A STUDY OF SODIUM FIRES

By
J. D. GRACIE
J. J. DROHER

ATOMICS INTERNATIONAL

A DIVISION OF NORTH AMERICAN AVIATION, INC.
P.O. BOX 309 CANOGA PARK, CALIFORNIA

CONTRACT: AT(11-1)-GEN-8
ISSUED: OCTOBER 15, 1960

DISTRIBUTION

This report has been distributed according to the Category "Reactors-General" as given in "Standard Distribution Lists for Unclassified Scientific and Technical Reports" TID-4500 (15 Ed.), August 1, 1959. A total of 625 copies was printed.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

CONTENTS

	Page
I. Introduction	1
II. Summary	2
III. Technology of Sodium Fires	6
A. Sodium Combustion Reactions	6
B. Description of Combustion Process	7
C. Residue and Smoke from Combustion	11
D. Combustion Rate	13
E. Temperature Profile	15
F. Ignition Temperatures	16
G. Effect of Gaseous Atmosphere	19
H. Pressure Increases Caused by Sodium-Air Reaction	24
I. Combination Sodium-Hydrocarbon Fires	38
J. Sodium-Water Reaction	39
IV. Leak Containment and Protection of Structural Members	44
A. Control of Leaking Sodium	44
B. Removal of Leaking Sodium	47
C. Pressure Control	48
D. Water Control	50
E. Smoke Control	50
V. Extinguishing Materials for Sodium Fires	53
A. Solid Materials	54
B. Liquid Materials	66
C. Gaseous Materials	71
D. Fire Blankets	71
VI. Procedures for Fighting Sodium Fires	77
A. General	77
VII. Personnel Protection	80
References	83

TABLES

	Page
I. Mode of Reaction of Sodium at Different Water-Vapor and Oxygen Levels	20
II. Comparison of Effect of Water Vapor and of Hydrogen upon Mode of Reaction of Sodium	21
III. Summary of Sodium Fire Tests Reported by Mangold and Tidball	26
IV. Effect of Oxygen Concentration on Pressure Increase in Gallery Mockup (First Series)	30
V. Effect of Oxygen Concentration on Pressure Increase in Gallery Mockup (Second Series)	31
VI. Effect of Sodium Temperature on Pressure Increase in Gallery Mockup (Third Series)	34
VII. Effect of Drive Pressure on Pressure Increase in Gallery Mockup	34
VIII. Effect of Absolute Humidity on Pressure Increase in Gallery Mockup	35
IX. Basic Chemical Equilibria for Sodium	40
X. Powder-Extinguishant Tests, Summary of Results	56
XI. Liquid-Extinguishant Tests, Summary of Results	68
XII. Liquid-Extinguishant Tests, Summary of Results	70
XIII. Resistance of Fabrics to Flame from a Bunsen Burner	73

FIGURES

1. Sodium Burning in Cylindrical Container	9
2. Evolution of a Sodium Fire	10
3. Temperature Rise, Burning Sodium Pool	12
4. Burning Rate <u>vs</u> Depth.	14
5. Burning Rate <u>vs</u> Area	14
6. Sodium-Fire Temperature Profile.	16
7. Temperature Profile of Sodium Spray in Air	17
8. Effect of Oxygen on Maximum Pressure Buildup, as Reported by Hines and Kelley	25

FIGURES

	Page
9. Pressure Changes in Experiments 5, 6, 7, and 8, as Reported by Hines and Kelley	28
10. Effect of Oxygen Concentration on Maximum Rate of Pressure Buildup in Gallery	33
11. Sodium-Leak Detector-Collector	46
12. Vacuum Sodium-Pickup Device	49

ABSTRACT

A study of sodium fires was performed to obtain detailed information on their characteristics and behavior in order to develop techniques for preventing, containing, and combatting such fires. Investigation was made of the technology of sodium fires, design criteria for improving the fire resistance of equipment and installations using sodium as a coolant, extinguishing materials and procedures for fighting sodium fires, and the evaluation of protective equipment.

I. INTRODUCTION

The large-scale use of sodium as a coolant for nuclear power reactors has created unusual problems in fire prevention and control. The extinguishing of fires involving sodium requires special materials and techniques; radioactive sodium presents additional problems. Hydrocarbon fluids have also been used in sodium-cooled reactors for certain auxiliary applications such as coolant for the shield or for the freeze seals. The extinguishing task, therefore, becomes further complicated if the fire involves both radioactive sodium and hydrocarbon materials.

Atomics International is engaged in exploring and improving the technology of sodium-cooled nuclear reactors. The lack of detailed information on characteristics and behavior of sodium fires makes it desirable to develop better techniques for preventing, containing, and combatting such fires. This information can also be utilized to develop more effective protective devices for personnel and for equipment. Accordingly, the following program was initiated:

- a) The compilation of information on the technology of sodium fires to gain a better understanding of how to combat such fires.
- b) The development of design criteria for improving the fire resistance of equipment and installations using sodium as a coolant.
- c) The investigation of the use of new materials, and utilization of certain of their physical-chemical properties, to combat sodium and sodium-hydrocarbon fires.
- d) The development of operational techniques and standards of sodium-fire prevention and fighting.
- e) The evaluation of equipment for protection of personnel working with sodium at elevated temperatures.

II. SUMMARY

The principal reaction products resulting from combustion of sodium are Na_2O (sodium monoxide) and Na_2O_2 (sodium peroxide). In excess sodium the monoxide reaction predominates, while in excess air the peroxide reaction predominates. The combustion reaction is characterized by very low flames and dense clouds of white oxide smoke. Heat must be supplied to start the combustion reaction of sodium at low temperature, but once started, enough heat is liberated to maintain the reaction and gradually raise the temperature of the molten liquid. If the liquid is well insulated thermally, it eventually can increase in temperature to 1630°F , the boiling point of sodium. This is the highest temperature which can be obtained in a pool of sodium under atmospheric pressure. Depending upon the configuration and the resulting heat losses to the surroundings, the pool may attain a much lower equilibrium temperature.

The combustion in air of sodium in a pool proceeds at a rate of about 0.15 to 0.3 lb/min per square foot of exposed surface. The rate tends to increase with pool depth and decrease with surface area. A spray of sodium reacts almost instantaneously.

When sodium is burned, much of the sodium can remain unreacted. Of the sodium that does react, only a small proportion is evolved as smoke. About 4100 to 4850 Btu of heat are liberated for each pound of sodium that burns completely (2280 to 2700 cal/gm). Preliminary tests conducted with gram quantities of radioactive sodium indicate that less than 10% of the initial activity was lost during burning. Therefore, if radioactive sodium is involved in a fire, it should not be assumed that all of the activity is released to the atmosphere. In cleaning the residue after a sodium fire, it should be realized that a large proportion of unreacted sodium may still be present.

Because heat is being generated at the surface of the pool and is being dissipated from the sides and bottom of the pool, a temperature gradient is formed in the pool which decreases with distance from the surface (a typical gradient is 30°F/in.). Above the surface of the pool the temperature decreases rapidly with distance (a typical gradient is 500°F/in.).

The ignition temperature of sodium in air is dependent upon several variables and will be characteristic of the particular system under consideration. The following values may be used as an approximation: Fine particles of sodium condensed from a vapor mist may ignite at room temperature; droplets of sodium sprayed into air may not ignite until about 250°F; a pool of sodium will not ignite until above about 400°F if the surface is disturbed to remove the oxide scum, and above about 550°F if the surface is undisturbed. In some cases, undisturbed sodium has been heated to above 800°F before there was any evidence of ignition.

At oxygen concentrations of 4 vol % and below, sodium at 1000°F did not undergo rapid combustion, as characterized by incandescence; however, a slow reaction, characterized by evolution of some smoke, occurred at oxygen concentrations down to 0.1 vol %. This indicates that a smoke hazard can exist independently of a combustion reaction characterized by incandescence.

Under controlled laboratory conditions and using oxygen under very low humidity conditions (less than 1 grain/lb), the specific type of reactivity is critically dependent upon the partial pressure of water vapor present, and, to a lesser extent, upon the oxygen partial pressure. The moisture content and/or the hydrogen content of a gas surrounding sodium at an elevated temperature can, in certain cases, exert an influence as important as the oxygen content upon the combustion of sodium. Hydrogen influences the reaction of sodium and oxygen in a manner directly comparable to that of water vapor. In the absence of these "catalytic" species, reaction between sodium and oxygen does not occur to a detectable extent even at temperatures up to 1000°F.

If hot sodium is sprayed into an enclosure, heat is transferred from the sodium to the gas in the enclosure, causing a rapid rise in pressure. This pressure rise is accelerated if additional heat is generated by the combustion of sodium. Tests were conducted which showed that the rate of pressure rise increased: (a) as the oxygen concentration was increased from 0 to 5 vol %; (b) as the sodium temperature was increased from 600 to 1200°F; (c) as the moisture content of the gas was increased from less than 3 grains/lb of gas to 300 grains/lb of gas. There was no significant effect of the spraying pressure between 30 and 60 psi. Placing a baffle near the point of leakage of sodium interrupted the spray and resulted in a lower rate of pressure increase than would have been obtained with unobstructed leakage.

A proper understanding of the sodium-water reaction is necessary in evaluating methods of preventing or extinguishing a sodium fire. Water applied to sodium in air will react violently; however, if air is excluded, and if adequate space for expansion is available, the reaction proceeds rather smoothly. If air is not excluded, the hydrogen-oxygen reaction (arising as a result of the hydrogen liberated by the sodium-water reaction) is usually responsible for much of the noise and violence commonly associated with the primary reaction. Reduction of the oxygen content of cover gases to below 5%, in sodium-water systems, prevents explosions between the generated hydrogen and oxygen. It is possible under certain conditions to apply water, in finely divided form and at very low rates, onto sodium in air so that the initial sodium-water reaction proceeds smoothly, and the hydrogen gas which is liberated does not react explosively with oxygen from the air.

The protection of structural members against detrimental effects of sodium, which might leak or spill from a process system, may be accomplished in a number of ways. These ways include: (a) prevention of contact of structural members with leaking sodium, by use of such items as spill pans, equipment enclosures, and vermiculite (expanded mica) insulation, (b) removal of leaking sodium by a vacuum pickup device, (c) pressure control measures to prevent buildup of excessive internal pressures, (d) water control measures to exclude water from a potential spill over, and (e) smoke control measures to remove quickly any caustic fumes which might be evolved.

Many materials are useful in extinguishing sodium fires. Included are Met-L-X,^{*} sodium carbonate, sodium stearate, large-grain vermiculite, G-1 foam powder,[†] lampblack, sand, and calcium carbonate. Liquid hydrocarbon materials also extinguish sodium fires, but a secondary hydrocarbon fire ensues which can be extinguished by application of sodium bicarbonate. At Atomics International, the established method of controlling fires resulting from sodium spills is the shovel application of dry calcium carbonate; Met-L-X (pressurized dry powder) extinguisher units are used to knock down high flames, when necessary for the shovel approach. Replacing the air in a vessel or closed

^{*}A product of Ansol Chemical Co., Marinette, Wisconsin

[†]A product of Pyrene Manufacturing Co., Newark, New Jersey

container with an inert gas will also extinguish a sodium fire by eliminating oxygen. Covering a container of burning sodium will eventually extinguish the fire by oxygen starvation.

Burning sodium can be extinguished rapidly and without mess by a pliable oxygen-excluding blanket. Blankets fabricated from special fabric materials were not capable of withstanding the temperatures encountered during a spill of sodium onto the ground; a blanket of stainless steel foil did perform effectively in such a situation.

The four steps to be followed in combatting a sodium fire are (a) protect yourself, (b) contain the combustibles, (c) extinguish the fire, and (d) clean up.

Most items of personnel protective gear are not able to withstand the continuous effects of burning sodium; however, most of these items are able to withstand the effects of burning sodium for a period of time long enough to permit the wearer either to remove any burning sodium adhering to the protective garments, or leave the area near the burning sodium and then remove the protective garments.

III. TECHNOLOGY OF SODIUM FIRES

A. SODIUM COMBUSTION REACTION

Sodium reacts with oxygen to form various oxides. The existence of four oxides has been definitely established,¹ but only two (sodium monoxide and sodium peroxide) are formed in any significant quantity during the sodium-air reaction. The initial reaction may be represented by:

Na_2O (sodium monoxide) is a white powder when pure, but is usually red or gray due to traces of impurities and excess sodium metal.² The pure monoxide turns yellow upon heating and sublimes at about 2300°F. It may be prepared by heating with less than the theoretical amount of oxygen.³ It also may be prepared² as an intermediate product in the manufacture of sodium peroxide from molten sodium and dry air, and this stage of the process is usually carried out at 350 to 430°F.

With excess oxygen at 460 to 750°F, the monoxide is oxidized to Na_2O_2 (sodium peroxide):

The two reactions leading to the production of Na_2O_2 are sometimes combined and presented in the form:

Na_2O_2 is manufactured commercially by heating sodium metal in a current of dry air at the aforementioned temperatures of 460 to 750°F. The product so obtained is about 95% pure. Pure Na_2O_2 is pale yellow and darkens on heating. The peroxide melts without decomposition at 1210°F and then starts to evolve oxygen.² The peroxide can also be reduced by sodium (or other metallic reducing agents) back to the monoxide according to the reaction:

During the combustion process the presence of water vapor in air results in the formation of some sodium hydroxide⁴ by the reaction:

To make an approximate calculation of the heat evolved in the combustion reaction, the following values (based upon data in the Liquid-Metals Handbook)^{5, 6} may be used:

	<u>Metric Units</u>	<u>Engineering Units</u>
Heat of Fusion of Sodium	27 cal/g	49 Btu/lb
Specific Heat of Sodium	0.3 cal/g/°C	0.3 Btu/lb-°F
Heat of Combustion of Sodium		
Na ₂ O as product	2280 cal/g	4100 Btu/lb
Na ₂ O ₂ as product	2700 cal/g	4850 Btu/lb

Because the above values vary with temperature, they must be used only as an approximation (within about 10%).

Sodium is apparently unreactive with nitrogen at all known temperatures. (However, in the presence of nitrogen activated by an electric discharge, sodium is reported to form the nitride or the azide. In the presence of carbon and metal oxides, sodium may react with nitrogen to form sodium cyanide.)⁶

B. DESCRIPTION OF COMBUSTION PROCESS

The common industrial fire involves a hydrocarbon burning in air. This type of fire may be recognized by high flames (caused by burning of volatile material as it is carried upward by thermal currents), and by clouds of black or gray smoke (caused by carbon particles which have not undergone complete combustion). In contrast, sodium fires are characterized by very low flames and be dense clouds of white (oxide) smoke.

If a pool of liquid sodium in a container is heated gradually, the initial oxidation reaction is characterized not by flames above the surface, but by flaky or beady, grayish colored oxide scum on the surface of the pool. As the temperature is increased, the flakes or beads protrude above the surface of the pool and start to burn. Incandescent regions appear first as pinhead-sized specks of light in a greenish-gray film on the surface of the sodium pool. The specks, which are agglomerated particles of the various oxides of sodium, grow in size to spherically shaped nodules with diameters ranging from 1/8 to 1/2 in. As the temperature increases, glowing orange-yellow nodules spread over the entire molten sodium surface and to the vertical surfaces of the container (Figure 1). Dense clouds of white smoke are evolved above the pool, while near the pool surface the smoke is a brownish yellow.

As the pool of sodium burns, the nodular oxide material moves toward the edges of the steel container and up the vertical surfaces. A large quantity of the oxide material sinks into the sodium pool where it tends to solidify and collect near the cooler vertical surfaces of the container (Figure 2). The residue from small fires in shallow pans frequently collects on and near the vertical surfaces, leaving the center region bare. Deep pools of burning sodium leave a residue which has a hollow core. Nodules of oxide, on occasion, have migrated up the sides and over the edge of a container leaving a solid residue which acts as a wick; in one instance, 4 lb of sodium added to a container were conducted out of the container and onto the ground (Figure 1).

