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INFLUENCE OF THERMAL CONDITIONING MEDIA ON CHARPY SPECIMEN TEST TEMPERATURE

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ABSTRACT: The Charpy V-notch (CVN) impact test is used extensively for determining the toughness of structural materials. Research programs in many technologies concerned with structural integrity perform such testing to obtain Charpy energy vs temperature curves. American Society for Testing and Materials Method E 23 includes rather strict requirements regarding determination and control of specimen test temperature. It specifies minimum soaking times dependent on the use of liquids or gases as the medium for thermally conditioning the specimen. The method also requires that impact of the specimen occur within 5 s of removal from the conditioning medium. It does not, however, provide guidance regarding choice of conditioning media. This investigation was primarily conducted to investigate the changes in specimen temperature which occur when water is used for thermal conditioning. A standard CVN impact specimen of low-alloy steel was instrumented with surface-mounted and embedded thermocouples. Dependent on the media used, the specimen was heated or cooled to selected temperatures in the range -100 to 100°C using cold nitrogen gas, heated air, acetone and dry ice, methanol and dry ice, heated oil, or heated water. After temperature stabilization, the specimen was removed from the conditioning medium while the temperatures were recorded four times per second from all thermocouples using a data acquisition system and a computer. The results show that evaporative cooling causes significant changes in the specimen temperatures when water is used for conditioning. Conditioning in the other media did not result in such significant changes. The results demonstrate that, even within the guidelines of E 23, significant test temperature changes can occur which may substantially affect the Charpy impact test results if water is used for temperature conditioning.

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KEYWORDS: acetone, air, Charpy V-notch, cooling rate, evaporation, methanol, nitrogen gas, oil, thermal conditioning, water.

INTRODUCTION

The Charpy V-notch (CVN) impact test is used extensively for determining the toughness of structural materials. For example, it is required by the *American Society of Mechanical Engineers Boiler and Pressure Vessel Code* [1] for both nuclear and nonnuclear applications; by *Title 10, Part 50 of the Code of Federal Regulations* [2] for nuclear plants; by the American Association of Highway and Transportation Officers [3] standard for bridges; and by similar international codes and standards. In the case of commercial light-water nuclear reactor pressure vessels, CVN specimens are tested prior to operation to verify acceptable as-fabricated toughness and during operation to monitor changes in toughness due to neutron irradiation. For both the preirradiated and postirradiated testing, full Charpy impact energy vs temperature curves are obtained and used to determine the effects of irradiation on fracture toughness of the reactor vessel. Research programs in many technologies concerned with structural integrity perform similar experimental studies.

The American Society for Testing and Materials (ASTM) Method E 23-88, "Standard Methods for Notched Bar Impact Testing of Metallic Materials," includes rather strict requirements regarding determination and control of specimen test temperature. It specifies minimum soaking times dependent on the use of liquids or gases as the medium used to thermally condition the specimen. For liquids, the specimen is required to remain in the bath at the desired temperature within ±1°C for at least 5 min. For gases, the soaking time is 30 min. Whatever method is used for heating or cooling the specimen, E 23 requires that impact of the specimen occur within 5 s after removal from the medium. The method does not, however, provide guidance regarding choice of conditioning media, except to note that temperatures up to 260°C may be obtained with certain oils. Commonly used media within the testing community include air, nitrogen gas, acetone, oil, and water. The primary objective of this experimental study was to compare the effects of these different conditioning media on the temperature of the test specimen between the time of removal from the medium and impact. A second objective was the comparison of test results of the same heat of steel from two laboratories which showed consistent differences in reported energy values, especially in the ductile-to-brittle transition region, one laboratory using heated air and the other using heated water.

Figures 1(a) and 1(b) are photographs of the computer-automated test system used for testing standard and subsize CVN specimens. The system includes a conditioning chamber where the test specimen is heated with hot air from a controlled heat gun, or cooled with cold nitrogen gas from a pressurized liquid nitrogen supply. More detailed descriptions of the testing system are provided in refs. 4 and 5. Another objective for this study was the overall characterization of the testing system performance regarding the use of heated air and cold nitrogen gas.

