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A FACILITY AND METHOD FOR EVALUATION OF THERMAL PROTECTION

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Naval Air Development Center
Warminster, Pennsylvania

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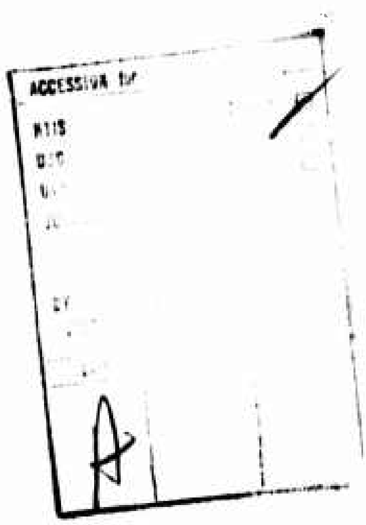

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The rationale, construction, operation and protection assessment methodology of the Naval Air Development Center Fuel Fire Test Facility is described. The historical background and developmental progress to date are reviewed and plans for future work discussed.

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A FACILITY AND METHOD FOR EVALUATION OF THERMAL PROTECTION

PURPOSE AND BACKGROUND

The facility to be described is a fuel fire pit with ancillary equipment and instrumentation to provide for exposure of full-scale, clothed manikins to total flame envelopment under precisely controlled conditions. The method is one designed to yield predictions of the proportion of surface area of a living subject expected to be burned under the experimental garment given the same exposure conditions. The ultimate purpose of the procedure is to provide realistic evaluations of the protective capacity of personal gear worn by aircrew personnel subjected to the thermal hazard of fire contact, particularly that occasioned by aircraft in carrier deck crashes.

Historically, this work dates back to 1960 when it became necessary to evaluate the protective capacity of the first aviator's coveralls made of the then newly-developed fire resistant Dupont fiber HT-1 (later known as Nomex) and developed by NADC for use in military clothing. Prior to this work, it was customary for textile developers to select the most suitable fabric on the basis of comparative differences in physical properties: no effort was made to relate these properties to actual protection achieved, either in absolute terms (occurrence of body burns) or relative terms (extent of severity of burns under one outfit as compared with another). To obtain the latter type of information, a technique was developed and used in the first fuel fire pit exposures conducted by NADC at the Fire Fighters School, Philadelphia Navy Base, with the assistance of the staff of the School as described in reference (1) pp 848-849: ..."experimental suits were fabricated and subjected to contact with fuel flames in a manner calculated to simulate a crash fire. ... A cable was strung across a 100-foot fuel pit and the dummy was suspended from the cable by a shackle. Another cable was attached to the shackle, led around a post beyond the far end of the pit and grasped by a runner. Fifty gallons of fuel were spread across 25-30 feet in the center of the pit to simulate one-half of a circle of flame about an aircraft in a deck crash. The fuel was ignited by tossing a lighted torch into the pit and the runner raced away from the pit at his best speed, pulling the dummy through the flames. An observer timed the flame-contact with a stop-watch." And with respect to the assessment of burn area: "A store manikin was covered with leather to provide a pliable surface, the heating characteristics of which could be determined and readily related to those of living skin. ... At 20 points on this surface calibrated detector paper and precise melting point indicators were placed. The dummy was then dressed in regulation Navy underwear under the experimental anti-G suits. ... The suits were examined after the run and the temperature indicated at 20 sites were noted. Previously obtained data on skin burns (2) permit the evaluation of these temperatures in terms of burns in living skin, while the placement of the detection sites permits the determination of the proportion of surface affected (3)."

Improvements and refinements in technique were made on this rudimentary facility over the years and documented on film as development of fire-resistant clothing proceeded. At the same time, small-scale laboratory methods were developed (4), improvements were made on calculations of tissue injury (5,6), and principles of protection were derived from the basic knowledge so acquired (7,8,9,10). As use of the pit technique increased, it became uneconomical to continue operations at a site 30 miles (48 km) away from the laboratory, therefore, in 1966 a facility modeled after the one described above was prepared at NADC utilizing a smaller area and the assistance of the Naval Air Station crash crew. It soon became apparent that the difficulties of variable winds, erratic fires and post-exposure heating existent in the Philadelphia facility were magnified by reduction in scale and absence of the unique capabilities of the Firefighters School. Therefore, to overcome these difficulties and provide reproducible, full-volume, controlled fires, a new concept based on a rotary path was initiated in 1967 and the prototype facility built in 1969.

