4. MAGNETIC SUSCEPTIBILITY

4.1. Principles

PHYSICAL BACKGROUND

Magnetic susceptibility is the degree to which a material can be magnetized in an external magnetic field. If the ratio of the magnetization is expressed per unit volume, volume susceptibility is defined as

$$\kappa = M / H, \tag{1}$$

where M is the volume magnetization induced in a material of susceptibility κ by the applied external field H. Volume susceptibility is a dimensionless quantity. The value depends on the measurement system used:

$$\kappa(\mathrm{SI}) = 4\pi\ \kappa(\mathrm{cgs}) = 4\pi\ \mathrm{G\ Oe}^{-1}, \tag{2}$$

where G and Oe are abbreviations for Gauss and Orstedt, respectively. The SI system should be used.

Mass, or specific, susceptibility is defined as

$$\chi = \kappa / \rho\ , \tag{3}$$

where ρ is the density of the material. The dimensions of mass susceptibility are therefore m^3/kg.

Magnetic susceptibility measured by the common methods is an apparent value because of the self-demagnetizing effect associated with anisotropy connected with the shape of magnetic bodies, such as magnetite grains (Thompson and Oldfield, 1986). When a substance is magnetized its internal magnetic field is less than the externally applied field. κ_i, the intrinsic susceptibility, relates the induced magnetization to the internal magnetic field, whereas κ_e, the extrinsic susceptibility which we actually observe, relates the induced magnetization to the externally applied field. The relationship between the two susceptibilities can be shown to be

$$\kappa_e = \kappa_i / (1 + N\kappa_i), \tag{4}$$

where N is the demagnetization factor. For a strongly magnetic mineral, such as magnetite, $N\kappa_i > 1$, and $\kappa_e \sim 1/N$. If N is known, there is a simple relationship between the concentration of ferrimagnetic grains and the magnetic susceptibility. This is the case for natural samples where the concentration of ferrimagnetic minerals is a few percent or less. The measured susceptibility κ can be approximated:

$$\kappa = f\kappa_e \sim f/N\ , \tag{5}$$

where f is the volume fraction of ferrimagnetic grains. It is found that for natural samples N is reasonably constant with a value close to 1/3. Thus, if the grain shapes are roughly spherical and the dominant mineral is magnetite, the volume fraction (f << 1) can be estimated by dividing the volume susceptibility by 3.

The commonly used magnetic susceptibility is measured at very low fields usually not exceeding 0.5 mT (millitesla). It is therefore also referred to as low-field susceptibility. For comparison, about 50 mT is required to change orientation in magnetite, and high-field susceptibility is obtained from hysteresis measurements at fields of a few hundred millitesla.

In practice, volume susceptibility is generally measured with core logging devices, for which calibration factors must be established to account for the specific geometry and effects of core conveyors and core liners. In the case of discrete specimen measurements, the mass of the specimen can be determined more accurately than volume and specific susceptibility is directly obtained. If average grain density and moisture content of the specimen are known, the specimen measurements can be compared with core logging measurements. Susceptibility values can then be normalized to mass and volume corrected for porosity. This can make susceptibility data more useful for quantitative estimates in conjunction with other mineral phases, such as carbonate, which are always normalized to dry mass.

Susceptibility values for some common minerals and rocks are listed in Table 4—1.

Table 4—1 Susceptibilities of common minerals and rocks (simplified from Hunt et al., 1995; supplemented with underlined values from Thompson and Oldfield, 1986).

	κ (10^{-6} SI)	χ (10^{-8} m^3/kg)
Non-iron-bearing		
Plastic (e.g., perspex, PVC)	~-5	~-0.5
Ice or water	-9	-1/-0.9
Calcite	-7.5 to -39	-0.3 to -1.4
Quartz, feldspar, magnesite	-13 to -17	-0.5 to -0.6
Kaolinite	-50	-2
Halite, gypsum, anhydrite	-10 to -60	-0.5 to -2.0
Serpentinite	3,100 to 75,000	120 to 2,900
Iron-bearing minerals		
Illite, montmorillonite	330 to 410	5 to 13 to 15
Biotite	1,500 to 2,900	5 to 52 to 95 to 98
Orthopyroxene, olivines, amphiboles	1,500 to 1,800	1 to 43 to 50 to 130
Goethite[a]	1,100 to 12,000	26 to 70 to 280
Franklinites	450,000	8,700
Iron[a]	3,900,000	50,000 to 2,000,000
Iron sulfides		
Chalcopyrite	23 to 400	0.6 to 3 to 10
Pyrite	35-5,000	1 to 30 to 100
Pyrrhotites[a]	460 to 1,400,000	10 to 5,000 to 30,000

Table 4—1 Susceptibilities of common minerals and rocks (simplified from Hunt et al., 1995; supplemented with underlined values from Thompson and Oldfield, 1986).

