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U.S. POSITION PAPER ON SODIUM FIRES, DESIGN AND TESTING

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I. INTRODUCTION

The first Specialists' Meeting on sodium fire technology sponsored by the International Working Group on Fast Reactors (IWGFR) was held in Richland, Washington in 1972. The group concluded that the state-of-technology at that time was inadequate to support the growing LMFBR industry. During the second IWGFR Specialists' Meeting on sodium fires, held in Cadarache, France in 1978, a large quantity of technical information was exchanged and areas were identified where additional work was needed. Advances in several important areas of sodium fire technology have been made in the United States since that time, including improved computer codes, design of a sodium fire protection system for the CRBRP, measurement of water release from heated concrete, and testing and modeling of the sodium-concrete reaction.

Research in the U.S. related to sodium fire technology is performed chiefly at the Energy Systems Group of Rockwell International (including Atomics International), the Hanford Engineering Development Laboratory (HEDL), and the Sandia National Laboratories (SNL). The work at the first two laboratories is sponsored by the U.S. Department of Energy, while that at the latter is sponsored by the U.S. Nuclear Regulatory Commission. Various aspects of sodium fire related work is also performed at several other laboratories.

The current status of sodium fire technology in the U.S. is summarized in this report.

II. SODIUM COMBUSTION PHENOMENA AND COMPUTER CODES

A. Combustion Phenomena

1. Ignition

Sodium reacts with oxygen under a wide range of conditions, but ignition is not attained until a self-sustaining temperature rise is established. The ignition temperature depends on the surface to volume ratio, the oxygen molar fraction and humidity of the gaseous atmospere, and the degree of sodium purity. For a sodium pool, the degree of agitation of the liquid surface and the rate of heat loss from the sodium are also important. A sodium pool will not normally ignite in air below 250°C unless the pool is disturbed. Pools that are partially oxidized before being extinguished have the potential for being reignited by pyrophoric products in the crust at temperatures near ambient.

The ignition temperature for a sodium spray is substantially lower than for a pool fire. For droplets of the size range postulated for accidents in reactor loops, ignition in air may occur at ∿120°C, but could occur at lower temperatures for fine mist conditions.

2. Combustion Chemistry

Although there are no current fundamental studies in the U.S. aimed specifically at sodium combustion chemistry, information on reaction chemistry and kinetics is obtained incidentally from experiments directed toward aerosol behavior and sodium fire extinguishment.

Generally, the aerosol released from pool and spray fires in atmospheres with oxygen concentrations greater than ∿10% O_2 consists of Na_2O_2, while Na_2O is formed at lower oxygen concentrations. Subsequent to release, transformation to NaOH and Na_2CO_3 can occur, depending on availability of H_2O and CO_2. The reaction product in the pool is chiefly Na_2O, with variable fractions of NaOH, Na_2O_2 and Na_2CO_3.

3. Kinetics

Sophisticated modeling of kinetic effects is incorporated in the sodium fire computer codes used in the U.S. The models account for oxygen and sodium vapor diffusion to the burning zone for both pool and spray fires. Large-scale tests have shown the pool burning rate in air under simulated accident conditions to be in the 25-40 kg Na/h m^2 range. The burning rate of spray drops is critically dependent on the drop size, oxygen concentration, and spray rate to vessel volume ratio and cannot be generalized.

4. Scale Effects

The model used in the SOFIRE-II computer code for calculating sodium pool burning dynamics is based on natural convection heat and mass transfer analogy. For turbulent gas boundary conditions, which almost certainly apply for accident cases of concern, the burning rate per unit area is predicted to be independent of the pool surface area. The effect of pool depth is uncertain, but for a given temperature, the rate may increase slightly with increasing pool depth due to greater turbulence in the pool and disruption of surface layers of reaction products which tend to inhibit sodium vaporization.