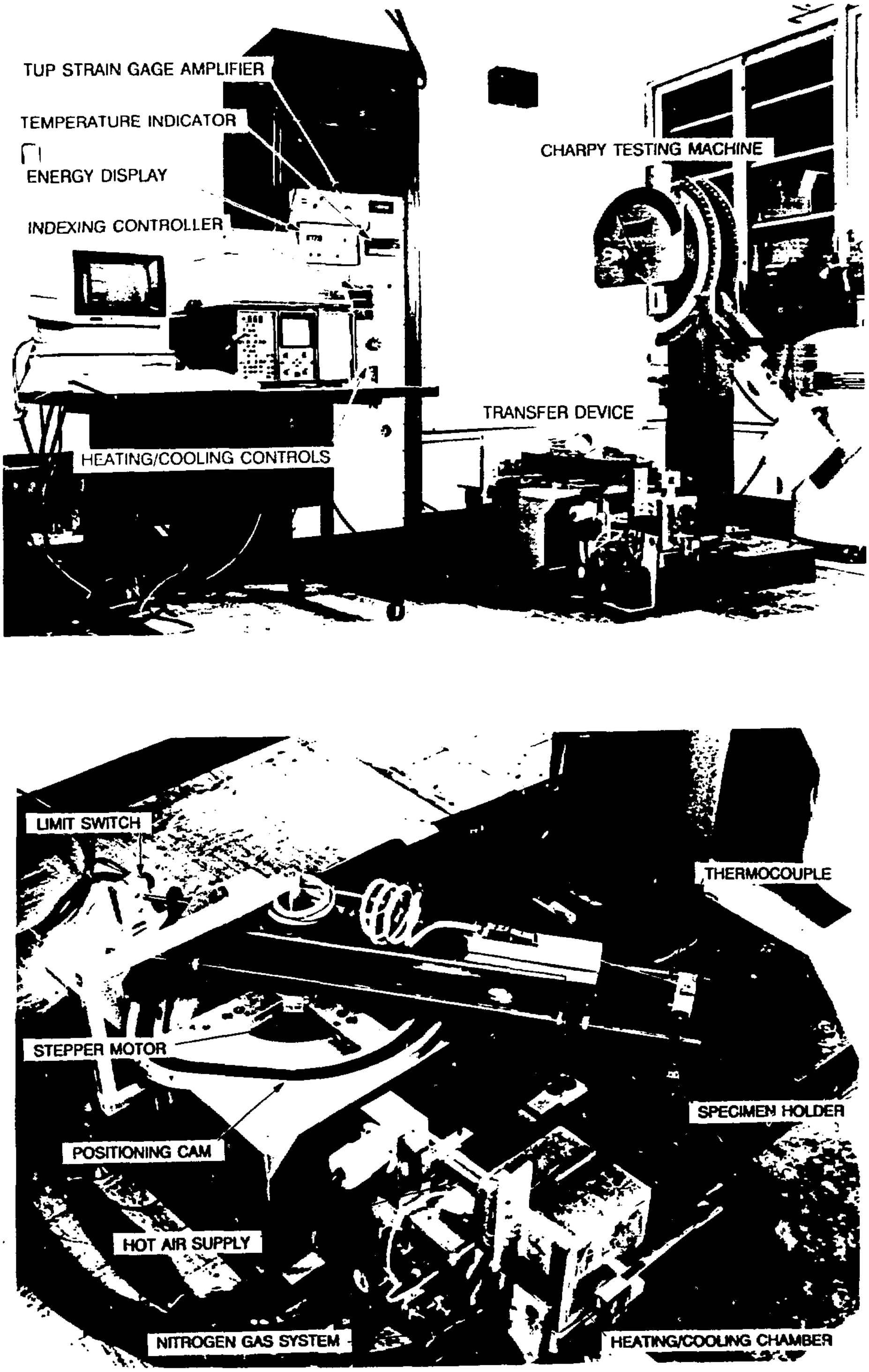

Fig. 1. Photographs of (a) Computer interactive Charpy impact test system and (b) Charpy transfer device, conditioning chamber for heating and cooling test specimens, and temperature control system.

PROCEDURES

A standard CVN impact specimen of a low-alloy steel was instrumented with five chromel-alumel thermocouples. Figure 2 schematically shows the locations of one surface and four "buried" thermocouples. The buried thermocouples were located approximately symmetrically relative to the notch, at mid-width, and along the longitudinal axis of the specimen. The thermocouple ends were beaded (welded), then welded onto the bottoms of 4.76-mm-deep drilled holes 4.76 mm in diameter; ceramic cement was used to fill the holes and allowed to harden. The surface thermocouple was tack-welded to the surface directly opposite the notch and at mid-thickness (Fig. 2). The thermocouples were connected to a Hewlett-Packard Model 3497 Data Acquisition/Control Unit, containing a 5 1/2-digit integrating voltmeter, which was connected to a Hewlett-Packard Series 200/300 computer. The maximum error of temperature measurement for a given thermocouple reading is estimated to be about 0.5°C.

For all the conditioning media investigated, comparisons were made of the temperature changes in the specimen after removal from the medium into laboratory air, and after removal from the medium directly to the anvil of the Charpy machine. For the tests in heated air and cold nitrogen gas, the instrumented CVN specimen was placed in the conditioning chamber of the testing system. For the tests in liquids, the instrumented specimen was placed in the liquid bath already stabilized at the target temperature. In all cases, temperatures were monitored during conditioning, and withdrawal did not take place until all five thermocouples had stabilized at the target temperature. The system was programmed to read all thermocouples at an interval of 0.25 s and provide a hard copy of the results. The thermocouples were read sequentially, and the acquisition rate resulted in about a 0.05-s time difference between readings.

RESULTS AND DISCUSSION

Figure 3 shows the results of conditioning the specimen with heated air from room temperature to 100°C. The spread in temperature readings from the five thermocouples does not change appreciably over the 8-min heating cycle, indicating that, for the heating rate used, the surface thermocouple reading is a reasonable representation of the temperature in the interior of the specimen. Figure 4 shows similar results of cooling with cold nitrogen gas to -100°C, although the spread in temperature readings increased somewhat throughout the cooling cycle of about 4 min. During CVN impact testing with this system, the specimen is kept at the target test temperature for 1 to 2 min to allow for complete stabilization. To track temperature changes following removal from the conditioning media, thermocouple 2 was chosen because it is one of the buried thermocouples located near the region of the specimen where fracture occurs.

Figure 5(a) shows the results of heating with air to target temperatures from 52 to 102°C followed by removal of the specimen from the chamber and immediate placement on the anvil of the machine. The start time for temperature recording (t = 0 s) was upon removal from the chamber. The vertical dashed line at 5 s represents the maximum allowable time specified in E 23 for impact of the specimen following

LEGEND:

1. TACK-WELDED SURFACE THERMOCOUPLE LOCATED CENTER OF SPECIMEN, BEHIND NOTCH.
2 BURIED THERMOCOUPLE (3/16" DEEP (TYP.)), 7/8" FROM LEFT END OF SPECIMEN.
3 BURIED THERMOCOUPLE, 3/4" FROM RIGHT END OF SPECIMEN.
4. BURIED THERMOCUPLE, 5/16" FROM LEFT END OF SPECIMEN.
5. BURIED THERMOCOUPLE, 1/4" FROM RIGHT END OF SPECIMEN.

