voltage. Such overvoltages can puncture insulation and result in additional ground faults. These overvoltages are caused by repetitive charging of the system capacitance or by resonance between the system capacitance and the inductances of equipment in the system.

A second ground fault occurring before the first fault is cleared results in a phase-to-ground-to-phase fault, usually arcing, with current magnitude large enough to do damage, but sometimes too small to activate the overcurrent devices in time to prevent or minimize damage.

Ungrounded systems offer no advantage over high-resistance-grounded systems in terms of continuity of service and have the disadvantages of transient overvoltages, difficulty in locating the first ground fault, and burndowns from a second ground fault. For these reasons, they are being used less frequently today than high-resistance-grounded systems, and existing ungrounded systems are often converted to high-resistance-grounded systems by resistance-grounding the neutral if it exists or, if the system is fed from a delta source, by creating a neutral point with a zigzag or other transformer and then resistance-grounding it.

Once the system is high-resistance-grounded, overvoltages are reduced; and modern, highly sensitive ground-fault protective equipment can identify the faulted feeder on first fault and open one or both feeders on second fault before an arcing burndown does serious damage. One final consideration for ungrounded systems is the necessity to apply overcurrent devices based upon their single-pole short-circuit interrupting rating, which can be equal to, or in some cases less than, their normal rating (see IEEE Std 141-1993).

8.3 Nature, magnitudes, and damage of ground faults

Ground faults on electric systems can originate in many ways, have a wide range of magnitudes, and cause varying amounts of damage. The most serious faults from the standpoint of rate of eroded material are arcing faults, both phase to phase and phase to ground.

8.3.1 Origin of ground faults

Ground faults originating from insulation breakdown can be classified, roughly, as follows:

a) Reduced insulation (e.g., due to moisture, atmospheric contamination, foreign objects, insulation deterioration)
b) Physical damage to insulation system (e.g., due to mechanical stresses, insulation punctures)
c) Excessive transient or steady-state voltage stresses on insulation

Good installation and maintenance practices ensuring adequate connections and the integrity of the insulation of the equipment have a significant effect in reducing the probability of ground faults. However, insulation breakdowns to ground can occur at any point in the system where phase conductors are in close proximity to a grounded reference. The contact between the phase conductor and ground is usually not a firm metallic contact, but rather usually includes an arcing path in air or across an insulating surface, or a combination of both. In addition to these arcing ground faults, certain bolted faults occur, usually during installation or maintenance, when an inadvertent firm metallic connection is made from phase to ground.

8.3.2 Magnitude of ground-fault currents

Ground-fault current magnitudes can vary greatly. Using the method of symmetrical components (see Chapter 2), the single line-to-ground fault current I_{GF} is calculated by the formula:

$$I_{GF} = \frac{3V_{L-N}}{Z_1 + Z_2 + Z_0 + 3Z_G}$$

where

Z_1 is the positive-sequence impedance,
Z_2 is the negative-sequence impedance,
Z_0 is the zero-sequence impedance.
Z_G is the combined impedance of the ground return circuit, including the fault arc impedance, the grounding circuit impedance, and the intentional neutral impedance, when present.

To illustrate how ground-fault currents can vary greatly in magnitude, consider a solidly grounded system with a bolted ground fault close to the generator terminals. In this example, Z_G could approach zero; and, assuming $Z_1 = Z_2 = Z_0$, then,

$$I_{GF} = \frac{V_{L-N}}{Z_1}$$

which is actually the formula for a bolted three-phase fault. In fact, with many generators, because Z_0 is smaller than Z_1, it is necessary to add an intentional neutral impedance Z_N to reduce the bolted ground-fault current to the magnitude of the bolted three-phase fault current.

For a ground fault in a high-resistance-grounded system, the neutral resistance R_N is large compared to Z_1, Z_2, Z_0, and the remainder of Z_G. Then, I_{GF} is approximately equal to $V_{L–N}$ divided by R_N.

For example, in a high-resistance-grounded 480 V system with a neutral resistance of 20 Ω, the ground-fault current is

$$I_{GF} = \frac{480/\sqrt{3}}{20} = 14\ \text{A}$$

This approximation is true because the fault arc impedances and the ground-circuit impedances are negligible when compared to 20 Ω.

