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SUBJECT: POSSIBLE RADIATION DAMAGE TO THE STATOR WINDINGS
OF THE HRT CIRCULATING PUMP

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POSSIBLE RADIATION DAMAGE TO THE STATOR WINDINGS
OF THE HRT CIRCULATING PUMP

1

CF-57-4-80Summary

A study of the degree and effects of radiation damage to the motor windings of the HRT 400-A canned rotor circulating pumps has been made. Based on the Way-Wigner equation for gamma emission of the fission products and the detail drawings of the 400-A pump and motor, the gamma flux was estimated at the stator windings.

With this gamma flux and the available radiation damage data, the effective life of the stator windings was estimated to be about one year, for normal operation of the pump and motor. If the purge flow fails or the purge lines become contaminated with hot soup solution, the lifetime of the windings may be only one month.

In addition the silicone resin will evolve hydrogen gas at a rate which has been calculated to be 0.62 ml/hr. At this rate a pressure of about two atmospheres due to hydrogen gas will develop in the stator can within one year. This pressure is greater than the stator can will support. A vent is required to remove this gas accumulation.

With the exception of polystyrene and phenol formaldehyde with an asbestos filler (Haveg 41) all plastic materials may be expected to fail within the dose range of $5 - 10 \times 10^8$ rads. Fortunately inorganics do not have this limitation. Published estimates give mica and ceramic insulations approximately 1000 times longer life in radiation than the organics. The use of these in future motors would effectively remove all likelihood of radiation damage to those portions of the motor where they are used.

Calculation of Gamma Source Strength at the Motor Windings

The rate of emission of gammas from fission product decay can be estimated using the Wigner-Way equation.⁹

$$\text{Rate of gamma emission} = 1.9 \times 10^{-6} t^{-1.2} \left(\frac{\text{photons}}{\text{sec-fission}} \right)$$

t = time after fission, days .

With this relation the source strength as a function of time after startup and time to shut down is given as:

$$S = 2.546 \times 10^{10} p \left[(\tau - T_0)^{-0.2} - \tau^{-0.2} \right] \left(\frac{\text{photons}}{\text{sec}} \right)$$

T_0 = time to reactor shutdown, days

τ = time after startup, days

p = reactor power level, watts

In the present HRT the approximate time required for the soup to reach the circulating pump from the reactor is 10 seconds. Thus for a system volume of 500 liters and a power level of 5 Mw, the gamma power density at the circulating pump is:

$$S_d = 1.56 \times 10^{12} \text{ photons/sec-cm}^3$$

The liquid holdup of the 400-A circulating pumps has been estimated to be 4900 cm³.¹¹

The gamma source in the pump can be best estimated as a disk having a diameter equal to that of the impeller. The source strength of this disk is then:

$$S_A = \frac{1.56 \times 10^{12} \times 4.90 \times 10^3}{\frac{\pi}{4} D^2}$$

D^2 = diameter of impeller $\equiv 13.5''$

$$\therefore S_A = 8.28 \times 10^{12} \text{ photons/sec-cm}^2$$

The flux at a point P_2 from a disk source of radius R_0 is given by:¹⁰

$$\phi = \frac{BS_A}{2} \left[E_1(b_1) - E_1(b_1 \sec \theta) \right] K \left(\frac{d}{R_0}, \frac{a}{R_0}, \bar{\mu} R_0 \right)$$

$$\bar{\mu} = \frac{\sum \mu_i t_i}{\sum t_i}$$

(The use of this equation is shown in Reactor Shielding Design Manual, p. 348)

Assuming somewhat different paths for the gammas, three cases were calculated to determine the gamma flux at the lowest portion of the motor windings. The average of these cases is used as a reliable estimate of the

gamma flux striking the motor windings. This gives $\phi_\gamma \cong 6.0 \times 10^{10}$ photons/sec-cm² at the motor windings for normal operation of the 400-A circulating pump.