5. Convection Effects

For conditions associated with large sodium fires in a plant, the sodium burning rate is expected to be limited by oxygen mass transfer to the burning zone. Higher gas velocities across the sodium surface, whether induced by natural or forced convection, will result in higher burning rates. This effect has been qualitatively observed in tests at the Harvard Air Cleaning Laboratory, where a jet of compressed air directed across the surface of a small sodium pool resulted in a factor of ∿2 increase in burning rate.

Convection patterns over a sodium pool may be affected by the fraction of cell floor area occupied by the pool. If the total floor area is covered by the pool, mixing of high oxygen content gas from higher elevations in the cell with gas near the pool surface may be inhibited and thus result in lower burning rates. This effect should be evaluated analytically and experimentally.

6. Effect of Atmosphere Composition

In the sodium fire computer codes used in the U.S., the burning rate is assumed to be directly proportional to the oxygen concentration in the atmosphere near the burning zone. This assumption has been verified experimentally at AI and at HEDL. If water vapor is present, it is assumed to compete with oxygen on a mole fraction basis. At oxygen concentrations above 5.0% O_2, any hydrogen formed by the sodium/water reaction is immediately reacted with oxygen so that there is no net production of H_2. At <5.0% oxygen concentration, hydrogen does not burn and will accumulate in the atmosphere.

B. Aerosol Phenomena

1. Aerosol Formation

The process of nucleation of reaction products in and near the burning zone has not been studied in detail in the U.S. High supersaturation partial pressures for Na_2O and Na_2O_2 are expected in the region near the burning zone. Nucleation and very rapid agglomeration of the primary aerosol particles are also expected to occur in this region. An AI test of an open air pool fire in a crosswind gave large particles deposited close to the pool, indicating rapid agglomeration immediately above the burning zone.

Transport of the aerosol particles away from the burning zone or back to the sodium surface is determined by forces exerted on the particles, chiefly those due to gravity, convection, diffusion, diffusiophoresis, and thermophoresis. Because there is no mechanistic model for this process, the fraction which escapes the burning zone to become suspended aerosol in the cell atmosphere must be determined empirically. For pool fires, this has been shown to be 0.25 to 0.30. For spray fires it is assumed to be 1.0, although this has not been verified experimentally.

2. Chemical Transformations

After the Na_2O_2 aerosol particles escape the burning zone, they may be exposed to additional chemical transformations by reactions with gaseous components in the atmosphere. Water vapor will react to form NaOH, releasing oxygen. Carbon dioxide will react to form

Na_2CO_3. Hydrates of these two products may be formed if there is sufficient water present. Tests at HEDL where CO_2 and steam were added to a 24-hr continuous spray fire in air showed that rapid and complete conversion to anhydrous Na_2CO_3 occurred for those conditions. It is not known whether formation of NaOH is a prerequisite intermediate step.

3. Aerosol Computer Codes

Significant advances have been made in aerosol behavior computer codes since the 1978 Specialists' Meeting. The HAA-3 code is being upgraded at Atomics International to extend the calculational regime to higher aerosol concentrations and to optimize the man-machine interface. The new version is called HAA-4. The HAARM-3 code has been improved by Battelle-Columbus Laboratory (BCL), including an attempt to model spatial heterogeniety by using a 3-zone model. HAA-4 and HAARM-3 both use the assumption of a log-normal size distribution. The QUICK code, developed at BCL, uses a discrete particle size distribution. A user's manual has been published. A variation of QUICK presently being developed will handle multiple sources of aerosol materials. MAEROS, being developed at SNL, is also a discrete particle size, multiple source aerosol code. An extensive data base of experimental measurements of aerosol behavior in closed vessels exists for validating codes. Plans are underway for additional experiments at high aerosol concentrations and with multiple aerosol sources, including tests in a large (850 m^3) vessel.

C. Sodium Fire Computer Code Development

1. Pool Fire Codes

The SOFIRE-II code is the principal U.S. code used for computing pool burning dynamics and the accompanying thermal transients in the pool and cell. One-cell and two-cell versions of the code are available. The burning rate is assumed to be controlled by the rate of oxygen diffusion to the pool surface. Improved pool fire codes are being developed in connection with the SOMIX spray fire code and the integral code, CONACS.

