MULTIVARIATE STATISTICAL ANALYSIS ON BLOWER DOOR TESTING POPULATION

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INTRODUCTION

The quantification of building airtightness is paramount in the determination of in-situ building energy use, building air quality, and moisture related building enclosure durability. Airtightness is also vital in predicting energy use. Furthermore, accurate preconstruction airtightness estimation can aid in the selection and sizing of an energy efficient heating ventilation and air conditioning system.

This paper studied 900,000 unique airtightness test records to identify the primary factors that influence building airtightness in Canadian homes. The tested homes comprise low rise single family detached homes spanning nine provinces and two territories. A multivariate statistical analysis related the building's airtightness to "as-built" characteristics including building volume, number of floors, and year of construction. The relationships and influence between these predictor variables was compared to the resultant measured air leakage rate. A successful linear regression model based on this existing data formed the basis for further study for the prediction of airtightness in both conventional and low energy homes.

LITERATURE

Building airtightness has been recognized as an important contributor to building energy performance since the 1970's with the construction of energy efficient residential dwellings in Twin Rivers, New Jersey[1] and in Saskatoon, Saskatchewan[2]. The discovery of significant thermal energy loss through insulated building enclosures above the predicted value was found to be due to uncontrolled air leakage[1]. There are a plethora of ways to describe airtightness, but most definitions can be simplified to the movement of air through the building enclosure. The most common practice to quantify and measure the air transfer through the building enclosure is via use of pressurized air leakage testing or the so-called "blower door test"[3]. Various test procedures[456] have been formalized. These tests utilize a pressurizing fan that applies a range of pressures on the building enclosure via suction or pressure. The pressure difference between the interior and exterior of the building in conjunction with the measured volumetric flowrate allow for an estimate of air leakage at a standardized pressure. The measure of airtightness is thus the volumetric flow rate divided by some other convenient measure. The measure could be time, volume, usable floor space, or enclosure area.

Airtightness Models

In the Netherlands, a study[7] examining N = 320 houses relating building air leakage to floor area, year of construction, dwelling type, construction method, enclosure area, and roofing type was conducted[7]. The authors found that building age was a strong predictor of airtightness. More specifically, older buildings in

their sample tended to be leakier than newer buildings in their study. Their regression model showed a coefficient of determination of $R^2 = 0.437$ using the most significant predictor variables.

In Greece, a study for a small sample of N=20 found that the average air change rate per hour was 7ACH at 50 Pa[8]. The regression model used a unique predictor variable called a "Frame Length Factor". The frame length factor considered the sum total length of a typical joint as a fraction of the building volume. With the inclusion of this regression variable, the coefficient of determination was found to be 0.55 for homes of medium air tightness and 0.35 for dwellings on the lower ACH range. The modeling approach was limited by the low building sample size.

A United Kingdom study using a sample size of N=287 for new dwellings built between 2006 and 2010[9]. The regression analyses had shown coefficients of determination of $R^2 = 0.48$ and $R^2 = 0.49$. The predictor variables in this study accounted for the building enclosure materials and workmanship. The study also included apartment style dwelling along with detached houses. The inclusion of heterogeneous housing typologies could have had the effect of strengthening the resulting coefficient of determination.

A seminal study in the United States[10] used over N= 134 000 records of single detached houses representing most climate zones in the continental United States. The study utilized several predictor variables specific to the housing construction, including floor area, house height, and foundation type. The regression formulation developed also controlled for whether or not the homes had already participated in energy efficiency programs. Climate zone was also considered using a 12 point system. The mathematical model predicted that 90% of US homes had a normalized leakage rate between 0.22 to 1.95NL. The median normalized air leakage rate was determined to be 0.67 with a $R^2 = 0.68$.

With the exception of the US study, the UK, Greek, and Dutch studies had a low sample size for their respective predictive models. Secondly, the building location were narrow and could have had an effect on the predictive power of the regression analyses for these various studies. The US study covered a wide geographic area, with good geographic representation per county. The US study additionally considered more predictive variables as compared to the other studies. The US study's housing representation was geographic in nature, with equal representation by county rather by population density. This method, although comprehensive, could over represent atypical workmanship or design practices in the regression formulation. In addition, the US study considered some housing construction practices that are not as common in Canadian jurisdictions. Namely, the HVAC duct work location in crawl spaces or attics located outside the building' thermal envelope which can have an important effect on building airtightness.

