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Sandwich pressurization systems for smoke control

These systems have proven to be efficient and cost-effective in numerous multi-story buildings in Australia

By Roger Marchant

Australian building legislation has in the past paid little attention to smoke control within multi-story buildings apart from the old *Australian Standard 1668, Fire Precautions in Buildings with Air Handling Systems*. The objective of that standard was to prevent the migration of smoke to other parts of a building by way of the installed air-conditioning ductwork. However, there was no requirement in the old *AS-1668* or in Australian building regulations (AMUBC) to minimize smoke spread through a multi-story building by connecting paths other than the air-conditioning ductwork (building service, elevator and ventilation shafts).

Because the old standard only applied to buildings employing a central air handling plant, in those early days (before some authorities woke up to the loophole) it was possible to construct a multi-story building with individual on-floor (unitary) air conditioners, to save the expense of a smoke control system. Occupants would then, for their safety, rely solely upon required stair pressurization systems to provide smoke-free paths of egress. Local *ad hoc* tests have demonstrated that smoke will migrate from the fire floor to other parts of a building via transfer paths such as elevator shafts, construction joints and ventilation ducts.

The traditional *AS-1668* modus operandi, at time of fire, consists of running the building air-conditioning plant in what we now call the purge mode. Using economy cycle dampers, all floors (including the fire floor) are supplied with 100% fresh air and exhausted to atmosphere. This is usually accomplished via a return air shaft, using either dedicated smoke spill fans or the air-conditioning return air fans.

In this purge mode, the fire stairs are maintained at a positive pressure to prevent smoke entry into these escape routes. Because the A/C system is *required to supply less air than that exhausted*, the building has all floors at a pressure below that of the elevator, service and stair shafts, with no induced pressure differential between the fire and other floors.

When doors to the fire floor are opened for occupant escape or firefighter access, pressure on this floor will increase because of the inrush of air from the pressurized stairs. This floor will then attain a higher pressure than that which occurs on the other floors.

The degree of positive pressure achieved will depend upon how much exhaust is provided, how much air enters the floor and how hot the fire is (entering air will expand because of heat). This condition will promote smoke migration from the fire floor to other floors via interconnecting paths.

Smoke will enter the elevator shaft, which will be at a lower pressure because the non-fire floors will be scavenging from it. This interconnecting path will transport large volumes of smoke to other parts of the building. It may also attain a temperature gradient and act as a chimney if the fire is not quickly extinguished. This problem will hamper firefighters who need the elevators to transport resources up to the forward command post two floors below the fire.

A recent hot smoke test[1] in Adelaide, Australia, verified the above scenario. Specifically, a 1.5 MW test fire in a below-ground car park smokelogged a large department store five floors above. Smoke migrated by way of an elevator shaft interconnecting these spaces because the store pressurization system failed to operate. The resultant automatic exhaust in the department store exacerbated the situation by decreasing pressure in the store. The situation was corrected by switching off all store exhaust systems and operating air-conditioning supply air to pressurize the store.

From the commentary document, the old *AS-1668* committee recognized (two decades ago) the desirability of a positive pressure differential between fire and non-fire floors, but did not

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believe the costs of control systems to achieve this were justified. Cost is now less of an imposition on the building owner, because multi-story buildings of any significance have computerized management systems that can be (carefully) modified to achieve this desired effect.

The new *AS-1668.1* includes for the design of zone pressurization systems and The Building Code of Australia has been amended to include this standard. From practical experience, I am convinced that positive zone pressurization is necessary if we are to successfully cope with the kinetic effects of the hot smoky gasses generated by a fire in a multi-story building.

Recognized smoke control methods

It would appear that there are but two principle dynamic methods of controlling the movement of smoke within a building: removal and containment. (I discount dilution as a practical form of control.)

The oldest control method is to exhaust or relieve smoke from above the hot layer.[2] If this layer is contained in a defined smoke reservoir (bounded by vertical screens or other geometric ceiling configuration), we can prevent the smoke from descending and spreading laterally. Applications of this principle typically include smoke and heat vents employed in industrial buildings[3] and smoke exhaust fans located at the top of atriums or in shopping malls.