In the event of purge pump stoppage or a thermal barrier failure the pump purge system will become contaminated with hot fuel solution. In this case the motor windings will be exposed to a nearly unattenuated gamma source. At the windings this source can be best represented as a cylinder having the dimensions as shown. At P_2 the gamma flux can be represented by:¹⁰

$$\phi_\gamma = \frac{BS_v R_o^2}{2(a + Z)} F(\theta, b)$$

(The use of this equation is shown in Reactor Shielding Handbook, p. 360)

For the case sketched above the flux at the motor windings will be:

$$\phi_\gamma = 1.4 \times 10^{12} \text{ photons/sec-cm}^2$$

Effect of Such a Gamma Flux on the Present Motor Windings

The windings in the 400-A pumps consist of No. 18 (0.040" diameter) copper wire, insulated with two layers of glass adhesive tape and triple dipped in silicone varnish. The terminal-to-winding wires are insulated with silicone rubber—fiberglass topping. It is estimated that the total length of this type wire does not exceed 2 feet. The stator lamination insulation punchings are made of fiberglass cloth bonded with silicone resin. The estimated volume of this laminated material in each pump is 31 cubic inches.¹¹

A search of the published literature on radiation damage to electrical insulating materials yielded the following summary of information available on silicone varnished glassfibers:

5

Material	Flux	Remarks	Source
1 Wire			
Silicone varnished glassfiber (9989 var.)	a) 10^{18} nvt of 1.6 Mev γ 's b) 10^{18} of 1.6 Mev γ 's 4.6 - 8.0 x 10^8 rads 10^{18} nvt of 1.6 Mev γ 's	<div style="display: flex; align-items: center;"> <div style="margin-right: 10px;">{ (6.9 x 10^8 rads)</div> <div> <p>Showed little or no damage. Insulation resistance changed from 10^2 to 9×10^3 megohms. Showed no visual change. Brittle, hard, easily torn.</p> </div> </div>	Narf-54-1T ³ KAPL-731 ⁷ Apex-172 ²
2 Silicone (rubber) Coated glass cloth			
3 Quadruple formex Varnished wire and formex Varnished double glassfiber wire (9555 var.)		Showed a light color change.	KAPL-731 ⁷
4 Silicone varnished Coated glassfiber	3.0 x 10^7 Roentgens	No serious change in electrical conductivity. No physical changes noticed.	ANL-OCS-75 ¹²
5 Asbestos, Silicone Resin (GE-76801)	1.1 - 2.0 x 10^8 rads	No apparent damage.	Apex-172 ²
6 Motor lead wire plastic covered	4.4 - 7.7 x 10^8 rads	Insulation broke easily.	Apex-172 ²
7 Silicone varnished glass Laminate and Silicone glass tape	10^{18} nvt from graphite pile at X-10 10^{18} nvt = 6.0 x 10^8 rads)	<p>Resistivity dropped from 10^{14} to 10^7 ohm-cm.</p> <p>Tensile strength increased 10%, shear strength decreased 5%, hardness increased 5%, specific gravity increased 5%. 7 ml/gr 10^{18} nvt of gas evolved.</p>	ORNL-1373 ⁶

From this table an estimate of the energy absorption from reactor radiations required to place in serious doubt the physical or electrical integrity of the silicone varnished glass laminate can be made. Primarily from the data of ORNL-1373 which show the resistivity of the insulating material dropping from 10^{14} to 10^7 ohm-cm (a change essentially from a very good insulation to a poor conductor), a dose limit of 6.0 to 10^8 rads is taken as the point at which the motor may fail. The report also states that $7 \text{ ml/gr} \cdot 10^{18}$ nvt of H_2 gas will be evolved.

The data show that if the resistivity were not decreased to such an extent the insulation would probably absorb three times as much energy before the physical properties would limit the integrity of the insulation.

The gamma flux at the motor windings was estimated to be 6×10^{10} gammas/sec-cm² for normal operation of the pump and 1.4×10^{12} gammas/sec-cm² if concentrated fuel solution is allowed to be in the purge lines.