In the meantime, the U.S. Air Force and the U.S. Army representatives were in contact with this laboratory and as the approach of evaluation of protective capacity on the basis of physiological effects of exposure became more appreciated and accepted (particularly by industry, the National Bureau of Standards and special interest groups, such as the Council on Fabric Flammability), the Army and the Air Force began to consider constructing their own facilities. So, in 1967-1968, while NADC was developing its new facility, the Army Natick Laboratories, Natick, Mass., built a facility similar in principle to the original set-up in Philadelphia, incorporating refinements such as a pre-exposure protective door and wall and motorized propulsion of the manikin through the flames. The difficulties of erratic fires, wind gusts and post-exposure heating, however, were not diminished by these measures.

In 1969, the NADC pit with a circular travel path, enclosed inside a wind-resistant fence, was completed and tested. It offered considerable improvement in reduction of wind effects and increased stability of the flames and completely eliminated pre- and post-exposure heating of the manikin. Yet greater improvement was desired in stabilization of the fire and instant, over-all ignition of the fuel. The final version, to be described in detail herein was completed in April of 1973 and since has been demonstrated to have achieved its purpose.

Concomitant with the development of the fuel pit and accessories, a more convenient and objective system for recording the surface temperature rise of the manikin before, during and after exposure, was sought. The original system depended on color changes and comparisons with calibration standards, a quite accurate procedure but one which required of the observer good color perception and some training. It appeared that to be more universally useful, a quick-response sensor and telemetering of the signals continuously would be a far better technique. Even though there was uncertainty as to whether such signals could be sent successfully from totally enveloping flames because of possible interference from ionizing gases, the development of this type of system was undertaken in 1970 while the modifications were being made on the pit itself. By this time, also, the concept of evaluating protection capacity on the basis of physiological effects, rather than material properties alone, was thoroughly entrenched. The National Bureau of Standards engaged this laboratory as technical consultant in establishing the direction and work program of the then newly organized Office of Flammable Fabrics, Institute of Applied Technology, and many commercial firms sought similar advice. The military services at this point had progressed to the phase of choosing the most suitable of a number of candidate fire-resistant fabrics for flight clothing. A tri-service meeting was convened at the Air Crew Equipment Department, NADC, in July 1970, and the various special requirements of each service were determined. Also, in July, and again in December 1970, testing was carried out at the Natick facility on experimental aviation coveralls furnished by the USAF and industrial sources (11). It was determined then that to obtain statistically valid results, due to the vagaries of the test conditions, at least 30 suits of each candidate material would have to be run. About this time, too, the Air Force determined to contract for a manikin to provide a greater number of test sites and automatic temperature recording. After numerous consultations with this laboratory, the contractor (12) devised sensors similar to the simulated skin described in reference (9) and used a recording system contained in the torso of the manikin (12), rather than attempting to parallel the telemetry system then under development here at NADC. Interpretation of the data with respect to blister criteria was based on the original data presented in reference (2). Assumptions and extrapolations were made to extend the observed data to prediction of depth of burn (12) even though no experimental data exist to justify such inferences. The system was used at Natick in 1973 (13) and continues in current use. Meantime, in September 1971, NADC successfully demonstrated the telemetry system using thermocouple sensors, oscilloscopic monitoring and magnetic tape recording at a site remote from the exposure (14). Later the thermocouples were replaced with the more rapid and sensitive flake thermistor sensors (Thinistors) and the telemetry circuitry was revised to accommodate the thermistor signals (15). The recorded data are computerized and interpreted in terms of burn area predicted as second degree or worse.

While the above developments were in progress, the subject of consolidation of fire pit facilities came under the scrutiny of Work Group "G" of the Joint AMC/NMC/AFLC/AFSC Commanders Panel on Consolidation of Functions and Facilities convened in February 1971. The entire subject area was thoroughly reviewed and it was then determined, as stated in the final report, 24 June 1971 (16), "Fire pit testing of fabric ensembles on mannequins pulled through a live fire is necessary to realistically evaluate the effects of flame on candidate ensembles of clothing. .....Fire pit testing is not yet a standardized technique. It is highly desirable. ..A live fire is a dynamic event, affected by wind, moisture, temperature and other difficult-to-define parameters. .....The NADC facility is methodology oriented. The NLABS facility is used for multiple testing of clothed mannequins to evaluate clothing ensemble protective characteristics. Each facility is thus designed for a different purpose. .....The Air Force makes use of both NADC and NLABS facilities." It was concluded that "the existing facilities at NADC and NLABS should continue as separate operations." The reasons advanced were that the purposes are different, and that it is not economically feasible to move personnel and equipment from either laboratory to the other's facility for use of the pit due to unpredictability of local weather, the number of personnel involved and the cost of transportation of personnel and equipment. It was stated also in reference (16) that "Instrumented mannequins capable of giving accurate time-temperature histories need to be developed. .....The dynamics of potentially survivable aircraft fires need to be standardized."