Iron-titanium oxides		
Hematite[a]	500 to 40,000	10 to _60_ to 760
Maghemite[a]	2,000,000 to 2,500,000	_40,000_ to 50,000
Ilmenite[a]	2,200 to 3,800,000	46 to _200_ to 80,000
Magnetite[a]	1,000,000 to 5,700,000	20,000 to _50,000_ to 110,000
Titanomagnetite	130,000 to 620,000	2,500 to 12,000
Titanomaghemite	2,200,000	57,000
Ulvospinel	4,800	100
Average rock values		
Sandstones, shales, limestones	0 to 25,000	0 to 1,200
Dolomite	-10 to -940	-1 to -41
Clay	170 to 250	10 to 15
Coal	25	1.9
Basalt, diabase	250 to 180,000	8.4 - 6,100
Gabbro	1,000 to 90,000	26 to 3,000
Peridotite	96,000 to 200,000	3,000 to 6,200
Granite	0 to 50,000	0 to 1,900
Rhyolite	250 to 38,000	10 to 1,500
Amphibolite	750	25
Gneiss	0 to 25,000	0 to 900
Slate	0 to 38,000	0 to 1,400
Schist, phyllite	26 to 3,000	1 to 110
Serpentine	3,100 to 18,000	110 to 630
[a]Remanence-carrying minerals		

ENVIRONMENTAL EFFECTS

Cores should be equilibrated to room temperature before measurement.

USE OF MAGNETIC SUSCEPTIBILITY

Magnetic susceptibility is used mostly as a relative proxy indicator for changes in composition that can be linked to paleoclimate-controlled depositional processes. The high precision and sensitivity of susceptibility loggers makes this measurement extremely useful for core-to-core and core-downhole log correlation. The physical link of magnetic susceptibility to particular sediment components, ocean or wind current strength and direction, or provenance, usually requires more detailed magnetic properties studies in a specialized shorebased laboratory.

4.2. Bartington MS2C Coil Sensor for Whole Cores (MSL)

EQUIPMENT

A Bartington Instruments MS2C system is integrated in the ODP MST for whole-core logging. The main unit is the widely used, versatile MS2 susceptometer for rapid measurements with a number of sensors. The unit has a measuring range of 1×10^{-5} to 9999×10^{-5} (SI, volume specific) or 1×10^{-8} to 9999×10^{-8} (SI, mass specific). It has five front panel controls: on-off switch, sensitivity range switch, SI or cgs unit switch, zero button, measure button, and continuous measurement switch. None of these controls needs to be operated because the instrument is controlled by the MST program. The unit switch should always be on SI. The range switch should be on the lower sensitivity (1.0), which allows rapid 1-s measurements. The MST program allows the collection of multiple 1-s measurements, which are immediately averaged. This is useful if the sampling period is set, for example, at 3 s for the GRA measurement and there is time to take three susceptometer readings simultaneously.

The MS2C loop sensor has an internal diameter of 80 mm, which corresponds to a coil diameter of 88 mm. It operates at a frequency of 0.565 kHz and an alternating field (AF) intensity of 80 A/m (= 0.1 mT). Temperature drift is less than 10^{-5} SI per hour. The resolution of the loop is 2×10^{-6} SI on the 0.1 range (9 s measuring time).

Dual-frequency Measurements

Fine-grained magnetic material (single-domain, about 0.003 µm diameter) exhibits frequency-dependent susceptibility. The coefficient of frequency dependence can be determined from measurements in dual-frequency mode. The high frequency used is 5.65 kHz. This mode of measurement is rarely used in general, has never been requested onboard *JOIDES Resolution*, and is therefore not implemented for routine measurements in the MST program.