Airtightness Trends

An Irish study[11] considered N=28 semi-detached dwellings that were built between 1944 to 2008. The variables in this study targeted particular features. These features comprised of the existence of cavity insulation, attic insulation or central heating. Based on the studies data, the author calculated the arithmetic mean for air tightness was 9.6 ACH. This level of airtightness was considered too loose based on the international standards at the time of publication. This study found that newer buildings were not necessarily more airtight and that the workmanship and construction quality had a greater influence on overall building air permeability.

Another equally small Estonian study[12] of N= 32 homes of new single detached homes build from prefabricated walls during 2003 to 2005 were examined for air tightness. The authors found that two storey buildings were leakier than one storey buildings. The average air leakage was 4.9 ACH and their forensic analysis showed that the majority of the leaks were either located near the exterior wall transitions with floors windows and roofs.

A Canadian study[13] characterized the airtightness of N=2263 homes by ACH and Normalized Air Leakage both by temporal and regional groupings. The Canadian regions comprised of British Columbia, the Prairies, Ontario, Quebec and the Maritimes provinces. The trend was that air tightness was general increased from older homes to newer homes. Regionally, the Prairies were considerable more air tight over time while the leakiest homes were found to be in British Columbia and Quebec. The study found increasing air tightness with time in all geographic regions. Results also indicated a marked decrease in regional variability in the temporal domain.

The aforementioned trend based studies had a relatively smaller sample sizes. Their aims included the study of general trends while not providing an explicit predictive formulation. The Canadian study, while larger in sample size, had grouped Prairie and Maritime jurisdictions in regional pools. This pooling of data may have been necessary based on data availability, or to other practical sampling limitations. The net effect was that it reduced the granularity of the data that was analyzed.

Taken as a whole, we wanted to take into account a large sample size that best represented both the unique Canadian geography and Canadian building typologies.

METHOD

Canadian National airtightness data was taken from the residential energy efficiency program from the Federal government. The collection of data was completed under the Natural Resources Canada' ecoEnergy Retrofit programs[14]. Homeowners were required to have their homes undergo a pre-retrofit energy evaluation. All leakage data was collected utilizing the fan (de)pressurization method, commonly referred to as a blower door test.

The data set used in this study comprised over 900 000 blower door tests performed on unique single detached homes constructed between the late 1700's through to 2016. The sample contains homes from 9 provinces and 2 territories. The data contained: build year, jurisdiction, number of storeys, test method, and building volume. The output values per house record included the effective leakage area and the air changes per hour at 50 Pascal.

The software used to run the multi-variate analysis was IBM's SPSS 10 which is a predictive analytics software package that allows for data analysis and model building.

Based on the literature review the authors expected to find the results to be log-normally distributed when plotted over the build year. The analysis will consider any possible correlation between a dwelling's age, volume, and height as it relates to both air leakage measures, ACH and Normalized Air Leakage. By focusing on jurisdiction, a measure of air barrier workmanship as it relates to ACH and Normalized Leakage was investigated. Finally, the question of a linear regression model as a predictor for the existing NRCan data set was investigated. A successful model can form the basis for a future model with additional predictor

variables.

LIMITATION

We acknowledge limitations in the data set. Some physical characteristics affecting an air-barrier's effective permeability such as foundation type, foundation to wall joint type, roofing type, the presence of a chimneys, and the presence of garages were not known. Hence the effect of these details may have been masked within other known variables. In addition, the airtightness tests were mainly "as operated test, with little or no sealing of intentional openings. Furthermore, the lack of massing details building perimeter, total floor space, and number of doors and windows, may further limit the power of the analysis. Lastly, the building enclosure materials where largely unknown.

RESULTS & DISCUSSION

Descriptive Statistics

Figure 1 shows a histogram of air leakage in ACH as compared to frequency confirms a log normal distribution. The shape of the distribution was expected since one "tail" of the distribution is constrained by "zero" air leakage while the other tail of the distribution can theoretically be several orders of magnitude larger than the restricted tail. A geometric mean often reflects a more meaningful estimate of the sample mean as compared to the arithmetic mean due to the exponential decay. The geometric mean ACH data was found to be 5.7 ACH, while the arithmetic mean was 18% greater at 6.7 ACH.