2. Spray Fire Codes

The SPRAY code has been updated to the SPRAY-3 version. This code utilizes gas convection, heat transfer and droplet combustion theory to calculate the pressure and temperature effects within an enclosure. Any oxygen or humidity concentration can be handled. A mean drop size is used to represent the drop size distribution.

The NACOM code uses discrete drop size groups rather than a mean size. The SOMIX-2 code is a two-dimensional compressible flow gas circulation code using cylindrical or rectangular geometry. Spray angle and orientation are user specified. The SOMIX code accommodates multilayer walls and wall to gas boundary layer heat transfer. A version of SOMIX will be made compatible with the integral code, CONACS, so that it may be used as an option module. It is generally recognized that additional confirmatory experiments are reqired for validation of these codes.

3. Integral Containment Codes

The first large computational system used in the U.S. to estimate cell temperatures, pressures, constituent composition, water release from concrete, hydrogen formation and burning, sodium-concrete reactions, aerosol deposition and leak rate during a sodium spill was the CACECO code. New integral codes are being developed at SNL (the CONTAIN code) and at HEDL (the CONACS code). The latter codes include improved models of sodium fire and other phenomena and add radiological transport and consequence calculation capabilities.

III. SODIUM FIRE PREVENTION AND MITIGATION

A. Sodium Fire Prevention

Prevention of sodium fires within sodium systems requires a high level of quality assurance application at four different work scopes: planning, design, fabrication, and operations. Sodium fire prevention through planning is accomplished by establishing specific performance criteria for a system that can be followed by the remaining work scopes. During this phase, the degree of quality assurance is determined as well as the overall requirements for design, fabrication and operation of the sodium system. The scope of design includes system definition, codes, standards and specifications, performance requirements, test requirements, test equipment and system design. Selection of material and components, the respective testing, rating and sodium compatibility are considered by a designer for prevention of sodium fires. Further passive or active fire protection systems must be integrated into the system by design. All quality assurance requirements, codes, standards and specifications implemented during design follow through procurement and fabrication. During this phase, all components of the sodium system are verified to comply with the design requirements as they are fabricated and installed within the system. During each of the previous work scope phases, quality assurance provides scheduled audits to follow and evaluate the progress of the specific work activities. These audits are conducted by both organizational and governmental quality assurance groups. After plant construction and acceptance testing is completed and turned over to an operating organization, trained operating personnel provide the major contribution for fire prevention. Proper operation of sodium subsystems, scheduled and preventive maintenance, inservice inspection and specific operating limits are important aspects of a plant fire prevention program.

B. Sodium Fire Mitigation

Sodium cooled reactor systems, either currently operational or in design, employ inert atmosphere cells in areas containing radioactive sodium. An inert atmosphere (1-2% oxygen in nitrogen) is maintained at all times to prevent a sodium fire in event of a sodium leak. Nonradioactive sodium piping and equipment are usually located in air filled cells. It is standard practice to employ either active or passive sodium fire protection in nonradioactive sodium cells. For either fire protection method, the objective is to ensure that the reactor plant can accommodate worse case accident spill conditions without compromising the capability for safely removing core decay heat.

1. Active Fire Protection Systems In Air Filled Cells

Active fire protection systems include the capability for rapid sodium drain from the afflicted loop and systems by which the fire retardant or extinguishing agent is supplied to a sodium component or handling cell. They can be activated either automatically or manually.

Previously, sodium systems employed an active fire protection system using preloaded bins of a fire extinguishing agent. Materials such as calcium carbonate or sodium chloride were the chief constituents in the bin-type active fire protection systems. Currently, NaX (sodium carbonate base) is a widely used extinguishing agent in the U.S. However, powder systems are believed to be unreliable for extinguishing large sodium fires.