The second method, containment, employs the use of air velocity in the opposite direction to smoke movement to overcome its kinetic energy. This method is very sensitive and can be misapplied. Remember, the "control" air volume will create excessive turbulence, thereby stirring up and increasing the smoke volume.

Some will argue that the smoke will be more dilute, hence implying less dangerous. Forget the academics; the dilute smoke will usually be black, opaque and very toxic.

Traditional stair pressurization systems use velocity to prevent smoke entry into stairs; apparently 0.8 m/s (158 fpm) will prevent smoke passing through an open stair door into the stairwell. I believe this velocity was derived from tests on standard door openings with a bulkhead above the door.

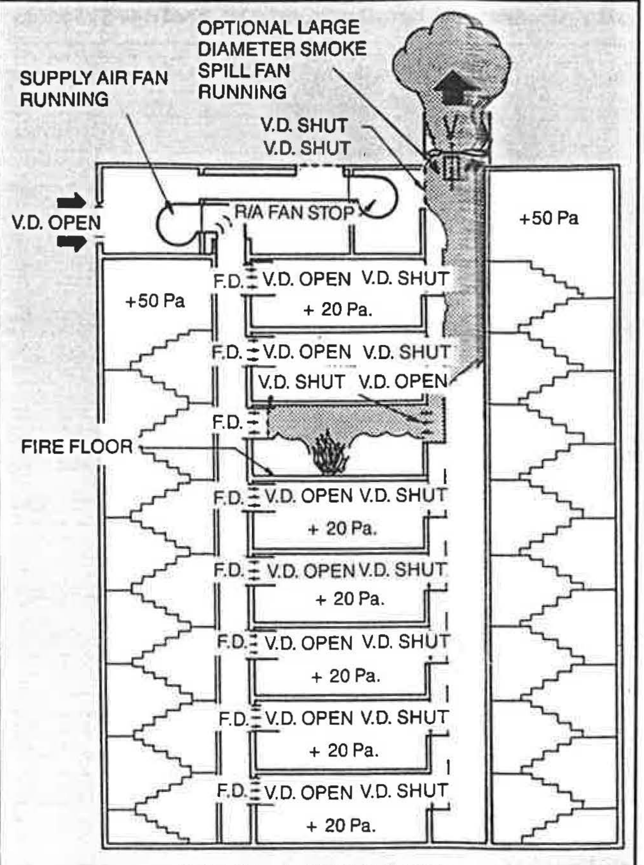
The bulkhead is a very important component of the test assembly. Most smoke layers have a jet stream of high temperature, fast moving gasses close to the ceiling. The bulkhead causes the jet stream and the smoke layer to turn down at the door opening. The turbulent eddy at this point is then prey to the low velocity air flowing through the door. However, if the door opening was flush with the ceiling, more than 0.8 m/s (158 fpm) would be required.

I prefer well in excess of 1 m/s (197 fpm) through any opening. In fact, 2 m/s (394 fpm) is very effective and, as explained later, is often achieved when using a sandwich (zone) pressurization system. If we employ this principle over large openings, huge quantities of air are required and large volumes of smoke can be generated. This may also exacerbate firefighting operations in the space where the smoke is contained.

Smoke control by sandwich pressurization

In Adelaide, there are now more than 25 buildings (ranging from 10 to 30 floors in height) that have sandwich (zone) pressurization smoke control systems. Now optional within the new *AS-1668*,[5] this method employs the building air-conditioning system to pressurize the non-fire floors, and to provide either relief or exhaust of the fire affected floor (see *Figures 1* and *2*).

The fire floor is sandwiched between the higher pressure zones (non-fire floors), hence the name sandwich pressurization. Non-fire floor pressurization is achieved by operating the air-conditioning system at 100% fresh air.



SECTION THROUGH BUILDING

NOTE: F.D. = FIRE DAMPER
V.D. = VOLUME CONTROL DAMPER

Figure 1. Central plant air conditioning.