Although the state of the art has progressed considerably since the time of that review and work has continued at both facilities, nothing has occurred to alter the original decisions. The fire pit station is reviewed annually and the conclusions are reaffirmed. It is anticipated, however, that at the conclusion of the final modifications in both the physical apparatus and the methodology, the best of all the developments can be incorporated in a single concept amenable to scalar reduction. Such an outcome would put the benefits of the entire development within the reach of many individual agencies. If scalar reduction should prove infeasible, at least the NADC system requires only a few full-scale assemblies to provide a valid evaluation of protective capacity.

Facility Description

The NADC fuel fire pit is housed in an enclosure, approximately 75x75 ft. (22.9x22.9 m), formed by galvanized steel sections 8 ft. (2.4 m) high, surmounted by 4 ft. (1.2 m) of chain link fencing. The fencing is slotted to provide partially open obstruction to wind currents rolling over the top of the solid lower portion of the walls. This open-work has the effect of breaking up the wind front before it reaches the pit itself. Portable screens, 4x8 ft. (1.2x2.4 m) are also available to reduce this effect, if need be. The fuel pit is 20x25 ft. (6.1x7.6 m), 8 inches (20.3 cm) deep, equipped with a fuel dispersion system and a grating to divide the surface into 20 equal compartments (Fig. 1). The dispersion system supplies fuel to each compartment from nozzles submerged in water which provides a base for the fuel. The grating protrudes ¼-½ inch (0.63-1.27 cm) above the surface of the fuel after dispersion. The purpose of the system is to provide even distribution of the fuel initially while the grating prevents pooling of the fuel under the influence of wind. Four ignitors, fed by a propane and air mixture are mounted at two sides of the pit to emit 18-inch flames which ignite the fuel at the four positions simultaneously. A protective wall is placed along one side of the pit between it and the crane rotor. On the back of this wall are mounted the electrical controls for actuation of the ignitors and the crane (Fig. 2). In Figure 2 can be seen also, suspended from the 20 ft. (6.1 m) boom of the crane, a clothed manikin with the telemetry antenna attached to the neck region. The distance of the manikin from the center of the crane determines the speed at which the manikin is moved across the pit, as the crane operates at a fixed speed. Thus, on actuation, the manikin begins to move from a central position behind the wall. In this way, there is no pre- or post-exposure heating of the manikin and the rate of traverse is a constant 10 ft/sec (3.05 m/sec) through the flames. Figure 3 shows the fuel storage area. Fuel is fed to the dispersion system through underground piping. The flow is at a constant rate and the amount is controlled by the pumping time. The sight gauges are used only to monitor tank filling.

During operations, an anemometer is mounted on the fence enclosing the pit area, but it is of limited usefulness since it cannot predict gusts but only indicate their presence.

Photographic coverage of each run is provided by two cameras aimed at the site through ports in the galvanized steel portion of the fence. One records in real time, the other in high speed for slow-motion viewing. Both provide visual information on the actual thermal contact between manikin and flames. Wedge calorimeters (16) may be used to indicate thermal flux at the outside surface of the ensemble. Still photos are taken of the condition of the experimental ensemble before and after exposure.

Methods and Results

The method of assessing protective capacity of an actual assembly relies on the satisfaction of a number of conditions: 1) The fire must reasonably represent an actual accidental fire in intensity and dimensions. 2) The exposure must be total, i.e., totally envelop the body, because partial exposures, such as might occur in an actual accidental situation, are not amenable to experimental replication and analysis. (Therefore, the results obtained are always "worst case" for the parameters studied.) 3) The exposure must be a square wave pulse because this is the only type of pulse for which comparable experimental burn data are available. 4) The surface temperature measurements must be relatable to skin temperature in the living body under the same conditions. This means that the measured temperature can be converted to living skin temperature by prior calibration on direct comparison between the sensor signal and the true skin temperature. 5) The velocity of movement of the manikin through the flames must be reasonably similar to that expected of an escaping victim, because the burn pattern produced on a stationary or on a high-velocity figure are very different. Typically, at the speed of 10 ft/sec, which is estimated to be a reasonable value under crash circumstances (1), the flames tend to part in the chest area and to roll up the back surface of the moving figure; the stationary figure is exposed equally front and back, while the rapidly moving figure may show cavitation effects in its wake. The facility described above satisfies the necessary conditons specifically by 1) using a fuel appropriate to the crash vehicle; 2) providing a solid volume of flames through the use of the grating and dispersion system; 3) preventing pre- and post-heating of the manikin by starting and stopping it behind the protective wall, thus achieving a square-wave pulse; 4) calibrating the sensor system directly against living skin temperature rise measurements; and, finally, 5) assuring a constant speed of movement through the flames by virtue of the fixed rate of rotation (4.8 rpm) of the crane. (It is possible to provide different speeds between 8.5 and 10.5 ft/sec (2.6 and 3.2 m/sec) by suspending the manikin at different distances from the center of rotation.)

