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DESIGN, OPERATION, AND SELECTION CRITERIA
FOR XE CALORIMETRIC NUCLEAR RADIATION DETECTORS

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REON TECHNICAL MEMORANDUM

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FOR XE CALORIMETRIC NUCLEAR RADIATION DETECTORS

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INTRODUCTION

The intent of this document is to recommend a calorimetric radiation detector design that can measure radiation environments adjacent to Aerojet-supplied XE hardware. In establishing criteria for calorimeter selection, a survey of several calorimeter designs was conducted. The survey failed to disclose any commercial "off-the-shelf" calorimeters designed for nuclear radiation detection and indicated that previous requirements have been satisfied by instruments fabricated in-house. Several calorimeter designs were analyzed to determine their suitability. The results of these analyses and resulting recommendations are presented below.

CONCLUSIONS AND RECOMMENDATIONS

The selection of a calorimeter depends upon the type of data required. If the data users are primarily interested in transient data, the AGC slope calorimeter design is recommended. If they are interested in measuring steady-state environments only, the hybrid foil asymptotic calorimeter is recommended. However, if the data users are interested in both transient and steady-state data, then the AGC slope calorimeter is recommended.

Since the performance of the recommended units has yet to be demonstrated, it would seem advisable to develop prototypes of both the AGC slope and hybrid foil asymptotic calorimeters and then select the one that best satisfies measurement requirements under actual or simulated test environments. However, it may not be possible (or even desirable) to develop and use a new design for the first XE test. Thus, the following course of action is recommended:

A. Develop and fabricate prototype calorimeters of both the AGC slope and hybrid foil configuration.

B. Evaluate the prototype designs and select the one that best satisfies the test requirements.

C. If a prototype selection cannot be made in time to satisfy the XE test schedule, use existing designs as an interim solution. These are:

1. The WANL slope calorimeter design, if the XE data users are interested in transient or startup data,

2. The cylinder asymptotic design, if the XE data users are interested in steady-state full-power data.

Calorimeter selection has been based, primarily, upon the accuracy to which each unit can measure radiation environments.

TECHNICAL DISCUSSION

There are, at present, two basic types of calorimeters. The first type includes those calorimeters possessing an element which continuously absorbs and retains heat from the environment. Since the slope of the element's temperature-vs-time fluctuation defines the magnitude of nuclear radiation, such a calorimeter is referred to as a slope calorimeter. The second calorimeter type is one that continuously absorbs heat from the environment and transfers it between different regions within the calorimetric system. Since the temperature difference between the various regions will asymptotically approach a constant value which defines the magnitude of nuclear radiation, such a calorimeter is referred to as an asymptotic calorimeter.

The response of a slope calorimeter can be described by a rather simple mathematical expression which lends itself to conventional data reduction techniques. The expression defining an asymptotic calorimeter's transient response is so complex that data cannot be obtained conveniently until

expiration of transient perturbations. Thus, short term (transient) measurements are best made with slope calorimeters while asymptotic calorimeters are well adapted for measuring long term (steady-state) radiation environments. Examples of each type will be discussed together with the approximation equation describing their primary operational characteristics.

A. SLOPE CALORIMETERS

The operating characteristics of an ideal slope calorimeter and two designs incorporating these operational characteristics are described below.

The internal energy of a solid object or element, other than nuclear or kinetic, may be thought of as heat contained within the element, the amount of which is indicated by the element's temperature. Various materials differ in the quantity of heat (dH) required to produce a given change (dT) in their temperature. The ratio of heat supplied to the resulting temperature change is the element's heat capacity.

$$\text{Element's Heat Capacity} = \frac{dH}{dT}$$

To obtain a constant that is characteristic of the element material, the term specific heat capacity (c) is used and is defined as the element's heat capacity per unit element mass.

$$c = \frac{dH/dT}{m}$$

The above may be used to analytically describe the thermal response of an idealized slope calorimeter by assuming the following:

1. The element's specific heat capacity is constant (independent of temperature).

2. The element's thermal conductivity is infinite.
3. The element is thermally isolated from its surroundings.

Therefore, the entire element is considered to be at uniform temperature which varies as heat deposition increases the element's internal energy.

$$dH = cm (dT)$$

Thus the rate of heat deposition per unit element mass may be described by

$$\frac{dH/dt}{m} = \frac{cm (dT/dt)_e}{m}$$

$$\dot{Q} = c \left(\frac{dT}{dt} \right)_e \frac{\text{erg}}{\text{gm}(e) - \text{sec}}$$

where: $\dot{Q}$ = Rate of energy deposition per unit mass of the absorbing medium, ergs/gm(e)-sec;

c = Specific heat capacity of the absorbing material, erg/°K - gm;

$(dT/dt)_e$ = Instantaneous rate at which the element's temperature is changing, °K/sec.