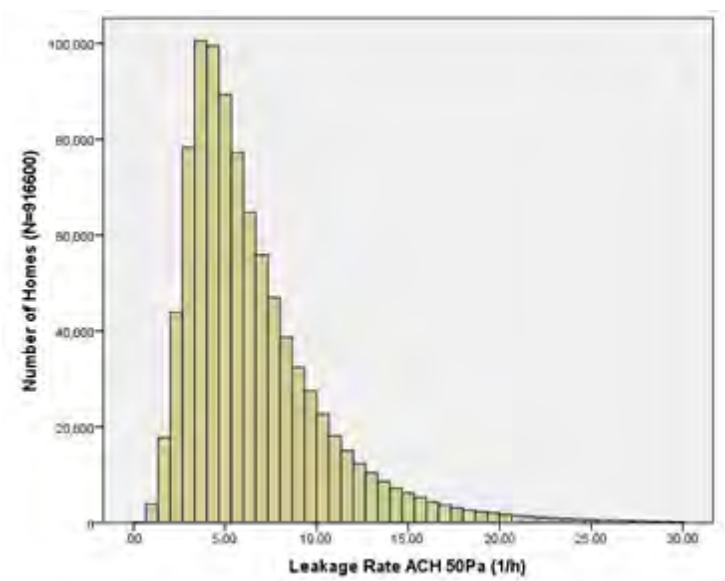

Figure 1: Air Leakage Rate Frequency

Table 1: Mean Air Leakage by Province

	ACH 50		
	A. mean	G. mean	Std. Dev
Alberta	5.6	4.8	3.6
British Columbia	7.9	7.0	4.2
Manitoba	5.2	4.3	3.6
New Brunswick	6.3	5.2	4.4
Nova Scotia	8.5	7.1	5.5
NWT	6.3	5.3	4.1
Nunavut	3.9	3.4	2.3
Ontario	6.8	5.9	4.2
PEI	6.4	6.4	4.2
Quebec	5.9	5.0	3.9
Saskatchewan	5.1	4.4	3.4

Segregating the mean air leakage by province reveals that Nunavut, Manitoba and Saskatchewan have the lowest air leakage rates on an ACH basis (Table 1). These lower leakage rates occur despite having some of the smallest interior volume (Table 8). Nova Scotia, British Columbia and PEI were shown to have the higher air leakage rates.

Table 2: Mean Air Leakage by Building Height

		ACH 50		
		A. mean	G. mean	Std. Dev
Storeys	1	6.3	5.3	4.1
	1.5	9.6	8.4	5.2
	2	6.8	5.8	4.2
	2.5	9.4	8.5	4.3
	3	9.0	8.1	4.2

When the air leakage rate is separated by building height (Table 2), it was found that single and double storey homes had the lowest leakage by 23%. However, these leakage rates may be mostly influence by the newness of the housing stock which was calculated to be 22 years younger than the mean housing age (Table 6).

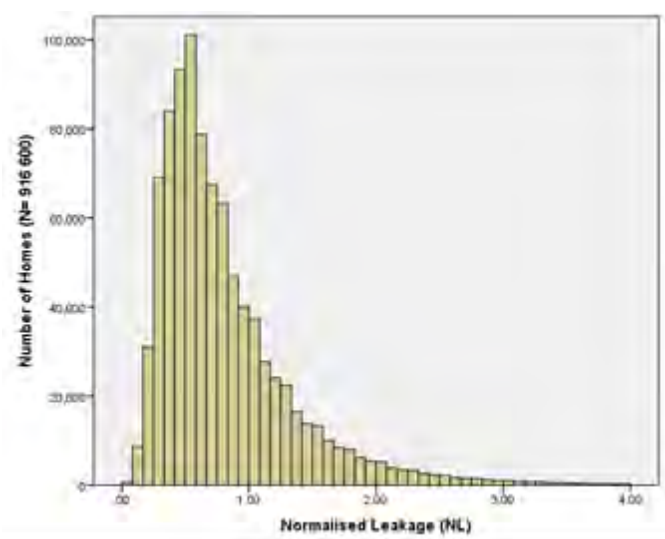

Figure 2: Alternate Mean Air Leakage Rate Frequency

As an alternative to air leakage on an ACH basis, Normalized Leakage was plotted for the data set to compare buildings independent of building height and building volume. Not surprisingly the normalized frequency plot (Figure 2) was also log normal with a geometric mean of 0.67 and an arithmetic mean of 0.81.