The experimental procedure consists of garbing the instrumented manikin in the experimental ensemble, checking the telemetry system, photographing the manikin for record purposes and preparing the pit for firing. The fuel is fed into the pit for 16 seconds at a rate of 0.856 gal/sec (3.24 l/sec) (total 13.7 gal or 51.85 l) and ignition is initiated at 40 seconds, when the fuel has spread completely over the water surface of each compartment. At 48 seconds, the crane is actuated to move the manikin through the flames, which at this time are fully developed. During the exposure the anemometer and the telemetry signals are monitored and any erratic effects noted. Camera coverage starts before the manikin enters the flames and continues until the manikin is stopped behind the protective wall. The fire is permitted to burn itself out (an additional 30 sec. approximately) and the manikin is then photographed to record effects on the experimental ensemble. The surface calorimeters are removed and readings noted. The experimental items are examined, condition noted, and items removed. When paper detectors are used in conjunction with the thermistor sensors, these are read in situ at this time also. The telemetry data recorded in analog form on magnetic tape are later converted to digital and analyzed at the remote CDC 6600 computer terminal in the laboratory. The analytical programs provide final data in the form of predicted burns, second degree or worse, over that surface of the living body corresponding to the manikin areas which were exposed (15). Customarily the head, hands, and feet are not included, because these areas receive special protection. Of course, where helmets, gloves or footwear are being evaluated, appropriate provisions are made to acquire the necessary information. Depending upon the purpose for which each evaluation is made, pertinent data are extracted and reported in sufficient detail to satisfy the practical need (e.g., ref 17). On a continuing basis, refinements are made in calibration of instrumentation and in analytical techniques to improve the usefulness of the information generated. Due to the uncertainties of the physiological effects of exposures beyond the parameters established by actual experimentation in living flesh, it is not considered profitable to attempt to extrapolate observed data into experimentally unexplored areas, such as depth of burn. Such predictions based on manikin temperatures are conjectural at best. They can also be misleading to the uninitiated or unwary in that the highly problematical nature of such indications may not be apparent to the user and with repetition gain false credence through familiarity and convenience. Information of this kind is worse than none at all. It is considered sufficient ordinarily to evaluate candidate protective clothing in terms of the absolute and relative extent of areas preserved from severe burns by the various outfits during comparable exposures. The reproducibility of the thermal impulses is such that valid results can be obtained with as few as three experiments on each candidate assembly.

Discussions and Conclusions

The physical conditions and experimental procedures for protection assessment are deceptively simple. Only those who have grappled with the vagaries of live, open-flame experimentation can appreciate the great difficulty with which valid data are obtained. When all controllable conditions are in order, together with fortuitous circumstances, such as zero wind velocity, occasionally billowing of the flames themselves due to internal turbulence may cause uneven exposure of the manikin. While such occurrences realistically represent the true state of affairs in an accidental fire, they effectively invalidate experimental data simply because only the maximal exposure is amenable to quantitative analysis. It has been estimated that at least 30 exposures are required in the Natick Laboratory facility; at NADC, present experience indicates that only three are normally required, even in the presence of winds gusting up to 25 mph (40 km/hr).