The energy absorption rate in rad/hr can be represented as:

$$E_{\text{abs}} = \phi_{\gamma} \mu_e E_{\gamma} J \left(\frac{\text{rad}}{\text{hr}} \right)$$

$$\phi_{\gamma} = \text{gamma flux, gammas/sec-cm}^2$$

$$\mu_e = \text{energy absorption coefficient for gammas of energy } E_{\gamma}, 0.029 \text{ cm}^2/\text{gr}$$

$$E_{\gamma} = \text{gamma energy, 0.7 Mev}$$

$$J = 5.767 \times 10^{-5} \frac{\text{rad-gr-sec}}{\text{Mev-hr}}$$

For $\phi_{\gamma} = 6 \times 10^{10}$ gammas/sec-cm², the energy absorption rate is:

$E_{\text{abs}} = 7.02 \times 10^4 \frac{\text{rad}}{\text{hr}}$. With the total allowable dose of 6.0×10^8 rads, the time required for a possible failure of the motor is:

$$t = \frac{6 \times 10^8 \text{ rads}}{7.02 \times 10^4 \text{ rad/hr}} = 8547 \text{ hrs. or 356 days}$$

If ϕ_{γ} were allowed to be 1.4×10^{12} , the energy absorption rate is $E_{\text{abs}} = 1.64 \times 10^6 \text{ rad/hr}$. The time required for a possible failure of the

motor in this case is:

$$t = \frac{6.0 \times 10^8 \text{ rads}}{1.64 \times 10^6 \text{ rad/hr}} = 366 \text{ hr or 15 days}$$

The data from Apex-172 seem to show that a silicone rubber coated glass cloth becomes brittle, hard, and easily torn for exposures of $4.0 - 8.0 \times 10^8$ rads. Since this is essentially the insulation of the terminal-to-winding lead wire it is expected that it would also exhibit these changes, and the motor may be shorted from this source at comparable times as estimated for the stator windings.

In addition to a general breakdown of the electrical and physical properties the actual chemical structure of organic materials is degraded by the energy absorption. This degradation is always accompanied by hydrogen gas evolution. For the silicone varnished laminated glass insulation the gas production is $7 \text{ ml/gr} \cdot 10^{18} \text{ nvt.}^6$ This is equivalent to $7 \text{ ml/gr} \cdot 6 \times 10^8$ rads.

The gas production rate may be represented by:

$$P_d = \frac{7 \text{ (ml)} V E_{\text{abs}}}{(\text{gr}) 6 \times 10^8 \text{ (rads)}} \left(\frac{\text{ml}}{\text{hr}} \right)$$

$$= 1.17 \times 10^{-8} V E_{\text{abs}}$$

V = volume of silicone glass insulation, cm^3

E_{abs} = energy absorption rate

$= 7.02 \times 10^4 \text{ rad/hr}$ for normal operation

$= 1.64 \times 10^6 \text{ rad/hr}$ if purge fails

Thus: $P_d = 0.62 \frac{\text{ml } H_2}{\text{hr}}$ for $E_{\text{abs}} = 7.02 \times 10^4 \frac{\text{rad}}{\text{hr}}$

$P_d = 14.5 \frac{\text{ml } H_2}{\text{hr}}$ for $E_{\text{abs}} = 1.64 \times 10^6 \frac{\text{rad}}{\text{hr}}$

The estimated gas volume around the windings is approximately 3600 cm².
 The average temperature expected in this section of the motor is 50°C.
 Using the perfect gas law, the pressure developed in the stator can be represented as:

$$P = \frac{p_d \rho t R T}{M V} \quad (\text{atm})$$

p_d = gas production rate, ml/hr

ρ = density of hydrogen at STP, gr/cm³

M = molecular weight, gr/gr mole

V = volume of gas space, cm³

R = gas constant, 82.057 $\frac{\text{cm}^3 \cdot \text{atm}}{\text{gr mole } ^\circ\text{K}}$

T = temperature, °C

t = hours of exposure to radiation .

For $p_d = 0.62$ ml/hr, $p(\text{atm}) = 2.05 \times 10^{-4} t$. Assuming no leakage from the stator can and an exposure time of 366 days the pressure developed due to hydrogen gas generation is nearly 2.0 atm.

The effect of this pressure on the stator can be quickly estimated.

The dimensions of the can are as follows:

Length of can = 16 in.

Inside diameter of can = 4.716 in.

Thickness of can = 0.020 in.

Gap between stator can and rotor can = 0.020 in.

