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U.S. Department of Commerce
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This report describes results from a Cooperative Research and Development Agreement between the National Institute of Standards and Technology and General Motors Corporation that addresses issues of post-crash automobile fire safety. This report was financed by General Motors pursuant to an agreement between General Motors and the United States Department of Transportation.

The National Institute of Standards and Technology (NIST) is applying its expertise in fire science to this program because of the potentially high impact of this program on vehicle safety in the United States. As a matter of policy, NIST does not test commercial products, especially without the consent of the manufacturers of those products. The National Highway Traffic Safety Administration and General Motors have selected the vehicles to be crash tested and the procedures for those tests. These exploratory tests are only meant to produce a variety of types of vehicle damage that might occur. Not all crash conditions were studied, and the repeatability of the tests cannot be determined since in most cases replicate tests were not conducted due to budgetary constraints. Thus, the results of the tests may facilitate identification of opportunities for improvements in vehicle fire safety, but cannot by themselves be extrapolated to the full fleet of vehicles and all crash conditions. In analyzing the data from these tests, certain vehicles, equipment, instruments or materials are identified in this report in order to specify the experimental procedure adequately. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the fire safety of a particular vehicle is superior or inferior to any other.

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Abstract

Three heating, ventilating and air conditioning (HVAC) units from a sports coupe were tested in a vehicle buck. The three units had nominally identical slots cut into them to approximate damage that might occur in a crash. They were subjected to the same 10 min pre-heating and subsequent flaming ignition conditions on an area of the unit within the engine compartment. The three units differed in the polymer resin content of their shells. One was a normal, non-flame-retarded unit, as used in production vehicles. The other two units utilized a commercial flame-retarded polypropylene resin for non-fiber-filled shell components; they differed only in the flame-retardant content and resin type used in the glass fiber-filled portion of the HVAC case. It was this latter portion of the case that experienced direct flame impingement from the propane igniter used in the tests. In the test with the normal production unit, flames were visible within the portion of the unit rearward of the forward bulkhead (inside the passenger compartment) within 135 s of the start of the igniter; the heat release rate from the overall fire reached 200 kW before being terminated 283 s after ignition. With the two units made from flame-retarded resins, no evidence of flames was seen in the passenger compartment sections and the growth of fire within the units was confined to the engine compartment components. Neither fire exceeded a heat release rate of the order of 5 kW.

Introduction

The work reported here supplements that done previously under Project B.10 and is an extension of that Project. It is part of a Cooperative Research and Development Agreement (CRADA) between General Motors Corporation and NIST. This study was financed by General Motors pursuant to an agreement between General Motors and the United States Department of Transportation.

The focus of the work discussed in this report is on the fire behavior of assembled HVAC units mounted in a front end buck which was made from the same sports coupe for which the HVAC units were designed. The buck comprised the front half of the vehicle body with all engine, drive train, suspension and interior finish components removed; the HVAC units were the only components installed in this test bed which was essentially inert steel for the purposes of these tests[1]. Three HVAC units were tested; one made from normal vehicle production line polymer resins and two made from flame-retarded resins, as described below. The purpose of the reported tests was to measure the effect of these retardant-modified resins on the course of fire development following a particular fire initiation sequence.

Description of Test Assembly

In the discussion below, when a position is described as forward, this means toward the front of the vehicle; rearward means toward the rear of the vehicle. Inboard means toward the vehicle centerline.

Figure 1a is a simplified schematic of the HVAC unit which also shows its relation to the forward bulkhead of the passenger compartment through which it was mounted. The unit contains two heat exchangers, a blower and three moveable doors to control the direction of airflow. One heat exchanger, the air conditioning evaporator unit, is contained within a case which resides fully within the engine compartment. The lower two thirds of this case is made from a chopped fiber glass/polyester resin material. This fiber-filled case extends toward the rear of the vehicle through the forward bulkhead and holds the blower rotor and motor, which reside fully within the passenger compartment. A door which selects outside air or inside air for conditioning sits on top of the blower motor; in the present tests, it was always in the position to select outside air. The frame of this door is composed of polypropylene; this same piece also extends through the forward bulkhead to form the top one third of the case encompassing the evaporator unit.

The second heat exchanger is the heater core. It is contained in a second section of the unit which is composed nearly entirely of polypropylene. A door within this section can close off any air flow through the heater core. In all of the tests performed here, this door was in this position to cut off flow through the heater core. As a result, during a fire exposure, any hot gas coming from the casing around the AC evaporator could pass freely into the flow distributor portion of the unit which was continuous with the heater core case. In the production vehicle the flow distributor section is attached to a monolithic assembly of ducts which carry air to the windshield defroster outlet, the central and side air outlets in the instrument panel and the small defroster vents for the forward ends of the side windows. This duct was not present in these tests. The doors which would have allowed flow into the instrument panel vents section of the ducting were closed in all cases so that any hot gases entering the flow distributor would tend to flow along the length of this section toward the outlets leading to the windshield and side window defroster vents.

The units were mounted into the forward bulkhead using the normal mounting screws for this purpose. Proper mounting calls for crushing a flexible foam elastomer gasket intended to seal the periphery of the hole in the bulkhead (a new gasket was used with

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[1] The body was painted and this paint could contribute some small heat release rate in some types of fires; there was no significant contribution from the paint or from other parts of the buck in the tests conducted here.

each unit). This proved possible for the first two tests which involved the flame-retarded units. For the last unit (normal production line unit) it was not possible to crush the top portion of the gasket, perhaps due to some heat-induced distortion of the bulkhead from the previous tests. A small gap (4 mm to 5 mm) along the top of the unit was sealed by stuffing it with ceramic fiber insulation. This did not appear to have any significant effect on the observed fire behavior of this unit.

In the complete vehicle, the rearward portion of the HVAC unit within the passenger compartment would be attached to the air distribution duct noted above which in turn is supported within the instrument panel. Thus, in effect, the HVAC unit receives some support other than at its attachment points to the forward bulkhead. In the first test the HVAC unit was not supported other than at its bulkhead attachment points and it consequently slumped somewhat, as described below. In the two other tests support was provided under the heater case to limit this slumping behavior but support in this region is not a normal part of the HVAC unit installation in the production vehicle.

The normal production unit (here denoted as unit C) used black, non-flame-retarded polypropylene for all the containment components which were noted above as being made from this polymer. Two of the flow control doors (inside/outside air selection and heater shut-off) were made from an unretarded nylon resin; both have soft foamed elastomer peripheral seals. The flow control doors leading ultimately to the instrument panel vents were steel with a foamed elastomer covering on the side facing away from the flow distributor section; the foamed elastomer was thus not exposed to any flames in these tests unless the unit became fully involved in flames. The lower case around the AC evaporator and blower was made from a composite material consisting of chopped fiberglass and a polyester resin.

In the modified unit designated here as A, all of the polypropylene components were molded from a commercial flame-retarded resin; these parts were an opaque white. This was the same resin as was tested in the form of a smaller part in Ref. 1. This resin was also tested by Tewarson at Factory Mutual Research Corporation (in the form of flat slabs) as part of Project B.10 [2].[2] The flame retardant system in this resin included decabromodiphenylene oxide, antimony trioxide and unspecified zinc compounds. The glass fiber-filled case surrounding the lower two thirds of the AC evaporator and the blower was made from an isophthalic polyester resin containing alumina trihydrate as a flame retardant. None of the gasket materials was modified by flame retardant addition nor were the nylon air flow control doors and their rubber seals.

In the modified unit designated here as B, the same flame-retarded polypropylene resin was used throughout in exactly the same manner as for unit A above. The only difference from unit A was the use of a differing resin in the glass fiber-filled case. Here the flame-retarded resin filling the fibers was based on an acid/base polyester resin that contained antimony trioxide plus aluminum silicate. As with unit A, none of the gaskets

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[2] Tewarson's results for this resin were as follows: peak heat release rate at an incident flux of 30 kW/m^2 was 185 kW/m^2; his Flame Propagation Index was estimated as 13, a result he identifies with a potentially propagating fire (though at a rate below that of unretarded polypropylene).

or nylon doors and their seals contained any flame retardants.