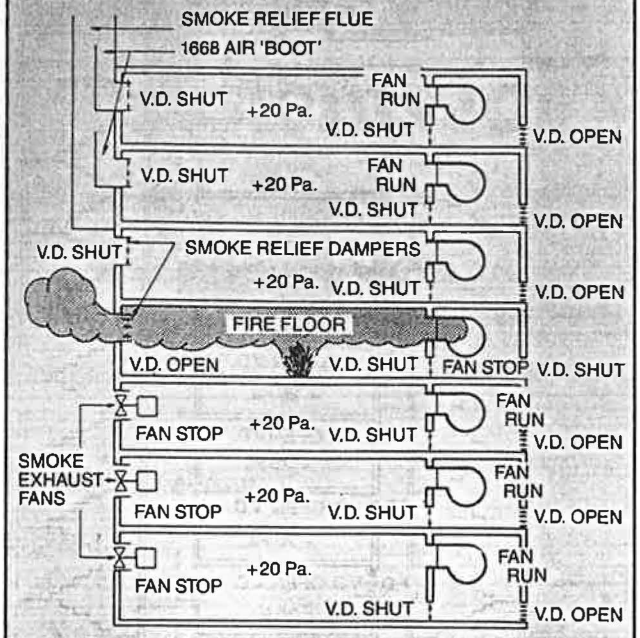
Smoke will principally be contained within the fire floor and the relief path from that floor to atmosphere. Leakage of air within the building via elevator shafts, stairs and construction joints will always be towards the fire floor and any selected smoke relief shaft, which will be at a lower pressure than all other parts of the building. This allows smoke to leave the building by a chosen path. For central plant systems, a return air shaft with or without fans may be used for this purpose.

This form of control relies on air velocity through cracks and openings in the structure to prevent smoke moving in the opposite direction via these paths.[4] The increase in air pressure necessary to create this velocity is usually created by the supply air fan backing up its performance curve. The pressure increase is the most obvious component of these systems.

Ad hoc smoke tests have shown that air infiltration onto the fire floor typically achieves crack velocities (through elevator shaft doors) of 3 to 4 m/s (591 to 787 fpm). Air may also back-flow through toilet and other miscellaneous exhaust ducts at 1.5 to 2.5 m/s (295 to 492 fpm) and through open stair doors at 1.0 to 2.5 m/s (197 to 492 fpm).

The new *Australian Standard 1668.1*

AS-1668.1 (Fire and Smoke Control) now specifies zone smoke control systems.[5] These employ the same components as a traditional purging system except that additional volume control dampers are necessary for central plant systems. It is the control



NOTE: V.D. = AIR CONDITIONING AUTOMATIC VOLUME CONTROL DAMPER

Figure 2. Unitary plant air conditioning.

of these dampers, or the unitary plant, that achieves the necessary pressure differentials between floors.

Section 5, clause 5.8 of the new standard details requirements for central plant zone pressurization systems. These require volume control dampers within the supply air ductwork to each floor that *supply air to every floor except the fire floor.* The fire floor is either relieved or exhausted by a shaft to outside the building.

An exhaust shaft serving all floors requires volume control dampers on each floor in addition to the traditional sub-duct fire separation. These dampers *close on non-fire floors* (creating a back-pressure) and *open on the fire floor.* Because all dampers used must fail in the open position, the system will revert to a purge mode (except a positive building pressure will result because there is less total exhaust than supply).

Exhaust fans must provide six air changes per hour in the largest compartment or handle the volume entering the largest floor when all pressurized exits serving that floor are open, whichever is greater. In a traditional office building with two pressurized exits, a velocity of not less than 1 m/s (197 fpm) is required through each open door. At around 1.75 m^3/s (3,700 cfm) per door, this equates to a required exhaust of at least 3.5 m^3/s (7,400 cfm) per floor.

To this air quantity, we must add infiltration from leakage paths such as lift doors, expansion due to temperature, curtain facade, and other factors. This will, in practice, probably make the at-floor exhaust not less than 4 m^3/s (8,475 cfm).

Therefore, in buildings having a net leasable floor area of up to about 800 m^2 (8,600 ft^2), the air volume through the exit doors will dictate the exhaust quantity to the fire floor. To size a smoke exhaust fan connected to a shaft, the designer must allow for leakage into the shaft through closed dampers on non-fire floors (indeed through the fabric of the shaft itself if it is masonry) and add this allowance to the required at-floor exhaust. If this fan fails (depending upon fire floor pressure), there should still remain a degree of sandwich pressurization between the non-fire floors and the fire floor, which should hinder smoke migration.