Nodular material removed from the surface of the pool contains a black viscous liquid, which becomes a light-yellow, granular solid upon cooling. This material is sodium peroxide. The residue which remains in the container after a fire is somewhat similar in appearance to the nodular material removed during a fire. It contains small flecks of unburned sodium interspersed in the solid, and in some instances an oxide layer covers unburned sodium. The residue adheres tenaciously to steel pans; to remove the solid residue it sometimes has to be fractured with a hammer, and small segments (4 to 6 in.³) then can be pried loose with a shovel. If the residue is heated with a butane torch, it becomes dark and tar-like in appearance and sticks readily to steel surfaces. Upon

A INITIAL OXIDATION REACTION

B AFTER APPEARANCE OF
INCANDESCENT REGIONS

C MIGRATION OF NODULAR MATERIAL OVER
EDGES OF CONTAINER

Figure 1. Sodium Burning in Cylindrical Container

Figure 2. Evolution of a Sodium Fire

cooling it resumes a light-yellow color. After prolonged heating with a butane flame, the material, upon cooling, becomes harder, denser, and a gray-yellow in color (probably as a result of reduction to the monoxide, which occurs at temperatures above about 1375°F).

During one series of tests, a small pool of sodium was heated in air to temperatures approaching 500°F; there was no apparent reaction, and consequently no nodules appeared. The pool was heated to 550°F and, after the reaction started, a small nodule appeared. The temperature increased steadily as a result of combustion until an equilibrium temperature of about 1200°F was reached (Figure 3), and the surface became covered with glowing nodules. When a butane flame was applied to the burning surface, raising the sodium temperature above 1300°F, the nodules disappeared (sodium peroxide melts at 1220°F), and the sodium became a red-colored pool of metal with wispy flames on the surface. When the butane flame was removed, the temperature of the molten metal decreased to the previous temperature just above 1200°F, and the nodules reappeared.

When a spray of sodium is burned, a shower of sparks and dense clouds of white smoke are evolved. The behavior of molten sodium is similar when sprayed into either an air atmosphere or an atmosphere of lower oxygen concentration down to 5 vol % oxygen. At or below 5 vol % oxygen, apparently insufficient oxygen is available for a combustion reaction⁶ characterized by either flames or incandescence (section III-G).

C. RESIDUE AND SMOKE FROM COMBUSTION

In most instances not all of the sodium in a fire is carried away in the form of smoke; most of the sodium remains as residue in the form of sodium oxide and unreacted sodium. The proportion of unreacted sodium is higher in a pool than in a spray due to the decreased surface-to-volume ratio. Stirring of the sodium in a pool serves to increase the available reacting surface, but even then the core of nodular materials in the residue consists of unreacted sodium.

Oxidation products in the residue and smoke consist of both sodium peroxide and sodium monoxide. In excess oxygen, the sodium peroxide reaction predominates; in excess sodium, the sodium monoxide reaction is the principal one; in the intermediate zone, substantial quantities of both oxides are formed.⁴

Figure 3. Temperature Rise, Burning Sodium Pool

Other reaction products include Na_2CO_3 and NaOH , formed by reaction with carbon dioxide and moisture in the air.

Tests were performed on a pool of sodium burning in air to determine the proportion of sodium evolved as smoke. It was not possible to arrive at any value for the general case. The ratio of the weight of the residue to the weight of sodium initially present varied from 0.8 to 1.4. Apparently changes in degree of combustion, wind conditions, pool temperature, depth of pool, etc., influenced the amount of oxide formed and the proportion evolved. Some tests have been performed using radioactive sodium containing small amounts of six-month-old fission products. Measurements of radioactivity were made on the sodium before burning and on the residue after burning. These tests indicated that only 10% of the fission-product activity was lost in burning; the ratio of weights of residue to sodium initially present was about 1.4.

Two important conclusions which may be drawn from the above observations are: (1) If radioactive sodium is involved in a fire, it should not be assumed that all of the activity is released to the atmosphere, and (2) in cleaning up after a sodium fire it should be realized that a large proportion of unreacted sodium may still be present.

D. COMBUSTION RATE

It is desirable to know the approximate combustion rate of sodium in air in order to predict the rate of energy release for any given size fire and also to predict the rate of smoke formation. This latter quantity would be particularly applicable to a fire involving radioactive sodium as it permits calculation of the rate of release of activity into the air. Experiments were performed to obtain the combustion rate as a function of area and of depth for pools of sodium burning in air.

In order to obtain an indication of this combustion rate, it was decided to measure the time between the start and finish of combustion for various initial weights of sodium. It was found that the average rate of combustion was about 0.15 to 0.3 lb/min of sodium (based upon initial weight) per square foot of exposed surface. This value tended to increase with depth (Figure 4) and decrease with surface area (Figure 5). During the test runs it was noted that the

Figure 4. Burning Rate vs Depth

Figure 5. Burning Rate vs Area

combustion reaction was slow during the last half of the burning period. From the quantity of smoke it was estimated that nine-tenths of the sodium was burned during the first half of the time. Applying these factors to the average rate, the numbers quoted above should be multiplied by $9/10 \div 1/2$ or $9/5$ to obtain an estimate of the maximum combustion rate, giving 0.25 to 0.55 lb/min of sodium per square foot of exposed surface.

As might be expected, the rate of combustion was even lower for similar tests on a pool of sodium in a low-oxygen atmosphere. Although a detailed study of the relationship between oxygen concentration and rate was not made, it was observed that a crucible of sodium in a 5% oxygen atmosphere burned from 25 to 50% longer than it did in air.

Because the reacting surface per unit volume is usually larger for sodium in a spray as compared to a pool, one would expect a higher combustion rate for sprayed sodium. A pound of sodium at 800°F was pressurized to 50 psig and forced into air through two openings, 0.002-in. wide by 0.6 in. long, in 24 sec. The sodium reacted completely and almost instantaneously, confirming the expected greater rate. In atmospheres of decreasing oxygen content down to 5% oxygen, as in the case of a spray in air, the sodium reacted as rapidly as it was ejected.

E. TEMPERATURE PROFILE

The temperature distribution through a pool of burning sodium is of interest because knowledge of the temperatures attained during combustion can be used to predict the extent of damage to equipment or structures, and to evaluate the effectiveness of protective measures. The highest temperature which can be attained in a pool of sodium under atmospheric pressure is the boiling point of sodium, about 1620°F. Under conditions in which heat is lost to the surroundings (by conduction, convection, and radiation) considerably lower temperatures may be attained. A temperature gradient, with a slope proportional to the rate of heat loss, is quickly established through the sodium.

Measurements were taken of the temperature profile in a pool of sodium in a stainless-steel container, 9 in. in diameter by 3 in. deep, placed on the ground. The sodium was heated to 800°F with a butane torch. Temperature readings were made at 1/4-in. intervals along the longitudinal axis of the container. During four successive tests, the temperature at the reacting surface rose rapidly to a maximum of 1100 to 1250°F. Initial measurements of the temperatures in the sodium pool indicated a steep temperature gradient from the bottom to the surface; after the sodium in the pool increased in temperature and equilibrium conditions were reached, a shallow gradient was observed.

Figure 6 shows a typical temperature profile during equilibrium conditions. For this configuration, a gradient of about 30°F/in. is indicated through the pool and of 300°F/in. just above the pool. Peak temperatures occurred at the sodium-air interface. Gusts of wind blowing across the surface of the burning sodium had little effect on either the pool or flame temperatures.

When the tests were repeated with a thermally insulated container, the temperature in the sodium pool reached about 1620°F throughout. As might be expected, as the heat was generated by combustion at the surface, vaporization occurred at the surface only and there was no bubble formation within the pool due to the decrease in temperature.

Figure 6. Sodium-Fire Temperature Profile

Under low-oxygen conditions the combustion rate was not great enough completely to overcome heat losses from the surface of the pool, and the sodium temperature did not increase to the boiling point; the maximum temperatures observed in an insulated container were between 1100 and 1200°F.

When a spray of sodium was ejected into air, temperatures of about 1600°F were easily attained because of the high surface-to-mass ratio. This maximum temperature occurred 2 to 8 in. away from the exit nozzle during one test. Beyond this distance combustion

was completed and the droplets were cooled. Figure 7 shows that temperatures below 400°F occurred at a distance of 26 in. Obviously, all of these values will vary, depending on the initial sodium temperature as well as the size and velocity of the droplets.

The temperature pattern of a burning spray in a low-oxygen atmosphere was similar to that for a spray in air except that the reaction temperatures were lower. The lower temperatures were probably due to a lower rate of heat generation during the flight of individual droplets through the low-oxygen atmosphere. Sodium at 800°F was discharged under a nitrogen pressure of 40 psig through a 0.001-in. -wide opening into an atmosphere of nitrogen containing 0.1% oxygen. Temperatures ranged from 750 to 800°F at stations 2, 8, and 14 in. away from the point of discharge; a station 20 in. away indicated maximum temperature of 385°F. The general temperature of the surrounding inert atmosphere reached 175°F.

F. IGNITION TEMPERATURES

The ignition temperature may be defined as that temperature above which the material under consideration will ignite and burn. Catalogs issued by sodium suppliers list an ignition temperature for sodium "in excess of 225°F." A precise value cannot be given because the ignition temperature of sodium in

Figure 7. Temperature Profile of Sodium Spray in Air

air is a vaguely defined point dependent upon such variables as: surface-to-volume ratio, surface condition, metal purity, absolute humidity, temperature of the surrounding atmosphere, and air velocity sweeping the surface. Therefore, the ignition temperature will be characteristic of the particular system involved.

Extremely fine particles of sodium (from condensed vapor) have been observed to ignite even at room temperature. Drop-size quantities of sodium have been observed to ignite at temperatures just above the melting point of sodium. For larger masses (e. g., a pool of sodium), ignition usually does not occur until the temperature is raised several hundred degrees above the melting point. During the Atomics International studies, it was observed that, in most cases, ignition of a pool of sodium in air did not occur until the temperatures above 400°F were reached. If the oxide scum on the surface was disturbed, ignition usually would occur just above 400°F. If the surface was not disturbed, then temperatures above 550°F were required for ignition; occasionally, sodium was heated to above 800°F before there was any evidence of ignition.

The reason for such behavior may be found in a report by Cowen and Vickers.¹ When sodium is heated from the cold condition in the presence of oxygen, it is likely to acquire a thick oxide film before the true ignition temperature is reached. If the oxygen is excluded until the sodium has reached the test temperature, the sodium will ignite at a lower temperature. Cowen and Vickers found that when 5- to 10-gram samples of sodium were heated in an open dish, the ignition temperature was in the range 830 to 880°F. When the sodium was heated prior to the gas being admitted, they found that ignition occurred above ~ 550°F.

Cowen and Vickers also reported that liquid sodium ignited at temperatures down to 250°F when forced through a small hole (varied from 0.008 to 0.020 in.) into air, irrespective of the moisture content. In this case, the lower ignition temperature was attributed to the fact that new surfaces of sodium were constantly exposed to air so that continuous reaction with the concomitant generation of heat was possible. In addition, the very small droplets which ignited formed sparks which induced further ignition. No ignition occurred when the liquid sodium was ejected into a nitrogen atmosphere, either moist or dry.

G. EFFECT OF GASEOUS ATMOSPHERE

One of the most important variables influencing the combustion of sodium is the oxygen content of the gas surrounding the sodium. Under certain conditions, other variables in the composition of the gas phase, particularly the moisture content and the hydrogen content, can also exert an important influence upon sodium combustion.

The importance of the moisture content and hydrogen content is often overlooked. Statements have been made in the literature that in an atmosphere with an oxygen content below 5%, no visual combustion of sodium would occur, and that above 10% oxygen, prompt combustion would occur in most cases. Detailed laboratory-scale studies reported by Longton^{8, 9} indicate that the humidity should always be specified as well as the oxygen content. For example, under conditions of high humidity, burning occurred at oxygen pressures as low as 10 mm (corresponding to 1.3% oxygen at atmospheric pressure). On the other hand, with superdry oxygen at pressures up to 900 mm, sodium did not exhibit any reaction at temperatures up to and including 1000°F.

Longton investigated the reaction of distilled sodium with respect to the principal variables: oxygen pressure, moisture content of the gas, and temperature. The specific type of reactivity displayed was critically dependent upon the partial pressure of the water vapor present, and, to a lesser extent, upon the oxygen partial pressure. Longton presented the information contained in Table I to show qualitatively the mode of reaction displayed at each oxygen and water vapor level (partial pressures are tabulated in millimeters of Hg).

This table shows that three distinct modes of reactivity are evident, each associated with a specific range of oxygen/water-vapor ratios. When the ratio of oxygen partial pressure to the water-vapor partial pressure exceeds 5×10^5 , no detectable reaction occurs at temperatures up to 1020°F, the maximum employed. At ratios less than 7×10^3 , reaction occurs readily and smoothly at 220°F, the minimum temperature adopted. In oxygen/water-vapor mixtures where the ratio lies within the range 9×10^3 to 4×10^5 , there is a region wherein the sodium does not react below a certain temperature, the ignition temperature. At and above this temperature, a vigorous combustion process develops.

TABLE I
MODE OF REACTION OF SODIUM AT DIFFERENT WATER-
VAPOR AND OXYGEN LEVELS*

Partial Pressure of Water (mm of Hg)	Partial Pressure of Oxygen (mm of Hg)									
	10	50	100	200	300	400	500	600	700	900
0.00002	†N	N	N	N	N	N	N	N	N	N
0.0001	§I	N	N	N	N	N	N	N	N	N
0.001	I	I	I	I	I	I	N	N	N	N
0.01	**R	R	I	I	I	I	I	I	I	I
0.1	R	R	R	R	R	R	R	R	R	I
0.25	R	R	R	R	R	R	R	R	R	R

*From table by P. B. Longton⁸

†N = No reaction at any temperature up to 1020°F. That is, did not react at a detectable rate ($< 2 \times 10^{-6}$ lb/ft²-min).

§I = No reaction until a certain temperature, the ignition temperature, was exceeded. Above the ignition temperature the reaction occurred immediately, leading to a vigorous combustion.

**R = Immediate reaction, without ignition at 220°F. Reaction occurred readily and smoothly.

To gain some idea of the value of the relative humidity for the data quoted above, it should be noted that water vapor with a partial pressure of 1 mm of Hg is roughly equivalent to 1 mg of water per liter of oxygen (at normal temperature and pressure), which in turn is roughly equivalent to 1 grain of water per pound of dry air. Therefore, at 70°F the highest humidity quoted in the table above corresponds to a relative humidity so small (less than 0.1%) that it cannot be read off a conventional psychrometric chart. Since the relative humidity, even in regions with a very dry climate, seldom drops below 20%, it should be noted that the above data are not applicable for spills of sodium into air. The data could be used, however, to predict behavior for an atmosphere of nitrogen or helium containing oxygen and water vapor of the amounts specified in the table.

Hydrogen influences the reaction of sodium with oxygen in a manner directly comparable to that of water vapor. Longton⁹ performed tests with a constant partial pressure of oxygen of 200 mm of Hg. Tests were performed at this reduced pressure without adding nitrogen or argon and Longton tabulated the mode of reaction in the manner shown in Table II.

TABLE II
COMPARISON OF EFFECT OF WATER VAPOR AND OF HYDROGEN
UPON MODE OF REACTION OF SODIUM*

P_{H_2O}	P_{O_2}/P_{H_2O}	Phenomenon	P_{H_2}	P_{O_2}/P_{H_2}	Phenomenon
0.00002	1×10^7	†N. R. / 1020°F	nil	-	†N. R. / 1020°F
0.0001	2×10^6	N. R. / 1020°F	0.00005	4×10^6	N. R. / 1020°F
0.001	2×10^5	§I. T. / 560°F	0.0005	4×10^5	§I. T. / 520°F
0.01	2×10^4	I. T. / 390°F	0.005	4×10^4	I. T. / 470°F
0.1	2×10^3	**G. R. / 230°F	0.05	4×10^3	**G. R. / 230°F

*From table by P. B. Longton⁹

†N. R. = No reaction detectable at the quoted temperature.