Modifications to Simulate Crash Damage

The focus throughout Project B.10 has been on the flammability of automotive components, particularly as it relates to their potential behavior in post-crash fires. Related projects have also been concerned with post-crash fires. In Project B.14, General Motors has used a front-end impact into a stationary pole as one scenario designed to produce crash damage prior to a fire test; this involved the same sports coupe as that from which the buck used here was made. Project B.3 included an engine compartment fire test of this same sports coupe subsequent to such a pole impact [3]. It should be noted that none of the controlled crashes of this vehicle resulted in the outbreak of a fire.

The vehicle buck used here was not distorted by any impact.[3] However, it was deemed important to attempt to include one facet of the post-crash configuration resulting from a pole impact as used in Projects B.3 and B.14. The pole there impacted the front of the vehicle on the side of the engine where the HVAC unit is mounted (passenger side). The resulting crush was sufficient to cause breaks in the HVAC case, both in the engine compartment portion and in the passenger compartment portion. Such breaks in the engine compartment side are potential passages for flame entry into the HVAC unit (and, possibly, subsequently into the passenger compartment) during a post-crash, engine compartment fire. The breaks provide fire entry pathways that could defeat the potentially enhanced fire penetration resistance represented by the altered polymer resins alone. The breaks were thus included to help prevent the change in polymer resins from yielding unrealistically enhanced fire penetration resistance.[4]

Since the vehicle buck was not subjected to any impact, the configuration of the forward bulkhead to which the HVAC unit it was mounted and of the HVAC unit itself were not the same as those in the crash tested vehicle used in Project B.14. The test configuration was unique, containing an undistorted forward bulkhead, as in an uncrashed vehicle, and a deliberately damaged HVAC case, to simulate crash damage.

General Motors found the vehicle crush and the attendant breaks in the HVAC unit to be variable, even in three successive pole crashes intended to be identical. Based on discussion with General Motors as to the location and size of potentially significant crash-induced openings in the HVAC case seen in these pole crashes, slots were cut into the units tested here. Figure 1b shows the locations of these; all three tested units followed this pattern. Three of the cuts were in the engine compartment. Two were vertical and ran the full height of the unit within the engine compartment, i.e., they ran up through both the glass fiber-filled portion of the AC evaporator case and through the

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[3] Impact-induced distortion and vehicle crush can alter the course of a fire, as can the presence of other flammable materials. The goal here was to limit the fire development variables and focus on the possible outcome of one change in vehicle design, i.e., the nature of the resins in the HVAC unit.

[4] It cannot be determined from available data whether a different break pattern would have yielded appreciably differing results as to the effectiveness of the polymer resin changes in preventing fire penetration into the passenger compartment.

upper polypropylene portion of this case. One was on the inboard side of the evaporator case, about 2.5 cm toward the front of the unit from the plane of the forward bulkhead; it was approximately 13 mm wide over the entire height of the case. The other was on the narrow, forward-most face of the evaporator case; it was approximately 6 mm wide over the entire height of the case. Both of these vertical cuts opened into the space surrounding the metallic AC evaporator unit; thus the only polymeric material which any entering flames would encounter immediately to the inside of the slots was the inside of the case wall.

The third cut in the engine compartment portion of the HVAC unit was a horizontal slot at the juncture of the upper polypropylene portion of the evaporator case with the lower, fiber-filled portion. This slot varied from zero to ca. 6 mm to 8 mm in width over its approximately 13 cm length. Material was cut from the polypropylene portion to make this slot. Again, any entering flames would see no other immediate polymeric material except the inside wall surface of the evaporator case.

The remaining opening was on the passenger compartment side, in the cover over the heater core. To simulate a broken-out portion of this cover, a square section approximately 6.4 cm on a side was cut from its lower inboard corner. This was not relevant to flame entry directly but could have had some influence on internal flows within the unit during the fire tests described below.

All of the above slots and cuts were made by hand using a band saw or jig saw. They were made as identically as possible by these means in all three test units but some minor variability was inevitably present.

Note that these openings simulate one potential post-crash effect that could influence fire penetration, as explained above. However, it was not possible to simulate any crush of the HVAC unit or of the steel bulkhead into which it was mounted. These latter effects could change the relative locations of components, possibly affecting the potential for fire spread among the parts and/or into the passenger compartment. Other normal engine compartment components were absent here. Also, the engine compartment fire used here had a low heat release rate[5] and was unconfined by a hood; it thus did not generate any pressure differential across the forward bulkhead. Some of the Project B.3 tests have shown that an engine compartment fire can, as it grows, induce a pressure differential which tends to push hot gases through openings in the forward bulkhead and into the passenger compartment [3].

Ignition Scenario

The scenario chosen here contains elements seen in engine compartment fire tests during the conduct of Project B.3. One such element is a slow build-up of heat in components that are remote from the active burning region. This is due to radiative and convective heating from the growing flame zone. The time history of this heating depends strongly on the relative placement of the various components, the ignition location, the

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[5] Relative to a fully involved engine compartment with all normal components present.

subsequent flow of hot gases and on radiative view factors. Such behavior is present in all growing fires and it varies considerably with the detailed scenario. The second element is intense localized heating when some burning material is immediately adjacent to the component of interest (e.g., as flames contact this component). The slow initial heating is potentially important because it can pre-heat objects in depth prior to actual flame exposure. This may significantly enhance their flammability since it shifts the local energy balance on elements of the fuel toward a more readily self-sustained condition.

As noted, the pre-heating is scenario dependent. Here the scenario for this slow heat-up was provided by a long tubular burner (48 cm) burning propane at one level (approximately 8 L/min, equal to an 11.2 kW heat release rate)[6] for the first 5 min of the test and then at a higher level (approximately 12 L/min, equal to 16.8 kW) for the remainder of the test.[7] This burner was oriented horizontally and was placed in the (otherwise empty) engine compartment at the height of the bottom of the evaporator case. It was roughly parallel to the inboard side of the evaporator case at a distance that varied from 22 cm to 28 cm from different parts of this side (see Fig. 1b). At this distance the main heating effect on the exposed side of the case was radiation from the sooty propane flame sheet above the burner. A heat flux gage placed at the 22 cm distance (before the HVAC was in place) gave a radiant flux[8] of 3.9 kW/m^2 at the lower propane flow rate and a flux of 6.4 kW/m^2 at the higher flow rate. During one of the tests, a surface thermocouple probe pressed onto the outer surface of the case gave a temperature on the closer, forward face of the evaporator case (fiber-filled part) of 150 °C after 7 min of exposure to this radiant flux regime. This temperature could be expected to increase further by the end of the 10 min pre-heat period that was used in all of the tests, since repeated measurements in the preceding 7 min did not indicate that it was reaching a steady state. The level of pre-heat was thus substantial but it was not sufficient to cause any visible chemical degradation of the evaporator case materials.

There was no hood present to enclose the engine compartment but a portion of the rear end of the pre-heat burner flame was deflected by the cowl at the base of the windshield, sending a plume of hot gas laterally under the cowl and across the top of the upper portion of the evaporator case. The temperature of this gas was measured[9] as 120 °C 3 mm to 4 mm above the top of the evaporator case during the lower propane flow

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[6] Propane flows were estimated from a manufacturer-supplied, typical air-based calibration for the rotameters used; the meter readings were corrected for the molecular weight of propane by the square root of the air-to-propane weight ratio. The heat release rate data from the burner flames indicate that the flows are accurate to about 10%.

[7] The detailed evolution of the fires in all the tests here can be expected to vary with changes in this pre-heating scenario. There is not sufficient data to ascertain whether the relative behaviors of the three differing HVAC units will change with scenario changes.

[8] The heat flux gages were calibrated against a secondary standard and are believed to be accurate to approximately ± 5% of the reading. A formal uncertainty assessment is the subject of a current NIST project.

[9] The gas temperature was measured using the same surface temperature probe as was used in the previously reported surface temperature measurements. The placement of the probe relative to the surroundings was such that any radiative correction to the gas temperature would have been positive, i.e., the gas temperature may have been higher than the reported values.

portion of the burner exposure and 200 °C during the higher flow portion. Thus both the side and top of the evaporator case were subject to sufficient heating to enhance their flammability in the next step, involving direct flame exposure.

