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LIQUID ROCKET PLANT

PRE-IRRADIATION ANALYSIS

ROSEMOUNT PRESSURE TRANSDUCER - MODEL 810C

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PREF-IRRADIATION ANALYSIS REPORT NO. 8771:2219

ROSEMOUNT PRESSURE TRANSDUCER-MODEL 810C

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I. ABSTRACT

Rosemount pressure transducer (Model 810C) was analyzed for its compatibility with and possible behavior in a radiation environment. Its threshold damage is based on the behavior of silicon, and is set at 10^{13} n/cm² and 10^8 ergs/g(C). Gamma heating rates in two flux levels are considered. Induced activities were computed and the total at the end of a 100 hr-GTR test is 0.09 curies.

II. SUBJECT DESCRIPTION

Rosemount pressure transducer, Model 810C is a 0-1000 psia instrument with compensated temperature ranges of -350 to -250, -175 to -15, and -50 to +350°F in 100-degree increments. Model 810C uses single crystal n-type silicon as a strain sensing material. The donor material is phosphorus. The materials of construction and weight percentages of each component were furnished by the manufacturer as follows:

<u>Material</u>	<u>Percent by Weight of Total Weight</u>
Stainless Steel (304)	96.5%
Silicon	1.8
Glass (Boron and Lithium free)	.1
Alloy 479 (Platinum Alloy)	.1
Resistors	.9
Soft Solder	.1
Duro [*] (Silico-ceramic)	.5
	<u>100.0</u>

III. SUMMARY

A. ANALYSIS OBJECTIVE

The basic purpose of the analysis was to estimate the damage threshold of the transducer, and to consider factors or limitations of its operation in a radiation environment.

* Physical Sciences Corporation (a mixture of oxides of Zn, Pb, Mg, Bi, Si, and Ti - percentage composition unknown).

III, Summary (cont.)

B. CONCLUSIONS

The change in resistivity of the silicon sensing element will be appreciable above flux levels of 10^{13} n/cm² and 10^8 ergs/g(C). Soft solder has a low melting point, but was considered allowable because the transducer specifications set the operating range within a tolerable temperature limit. Guidelines of exposure limitations from the gamma heating standpoint were set. The conclusion is that combined radiation and convection effects will allow the transducer to operate in gamma radiation fields up to 4.8×10^7 ergs/gram(C)-sec. Above this limit methods of shielding or cooling the transducer will need to be devised. The above limit is about 1.7% of the prescribed HERVA field.

The induced activity in the transducer at the end of a 100-hour test at GTR will be about .09 curies, caused principally by the manganese content of stainless steel.

IV. ANALYSIS

A. RADIATION COMPATIBILITY OF MATERIALS

1. Silicon

The silicon crystal is the sensing element in this device and the physical properties demanded upon for its proper operation include (a) elastic properties and (b) piezoresistive properties, both of which can be affected by radiation. Numerous research studies on silicon crystals in irradiation fields have been reported in the literature. Abstracts of documentation of such work were furnished (2 August 1963) by Radiation Effects Information Center of Battelle Memorial Institute. The results which are reported can be used to give only qualitative predictions of the behavior of the silicon sensor.

It is found in silicon that the majority carrier concentrations in both n-type and p-type specimens decrease steadily with irradiation and become nearly intrinsic, with resistivity over 10^4 ohm-cm. at room temperature.

The gage factor of a strain type transducer is dependent upon the resistivity of the silicon crystal which in turn is directly dependent on the majority carrier concentrations and majority carrier mobilities.

The gage factor is

$$G.F. = \frac{\Delta R}{R \Delta \epsilon}$$

IV, A, Radiation Compatibility of Materials (cont.)

where R is the no-strain resistance of a material, ΔR is the change in resistance caused by a strain of $\Delta \epsilon$ microinches per inch. The resistance of a material is given by $R = \rho \frac{L}{A}$, where ρ is the resistivity and L and A are length parallel to current flow and cross-sectional area respectively. In semiconductors the changes in resistance are principally due to a change in resistivity.

The resistivity of either n-or p-type silicon is very sensitive to changes in carrier concentration. Radiation of the crystal causes the resistivity to vary directly as carrier concentration.

Chavin et. al (6), stated that radiation flux levels of 10^{12} n/cm² and 10^7 ergs/g(C) could be reached before pronounced changes would be evident in silicon strain gage transducers. Changes that can be expected above flux levels of 10^{13} n/cm² and 10^8 ergs/g(C) will preclude the semiconductor from further operation.

Cole (8) reported changes in resistivity of n-type silicon exposed to 5×10^{15} neutrons/cm² at 100°C. A specimen with pre-irradiation resistivity of 0.02-.03 ohm-cm had post-irradiation resistivity of 3000-3500 ohm-cm. The irradiation took place in an oxygen atmosphere. The pre-irradiation resistivity of a sample exposed in vacuum was 0.3-0.4 ohm-cm. After irradiation the resistivity was 4000 - $>10,000$ ohm-cm.