Secondary sodium fire protection in the Fast Flux Test Facility (FFTF) is provided by space isolation combined with nitrogen flooding. Steel catch pans are provided to prevent sodium-concrete interactions. The principle of extinguishment by space isolation is to prevent oxygen entry into the cell in which sodium is burning and thus to allow the oxygen concentration to decrease by the sodium-oxygen reaction to below the level required to sustain combustion. Area isolation is provided by concrete walls, metal partitions, flexible rubber boots, flued heads, fire/smoke dampers with fusible links and self-closing personnel access doors. Nitrogen gas is manually injected at a sufficient rate to slightly pressurize the cell in order to prevent the in-flow of air. Large-scale sodium fire tests demonstrated the effectiveness of this concept. However, recent testing has shown that the cells leak at higher rates than intended, and the effectiveness of the space isolation feature is being reassessed. An effort is underway to improve the capability for rapid draining of the sodium to minimize the quantity of sodium involved in a leak.

The Experimental Breeder Reactor (EBR-2) uses an active fire protection system in both primary and secondary sodium heat transport cells. These systems operate in a normal air environment and the cells are provided with catch pans to contain spilled sodium. Large pressurized extinguishing agent dispensers are located throughout the primary and secondary cells and are remotely actuated. MET-L-X (sodium chloride) is used as the extinguishing agent.

2. Passive Fire Protection In Air Filled Cells

Systems which employ passive fire protection features use structures and design concepts to mitigate the consequences resulting from a sodium spill. Such systems include drainage from an affected cell (or cells) to a permanent hold-up tank or containment which excludes the oxygen necessary to support sodium combustion.

Currently, the Clinch River Breeder Reactor (CRBR) design incorporates a sodium fire protection system which inherently reduces the consequences resulting from a sodium fire by nature of design. The CRBR sodium fire suppression system involves a structure which contains the inventory of spilled sodium within a component cell and provides a mechanism which excludes the transport of available oxygen from the cell to the sodium pool surface. A network of commercially available structural panels, called "Q-deck", covers a catch pan over the entire floor surface area. Each Q-deck panel is provided with drain pipes to allow spilled sodium to drain from the surface into the catch pan. After complete sodium drainage into the catch pan, the Q-deck structure provides a barrier for available oxygen within the affected component cell to communicate with the sodium. Extensive small-scale testing has been performed at approximately 1/100th scale. At the present, AI-ESG is undergoing a series of tests which are approximately one-tenth scale, to further demonstrate the effectiveness of the CRBR fire suppression concept.

3. Air Cleaning

Recently, a series of tests have been performed by HEDL on a submerged gravel scrubber (SGS) which is considered for use as a potential breeder reactor containment vent air cleaning system. This air cleaning system is comprised of a gravel scrubber submerged in water and a high efficiency demister. During tests, this air cleaning system demonstrated high aerosol removal efficiencies, (>99.98%) with flow rates up to 0.47 m^3/s and aerosol concentrations to 25 g/m^3. A 5 m^3/s unit is currently being planned for installation at the HEDL sodium fire test site.

Other air cleaning systems that have been investigated include HEPA filters, dry sand and gravel filters and conventional aqueous scrubbers. Although the first two air cleaning systems demonstrated high efficiencies, their mass loading capacities were low. The aqueous scrubber system was found to have both high mass loading capacities and good aerosol removal efficiencies. Efficiencies >99.9% were demonstrated at flow rates up to 0.8 m^3/s and aerosol concentrations up to 50 g/m^3. The major components of the aqueous scrubber system consisted of a spray quench chamber, an eductor venturi scrubber, and a high efficiency fibrous scrubber assembled in a series configuration.

The FFTF has been equipped with a containment vent/purge and effluent cleanup system as a development project. The cleanup system consists of an ejector venturi and high efficiency fiber scrubber in series. It is designed for 99% aerosol removal at 2.8 m^3/s flow rate.

Effluent gas from the EBR-2 test cells are passed through a graded media filter bank which is comprised of stainless steel wool packing. AI-ESG has recently installed a two-stage scrubber to remove sodium oxide aerosols from the effluent gas of the Large Scale Fire Suppression Test Facility. This scrubber unit is commercially built and consists of a two-plate impactor type first stage which is water scrubbed and a fibrous type second stage.