With respect to collection and interpretation of the manikin surface temperature rise data, a good deal of technical refinement has been made over the years. The NADC telemetry system provides surface temperature measurements at the rate of 222/sec at each of the 18 sites regularly sampled. The Air Force system provides sub-surface temperatures at the rate of 3/sec at 124 sites. Thus, while the NADC system samples far fewer sites, it is much faster and permits close monitoring of the shape of the temperature-time curve before, during and after exposure. Any fluctuations due to erratic behavior of the flames are immediately apparent and in the absence of such behavior heating is quite even and fewer sites necessary. Then in selecting data for calculation of the damage integral, only a comparatively few points are required, since the usable curves are continuous. These points are indicated on the tape, which is tagged at the beginning, end, and two mid-points of the passage of the manikin through the flames on each exposure (15). However, despite these refinements, the basic theory has not changed. Damage assessment still relies on detection of temperature rise with exposure time over a substantial part of the manikin body surface, correlation of this rise with that occurring in living skin under the same circumstances and conversion of the temperature-time histories into damage rate and total damage. All current systems use the parameters established in ref.(2)for computing damage. However, if the exposure is truly a square wave impulse, it is not necessary to compute damage, but only to know the maximum true skin temperature indicated and the total exposure time. For instance, empirical data selected from ref. (2), together with that from various unpublished experiments, provide the relationship as shown in Fig. 4 between maximum skin surface temperature and duration of a square wave pulse of intensity appropriate to produce the corresponding temperature peak in the time indicated. Thus, if the exposure time is held constant at three seconds, an indicated maximum skin surface temperature of 65°C or greater denotes an injurious exposure. Similarly, if the exposure time of 10 seconds and the indicated peak skin temperature exceeds 55.7°C, severe injury is predicted to occur within 24 hours of the insult. At all exposure times, it is necessary that no equilibrium be reached or discontinuity in temperature rise occur, as such an occurrence would invalidate the system. Provided that these experimental conditions are rigidly met, an extremely convenient method results, for it is then necessary to measure only the equivalent skin surface temperature critical to the endpoint of blistering appropriate to the exposure time used. Thus, the essential information of severe or non-severe injury is quickly obtained at each measuring site. This system is so simple, in fact, that it is wide-open to serious abuse in the hands of the naive operator. For instance, if the incident flux is undulating, then it is quite possible that the maximum skin temperature abserved would be less than the critical value for a square wave impulse of the given exposure time, but that the skin temperature could have reached a lower than critical level rapidly and been maintained there for a time sufficient to produce a severe burn at the lower temperature. The converse is also possible, i.e., a higher temperature than that critical for a square-wave impulse could be reached rapidly with a precipitous fall-off to a low level, such that no burn results despite the fact that one is indicated. In the latter instance, the error is on the side of safety and therefore is of less importance than the former, where a severe burn might occur when none was indicated. However, given proper, controlled conditions, it then remains only to calculate the percentage of body surface indicated as seriously burned, a simple matter described in detail earlier (1).

The final improvements envisioned for the present facility include installation of remote control switches, so that the operator may conduct the entire exposure from outside the enclosure; development of techniques for multiple exposures simulating intermittent flame contact, as might occur in active firefighting; addition of sensors mounted on the boom of the crane to provide maximum flame flux and temperature measurements; and additional readout markers mounted on the rotor of the crane to provide for more frequent correlation points to relate manikin protection and time data to the telemetered temperature signals.

It is concluded from this review that the main difficulties associated with full-scale evaluation of fire protective clothing have been identified and largely surmounted for present practical purposes. Evaluations now can be made reliably with reasonably small numbers of prototypes of interest to the Navy flyer. Modifications in apparatus and method can be made to provide for other studies. Future effort should be directed toward engineering development of scalar models on the one hand and, on the other, basic research into the depth of burns associated with thermal exposures to radiation and to flame contact: engineering effort on scalar modelling may greatly reduce the time and cost of obtaining valid burn protection assessments, thus bringing this capability into reach for many laboratories not now in a position to pursue these measurements; basic biophysical research may provide a valid experimental basis for extending prediction of burn effects by non-biological means to include depth of tissue injury, a feat not presently possible.