CALIBRATION

Drift Correction

The Bartington instrument is automatically zeroed at the beginning of each run, before the core enters the loop. Instrument drift may occur during the period of a core section scan. To correct for the drift, a zero-background measurement (MS_{bkgd}) is taken at the end of a core section log. The drift is corrected under the assumption that it is linear over the time of interest (about 10 min.). The time elapsed between the zeroing of the instrument at the beginning of the run and the background measurement, t_{bkgd}, is measured. For each measurement within the core (MS_{meas}) the elapsed time (t) is also measured, and the background-corrected susceptibility, Ms_{corr}, is calculated as

$$MS_{corr} = MS_{meas} + MS_{bkgd} / t_{bkgd} \times t \,. \qquad (6)$$

Absolute Susceptibility Values

The Bartington instrument output values are relative, volume-specific susceptibilities ($\kappa_{relative}$), which must be corrected before they can be reported in

SI units. Currently, no correction is implemented for standard queries from the database. Three ways of correcting the susceptibilities are described here. The third method is recommended for implementation on *JOIDES Resolution* in the near future.

1. *Bartington correction factors.* Theoretically, the instrument output is in volume-specific SI units for cores with diameters (d) passing exactly through the coil diameter (D), i.e., if $d/D = 1$. Bartington provides a table relating values of d/D to correction factors that must be applied to the relative susceptibility readings from the meter. For d = 66 mm and D = 88 mm, d/D is 0.75 and the corresponding correction factor is 1.48. Then,

$$\kappa = \kappa_{relative} / 1.48 \times 10^{-5} = 0.68 \times 10^{-5}\ \kappa_{relative}\ . \qquad (7)$$

This correction does not take into account other effects such as those from core liner and core conveyer boat, etc.

2. *Calibration with laboratory measurements.* Absolute susceptibility is easily measured on sample cubes in shorebased or shipboard laboratories (Kappabridge). These measurements can be compared with corresponding readings from the Bartington instrument. Empirical correlation from Leg 154 and Leg 162 data gave correction factors of 7.7×10^{-6} and 8.0×10^{-6}, respectively. On Leg 154, volumes of specimens were not exactly determined and may have been slightly smaller than assumed, which would underestimate the factor.

3. *Calibration with core standard (Figure 4—1).* The most straightforward approach is to calibrate the instrument using a piece of core liner (40 cm long) filled one-half with a homogenous mixture of magnetite (about 0.5%, pseudo-single domain) and epoxy ($\kappa_{standard} \sim 1000 \times 10^{-6}$) and one-half with pure water ($\kappa_{water} = -9 \times 10^{-6}$). The magnetic susceptibiltiy of the standard core is determined once and precisely from splits. The instrument response is then related to the actual volume susceptibiltiy, which also eliminates effects related to core geometry and the core conveyor system. Once this method is implemented, calibration coefficients can be routinely applied to future measurements and standard data queries will return absolute susceptibility in SI units.

PERFORMANCE

Precision

Precision is 2×10^{-6} (SI). Susceptibility values in natural, marine sediment samples over an interval of only a few meters (Milankovitch or millennial scale cyclicity) can range from a few tens to several thousands of 10^{-6} SI units. Typically, variations are 2 to 3 orders of magnitude greater than the precision. This makes magnetic susceptibility one of the most precise proxies for stratigraphic changes and extremely useful for core-to-core correlation.

Accuracy

Accuracy is 5% (according to Bartington).

Spatial Resolution

We determined the full-width-half-maximum (FWHM) response from measurements of four thin discs with varying amounts of iron dust (Figure 4—2). The discs were mounted 20 cm apart from each other in a core liner, representing thin strata of high susceptibility. Relative susceptibility values ranged from 40×10^{-6} to 200×10^{-6}. The four widths associated with half-maxima ranged from 4.0 to 4.4 cm. The width along the core axis corresponding to >99% response is about 15 cm. It is recommended that the first and last measurement in each core section be taken 3–4 cm away from the edge to avoid any deconvolution of edge effects.