§I. T. = Sample ignited at the quoted temperature.

**G. R. = Immediate slow reaction, without ignition.

Table II shows that hydrogen influences the reaction of sodium and oxygen in a manner directly comparable to that of water vapor. Identical modes of chemical reactivity are displayed as the hydrogen or water content of the oxygen gas is increased. In the absence of these "catalytic" species, reaction does not occur to a detectable extent even at temperatures up to 1020°F (the maximum test temperature). Hydrogen present to a partial pressure of 0.05 mm Hg induces the reaction to occur readily at 230°F, while partial pressures of 0.0005 to 0.005 mm cause the abrupt transition, at a specific temperature, from a state of no reaction to a vigorous combustion process.

The experimental hydrogen partial pressures were selected by Longton to have values exactly half those of the series of experiments with water vapor because the primary reaction of sodium with water vapor is most likely to be:

According to this equation, one mole of water vapor liberates half this quantity of hydrogen, and it is currently considered by Longton that hydrogen plays an important role in the systems he has studied.

Because oxygen is required for the combustion of sodium it is obvious that a sodium fire cannot proceed if sufficient oxygen is not present. One of the most effective methods of extinguishing a sodium fire within an open container is to place a cover (even a loose-fitting cover) over the container. Additional air cannot enter the container at a sufficient rate to replace the oxygen which has been consumed, and the fire dies out due to lack of oxygen. If the lid is removed before the sodium cools to below the ignition temperature, the fire can start again and burn until the lid is replaced.

It is sometimes assumed when oxygen exhaustion is utilized to stop a sodium fire as described above, that 0 to 5% oxygen is in the remaining atmosphere. Nelson and Nelson⁷ conducted large-scale tests to determine the oxygen concentration at which a sodium fire would stop burning. Sodium was injected into a chamber containing air with an initial relative humidity ranging from 58 to 82%; chemical analysis of the air remaining after the fire disappeared indicated an average oxygen concentration of 11.5%. No apparent effect of humidity was noted over the range tested.

Nelson and Nelson performed a second series of tests during which the oxygen content of the chamber was controlled at values varying from 5 to 12.6% (the chamber was evacuated to a predetermined pressure and then charged with nitrogen to atmospheric pressure). Sodium at initial temperatures varying from 800 to 1072°F was injected into the chamber. Results were summarized, based upon initial oxygen content, as follows:

0 - 5% O ₂	<u>No</u> visible combustion
5 - 10% O ₂	Sparking only in cases of fine dispersal
10 - 15% O ₂	Prompt combustion to be anticipated in most cases.

Tests were performed at Atomics International to determine the minimum concentration of oxygen in which a pool of sodium would burn. An electrically heated crucible was charged with about 0.2 lb of sodium. The sodium was maintained at a constant elevated temperature, and oxygen was slowly admitted to the chamber until burning was observed. During the runs, nitrogen was used to maintain the pressure within the test chamber at one atmosphere; the humidity of the gas mixture was held constant at 3 grains/lb. Using sodium at 800°F, the following observations were made:

<u>Percent O₂</u>	<u>Observation</u>
0.1	No smoke
0.5	Haze starting to appear
6.5	Burning nodules appeared.

Using sodium at 1000°F, the observations tabulated below were made:

<u>Percent O₂</u>	<u>Observation</u>
0.13	Silvery surface; slight smoke
2.0	Heavy smoke
4.6	Surface covered with nodules burning vigorously; temperature increased to 1280°F.

These tests for a pool of 1000°F sodium in air were repeated under conditions of higher humidity of 140 grains/lb. Observations are tabulated below:

<u>Run</u>	<u>Percent O₂</u>	<u>Observation</u>
1	0.5	Some smoke
	4.8	Small glowing spots
2	2.5	Slight glow of oxide film
	3.1	Dense smoke; no incandescence
	5.2	Burning.

It may be seen that increasing the humidity from 3 to 140 grains/lb had no significant effect on the oxygen concentration at which sodium ignites.

The tests were then repeated for a spray of sodium instead of a pool of sodium. Sodium was heated to 1000°F, and successive sprays were ejected into the chamber after increasing the oxygen content in increments of a fraction of one percent. The following results were obtained with a constant humidity of 3 grains/lb (observations again are given only for points at which a significant change occurred):

<u>Percent O₂</u>	<u>Observation</u>
0	No smoke
0.5	Some smoke
5.0	Incandescence; dense smoke and rapid pressure increase

When the above test with a spray of sodium was repeated under higher humidity conditions of 210 grains/lb, a spray of 1000°F sodium did not exhibit incandescence with 4% oxygen.

While these measurements somewhat confirm the 5% oxygen limit set by Nelson and Nelson,⁷ the results also suggest that the limit should be decreased to 4%. Also, although a pool of sodium may not exhibit incandescence below 4% oxygen, it should be noted that smoke occurred at oxygen concentrations down to 0.1%. This indicates that the smoke hazard can exist independently of a combustion reaction characterized by incandescence. Even though oxygen concentration in the gallery of a sodium-cooled reactor is maintained below 4 or 5%, contaminated smoke is likely to accompany a leak of radioactive sodium.

H. PRESSURE INCREASES CAUSED BY SODIUM-AIR REACTION

In designing a reactor building and other enclosures, such as a pipe gallery, for a sodium-cooled nuclear power plant, it is desirable to know the maximum pressures that might result in the enclosure if a failure of equipment permitted sodium at elevated temperatures to escape and react with the oxygen in the air within the enclosure.

Mangold and Tidball¹⁰ have reported on tests in which 32- to 196-lb quantities of sodium at 850°F were driven into a hemi-cylindrical chamber (with a volume of 3880 ft³); the sodium was pressurized with 50-psig nitrogen and forced through a pipe nozzle into the chamber. During these tests the oxygen concentration was varied from 21 vol % down to 2.75 vol %, this latter value representing the only test they performed below 6 vol % oxygen. Table III summarizes the data which Mangold and Tidball presented in their report.

Mangold and Tidball found that the combustion rate of sodium in air was too rapid for extinguishing agents to be effective, and therefore they studied several methods of fire prevention. Their work indicated that limited oxygen and water-cooled chamber walls (to cause rapid cooling of the sodium) were the most effective fire preventive methods for their particular (simulated ship-board) situation.

Hines and Kelley¹¹ conducted tests to measure the maximum pressure caused by forcing a spray of 850°F sodium into a 532-l (18.8-ft³) container containing various concentrations of oxygen. Their experiments showed that the maximum pressure decreased as the initial oxygen content was decreased from the normal 21 vol % to 10.5, 5.3, and 0.6 vol %. The effect of oxygen content upon maximum pressure is shown graphically in Figure 8. In all of these tests a nitrogen pressure of 360 psig was used to drive the sodium into the container in 20 sec; the nitrogen supply was shut off immediately after the

Figure 8. Effect of Oxygen on Maximum Pressure Buildup as Reported by Hines and Kelley¹¹

sodium entered so that this gas did not affect the pressure rise. For the conditions described above, the maximum pressure attained was 38 psig for the normal oxygen content of 21%. The plot also shows that decreasing the oxygen content of the air has little effect on the maximum pressure at oxygen concentrations high enough to sustain life (approximately 14 vol %).

TABLE III*

SUMMARY OF SODIUM FIRE TESTS REPORTED BY MANGOLD AND TIDBALL¹⁰

Test No.	Sodium Dumped (lb)	Peak Chamber Pressure (psig)	Oxygen (vol %)		Plate Bulge (in.)	Nozzle Diam. (in.)	Remarks
			Before	After			
1	~ 40	4.5	21	-	1	0.109	Slow dumping
2	33	1.7	21	-	0	0.109	Water-cooled walls
3	47	1.0	2.75	2.62	0	0.364	-
4	32	3.3	9.69	8.43	1/2	0.364	-
5	43.5	4.3	13.44	12.17	1/2	0.364	Slow dumping
6	41.5	7.0	20.28	14.87	1	0.364	-
7	37.5	2.2	6.97	6.31	1/2	0.364	-
8	45	Opened relief [†]	11.92	9.76	1	0.364	Rapid dumping
9	92.5	7.0	17.84	15.13	1/2	0.622	Water-cooled walls
10	196	Opened relief [†]	20.77	8.11	1/2	0.622	Water-cooled walls
11	196	Opened relief [†]	8.20	7.63	1/2	0.622	Water-cooled walls

*On Tests 1, 6, and 8, sodium oxide was deposited like snow throughout the chamber. Less oxide was deposited in other tests with very little in Tests 2 and 3. In all tests the sodium ran down the walls from the spot of first contact. On Test 5 the valve was not fully opened and the sodium was dumped slower. Due to a plug in Test 8 the system pressure was increased to 200 psi, causing more rapid dumping.

[†]Relief valves were set to open at 13.3 and 15.3 psig.

Pressure changes were also recorded as a function of time by Hines and Kelley (Figure 9). Those curves indicate that ignition of the sodium occurred as soon as it entered the container when the oxygen content was 21 or 10.5%, as evidenced by a sharp increase of pressure with time. In the case of the 5.3% oxygen content, ignition did not occur until the last of the sodium was being introduced. This was attributed to the possibility that the oxygen content was insufficient to cause ignition until the propelling nitrogen broke through the sodium in the injecting pipe and nozzle, producing markedly greater dispersion. The pressure increase with an oxygen content of 0.6% oxygen was slow and smooth.

Additional tests by Hines and Kelley showed that decreasing the injection pressure (used to drive the sodium through the nozzle into the container) markedly decreased the maximum pressures attained in the reaction. This was thought to be due to the decrease of both the rate of flow and the degree of dispersion of the sodium.

Hines and Kelley also pointed out that experiments with a small 1-l (0.035 ft³) container showed the significance of the heat lost to the container itself. Unless the container was of sufficient size to permit the sodium particles to ignite and approach thermal equilibrium with the gas phase before striking the walls of the vessel, incomplete combustion and incomplete heat distribution between the particles and the gas phase occurred. The chilling effect of the container walls prevented part of the sodium from igniting and absorbed a large part of the heat of the ignited particles that would have been transferred to the gas in a vessel of larger size.

To supplement the data of Hines and Kelley, additional tests were performed at Atomics International. These tests were primarily aimed at obtaining additional data for oxygen concentrations ranging between 0 and 5% (the range commonly encountered in existing installations). Two additional modifications were made in an attempt to simulate more closely the conditions in existing installations: (1) The gallery was provided with a pressure-relief system instead of the total containment method used by Hines and Kelley; (2) The differential pressure used to force the sodium through a hole or crack was reduced from

Figure 9. Pressure Changes in Experiments 5, 6, 7, and 8, as Reported by Hines and Kelley¹¹

360 psi to the range of 40 to 50 psi, which is more representative of the peak pressures normally encountered in sodium-cooled reactors; this was important since Hines and Kelley observed that the driving pressure markedly affected the resulting pressure.

Apparatus for these tests was fabricated to simulate the enclosure around the piping in the primary cooling system of a sodium-cooled reactor; this region of the reactor is referred to as the pipe gallery, or more simply, the gallery. Viewing ports were provided in the gallery mockup to permit visual observation of the reaction to detect evolution of smoke and sodium incandescence; these ports also permitted the viewer to determine if ignition occurred before or after the particles of sodium impinged on the walls of the gallery.

The mockup was constructed from 1/4-in.-thick steel in the form of a box, 3 by 4 by 4 ft; the resulting volume of 48 ft³ is about 1/100 of that in the gallery of the Sodium Reactor Experiment.* A pressure transducer coupled to an oscillograph was utilized to measure rapid pressure transients within the mockup. A U-tube manometer was installed to measure static pressures and to determine absolute pressure in the system. A pressure-relief valve was provided to prevent excessive pressure buildup in the mockup, and, as an added precaution, a rupture disk was installed. Thermocouples were spaced throughout the mockup interior to monitor the temperature distribution.

In performing a test, the following was a typical procedure: The mockup was purged with nitrogen. Oxygen was admitted to the system until the concentration was at the desired value; the concentration was measured with a Beckman Model E-2 oxygen analyzer. The gallery pressure was adjusted to a pressure (1/2 in. Hg) slightly above atmospheric pressure. A charge of sodium (weighing approximately 1/2 lb) was heated in a 2-in. schedule-40 pipe, 5-1/2 in. long, by direct application of a butane flame until the sodium reached 1100°F. The flame was removed and the sodium was permitted to cool to 1000°F. At this time, a valve was opened which admitted nitrogen (22 in.³ at 50 psig) to the space above the sodium. (Calculations show that this amount of gas caused

*The SRE is a 20-Mwt, sodium-cooled, experimental reactor, designed, built, and operated by Atomics International.

pressure in the gallery mockup to be increased by only 0.012 psi.) The pressurized gas forced the sodium through a 1/4-in. -diameter tube, the end of which was flattened into an oblong opening 0.001 in. wide. The sodium issued from this tube into the gallery mockup as a spray.

Using the above basic procedure, tests were performed to determine the effect on the rate of pressure increase caused by a spray of sodium in the gallery mockup of (1) oxygen concentration, (2) sodium temperature, (3) drive pressure, (4) humidity, and (5) the use of a spray baffle.

The series of tests to determine the effect of oxygen concentrations on the rate of pressure increase was performed at concentrations of 0, 1, 2, 3, 4, 4.5, and 5 vol % oxygen with absolute humidities less than 3 grain/lb; a test at 4 vol % oxygen also was made at a humidity of 210 grain/lb.

Data for these first tests are shown in Table IV.

TABLE IV
EFFECT OF OXYGEN CONCENTRATION ON PRESSURE INCREASE
IN GALLERY MOCKUP* (First series)

Oxygen Concentration (vol %)		Maximum Temperature Observed in Gallery		Maximum Pressure		Maximum Rate of Pressure Increase (psi/sec)
Initial	Final	°F	Time (sec)	psig	sec	
0	0.	-	-	1.5	18	0.09
1.0	0.9	650	31	1.5	36	0.08
2.0	1.8	900	4	1.8	8	0.25
3.0	2.0	1040	26	3.4	11	0.75
4.0	1.8	1225	36	>4.0 [†]	2.5	1.9
4.5	-	1125	10	>3.5 [†]	1.5	2.8
5.0	2.9	625	20	>3.0 [†]	1	4.8
4.0 [§]	3.3	1125	11.5	>3.5 [†]	1	4.3

*The following parameters were held constant in all the above runs:

Sodium temperature 1000°F

Driving pressure 50 psi

Absolute humidity <3 grain/lb, (except in single run indicated).

[†]Rupture disc burst.

[§]This run made at absolute humidity of 210 grain/lb.

At the end of this series of tests it was observed that the driving pressure used to eject the sodium had caused the slits in the tubing to open to between 0.004 and 0.006 in. at the center.

New spray nozzles were prepared by flattening 1/4-in. -diameter tubing to a 0.002-in. opening, and the tests were repeated. Data are summarized in Table V.

TABLE V
EFFECT OF OXYGEN CONCENTRATION ON PRESSURE INCREASE
IN GALLERY MOCKUP* (Second series)

Oxygen Concentration (vol %)		Maximum Temperature Observed in Gallery		Maximum Pressure		Maximum Rate of Pressure Increase (psi/sec)
Initial	Final	°F	Time (sec)	psig	sec	
0	0	1000	15	0.5	20	0.04
0	0	875	5.5	0.9	17	0.08
0	0	-	-	1.8	18	0.10
2.0	1.8	850	4	1.8	9.8	0.18
3.0	2.5	950	17	3.0	33	0.17
3.1	1.8	1025	29	4.0	21	0.50
3.1	2.6	850	19	>4 [†]	4	1.0
4.0	1.8	1060	32.5	>4 [†]	7.5	0.8
5.0	-	1100	3.5	>4.8 [†]	6.5	1.2
5.0	1.2	1250	23.5	>4.5 [†]	4.5	1.6

*Following parameters were held constant:

Sodium temperature 1000°F

Driving Pressure 50 psi

Absolute humidity <3 grain/lb.

