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Westinghouse Astronuclear Laboratory

**SHIELDING ELECTROMAGNETIC PULSES BY USE
OF MAGNETIC MATERIALS**

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ABSTRACT

An experimental verification of previous theoretical work on the diffusion of saturated regions in magnetic materials has been accomplished. The diffusion times for the saturated region in Hipernom[®] tubes have been measured for various magnetic field excitations and pulse durations. The calculated and experimentally obtained diffusion times are in excellent agreement. Excitation pulse currents up to several thousand amperes have been impressed on the test samples which varied in thickness from 5 to 18 mils. Saturation diffusion times for a 6 mil tube varied from 6 to 0.3 μ sec. depending on the impressed magnetic field amplitude as predicted by the theory. Prior to punch through of the saturated region, little or no magnetic field leakage was detected in the interior of the test samples.

[®] Hipernom is the Westinghouse Registered Trademark for a 79 percent nickel, 4.5 percent molybdenum, remainder principally iron, magnetic alloy.

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SECTION 1

INTRODUCTION

The theory of diffusion of saturated regions into a magnetic material under high level pulse excitation was presented by Dr. F. J. Young at the 1968 EMC symposium.¹ The work reported here is an experimental verification of the previous theoretical work. In particular, the saturation diffusion time for specific magnetic material tubes has been measured at various driving pulse currents. Tubes of Hipernom[®] and other magnetic and non-magnetic materials have been subjected to capacitor discharge current pulses in the 100 to 10,000 ampere range while measuring their attenuation to the applied current by the conducted current method. In this method, the primary capacitor discharge current is forced to flow on the outer surface of the tube and the leakage is measured by the signal observed on a wire run through the interior of the tube and shorted to it at the driving point. The output signal is obtained between the center wire and the tube at its opposite end.

The pulse current levels applied were large enough in all the cases to saturate at least a thin near surface layer of the magnetic materials and pulse levels were varied over a wide enough range to be able to completely saturate through the material on the larger pulses. The shielding observed remained quite high for all cases where the saturation did not penetrate through to the inner surface of the magnetic material. In those cases where the current-time integral was large enough to drive the saturation through the tube, the signal observed on the center wire remained small until the saturation began to penetrate through to the interior. The signal then rose sharply indicating a rapid increase of field inside the tube. It is this saturation diffusion time which has been measured, compared with the theory, and comprises the data reported in this paper.

[®] Hipernom is the Westinghouse Registered Trademark for a 79 percent nickel, 4.5 percent molybdenum, remainder principally iron, magnetic alloy.

¹ F. J. Young, "Ferromagnetic Shielding Related to the Physical Properties of Iron", 1968 IEEE Electromagnetic Compatibility Symposium Record, July 1968 (IEEE 68012-EMC) pages 88-95.

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SECTION 2

THEORY AND BACKGROUND DISCUSSION

The shielding provided by non-magnetic electrical conductors is relatively well understood and consists of a reflection at the air-metal interface and an exponential attenuation with distance into the material with magnitude decreasing by 1/3 (8.7 dB) for every skin depth penetration into the conductor. Magnetic materials, on the other hand, have additional attenuation factors due to not only their ability to store energy in the magnetic field produced in tracing a path along a B-H (magnetic flux vs magnetizing force) curve to saturation for a portion of the material near the surface facing the impinging wave, but also to their high permeability in the unsaturated region greatly decreasing the characteristic skin depth.