Section 6 of the new standard details zone smoke control using on-floor unitary air handling systems. These must supply *100% fresh air to non-fire floors and stop on the fire floor,* which is relieved to outside the building or exhausted by shaft or local fan. Under the Building Code of Australia, zone pressurization systems are mandatory in all buildings employing unitary plants.

Central plant and on-floor systems may be used to pressurize the stairs via leakage from the pressurized floors. In practice, this works well and has been utilized in South Australia for many years now. However, it is important that stairwells have a relief path to atmosphere to prevent over-pressurization.

It is intended that central plant zone pressurization systems used to pressurize stairs incorporate:

- A standby supply air fan, or
- A standby drive arrangement, and
- Dual fresh air intakes on opposite sides of the building such that, if one is contaminated, it will shut down and the other intake be utilized.

The control of the dual air intakes must be arranged so that, if one intake becomes contaminated, enough time is available to permit it to close down and the fresh air plenum to clear, before the fan itself is stopped by the supply air smoke sensor.

Discussion

A common misconception is that smoke control systems within multi-story buildings are intended to keep the smoke on the fire floor at high level, clear of the occupants. This is not a practical proposition.

Instead, the intent is to prevent smoke from threatening building occupants on floors remote from the fire. In reality, the fire floor will rapidly smokelog down to the floor because the air-conditioning system will be completely overwhelmed by the fire. Hopefully, the occupants of the fire floor will be driven out of that area into safe refuge/escape zones.

Currently, it is not possible to accurately predict the pressure differentials that will be achieved by a proposed system. These can only be measured on completion. As far as I know, there is no accurate design data for the unfortunate design engineer. I believe this has created a further misconception that an enormously expensive and complicated pressure control system is required to maintain the pressure difference of not less than 20 Pa (0.08 in. wg) between the fire and non-fire floors.

A practical solution resolves this dilemma: Select an appropriate fan performance curve that will prevent very high pressures at low volume flow (try not to use forward curved fans). Further, specify fans that can be repitched or incorporate drive pulleys that can be changed after installation (with sufficient commissioning costs allowed for this). This simple prescription enables the system to be tailored for the building at commissioning time.

In practice, pressure differential control is extremely simple (crude, but foolproof). Air leaks into the fire floor while the pressurizing system rides the supply fan performance curve. The 20 Pa (0.08 in. wg) is a minimum; go as high as possible.