†Rupture disc burst.

Results of these two series of tests are plotted in Figure 10. It may be seen that the rate of pressure rise increases with the oxygen concentration. The rate of rise during the second series of tests was slower; this indicates that the rate of pressure rise is also a function of the rate of admission of sodium and the degree of dispersal of the sodium particles.

An additional item of interest was the fact that neither the maximum pressure nor the rate of pressure rise went to zero at an oxygen concentration of zero. (Hines and Kelley had extrapolated their data, (see Figure 8), to show that maximum pressure did go to zero at an oxygen concentration of zero.) The pressure increase at 0 vol % oxygen is caused by a rise in temperature of the nitrogen gas caused by transfer of heat from the spray of sodium at 1000°F.

Rupture discs were used in these tests to simulate more closely the actual situation in a typical gallery. In such a gallery, pressure-relief is necessary to prevent lifting of removable shielding blocks by excessive internal pressure (e. g., assuming a concrete density of 4.0, an internal pressure of 10 psig could lift a 5-ft-thick concrete block). After a rupture disc burst during the tests, the exhaust pipe was capped when the gallery pressure reached atmospheric. In every case, the pressure in the gallery mockup subsequently dropped from 6 to 10 in. of Hg below atmospheric. This observation is important because an external pressure differential of a few psi could cause the walls of the gallery to collapse unless suitable precautions are taken.

A third series of tests was performed to determine the effect of sodium temperature. Temperatures ranging from 600 to 1200°F were selected as typical of those encountered in present designs of sodium-cooled reactors. The oxygen concentration was held constant at 3.0 vol %. Results are tabulated in Table VI.

Results in the following table show that both maximum pressure obtained and rate of pressure rise increase with sodium temperature. This is due, primarily, to the increase in heating of the gas, resulting from the increase in both heat content and heat transfer with sodium temperature.

A fourth series of tests was performed to determine the effect of varying the rate of admission of sodium spray into the gallery mockup. The driving pressure above the 1/2-lb charge of liquid sodium was varied from 30 to 60 psi. Results are shown in Table VII.

Figure 10. Effect of Oxygen Concentration on Maximum Rate of Pressure Buildup in Gallery

TABLE VI
EFFECT OF SODIUM TEMPERATURE ON PRESSURE INCREASE
IN GALLERY MOCKUP*

Sodium Temperature (°F)	Oxygen Concentration (vol %)		Maximum Temperature Observed in Gallery		Maximum Pressure		Maximum Rate of Pressure Increase (psi/sec)
	Initial	Final	(°F)	Time (sec)	psig	sec	
600	3.0	2.8	440	8	0.8	16.5	0.05
800	3.0	2.6	540	11	1.8	14.8	0.16
1000	3.1	2.5	950	17	3.0	33.0	0.17
1200	3.0	2.7	850	5.8	2.0	14.9	0.20

*Following parameters were held constant:

Initial oxygen concentration 3 vol %

Driving pressure 50 psi

Absolute humidity < 3 gr/lb.

TABLE VII
EFFECT OF DRIVE PRESSURE ON PRESSURE INCREASE
IN GALLERY MOCKUP*

Drive Pressure (psi)	Oxygen Concentration (vol %)		Maximum Temperature Observed in Gallery		Maximum Pressure		Maximum Rate of Pressure Increase (psi/sec)
	Initial	Final	(°F)	Time (sec)	psig	sec	
30	3.0	2.6	850	6	2.5	21	0.26
50	3.1	2.4	850	5.8	2.0	15	0.20
60†	3.0	-	750	19.5	4.0	25	0.32

*Following parameters were held constant:

Sodium temperature 1000°F

Initial oxygen concentration ~ 3.0 vol %

Absolute humidity < 2 gr/lb.

†This run made at sodium temperature of 1200°F

The small variation in values for either rate of rise or maximum pressure indicate that there is no significant effect of driving pressure in the 30- to 60-psig range.

A fifth series of tests was performed to determine the effect of the moisture content in the gaseous atmosphere in the gallery. Runs were made at values of absolute humidity up to 300 grains/lb, which corresponds to 100% relative humidity (saturated with moisture) for air at 100°F. For purposes of comparison, runs were made at initial oxygen concentration of both 3 and 4 vol % and are tabulated in Table VIII.

TABLE VIII
EFFECT OF ABSOLUTE HUMIDITY ON PRESSURE INCREASE
IN GALLERY MOCKUP*

Initial Oxygen Concentration	Absolute Humidity	Maximum Temperature Observed in Gallery		Maximum Pressure		Maximum Rate of Pressure Increase (psi/sec)
		(°F)	Time (sec)	psig	sec	
3	< 3	950	17	3	33	0.17
3	80	1075	5	>3†	14.5	0.34
3	300	1000	10.5	>4.8†	5.0	1.3
4	< 3	1225	36	>4 †	2.5	1.9
4	210	1125	11.5	>3.5†	1.0	4.3

*Following parameters were held constant:

Sodium temperature 1000°F

Driving pressure 50 psi.

†Rupture disc burst.

From the above data, it may be seen that there is a pronounced effect of the moisture content of the gaseous atmosphere in the gallery upon the rate of pressure increase. This indicates the importance not only of removing any moisture evolved during curing of the concrete making up the walls of the gallery, but also of adequately sealing the concrete against in-leakage of ground water.

The rapid pressure increases observed in the different spray-leak tests were attributed to the large increase in surface area caused by formation of spray droplets; this increased surface increased the area available for heat transfer and for reaction with oxygen in the gallery atmosphere. It was reasoned that it might be possible to minimize pressure increases by utilizing some material to prevent the leaking sodium from being released as a spray in the gallery. The material most likely to be encountered in application to an actual reactor would be the thermal insulation surrounding the vessels and piping. Accordingly, a block of Kaylo^{*} thermal insulation was placed 1/4-in. below the spray nozzle, and sodium at 1000°F was injected into the gallery mockup, using a driving pressure of 50 psi. (The initial oxygen concentration in the gallery mockup was 5 vol %, and the humidity was less than 3 grains/lb.) The maximum rate of pressure increase using the Kaylo insulation below the spray nozzle was only 0.09 psi/sec; this may be compared to a value of 1.2 to 1.6 psi/sec, listed in Table V, for a test under comparable conditions except that a spray baffle was not used. These results show that the pressure increase in the gallery is minimized if some material is used to prevent droplets of sodium from traveling distances larger than 1/4-in. through the air. Although the insulation material deteriorated as a result of contact with the hot sodium, showing deep cracks and striations, it did serve to keep the pressure increase down to values equivalent to those obtained with 0 vol % oxygen. The same spray-stopping effect could have been obtained with a sheet of stainless steel foil, and the foil is recommended for this purpose. The test does point out, however, that the thermal insulation normally used around piping and vessels should help to prevent spray formation, in case of sodium leakage, until the insulating material deteriorates.

The method by which sodium becomes exposed to the air could be classified in three broad categories: stagnant pool, pressurized spray, and as an explosive ejection. The first of these would cause a very slow pressure increase as the surrounding atmosphere was heated by the pool of sodium. The second of these has been discussed above. The third, the explosive ejection, although the

*Thermal insulation manufactured by Owens-Illinois Glass Company, Toledo, Ohio. It is described by the manufacturer as a chemical compound of lime and silica.

least likely, is potentially the most severe case. The only effective difference between the explosive ejection and the high-pressure spray discharge is one of reaction rate. Under given temperature conditions, the rate of reaction is a function of the rate of sodium surface exposure which depends upon the mass flow rate and particle size of the sodium discharge. In a spray discharge, it is extremely improbable that a very large discharge rate and fine particle dispersion could exist simultaneously. Only in the explosive ejection of a large mass of finely dispersed sodium are the optimum conditions for the most severe reaction possible. Humphrey⁴³ has reported on detailed tests on the explosive ejection of sodium.

In the tests reported by Humphrey, 200- to 1600-gram (0.44- to 3.5-lb) quantities of sodium at 400°C (750°F) were explosively ejected into a vessel with a volume of 2032 l (71.7 ft³). In all cases, the initial reaction vessel atmosphere was at normal atmospheric pressure, temperature, and oxygen concentration (with the exception of two argon atmosphere tests). The tests included variations in quantity of sodium, distribution, force of ejection, and water content of the atmosphere.

The pressure rise per unit of sodium ejected decreased with increasing sodium-oxygen molar ratios up to the stoichiometric amount (2:1) required for formation of sodium monoxide. The peak pressures showed a rise, in gradually decreasing increments, until the highest experimental peak pressures (78 to 85 psig) were realized in the 2.54- to 3.05-molar ratio runs. The magnitude of the peak pressures developed were not determined so much by the initial ejection mechanism as by the unique conditions existing in the reaction vessel. There was fast and complete reaction of all water vapor in the system.

A characteristic distribution of sodium and its reaction products was observed by Humphreys. Unreacted sodium impinged upon the vessel walls and top in a definite spray pattern. Essentially all of the reaction products (mostly sodium peroxide) came to rest on the bottom of the reaction vessel as a very light, fluffy powder. Humphreys points out that a possibly beneficial effect of reaction product fallout in a nuclear accident might be to sweep down the major portion of nonvolatile fission-product particles. Thereafter, any atmosphere leakage from the containment shell would involve only relatively small fractions of the radioactive material originally introduced.

I. COMBINATION SODIUM-HYDROCARBON FIRES

The use of organic fluids to cool components in a sodium system introduces the possibility of hydrocarbon fire as well as a combination fire involving sodium and hydrocarbon. Although a hydrocarbon fire produces higher flames and more heat per unit weight of fuel, it is easier to extinguish than a sodium fire. Typical hydrocarbon fluids used as coolants vaporize and ignite at temperatures between 200 and 600°F, and combustion occurs in the vapor region just above the liquid surface. A momentary interruption of the flame, accompanied by cooling of the fuel a few hundred degrees, can snuff out a hydrocarbon fire. Sodium, on the other hand, can reach an equilibrium temperature during burning up to 1620°F, its boiling point; the flames are low and seem almost to adhere to the liquid surface. Being at a temperature well above the ignition point, the burning sodium is not likely to be extinguished even if the flames are interrupted and the temperature of the sodium is reduced several hundred degrees.

In the case of a combination sodium-hydrocarbon fire, where only a small portion of the sodium is in intimate contact with the hydrocarbon the conflagration will essentially consist of two separate fires as described above. The sodium will tend to re-kindle the hydrocarbon until the two materials are separated.

Where sodium and hydrocarbon liquid are mixed or are confined to the same container, the hydrocarbon will tend to float on the sodium. The hydrocarbon fire will be characterized by tall flames and dark smoke; the white sodium-oxide smoke will not be evident because the sodium is blanketed by a layer of hydrocarbon liquid, which prevents burning of the sodium. If the sodium is at an elevated temperature and the hydrocarbon is at a much lower temperature, the temperature of the sodium will tend to drop after mixing; the extent of the reduction will depend upon the relative mass, temperature, and heat capacity of the hydrocarbon fluid, as well as its heat of combustion.

The best technique for extinguishing a combination sodium-hydrocarbon fire was found to be the use of sodium bicarbonate to extinguish the hydrocarbon

fire and a second material, such as Met-L-X or calcium carbonate, to extinguish the sodium fire. A large-scale test fire involving 100 gal of sodium and 50 gal of tetralin, covering an area of about 50 ft², was extinguished in 12 min using 350 lb of sodium bicarbonate and 1000 lb of calcium carbonate.

J. SODIUM-WATER REACTION

Because a proper understanding of the sodium-water reaction is necessary to evaluate possible methods of preventing or extinguishing a sodium fire, related features of the sodium-water reaction will be discussed below.

The sodium-water reaction in the absence of air and in excess water is not violent and proceeds relatively smoothly. At sodium temperatures above 550°F, the reaction of sodium with water becomes increasingly milder. The reaction rate is essentially controlled by the contact surface available, so that the total reaction time is dependent on the rate of mixing. In general, for pound quantities (or greater) of sodium this reaction occurs over a relatively long period of time (of the order of seconds or greater), and the energy released per unit of time is low. The hydrogen-oxygen reaction, arising as a result of the hydrogen liberated by the sodium-water reaction, is usually responsible for much of the noise and violence commonly (and erroneously) associated with the primary reaction. For each mole of sodium which reacts, approximately as much energy is liberated by the secondary hydrogen-oxygen reaction as the primary sodium-water reaction. The energy from the hydrogen-oxygen reaction is released in a relatively short period of time (milliseconds) which results in detonation and a shock wave. Reduction of the oxygen content of cover gases to below 5%, in sodium-water systems, prevents explosions between the generated hydrogen and oxygen.

The possible reactions of interest have been tabulated and discussed.¹² This tabulation is presented in Table IX.

TABLE IX
BASIC CHEMICAL EQUILIBRIA FOR SODIUM¹²

Reaction 1. $\text{Na}(\ell) + \text{H}_2\text{O}(\ell) \rightarrow \text{NaOH}(\text{s}) + 1/2\text{H}_2(\text{g}), \Delta H^\circ_{298} = -35.2 \text{ kcal/mole}$

Reaction 2. $\text{Na}(\ell) + \text{NaOH}(\text{s}) \rightarrow \text{Na}_2\text{O}(\text{s}) + 1/2\text{H}_2(\text{g}), \Delta H^\circ_{298} = +1.59 \text{ kcal/mole}$

Reaction 3. $\text{Na}(\ell) + 1/2\text{H}_2(\text{g}) \rightarrow \text{NaH}(\text{s}), \Delta H^\circ_{298} = -13.7 \text{ kcal/mole}$

Reaction 4. $2\text{Na}(\ell) + 1/2\text{O}_2(\text{g}) \rightarrow \text{Na}_2\text{O}(\text{s}), \Delta H^\circ_{298} = -100.7 \text{ kcal/mole}$

Reaction 5. $\text{H}_2(\text{g}) + 1/2\text{O}_2(\text{g}) \rightarrow \text{H}_2\text{O}(\ell), \Delta H^\circ_{298} = -68.4 \text{ kcal/mole}$

Reaction 1 occurs in excess water; the end products are hydrogen gas and sodium hydroxide, dissolved in the excess water. This is also the reaction that occurs with equimolar amounts of sodium and water.

Calculations of the free energies show that the reaction of sodium and water below the melting point of sodium hydroxide ($\sim 600^\circ\text{F}$) will proceed to sodium hydroxide and hydrogen even in excess sodium. If the temperature is allowed to exceed the melting point of sodium hydroxide, then sodium hydroxide will react with additional sodium to produce sodium oxide and hydrogen.

In excess sodium, the hydrogen produced from either Reaction 1 or 2 may react with sodium to form the hydride, as shown in Reaction 3. The hydride decomposes at temperatures above 790°F .

The heat-of-reaction data for sodium and water show that the amount of heat released is primarily determined by the hydroxide formation (Reaction 1), and this reaction is the important one from energy-release considerations if oxygen is not present. The formation of the oxide in excess sodium (Reaction 2) is significant only at higher temperatures. Hydride formation (Reaction 3) only occurs in excess sodium and only below the decomposition temperature of NaH.

The additional reactions (4 and 5) given in Table IX indicate that oxygen should be excluded from any sodium system, since the direct reactions between sodium and oxygen and hydrogen and oxygen can add greatly to the total energy release.

It is known that the caustic formed from a sodium-water reaction does afford some protection for the remainder of the sodium metal. The sodium-water reaction is essentially irreversible by hydrogen pressure, requiring an over-pressure of 10^{50} atmospheres to reverse the reaction.

Tests were performed at Nuclear Development Corporation of America on the reaction rates of small quantities ($\sim$ milligrams) of sodium with water in an argon atmosphere. Pertinent results are listed in the following two paragraphs.¹³

The reaction of initially hot (~ 400 to 900°F) sodium with water results in a fast and unstable reaction which is characterized by a red glow of the sodium droplet. Sodium droplets initially above 1000°F reacted more smoothly with water.