The elastic constants of single crystal silicon have been found to have been changed by the thermal neutron irradiation (3×10^{19} nvt) (3). Striking changes were observed in the values of C_{11} and C_{12} .

The temperature of the lattice exerts an influence on the damage process or any healing which may go on at the same time. A lower damage rate for electron-bombarded silicon has been observed for samples irradiated at lower temperatures (down to 10°K) (4). The effect of lower damage rates with lower irradiation temperature is also summarized in Ref 9.

2. Auxiliary Materials

The auxiliary materials are considered to be compatible with the radiation environment in which they will be exposed. The materials will become activated, which for the purposes of post-irradiation examinations are important. Silicon and phosphorus both absorb thermal neutrons and emit gamma rays with energy as high as 10.5 Mev. (5). The heating effect of the secondary gammas was computed to be negligible compared to primary gamma heating. Such energetic rays however, could contribute to radiation damage to the crystal itself.

The instrument specifications are such that the melting point of soft solder is not applicable.

IV, Analysis (cont.)

B. GAMMA HEATING EFFECTS IN 810C TRANSDUCER

Absorption of gamma energy in the crystal sensor of the transducer will cause heating which, if not properly dissipated, can adversely effect the operation of the transducer.

The temperature limits of the 810C are stated by the manufacturer as follows: "Operation over any preselected 100°F span between -320°F and +165°F will produce a maximum thermal calibration shift of $\pm .5$ percent full scale."

In addition to this limitation is the fact that if placed in an intense radiation field with no protection, the unit can be destroyed by intense heating.

Dimensions of the transducer elements were not furnished by the manufacturer and estimates of gamma heating rates were made by scaling a pressure assembly drawing. The cylindrical silicon crystal was assumed to be 0.4" high and 0.45" diameter, with a weight of 2.52g.

Gamma ray absorption is considered as the main source of heating within the silicon crystal, and evaluations were based on the GTR reactor spectrum. The effects of two values of exposure rates were considered - .18 ergs/g(C) sec-watt and 1.8 ergs/g(C) sec-watt. The former value corresponds to the gamma dose rate on the 10" line (distance from reactor closet) of North face of GTR. At three megawatts power, the exposure rates are 4.8×10^5 ergs/gm(C)-sec and 4.8×10^6 ergs/gm(C)-sec, respectively.

The above values represent the energy absorption rate of silicon, inasmuch as in the GTR reactor the ratio of energy absorption of carbon to that of silicon is unity. (7)

Using the conversion $1 \text{ BTU} = 1.055 \times 10^{10}$ ergs and taking specific heat of silicon $0.2 \text{ BTU/lb-}^\circ\text{F}$ or $4.4 \times 10^{-4} \text{ BTU/gram-}^\circ\text{F}$, the rates of temperature increase in the crystal with no energy dissipation from it are 372°F/hr and 3720°F/hr

These values indicate the need for consideration of energy dissipation from the crystal. The method by which the crystal can lose heat energy are by radiation from its surface, conduction into the bulkhead at its base, and free convection into the space around the crystal. A detailed transient analysis of the heating rate of the crystal would be necessary to establish temperatures from combined effects; however, separate considerations of each effect lead to guidelines of exposure limitations for the transducer.

IV, B, Gamma Heating Effects in 810C Transducer (cont.)

If the temperature of the crystal is to remain constant the heat input to the crystal must be equal to the heat dissipation.

1. Radiant Heat Transfer

The maximum amount of heat dissipated by radiation is when the surface is a perfect radiator ($\epsilon = 1$) emitting to a medium at zero absolute. This will not be the true situation for the transducer crystal because the steel shroud will also absorb radiation which must be considered in a detailed analysis.

$$WQ = \epsilon \sigma T^4 A$$

$$= \text{Stefan - Boltzmann Constant} = 5.71 \times 10^{-5} \text{ ergs/sq cm-sec-(}^\circ\text{K)}^4$$

$$A = 3.64 \text{ cm}^2 = \text{emission area of crystal}$$

$$Q = 4.8 \times 10^5 \text{ ergs/gram - second, and } 4.8 \times 10^6 \text{ ergs/gram-sec}$$

$$W = \text{weight of crystal} = 2.52\text{g.}$$

The temperature of the crystal at which equilibrium will be achieved is:

$$T_{^\circ\text{K}} = \left[\frac{WQ}{\sigma A} \right]^{0.25}$$

The values of T obtained by this expression are 276°K and 491°K for the respective heating rates.