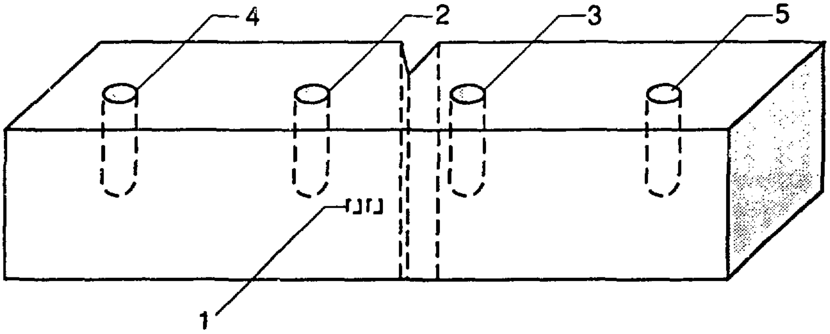

Fig. 2. Schematic drawing showing thermocouple locations on Charpy specimen used for influence of thermal conditioning media studies.

removal from the conditioning medium. Very little change is apparent even over a 10-s period. Figure 5(b) provides a plot of the temperature change (cooling) vs time for that experiment. After 5 s the greatest change is about 1°C. The accuracy of the thermocouples is estimated to be about 0.5°C and, thus, the ordering of the temperature changes relative to the target temperatures are likely obscured by the fact that the measured changes are of the same order as the measurement accuracy. Figures 6(a) and 6(b) show similar plots for cooling with cold nitrogen gas to temperatures from 0 to -101°C. After 5 s, the greatest rise in temperature is about 1.5°C from a target temperature of -101°C.

The results of heating with oil are shown in Fig. 7. The greatest decrease in temperature after 5 s is about 1°C from a target temperature of 204°C. Similar results were obtained for cooling to temperatures from 0 to -75°C in mixtures of methanol and dry ice, and acetone and dry ice, respectively. After 5 s, the temperature changes were less than 1°C. A heated bath of acetone at a target temperature of 50°C was also investigated and Fig. 8 shows the temperature changes for the experiments conducted in acetone. For target temperatures from 0 to -75°C, temperature decreases initially occur after removal from the bath; the same result was observed for the methanol and dry ice. This is the result of evaporation of the liquids and the resultant evaporative cooling of the specimen. At 50°C the same phenomenon occurs but with greater changes in specimen temperature, although still less than 2°C after 5 s. At 50°C, the acetone is near its boiling point and evaporation occurs rapidly. At the cold target temperatures, the evaporative cooling effect reaches a maximum at about 5 s.

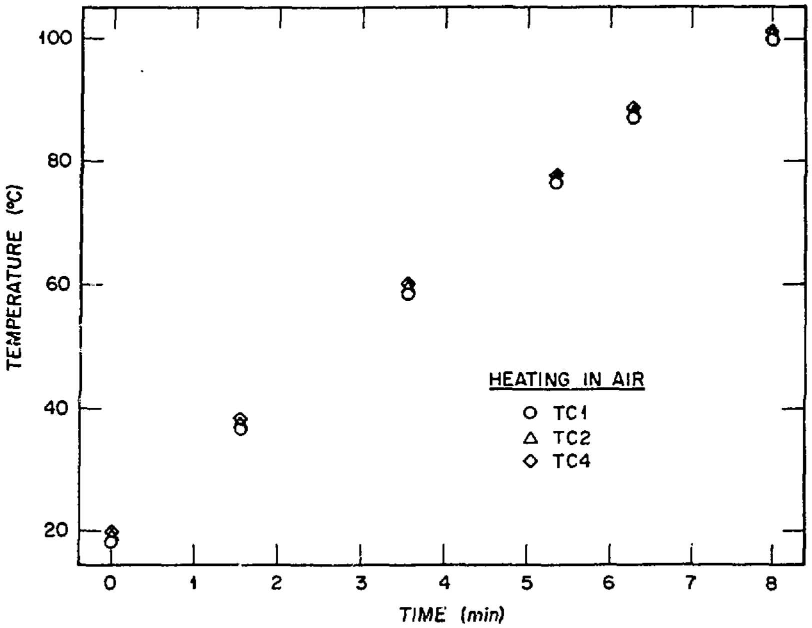

Fig. 3. Plot of temperature vs elapsed time for all five thermocouples during heating of the specimen with air in the conditioning chamber. The measurements indicate that exterior and interior temperatures of the Charpy specimen are essentially the same during heating to 100°C in 8 min.

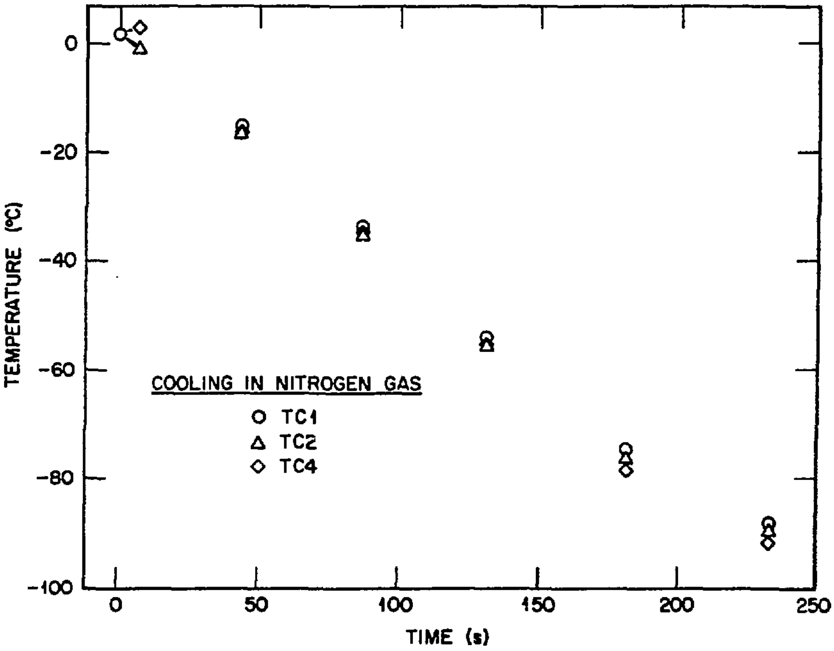

Fig. 4. Plot of temperature vs elapsed time for all five thermocouples during cooling of the specimen with nitrogen gas in the conditioning chamber. The measurements indicate that exterior and interior temperatures of the Charpy specimen are essentially the same during cooling to -100°C in 6 min.

