a strong effect on the warming rate, a great deal of trouble can be saved by performing low temperature testing in the cold months; a cloudy winter day is best!

The amount of time which elapses between the cessation of cooling and the moment of impact is of critical importance for a successful low temperature test. Every effort should be made to reduce this time, including pre-rigging the test unit in the drop orientation, careful planning, and performing dry runs or other operational training. Using cooling equipment which is remote from the drop test site adds a significant delay and should be avoided, although this has been successfully done using insulating blankets. Based on the warm-up rate and the time it takes to prepare for the drop, a sub-cooling margin can be chosen. As a first estimate, a margin of 10 °C can be used. Based on the package alluded to above, a chamber-to-impact elapsed time of one-half hour would be acceptable for a 20 °C per hour warm-up rate and 10 °C of sub-cooling.

5.0 Conclusions

Low temperature testing can add a difficult challenge to certification testing. If possible, advantage should be taken of public-domain performance data or smaller-scale cold bench testing. If low temperature prototype testing is required, the selection of the chilling equipment is of primary importance. Refrigerated vans occupy the lighter-duty end of the scale, for smaller packages or colder weather. For larger packages or hot weather, blast chillers may be required. The next largest challenge is keeping the unit cold until the impact can occur, which involves the right degree of sub-cooling and the efficient choreography of pre-test activities.

6.0 References

1. W.R. Holman, R.T. Langland, *Recommendations for Protecting Against Failure by Brittle Fracture in Ferritic Steel Shipping Containers Up to Four Inches Thick*, NUREG/CR-1815, UCRL-53013, U.S. Nuclear Regulatory Commission, Washington, D.C. 20555, August 1981.