A current flowing on a wire or a tube sets up a TEM (transverse electric and magnetic) field. Using cylindrical coordinates, the E-field is oriented in the z direction (along the axis of the wire) and the H-field is oriented in the θ direction (circumferential). At the outside boundary of the tube, the H field both inside and outside the surface is given by the relationship

$$H_s = \frac{I}{2 \pi r} \quad (\text{amp turns/m}) \quad (1)$$

where I is the current flowing and r is the tube radius in meters. If the tube is a magnetic material, the near surface region will begin to saturate if H_s exceeds H_c , the material coercive force. If the current is considered as a step function or a square pulse, there will be a characteristic diffusion time for the saturated wave front which is given by

$$\tau_d \simeq \frac{B_s^2 d^2}{2 H_c^2} = \frac{\pi r \sigma B_s^2 d^2}{I^2} \quad (\text{seconds}) \quad (2)$$

where B_s is the saturation magnetization in W/m², τ_d is the diffusion time, σ is the material conductivity in mhos/m, and d is the material thickness in meters.

It is also possible to express the saturation in terms of charge in an applied pulse. If it is desired to find the amount of charge required to saturate a given thickness, Equation (2) may be rearranged using $Q = \int_0^t I(t) dt$ or $I \times t$ to yield

$$Q \simeq \pi r \sigma B_s d^2 \text{ (coulombs).} \quad (3)$$

The relationship of saturation depth to surface field or tube current is given by

$$\delta \simeq \sqrt{\frac{2 H_o t}{\sigma B_s}} = \sqrt{\frac{I t}{\pi r \sigma B_s}} \text{ (meters)} \quad (4)$$

where t is the amount of time that the pulse has been applied. Similarly, the saturation depth may be expressed in terms of pulse charge

$$\sigma \simeq \sqrt{\frac{Q}{r B_s}} \text{ (meters)} \quad (5)$$

As an example, choosing a current pulse of 10^3 amperes 0.1 μ sec long, the maximum saturation depth, σ , for a Hipernom tube with a diameter of 2 cm would be

$$\delta \simeq \sqrt{\frac{I t}{r B_s}} = \sqrt{\frac{10^3 \times 10^{-7}}{x 10^{-2} \times 1.6 \times 10^6 \times 0.75}} = 5.15 \times 10^{-5} \text{ m or 2 mils.}$$

For the above calculation, the electrical conductivity of Hipernom, σ , was assumed to be 1.6×10^6 mhos/m and B_s was 0.75 W/m^2 .

At the inner edge of the saturated region, the magnetic field is H_c , the coercive force, regardless of the magnitude of the incident field if we assume an ideal rectangular B-H loop. The unsaturated portion of the magnetic material then further attenuates the field exponentially, decreasing 8.7 dB for each skin depth at each frequency to be considered.

As long as the incident magnetic field is large enough to saturate the magnetic material, the saturated region will continue to propagate inward. When the surface field has dropped below H_c , the inward progress of the saturated region will stop and the field established in the material will decay. That portion of the material which was saturated will follow the B-H curve for the material to the remanent magnetization as shown in Figure 1 and the field in the unsaturated region will decay toward zero.

Figure 1. B-H curve and Cross Section of Magnetic Material

In the case of multiple EM or current pulses of the same orientation or direction, the region which was previously saturated must be once again forced into saturation with the time to accomplish this given by Equation (2) if one uses $(B_s - B_r)$ instead of B_s . The remaining time that the EM pulse is present after resaturating the entire thickness previously saturated goes into driving the saturated region further into the material. A pulse of 1000A, 0.1 μ sec. long will saturate the material to a depth of about 2 mils. If we assume $B_r = 0.5 B_s$ (a good estimate for somewhat cold-worked Hipernom) and $B_s = 0.75 \text{ W/m}^2$, then the occurrence of a second pulse of the same magnitude a short time later will saturate the previously saturated region in a time

$$t = \frac{\pi r \sigma (B_s - B_r) d^2}{I} = 5 \times 10^{-8} \text{ sec}$$

as one would expect. The remainder of the time that the EM pulse is applied ($5 \times 10^{-8} \text{ sec}$) would then drive the saturated region in a total distance given by

$$\delta_1 \approx \sqrt{\frac{10^{-7} + 5 \times 10^{-8}}{10^{-7}}} \times 5.15 \times 10^{-5} \text{ m}$$