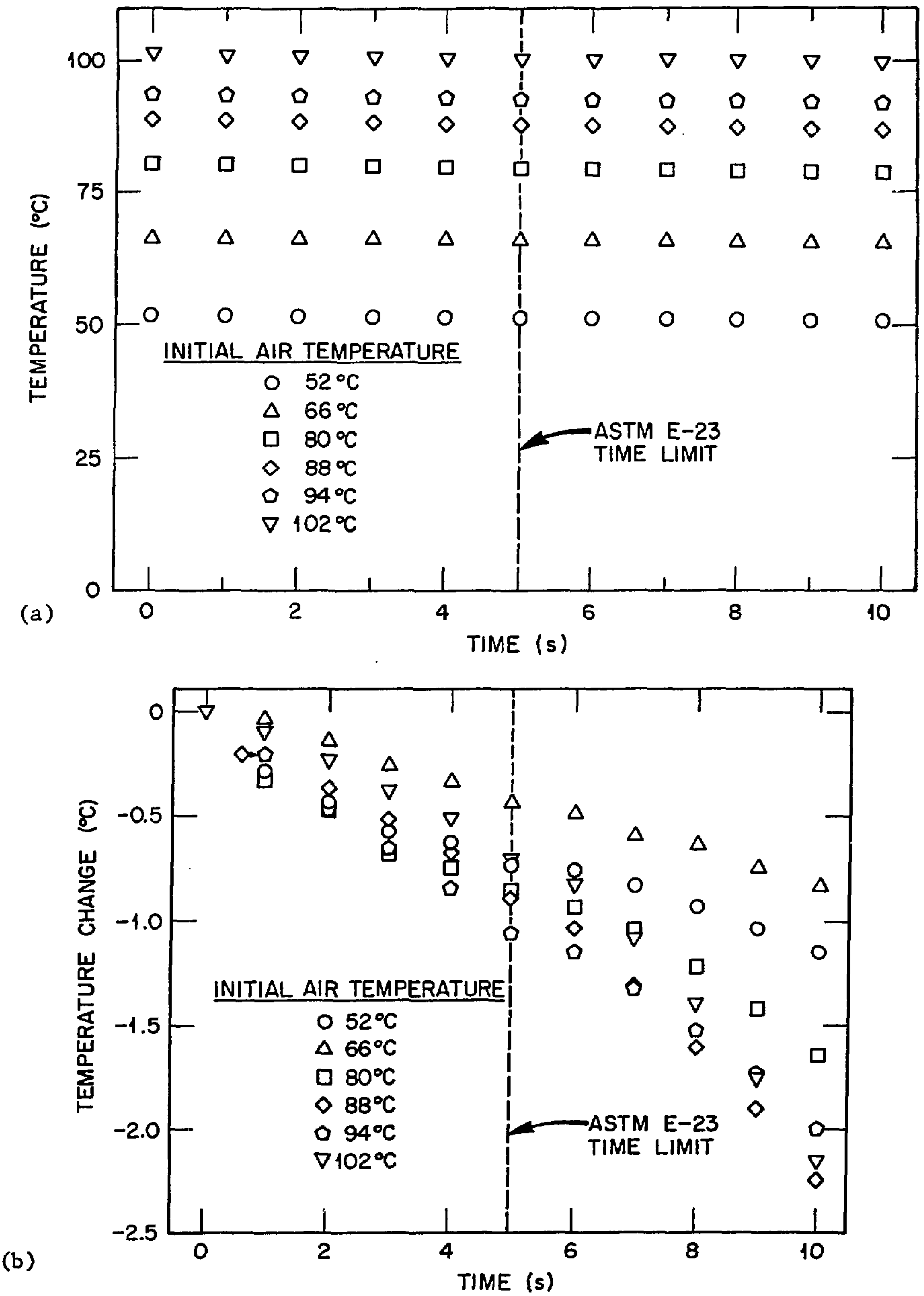

Fig. 5. Plots of (a) temperature, and (b) temperature change, from buried thermocouple 2, vs elapsed time following removal of the specimen from the heated air environment to the anvil of the Charpy machine for conditioning temperatures from 52 to 102°C. As shown in (b), the temperature decrease is about 1°C or less after 5 s.