Precise calculation of low-voltage ground-fault current magnitudes in solidly grounded systems is much more difficult than the previous example. The reason is that the circuit impedances, including the fault arc impedance, that were negligible in the high-resistance example play an important part in reducing ground-fault current magnitudes. This applies even in most cases where a sizable grounding conductor is carried along with phase conductors.

The primary consideration in applying ground-fault protection is whether a selectively coordinated system can be achieved and, if not, to establish the extent to which lack of selectivity is acceptable.

The two main setting characteristics that need to be determined for ground-fault relays are

- Minimum operating current
- Speed of operation

Selection of the minimum operating current (or pickup) setting is based primarily on the characteristics of the circuit being protected. If the circuit serves an individual load (e.g., a motor, transformer, heater circuit), then the pickup setting can be low, such as 5 A to 10 A. If the protected circuit feeds multiple loads, each with individual overcurrent protection [e.g., a panelboard, feeder duct, motor control center (MCC)], the pickup settings are higher. These higher settings (in the order of 200 A to 1200 A) are selected to allow the branch phase-overcurrent devices to clear low-magnitude ground faults in their respective circuits, if coordination is possible. Furthermore, low-level faults in some parts of the system may be self-extinguishing and, therefore, allow uninterrupted operation of other equipment.

8.3.3 Damage due to arcing faults

The arcing fault causes a large amount of energy to be released in the arcing area. The ionized products of the arc spread rapidly. Vaporization at both arc terminals occurs, and the erosion at the electrodes is concentrated when the arc does not travel. While the arc tends to travel away from the source, this movement does not necessarily occur at low levels of fault current or at higher levels of current in circuits with insulated conductors. If an arcing fault is allowed to persist indefinitely, it is a potential fire hazard, causes considerable damage, may result in a more extended power outage, and subjects nearby employees to burns from arc flash.

Shunt trip fusible switches can be equipped with antisingle-phasing provisions that consist of installing small actuator fuses in parallel with the line fuses in the switch. When a line fuse opens, these fuses also open and subsequently close a contact to actuate a signal or switch-opening circuit to open all three poles of the switch. Figure 8-6 shows this particular scheme, which can also be used in conjunction with ground-fault protective relaying. Other equipment utilizes voltage relays in place of the actuator fuses to trip interrupter switches. These antisingle-phasing devices are often specified to clear a ground fault that may cause only one fuse to open. If the fault remains and is of such high impedance that it does not open any fuses in any other phases, the opening of the first fuse causes all three poles of the switch to open and the fault is cleared.

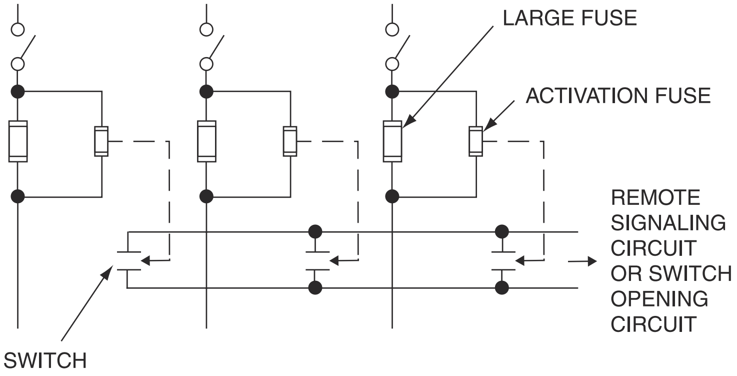

Figure 8-6—Antisingle-phasing provisions for fusible switches

Fused circuit breakers and service protectors, as well as circuit breakers, have antisingle-phasing devices incorporated in their basic designs.

The basic need for ground-fault protection in low-voltage grounded systems is illustrated in Figure 8-7a and Figure 8-7b. A 1000 kVA transformer, with a 1600 A main circuit breaker and typical long-time and short-time characteristics, optionally with a fused switch, is shown.

A 1500 A ground fault (Point I) on the 480Y/277 V grounded neutral system would not be detected by the main circuit breaker or fuse. A ground relay set at 0.2 s time delay would cause the circuit breaker or bolted pressure switch to clear the fault in about 0.33 s. A 4000 A ground fault (Point II) could persist for about 33 s, even if the circuit breaker's minimum long-time band were used. The fuse would require up to 5 min to clear this fault. The ground-relayed circuit breaker or bolted pressure switch would clear the fault in about 0.25 s. An 8000 A ground fault (Point III) would be cleared within about 0.2 s to 0.4 s by the circuit breaker short-time device, assuming it is present; otherwise, between 8 s to 20 s would elapse before the long-time device clears the fault.