Table 3: Alternate Mean Air Leakage by Province

	Normalised Leakage		
	A. mean	G. mean	Std. Dev
Alberta	0.65	0.54	0.47
British Columbia	0.96	0.83	0.55
Manitoba	0.60	0.48	0.47
New Brunswick	0.75	0.59	0.59
Nova Scotia	1.07	0.85	0.78
NWT	0.75	0.63	0.49
Nunavut	0.46	0.40	0.26
Ontario	0.84	0.71	0.56
PEI	0.80	0.64	0.60
Quebec	0.70	0.57	0.52
Saskatchewan	0.57	0.47	0.44

When compared on a on a Provincial basis (Table 3) Nunavut, Saskatchewan, and Manitoba remain the provinces that produced the tightest homes based on the data set. Nova Scotia, British Columbia, and Ontario were the leakiest homes on normalized basis.

Table 4: Alternate Mean Air Leakage by Building Height

		Normalised Leakage		
		A. mean	G. mean	Std. Dev
Storeys	1	0.68	0.57	0.48
	1.5	1.19	1.02	0.70
	2	0.91	0.76	0.60
	2.5	1.35	1.20	0.66
	3	1.37	1.21	0.68

Single storey home show even less air permeance (Table 4) as compared to two storey homes (Table 2). The single-story building is 33% less leaky as compared to the double-story mean. The relative leakiness between the single and dual storey buildings on an ACH basis was 9%. The leakiest building configuration became the 3 floor house (Table 4) as compared to the 2.5 storey house on the ACH basis (Table 2).

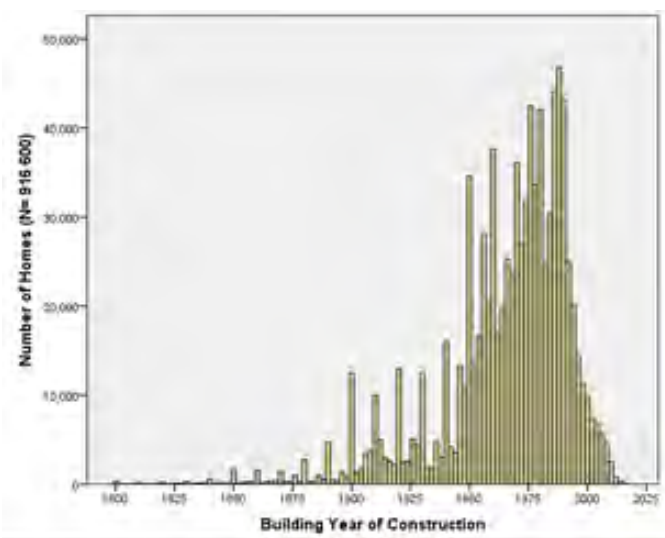

Figure 3: Frequency plot of Building Year of Construction

The frequency plot for the Build Year showed a marked heterogeneity (Figures 3). Upon further investigation, it was found that the plot of that of a superposition of many distributions, reflecting the

predominance or prevalence of certain housing configurations at certain periods in time. The geometric mean and the arithmetic mean for building age were found to nearly equal at 1965.

Table 5: Mean Building Year by Province

	Build Year		
	A. mean	G. mean	Std. Dev
Alberta	1971	1971	19
British Columbia	1971	1971	21
Manitoba	1957	1956	26
New Brunswick	1966	1966	30
Nova Scotia	1955	1955	37
NWT	1981	1981	13
Nunavut	1990	1990	13
Ontario	1965	1964	29
PEI	1958	1958	39
Quebec	1966	1966	29
Saskatchewan	1964	1964	22

On a provincial basis Nova Scotia, Manitoba, and Prince Edward Island had the oldest building stock from the data set (Table 5). Nunavut and North West Territories had the newest mean building stock.