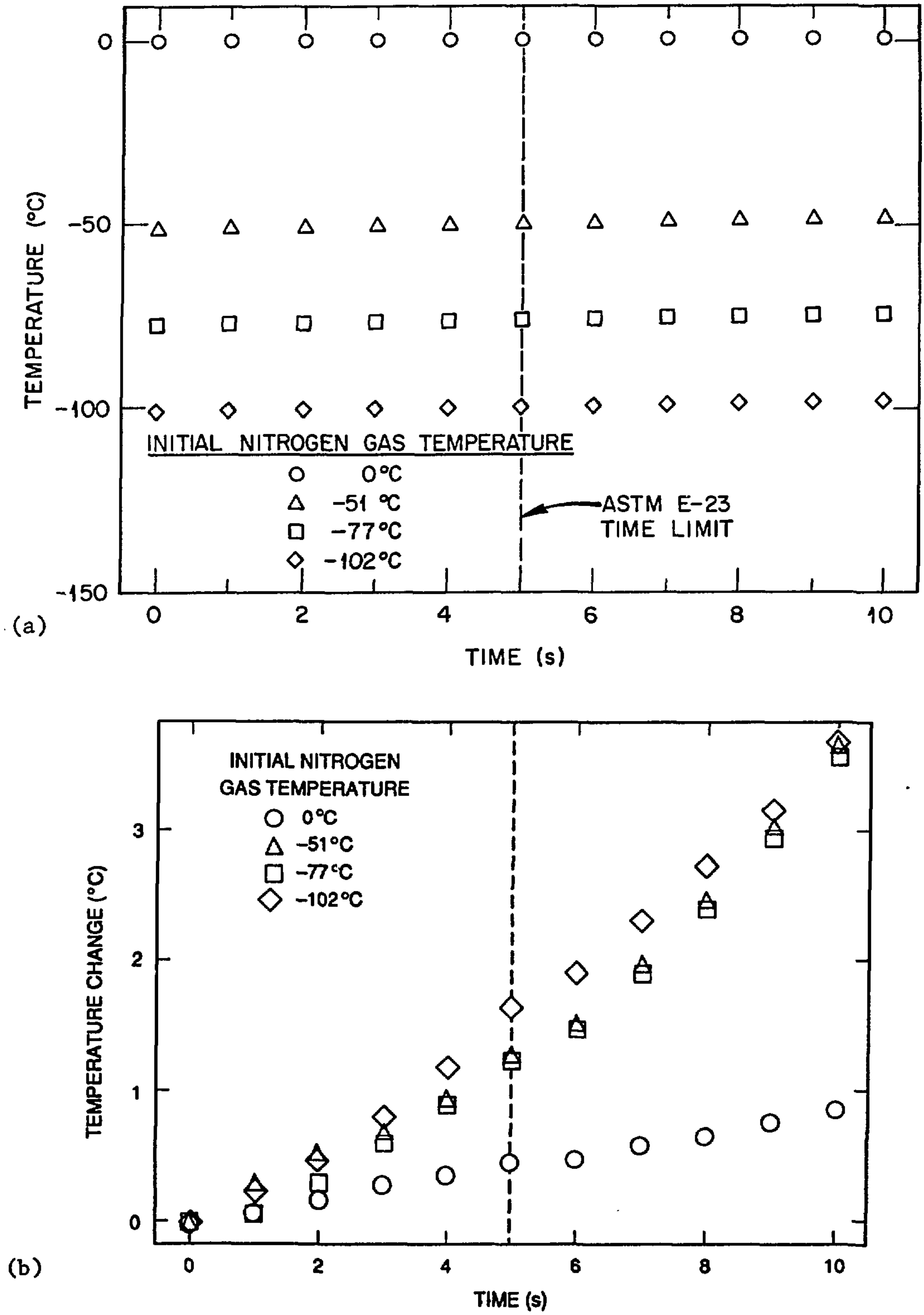

Fig. 6. Plots of (a) temperature, and (b) temperature change, from buried thermocouple 2, vs elapsed time following removal of the specimen from the cold nitrogen gas environment to the anvil of the Charpy machine for conditioning temperatures from 0 to -102°C. As shown in (b), the temperature increase is about 1.5°C or less after 5 s.

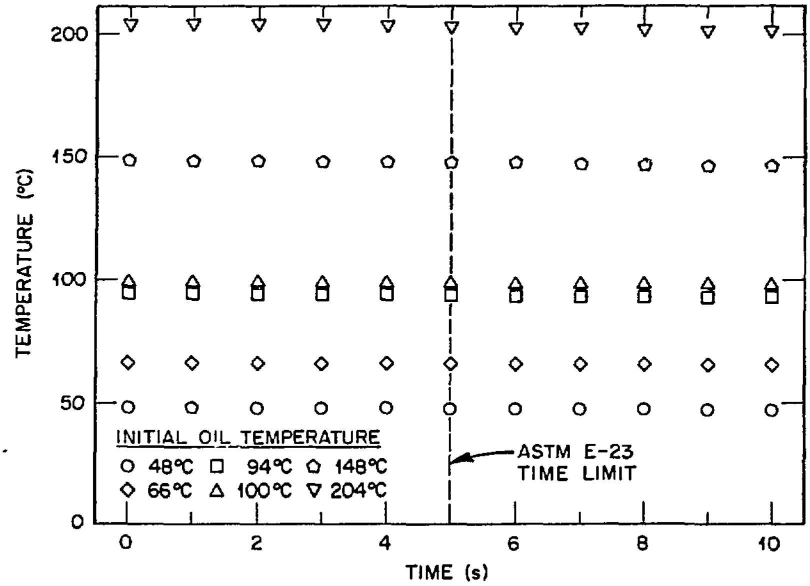

Fig. 7. Plot of temperature, from buried thermocouple 2, vs elapsed time following removal of the specimen from the heated oil bath to the anvil of the Charpy machine for conditioning temperatures from 48 to 204°C. Virtually no cooling takes place after 5 s.

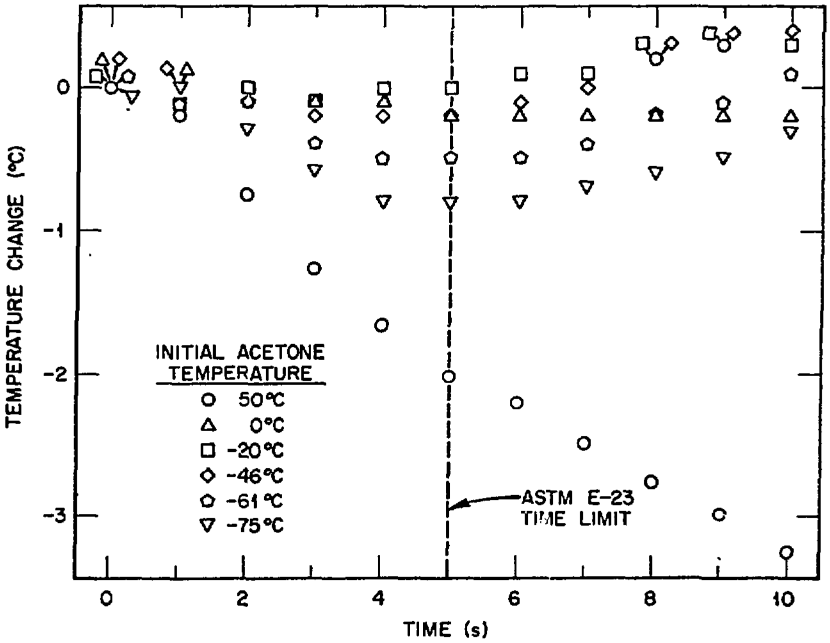

Fig. 8. Plot of temperature change, from buried thermocouple 2, vs elapsed time following removal of the specimen from a heated acetone bath and a cold bath of acetone and dry ice to the anvil of the Charpy machine. For conditioning temperatures from 0 to -75°C, the temperature changes are less than 1°C after 5 s; for a temperature of 50°C, the temperature change is about 2°C after 5 s. Evaporative cooling of the specimen takes place for both the hot and cold conditions.