The symbol gm(e) represents grams mass of the element material. It can be converted to the more familiar term grams per mass carbon "gm(c)" by multiplying the right-hand-side of the preceding equation by a numeric constant.

By attaching a thermocouple to a thermally-isolated element that is exposed to nuclear radiation, the radiation level can be inferred by monitoring the slope (time-derivative) of the element's temperature fluctuation. Hence the term "slope calorimeter."

In obtaining an expression to describe the element's time-temperature fluctuation, it was assumed that the element was perfectly insulated. However, this assumption cannot be realized in practice since three modes of thermal loss exist. These are:

1. Thermocouple lead loss
2. Surface convection and radiation losses
3. Conduction losses to the surrounding and supporting structures

Thermocouple lead loss is usually small when compared to the rate of heat deposition within the element and may be neglected except when extremely small elements are used. However, the thermocouple wires should be as small as possible.

Surface radiation losses can be reduced by lowering the emissivity of the element's surface and surrounding the element with an enclosure designed to duplicate the element's temperature perturbations. Surface convection losses can be minimized by inhibiting the flow of gaseous currents about the element or by removing the gas through evacuation of the element's surrounding enclosure.

Conduction losses are always present since it is necessary to provide some type of support for the element. Usually the support structure consists of one or more hollow cylindrical rods.

In arriving at a simplified description of support rod induced thermal loss, it is assumed that:

1. The amount of heat deposition within the support rod or rods is negligible.

2. All regions of the element are at the same temperature.

3. The thermal conductivity of the element support structure is independent of temperature.

With these assumptions, the following energy balance equation becomes applicable.

Net rate of heat entering the element = Rate of heat accumulation within the element

$$\dot{Q} - \dot{q} = c (dT/dt)_e$$

where $\dot{q}$ is the rate at which heat flows out of the element by conduction through the element support as shown in Figure 1.

Figure 1

GENERAL SLOPE CALORIMETER CONFIGURATION

By assuming a linear temperature gradient across the support rod, the rate of conductive heat flow ($\dot{q}$) away from the element per unit element mass is:

$$\dot{q} = \frac{k_s A_s}{m L_s} (T_e - T_s)$$

where: k_s = Effective thermal conductivity of the support rod,
erg/cm-sec-°K

A_s = Cross-section area of the support rod, cm²

L_s = Support rod length, cm

T_e = Temperature of the element, °K

T_s = Temperature of the support rod - calorimeter enclosure
interface, °K

Having defined the outward flow of heat from the element, the energy balance equation describing the net rate of energy deposition within the element becomes

$$\dot{Q} = c (dT/dt)_e + \frac{k_s A_s}{m L_s} (T_e - T_s) \frac{\text{erg}}{\text{gm}(e) - \text{sec}}$$

which may be reduced to the general form

$$\dot{Q} = Y (dT/dt)_e + P (\Delta T) \frac{\text{erg}}{\text{gm}(e) - \text{sec}} \quad (1)$$

where Y and P are referred to as slope calorimeter calibration constants.

Equation (1) is perfectly general and may be used to describe the operation of slope calorimeters. The characteristic response of slope calorimeters to a step-wise increase in the nuclear radiation environment may be found by solving equation (1) to obtain

$$T_e - T_s = \frac{\dot{Q}}{P} (1 - e^{-Pt/Y}) \text{ } ^\circ\text{K}$$

Thus, the response of a slope calorimeter is exponential and its reaction to a pulse of nuclear radiation is shown in Figure 2 where the support rod-to-calorimeter enclosure interface temperature (T_s) is assumed constant. Since the time constant of a slope calorimeter is Y/P seconds, its frequency response is approximately $P/2\pi Y$ cycles per second. Noting that the frequency response of the recording instrumentation system should be at least twenty times the transducers if phase and magnitude distortions are to be minimized, the instrumentation channel frequency response should exceed $10 P/\pi Y$ cycles per second.

Figure 2

SLOPE CALORIMETER RESPONSE

By studying Figure 2, it becomes obvious that a slope calorimeter responds instantaneously to variations in the nuclear environment. If the calibration constants are known, equation (1) can be used to define the instantaneous nuclear environment in terms of rates of energy deposition per unit mass of carbon or any other material.