Arc energies for these assumed faults are tabulated in Table 8-1. Arc voltages are assumed to be 100 V. Because the arc voltage tends to have a flat top characteristic (nonlinear arc resistance), the energy of the arc in watts per second can be estimated by obtaining the product of the current in rms amperes, the arc voltage in volts, and the clearing time in seconds. Approximate calculation of the energy required to erode a certain amount of electrode material shows that 50 kWs of energy divided equally between conductor and enclosure vaporizes about 2.05 cm^3 of aluminum or 0.82 cm^3 of copper. The calculation assumes that most of the arc energy goes into the electrodes, while the energy lost to the surrounding air is neglected. Comparisons were made from several arcing fault tests (see Conrad and Dalasta [B10]; Fisher [B14]), and good correlation was obtained between calculated energy from test data and measured conductor material eroded.

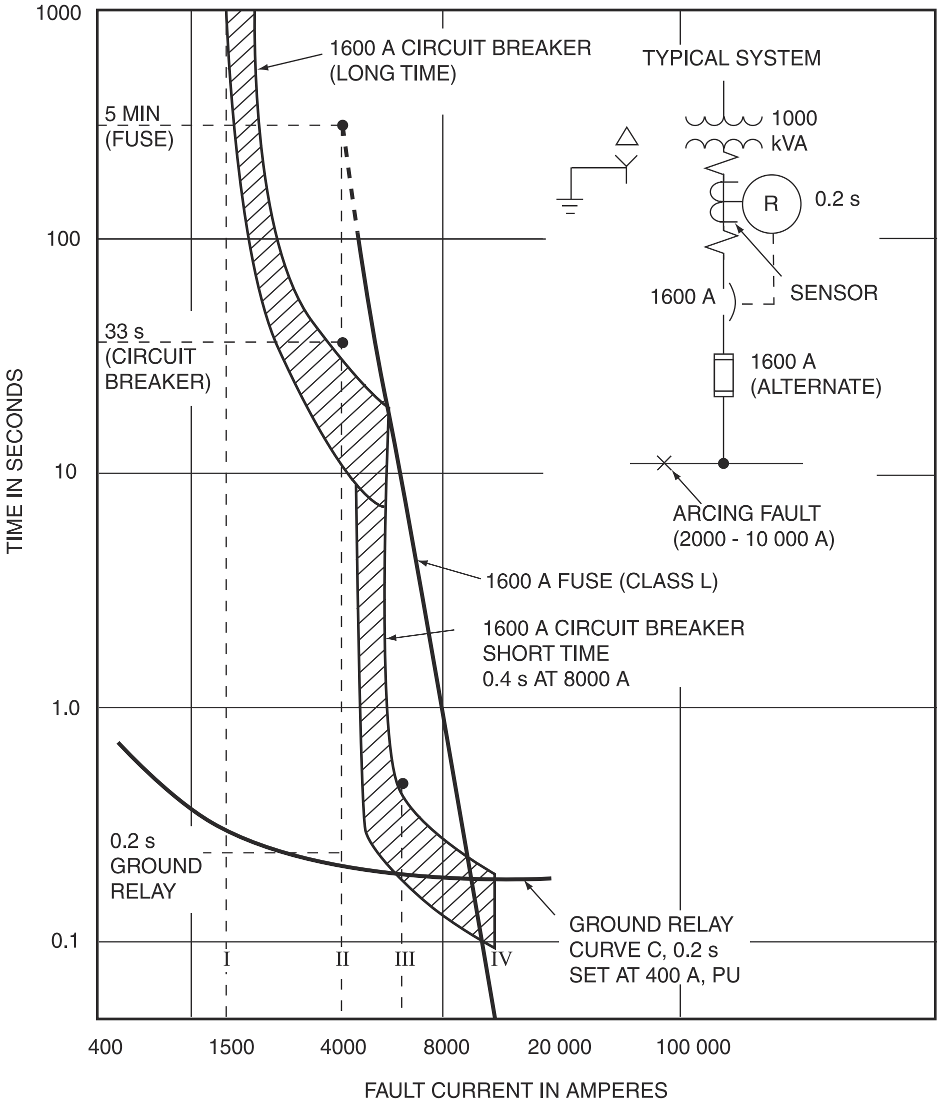

Figure 8-7a—Time-current plot showing slow protection provided by phase devices for low-magnitude arcing ground faults