Table 6: Mean Building Year by Building Height

		Build Year		
		A. mean	G. mean	Std. Dev
Storeys	1	1969	1969	18
	1.5	1939	1939	33
	2	1965	1964	34
	2.5	1923	1923	31
	3	1929	1929	34

Table 6 shows that building typologies may have changed over time. The 1.5, 2.5 and 3 story single family detached style homes significantly older than 1 and 2 floor buildings.

Table 7: Mean Air Leakage Compared to Mean Building Year

	ACH		Build Year		
ACH Range	G. Mean	Std. Dev	G. Mean	Std. Dev	Number of Houses
0 < ACH < 1	0.8	0.1	1997	16	1071
1 < ACH < 2	1.6	0.3	1991	16	20267
2 < ACH < 4	3.1	0.5	1981	16	220987
4 < ACH < 8	6.0	1.1	1968	23	433123
8 < ACH <16	10.4	2.1	1945	31	204947
16 < ACH < 32	19.9	3.7	1932	34	31289
32 < ACH < 64	37.8	5.5	1935	33	1904
64 < ACH	69.4	4.9	1948	21	6

The mean build year as a function of air leakage rate showed two trends as summarized in Table 7. The mean age of the building increased as the mean air change per hour increased. Furthermore, the dispersion of the air leakage, as illustrated by the standard deviation, increased from 0.1 to 4.9 as building age increased.

Table 8: Mean House Volume by Province

	Volume m^3		
	A. mean	G. mean	Std. Dev
Alberta	568	533	218
British Columbia	589	550	234
Manitoba	498	470	185
New Brunswick	520	488	198
Nova Scotia	502	466	203
NWT	418	376	194
Nunavut	391	374	131
Ontario	621	573	271
PEI	570	531	219
Quebec	521	492	195
Saskatchewan	489	465	162

Building volume was found to be best described as a log normal distribution. Hence, the geometric mean was determined to be a better descriptor of mean volume statistic. Ontario was found to have the largest homes by volume 18% above the mean, while Nunavut and the North-West Territories had the smallest home by volume at approximately 23% below the mean. Interestingly, the similarity in small size and building age for Nunavut and the NWT did not translate to similar air tightness values (Table 8).

Table 9: Mean House Volume by Building Height

		Volume m3		
		A. mean	G. mean	Std. Dev
Storeys	1	494	467	177
	1.5	502	473	189
	2	669	623	270
	2.5	748	698	314
	3	791	731	364

Table 10: Mean Air Leakage As Compared To House Volume

	ACH		Volume m3		
ACH Range	G. Mean	Std. Dev	G. Mean	Std. Dev	Number of Houses
0 < ACH < 1	0.8	0.1	752	811	1071
1 < ACH < 2	1.6	0.3	670	374	20267
2 < ACH < 4	3.1	0.5	630	277	220987
4 < ACH < 8	6.0	1.1	546	220	433123
8 < ACH <16	10.4	2.1	456	187	204947
16 < ACH < 32	19.9	3.7	350	153	31289
32 < ACH < 64	37.8	5.5	247	118	1904
64 < ACH	69.4	4.9	177	17	6

The largest homes unsurprisingly had the lowest air leakage rates as measured by ACH. However, Table 10 also showed that the tightest homes with ACH's under 2 had the greatest variability in volumetric size as evidenced by associated standard radiation.

Regression Statistics

It was found that "Building Year" was the most important predictor variable tied to building air leakage. A

summary of the regression correlation matrix can be seen below (Table 11). Furthermore, the use of the model output was compared. A linear regression analysis using Air Changes per Hour was contrasted to the Normalized Leakage in Table 12). The comparison showed a slight improvement the in the Pearson correlation coefficient r, which varied between from 0.565 to the 0.592.