The experiments with water as the conditioning medium were conducted at six target temperatures from 52 to 100°C. Figure 9(a) shows the temperature profiles for each of the six temperatures. It is obvious that the temperature changes are greater as the target temperature approaches 100°C. Figure 9(b) shows the temperature changes vs time and amplifies that observation. At the two lowest target temperatures, the cooling is only about 1°C after 5 s. At the higher target temperatures, however, the cooling effects become significant. At 100°C, the temperature decrease is over 9°C after 5 s, and about 19°C after 10 s. The change from 5 to 10 s is noted to amplify the observation that significant changes in temperature can occur in very little time at those temperatures when water is used as the conditioning medium.

Figures 10(a) and 10(b) show the temperature changes which occur at the various locations in the specimen from a target temperature of 100°C. Thermocouples 4 and 5, near the specimen ends, show greater changes in temperature than do thermocouples 2 and 3, located near the notch region. It is likely that greater cooling takes place near the ends because cooling occurs through the ends as well as the side surfaces. The fact that the specimen rests on the room temperature anvil near the ends of the specimen likely has some effect on that observation; however, an experiment was performed in which the specimen was removed from the 100°C water and left in still air, that is, not placed on the anvil, and the cooling rates were about the same as for those moved directly to the anvil. Thus, the cooling mechanism appears to be primarily due to evaporation of the water.

It should be noted that, even given the sequential nature of the thermocouple readings, a 10°C change in 5 s would result in a maximum difference of about 0.1°C between the first and last thermocouple readings during the 0.25-s cycle. Thus, the sequential procedure used to read the temperatures does not have a significant bearing on the observations. The average temperature change for the two buried thermocouples in the central region of the specimen is about 10°C after 5 s. A simple heat transfer analysis was performed to compare with the experimental results [6]. Heat losses during the experiment occur as the result of evaporation, natural convection, and radiation. To obtain accurate (±5%) results, a much more sophisticated analysis would be required because the problem is basically three-dimensional and transient. A correlation developed by Langhaar [7] was identified as an appropriate simplified model that combines heat transfer by all three aforementioned mechanisms. Prior to use of that model, however, a simple calculation was performed to check the film thickness of water required on the specimen to result in a temperature drop of 15°C by evaporation alone. A film thickness of 0.056 mm (0.0022 in) was calculated and, without considering surface tension and wettability, that result seems reasonable as a possible film thickness. Then, using the Langhaar model with the assumptions of the surrounding air at 22°C, a wind velocity (walking) of 0.894 m/s (2.93 ft/s), and a uniform rate of cooling, the average time (average for specimen temperatures of 100 and 85°C) the model predicts to dissipate the 297 J (heat loss required for a 15°C temperature drop) from the surface area of the Charpy specimen is about 18 s, or about 1°C/s. That compares with the observed cooling rate of about 2°C/s. Considering that a very simplified model was used for this application, the model calculation demonstrates that the experimental observations are credible. Regarding the postulated dominance of