With the above assumption, it is seen that heat dissipation from the crystal by radiant heat transfer will balance the gamma heating rate when the crystal reaches 36°F and 423°F for the assumed exposure rates under perfect radiating conditions.

2. Convective Heat Transfer

A simplified expression for the free convection heat transfer coefficient from a vertical plate is given by:

$$h_c = 0.28 (\Delta t/L)^{0.25} \text{ BTU/hr-sq ft - } ^\circ\text{F (8)}$$

where t = temperature differential between surface and fluid and L = vertical height, feet. The total heat, Q , dissipated by convection is $Q = h_c A t = 0.28 (\Delta t)^{1.25} \times (1/L)^{0.25} A$.

IV, B, Gamma Heating Effects in SLOOC Transfer (cont.)

For the heating rates previously considered; i.e., 4.8×10^5 ergs/gram-sec and 4.8×10^6 ergs/gram-sec, the conversions to corresponding units are 4.8×10^5 ergs/gram-sec $\times \frac{1 \text{ BTU}}{1.0548 \times 10^{10} \text{ erg}} \times \frac{2.52 \text{ g/cm}^2}{3.64} \times 3600 \text{ sec/hr} \times (30.48)^2 \text{ cm}^2/\text{ft}^2$

$$Q/A = 106 \text{ BTU/hr-ft}^2$$

To maintain this dissipation rate by free convection, the temperature differential between the crystal and the enclosing gas will be 59°F and 370°F for the respective dose rates. It is obvious that free convection cannot be counted upon to keep the crystal within operable temperature limits at the higher dose rate. Free convection will be effective for the lower exposure rate only if the temperature gradient between crystal surface and the surrounding gas is 59°F or greater. Whether this is so depends upon the temperature gradient between the gas and steel transducer casing which in turn depends upon the ambient conditions of the transducer as well as the casing heating rate.

2. Conclusions

The conclusion reached without conducting more detailed analysis is that combined radiation and convection effects will probably allow the transducer to operate in gamma radiation fields up to 4.8×10^5 ergs/gm(C)-sec. For tests or operation in more intense fields, the effect of radiation heating should be thoroughly analyzed and methods of shrouding or cooling the transducer should be devised. The NFRVA tolerance limit of instruments is prescribed as 2.5×10^7 ergs/gm(C)-sec.

Summary of Simplified Heat Transfer Analyses

Gamma	Equilibrium	Temperature Difference
Exposure Rate	Radiation Temp.	For Free Convection Equilibrium
ergs/gm(C) Sec	°F	t, °F
8×10^5	36	59
4.8×10^6	423	370

* 10" line of North face GTR reactor

IV, B, Gamma Heating Effects in 810C Transfer (cont.)

At an exposure rate of 4.8×10^5 erg/gram(C)-sec the expected life-time of the transducer would be less than 4 minutes if 10^8 ergs/gram(C) is the maximum dose from the electrical resistivity consideration.

C. INDUCED RADIOACTIVITY

Induced radioactivity was evaluated by the expression

$$A = nv_0 \sigma_{a0} N(1-e^{-\lambda t})F$$

where $A = \lambda N_a(t)$, disintegrations/sec

nv_0 = thermal neutron flux, $n/\text{cm}^2\text{-sec}$

σ_{a0} = activation cross section of a particular isotope

F = isotopic abundance percentage/(100)

N = number of nuclei in sample

$$\left(\text{Nuclei}/\text{cm}^3 \times \frac{1}{\rho} \times w \right)$$

ρ = density, g/cm^3

w = mass of sample

In the 810C transducer most of the induced activity is contributed by the components of type 304 Stainless Steel. The principal components are given in the following table. The activities were based on the assumption of 121 grams of SS in the transducer. The following table summarizes the computed activities at the end of a 100-hour GTR test with a thermal neutron flux of 9×10^9 $n/\text{cm}^2\text{-sec}$.

Induced Activities in 810C Transducer

<u>Material</u>	<u>Grams</u>	<u>Curies</u>
Fe	85	1.3×10^{-4}
Mn	2.4	8.6×10^{-2}
Cr	24.2	3.9×10^{-3}
Ni	1.2	5.6×10^{-4}
Si (Crystal)	2.5	4.4×10^{-5}

V. PROPOSED TESTS FOR IRRADIATION EVALUATION

The manufacturer has proposed that measurements to determine the sensing device operating characteristics in radiation fields include the measurement of bridge impedance and bridge sensitivity under various dosages of radiation exposure, at various operational temperatures required for sensor. This will allow an error analysis to be made of Model 810C.

The transducers should be exposed in a flux low enough so that their lifetimes are long enough to plot accurately their performance as a function of exposure.

A knowledge of the radiation heating of the transducer is important if it is to be used in the presently specified NERVA environment for functions that require relatively long operational stability. This probably will not be determined in irradiations at GTR because of the low flux rate.

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