Direct flame exposure began after 10 min of the above pre-heating. It came from a second tubular burner fed with propane at a flow rate of approximately 2.5 L/min (equal to a heat release rate of 3.5 kW). This burner was also oriented horizontally and was placed against the base of the inboard side of the evaporator case. Because of the somewhat concave shape of this side, the burner tube only made direct contact at each end; elsewhere the tube was up to 2.5 cm from the surface of the evaporator case. This burner was directly between the two vertical slots simulating crash-induced breaks in the case. Flames issued straight up the side of the case over a 13 cm width. At the above propane flow rate, the flame tips reached just above the juncture of the two types of evaporator case materials, 2/3 up its full height. The placement of the burner was deliberately such that it did not force flames into the two slots to either side of it. However, there was an aerodynamic effect that caused the flames on the forward-most end of the burner to curl past the slot cut into the front face of the evaporator case. This second burner, initiated 10 min after the first burner, was also left on for the duration of the test.

Test Instrumentation

The buck was placed under the NIST Furniture Calorimeter hood so that the fire plume could be captured. The heat release rate from the combined fires (propane burners plus polymer burning) was measured by oxygen consumption calorimetry. This device is intended for heat release measurements on fires up to 600 kW. Since the fire in the HVAC unit was potentially several hundred kW, the hood was run at its full capacity flow rate. This had the result of decreasing the signal-to-noise ratio in the low heat release rate measurements seen in two of the tests described below. The system was calibrated at two known heat release rates (via measured natural gas flow rates) before and after the test series described below. When calibrated in this manner, the system has an inherent accuracy limit (two standard deviations) of ± 5 % for the burning of undefined fuels [4]; more typically, noise in the calibration brings the uncertainty estimate up to about ± 8 % to 10% (two standard deviations). The noise level in low-level, brief heat release peaks can increase the inaccuracy of their measurement since the data cannot be effectively averaged over time.

The tests were video-taped with Hi-8 camcorders from two viewpoints. One camcorder viewed the HVAC unit and the burners from the engine compartment side. The other viewed the HVAC unit from the passenger compartment side.

Ten thermocouples (24 gage wire, bare junction, chromel/alumel) were used in each test. They were placed to help clarify the path of any fire growth into the HVAC and into the passenger compartment area, thus a high degree of temperature measurement accuracy was not essential (see footnote 13). They were placed at various locations discussed below to indicate when or if flames arrived; their junctions were not in contact with solid surfaces. Care was taken to support the thermocouple wires from points that would not move early in any fire spread process as a result of shape changes in thermoplastic materials.

Figure 1b shows the approximate thermocouple locations, as seen from above; the locations could not be precisely reproduced in each HVAC unit. TC 1 was high in the AC evaporator case, at about the same distance from the forward bulkhead plane as the rear slot cut into the inboard side of the case. TC 3 was roughly in the same plane relative to the forward bulkhead but just 2 cm to 3 cm above the bottom of the evaporator case. TC 2 was at about the same height as TC 1 but was placed well forward in the evaporator case, a few cm behind the slot cut in the forward face of the case. TC 4 was placed at the top of the blower impeller, near the area closest to the evaporator case. TCs 5 and 6 monitored any flow coming from the evaporator case into the heater case. TC 5 was near the top to detect buoyant gas flows; TC 6 was near the bottom to detect hot melt/drip material. TC 7 was high in the distributor section to detect buoyant gases trying to flow out of the front of the unit (toward the side window defrost vents). All of the preceding thermocouples were replaced in each new test unit. TCs 8, 9 and 10 were exterior to the HVAC unit and above it, inside the passenger compartment space. All were ca. 1 cm under the metal shelf formed by the outside air intake cowl at the base of the front windshield. All were approximately 4 cm to the rear of the forward bulkhead. TC 8 was approximately in line with the center of the top of the hole through the forward bulkhead. TC 9 was 13 cm inboard of TC 8; TC 10 was 26 cm inboard of TC 8. All three of these thermocouples were intended to detect, as early as feasible, any melt/burn-through in the top of the heater core case or the air distributor case. In a production vehicle, flames emerging in such locations would be just below the underside of the sound insulator pad that covers the inside of the forward bulkhead area.

Test Results and Discussion

HVAC Unit A. Figures 2 and 3 show the heat release rate and thermocouple results, respectively, from the test of unit A.[10] Note that the temperature scales in the upper and lower portions of Fig. 3 differ substantially.

Figure 3 shows that the 10 min pre-heat period caused at least some temperature rise at all of the thermocouple locations. Heat convecting off the inside of the externally irradiated sidewall of the evaporator case is presumably the source of heat spreading within the unit. It is also possible that there was some more direct contribution from the hot gas passing over the top of the evaporator case, as described above; a small portion could have been drawn into the top of the slots cut into the case. There was no direct visual indication to test observers or to the video cameras of flame entry, however.

An unexpected part of the pre-heat period is the early onset of the temperature rise seen by TCs 8 and 9, since these thermocouples were in the passenger compartment, outside of the HVAC unit (immediately above the heater case area). It was not anticipated that a readily measurable amount of heat would reach this far so soon after the pre-heat burner

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[10] TCs 5 and 6 were inadvertently reversed in this test; TC 5 was low and TC 6 was high.

was ignited, since there should be no short , highly transmissive heat flow path to these TC locations. One indirect heat path is via radiative heating of the forward bulkhead on the inboard, engine compartment side of the HVAC unit, followed by conduction through the bulkhead and then convection upward toward these TCs. This path would have heated TC10 more strongly than TCs 8 and 9. Figure 3 shows that TC 10 did also respond quickly but with a lesser rise rate than TCs 8 and 9. Thus this path may have been a contributor to the early rise seen in all three TCs but it appears that another path must have been involved as well which could more strongly affect TCs 8 and 9. A possibility is the following. Post-test inspection of both HVAC unit A and unit B showed that a joint in this area, between the cover for the heater case and the body of the case itself, was spread open.[11] It was spread open more in unit A (to at least 2 cm). This unit had no physical support in the passenger compartment to hold up the weight of the unit and the part in the passenger compartment clearly slumped downward at a later time, as described below. Unit B was supported to minimize such slumping, which distorts the upper heater case portion of the unit. There was no sign that unit B did slump, yet this closure joint was open about 1 cm after the test. Unit B also showed this same temperature rise at TCs 8 and 9, during the pre-heat interval. It is possible then that for both units the joint began to spread open during the pre-heat interval, allowing hot gases to emerge and reach TCs 8 and 9.

When the igniter was turned on at 720 s,[12] TC 2 in the forward, upper region of the evaporator case responded strongly (ca. 600 K in ca.100 s), even before flames were visibly attached (indicating local ignition) on the any part of the HVAC unit. This appears to have been a consequence of the forward end of the igniter flame being drawn diagonally across the forward, vertical slot cut into the evaporator case several centimeters below this thermocouple.

The polypropylene upper section of the evaporator case began to ignite at about 800 s, in the area near TC 2. Figure 3 shows that this was the only thermocouple to reach temperatures of more than 300 °C during this test. Over approximately the next 800 s the flames spread over the inboard and top portions of this upper evaporator case. Flames did not spread onto the outboard side of the top cover which had not received any radiative pre-heating. There was no clear indication of flames attached to the fiber-filled lower portion of the AC evaporator case, though such flames are not always easy to discern in the presence of an adjacent igniter flame. In any event, at the end of the test, the igniter-exposed part of this lower case was white, indicating that all of the resin had been driven out, probably by burning. The glass fibers retained the original part shape and showed no holes.

The top of the evaporator case was the only object which burned unambiguously. The peak heat release rate from this was about 5 kW, as Fig. 2 indicates. There was no indication of flame spread into any portion of the HVAC unit rearward of the forward

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[11] The foam rubber gasket intended to seal this closure was undamaged in both units.

[12] The times reported in the Figures are those in the data file. There was a 120 second interval in the beginning of the file to get baseline data for the heat release rate measurements. Thus, for example, the start of the igniter at 720 s occurred 10 minutes after the pre-heating burner had been turned on.

bulkhead (i.e., within the passenger compartment).