$$= 6.32 \times 10^{-5} \text{ m or 2.5 mils.}$$

For additional pulses, the above process may be repeated until the material either saturates all the way through or the subsequent pulses merely cause the previously saturated region to be driven from B_r to B_s . In the case discussed above ($B_r = 0.5 B_s$ and $I \times t = 10^{-4}$ coulomb), the maximum Hipernom thickness which can ever be saturated for a 2 cm diameter tube is

$$\delta = \sqrt{\frac{I t}{\pi r \sigma (B_r - B_s)}} = 7.28 \times 10^{-5} \text{ m or 2.9 mils.}$$

As a result of the above discussion, it may be seen that much of the intrinsic EMP shielding capability of a magnetic material comes from its ability to saturate in the near surface region thereby preventing any fields greater than H_c from penetrating the inner edge of the saturated region regardless of the magnitude of the driving pulse. If a field of $H_s = 10^4$ ampere turns/m (125 Oersteds) impinges, that appearing just inside the saturated region is H_c or 0.01 Oe for annealed Hipernom. Thus, the saturation mechanism alone is providing more than 80 dB of shielding in this case. The remaining unsaturated material can then provide much more shielding which makes the magnetic material a far superior shield as compared to non-magnetic materials.

Considering the above-applied maximum field and assuming a frequency of 10 MHz, we may now calculate, as an example, the theoretical shielding provided by a 4 mil (0.01 cm) thick solid Hipernom tube of one cm radius. The maximum saturation depth is determined by the $\int I(t) dt$ or the $I \times t$ product as before, but this integral must be determined over a 1/2 cycle period. This is assuming that the RF signal is suddenly applied so that the maximum saturation occurs on the first applied half cycle. The next half cycle will cause saturation in the opposite direction, but since the total magnetization change in so doing is $2 B_s$,

the region of negative direction saturation will be $\frac{1}{\sqrt{2}}$ thinner thereby leaving a small region of the originally saturated material at B_r . This region will remain at B_r and will see an approximately square wave magnetic field alternating between + and - H_c at the boundary between it and the alternating saturated region. This alternating field then diffuses in through the remainder of the material being attenuated considerably in both the unsaturated material and the material remaining at B_r . This thin region at B_r may be neglected if one desires a conservative attenuation number since it is difficult to set a value for the incremental permeability in this region.

$I \times t$ for a half cycle at 10 MHz with $I_{\max} = 10^3$ amps can be determined using $I_{\text{avg}} = 0.63 I_{\max}$ with t being 5×10^{-8} sec. Thus, with $I_{\max} = 10^3$ amps, the product of $I \times t$ is $1.63 \times 10^3 \times 5 \times 10^{-8} = 3.15 \times 10^{-5}$ coulomb. The maximum saturation depth in Hipernom may be found by use of Equation (3).

$$\begin{aligned} \delta &= \sqrt{\frac{I t}{\pi r \sigma B_s}} \\ &= \sqrt{\frac{3.5 \times 10^{-5}}{\pi \times 10^{-2} \times 1.6 \times 10^6 \times 0.75}} \\ &= 2.9 \times 10^{-5} \text{ m or } 1.38 \text{ mils.} \end{aligned}$$

The shielding provided by the saturating region is determined by the ratio of H_s to H_c . Here H_s is 1.6×10^4 amp turns/m or 200 Oersteds. H_c is assumed to be 0.01 Oe thus providing 86 dB of shielding in the saturated region.

The unsaturated Hipernom thickness of 2.6 mils will provide additional attenuation of one Neper (8.68 dB) for each skin depth where the skin depth is given by the relationship

$$d = \sqrt{\frac{2}{\omega \mu \sigma}} \text{ meters} \quad (6)$$

where $\omega = 2 \pi f$ and $\mu = \mu_0 \mu_r$, the permeability of the medium in Henrys/m. At 10 MHz, the attenuation in this unsaturated region is about 1000 dB assuming an average μ_r of about 5×10^4 . Even for badly cold-worked Hipernom where μ_r might be as low as 5000, the attenuation in this region would still be about 300 dB.