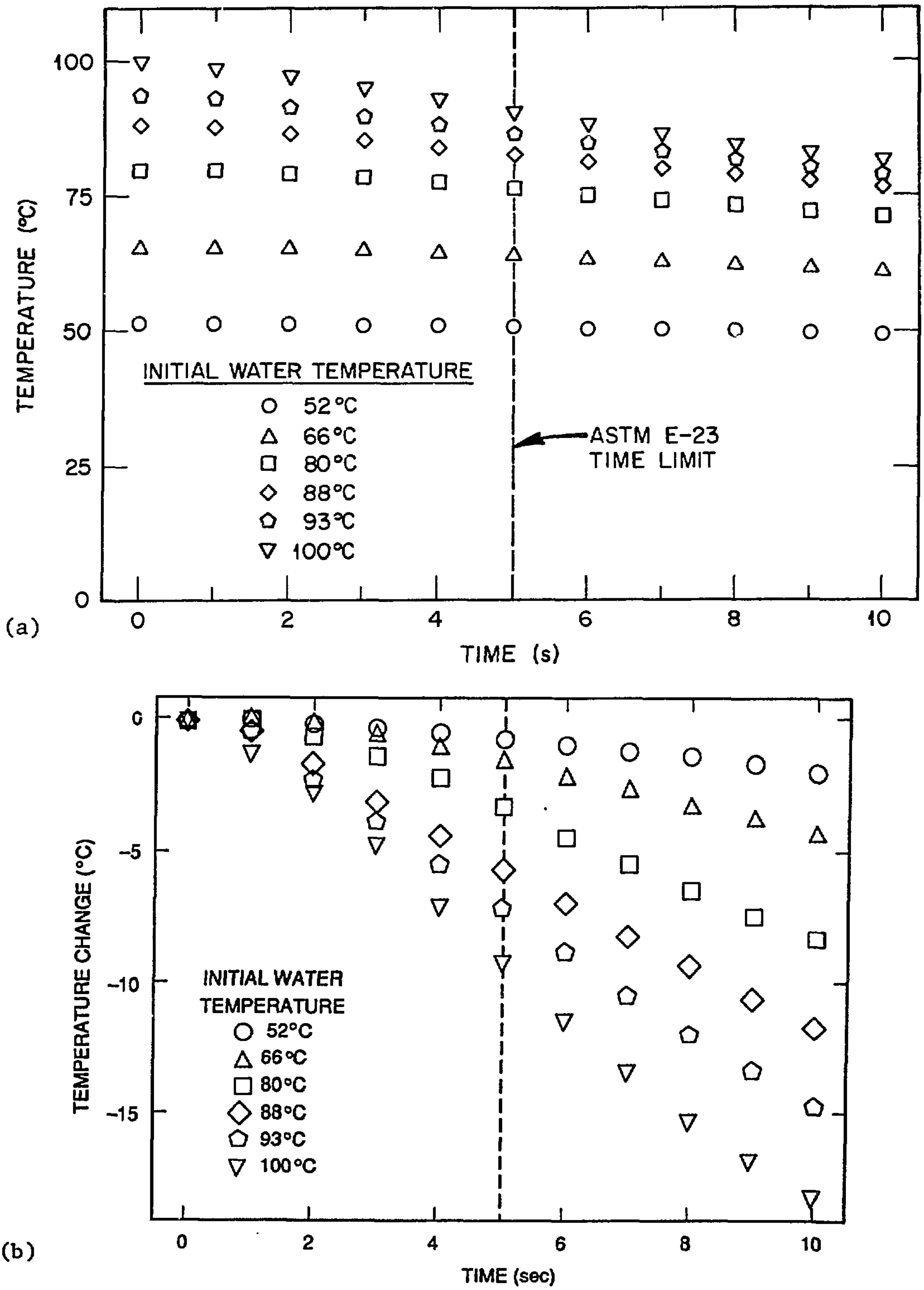

Fig. 9. Plots of (a) temperature, and (b) temperature change, from buried thermocouple 2, vs elapsed time following removal of the specimen from the heated water bath to the anvil of the Charpy machine for conditioning temperatures from 52 to 100°C. As shown in (b), the evaporative cooling effects increase as the conditioning temperature approaches 100°C, resulting in a decrease of about 10°C in the interior temperature of the specimen.

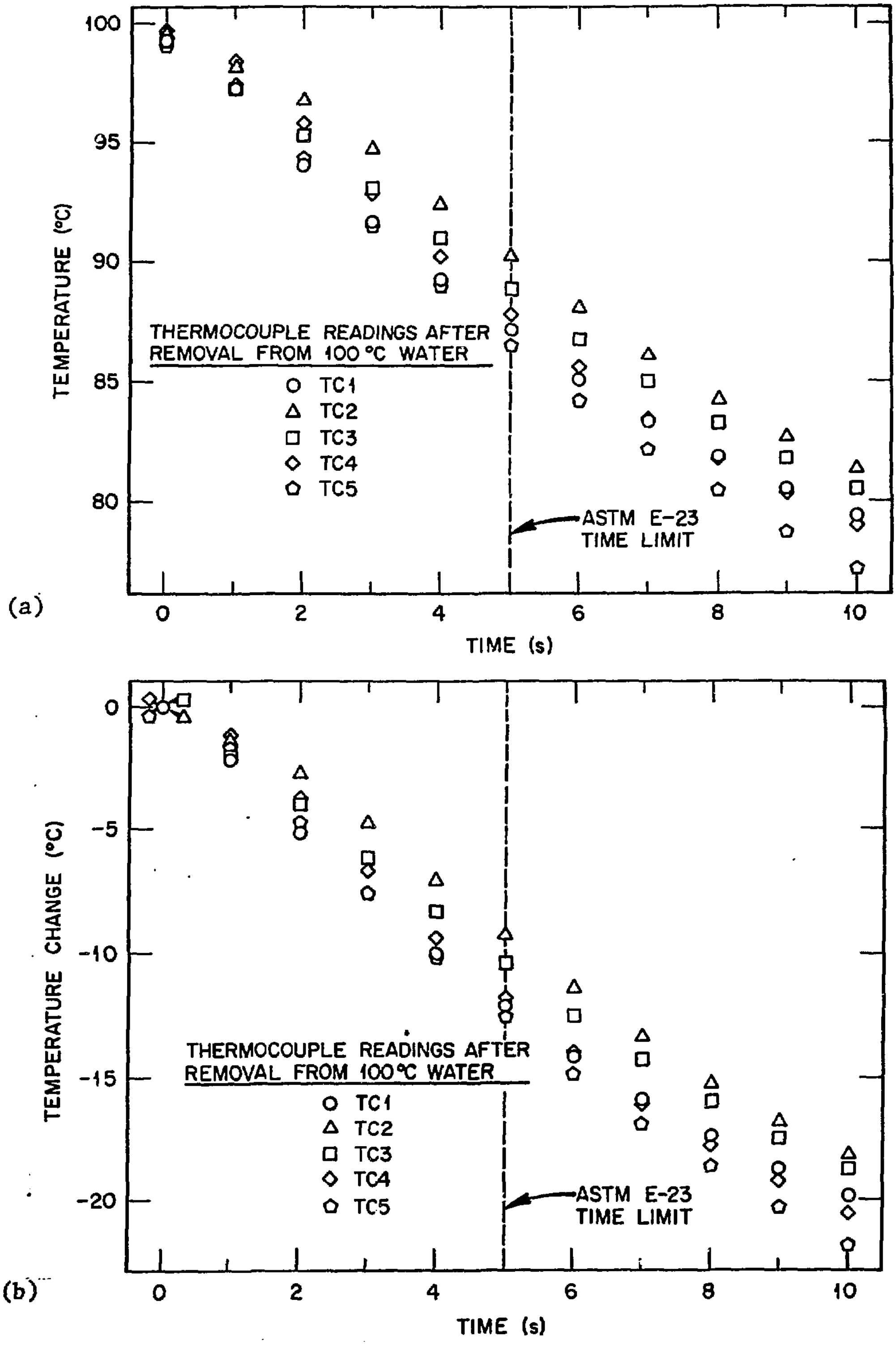

Fig. 10. Plots of (a) temperature, and (b) temperature change, from all five thermocouples, vs elapsed time following removal of the specimen from the heated water bath to the anvil of the Charpy machine for a conditioning temperature of 100°C. Thermocouples 4 and 5, near the ends of the specimen, experience greater cooling rates due to heat loss from the ends as well as the sides of the specimen.

evaporative cooling, a simple calculation was performed using a lump model for purely natural convection in air (using an average heat transfer coefficient of 8.5 W/m^2/°C for all surfaces). That calculation indicated a cooling rate of 0.080°C/s, more than ten times less than that indicated by the Langhaar model and twenty times less than the experimental results. The Langhaar model calculations showed, in fact, that only about 10% of the heat flux from the water on the specimen surface comes from convection. Thus, the comparison demonstrates that evaporation of water from the specimen is the primary cooling mechanism.