The part of the unit to the rear of the forward bulkhead slumped abruptly downward at 1035 s. The movement was halted when the air distributor case came to rest on top of the transmission tunnel in the buck; the rearmost part of the unit moved down about 2 cm to 3 cm. The movement was caused by the cantilevered weight of the passenger compartment section held up only at the forward bulkhead and the thermal softening of the material near the top of the forward bulkhead hole through which the unit passed. There was nothing in the temperature or heat release rate data to indicate that this happened but it was plainly visible to both camcorders. From the mechanical placement of the HVAC parts, one can reasonably infer that this is the point at which the joint atop the heater case achieved its greater degree of openness for unit A than was noted above for the same closure in unit B. Figure 3, however, shows that TCs 8 and 9, above the top of the closure joint, began rising at about 820 s. In fact a weak flow of smoke was noted in this area, above the exterior of the heater case, at about this time. Evidently, as noted above, this joint began to open even during the pre-heat interval and the appearance of flames in the top of the evaporator case caused hotter gases to begin leaking from the opening by 820 s. Note, however, that these hotter gases are low in temperature compared to flame gases[13]. The fact that the temperatures recorded by TCs 8 and 9 remained in the neighborhood of 200 °C even after the end of visible flaming anywhere on the unit implies that much of the heat this represents was coming from the igniter flame.[14]

HVAC Unit B. Figures 4 and 5 show the heat release rate and thermocouple results, respectively, from the test of unit B. Note again that the temperature scales in the upper and lower portions of Fig. 4 differ.

Recall that HVAC unit B differed from unit A only with regard to the resin in the glass fiber-filled lower section of the evaporator case and blower housing. The same flame-retarded polypropylene replaced the unretarded PP resin used to mold the bulk of the unit.

Figures 4 and 5 bear a strong resemblance to Figs. 2 and 3; in fact, much of the fire test behavior was the same for the two units[15]. However, unit B did start out with a notable difference. There were flames visibly attached to the lower, fiber-filled portion of the evaporator case within about 30 s of the start of the igniter flame adjacent to this area of

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[13] Throughout Project B.3 and B.10, the arrival time of flames at a thermocouple location has been taken to occur as when that thermocouple reads 600 °C. Typical sooty diffusion flame temperatures are 300-400°C higher than this but this lower number helps compensate for the lag time of the rather large thermocouples typically used and for their tendency to underestimate local gas temperatures via radiation and conduction losses from the junction.

[14] The temperature rise of TC 6 (to 70 °C by the end of the test) is less than one might expect given its location high in the air flow space (lumen), rearward of the joint in the HVAC case discussed above. Evidently the hottest gases went preferentially out through the opening in this joint (driven upward through it by buoyancy) and only a minority went rearward in the lumen toward TC 6 and, ultimately, TC7.

[15] The signal to noise ratio in the heat release rate measurements was such that differences of about 1 kW could not be clearly distinguished.

the case. The flames were not large compared to the igniter flames but they were rendered visible when they attached to local points above the base of the igniter flame jets. These flames did not spread laterally more than a centimeter or so beyond the area directly subjected to the igniter flames though there was some visual indication that they did also appear on the inner side of this same area of the lower wall of the evaporator case. Figure 4 indicates that these flames did not contribute much to the overall heat release rate which again peaked at about 5 kW at a time well after any visible flames were attached to the lower case. Thus, the main heat release contributor was again the polypropylene top of the evaporator case. Again, it burned only on the side toward the radiator flame and on the top of the unit where the material was pre-heated.

In Figure 5 one sees that again only TC 2, placed in the upper forward area of the evaporator case, exceeded the 600 °C criterion for the presence of flames. TCs 1 and 3, high and low in the rear of the evaporator case, respectively, showed spikes to about 550 °C. This indicates nearby flames, possibly from a mass of flaming material from the top of the evaporator case which fell partially to the bottom; this material had a clear tendency to sag into the lower part of the evaporator case.

The thermocouples TC 8 and 9 again show a rise before the igniter came on, followed by a more rapid rise after it started. Again smoke was seen coming from this external area of the HVAC, this time immediately after the igniter started, confirming a leak existed there at this time. The bottom of the heater case was mechanically supported throughout this test so no sagging of the heater case or blower case occurred. However, the flow distributor section did slowly sag downward, starting at about 810 s, requiring about two minutes to reach the top of the transmission tunnel, where it was halted. This again was presumably the motion that caused most of the opening (ca. 2 cm wide) seen after the test in the joint between the top of the heater case cover and the main body of the heater case.

All data again indicate no significant spread of flames into the HVAC unit sections to the rear of the forward bulkhead (i.e., into the passenger compartment).

HVAC Unit C. Figures 6 and 7 show the heat release rate and thermocouple results, respectively, from the test of unit C, made from polypropylene and polyester resins having no flame retardants (normal production line materials). Note that the ordinate scales and abscissa scales in these figures differ significantly from those in the previous figures.

The fire involvement and spread process was more rapid and extensive than with the previous two units. Some significant milestones in this process, visible on the video tapes, were as follows[16]:

- Ignition of both lower and upper parts of the AC evaporator case around the igniter flame impingement area occurred at 740 s.
- Smoke emerged from the unit on the passenger compartment side at 770 s, evidently

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[16] Again note that the times given are those in the data file and that 120 s of background data were taken before the pre-heating began. Thus all events occurred 120 s sooner after the start of pre-heating.

from the top seam where the heater core cover meets the body of the heater case.

- Flames were visible above the top of the HVAC unit at 855 s, on the section rearward of the forward bulkhead (in the passenger compartment), along the inboard side of the same seam as was involved in the smoke leak at 770 s.
- Flames were visible inside the bottom of the heater case at 930 s, as seen through the lower inboard hole cut in the heater core cover.
- At 945 s, the bottom fell out of the heater case, dropping flaming material onto the toeboard to the rear of the forward bulkhead (i.e., in the passenger compartment).
- At 1003 s, the still growing fire to the rear of the forward bulkhead was subjected to water from a hose to initiate extinguishment.

The fire was extinguished at the above time because the shape of the buck was beginning to cause a significant amount of smoke to escape from collection by the overhead hood. The fire was continuing to grow at this time and was impinging extensively on the inside of the windshield. Essentially the full top of the unit was involved in flaming; roughly one third of the bottom of the unit was visibly involved. Figure 6 indicates that the heat release rate from the burning material in the HVAC unit (minus the ca. 21 kW from the two propane flames) was about 200 kW when the fire extinguishment began.

The thermocouple results are in Fig. 7. TC 9 again indicates that some hot gas leakage was occurring, essentially from the beginning, into the space immediately above the heater area at the top joint between the heater case cover and the body of the case. There was no significant sagging of the HVAC unit so as to distort this area until much later in the test (at about 840 s). TC 2 indicates involvement of the area at the top front of the AC evaporator case by about 40 s after the igniter flame came on. TC 1 and TC 3 imply that spread rearward along the polypropylene top of the evaporator case yielded flaming melt/drip material which then spread flames to the lower rear portion of the evaporator case, near the forward bulkhead. This spread could also have been due in part to lateral flame spread on the interior of the lower, fiber-filled part of the evaporator case but the video tape shows flaming melt drips from the polypropylene tended to precede lateral spread on the lower evaporator case exterior. Subsequent flame spread from the rear of the evaporator case into the HVAC sections rearward of the forward bulkhead i.e., into the forward part of the heater case, appeared to require a few tens of seconds. Then flames appear to have emerged simultaneously high and low in the heater case at about 930 s, as indicated by TCs 5 and 6. TC 4 shows little indication of spread into the blower area but flames were in fact visible in this section very near the end of the test. Flames spread inboard high in the air distributor section, reaching TC 7 by 990 s. This lateral spread high in the unit could have been aided by a chimney effect (enhanced buoyantly-driven upward heat flow) starting when the bottom fell out of the heater case at 945 s.

Overall, for the section of the HVAC unit rearward of the forward bulkhead, it was apparent in this test that the upward/outward flame spread mechanism resulting from buoyant flow of hot flaming gases tended to be faster than downward/lateral spread resulting from the dripping of flaming polymer melt material.

Interaction of fire in this HVAC unit with other materials in the instrument panel area of a production vehicle would begin as soon as flames emerge from the unit in the area rearward of the forward bulkhead. Here that first emergence of flames was noted at 855 s into the test data file. Since the ignition of other materials imparts new flows and increased competition for available oxygen, the fire in a production vehicle may well take an increasingly different path from this point onward[17]. Different selection of open versus closed "doors" within the HVAC unit could also be expected to yield a differing overall fire growth process.