4. Detection

Several different methods for sodium leak or fire detection are used in the U.S. The methods used for leak detection include spark plug detectors, sodium ionization detectors (SID), and plugging filter aerosol detectors (PFAD). For sodium fire detection, SIDs, PFADs, and photoelectric smoke detectors are used.

Currently, EBR-2 uses spark plug detectors to detect sodium leakage and ionization detectors to detect sodium smoke. The FFTF uses SIDs, PFADs and ionization smoke detectors for sodium vapor and smoke detection. AI-ESG uses photoelectric and ionization smoke detectors to detect the presence of sodium fires at each of their facilities.

IV. EFFECTS OF SODIUM FIRES AND SPILLS ON LMFBR PLANT STRUCTURES

The effects of sodium spills on LMFBR plants may be characterized as effects resulting from direct exposure of equipment and structures to the leak/fire environment or effects resulting from exposure of equipment to combustion product aerosols that may be dispersed throughout the plant. Here these effects are considered for steel and concrete structural materials, insulation materials, and for equipment and instrumentation.

A. Structural Materials

The U.S. has devoted an exhaustive effort toward designing LMFBR plants to respond safely to large sodium spills and sodium fires. Particular attention has been given to protecting structural concrete from the effects of sodium spills. A general viewpoint prevails in this country that steel liners or catch pans will provide such protection. Large-scale tests involving sodium heated in excess of 650°C have demonstrated that this is the case. In some instances, liners are vented on the unexposed side to allow escape of gases from heated concrete. Several computer codes (COWAR, USINT, WATRE) have been developed to compute the gas evolution from heated concrete, and confirming experiments have been performed at up to 1.1-m^2 concrete surface area.

The extent and consequences of sodium-concrete interactions is an area of active study in the U.S., with major research ongoing at Sandia National Laboratory and at HEDL. The nature of the interactions has been found to depend on the chemical composition of the aggregate material. Concrete made with siliceous aggregate is, at least under some circumstances, considered susceptible to extensive attack by sodium. Somewhat similar results have been observed with concrete having magnetite aggregate. Calcareous aggregate concrete has exhibited vigorous interaction for short periods of time, but it has also been observed to slow or stop, perhaps because of an interfacial layer of reaction products preventing intimate contact of sodium with the reactive constituents of the concrete. Ongoing research efforts are attempting to develop a mechanistic understanding of the reaction between sodium and concrete.

Only limited efforts have been expended to find concretes or other structural materials that are immune to sodium attack. Several exploratory studies of sodium attack on ceramics have shown that attack may be due to (1) gross chemical reactions, (2) thermal shock, or (3) reaction with impurities concentrated at the grain boundaries in the ceramic. Criteria for gross chemical attack are easily established from thermochemical analysis. Other forms of attack depend on both the composition and manufacturing method of the material. Definition of the susceptibility of materials to other forms of attack may be done by experiment. Magnesium oxide, aluminum oxide, and silicon nitride, when pure, exhibit good compatibility with sodium.

B. Thermal Insulation Materials

Experimental data have been collected to show that conventional insulation materials are degraded significantly when exposed to molten sodium. Materials, such as firebrick, that are made with silicon oxide react chemically with molten sodium. High porosity insulations made without silicon oxide absorb sodium within their porosity and, thus, their insulation value is reduced significantly.

C. Equipment and Instrumentation

Design trends in the U.S. have emphasized avoidance of sodium spills, barriers to protect structures and equipment in the event of a spill, and redundancy in safety-related equipment. Generation of a broad data base on equipment survivability in a sodium leak/fire environment has not been necessary because equipment redundancy assures safe plant shutdown even if equipment exposed to sodium ceases to function. Even so, key safety-related components are designed and qualified to operate in design basis sodium fire environments.

Criteria have been developed for safety grade equipment and instrumentation to survive "beyond-design-basis" aerosol environments, and qualification of instruments to survive such environments is an area of active study.