There is an additional reflection loss at the inner surface which may vary between zero and 25 dB depending on the ratio of impedances of the two media at the frequency of interest. This loss may be determined by use of tables and equations in Reference 2.

The previous discussion is somewhat academic in nature as applied to shielding by magnetic materials where the total loss calculations are greater than 160 dB. In cases such as this, stray leakage at joints, ground loops, etc. limits the measurable shielding attainable to much less than that theoretically calculated. For example, if a particular joint provides 150 dB attenuation at a given frequency, it makes little difference whether the Hipernom provides 400 or 4000 dB attenuation. The measured attenuation will be related strongly to the joint characteristics and will be limited to the maximum attenuation of the most leaky part of the system.

²S. A. Schelkunoff, "The Electromagnetic Theory of Coaxial Transmission Lines and Cylindrical Shields," Bell System Technical Journal, Volume 13, October 1934, pp 532-579.

SECTION 3

EXPERIMENTAL SETUP AND PROGRAM

A test program was initiated using a capacitor discharge to generate high current pulses to which the test sample was subjected. Figures 2 and 3 show the principal portions of the test setup.

A 0 to ± 30 kV power supply was used to charge the energy storage capacitor through a ten megohm high voltage resistor. The capacitor charging ground return was established through the test sample to the copper enclosure. A spark gap switch was used to discharge the energy in the capacitor through the test sample by suddenly grounding the high voltage end of the capacitor to the copper enclosure. Thus, if the capacitor were charged using a negative power supply output, a positive pulse would propagate down the test sample when the spark gap switch was fired.

The copper enclosure (0.030") serves the purpose of a ground plane and low impedance ground return for the pulse current as well as a shield to prevent excessive spurious signal radiation from the test fixture. The output was obtained by passing the Hipernom tube through the end of the copper box and into the shielded room and taking the output signal between the center wire and the tube. As shown in Figure 3, the readout electronics consisted of a 20 or 40 dB gain pulse amplifier, a 20 or 40 dB attenuator, a matching transformer and a Tektronix 519 oscilloscope. A Tektronix 585 oscilloscope was used in place of the 4013P and 519 when observation times larger than 10 μsec were necessary. The oscilloscope sweep was triggered at the time of the firing of the spark gap switch.

The driving pulse currents were measured with three types of Stoddart wide band RF current transformers modified for high energy pulse use. These were types 91550-1, 91550-3, and 93686-4 having transfer impedances ($V_{\text{out}}/I_{\text{in}}$) of 5 Ω , 0.046 Ω , and 0.075 Ω respectively.

The test setup described above has been used with 0.0014 μF , 0.05 μF or 0.5 μF capacitors installed to provide a larger variation in possible pulse charge. With no series resistance, the current waveshape was oscillatory in nature as shown in Figure 4. A 12 Ω series resistance, however, lengthened the initial discharge such that with the 0.5 μF capacitor, the current pulse was a reasonable approximation to a step function for several microseconds.

Figure 2. Pulse Test Apparatus

Figure 3. Experimental Measurement Setup

Figure 4. Input Current Waveshape with 0.0014 μF Capacitor and No Series Resistance Horiz = 1 $\mu\text{sec}/\text{cm}$ Vert = 600 A/cm

Figure 5 shows such a typical discharge current pulse as picked up by a Stoddart 93686-4 current transformer.

Three nominally 1 inch diameter tubes of Hipernom 2 feet long were tested in this program. Most of the saturation diffusion time data were taken on a six mil thick welded seam convoluted tube which had been annealed after forming. Comparative data were also taken on two 18 mil thick Hipernom tubes, one annealed and the other highly work hardened. Properly annealed Hipernom has a B-H characteristic similar to that shown in Figure 6 while work hardened Hipernom will be greatly degraded in magnetic properties. By comparing the saturation diffusion times on the annealed and unannealed tubes, it was possible to verify that permeability has little effect on the saturation diffusion.