Summary and Conclusions

Three HVAC units, nominally identical except for resin content, were subjected to a specific fire scenario originating in the engine compartment of a vehicle test buck. All three had nominally identical slots or holes cut into four locations on the outer shell of the units to simulate possible crash damage. Three of these openings were in the AC evaporator case on the engine compartment side if the forward bulkhead.

The two units which were composed predominantly of flame retarded resins gave minimal fire involvement in the conditions used in these tests. The top of the AC evaporator case burned in both tests, yielding a net heat release rate peak of about 5 kW. In neither test was there any fire spread into the portion of the HVAC unit which resided to the rear of the forward bulkhead (i.e., in the passenger compartment).

The reference case gave a fire which reached 200 kW and was continuing to grow when it was extinguished with a water hose. Flames reached the part of the HVAC unit to the rear of the forward bulkhead (within the passenger compartment) about 135 s after the ignition source in the engine compartment was started. Over the next three minutes the fire spread predominantly laterally along the upper parts of the heater case and air distributor section. Lateral growth low in these units was relatively slow, involving mainly the heater case at the time of extinguishment.

The results here are the product of one particular scenario. It is worth noting that the simulated crash damage did not involve any crush of the HVAC cases which could have altered the fire growth potential in all of the units by bringing materials into closer proximity, modifying heat exchange and oxygen access with unpredictable consequences for fire growth.

Acknowledgments

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[17] Any change in ignition scenario could also lead to a different fire growth process.

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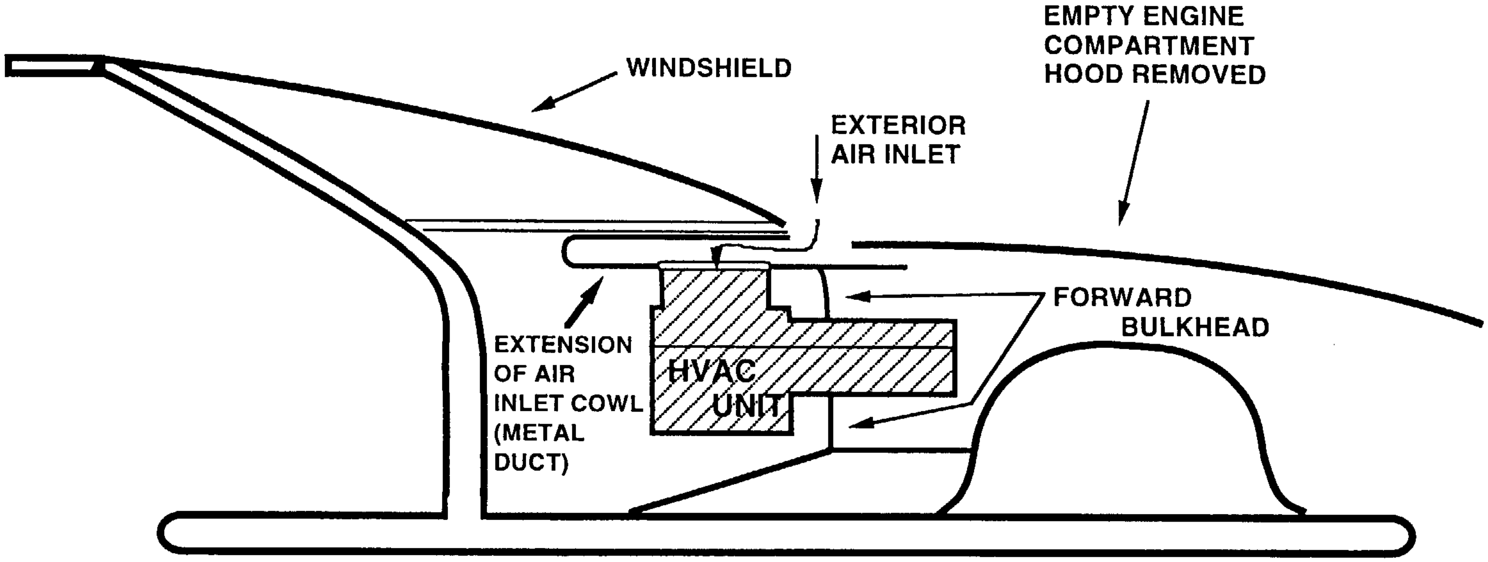


SECTION SIDE VIEW

FIGURE 1a. Sketch of approximate placement of HVAC unit (cross-hatched) in relation to forward bulkhead and other components of buck.

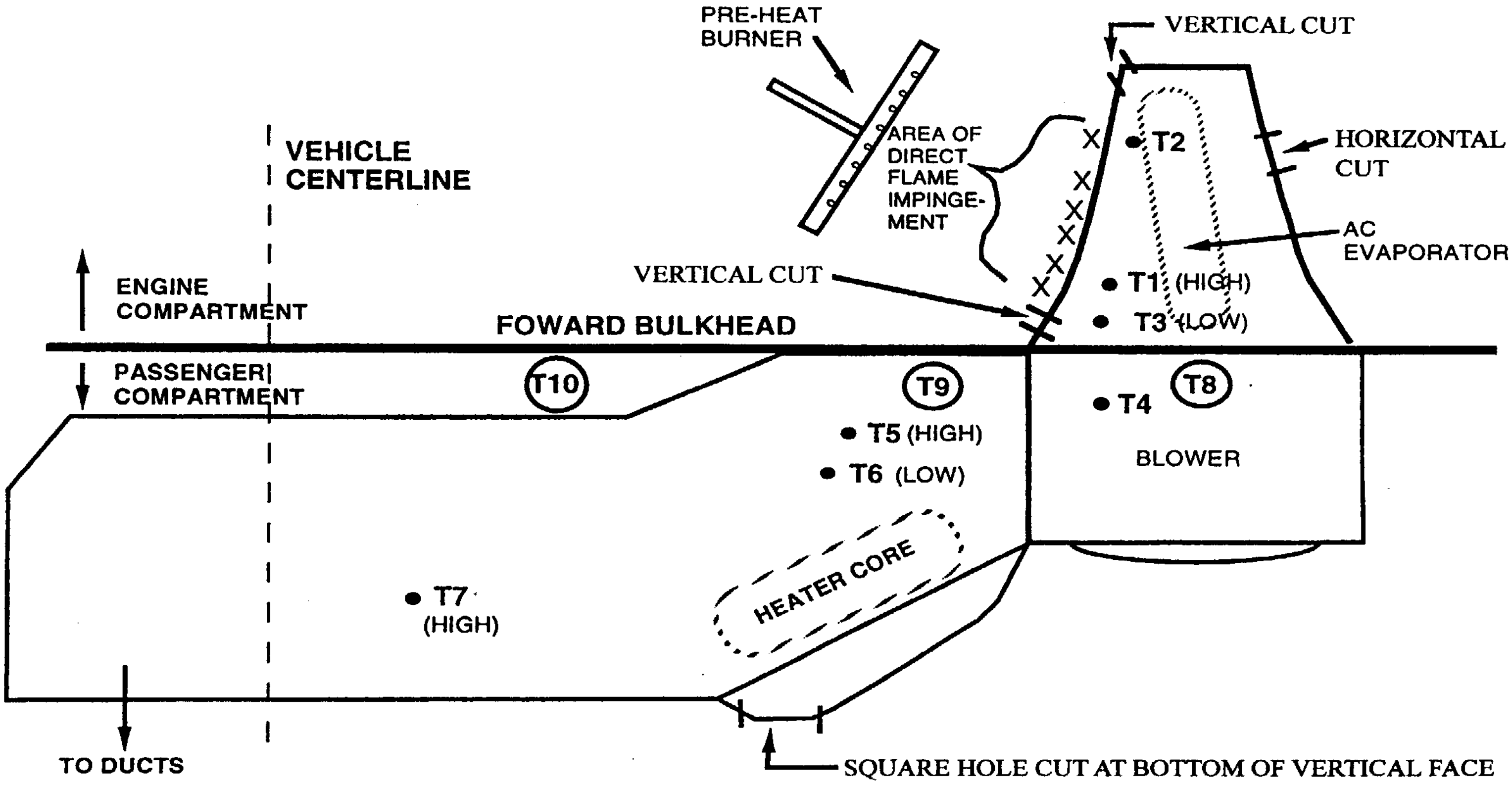


FIGURE 1b. Sketch of simplified topview of HVAC unit; total lateral length of unit is approximately 91cm (36 in); cuts are explained in the text; T1 - T10 are thermocouples.