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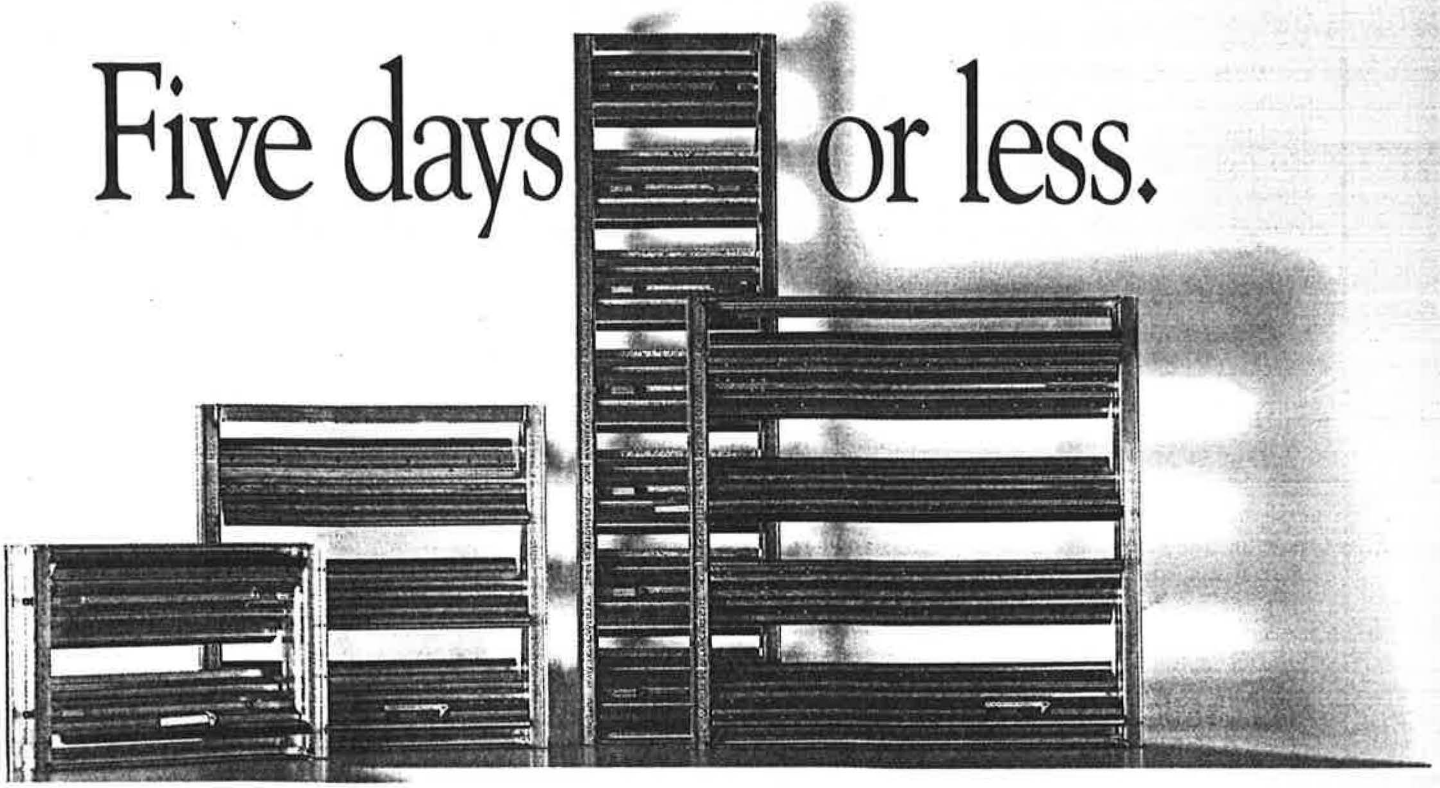
Five days or less.



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Smoke control sandwich pressurization systems

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We have achieved 140 Pa (0.56 in. wg) between fire and non-fire floors, and maintained 110 newtons (25 lb) force at the handle of the door across which this pressure differential was measured. (Force at door handle equals pressure times area, taken as a force midway between door jambs, acting as a moment about the door hinges.)

Table 1 summarizes tests of stairwell pressure differentials and door opening forces achieved in a building that employed a sandwich pressurization system leaking into the fire stairs. Because relief to the outside had not been provided, this system had too great a pressure differential across the upper stairwell doors. This caused unacceptably high door opening forces (more than 110 newtons; 25 lb).

Prior to the installation of relief grilles, the tests detailed in *Table 1* were conducted by opening various door combinations, using the open top door of each stair as a relief into the roof plantroom fresh air plenum. The figures are as presented by the commissioning engineer. Unfortunately, door closures have adjustable and varied torque settings and no absolute reference pressure was measured between the stair and outside the building.

During full-scale fire tests, it has been established[6] that a maximum fire pressure of 16 Pa (0.06 in. wg) was developed at an exit door. Further from the door, 15 to 20 Pa (0.06 to 0.08 in. wg) is suggested. In sprinklered buildings, 5 to 10 Pa (0.02 to 0.04 in. wg) is suggested. Current systems installed in South Australia appear to develop pressure differentials between non-fire and fire floors of between 50 to 100 Pa (0.2 to 0.4 in. wg).

Academic discourse as to what pressures are created by fires in sprinklered and unsprinklered buildings tends to fade into the background as they appear well below these easily achieved figures.

Table 1. Tests of Stairwell Pressure Differentials and Door Opening Forces

Stair No. 1	1 Pascals	2 Pascals	3 Pascals	4 Pascals	5 Newtons	6 Newtons
Floor 10W	60.0	100.0	65.0	110.0	69.0	74.0
Floor 8W	30.0	70.0	45.0	120.0	69.0	98.0
Floor 6W	30.0	70.0	47.0	100.0	69.0	108.0
Floor 4W	40.0	70.0	60.0	110.0	59.0	108.0
Floor 2W	40.0	72.0	60.0	115.0	64.0	103.0
Stair No. 2	**1 Pascals**	**2 Pascals**	**3 Pascals**	**4 Pascals**	**5 Newtons**	**6 Newtons**
Floor 10E	60.0	90.0	65.0	120.0	69.0	74.0
Floor 8E	30.0	70.0	45.0	120.0	69.0	98.0
Floor 6E	30.0	65.0	45.0	105.0	69.0	108.0
Floor 4E	42.0	70.0	65.0	112.0	69.0	108.0
Floor 2E	40.0	60.0	50.0	120.0	59.0	103.0

Table Legend

Column 1: Differential pressure across closed fire floor door (stairwell – office) with bottom exit door to stairwell open.