If it could be assumed that the can would not buckle, the expected deflection

of the can would be:

$$\sigma = \frac{pr}{t} = \frac{29.4 \text{ (psi)} 2.359}{0.02}$$

$$= 3466 \text{ psi}$$

$$\sigma = E \frac{\Delta r}{r}$$

$$\Delta r = \frac{\sigma r}{E} = \frac{3466 \times 2.358}{30 \times 10^6}$$

$$= 0.000272 \text{ in.}$$

Since the water gap is 0.020 inch, the danger due to a simple deflection with no buckling of the can is negligible.

Using the ASME Code (Section 8, Subsection A, Part UG-28, page 8, Thickness of Shells Under External Pressure) the effect of buckling can be taken into account.

With, t = minimum required thickness of shell
 L = length of vessel section
 D_o = O.D. of shell
 p = external design pressure .

Using the suggested chart, Figure UHA-282, page 151:

$$\frac{D_o}{t} = \frac{4.716}{0.02} = 236$$

$$\frac{L}{D_o} = \frac{16.0}{4.716} = 3.5 .$$

From the Figure:

$$B = 1400 = \frac{pD_o}{t}$$

$$p = \frac{1400}{236} = 5.9 \text{ psi}$$

There is probably a safety factor of three or four built into these graphs, but they definitely show that the can is quite likely to buckle and thus bind the rotor for pressures of less than 2 atm.

Some Observed Motor Failures

There have been several well documented cases of motor failure due to reactor radiation. The conditions and results of these tests are tabulated below:

Motor Type	Environment	Exposure Time	Temperature	Observations and Method of Failure
Jet Fuel Metering 27 volt D.C.	$5 \times 10^{11} n_t$ $5 \times 10^{10} n_f$ $5 \times 10^{11} \gamma$	30 hrs.	80°	During latter 15 hrs. the current and revolution rate varied considerably. After 30 hrs, motor stopped. Rotor appeared undamaged but plastic brush mounting was embrittled.
1000 rpm, 115 v, 60 cycle, single phase induction	$10^{12} n_t$ $6.5 \times 10^{11} n_f$ $5 \times 10^{11} \gamma$	64.5	175°F	Motor operated satisfactorily at end of exposure. From condition of insulation in windings it was estimated that the useful life of the motor was shortened by 20%.
115 v, 400 cycle A.C.	$10^{12} n_t$ $6.5 \times 10^{11} n_f$ $5 \times 10^{11} \gamma$	130	80°F	After 100 hrs. the field current was 1-1/2 times the normal value. After 130 hrs. the current had doubled and the motor ceased operating. The field coils had shorted and could not turn the rotor. The rotor was practically unchanged.

In addition to the listed samples similar reports can be found in Apex-172.

Conclusions

Nearly all plastic materials which can be used for electrical insulation become highly liable to failure within the dose range of 5 to 10×10^8 rads. The exceptions to this seem to be polystyrene and phenol formaldehyde with an asbestos filler (Haveg 41) which can be expected to retain their properties up to about 5×10^9 rads.

The specific insulation silicone resin, fiberglass tape, used in 400-A canned rotor pumps is expected to remain serviceable up to about 6×10^8 rads which will be about one year at expected operating conditions and with no soup in the purge stream. If concentrated soup solution is allowed in the purge stream the motor may fail within one month. The specific property of the insulation which deteriorates within this period is the electrical resistivity which drops from 10^{14} to 10^7 (essentially from a good insulator to a poor conductor). The physical properties of the insulation (tensile strength, hardness, etc.) would be expected to remain serviceable up to about 2×10^9 rads, which for the above-named conditions would give expected motor lifetimes of three years and 3 months, respectively.

There will be hydrogen gas evolution due to radiation damage to the silicone resin in the stator can. A production rate has been found by Sisman and reported in ORNL-1373 as 7 ml/gr- 6×10^8 rads. With the radiation levels expected in the stator can this yields a gas production rate of at least 0.62 ml/hr. If there is no gas leakage from the stator can, an exposure time of one year will develop a hydrogen gas pressure of about two atmospheres. A pressure this great is higher than the stator can will support.

It has been estimated² that the use of inorganic compounds (ceramics, mica, etc.) rather than organics will increase the estimated service life of electrical insulating materials by a factor of 1000.

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