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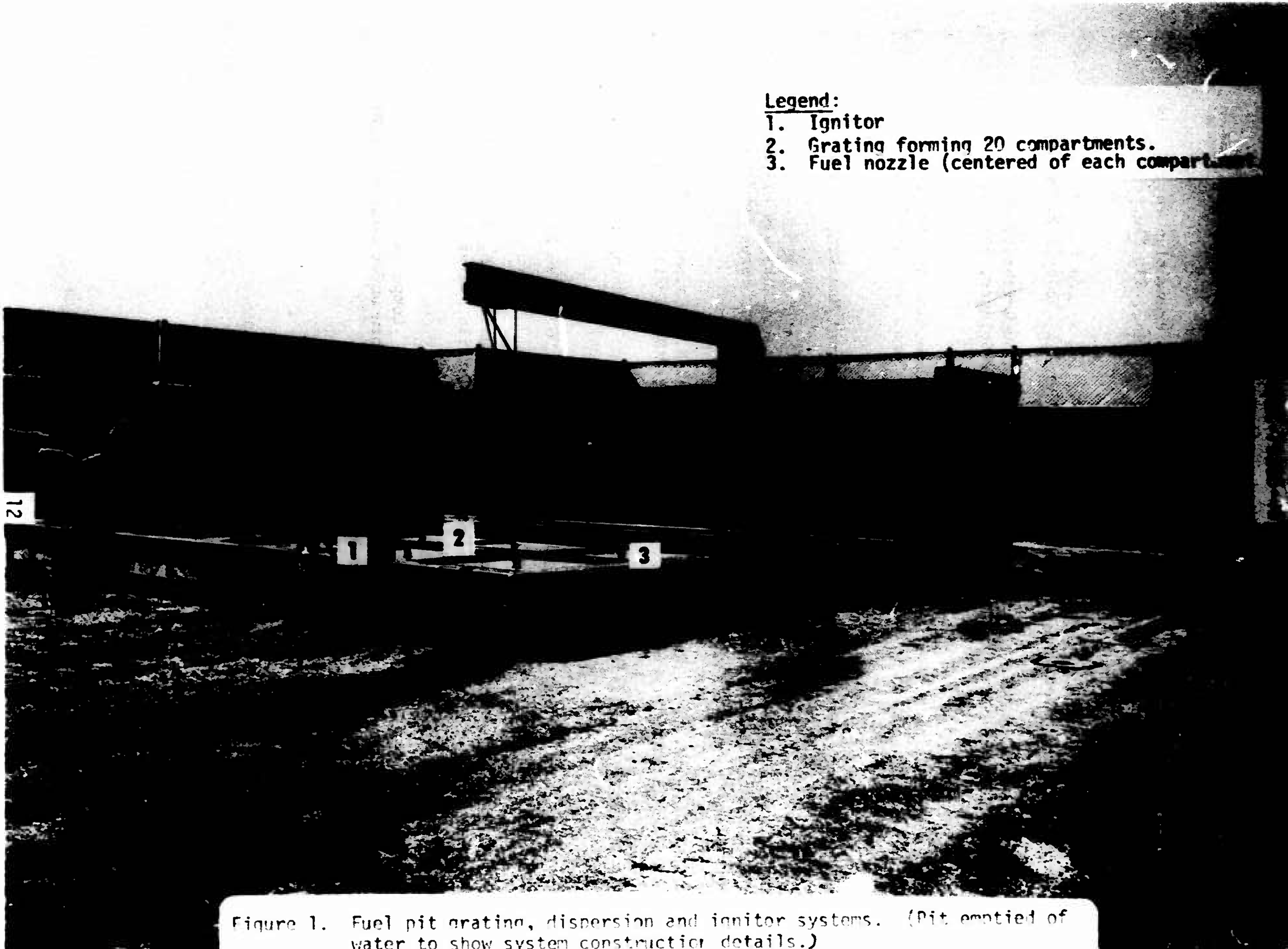
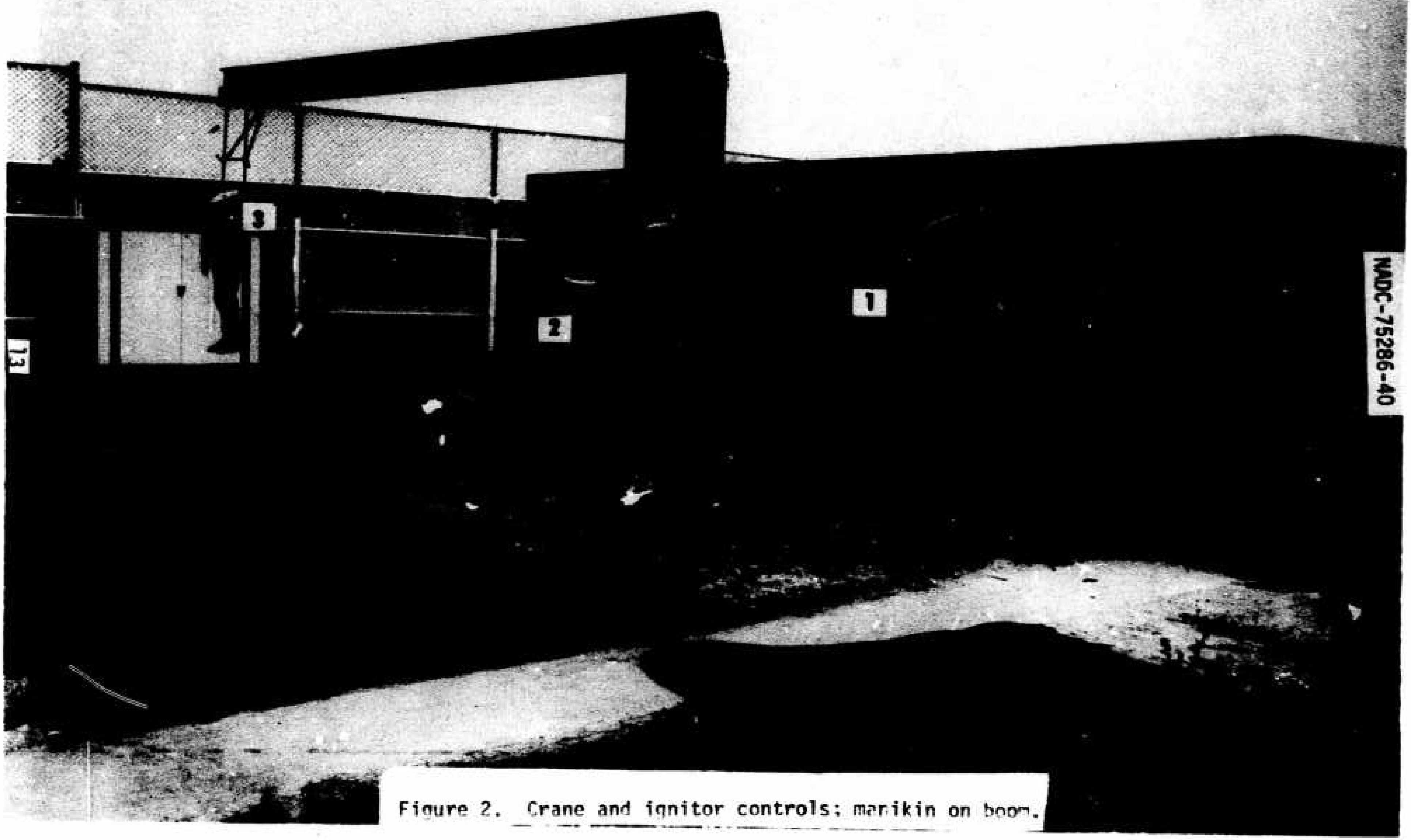