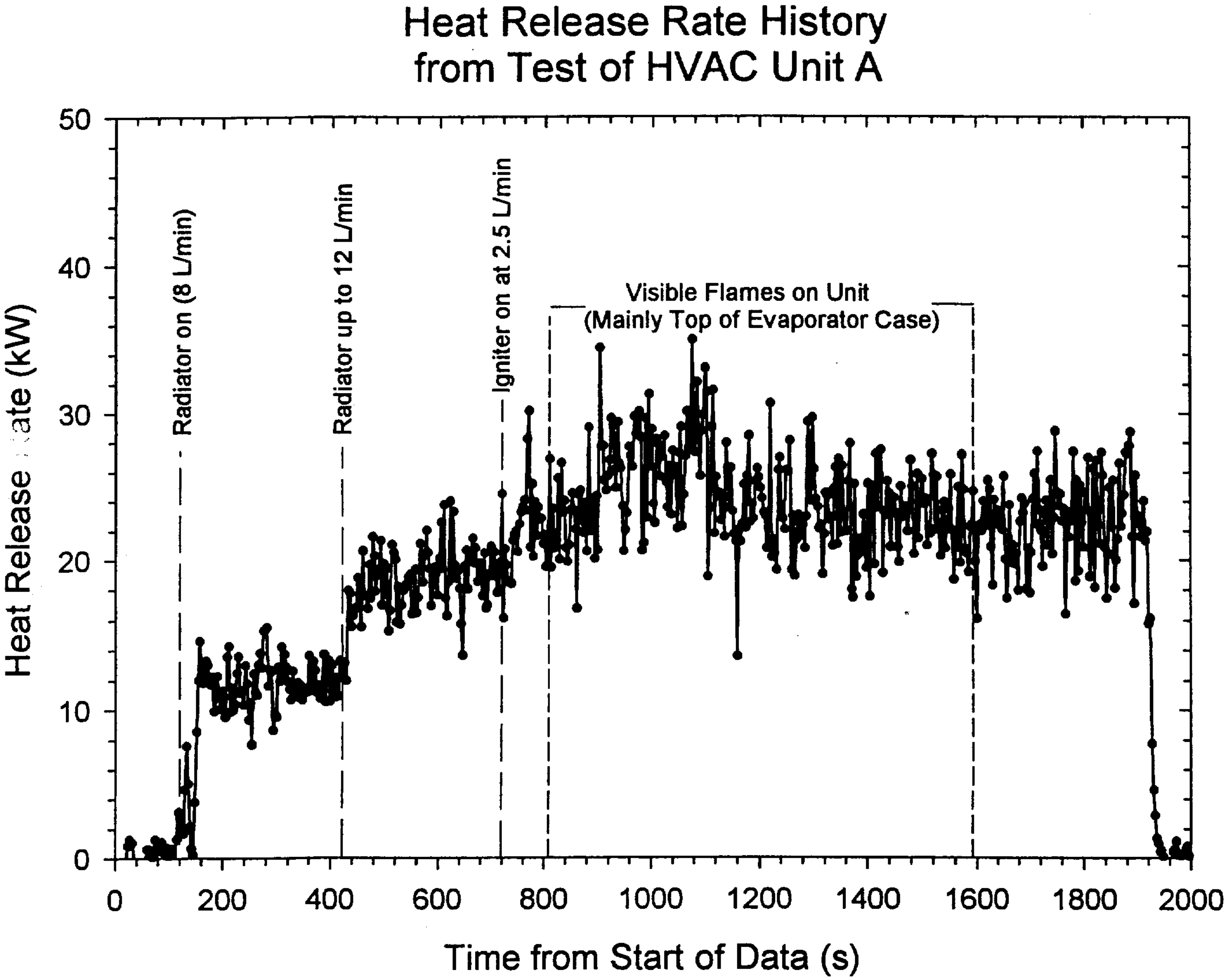
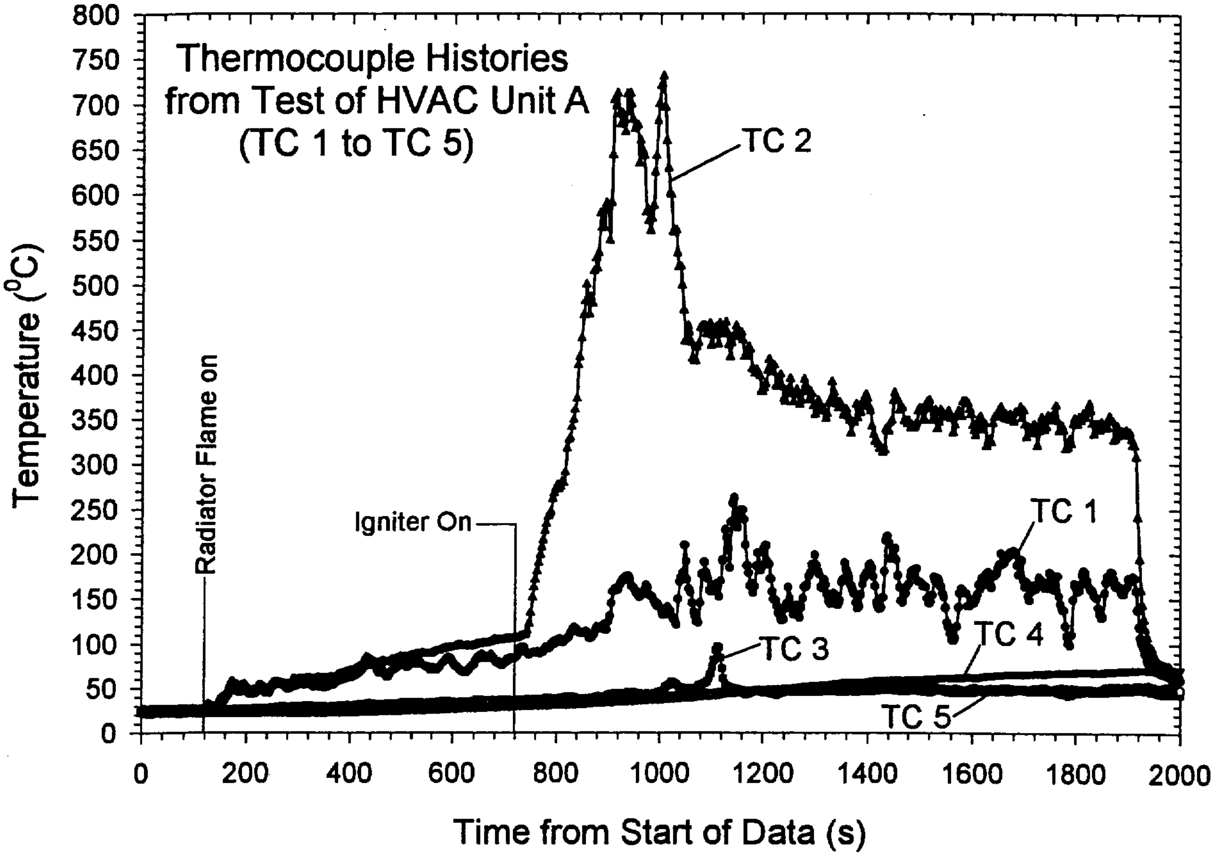


Figure 2 Heat Release Rate versus Time during test of HVAC unit A;
heat release is total from burners plus burning of test assembly.