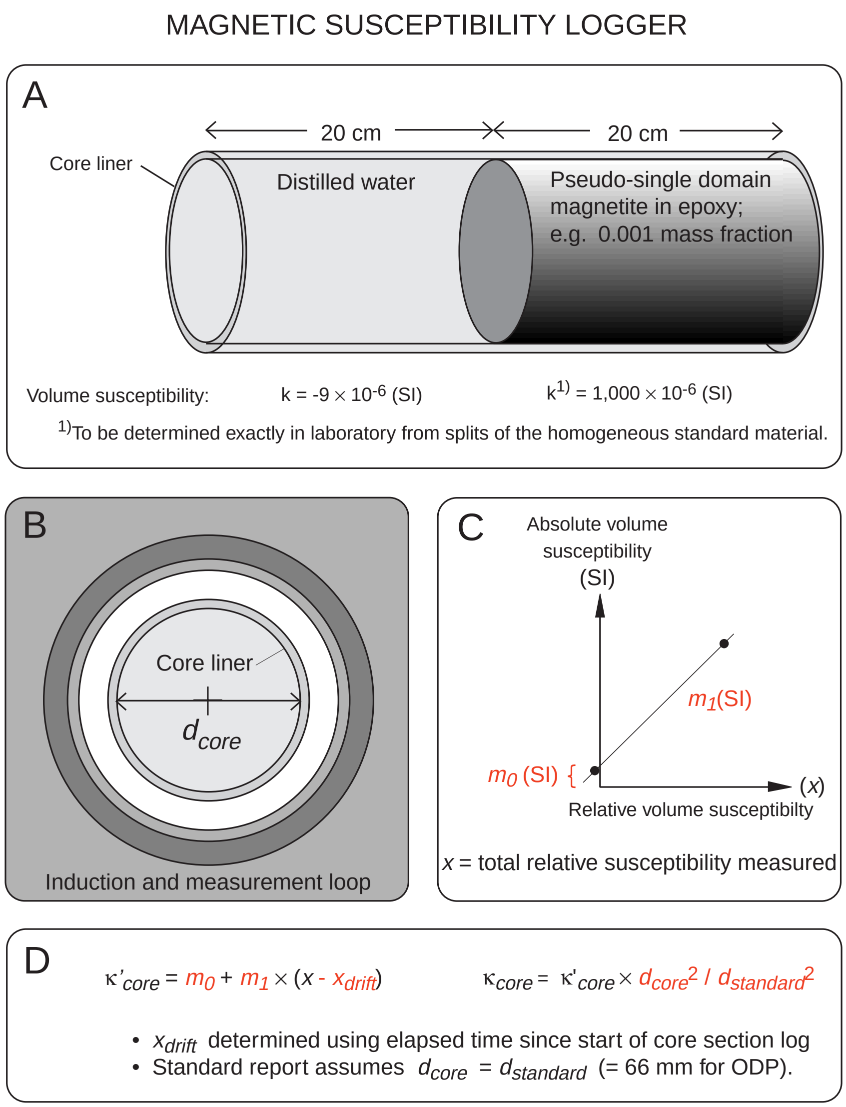

Figure 4—1 Schematic of proposed magnetic susceptibility logger calibration. A. physical standard used (To be implemented). B. Measurement geometry. C. Calibration principle. D. Application of calibration to core measurement.

MEASUREMENT

The magnetic susceptibility is logged downcore automatically.

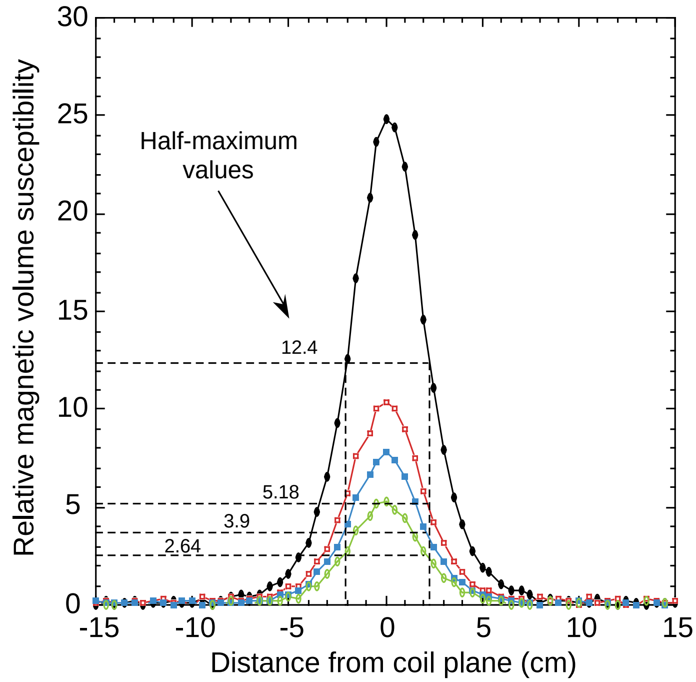

Figure 4—2 Magnetic susceptibility response curves from the MS2C coil system. The curves were obtained from the measurement of four thin discs with various amounts of iron powder mounted in a piece of core liner.