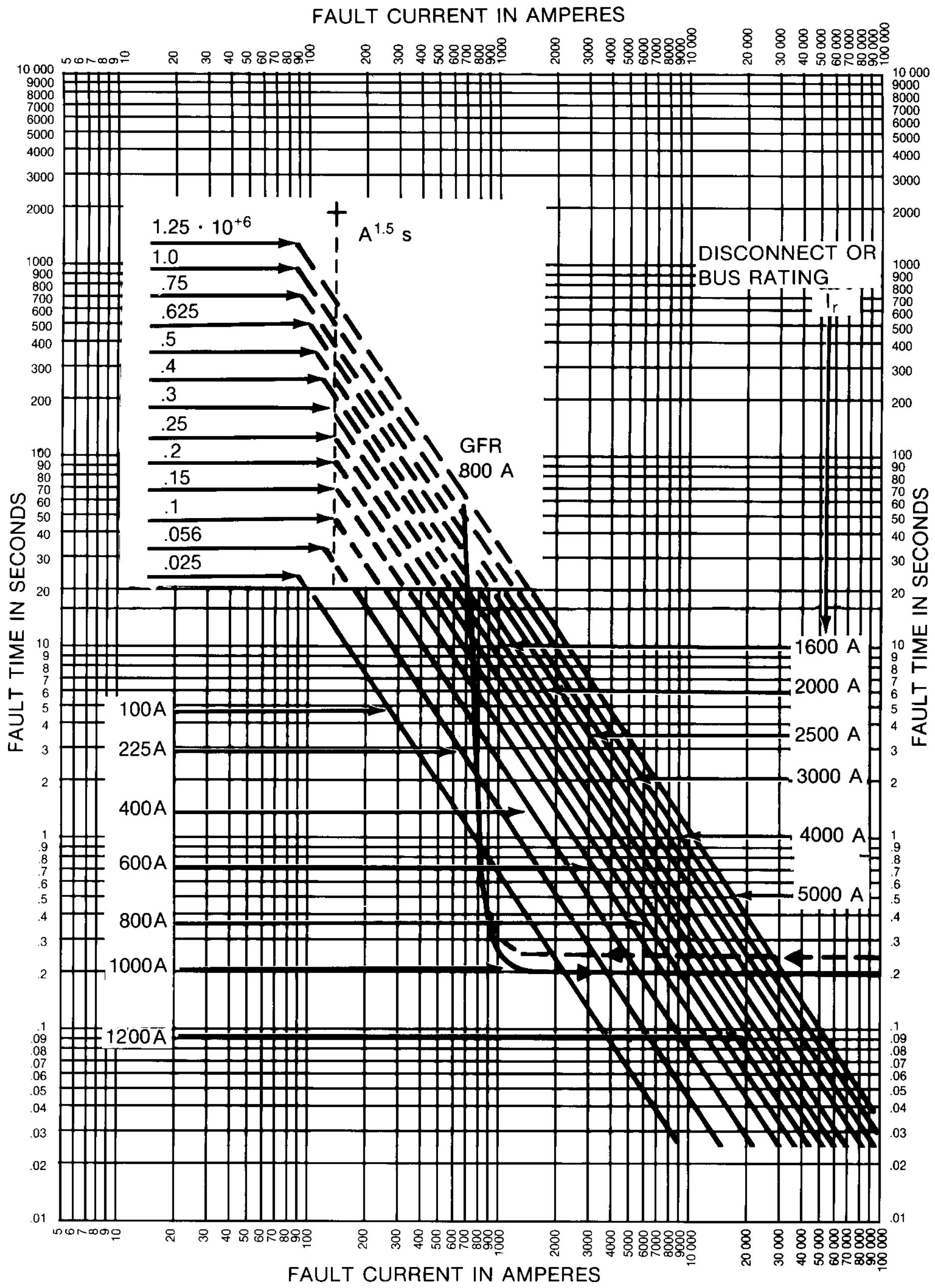

Figure 8-7b—Assumed tolerable damage levels

Table 8-1—Arc energies for assumed faults of Figure 8-7a

Figure 8-7a points	Fault (A, rms)	Main device	Clearing time (s)	Arc energy (kWs)
I	1500	Relay Circuit breaker Fuse	0.33 ∞ ∞	50 ∞ ∞
II	4000	Relay Circuit breaker Fuse	0.25 33.00 300.00	100 13 200 120 000
III	8000	Relay Circuit breaker Fuse	0.25 0.4 10.00	200 320 8000
IV	20 000	Relay Circuit breaker Fuse	0.25 0.20 0.01	500 400 20

For the assumed 8000 A fault, even though the current values are the calculated result using all source, circuit, and arc impedances, the actual rms current values passing through the circuit breaker can be considerably lower. The reason is the spasmodic nature of the fault caused by

- Arc-elongating blowouts effects
- Physical flexing of cables and some bus structures due to mechanical stresses
- Self-clearing attempts and arc reignition
- Shifting of the arc terminals from point to point on the grounded enclosures (and on the faulted conductors for noninsulated construction)

All of these effects tend to reduce the rms value of arcing fault currents. Therefore, a ground fault that would normally produce 8000 A under stabilized conditions might well result in an effective value of only 4000 A and would have the arc energies associated with Point II in Table 8-1.

Expressing acceptable damage in terms of kWs, or kW cycle units, with an assumption of 100 V arc drop in 480Y/277 V circuits has been proposed.

Investigations show that damage in standard switchboards at normal arc lengths is proportional to time and 1.5 power of ground-fault current magnitude (see Stanback [B42]). Thus, the arc voltage magnitude question at varying and unpredictable fault currents may be excluded and damage prediction simplified.

According to the study, specific damage or burning rate

$$k_s = \frac{\text{damaged volume } V_D}{\text{current}^{1.5} \times \text{time}} [\text{in}^3 / \text{A}^{1.5}\ \text{s}]$$

with

k_s is 1.18×10^{-5} cm^3/A$^{1.5}$s for copper,

k_s is 2.49×10^{-5} cm^3/A$^{1.5}$s for aluminum,

k_s is 1.08×10^{-5} cm^3/A$^{1.5}$s for steel.