Figure 1. Fuel pit grating, dispersion and ignitor systems. (Pit emptied of water to show system construction details.)



Legend:
1. Crane actuator switch.
2. Propane - air ignitor fuel system.
3. Manikin (with telemetry disc antenna) suspended from boom.

Figure 2. Crane and ignitor controls; manikin on boom.

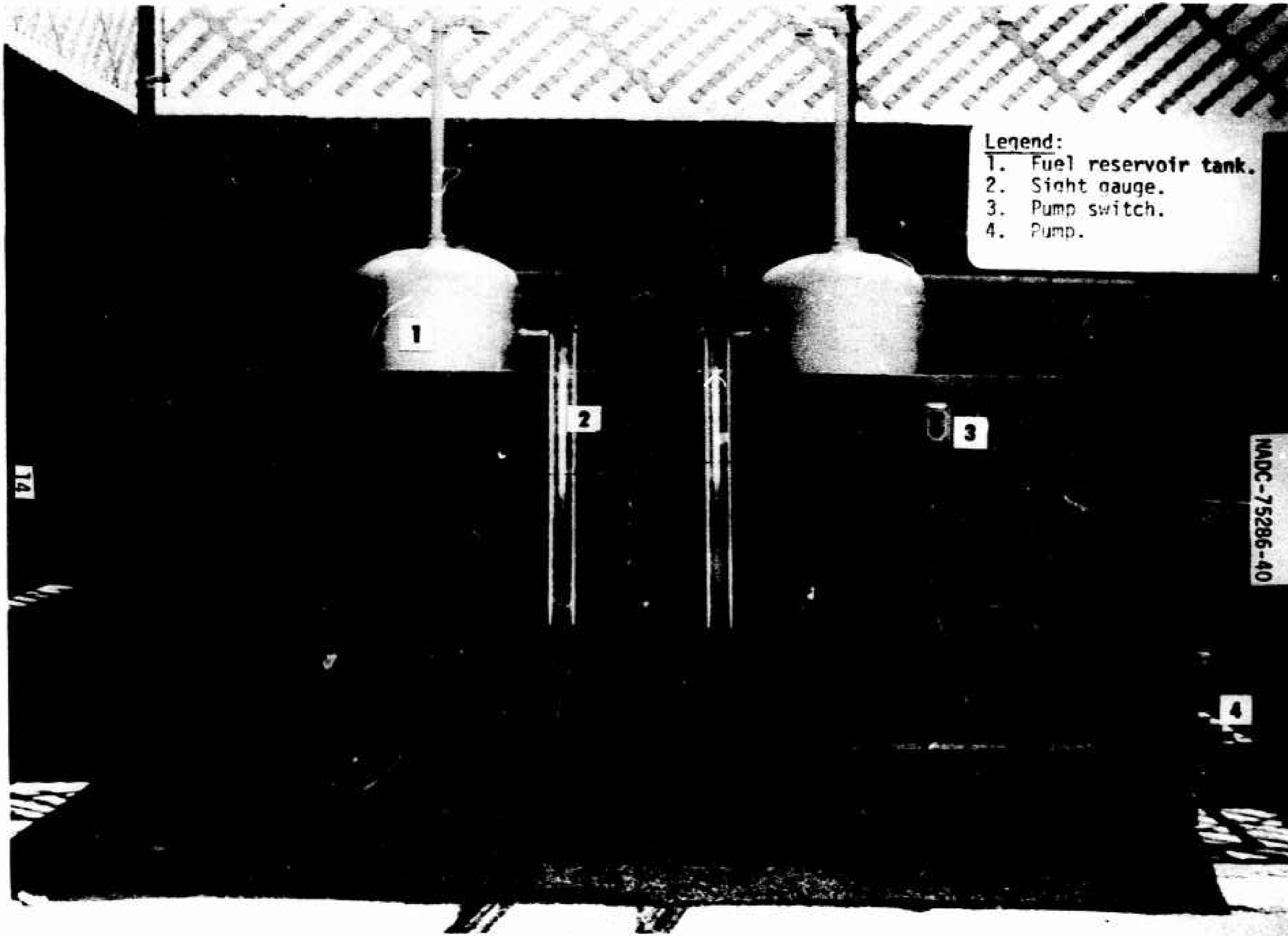


Figure 3. Fuel storage tanks, sight gauges and pump.