A number of materials forming foam on the water surface were found to moderate the reaction by reducing the area of contact between the water and the sodium. An oil layer or film (mineral oil or biphenyl) floating on the water slowed the reaction greatly when the sodium became enmeshed in the heavy oil film. The addition of salts which produce no precipitate with sodium hydroxide does not affect appreciably the reaction of sodium with water; the addition of salts which form precipitates with sodium hydroxide results in an initial slowing of the reaction, but in some cases results in an uneven violent reaction, due to effects of the coating of precipitate on the sodium. The addition of substances which promote foaming of the water results in a definite slowing of the reaction of cool molten sodium with water. The action observed is a floating of the sodium droplet on a foam of hydrogen bubbles, which reduces access of the water to the sodium. Any additives to the water which reduced the cooling action of the water by increasing the viscosity caused a marked increase in reaction rate, tending toward violent reaction.

The concussion and heat from the hydrogen-oxygen explosion following a sodium-water reaction often represent serious dangers to persons and property. These hazards are compounded by the presence of unreacted sodium. Water usually reacts with only part of the available sodium before the hydrogen-oxygen explosion occurs. The heat of the explosion serves to raise the temperature of the sodium (melting the sodium if it were solid) and the force of the

explosion projects droplets of both burning and nonburning metal into the air. The flaming droplets, though small, are capable of readily penetrating ordinary clothing, and their contact with human tissue can result in third-degree-burn injury. The penetrating power of the sodium droplet probably comes from the decreased viscosity caused by the temperature rise which the droplet attains through combustion while in flight. The relatively high thermal capacity tends to keep the temperature high during the subsequent contact with clothing or human tissue. Projected burning metal is the primary burn-injury hazard to personnel engaged in combating sodium fires.

Sodium droplets from sodium-water reactions occurring in 5-lb test fires at AI have been projected from 25 to 35 ft cross wind from the point of the reaction. The heaviest spattering of the low-density liquid occurred directly downwind, the distance varying in each case with the wind velocity. Some droplets, however, also fell upwind.

The temperature of the sodium need not be high, nor the quantity of either reactant large, for hazards to arise from the sodium-water reaction. Several drops of sodium at a temperature just above the melting point, falling on a wet concrete surface ignited and projected up a trouser leg causing a minor burn injury. A bar of cold steel inserted into a pan of hot sodium has been found to carry enough condensed moisture to cause sodium to be projected.

Worthy of note is the fact that contact between sodium and water in air does not inevitably result in an explosion. It is possible to apply water in such a form or at such a rate that the initial reaction proceeds smoothly and the hydrogen gas which is liberated does not explode. Water in the form of steam has been widely used to clean containers or equipment covered with a film or layer of sodium without the occurrence of any violent reaction. This is attributed to the fact that the concentration of the water reactant limits the quantity of water available for reaction, and the sodium-water reaction proceeds relatively slowly and smoothly; in addition, the blanket of steam serves to exclude the air.

Tests were performed to determine whether this same behavior would be exhibited by water in the form of a fine spray and in the liquid phase instead of the gaseous phase; the water then could absorb heat during its phase change and thus cool the fire before forming steam to exclude air.

A preliminary test was performed by placing a 1-lb brick of solid sodium on a steel grate (to keep water from collecting around the sodium) and exposing the sodium to atmospheric moisture from a light drizzle for 8 hours. During this exposure the brick of sodium was completely covered by moisture, which appeared only to wash away the initial coating of white oxide, hydroxide, and carbonate. The white coating accumulated in a puddle on the ground near the edge of the brick; the sodium remained a clean pink metallic color. There was no smoke, no fire, and no explosion. The small size of the water particles effectively limited the quantity of water available to the reaction at any point on the sodium surface; the reaction rate was thereby maintained at a level low enough that the heat of the reaction could be absorbed by the relatively large mass of sodium without raising the temperature at any point to the ignition temperature of sodium. The hydrogen diffused away as rapidly as it was formed so that an explosive concentration could not accumulate.

A second test was then performed in which a pan containing a block of sodium was covered and heated to 1000°F. The cover was removed, and the sodium started burning. The burning sodium was then exposed to a light drizzle. The flames from the burning sodium glowed more brightly, but there was no violent reaction. It is possible that the water from the fine mist-like rain was converted to steam and never reached the sodium surface. The brighter flames, however, suggested the possibility that hydrogen was being liberated (from the sodium-water reaction) at such a rate that the hydrogen burned as rapidly as it was formed. Nodules of oxide, which had formed previously in the burning sodium, decreased in size as they tended to dissolve in the sodium due to the increase in temperature. It may be seen that this method did not produce a violent reaction in either test.

While under certain rigidly controlled conditions the reaction of sodium and water is not violent, in the conditions encountered in extinguishing a sodium fire the reaction can proceed explosively. Therefore, the use of water as an extinguishing agent, or the contact of water with sodium, definitely should be avoided.

IV. LEAK CONTAINMENT AND PROTECTION OF STRUCTURAL MEMBERS

Sodium spilling from a sodium-process-piping system, a coolant loop, or a test loop will burn if the temperature of the leaking metal is above the sodium ignition point, creating heat and smoke. Even without the combustion reaction, however, the heat content of sodium may be great enough to raise the temperatures of other nearby materials to the point where they may be destroyed. Hydrocarbon materials may vaporize and ignite, solders may melt, and concrete and structural steel may weaken under prolonged exposure to coolant system sodium at normal operating temperatures. The heat stored in sodium (by virtue of its high thermal capacity relative to air or nitrogen) could, in the event of a large leak in an enclosed system, suddenly raise the surrounding temperature to near the system operating temperature. In addition to the structural damage resulting from the direct application of heat, the pressure rise from gas expansion could destroy the integrity of the enclosure.

Hot sodium under pressure, spraying from a small crack or pinhole, can react rapidly with oxygen. Temperatures near 1600°F may be attained in the vicinity of such a leak in air. Even where the oxygen content of the atmosphere is reduced, such as in a reactor primary coolant-loop enclosure, a spray leak can react rapidly with the small quantities of oxygen present. The energy release of the reaction may cause a pressure rise sufficient to rupture the enclosure unless suitable pressure relief equipment is incorporated in the installation.

There are many protective measures which may be used to eliminate or minimize damage to structural members by leaking sodium. These measures consist of preventing contact with the leaking sodium, removing leaking sodium, or using devices to minimize damage to structural members which may come in contact with sodium at elevated temperatures. These measures will be discussed below.

A. CONTROL OF LEAKING SODIUM

Where it is likely that a quantity of sodium might be spilled from a system, containers for the leaking sodium should be provided; these containers are commonly referred to as spill-pans. Since the total quantity of smoke and heat liberated per unit time will vary directly with surface area, shallow

spill-pans should not be used as containers for large-volume leaks. They should serve rather as collection devices and be sloped to conduct the metal to suitable closed vessels. Since cooling has a depressing effect on reaction rate, the vessels should be so placed, if possible, so that they can be cooled by convective currents of the gaseous medium surrounding them. The ratio of cooling surface to reacting surface should be as large as possible. All open containers should be of such configuration and so oriented to permit covering with tight-fitting metal lids to exclude the air.

Liquid sodium should be kept off either the ground or concrete; spill-pans represent desirable preventive equipment for this purpose. Where sodium might contact column bases and other support members located within the spill-pan area, pipe sleeves and skirts welded to the pan should be installed. If there is a danger of sodium spilling into the sleeve from an overhead leak, a suitable sheet-metal cap should be provided over the open end, leaving adequate space between cap and sleeve to afford good convection cooling inside the sleeve.

Where the possibility is high that sodium may jet or be blown beyond the limits of the spill pan, deflectors or collectors should be installed. The thermal insulation commonly used on high-temperature piping systems also serves to collect and conduct away small amounts of leaking sodium. By backing up the thermal insulation with a long strip of 0.002-in. -thick stainless-steel foil of sufficient width to cover the bottom half of the insulation, and held in place by a steel insulation jacket, sodium leaking from any point along the pipe can be conducted to a collection point, thus keeping the leaking metal confined. The foil also can be placed between the insulation and the sodium pipe if conduction is the sole consideration. If, however, it is desired to use a leak-detector system of the type shown in Figure 11, a simpler, more reliable installation will be possible with placement of the foil outside the insulation.

Equipment enclosures, of light-gauge sheet metal secured by sheet-metal screws to a steel frame, may be added to a spill-pan to minimize the smoke nuisance from a sodium spill. Such devices have successfully contained the smoke and fire when all the sodium (~100 lb) spilled from a small loop.

Figure 11. Sodium-Leak Detector-Collector

Loose vermiculite surrounding a system or a segment of a system can be incorporated into such a sheet-metal enclosure to serve as an insulating material as well as a fire smothering device. It is so effective as an insulator that the spilled sodium may remain at temperatures above the ignition point for hours. This characteristic may be used to advantage if a vacuum pickup device is available to clean up the spill while the sodium is still fluid.

Sodium leaking onto the ground may be confined to a relatively small area by means of a dike of earth or powder extinguishant. Because the popular sodium-fire extinguishants all have densities greater than sodium, they tend to sink onto the burning pool. If the extinguishant is applied in large quantities, enough sodium may be displaced to raise its level, thus causing the sodium and the fire to spread. The sodium may be contained during fire extinguishing by applying the powder from the edges toward the center until the pool is completely covered.

B. REMOVAL OF LEAKING SODIUM

Many of the methods discussed above not only prevent leaking sodium from contacting structural members but also serve to conduct away, or remove, the sodium from the point of leakage. Tests performed during this investigation have shown that fluid sodium, being a relatively low-density material, may also be easily removed by means of a vacuum pickup device.

Using an electric-motor-driven vacuum-cleaner fan mounted on a 50-gal drum, tests showed that sodium burning in air could be picked up without greatly accelerating the sodium-air reaction. An aspirator-type vacuum cleaner using a cylinder of compressed nitrogen offered the advantage of greater portability since it did not require electrical power. This aspirator unit was tested with water and found to be capable of removing liquid at a rate of 50 gpm; one cylinder of nitrogen was good for slightly more than 3 min of operation.

Instead of the rigid pipe used in the initial tests, a flexible metal hose was used with the aspirator unit to pick up the burning sodium in additional tests. The sodium was again picked up readily (although the oxide nodules were difficult to pick up), but air leaking through the convolutions of the hose

accelerated the combustion reaction at several places along the length of hose which ultimately burned through. An improvised vinyl membrane was used to seal the outside of a similar flex hose; although the membrane was insulated from the hose by 1/2-in. -thick fiber glass, the vinyl was damaged during the pickup test. This hose was able, however, to pick up both oxide nodules and sodium readily.

A corrugated-stainless-steel hose then was installed on the unit. This unit worked effectively and was tested under the following adverse conditions. Fifty pounds of sodium burning in a pool was picked up rapidly. When the nozzle was jammed into the earth surrounding the sodium, the removal of dirt with the burning sodium did not impair the effectiveness of the unit nor did it result in any undesirable reaction. Thermocouples indicated that the sodium was cooled during pickup: inlet nozzle, 1200°F; along tube, 900°F; and inside drum, 700°F.

It was concluded that the vacuum pickup method is an effective means for removing large quantities of burning sodium.

A typical pickup unit combining the collection barrel, vacuum head, pressure regulator, driving-gas cylinder, and flexible hose into a self-contained mobile unit, is shown in Figure 12. To ensure operation under all conditions, (1) the nitrogen cylinder should be thermally insulated from the drum, (2) the pickup hose should be covered with thermal insulation at regions where it will be held by the operator, and (3) an easily accessible shutoff valve should also be installed.

C. PRESSURE CONTROL

To maintain the integrity of the pipe gallery under normal and abnormal internal and external pressure variations, the enclosure should be equipped with a pressure regulating device which will maintain the inert atmosphere at a pressure slightly above barometric during:

- 1) External pressure variations accompanying changes in the weather (weather fronts, rainstorms, tornados, etc.).
- 2) Internal pressure variations due to heating and cooling of the enclosure atmosphere during normal operations.

Figure 12. Vacuum Sodium-Pickup Device

- 3) Internal pressure increase which would accompany a temperature increase and gas displacement during the maximum credible sodium leak.

D. WATER CONTROL

Consideration must be given to measures for the exclusion of water from the environs of sodium systems. Although increased atmospheric moisture does not significantly reduce the ignition temperature or the flame point, it does tend to accelerate the sodium-oxygen reaction.

It has been shown that sodium will not burn in superdry oxygen even at 1050°F.⁸ If, however, spray preventive measures are built into the system and backed up with a suitable gallery pressure control device, the problem of water vapor is reduced in importance.

A pool of water is undesirable in the area around a sodium system. Measures to prevent its occurrence, and to remove it in the event it does occur, should be built into all systems. Enclosures should be equipped with suitable barriers to the entrance of ground water as well as protection against surface water runoff and leakage from nearby water pipes. Dehumidifying equipment may also be needed if exposed concrete structures exist inside the enclosure. Experience has shown that large quantities of the water in the concrete will be drawn out following the initial curing period. Unless the water vapor is removed, it is likely to condense on the floor of the enclosure.

E. SMOKE CONTROL

Although the dense, white, sodium oxide smoke, characteristic of a sodium fire, is not toxic,⁶ the inhalation of this smoke can cause coughing and a choking sensation; inhalation of large quantities can cause serious damage to the mucous membrane. The smoke settles as a fine, white, deliquescent powder which will cause irritation upon contact with moist skin. Sodium monoxide smoke frequently collects on foliage and other surfaces in the vicinity of a fire, hydrolyzing rapidly to form a sodium hydroxide solution.

In some circumstances, the sodium itself may be radioactive, thus complicating the problem. Sodium-24, formed from Na^{23} by thermal neutron capture, is a radioactive isotope with a halflife of 15 hours. Sodium-24 undergoes beta decay (1.4 Mev) followed by two gamma emissions (1.38 Mev and 2.76 Mev). Some form of smoke control is especially required in case of a fire involving radioactive sodium.

In a sodium-cooled nuclear reactor, the problem of radioactive smoke can be handled by enclosing the entire primary coolant system, which contains the radioactive system, in a gas-tight enclosure filled with an inert atmosphere (usually nitrogen). This blanket of inert gas need not be circulated and can remain stationary except for thermal convection currents and small amounts periodically withdrawn for sampling. All of this gas may be passed through a special gas system, prior to discharge into the atmosphere. This gas handling system may be equipped with instruments to monitor the gas for radioactivity; if the activity is above the limit considered dangerous, the gas can be compressed and stored until the activity has decayed to a safe level.

For other installations where a gas-tight enclosure is not utilized, means for removing sodium oxide smoke can be provided in the form of a smoke exhaust near the top of the enclosure. By drawing a curtain of high-velocity air across the floor, the smoke would be kept from wide dispersal and personnel could safely occupy the area to take other direct measures to control the leak and fire.

A satisfactory method of sodium smoke abatement is desirable if the smoke must be discharged immediately to the atmosphere. This requirement is raised by the extremely caustic fumes given off by the burning sodium. LeMar¹⁴ has studied different systems for liquid-metal smoke abatement; these systems included two types of scrubber systems, an electrostatic precipitator, and two types of filters. It was assumed by LeMar that the method of smoke abatement should have a weight collection efficiency of at least 90% and be within the realm of economic acquisition. After 90% of the particulate in liquid-metal smoke has been removed, the effluent becomes practically invisible and the remainder is dissipated in the atmosphere very quickly; the fume is then rendered harmless by dilution.

As a result of his tests using sodium, NaK and lithium, the following conclusions and recommendations were made by LeMar:

- 1) Either type of scrubber system or a modified electrostatic precipitator is recommended for use in the abatement of liquid-metal smoke. Smoke removal efficiencies of the order of 99% were attained.
- 2) Capillary-cell filter units, as manufactured, will not adequately abate liquid-metal fumes. Filter casings packed with bulk dynel fiber will not reduce liquid-metal smoke without developing prohibitive pressure losses.
- 3) Use of the dry, bonded dynel fiber filter for liquid-metal fumes is not feasible. This filter tends to load up, due to the hygroscopic nature of the fumes, at a rate which makes its use impractical for this purpose.