The accuracy of calorimetric data depends upon temperature measurements and the ability to measure or predict the calorimeter calibration constants. In general, the more simple the calorimeter configuration, the more accurately the calibration constants can be predicted. In general, (P) is the most difficult constant to define.

Previous discussions assumed negligible heat deposition within the support rods and that the support rod thermal conductivity was independent of temperature. Both of these assumptions are invalid, and the effective value of (P) is found to be dependent upon the magnitude of the nuclear radiation environment and the absolute temperature and configuration of the support rod. It will suffice here to state that the value of (P) can be extremely difficult to define theoretically.

The calibration constants can be inferred by placing a slope calorimeter in an oven and heating it until thermal equilibrium is attained. The calorimeter is then removed and allowed to cool. By measuring both the rate and amplitude of temperature variations at two time points and using equation (1), two equations with two unknowns are obtained which may be solved simultaneously to yield approximate Y and P values.

Two candidate designs are now described.

1. WANL Slope Calorimeter Design

Figure 3

WANL SLOPE CALORIMETER DESIGN

This design contains a metal element which is supported with seven hollow rods. Radiation losses are minimized by surrounding the element with a shield made of the same material as the element so that it will tend to follow the element's temperature perturbations and reduce radiation losses. The case enclosure is evacuated to reduce convective losses. Since the support rods are made with alumina, thermal losses will be significant and must be accounted for during data reduction. Some of the obvious advantages and disadvantages of this design are listed.

a. Advantages

(1) This unit has been fully designed, tested, and used on past test vehicles.

(2) Data obtained would provide good correlation to that obtained from similar calorimeters during previous testing.

(3) The reliability of this design has been established.

(4) The calibration constants have been determined.

(5) Manufacturing techniques have been perfected.

b. Disadvantages

(1) Since the case temperature is measured at only one point, the case structure becomes part of the support structure for the center element. Under these conditions, the value of P must, necessarily, be poorly defined as temperature distributions about the case and heat flow paths through the case are essentially unknown.

(2) Because of large uncertainties in the value of P , the design will only yield accurate data at the beginning of a long duration test.

2. AGC Slope Calorimeter Design

Figure 4

AGC SLOPE CALORIMETER DESIGN

This design contains a metal element that is supported by a single hollow rod. Radiation losses are minimized by gold plating the inner case surface and designing the case so that the case temperature adjacent to the element will follow the element temperature. Convection losses are reduced by evacuating the case enclosure. The constantan wire is attached to the copper sphere surface at a point which best represents the average sphere (element) temperature during both transient and steady-state operation. Since the support rod is made with constantan, thermal losses will be significant and must be accounted for during data reduction. Some of the obvious advantages and disadvantages of this design are listed.

a. Advantages

(1) The simple geometry of this design improves the accuracy with which the calibration constants may be predicted.

(2) Temperature measurements are made at the support rod terminals which further improves the ability to accurately predict P values.

(3) The number of conductors is minimized to reduce cable size and nuclear radiation induced cable heating.

(4) Since P is fairly well known, it should be possible to acquire reasonably accurate data during both transient and steady-state test periods.

b. Disadvantages

(1) The reliability of this design has not been established.

(2) Unknown manufacturing difficulties may appear, making it difficult to satisfy existing test schedules.

B. ASYMPTOTIC CALORIMETERS

There are two common forms of asymptotic calorimeters, the circular foil (Figure 5) and the right cylinder (Figure 8). In both configurations, heat deposition generates a temperature gradient whose magnitude may be related to the amplitude of the nuclear environment. That is, nuclear environments may be described by measuring temperature gradients within asymptotic calorimeters.

1. Foil Asymptotic Calorimeters

The foil asymptotic calorimeter incorporates a thin circular constantan foil that is welded about its periphery to a copper heat sink (Figure 5).

Figure 5
FOIL ASYMPTOTIC CALORIMETER

When the foil is exposed to a nuclear environment, the heat deposited in the foil will flow, radially, from the center of the foil toward its periphery. If it is assumed that there exists perfect thermal isolation (no radiation or convective heat loss), uniform heat deposition, and that the foil's thermal conductivity (k) and specific heat capacity (c) values are independent of temperature, the following thermal wave equation results:

$$\frac{d^2 T}{dr^2} + \frac{1}{r} \frac{dT}{dr} + \frac{\dot{q}}{k} = \frac{1}{a} \frac{dT}{dt}$$

where:

r = a radial distance measured from the center of the foil, cm

$\dot{q}$ = rate of heat deposition per unit volume, erg/cm³-sec

k = thermal conductivity of the foil, erg/cm-sec-°K

$a = k/\rho c$ = thermal diffusivity of the foil, cm²/sec

ρ = density of the foil, gm/cm³

c = specific heat capacity of the foil, erg/°K-gm

Solving the above yields

$$T_o - T_s = \frac{\dot{q}R^2}{4k} - \frac{2\dot{q}}{Rk} \sum_{m=1}^{\infty} e^{-a\beta_m^2 t} \frac{1}{\beta_m^3 J_1(R\beta_m)}$$

where β_m is the positive root of $J_o(R\beta) = 0$. After the transient portion

has expired, the above reduces to:

$$T_o - T_s = \frac{\dot{q}R^2}{4k}$$

where:

T_o = temperature at the center of the foil, °K

T_s = temperature at the periphery of the foil, °K

R = effective foil radius (distance from the center of the foil to point at which the foil contacts the copper heat sink), cm

However, the rate of heat deposition per unit mass ($\dot{Q}$) is of more concern than the rate of deposition per unit volume ($\dot{q}$). These two quantities are simply related by:

$$\dot{Q} = \dot{q}/\rho$$

Therefore:

$$\dot{Q} = \frac{4k}{\rho R^2} (T_o - T_s)$$

$$\dot{Q} = W (\Delta T) \text{ ergs/gm(cn)-sec} \quad (2)$$

where W is defined as the asymptotic calorimeter calibration constant, and the unit gm(cn) stands for grams-constantan.

Foil temperatures are measured with two copper wires and one constantan wire. Channel T1 measures the temperature differential across the foil (ΔT) while channel T2 measures the temperature at the center of the foil (T_o). The T_o value is required to correct the calibration constant (W) when foil temperatures differ appreciably from predicted values.

Radiation losses are minimized by polishing all metal surfaces while convective losses are minimized by evacuating gas from the calorimeter assembly.

The foil size required to produce adequate thermo-electric signal levels may be reduced by adding a small cylindrical copper mass to the center of the foil as shown in Figure 6.

Figure 6

HYBRID FOIL ASYMPTOTIC CALORIMETER

The presence of a finite mass alters the operating characteristics of the calorimeter. If the mass were very small, the unit would behave as an asymptotic calorimeter and its operations would be described by equation (2). If a rather large mass were used so that the rate of heat deposition in the mass was large relative to the rate of heat deposition in the foil, the unit would behave as a slope calorimeter and its operations would be described by equation (1) except that P would be defined, approximately, by

$$P = \frac{2 \pi k s}{m \ln(R/R_m)}$$

where k is the foil thermal conductivity, s is the foil thickness, m is the amount of mass attached to the center of the foil, R_m is the radius of

the cylindrical mass, and R is the radius of the foil-heat sink interface. In general, the condition frequently encountered is the intermediate case of a moderate sized mass so that the unit represents a hybrid design which can be thought of as a modified (hybrid) foil asymptotic calorimeter. The thermal equation for the hybrid unit has not been derived as of this writing. Although the hybrid design may be made smaller than the foil asymptotic calorimeter, its response time is slower.

Of all the calorimeter designs considered, the foil and the hybrid foil asymptotic calorimeter are, potentially, the most accurate since they lend themselves readily to calibration. The calibration setup is shown in Figure 7.

Figure 7
FOIL ASYMPTOTIC CALORIMETER CALIBRATION

The optical filter is used to shape the magnitude of incident infrared heat. This is done when calibrating the calorimeter shown in Figure 6. The larger rate of heat incident upon the center of the foil simulates the extra heat delivered to the foil by the attached copper mass. When calibrating a simple foil configuration (Figure 5), the optical filter will be removed.

The temperature and material of the calibration stand may be varied to approximate the test article to which the calorimeter will be mounted. The infrared heat flux may be adjusted to simulate the expected nuclear heating rate.

Some of the obvious advantages and disadvantages of this design are listed.

a. Advantages

(1) Asymptotic foil calorimeters for measuring infrared heat have been manufactured for many years. All that would be required to convert these existing units into nuclear radiation detectors would be the addition of the stainless steel shield, the constantan wire, and the copper mass.

(2) The calibration constant for these calorimeters can, potentially, be determined more accurately than those of any other calorimeter design.

(3) The reliability of a very similar design (infrared detectors) has been established as being excellent.

b. Disadvantages

(1) Although manufacturing techniques have been developed for infrared detectors, the conversion of infrared units into nuclear radiation detectors may pose some problems.