Because selection of conductors is often based on nearly uniform current densities (e.g., 125–155 A/cm^2), acceptable damage could then be based on conductor or disconnect ratings or on cross-sectional area.

Thus, if based on

$$I_F{}^{1.5} t = k_e I_R$$

where

I_F is fault current,

I_R is disconnect or bus rating,

the acceptable damage $V_D = k_s k_e I_R$ can be used as a constant for a given system and disconnect rating. Acceptable damage could then be held by appropriate selection of current and time settings for ground-fault protective devices.

For example, if I_R = 1000 A and k_e = 250 [A$^{0.5}$ s] (as assumed in NEMA PB 2.2-1999) acceptable damage,

$$I^{1.5} t = 250 \times 1000 = .025 \times 10^{+6}\ [\text{A}^{1.5}\ \text{s}], \text{ or}$$

$$V_D = 1.18 \times 10^{-5} \times 0.25 \times 10^{6} = 2.95 \text{ cm}^3 \text{ for copper,}$$

conductors are not exceeded for faults between 800 A and 10 000 A, with relay settings as shown in Figure 8-7b if clearing time of the circuit breaker or bolted pressure switch does not exceed 200 ms.

The above computations are based on 277 V single-phase test results and the assumption that the damage would be proportional to the arcing fault current. Therefore, some discretion should be used when referencing the example in Figure 8-7b (see Love [B32]).

8.3.4 Selection of low-voltage protective device settings

Maximum protection against ground faults can be obtained by applying ground protection on every feeder circuit from source to load. The minimum operating current for all series devices may be set at about the same pickup setting, but the time curves are selected so that each circuit protective device is opened progressively faster, moving from the source to the load. The load switching device can be opened instantaneously or with brief delay upon occurrence of a ground fault.

The delay required between devices is determined by the addition of

- The trip-operating time of the overcurrent device
- The clearing time of the overcurrent device
- A margin of safety

The trip-operating time of today's molded-case circuit breakers (MCCBs), service protectors, power circuit breakers, or shunt-tripped switches is usually about 3 cycles. Current-limiting fuses clear in about .004 s when operating in their current-limiting range.