Figure 5. Input Current Waveshape Horiz = 1 μ sec/cm Vert = 600 A/cm

Figure 6. Typical D. C. Magnetization Curve for Hipernom Alloy

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SECTION 4

EXPERIMENTAL RESULTS

The six mil Hipernom tube was subjected to discharge pulses using the 0.0014 and 0.05 μF capacitors at charging voltages from 2 to 20 kV producing peak currents up to 3000A. For charge values below that required for saturation through as given by Equation (3),

$$Q_s \approx \pi r \sigma (B_s - B_r) d^2 \text{ Coulombs,}$$

the leakage signal as measured on the center wire was too small to measure accurately (<5 mV). Thus, the attenuation provided by the material is quite large as predicted. For comparison, a 5 mil brass tube was checked and showed about 4V output for a 400 Amp peak current input pulse which had a 4 MHz ringing frequency. Calculation of the charge required for saturation through a 1 inch diameter, six mil thick demagnetized Hipernom tube ($B_r = 0$) yields $Q \approx 1.13 \times 10^{-3}$ coulomb. Thus, since $Q = CV$, it should take a charging voltage of about 20 kV with the 0.05 μF capacitor to achieve punchthrough of the saturated region. Experimentally, there was evidence of slight saturation punchthrough on this sample at charging voltages above 10 kV. As 20 kV was reached, the saturation became quite pronounced as indicated in Figure 7 by the sharp rise of the waveform at 0.5 microsecond. Some evidence of saturation is seen at lower charging voltages because the Hipernom does not have an idealized rectangular B-H loop but is quite curved along the initial magnetization path as shown in Figure 6. Thus, the saturation edge (the transition from H_c to B_s) is diffuse and ill defined spatially rather than being of zero width as would be the case with an idealized rectangular B-H curve. Considering the diffuse nature of the saturation edge with real magnetic materials, the experimental evidence of saturation at charging voltages between 10 and 20 kV is in excellent agreement with the theory.

The six mil Hipernom tube was next pulsed with the 0.5 μF capacitor through a 12 Ω series resistance to study the correlation between current and saturation diffusion time. The series resistance produced a discharge current waveform of the sort shown in Figure 5 which is reasonably close to a step function during the time that diffusion of the saturated wavefront

Figure 7. Output Signal with Saturation Punchthrough on 0.006" Hipernom Tube
(C = 0.05 μ F Ringing Frequency = 0.7 MHz Horiz = 1 μ sec/cm Vert = 50 V/cm

is proceeding. The current was varied by varying the capacitor charging voltage between 2 and 20 kV yielding peak currents between 180 and 1800 amps. The charge was sufficient with the 0.5 μ F capacitor that saturation punchthrough could be achieved at all voltages from 2 kV upwards. Figure 8 is a typical output signal waveform showing an output signal rise about 2 μ sec after the beginning of the current pulse. For the purpose of comparison with the theory, a point at 50 percent of the peak output signal was chosen as the saturation punchthrough time. It is also interesting to note the 10 percent point as a measure of the beginning of saturation punchthrough.