Detailed data are given by LeMar for the above systems on names of manufacturer, capacity, approximate physical size, and approximate price. Photographs show that the exhaust gases are in the form of a white cloud of smoke when the electrostatic precipitator is off and are rendered invisible when the precipitator is on. Thus, several effective methods of sodium smoke abatement are available.

V. EXTINGUISHING MATERIALS FOR SODIUM FIRES

Since magnesium presents an even more severe heat removal problem than does sodium, and since magnesium has similar restrictions concerning the use of water or halogenated extinguishing materials, the extinguishing techniques developed for magnesium were examined for possible application to sodium. Using a list prepared by Greenstein and Richman¹⁵ for magnesium-fire extinguishing agents as a basis, the desirable characteristics of sodium-fire extinguishing agents are as follows:

- a) It should be compatible with sodium (no violent chemical reaction).
- b) It should not support the combustion of sodium; it should prevent or inhibit further combustion.
- c) It should have a high heat absorbing capacity.
- d) It should be nonflammable.
- e) It should be compatible with agents used in fighting other fires which may occur simultaneously.
- f) It should be stable under storage conditions; it should not be hygroscopic.
- g) It should not be corrosive to the materials normally used in the construction of fire-extinguishing equipment.
- h) It should have a low toxicity hazard. This also applies to the decomposition products formed on contact with a fire as well as the extinguishing agent.
- i) It should have a lower density than sodium so the extinguishing material will float on top of a pool of burning sodium.
- j) It should be available in sufficient quantity and at reasonable cost.
- k) It should not contain any high-capture-cross-section materials if used near a nuclear reactor.

For purposes of this discussion, the materials used to extinguish a sodium fire are grouped most conveniently according to their physical states (almost all of the solid materials tested were powders, and almost all of the liquids tested were hydrocarbons).

The choice of gaseous materials is very limited. All the materials extinguish a sodium fire by excluding oxygen and/or by cooling the sodium to below the ignition temperature.

If the material is a liquid, it should also have a freezing point low enough to permit use under the widest climatic conditions; viscosity should be low enough, particularly at low temperatures, to permit easy handling and application.

Small-scale reaction tests, using test-tube quantities of burning sodium, were performed on promising extinguishing agents. If no violent reaction was observed, tests using 5-lb quantities of burning sodium as a standard fire were performed to evaluate the materials as extinguishing agents. Measurements were made on:

- a) Time to extinguish the fire
- b) Quantity of extinguishing agent used
- c) Temperature of the sodium pool during and following application of the extinguishing agent.

In addition, visual observations were made of the behavior of the fire.

To start a standard test fire, sodium bricks were placed in a 225-in.² container and heated to approximately 1000°F with a butane torch. By playing the flame from the torch directly on the surface of the sodium, an inert gas blanket, which prevented combustion, was maintained. When the torch was removed, the sodium started to burn and nodules of oxide rapidly covered the surface.

A. SOLID MATERIALS

Powder extinguishants were applied by shovel. They were sprinkled lightly (to prevent splashing) over the entire sodium surface to form a layer to exclude the air. To permit a comparison of quantities required, no more material was used than that required for extinguishing. The reaction of some powders indicated that they had become damp. Some of the powders were dried in a rotating drum heated externally by a gas flame. Samples were withdrawn periodically and further heated in an evaporating dish in an electric furnace at 300°F. Drying was continued in the rotating drum until these samples indicated no weight change after heating in the electric furnace.

Test data for the powder extinguishants are summarized in Table X. Those materials which were dried, as described above, are indicated by an asterisk. Additional comments on the powder-type extinguishants are listed below:

Aluminum Powder - was tried in an attempt to absorb the heat of the sodium by melting the aluminum; the aluminum powder ignited, burned, and caused a rapid temperature increase.

Alumina Beads - (small hollow spheres of aluminum oxide) were tested to see if they would float (aided by surface-tension effects) on the surface of the molten pool to form an oxygen-excluding layer. The beads, however, sank into the pool, but they did lower the pool temperature rapidly. When enough alumina beads were added to fill the pool and cover the surface, the fire was extinguished.

Ammonium Phosphate - sparked vigorously during small-scale reaction tests; full-scale testing was deemed inadvisable.

Attaclay - (a natural clay product which is commonly used as a filler or extender for insecticides) was used to extinguish a sodium fire which occurred recently in a chemical plant. In small-scale tests it covered the sodium, reacting with it slowly without any smoke or flame. In two of three large-scale tests, however, bright flashing sparks occurred which discouraged further application. In the third test the fire was covered and appeared to be out, except at the edges where there was a peripheral strip of burning nodules 1/2-in. wide.

Biphenyl and Terphenyl - were selected because of their low density and high flame point. They were expected to absorb heat and to float on the sodium. Preliminary tests showed that these materials were capable of extinguishing a sodium fire when used in volumes equivalent to that of the sodium.

Temperature drops during the first two minutes were 860 and 680°F, respectively using biphenyl and terphenyl. A secondary fire with high flames (3 to 6 ft) ensued in each case. The persistent secondary fire could not be extinguished easily with the sodium bicarbonate.

Cadmium Carbonate - reacted violently, projecting almost all of the sodium out of the pan.

TABLE X

POWDER-EXTINGUISHANT TESTS, SUMMARY OF RESULTS

	Weight Used (lb)	Time to Extinguish (min)	Temperature Change Dur- ing Initial 3-min Period (° F)	Remarks
Aluminum Powder	10.0	NE [†]	+230	Exothermic; stopped test
Alundum Beads	21.5	2.2	-470	Covered, but burned through
Ammonium Phosphate		NE [†]		Sparked; stopped test
Attaclay (magnesium aluminum silicate)	13.0	NE [†]		Flashed; burned through at edges
Biphenyl		NE [†]		Tall flames; stopped test
Cadmium Carbonate		NE [†]		Reacted violently.
Calcium Carbonate	14.0	1.5		
	*14.0	2.5 [†]	+200	
	*10.5	NE [†]	+300	Stopped test
Ferric Oxide		NE [†]		Rapid combustion; stopped test
G-1 (Pyrene)	29.0	4.0		
	13.0	3.5		
	14.3	3.0	-50	
Graphite Waste	30.0	4.3		
Lampblack	* 5.0	3.3	+40	
	4.8	6.8	-20	
Lead Powder	30.0	3.3	+200	Exothermic
Magnesium Carbonate	*	NE [†]		High flames; sank; ineffective

*Dried

[†]NE = not extinguished

TABLE X (Continued)

POWDER-EXTINGUISHANT TESTS, SUMMARY OF RESULTS

Material	Weight Used (lb)	Time to Extinguish (min)	Temperature Change Dur- ing Initial 3-min Period (°F)	Remarks
Magnesium Oxide (heavy U. S. P.)	14.0 12.0 7.8	2.5 1.8 NE†	-300	Floats, but burns through Floats, but burns through Floats, but burns through
Magnesium Oxide- Sodium Carbonate (1:1)	25	NE†	-400	
Magnetite	17.0	2.3		Rapid combustion; stopped test
Met-L-X (Ansul)	21.0 4.0 10.0	2.0 1.8 3.0	-270	
Mica (Ground 325 Mesh)	*14.0 7.0 * 8.0	2.8 3.5 2.5	+200	
Polystyrene	2.0	1.8	-490	
Polystyrene (cross- linked)	2.0	NE†	+200	Sparked; burned with persistent flame
Sand (Crystal White No. 30)	42.0 *10.5	2.3 2.2	+400	
Sand (Foundry)	*24.0 9.0 * 9.0	2.5 3.5 1.8	+200 +300/min	
Saran	5	NE†	+350	Sparked; flashed; vigorous secondary fire

*Dried

†NE = not extinguished

TABLE X (Continued)

POWDER-EXTINGUISHANT TESTS, SUMMARY OF RESULTS

Material	Weight Used (lb)	Time to Extinguish (min)	Temperature Change During Initial 3-min Period (°F)	Remarks
Silica Flour	2.0 *11.5	NE† 1.8	+500 +360	Stopped test
Soapstone	11.0	2.5	+300	
Sodium Bicarbonate	30.0 30.0	NE† NE†		No effect
Sodium Bicarbonate and Biphenyl (1:1)	12	NE†	-660	
Sodium Bicarbonate and Biphenyl (1:3)	10	2.8	-1000	Persistent secondary fire
Sodium Bicarbonate and Biphenyl (3:1)	10	1.8	-700	Weak secondary fire
Sodium Bicarbonate and Carbonate (Quick-Aid)	20.0 19.5			Covered, but burned through Covered, but burned through
Sodium Carbonate, Soda Ash (commercial grade)	*37.0 *16.5 *15.0	5.0 2.8 6.3	-350	
Sodium Hydroxide (commercial grade)	25.0	2.5 NE†		Reacted violently
Sodium Phosphate (monobasic)		NE†		Sparked; stopped test
Sodium Silicate	*	NE†	+200	Sparked; flashed
Sodium Silicate, (anhydrous)	*	NE†		Sparked; flashed like above

*Dried

†NE = not extinguished

TABLE X (Continued)

POWDER-EXTINGUISHANT TESTS, SUMMARY OF RESULTS

Material	Weight Used (lb)	Time to Extinguish (min)	Temperature Change Dur- ing Initial 3-min Period (°F)	Remarks
Sodium Stearate	7.0	1.5	-200	
Sodium Sulfate	*	NE†		Sparked; stopped test
Terphenyl		NE†		Tall flames; stopped test
Titanium Dioxide	6.0	2.0	+100	Sparked; flashed
Vermiculite (No. 1- large grain)	5.0	1.6 2.5		Burned through at edges
Vermiculite (No. 2)		NE†		Covered then burned through
Zirconium Silicate	*19.5	2.5	- 90	Sparked
	*25.0	2.8	-180	Sparked

*Dried.

†NE = not extinguished

Calcium Carbonate - was capable of extinguishing the standard fire; however, in each of three runs, the application of powder was accompanied by flashing, indicating that the powder contained moisture. Material for the third run was taken from a heated storage bin used to keep a large supply of dry extinguishant readily available. Application was accompanied by flashing sparks and sharp temperature increases. Although the material reacted as though damp, heating of a 90-g sample for 24 hours at 285°F failed to reduce its weight, indicating that it was as dry as could be expected in a heated storage container.

Ferric Oxide - also caused an exothermic reaction characterized by sparks, flame, and a rise in temperature; the test was stopped. This material formed a slag when compatibility tested at KAPL.¹⁶

G-1 Powder - extinguished quickly and with relatively small quantities; however, the cooling rate was slow.

Graphite Powder - (from the dust-collector hopper in a graphite machine-shop) extinguished the fire. A relatively large weight of material and a long period of time were required, and the cooling rate was slower. No sparking or flashing occurred during the application.

Raw Lampblack - (previously tested for sodium compatibility by KAPL¹⁶) extinguished the fire without hazardous reaction and required only a relatively small amount of material. It also proved to be an excellent insulator holding the molten sodium above the ignition point for 2-1/4-hours.

Lead Powder - was also expected to cool by absorbing heat during fusion of the lead. A reaction occurred, however, which was somewhat exothermic. The fire was extinguished, and the alloy which was produced would not burn, even though its temperature was well above the sodium ignition point.

Magnesium Carbonate - caused some sparking and a temperature increase at first. The fire was not extinguished, but it probably could have been if more powder had been available. A very hard crust formed on the cooled sodium.

Magnesium Oxide - (compatibility tested at KAPL¹⁶) appeared to float; however, the quantity used indicated that it sank into the pool, building up a foundation for the oxygen-excluding layer. The fire at the middle of the pan was rapidly and easily controlled by application of this material. At the periphery of the pool, however, nodules of oxide kept burning through. There was no hazardous reaction during application, and the cooling rate was rapid.

Magnesium Oxide - Sodium Carbonate - in a 1:1 volume ratio was tried to combine the good cooling characteristics of the sodium carbonate with the blanketing action of magnesium oxide. No reaction occurred during the application and cooling was rapid; however, the fire was not extinguished even though a relatively large amount of extinguishant was used.

Magnetite ($\text{FeO} \cdot \text{Fe}_2\text{O}_3$) - was expected to form a slag on the surface of the pool as a result of the oxidation to Fe_2O_3 . Application of magnetite was accompanied by sparks and flame. An exothermic reaction occurred, but the fire was extinguished and a hard crust was formed.

Met-L-X - was the outstanding powder extinguishing agent tested. This material is coated (to stay dry) sodium chloride and it performed well consistently. No sparking or popping occurred during any of the runs. It is noteworthy, however, that the quantities of material used in three test runs varied from 4 to 21 lb. It was during the first run, in which the powder was applied prematurely at a sodium temperature of 825°F, that the largest quantity (21 lb) was used. In successive runs, where the temperatures were permitted to reach equilibrium (near 1200°F) before application was started, only 4 and 10 lb were used. This quantity difference is attributed to the fact that sodium chloride fuses at temperatures slightly above 1200°F; it appears that Met-L-X is more effective if used on a hotter fire where it fuses to form a crust rather than sinking into the sodium pool.

Mica (ground mica) - extinguished the fire although its application was accompanied by an exothermic reaction. It was less effective than the large particles of vermiculite.

Polystyrene - was expected to produce a low-density plastic coating over the sodium. A secondary fire occurred which was extinguished with sodium bicarbonate. The primary and secondary fires were out promptly, and there was a rapid drop in temperature.

Polystyrene Cross-linked - produced a lesser secondary fire. It flashed and burned vigorously; the secondary fire was much more persistent than in the case of polystyrene.

Sand - also reacted and produced flames, sparks, and dense brown smoke. The reaction occurred even for dry sand; a temperature increase accompanied the flashing and sparks which occurred during the first 30 sec, but the fire was extinguished by further application of sand.

Foundry Sand (compatibility tested by KAPL¹⁶) - extinguished the fire in each of three runs. Application of the sand was accompanied by sparking, a rapid increase in temperature, and dark brown smoke. Behavior during application of dried foundry sand was similar to that when the sand was damp.

Saran^{*} (plastic powder) - was expected to have good cooling properties similar to the other hydrocarbons, but to burn less readily. It did not measure up to expectations, and its performance was not as good as polystyrene.

Silica Flour - was tested with the expectation that sodium silicate might form a layer of fused glass as the fine powder was dusted on the fire; this did not occur. Although the fire was extinguished, 11 lb of silica flour were used in the first run. The application was accompanied by sparking and brown smoke. The reaction during the second run was so intense as to discourage further application.

Soapstone - extinguished the fire, but the application was accompanied by sparking and a temperature increase.

Sodium Bicarbonate and Carbonate (Quick-Aid)[†] - a dry powder extinguishing agent, was accompanied by sparking after application. The burning surface appeared to be covered after 2-1/2-min, during which a relatively large amount of powder was applied. Small geysers of powder were observed on the surface due to the generation of gas; sodium oxide nodules ultimately appeared at these points. This material was ineffective.

*A product of Dow Chemical Company, Midland, Michigan.

†A product of General Detroit Corp., Detroit, Michigan.

Sodium Bicarbonate - fire extinguishant (Ansul "Plus 50") behaved in a manner similar to sodium bicarbonate and carbonate (Quick-Aid) except that no sparking occurred. It also was ineffective.

Sodium Carbonate (Soda Ash) - proved to be a good extinguishant by putting the fire out promptly and causing rapid cooling, but relatively large quantities of material were required. In one of three runs the application was accompanied by flashing, probably from moisture picked up through prolonged exposure of the material to air. The tendency to require more material on a lower temperature fire was also observed in these tests.

Sodium Hydroxide - sprinkled on an 850°F fire put out the fire by fusing over the surface. A relatively large amount of extinguishing agent was used. When sprinkled onto the standard 1000°F fire, it reacted violently, blowing the bottom out of the container pan and spewing sodium into the air.

Sodium Phosphate - sparked vigorously during small-scale reaction tests; full-scale testing was deemed inadvisable.