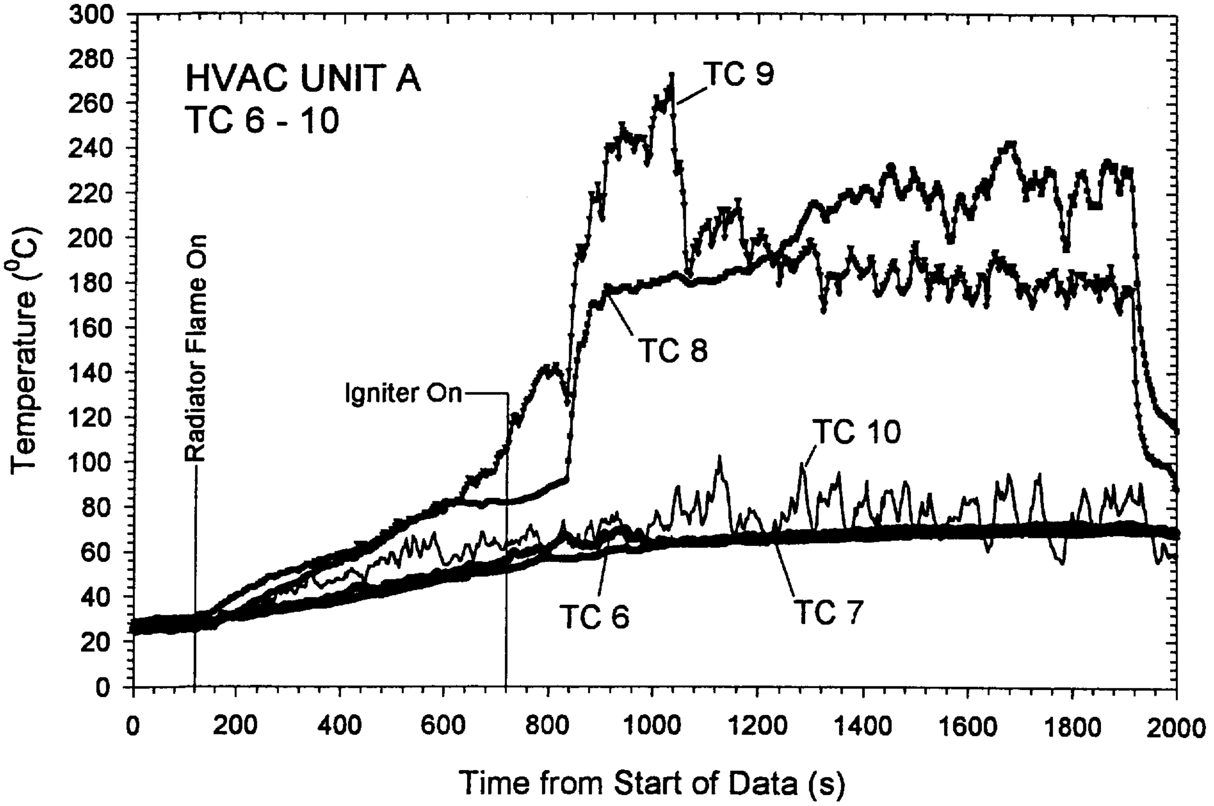


Figure 3 Temperature -Time results from 10 thermocouples in and around HVAC unit A.

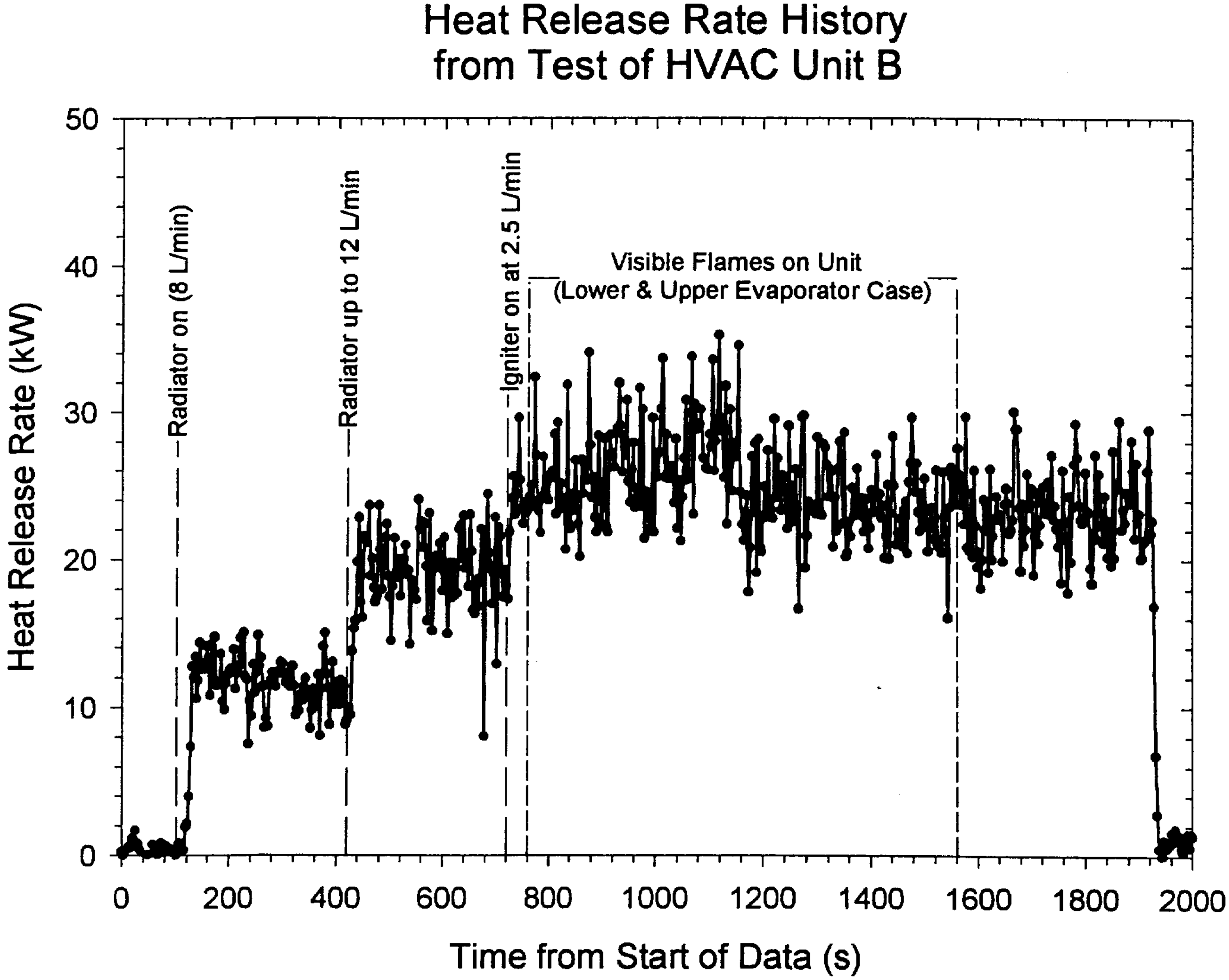
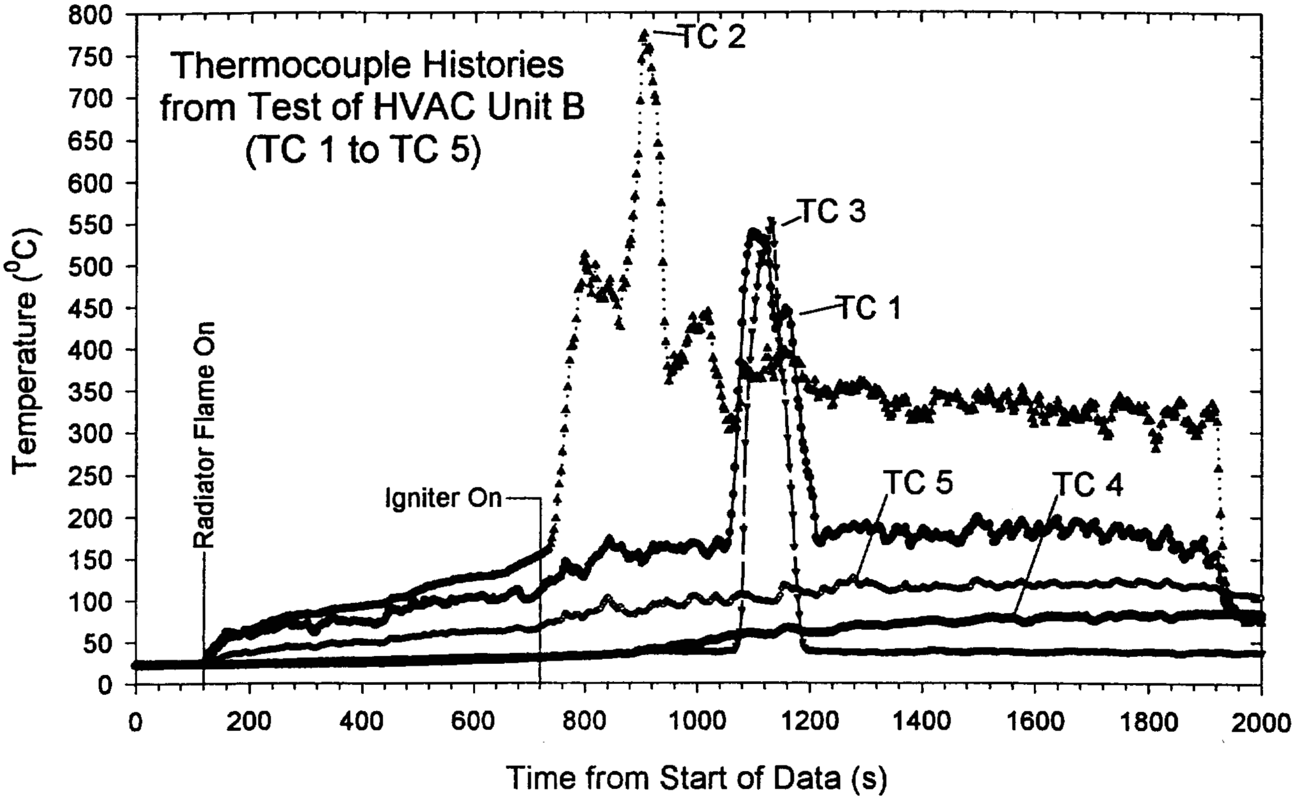