Data were taken two ways at pulse voltages of 2, 5, 10, and 15 kV. First, a saturation time measurement was made on the first pulse at each charging voltage immediately after having degaussed the tube. This measurement would correspond to the case where the magnetization was switched from 0 to B_s (0.75 W/m^2). A number of pulses were then made at each charging voltage without degaussing the sample between pulses. After 10 or more pulses (the entire sample had been saturated completely and returned to B_r), another set of data was taken which showed a decreased saturation punchthrough time. This is as expected, since by Equation (2) replacing B_s with $B_s - B_r$ reduces τ_d , the diffusion time, proportionately. Table I is a tabulation of the experimental punchthrough times taken both at the 10 and 50 percent signal amplitude points for the degaussed and the saturated conditions. The calculated punchthrough times using Equation (2) are also tabulated for comparison for the case $B_r = 0$ (degaussed) $B_r = 0.25$, and $B_r = 0.5$. Comparing the degaussed data with that calculated for $B_r = 0$, an excellent agreement is shown for all voltages except the 2 kV case. At 2 kV, saturation is just getting through to the inner surface and the curvature of the B-H curve makes it difficult to make a good comparison. For the saturated case, an excellent agreement is shown with the tabulation for if we assume $B_r \approx 0.4 \text{ W/m}^2$ which is a good number for B_r on this material.

One last experiment was aimed at the possibility of such properties as μ and H_c entering into the rate of saturation diffusion. For a rectangular B-H loop material, as seen by Equations (2) and (3), only B_s or $B_s - B_r$ and the conductivity should affect the rate of saturation diffusion. Two identical 18 mil, 1 inch diameter Hipernom tubes were used, one annealed and the other heavily cold worked. The annealed tube has permeability values in

Figure 8. Typical Output Pulse Waveform Showing Saturation Capacitor is $0.5 \mu\text{F}$ with 12Ω series R Horiz = $5 \mu\text{sec/cm}$ Vert = 5 V/cm

TABLE 1

CALCULATED AND MEASURED SATURATION DIFFUSION TIMES FOR A 1 INCH HIPERNOM TUBE

Pulse Voltage (kV)	Average Current (Amps)	Discharge Energy (Joules)	Calculated diffusion times ($B_s = 0.75 \text{ W/m}^2$)			Measured diffusion times			
			$B_r = 0$	$B_r = 0.25 \text{ W/m}^2$	$B_r = 0.5 \text{ W/m}^2$	Degassed Hipernom		Saturated Hipernom	
			$B_r (\mu\text{sec})$	$B_r (\mu\text{sec})$	$B_r (\mu\text{sec})$	$B_r = 0$		$B_r = 0.4 \text{ W/m}^2$	
						10%	50%	10%	50%
2	160	1.0	6.6	4.4	2.2	4	6	2	3
5	400	6.25	2.6	1.76	0.88	2	2.6	1	1.6
10	800	25	1.3	0.88	0.44	1.2	1.45	0.6	0.9
15	1200	56	0.9	0.6	0.3	0.8	0.8	0.4	0.7

the 50,000 to 200,000 region and H_c around 0.01 Oe. The cold worked tube has a permeability in the order of 200 and $H_c > 0.5$ Oe. Both tubes were pulsed using the 0.5 μ F capacitor and a charging voltage of 10 kV which should be near the minimum needed to saturate 18 mils. Slight signal output occurred in the annealed sample at 1.5 μ sec and a similar time was observed for the work hardened sample. This can be interpreted to indicate that if there are any permeability or coercive force effects, they are relatively small. This is also based on the fact that B_s is relatively constant in Hipernom regardless of the amount of work hardening present.

SECTION 5

CONCLUSIONS

We have seen that under conditions where saturation does not penetrate completely through Hipernom, it is a far superior EM pulse or steady state EM field shielding material than an equivalent thickness of non-magnetic conducting material. The attenuation measurements on annealed Hipernom tubes have shown that they are limited by the amount of isolation achievable in the test setup (about 160–180 dB) and the sensitivity of the measurement equipment.

An excellent correlation between calculated and measured saturation diffusion times for Hipernom has also been obtained. In many cases, the theoretical and experimental numbers agree within a few percent and are never further apart than a factor of 2. This is indeed excellent agreement when dealing with such a complex non linear magnetic material and comparing the experimental data with theoretical treatment.

Further, it has been demonstrated that, as predicted by the theoretical treatment, permeability and coercive force are relatively unimportant in the diffusion of saturation in magnetic materials.