This coordination by time delay is similar to other overcurrent coordination. However, another method of coordination, called zone selective interlocking (ZSI), is available for ground-fault protection using solid-state relays and electronic trip devices. Ground faults, for minimum damage, should be cleared as quickly as possible regardless of their magnitude. Zone coordination assures instantaneous tripping of all ground-fault relays for faults within their zone of protection, with upstream devices restrained to a time delay in response to ground faults outside their zone. This restraining signal requires as few as one pair of wires from the downstream zone to the upstream relay to carry the interlocking signal. ZSI provides the fastest tripping, for minimum damage, with full coordination so that only the affected part of the system is shut down on ground fault. ZSI is discussed further in 8.5.4.1.

Bolted-pressure and high-pressure contact fused switches using the ground-fault protection schemes can be shunt tripped to open quickly.

From the standpoint of damage alone, speed of clearing is paramount. However, in some situations, delay is desirable, primarily to obtain coordination between main and feeder circuits and branch currents. Consider a typical 480Y/277 V application consisting of a 3000 A main, an 800 A feeder, and a 100 A branch circuits. If the branch circuits do not have ground-fault protection, then the feeder ground-fault protection should be set with a time delay to allow the branch circuit phase-overcurrent device to clear moderately high-magnitude ground-fault currents without opening the feeder through its ground-fault protection. When full coordination is essential, setting the feeder ground-fault pickup above and to the right of the branch circuit devices is desirable. While infrequent loss of coordination may be acceptable between feeders and branch circuits, full coordination should be maintained between main and feeder overcurrent protective devices. Setting main service ground-fault protection at less than 0.1 s (or 6 cycle) response time is generally not recommended. Proper settings reduce effects of inrush, startups, and switching currents and prevent nuisance openings.

Another reason for delayed clearing of ground faults on main or large feeder circuits is the threat of circuit interruption where the power outage itself is of greater consequence than the incremental difference in fault damage.

In summary, the sensitivity (or minimum operating current setting) of ground-fault protection in solidly grounded low-voltage systems is determined by the following considerations:

a) When the ground-fault protection is used on devices protecting individual loads, such as motors, the lowest available settings can be used, providing the devices do not cause false opening from inrush currents.

b) For the main and feeder circuits, the setting for ground-fault protective devices is normally in the range of 10% to 100% of the circuit trip rating or fuse rating. If downstream devices do not have ground-fault protection, then the circuit ground-fault protection may have to be set higher than the downstream phase-protective device opening characteristics to ensure full coordination. Many times, the main ground-fault protection needs to be set at the code maximum of 1200 A in order to selectively coordinate with the downstream phase- and ground-fault protection.

8.3.5 Sensing, relaying, and trip devices

The signal for ground-fault protective devices may be derived from the residual of phase CTs, window CTs, or sensors. The CTs or sensors provide isolation between main busses and relaying equipment and should be located in a specific path to detect proper ground-fault currents under all operating conditions.

Sensors are often designed with other than 5 A or 1 A nominal secondary rating and for use with specific relays or trip devices as a system. If part of such a system, the relays normally have dials marked in terms of primary ground-fault current amperes.

Ground-fault relays or trip devices may be either self-powered (i.e., fault current) or externally powered (i.e., operation or trip power), or incorporate both methods. Outputs may be contact or solid-state (e.g., thyristors).

AC control power, derived from an auxiliary transformer of proper capacity, is frequently used in systems of 600 V and below and is sometimes supplemented by capacitor trips. The primaries of control power transformers should be connected line to line to reduce effects of voltage dips during ground faults, and the trip device should be capable of operating at 0.866 times rated voltage. The need for overcurrent protection and transfer to an alternate control power source should be evaluated.

Supplementary or backup ground-fault protection may be accomplished by monitoring the equipment environment. Such systems detect ionized gases and other fault-current by-products, such as abnormal light and heat. By early detection of one or more of the by-products of a ground-fault current and prompt opening of the interrupting device serving the fault, the magnitude of the damage may be reduced. Supplementary sensing is particularly desirable when the primary means of ground-fault sensing is set relatively high to prevent nuisance opening or to satisfy coordination requirements. To maximize the