Figure 4 Heat Release rate versus Time druing test of HVAC unit B:
heat release is total from burners plus burning of test assembly



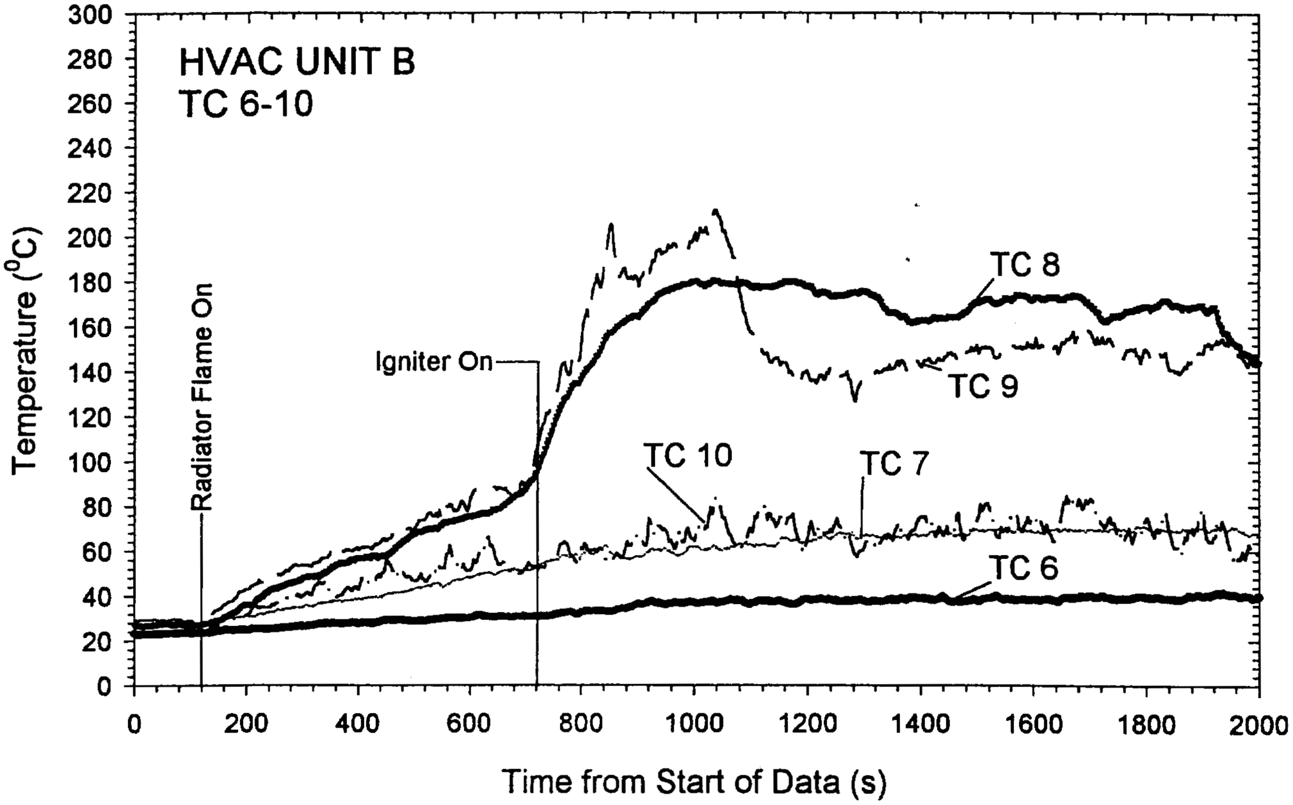


Figure 5 Temprature - Time results from 10 thermocouples in and around HVAC unit B.

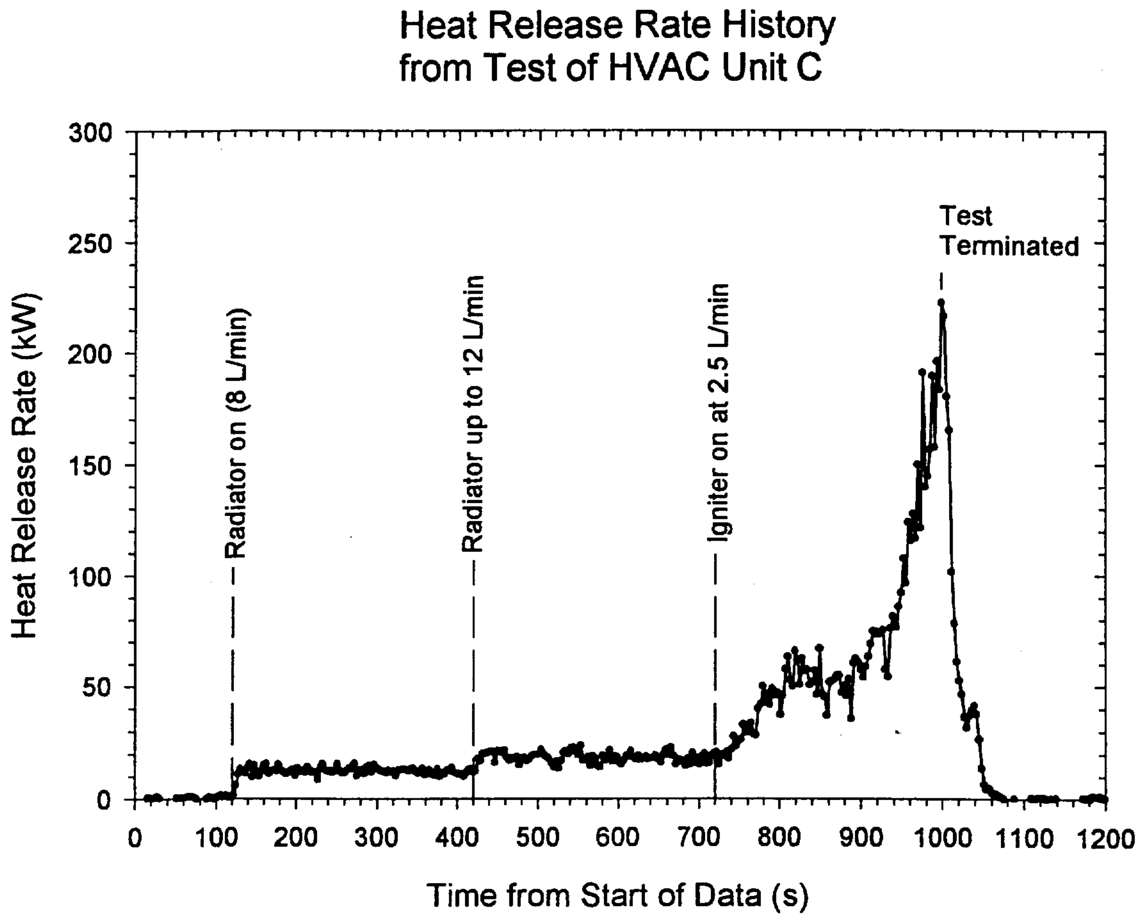


Figure 6 Heat Release Rate versus Time during test of HVAC unit C;
heat release rate is total from burners plus burning of test assembly.