DATA SPECIFICATIONS

Database Model

Table 4—2 MSL database model.

MSL section
msl_id [PK1]
section_id
run_number
run_date_time
core_status
liner_status
requested_daq_interval
req_daqs_per_sample
bkgd_susceptibility
bkgd_elapsed_zero_time
core_temperature
loop_temperature

MSL control 1
msl_ctrl_1_id [PK1]
run_number
run_date_time
core_status
liner_status
requested_daq_interval
req_daqs_per_sample
standard_id
bkgd_susceptibility
bkgd_elapsed_zero_time
core_temperature
loop_temperature

MSL control 3
msl_ctrl_3_id [PK1]
run_number
run_date_time
req_daqs_per_sample
standard_id
bkgd_susceptibility
bkgd_elapsed_zero_time
core_temperature
loop_temperature
meas_susceptibilty_mean
sample_elapsed_zero_time
actual_daq_period

MSL section data
msl_id[PK1] [FK]
mst_top_interval [PK2]
mst_bottom_interval
meas_susceptibility_mean
sample_elapsed_zero_time
actual_daq_period
core_diameter

MSL control 1 data
msl_ctrl_1_id [PK1] [FK]
mst_top_interval [PK2]
mst_bottom_interval
meas_susceptibility_mean
sample_elapsed_zero_time
actual_daq_period
core_diameter

Notes: MSL control 1 are control measurements run the same way as a core section. MSL control 3 are control measurements from a standard mounted on the core boat.

Standard Queries

Table 4—3 MSL report

Short description	Description	Database
A: Results		
Sample ID	ODP standard sample designation	Link through [MSL Section] section_id
Depth	User-selected depth type	Link through [MSL Section] section_id
Mag. susc.	Drift-corrected magnetic susceptibility	=[MSL Section Data] meas_suscept_mean -[MSL Section] bkgd_susceptibility / [MSL Section] bkg_elapsed_zero_time * [MSL Section Data] sam_elapsed_zero_time
B (optional): Parameters and measurements		
Run	Run number	[MSL Section] run_number
Date/Time	Run date/time	[MSL Section] run_date_time
Core Status	HALF or FULL	[MSL Section] core_status
Liner Status	NONE, HALF or FULL	[MSL Section] liner_status
Req. Interval	User-defined sampling interval (cm)	[MSL Section] requested_daq_interval
Daqs/sample	User-def. data acquisitions per sample	[MSL Section] req_daqs_per_sample
Bkgd. Susc.	Background at end of section run	[MSL Section] bkgd_susceptibility
Bkgd. Time	Time elapsed since start of section. run	[MSL Section] bkgd_elapsed_zero_time
Core Temp.	Core temperature	[MSL Section] core_temperature
Loop Temp.	Loop temperature (to be implemented.)	[MSL Section] loop_temperature
Mag. Susc.	Measured magnetic susceptibility	[MSL Section Data] meas_suscept_mean
Elapsed Time	time elapsed since start of run (s)	[MSL Section Data] sam_elapsed_zero_time
Period	Actual sampling period	[MSL Section Data] actual_daq_period
Core Dia.	Core diameter, default = 6.6 cm	[MSL Section Data] core_diameter