Sodium Silicate - was used, to try to fuse a layer of glass on the surface of the burning pool, but application of this material caused sparking to such an extent that further use appeared unsafe and the test was stopped. A second small-scale reaction test was run using anhydrous sodium silicate; results were similar to the first test.

Sodium Stearate - extinguished the fire rapidly, without any apparent reaction, and only a small amount was required. This was the outstanding layer forming material.

Sodium Sulfate - sparked vigorously during small-scale reactions tests; full-scale testing was deemed inadvisable.

Terphenyl - See discussion under biphenyl.

Titanium Dioxide - extinguished the fire, but flashing and sparks occurred during application and the temperature increased rapidly. A crust was formed and cooling was very slow.

Vermiculite (large-particle size, No. 1) - extinguished rapidly and without undesirable reaction. The extinguishant-sodium weight ratio was only 1:1. Because of its low bulk density, the extinguishant floated on the surface.

Vermiculite (small particle size, No. 4) - was selected because its particle size was small enough to be applied by means of a gas-driven, dry-powder fire extinguisher. Unlike the large-grain material, the small grains sank into the pool almost immediately. Although most of the burning surface was covered in 1.3 min, the sodium kept burning through. This material was far less effective than large-grain vermiculite.

Zirconium Silicate - appeared to react with the sodium and the resulting sparking and popping caused the application to proceed very slowly. The nodules of oxide were covered in 2 min, but the sodium kept burning through. As anticipated, a hard crust was formed and cooling was rapid. Sparking occurred also when dried zirconium silicate was used.

In some cases, when the extinguishing powder was a hydrocarbon, a secondary fire ensued. An attempt was made to extinguish both the sodium and the secondary fire in one application by premixing the powder with sodium bicarbonate. In these tests sodium bicarbonate was mixed with biphenyl in three different ratios, 1:1, 1:3, and 3:1.

Sodium bicarbonate and biphenyl (1:1) - represented a first attempt at a powder to extinguish both sodium and secondary fire in one application. The secondary fire was not extinguished by the sodium bicarbonate; however, significant cooling was observed.

Sodium bicarbonate and biphenyl (1:3) - reduced the temperature constantly during application, causing the pool temperature to drop to 600°F in 1 min. A secondary fire ensued with 2-ft-tall flames and which gave off black smoke. The secondary fire was easily extinguished by an application of additional sodium bicarbonate.

Sodium bicarbonate and biphenyl (3:1) - also caused the temperature to decrease steadily as the extinguishant was applied. Because the fraction of biphenyl was lower, the secondary fire burned with a clean flame and little

smoke; the secondary fire was easily extinguished by dusting with an additional amount of sodium bicarbonate.

The tests described above show that many materials are capable of extinguishing sodium fires. The mechanism of fire extinction is principally that of a smothering action; the cooling action caused by the powders was not very pronounced. It is noteworthy that, in all but a few cases, the weight of the powder extinguishant exceeded the weight of the sodium; in most cases, even though the material was applied sparingly, quantities of extinguishant three to six times that of the sodium were required.

The outstanding extinguishing materials in the above tests were Met-L-X, sodium carbonate, sodium stearate, polystyrene, biphenyl-sodium bicarbonate mixture, magnesium oxide, large-grain vermiculite, G-1 powder, lampblack, sand, and calcium carbonate. The first five materials rapidly stopped the flames and smoke being evolved, exhibited good cooling characteristics, and required relatively small quantities of material. In the case of polystyrene and biphenyl-sodium bicarbonate, secondary fires ensued which were extinguished rapidly with further additions of sodium bicarbonate. Some difficulty was observed with magnesium oxide in extinguishing the fire at the periphery of a pool of sodium. Large-grain (No. 1) vermiculite, G-1 powder, and lampblack were effective extinguishants, but the temperature of the sodium pool remained high because of their thermal insulation properties. Sand and calcium carbonate reacted exothermically, which may be somewhat indicative of the difficulty of obtaining completely dry powder; however, these latter two materials did extinguish the fire.

All of the materials described above are capable of extinguishing a sodium fire, and the choice of which one to use would depend in part on fire size and configuration. For fires requiring application of pressurized powder from a distance, the Met-L-X powder is very convenient. Vermiculite is very useful in that it can be preplaced around piping or a vessel to serve as thermal insulation; in the event of a leak, the sodium is contained in the vermiculite. When sodium was poured on top of the different materials being tested, vermiculite was the only material which would float on the sodium surface; the other materials either formed a crust under the sodium or sank to the bottom of the

sodium. In addition, the vermiculite is very easy to clean up using an industrial-type vacuum cleaner. Calcium carbonate is relatively inexpensive and quite effective if it is stored in a heated bin prior to use. Because it is inexpensive, relatively large quantities of dry calcium carbonate, stored in covered metal containers, can be placed in locations judged to have a potential fire hazard; in case of a sodium fire, this material is on hand and readily available for backup use in addition to portable pressurized containers of such material as Met-L-X.

B. LIQUID MATERIALS

Greenstein and Richman¹⁵ found that many powder materials have been used as magnesium extinguishants, but none of these materials was particularly effective as a cooling agent. Consequently, they tried a new approach with the emphasis upon cooling. They found that many oils would cause rapid cooling, and that secondary fires caused by the oils could be stopped if the oils were mixed with certain additives, such as monochloro-monobromo-methane or di-isodecyl phthalate. McCutcheon¹⁷ found that magnesium fires could be extinguished with 9 to 17% solutions of orthoboric acid in triethylene glycol. All of this work suggested a closer scrutiny of the possibility of utilizing liquid extinguishants for sodium fires.

Rapid extinction is always desirable in the event of a sodium fire to prevent thermal damage and to stop the emission of noxious (and possibly radioactive) smoke. Because most of the popular powder extinguishants have a greater density than sodium, they tend to sink to the bottom of the molten-metal pool and require the use of relatively large quantities of extinguishant. Sinking of the powder and careful application required to prevent splashing tend to slow the extinction process. A material in the liquid state could be poured onto the sodium and, if it would spread across the surface, it would speed up the extinction process. In addition, liquid materials are more apt to undergo boiling and thus cool the sodium to below the ignition temperature. Finally, if a liquid would undergo thermal decomposition and form a crust-like material on the surface of the sodium, this layer might exclude air.

Tests were performed to measure effectiveness and behavior of liquid extinguishants on sodium fires. Liquids of relatively low density, high flash point, and high auto-ignition temperature, were selected for testing. A standard fire for these liquid extinguishant tests was 2-1/2-lb of sodium at 1000°F, in a 9- by 5- by 3-in. steel pan. In the first series of tests, the liquid was poured onto the burning sodium, by means of a long-handled container. In the second series of tests, sodium was spilled from a ladle onto the extinguishing agent. Secondary fires were extinguished by dusting with sodium bicarbonate. Results of these tests are tabulated in Tables XI and XII.

In the first series of tests, all but one of the liquids formed an oxygen-excluding layer over the burning sodium; the exception was the mixture containing monobromo-monochloro-methane, which as expected reacted with the sodium with explosive violence. Although hydrocarbon fires occurred in each case, with the exception noted above, the sodium fire appeared to be extinguished; no white smoke or glowing nodules of oxide were visible. The secondary fires were extinguished by applying sodium bicarbonate. (Carbon dioxide gas was tried in several instances, but it did not extinguish the hydrocarbon fire.) Cooling, caused by vaporization of the liquid extinguishant, was pronounced and rapid.

In the second series of tests, in which sodium was poured onto selected liquid extinguishants, the sodium fire was extinguished in all but two cases; cooling was more rapid in the second series than in the first, probably because of additional cooling caused by movement of the sodium stream through the air during pouring. Preliminary tests were also conducted using diatomaceous earth and Filtrol as carrier agents for the liquid extinguishant. Results of these tests were not promising, so further work was not performed.

The liquid extinguishants tested appear to offer a somewhat limited application because they require a collection container and an extinguishant for the secondary fire. If preplaced in an enclosure where the oxygen concentration is maintained below the lower flammability limit of the liquid, the liquid might serve to stop oxidation of the sodium; however, other aspects, such as the rate of pressure increase, would have to be examined. In an open-air location,

TABLE XI

LIQUID-EXTINGUISHANT TESTS, SUMMARY OF RESULTS
 Extinguishant (36 in.³) dumped onto sodium (72 in.³) at 1000°F

Material	Na Temp (°F)	Time to Extinguish (sec)	Temp at Extinction (°F)	Temp After 2 Min (°F)	Temp After 5 Min (°F)	Observations
Standard Fuel Oil	1000	60	700	660	580	High flames; froth which bubbled
Isopropyl Diphenyl	1000	45	700	540	480	High flames
Crude Cottonseed Oil	1100	60	750	600	580	Low flames, tough film on surface
Refined Cottonseed Oil	1000	60	780	690	580	Low flames
Peanut Oil	1000	35	740	700	550	Low flames
Corn Oil	1000	45	820	640	540	Low flames
M-X*	1000	35	760	580	480	High flames; foamed extensively over pan
Motor Oil	1100	30	600	630	520	High flames; foamed extensively over pan
Lard Oil	1000	55	840	700	550	High flames; foamed; formed shell over sodium
Neatsfoot Oil	1160	65	810	800	620	High flames, soft shell
Tetralin	1100	50	740	680	580	Very high flames, brittle crust
Linseed Oil	1000	55	780	700	570	Low flames, crust
Castor Oil	1000	70	740	700	550	Low flames, poor cooling

*A product of Buffalo Fire Appliance Corp., Dayton, Ohio

TABLE XI (Continued)

LIQUID-EXTINGUISHANT TESTS, SUMMARY OF RESULTS
 Extinguishant (36 in.³) dumped onto sodium (72 in.³) at 1000°F

Material	Na Temp (°F)	Time to Extinguish (sec)	Temp at Extinction (°F)	Temp After 2 Min (°F)	Temp After 5 Min (°F)	Observations
Coconut Oil	1000	30	700	660	520	Low flames, temp drop to 500°F (15 sec), increase to 700°F
Silicone Fluid	1035	105	720	700	620	Low flames, difficult to extinguish, foamed extensively
Santowax O-M	1100	-	-	-	-	Burned vigorously, dirty fire, black smoke
Motor Oil + Di-Isodecyl Phthalate (1:1)	1200	90	800	800	700	Secondary fire, easily extinguished by single dusting of bicarbonate
Motor Oil + Mono-bromo-Mono-chloro-Methan (1:1)	1200	-	-	-	-	Exploded

TABLE XII
LIQUID-EXTINGUISHANT TESTS, SUMMARY OF RESULTS
Sodium (72 in.³) at 1000°F dumped into extinguishant (36 in.³)

Material	Sodium Temp (°F)	Time to Extinguish (sec)	Minimum Temperature (°F) After Time (sec)	Remarks
Standard Fuel Oil	1100	NE*	540 in 30	Continued to flash, unable to extinguish with CO ₂ , foamed
Isopropyl Diphenyl	1100	NE*	600 in 30	Nodules burned through in 90 sec; unable to extinguish with CO ₂ ; foamed
Crude Cottonseed Oil	1000	90	640 in 30	Secondary fire easily extinguished with sodium bicarbonate
Peanut Oil	1000	180	800 in 45	Difficult to extinguish with sodium bicarbonate; continued to flash back for several minutes
Corn Oil	1200	40	800 in 40	Easily extinguished with sodium bicarbonate
Diesel Fuel	1000	45	690 in 15	Very hot secondary fire; flashed back in 2 min
M-X	1000	15	690 in 27	Extinguished easily with one dusting of sodium bicarbonate

*NE = not extinguished

where the occurrence of hydrocarbon flames might be less serious than the occurrence of sodium oxide smoke, the liquid extinguishant might be used in conjunction with an automatic spray system to apply sodium bicarbonate. For cases where rapid cooling of the sodium is vital, further development of liquid extinguishants is indicated.

C. GASEOUS MATERIALS

Although no tests were performed upon open fires using gaseous extinguishants, it is known that an inert gas can extinguish a sodium fire in a container by exclusion of air. For example, if sodium contained in a vessel begins to burn, it is possible to extinguish the fire by flooding the gas space, above the sodium, with an inert gas such as argon, helium, or nitrogen.

There is a widespread belief that if CO_2 is used on a sodium fire there will be an explosive reaction. In tests on sodium fires at Atomics International, CO_2 was applied to sodium fires with neither detrimental nor beneficial effect. The sodium fire was not extinguished, but on the other hand no violent reaction was observed, as long as the CO_2 was not applied too rapidly. If applied rapidly, the liquid CO_2 was not completely vaporized and droplets of CO_2 liquid would crackle and sputter upon contact with the hot sodium. In the case of a combination sodium-hydrocarbon fire, the CO_2 was useful in knocking down the high flames caused by the burning hydrocarbon material, thus permitting personnel a closer approach to the sodium fire; the CO_2 did not have any significant effect upon that portion of the fire caused by the burning sodium. The safe behavior of sodium bicarbonate, which extinguished the secondary hydrocarbon fire by evolution of CO_2 , is also an indication that CO_2 and sodium do not react violently under the usual conditions of fire extinction.

D. FIRE BLANKETS

Tests with powder materials showed that relatively large quantities of extinguishant were required, and that careful application necessary to avoid splashing, resulted in slow extinction of the fire. It was thought that an oxygen excluder which could be placed on the fire as a unit would offer prompt extinction, thus minimizing the exposure of personnel and equipment to caustic smoke.

It was decided that such an oxygen-excluding unit should be pliable, like a blanket, to facilitate handling and to permit rolled or folded storage. A pliable membrane would also tend to conform to irregular surfaces and prevent entry of air at the periphery. The purpose of the tests described below was to develop such an extinguishing blanket.

First, fabrics were tested for their fire resistance, and then small- and full-scale blankets were fabricated and tested on various sized fires burning both in metal pans and on the ground.

Tests at KAPL¹⁶ on the resistance of various fabrics to sodium at 700°F had revealed no single-ply fabric which would retain its integrity; however, some laminations of fabrics were found to be capable of containing small quantities of sodium at 1000°F without burning through. It was decided that the blanket should be made up of a thermally insulating layer of fabric covered by an air-excluding layer of fabric. Fiberglass* was selected for the thermally insulating layer, and silicone-rubber-coated glass cloth, a pliable, heat-resistant (600°F) fabric, was selected for the air-excluding layer.

Tests were conducted at Atomics International on the resistance of various combinations of these fabrics to the flame from a Bunsen burner. In some cases, aluminum foil was added to the combination to conduct the heat away and minimize hot spots. Results are tabulated in Table XIII. It may be seen that Fiberglass backed with silicone-rubber-coated glass cloth did not burn through during a 10-min exposure to the flame; similar resistance to the flame was obtained with Fiberglass backed with aluminum foil and topped with cotton twill.

A 12- by 12-in. blanket was fabricated with a sheet of aluminum foil placed between the Fiberglass insulation and the silicone rubber. This blanket was applied to burning sodium covering an area of about 64 in.² The blanket was promptly consumed by flames which flashed around the edges of the blanket.

*A product of Owens-Corning Fiberglass Corp., Toledo, Ohio.

TABLE XIII
RESISTANCE OF FABRICS TO FLAME FROM A BUNSEN BURNER*

Material [†]	Temperature (°F)	Time to Burn Through (sec)	Remarks
Glass cloth coated with silicone rubber	1600	3	Rubber coating burned off; glass threads still intact.
Fiberglass insulation	1300-1600	58	Fibers changed color from pink to white (probably the binder burning off).
Aluminum foil backed with silicone-rubber-coated glass cloth	1450-1600	9.5	Rubber coating burned off the glass fabric.
Fiberglass backed with aluminum foil topped with silicone-rubber-coated glass cloth	1275-1600	275	Glass fibers fused and turned white where contacted by flame.
Fiberglass backed with cotton twill	1300-1500	180	Cloth charred at edge.
Fiberglass backed with silicone-rubber-coated glass cloth	1350-1600	Did not burn (600)	Glass fibers fused and turned white where contacted by flame.
Fiberglass backed with aluminum foil topped with cotton twill	1300-1500	Did not burn (600)	Fiberglass fused to aluminum.