Table 11: Regression Variables for Varying Leakage Metrics

Regression Variable Correlations			
Leakage Metric	Build Year	Number of Storeys	Building Volume
ACH	-0.500	0.086	-0.315
NL	-0.514	0.234	-0.247

Table 12: Comparison of Pearson Correlation and Coefficient of Determination

Regression & Leakage Metric		
	r	R^2
ACH	0.565	0.319
NL	0.592	0.350

Table 13: Linear Regression Model Strength by r and R^2 per Province

Regression Analysis				
Province	r	R^2	N	p value
Alberta	0.523	0.274	49000	0.000
British Columbia	0.539	0.291	111000	0.000
Manitoba	0.676	0.457	26000	0.000
New Brunswick	0.592	0.350	45000	0.000
Nova Scotia	0.623	0.388	51000	0.000
North West T.	0.589	0.347	950	0.000
Nunavut	0.658	0.433	70	0.000
Ontario	0.604	0.365	460000	0.000
Prince Edward Island	0.690	0.476	4000	0.000
Quebec	0.540	0.292	114000	0.000
Saskatchewan	0.649	0.421	55000	0.000

A regression analysis was also performed on the data as grouped per province (Table 13). All models were shown to be significant with a p value < 0.000. Since all Pearson correlation coefficients r, were within the range of 0.5 to 0.7 one can classify the relationship between the ACH predictive variables of building age, volume, and height to be moderate. However, the coefficient of determination, R^2, showed that the all provincial regression models only explained between 27% to 48% of the variation into the data.

Table 14: Regression by Mean Build Year

Regression Analysis				
Range Year Built	r	R^2	N	p value
1950 > T	0.375	0.141	174000	0.000
1950 < T < 1970	0.322	0.104	212000	0.000
1970 < T < 1990	0.336	0.113	346000	0.000
1990 < T < 2015	0.351	0.123	108000	0.000
All Years	0.565	0.319	916000	0.000

The air leakage data was also separated into build year categories. Table 14 showed that the regression model was is the strongest when data from all years were considered. The strength of the correlation was weakened when a regression analysis was performed on less houses.

Table 15: Linear Regression Coefficients from SPSS

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	136.267	.268		509.292	.000
	Vol_m3	-.005	.000	-.291	-304.659	.000
	Storeys	1.041	.008	.129	135.600	.000
	BuildYear	-.065	.000	-.432	-480.454	.000

a. Dependent Variable: ACH50

Table 15 shows that the three coefficients for the regression model based on Air Changes per Hour. The predictive variables of volume, building height, and building year had their coefficients B determined. Building volume, measured in meters cubed had its associated coefficient determined to be -0.005. Building height, represented by storeys had the coefficient +1.041. Lastly the build year had a coefficient determined to be -0.065. All coefficients were found to be significant ($p < 0.000$). The resultant model for this regression was found to be:

ACH = 136.267 - 0.005*(Building Volume) + 1.041*(Storeys) -0.065*(Build Year)

Based on the equation above on can predict the air leakage in a Canadian building with the knowledge of the Building Volume, building height and year of construction with moderate accuracy ($r=0.56$) while explaining 32% of the variation in air leakage. The results from this study was the most consistent with both the Canadian and United States studies. Both the United States study and this study predicted a mean normalized air leakage of 0.67 across each respective population. The strength of the US model was stronger with $R^2 = 0.68$ compared to $R^2 = 0.32$. However, the US study considered design peculiarities not common in the Canadian context. Furthermore, our study and the smaller Canadian study had found that Prairie Provinces had the tighter houses. However, there was less agreement on which houses were the least air tight.

Since building age was seen to be the most influential predictor variable, it will be necessary to examine what possible independent factors associated with building age can be isolated explicitly for analysis. This and previous studies suggest that building age may be a proxy for specific and measurable building details and building workmanship. Future steps in the analysis would be to verify an expanded set of predictor variables that increase the absolute value of the covariance between air leakage and new building variables.

CONCLUSION

A detailed study of a large national data set was performed. A regression equation predicting pressurized air leakage was constructed based on Canadian homes at the pre-retrofit stage. This data set contained homes in 11 of 13 of the jurisdictions throughout Canada. Air leakage was examined by building jurisdiction, overall

building height, building volume, and build date. Pearson's correlation coefficient, $0.565 < r < 0.592$ ($p < 0.000$), showed a moderate relationship between air leakage and the predictor variables. The coefficient of determination was found to explain between 35-32% of the air leakage ($0.350 > R^2 > 0.319$). Further study of this data could be used to add another climate zone in the form of Heating Degree Days as a fourth predictor variable. Future study may also consider non-linear regression models to add explanatory power to the air leakage model**.** Lastly, additional buildings details regarding building massing, wall details, wall materials, and workmanship would be useful in providing additional statistical power to the regression model.

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