Table 4—4 *MSL control 1 measurements (to be implemented).*

Short description	Description	Database
Mag. susc.		=[MSL Ctrl 1 Data] meas_suscept_mean -[MSL Ctrl 1] bkgd_susceptibility / [MSL Ctrl 1] bkg_elapsed_zero_time * [MSL Ctrl 1 Data] sam_elapsed_zero_time
Run	Run number	[MSL Ctrl 1] run_number
Date/Time	Run date/time	[MSL Ctrl 1] run_date_time
Core Status	HALF or FULL	[MSL Ctrl 1] core_status
Liner Status	NONE, HALF or FULL	[MSL Ctrl 1] liner_status
Req. Interval	User-defined sampling interval (cm)	[MSL Ctrl 1] requested_daq_interval
Daqs/sample	User-def. data acquisitions per sample	[MSL Ctrl 1] req_daqs_per_sample
Standard	Standard name	[Phys. Properties Std.] standard_name
Std. Set	Standard set name	[Phys. Properties Std.] standard_set_name
Std. Expected	Expected value (range) (g/cm^3)	[Phys. Prop. Std. Data] property_value
Bkgd. Susc.	Background at end of section run	[MSL Ctrl 1] bkgd_susceptibility
Bkgd. Time	Time elapsed since start of section run	[MSL Ctrl 1] bkgd_elapsed_zero_time
Core Temp.	Core temperature	[MSL Ctrl 1] core_temperature
Loop Temp.	Loop temperature (to be implemented.)	[MSL Ctrl 1] loop_temperature
Interval	Interval top	[MSL Ctrl 1 Data] mst_top_interval
Mag. Susc.	Measured magnetic susceptibility	[MSL Ctrl 1 Data] meas_suscept_mean
Elapsed Time	time elapsed since start of run (s)	[MSL Ctrl 1 Data] sam_elapsed_zero_time
Period	Actual sampling period	[MSL Ctrl 1 Data] actual_daq_period
Core Dia.	Core diameter, default = 6.6 cm	[MSL Ctrl 1 Data] core_diameter

Table 4—5 *MSL control 3 measurements (to be implemented).*

Short description	Description	Database
Mag. susc.		=[MSL Ctrl 3] meas_suscept_mean -[MSL Ctrl 3] bkgd_susceptibility / [MSL Ctrl 3] bkg_elapsed_zero_time * [MSL Ctrl 3] sam_elapsed_zero_time
Run	Run number	[MSL Ctrl 3] run_number
Date/Time	Run date/time	[MSL Ctrl 3] run_date_time
Daqs/sample	User-def. data acquisitions per sample	[MSL Ctrl 3] req_daqs_per_sample
Standard	Standard name	[Phys. Properties Std.] standard_name
Std. Set	Standard set name	[Phys. Properties Std.] standard_set_name
Std. Expected	Expected value (range) (g/cm^3)	[Phys. Prop. Std. Data] property_value
Bkgd. Susc.	Background at end of section run	[MSL Ctrl 3] bkgd_susceptibility
Bkgd. Time	Time elapsed since start of section run	[MSL Ctrl 3] bkgd_elapsed_zero_time
Core Temp.	Core temperature	[MSL Ctrl 3] core_temperature
Loop Temp.	Loop temperature (to be implemented)	[MSL Ctrl 3] loop_temperature
Mag. Susc.	Measured magnetic susceptibility	[MSL Ctrl 3] meas_suscept_mean
Elapsed Time	time elapsed since start of run (s)	[MSL Ctrl 3] sam_elapsed_zero_time
Period	Actual sampling period	[MSL Ctrl 3 Data] actual_daq_period

4.3. MS2E1 Point Sensor for Split-Core Logger

At the end of 1996, ODP has purchased a magnetic susceptibility probe type MS2F manufactured by Bartington. This miniature probe is ideally suited for measurements on splitcore surfaces with roughness <1 mm. The FWHM response measured in two axes on the plane of the sensing surface has linear dimensions of 3.8×10.5 mm, giving a spatial resolution 1 order of magnitude better than with the loop sensor (FWHM of 42 mm). The depth response below the surface of investigation drops to 50% at 1 mm and to 10% at 3.5 mm depth, requiring full contact with a smooth surface. The sensor operates at a frequency of 2 kHz and has the same resolution (2×10^{-6} SI on 0.1 range) and slightly larger measuring time (1.2 s at 1.0 setting) than the coil sensor.

The MS2E1 sensing surface is at the end of a ceramic tube and is protected by a thin ceramic (aluminum oxide) plate that must be in immediate contact with the surface of investigation during the measurement. The tube is mounted on a metal enclosure that houses the electronic circuitry. Soft or wet cores may be protected by a thin plastic film of a thickness less than 0.05 mm. This also prevents the pickup of potentially contaminating material that could create inaccuracies.

This sensor will be implemented on either the archive-half or working-half core logging system. Both systems are in the design stage.