*Material Specifications: Fiberglass; Aircraft insulation blanket, 1/2-in. Fiberglass PF105. Coated glass cloth; Seaman Products Co., glass cloth No. 119, silicone rubber coated, Aluminum foil; Mirro, household aluminum foil, regular weight. Cotton twill; cotton twill, 7 ounce, flame proofed.

†Laminated fabrics are named in order beginning with fabric nearest to flame.

This test pointed to the vulnerability of the blanket edges. It also appeared that Fiberglass might react with sodium at combustion temperatures. Consequently, another 12- by 12-in. blanket was prepared, but this time the aluminum foil was placed on the fire side of the Fiberglass, which was covered with a ply of flame-proof cotton twill to protect it from puncture. The blanket was placed over a similar sodium fire and the edges pressed firmly to the steel pan in which the sodium was burning. The fire was immediately extinguished. The heat resistance of this combination is evident from the fact that the sodium rekindled immediately upon removal of the blanket 3 min later. Although the cotton and the foil layers were burned through and there was some damage to the Fiberglass, the air-excluding layer was undamaged.

A similar blanket was placed over burning sodium in an 8-in. -diameter by 3-in. -deep container. Flames flashed all around the rim, burning the cotton fabric and insulation binder, but a 2-in. overlap around the edges of the blanket prevented the flames from entering at the edges and burning the air-excluding layer. The smoke ceased to escape the instant the blanket was set in place; when the blanket was removed an hour later, the fire rekindled.

These tests demonstrated that a pliable laminated blanket could be made which was capable of smothering a sodium fire and withstanding the temperatures involved. This combination of fabrics was then made into a larger blanket for tests on fires spread over a larger area. A blanket was fabricated as a disc 5 ft in diameter. Its edge was weighted with a light chain to facilitate placing on the fire and to effect a good air seal by pressing the edge against the ground. Thirty pounds of sodium were heated to ignition temperature on level ground covering an area of about 10 ft². The fire burned with a high flame indicating that the sodium was reacting with the soil. When all the sodium was burning vigorously, the blanket was applied. The seam along the diameter (a single-stitch seam) gave way, and the central portion of the blanket was consumed by flame; this failure was ascribed to failure of the center seam.

A new blanket was fabricated with a center seam made with glass thread in a multistitched "French" seam. Both sides of the seam were brush coated with silicone rubber to ensure integrity of the air excluding layer. This blanket

was laid over an intense fire (1600°F), but one that was smaller in size (5 lb of sodium spread over about 4 ft² of ground area) than was used in the previous test. The fire burned through the center of the blanket in 5 sec.

The failure of the blankets and the observation that temperatures near 2000°F were attainable in a sodium-soil fire indicated that the fire blanket would have to be capable of withstanding these higher temperatures to be effective. Consequently, a single-ply blanket was fabricated from 0.002-in. stainless-steel foil. This blanket had a welded seam at the diameter; the hem containing the chain weight was made of stainless-steel screen. Although not as pliable as the fabric blankets, the stainless foil blanket could be rolled into a tube about 10-in. in diameter; folding was not attempted to avoid permanently deforming the sheet.

The blanket was applied by two men to a fire involving 30 lb of sodium, spread over 20 ft² on the ground. The blanket slowed the evolution of smoke almost immediately; flames about 1 ft high appeared all around the blanket circumference. These flames were extinguished and the smoke stopped by banking with dirt. The blanket, though discolored, was undamaged.

Seven minutes after application, the temperature under the blanket was down to 415°F. Twelve minutes later the temperature was down to 250°F and the blanket was removed; no evidence of sodium remained. Apparently the liquid sodium remaining had reacted with the soil without the emission of smoke, for when the area was washed down afterwards with water, no explosive or smoke-liberating reaction occurred.

The fire blanket tests showed that burning sodium can be extinguished rapidly and without mess by a pliable oxygen-excluding blanket. By its use the emission of caustic (and in some cases, radioactive) smoke can be halted quickly, permitting leak-repair work to proceed promptly.

The fabric blanket, however, is not capable of withstanding the temperatures likely to occur when the sodium is spilled on the ground. A blanket of stainless-steel foil will perform effectively in such a situation.

The use of an integral oxygen-excluding membrane, such as these blankets, is limited by the configuration of the area in which the leak occurs. Where obstructions prevent the blanket from covering the fire completely, it may be necessary to cover the inaccessible portion of the fire with powder extinguishant.

VI. PROCEDURES FOR FIGHTING SODIUM FIRES

A. GENERAL

The behavior of sodium which has leaked from a process system is somewhat unpredictable. Sodium, even at 800°F in air, may not burn. If it does burn, the combustion reaction may be impressive only in its quiescence, but burning sodium represents a hazard to both equipment and to personnel. Because of its extreme chemical activity, sodium must be approached with great caution. Extinction of sodium fires must be performed strictly according to proven-safe techniques. There are four main steps to be followed:

1. Protect Yourself

In addition to the hazards normally associated with fire fighting, sodium presents two extraordinary hazards against which the fire fighter must protect himself: caustic smoke and projected droplets of hot metal. Demand-type respirators, flame-proof coveralls, a hard hat with face shield, one-piece all-plastic goggles, and leggings and gloves of chrome leather should be worn by all personnel who approach a large spill.

Before going into an area of suspected external or internal radiation hazard, the fire fighters should call for a check of the radiation level by a Health Physicist. The Health Physicist will advise them of the specific hazard in terms of how long the firemen may remain in certain hazardous areas. While the monitor is checking the level of radioactivity, the fire fighters may put on their protective gear which should include, in addition to the items enumerated above, a surgeon cap, a double-ply cotton hood, and a demand-type respirator with built-in goggles (these goggles replace the one-piece all-plastic goggles).

2. Contain the Combustibles

Any leakage of sodium should be stopped as near the source as possible. In some cases, this may be accomplished by simply closing a valve. Any cover gas above the sodium should be vented until the system is at atmospheric pressure to decrease the driving force for leakage. If leakage of sodium continues, if possible the sodium may be transferred to another vessel (e. g., dumping the sodium in a pipe loop into a storage tank). All electric power in the region of the spill should be disconnected.

Removal of thermal insulation from the leak area may help to cool the pipe or vessel, and this may slow or stop the leak. If the region near the leak can be approached by personnel, a metal pan or other collection device should be positioned to collect any leaking sodium. Liquid sodium on the ground should be contained within a dike made up of a powder extinguishant, such as calcium carbonate.

3. Extinguish the Fire

The burning sodium should be extinguished by excluding oxygen or air. This may be done by placing a layer of powder extinguishant over the sodium. If the sodium is in a closed container, it may be possible to flood the gas space above the sodium with an inert gas, such as argon or nitrogen. In the case of a small fire burning in a metal pan, often the simplest method is to place a metal cover over the pan; even though the cover does not effect a completely air-tight seal, the fire may be extinguished within a few minutes because of oxygen starvation.

If the sodium is burning in conjunction with some hydrocarbon material, the flames from the hydrocarbon fuel may be knocked down by repeated applications of sodium bicarbonate. The high heat capacity of the sodium may cause the hydrocarbon to flash back and re-ignite. If this occurs, an attempt should be made to isolate the hydrocarbon from the sodium by some sort of dam or fire break.

4. Cleanup

The caustic nature of the combustion products as well as the potential hazard of unreacted sodium, makes it desirable to perform a complete cleanup operation after the fire is out and the materials are cool enough to handle. All residue, unburned sodium, and sodium-contaminated insulation should be shoveled into metal cans (provided with a cover) for disposal.

The spill area should be carefully cleaned to ensure that all unreacted sodium, from the leak or spill, has been removed. In some cases, this is best accomplished by a careful steam cleaning operation. The volume of steam is reduced or cut-off, when popping or hissing indicates the steam is aimed at a

region of unreacted sodium; control of the rate of application of steam permits control of the sodium-water reaction.

If radioactive materials are involved, the cleanup operation should be under the direction and supervision of Health Physics personnel.

VII. PERSONNEL PROTECTION

The importance of adequate protection for persons in the vicinity of a sodium spill or leak has been indicated previously in this report. Protective garb is prescribed primarily to prevent contact of the body with high-temperature sodium or caustic combustion products; heat and smoke are the most severe short-term hazards. Tests of various fabrics and items of protective garb are described below:

Tests were conducted to determine the resistance of various fabrics to the temperatures of burning sodium. Sodium at 1200 to 1400°F was spilled on test patches of the several fabrics. Three runs were made. In the first run a sheet of 6-oz Nylon, Orlon, single- and double-ply cotton and Dynel were each drawn taut over the end of a hollow cylinder with the fabric in a horizontal plane. A second run used the same cylinders, but the plane of the fabric was inclined 30° off the horizontal. In both runs all fabrics were penetrated almost instantaneously.

In a third run, patches of each of the fabrics were tacked to a horizontal board, each with a pad of fiberglass under the fabric to represent under garments, which might be expected to enhance the resistivity of the fabrics to burning sodium. In this run, chrome leather (which had shown up well in the glove tests described below) was also tested. All of the materials except the chrome leather were penetrated almost instantly. The chrome leather shriveled and turned black and was ultimately penetrated, but retained its integrity for 20 to 30 sec.

Although none of these fabrics came up to expectations, experience at Atomics International has shown that two plies of flame-proofed cotton afford a high degree of protection against burn injury from splashing sodium whereas a single ply is almost useless. The ideal protective garb therefore must provide two-layers of flame-proof fabric. Where the probability of a splash or spill is high, protection should be provided in the form of a chrome-leather garment.

Additional tests were performed to evaluate two plastic materials considered for use as protective clothing while combatting a sodium fire. The materials consisted of Gra-lite (Dickson Co.) and a plastic-coated cotton fibre (MSA). No visible effect was observed on either fabric as a result of a 24-hour immersion in 2 molar NaOH. The sodium tests consisted of pouring small quantities (approximately 1 oz) of hot sodium onto a sheet of each material; the sheets were stretched taut in a horizontal plane. No visual effects were observed using droplets of sodium at 250, 500, 750, and 1000°F. However, at 750 and 1000°F, if the droplets of sodium were burning, the temperature increased rapidly and the sheets were penetrated as follows:

Material	Penetration Time for Sodium at Initial Temperature of	
	750°F	1000°F
Gra-lite	30 sec	6 sec
MSA	2 sec	1 sec

In addition to testing fabric materials, tests were performed on specific types of protective garb. Pertinent observations are listed below:

Coveralls: Flame-proofed, pocketless, cuffless, cotton overalls are prescribed for wear by persons working with or near sodium. It is expected, therefore, that this minimum protective cover will already protect those in the splash zone at the time a leak or fire occurs. Although not impervious to burning sodium, coveralls of flameproofed cotton have been found to afford reasonable protection against burn injury from splashes of burning sodium. Pockets and cuffs are undesirable because they tend to collect sodium; tight fitting collars are desirable because they may prevent sodium from entering the clothing at the neck. The removal of coveralls in the event of an emergency will be facilitated if the garment is slightly larger in size than normally used.

Gloves: The hands of persons regularly handling sodium must be protected against possible exposure to sodium hydroxide as well as the dangers of burning sodium. A number of gloves including butyl rubber, polyethylene, polyvinyl chloride, and neoprene were able to withstand 24-hour exposure to a concentrated sodium hydroxide solution without visible damage to the material. A similar

test on a chrome-leather glove showed that the leather was severely weakened at the exposed area. When exposed to burning sodium, however, all but the leather glove were penetrated so rapidly that a wearer would have had difficulty in removing the glove in time to prevent burn injury. The chrome-leather (welders) glove was not penetrated, but it did shrivel, turn black, and the strength of the leather was reduced significantly by the exposure.

Face Shield and Goggles: Protection against eye injuries is an essential of the fire-fighter's gear. Such protection can be provided by goggles and a face shield. A test conducted at Atomics International showed that the plastic face shield (B. F. McDonald part No. 34358) effectively resisted penetration by burning sodium, initially at 1000°F, for 6 sec of continuous spillage. The shield at that point was penetrated; the plastic did not burst into flames and burned only with difficulty.

Hats: Hard hats also serve to protect the head of the wearer from contact with splashes of sodium. Three hard hats were exposed to burning sodium, initially at 1000°F, spilled from a container positioned 12 in. away. None of the hats (Stamped Aluminum, B. F. McDonald; laminated bakelite, MSA; plastic-bonded glass fibers, Jackson SH-1) were immediately penetrated by the sodium. Both of the plastic hats ignited in about 15 to 30 sec, but required 3 to 5 min for the sodium to burn completely through; the aluminum hat was unaffected. The 3- to 5-min period of time is considered ample time for the wearer to withdraw from the immediate vicinity of the burning sodium, so that other factors (e. g., impact resistance, susceptibility of wearer to electrical shock) also can be considered in choosing the hard hat.

The tests described above indicate that none of the tested fabrics or items of protective gear can withstand the continuous effects of burning sodium; however, many of these items are able to withstand the effects of burning sodium for a period of time long enough to permit the wearer to either remove any burning sodium adhering to the protective garb, or remove himself from the source of burning sodium and remove the protective garb.

REFERENCES

1. H. C. Cowen and H. Vickers, "The Oxidation of Sodium. A Review of Progress from 1-4-54 to 31-12-54," R & DB (C) TN-121 (declassified reprint, April 15, 1955)
2. Kirk-Othmer, Encyclopedia of Chemical Technology, vols. X and XII, (New York, Interscience Encyclopedia, Inc., 1953)
3. J. W. Mellor, A Comprehensive Treatise on Inorganic and Theoretical Chemistry, Vol. II (London, Longmans, Green, and Co., 1952)
4. J. R. Humphreys, Jr., "Sodium-Air Reactions as They Pertain to Reactor Safety and Containment," Proceedings of the International Conference on the Peaceful Uses of Atomic Energy (Geneva, June 1958), XV, 1893
5. R. N. Lyon (ed.), Liquid Metals Handbook, NAVEXOS P-733 (Rev.), (June 1952)
6. Liquid Metals Handbook, "Sodium-NaK Supplement, Atomic Energy Commission and Department of the Navy (July 1, 1955)
7. C. O. Nelson and D. B. Nelson, "Sodium Air Reaction Experiments," KAPL-639 (January 1952)
8. P. B. Longton, "Alkali Metal-Gas Reactions Part IX: The Influence of Moisture on the Reaction of Sodium with Oxygen," IGR-TN/C-535 (April 1957)
9. P. B. Longton, "Alkali Metal-Gas Reactions Part X: The Influence of Hydrogen on the Reaction of Sodium with Oxygen," IGR-TN/C-536 (April 1957)
10. F. L. Mangold and R. A. Tidball, "Sodium Fire Studies," NA-3812 (April 23, 1952)
11. Edward Hines and J. K. Kelley, "Determination of the Maximum Pressures Attained During the Reaction of Sodium with Air in Closed Systems," Detroit Edison Report 55-C-80 (February 15, 1956)
12. Nuclear Development Corporation of America, "Chemical Considerations in the Sodium Cooled D₂O Moderated Reactor (SDR)," NDA-84-6 (April 30, 1958)
13. E. Bernsohn, L. Corrsin, H. Steinmetz, and B. Marano, "Sodium-Water Reaction Rate Studies," NDA 84-19 (May 15, 1959)
14. H. K. LeMar, "Liquid Metals Smoke Abatement," PWAC-235 (November 1, 1957)

REFERENCES

15. L. M. Greenstein and S. I. Richman, "A Study of Magnesium Fire Extinguishing Agents, " WADA-TR-55-170 (May 1955)
16. C. O. Nelson, "Summary Report of Reaction Tests of Various Materials Tested with Sodium and Potassium, " KAPL-557 (June 1951)
17. Roy T. McCutchan, "Investigation of Magnesium Fire Extinguishing Agents, " WADA-TR-54-5 (January 1954)