Column 2: Differential pressure across closed fire floor door (stairwell – office) with adjacent non-fire floor door and bottom exit door to stairwell open.

Column 3: Differential pressure across closed fire floor door (stairwell – office) with adjacent non-fire floor door, bottom exit door to stairwell and roof plantroom relief door open.

Column 4: Differential pressure across closed non-fire floor door (stairwell – office) with bottom exit door to stairwell open.

Column 5: Force required to open fire stair doors with air-conditioning system off.

Column 6: Force required to open fire stair doors with adjacent non-fire floor door, bottom exit door to stairwell open and roof plantroom relief door open.

Unsprinklered buildings are likely to have fully flashed-over fires on the fire floor, and I doubt that any smoke control system can effectively deal with that situation. This suggests that sprinkling is an essential component of a successful smoke control system.

Overseas designers have installed smoke control systems that pressurize a few floors above and below the fire floor. This will not work because the elevator and other shafts will not be adequately pressurized, so any smoke entering these distribution paths will end up on other floors within the building. All floors must be pressurized.

We have found that, in many buildings, independent stair pressurization systems are not required if the building has sufficient floors and infiltration gaps around the closed doors accessing the stair. Stair pressurization will occur because of leakage into the stairwell from the pressurized non-fire floors. We often achieve 2 m/s (394 fpm) through open doors to the fire floor with all other doors to the stairwell shut, except for the bottom escape door to outside the building. When more doors are opened into the stairwell, leakage rates into the stair improve and the velocity through the open doors to the fire floor will increase.

Successful stair pressurization has generally been achieved by normal leakage. However, in some instances, small fire dampers have been installed to open up ceiling plenum spaces to the stairwell.

In low-rise buildings, small supplementary stair pressurization fans may be required if there is not enough leakage area. These will not need to supply air for open doors, onto non-fire floors, because these are pressurized. Once the building reaches 10 or more floors, there is usually sufficient door leakage to pressurize most escape stairs. However, the length of corridor at the base of the stair (offering resistance to air flow) affects the pressurization of the stairwell at the lower floors, hence the velocity through the doors at these levels.

Stairwell pressurization is technically a defunct term. *Australian Standard 1668.1* is not concerned with how much pressure a system generates in a stair, just the maximum force required to open the fire floor door (110 newtons; 25 lb) and the minimum fresh air velocity through it (1 m/s; 197 fpm).

In central exhaust systems, over-exhausting the fire floor can be overcome by "cracking" the exhaust dampers on non-fire floors. However, do not design this way. Buildings and dampers are extremely leaky, a lot more than most people think.

For central plant systems, fire-rated wiring to fans is required. On-floor fans do not need fire-rated wiring because the fan on the fire floor stops. Only where the wiring is exposed to fire on other (possible fire) floors does it need to be fire-rated. In the future, we should consider the "essential services tower concept" and incorporate such reticulation within the design of the fire-rated stairwells used for egress.

One of the best South Australian systems tested to date uses an on-floor plant, located in fire-rated rooms in the services core, accessible from a fire stair. Stair pressurization fans, fire-rated wiring and smoke exhaust fans are not necessary. Fire floors are relieved to atmosphere using solenoid dampers distributed around the building facade (fail-safe open), located above a return air plenum ceiling.

Pressure differentials between floors exceeded 50 Pa (0.2 in. wg) and velocities onto fire floors through open stairwell doors exceeded 2 m/s (394 fpm). I believe this to be the preferred smoke control system, with all control accomplished by fans and equipment remote from the fire and its hot smoky gasses. This simple philosophy is really the secret to a successful design.

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