These experiments show that evaporative cooling can cause significant changes in the specimen temperature when water is used for conditioning. Figure 11 shows a plot of the temperature decrease at 5 s after removal from the water bath vs the water bath temperature. The magnitude of the changes increase and the rate of change increases rapidly as the test temperature approaches 100°C. At 100°C, the temperature change in 5 s is about 10°C, while it is less than 1°C at a test temperature of 50°C. The effects of the evaporative cooling at the 5-s limit become increasingly significant at temperatures above about 65°C. The changes at 7 and 10 s following removal from the bath are also plotted in the figure and show the same trend. As shown earlier, the cooling changes which occur when heated air is used as the conditioning medium are minimal. The temperature changes which occur when using heated air will become significant at temperatures well above 100°C; however, this investigation was conducted to compare various conditioning media with heated water and, therefore, was limited to 100°C. Within the range studied for the other conditioning media, -100 to 50°C, temperature

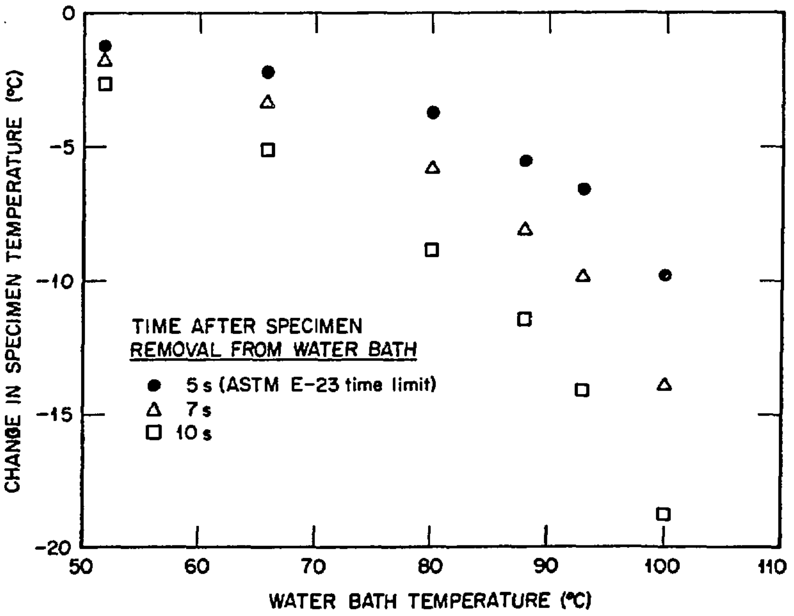

Fig. 11. Plot of temperature decrease at various elapsed times vs bath temperature following removal of the specimen from the heated water bath to the anvil of the Charpy machine. For water bath temperatures ranging from about 52 to 100°C, evaporative cooling decreases the interior specimen temperature from 2 to 10°C after 5 s, respectively.

changes at 5 s after removal from the environment were also small, 1°C or less. Two exceptions are heated acetone (not recommended) at 50°C and nitrogen gas at -100°C, both of which cooled the specimen about 2°C after 5 s.

The potential effects of these temperature changes on impact properties is highly dependent on the material being investigated. For a typical low-alloy pressure vessel steel tested in the mid-transition region, a decrease of 10°C in test temperature would cause a decrease in absorbed energy of about 12 J (8.8 ft-lb). In the determination of the reference NDT temperature, RT_{NDT}, for nuclear reactor vessel steels, the attainment of 68 J (50 ft-lb) at 33°C (60°F) above the NDT temperature is required for the RT_{NDT} to be equal to the drop-weight NDT. If the 50-ft-lb criterion is not met, testing must be performed at higher temperatures until 50 ft-lb is obtained (specific requirements for number of specimens, retests, etc. are delineated in Subsection NB, Section III of the ASME Code[1]). Thus, the Charpy impact toughness of steels which have a ductile-to-brittle transition in the 50 to 100°C range could be affected by the evaporative cooling effect; an artificially high RT_{NDT} could be determined. The degree to which this cooling affects such determinations is dependent on the specific material. In the same way, the testing of irradiated surveillance specimens from commercial nuclear power plants may result in an artificially high irradiation-induced transition temperature shift which can influence the operation of the reactor vessel. Finally, in the certification of materials where impact toughness requirements are specified, the impact energy obtained at the target test temperature would be artificially low. There are, of course, many factors in these and other examples which complicate the simplified scenarios described; however, the significant effects of evaporative cooling on the test specimen temperature are certain.

Regarding the heating of specimens with air and the cooling of specimens with nitrogen gas, the results showed that the interior regions of the Charpy specimen achieve the target temperature at about the same rate as the specimen surface. The need for soaking the specimen at the test temperature for 30 min seems unnecessarily restrictive. Many investigators have the equipment (use of buried thermocouples, etc.) to demonstrate that the target temperature is achieved throughout the specimen in less time than specified by ASTM Method E 23. It is recommended that a provision be considered for inclusion in the method that would allow such users to take advantage of those capabilities in the conduct of Charpy impact testing.

CONCLUSIONS

A study was performed to investigate the effects of various thermal conditioning media on temperature changes in the standard Charpy impact specimen during the time between removal from the environment and impact. The conclusions are:

1. Conditioning in heated water between 50 and 100°C results in significant evaporative cooling of the specimen at 5 s after removal from the water bath; the effects are increasingly greater approaching 100°C where the temperature decrease was 10°C.

2. The use of heated air up to 100°C results in temperature changes less than 1°C at 5 s after removal from the chamber.

3. The use of oil up to 100°C results in temperature less than 1°C at 5 s after removal from the bath.

4. The use of mixtures of acetone or methanol with dry ice from 0 to -75°C resulted in temperature changes less than 1°C at 5 s after removal from the bath.

5. The use of cold nitrogen gas from 0 to -100°C resulted in temperature changes less than 2°C at 5 s after removal from the chamber.

6. The use of heated water for specimens tested in the ductile-to-brittle transition region can have a significant effect on the test temperature, with the magnitude of the effects on the Charpy impact toughness dependent on the specific material.

7. A warning to users of ASTM Method E 23 should be considered for inclusion in the method regarding the potential effects of using heated water baths for thermal conditioning.

8. A provision should be considered for inclusion in the method which would give flexibility in the soaking time requirement for gas environments when the user can demonstrate that the target temperature of the specimen is achieved in less time than specified.

ACKNOWLEDGMENTS

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