2. Right Cylinder Asymptotic Calorimeter

The cylinder asymptotic calorimeter incorporates a constantan right cylinder that is attached to a heat sink at one end as shown in Figure 8.

Figure 8
RIGHT CYLINDER ASYMPTOTIC CALORIMETER

When the cylinder is exposed to a nuclear environment, the heat deposited in the cylinder will flow to the copper heat sink. Assuming perfect thermal isolation (no radiation or convective losses), uniform heat deposition, and that the cylinder's thermal conductivity (k) and specific heat capacity (c) values are independent of temperature; the following thermal wave equation results.

$$\frac{d^2 T}{dy^2} + \frac{\dot{q}}{k} = \frac{1}{a} \frac{dT}{dt}$$

where:

k = thermal conductivity, erg/cm-sec-°K

$\dot{q}$ = rate of heat deposition per unit volume, erg/cm³-sec

a = thermal diffusivity, cm²/sec

Solving the cylinder asymptotic calorimeter thermal wave equation yields:

$$\Delta T = T_o - T_s = \frac{\dot{q}L^2}{2k} \left[1 - \frac{32}{\pi^3} \sum_{n=0}^{\infty} \frac{(-1)^n}{(2n+1)^3} e^{-\frac{a(2n+1)^2\pi^2}{4L^2} t} \right]$$

After all transient portions have expired, the above reduces to:

$$T_o - T_s = \frac{\dot{q}L^2}{2k}$$

where T_o = temperature of the free end of the cylinder, °K

T_s = temperature of the cylinder where it is attached to the copper heat sink, °K

L = cylinder length, cm

k = thermal conductivity of the cylinder material, erg/cm-sec-°K

It is more important to describe the heat deposited per unit mass ($\dot{Q}$) than per unit volume ($\dot{q}$) where $\dot{Q} = \dot{q}/\rho$.

Therefore; $\dot{Q} = \frac{2k}{\rho L^2} (T_o - T_s)$

$$\dot{Q} = W (\Delta T) \frac{\text{erg}}{\text{gm}(cn)\text{-sec}}$$

Note that the final equation is identical in form to equation (2). This should be expected since equation (2) is the general equation for asymptotic calorimeters.

In practice, radiation losses from the cylinder can be minimized by polishing both the cylinder and the inner shield surface and by designing the shield so that its temperature will follow the cylinder temperature. Convective heat losses can be minimized by evacuating gases from the calorimeter assembly.

The cylindrical asymptotic calorimeter has the simplest geometric design of any calorimeter. Thus it lends itself readily to heat transfer analysis and its thermal response can be theoretically predicted with more assurance than any other design. However, the foil asymptotic can be calibrated more accurately.

This calorimeter design has been used successfully by the National Reactor Testing Station at Idaho Falls for many years. Three conductors (two copper and one constantan) are used to measure the rate and magnitude of temperature variations within the calorimeter. Channel ΔT measures the temperature gradient across the cylinder while channel T_s monitors absolute cylinder-heat sink interface temperatures. Absolute temperature measurements are required to correct W values when the absolute cylinder temperature differs appreciably from predicted values.

The advantages and disadvantages of this design are listed.

a. Advantages

- (1) The design is both simple and proven.
- (2) Theoretical predictions of the thermal response of this calorimeter are more reliable than those for other designs.
- (3) Manufacturing techniques have been established.

b. Disadvantages

(1) No major disadvantages other than its poor response to transient nuclear environments.

3. Asymptotic Calorimeter Response

The response of an asymptotic calorimeter to a pulse of nuclear radiation is shown in Figure 9.

Figure 9

ASYMPTOTIC CALORIMETER RESPONSE

As seen from Figure 9, data can only be acquired after thermal stabilization is achieved within the calorimeter. The time required for stabilization is indicated by t_r . For a foil asymptotic calorimeter, T_o is the center foil temperature and T_s is the peripheral foil temperature. For the right cylinder asymptotic calorimeter, T_o is the temperature of the cylinder's free end while T_s is the temperature of the "cylinder-heat sink" interface. To a first approximation, the transient response of asymptotic calorimeters is exponential.

For foil asymptotic calorimeters, the transient exponential response time is approximately $R^2/5.76a$ seconds so that the instrumentation channel frequency response should exceed $57.6a/\pi R^2$ cycles per second.

For cylindrical asymptotic calorimeters, the transient exponential response time is approximately $4L^2/\pi^2 a$ seconds so that the instrumentation channel frequency response should exceed $2.5\pi a/L^2$ cycles per second.

An approximate expression for the response time of hybrid asymptotic calorimeters has not been derived as of this writing.