2. Krieth, Frank, *Principles of Heat Transfer*, 3rd Edition, Intext Press, 1973.

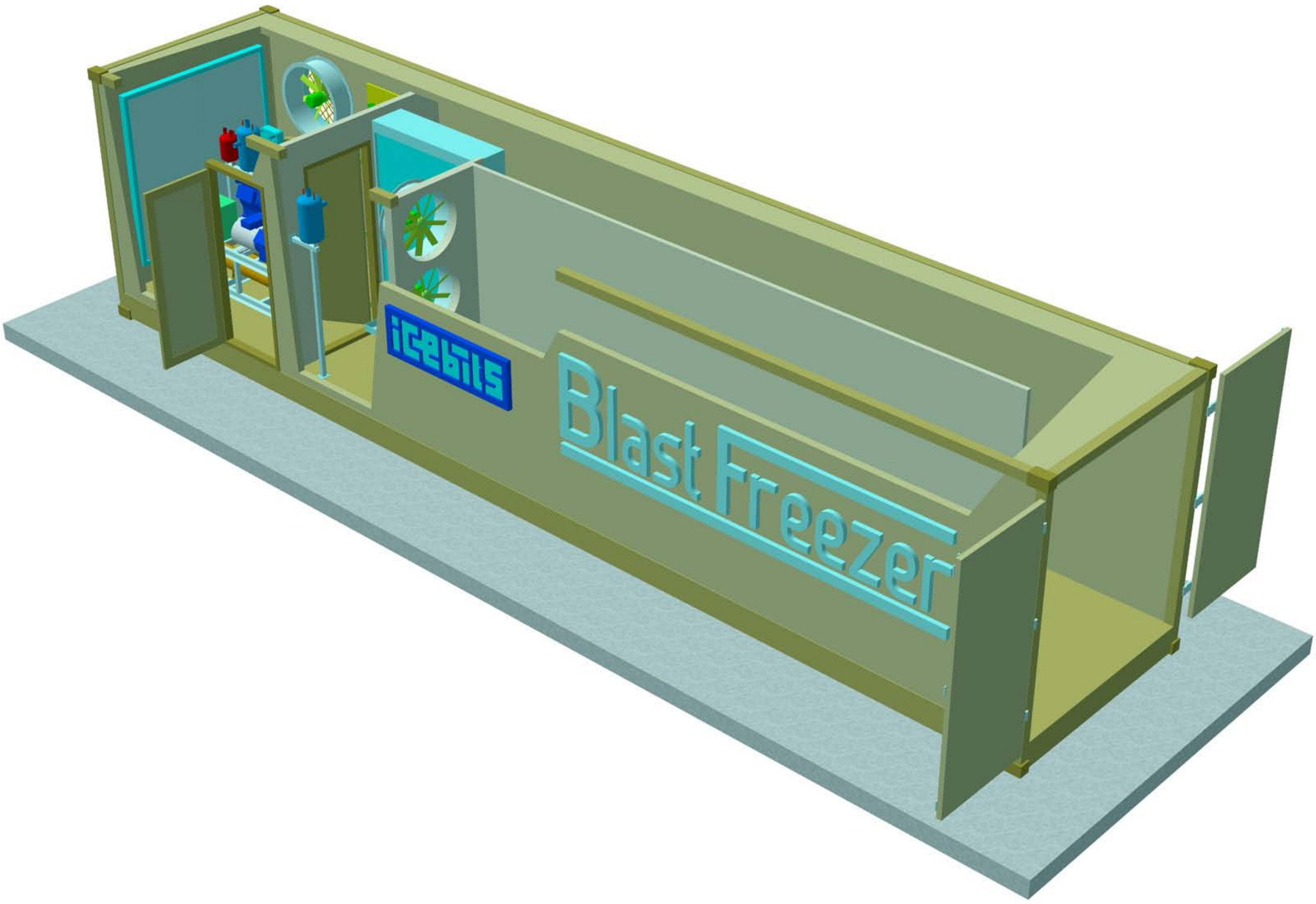

Figure 1 – Blast Cooler in a portable container

Figure 2 – Temporary Cooling Chamber. Portable Blast Chiller Unit is to the right of the open lid.

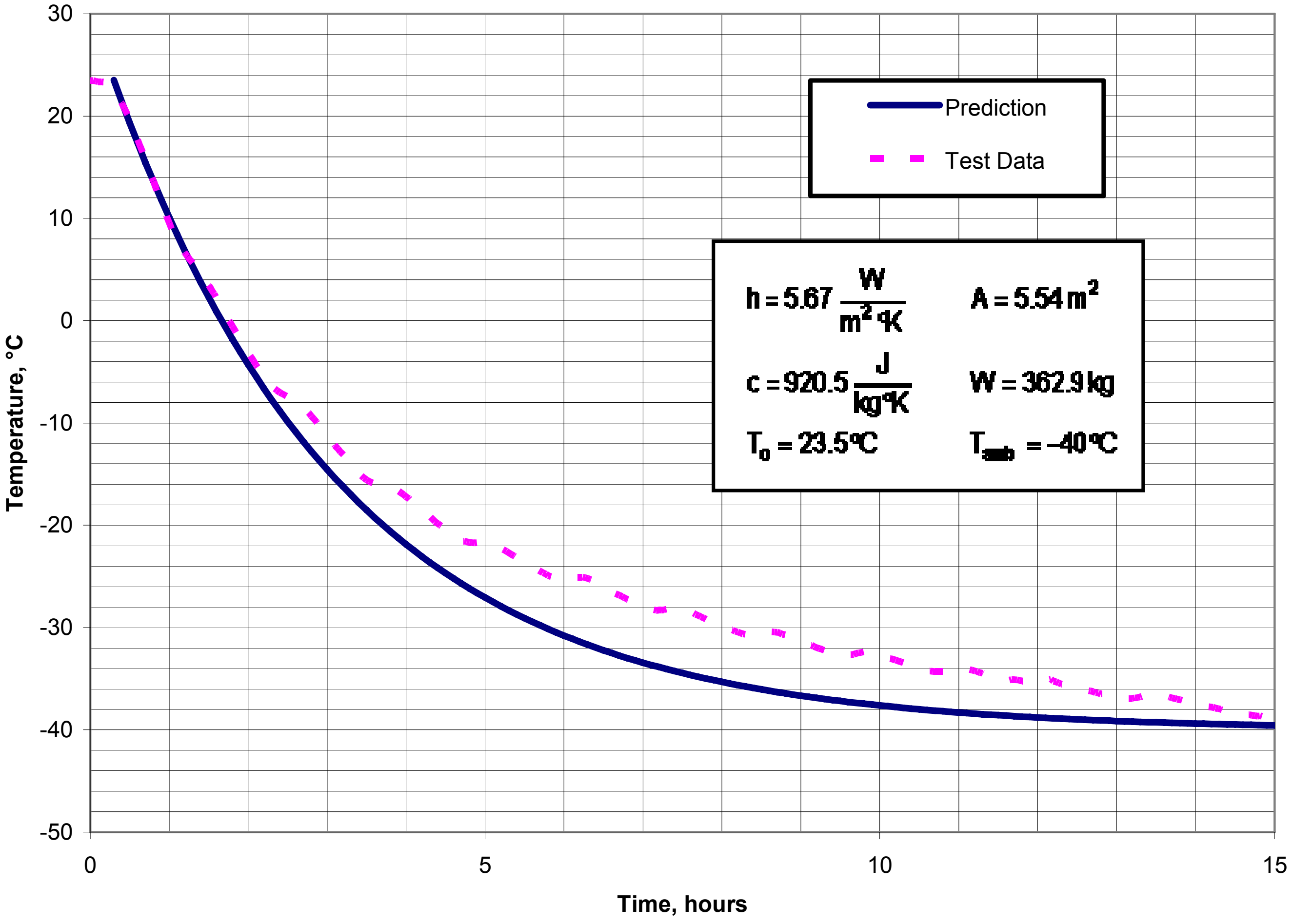

Figure 3 – Test Package Temperature Prediction vs. Shallow Test Thermocouple