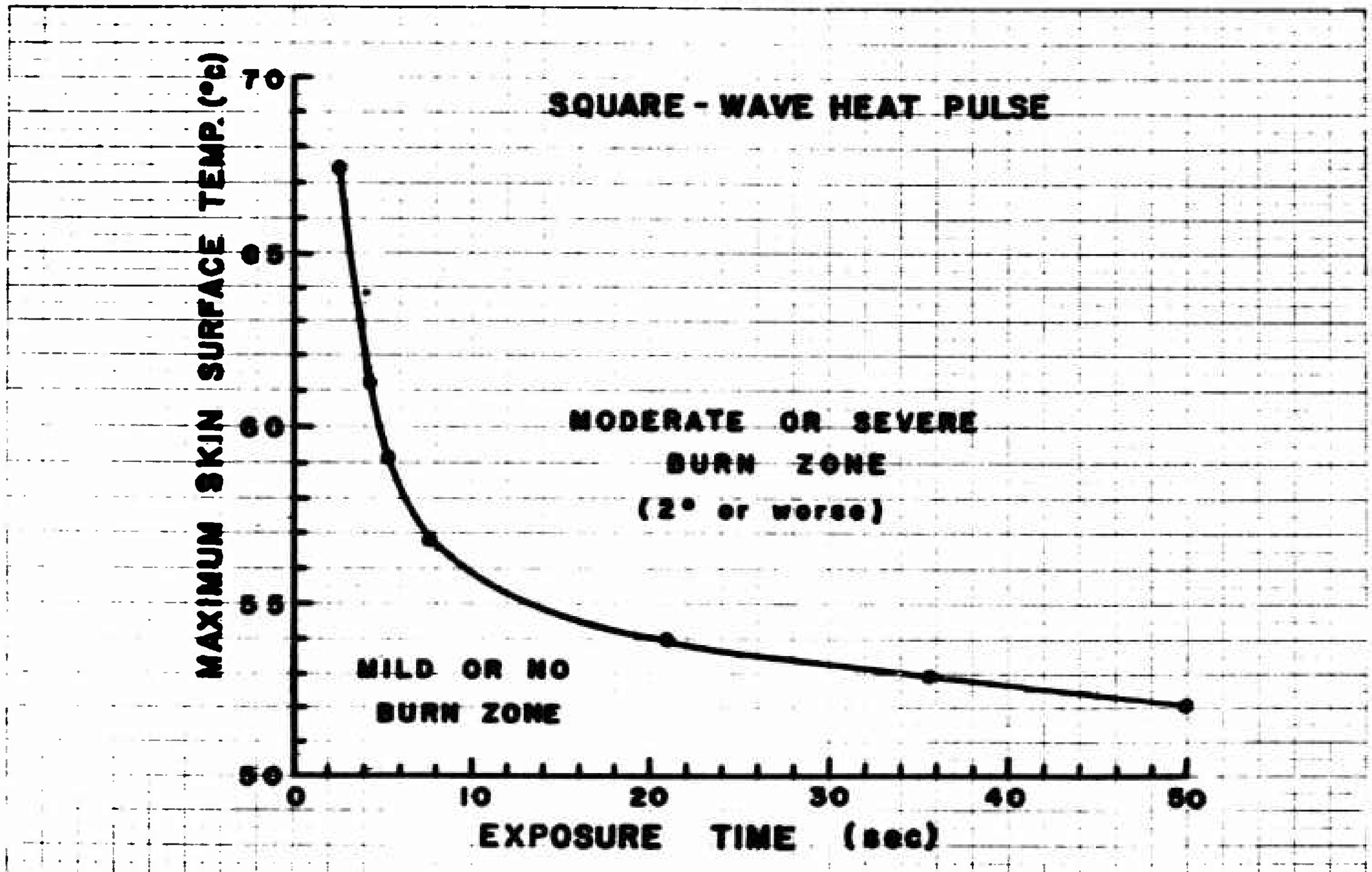


Figure 4. Maximum skin surface temperature occurring on exposure to a square wave pulse of various thermal intensities and duration times causative of blistering.