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EVALUATION OF VARIOUS OPTIONS FOR THE COMPRESSION AND DISTRIBUTION OF COMPRESSED HELIUM GAS TO THE SATELLITE REFRIGERATION SYSTEM OF THE ENERGY DOUBLER

PREPARED UNDER FERMILAB SUBCONTRACT NO. 94199
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FOR

FERMI NATIONAL ACCELERATOR LABORATORY
BATAVIA, ILLINOIS

1 March 1979

I N D E X

EVALUATION OF VARIOUS OPTIONS FOR THE COMPRESSION AND DISTRIBUTION OF COMPRESSED HELIUM GAS TO THE SATELLITE REFRIGERATION SYSTEM OF THE ENERGY DOUBLER

1. Introduction:

The basic requirement is 24 times 50 gm/sec (1,200 g/sec) of helium gas to be distributed to 24 satellite refrigerator cold boxes. Spacing of the cold boxes is at 800 ft intervals. The tunnel will contain an 8 in. IPS, Schedule 5 pipe which will run in parallel with the doubler. This pipe will be used for various purposes, as follows:

a) Collect gas during cooldown of the magnets.

b) Collect gas during quenches of parts or all of the accelerator.

c) Collect gas from leads and safety leads.

Compressed gas will be returned to the CHL from each satellite station through a 3 in. IPS, Schedule 5 pipe which will be located outside the tunnel and parallel the ring.

Under normal operating conditions of the doubler, 46.1 g/sec of helium gas at 20 atm and ambient temperature will be fed to the satellite refrigerator cold box. Gas is returned from the cold boxes at a rate of 50 g/sec at 1.05 atm and ambient temperature. This gas is compressed and 3.9 g/sec is returned to the CHL at a pressure of 20 atm.

Various combinations of compressor arrangements are possible. The basic arrangement is one compressor located at each satellite cold box. In that case, the 3 in. and 8 in. lines are not used for gas distribution between satellite cold boxes. A total of 24 compressors is required with power at each station. If one compressor drops out, gas may be supplied to that station from all other stations through the 3 in. line. The 8 in. line may be used to distribute low pressure gas to a number of adjacent compressors.

The purpose of this report is to examine other combinations of compressors, different size and number of compressors based on availability, and the final cost of any proposed alternatives to the basic system.

The following combination of number of compressors and number of stations were studied:

	# Stations	Compressors Per Station	Total Compressors
Case I	24	1	24
Case II	12	2	24
	12	1	12
Case III	8	3	24
	8	2	16
	8	1	8
Case IV	6	4	24
	6	3	18
	6	2	12
	6	1	6
Case V	4	6	24
	4	5	20
	4	4	16
	4	3	12
	4	2	8
	4	1	4
Case VI	3	8	24
	3	7	21
	3	6	18
	3	5	15
	3	4	12
	3	3	9
	3	2	6
	3	1	3

To compare the various cases, the pressure drop was calculated for the flow in the 3 in. and 8 in. pipelines. Calculations were made for 800 ft length sections of pipe based upon the flow through each of the sections for every case. Note that for Case I there is essentially no flow in the headers because each refrigerator cold box is supplied by its own compressor.

Figures I through VI indicate typical flow patterns for the various cases investigated. For simplification, flow values have been indicated in units where each unit represents 396.5 lb/hr (50.0 g/sec). The flow directional arrows represent discharge flow. For suction flow the unit values remain the same, but the directional arrows are reversed.

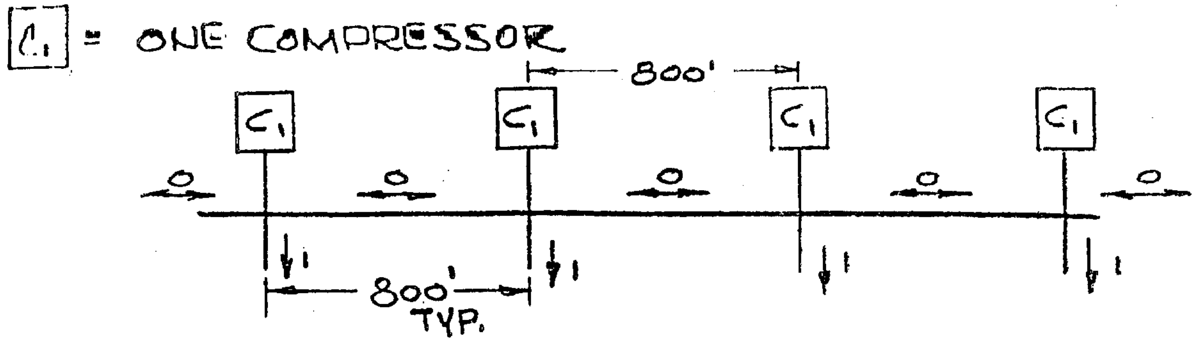

Fig. I: Case I - 24 Stations

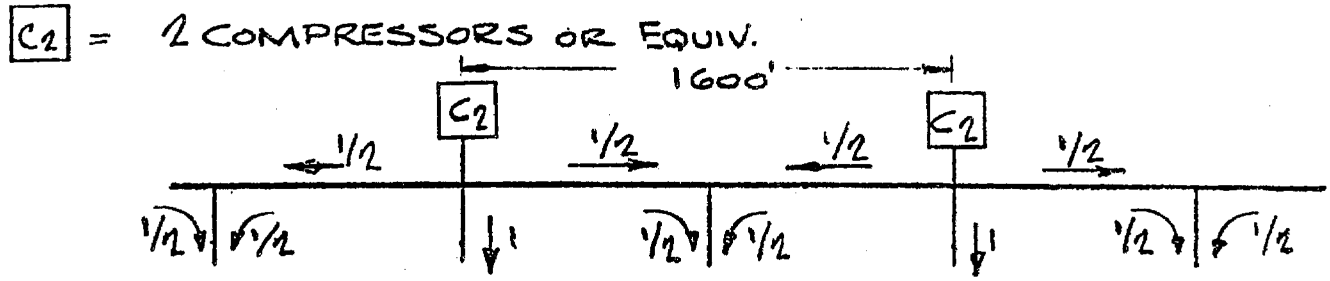

Fig. II: Case II - 12 Stations

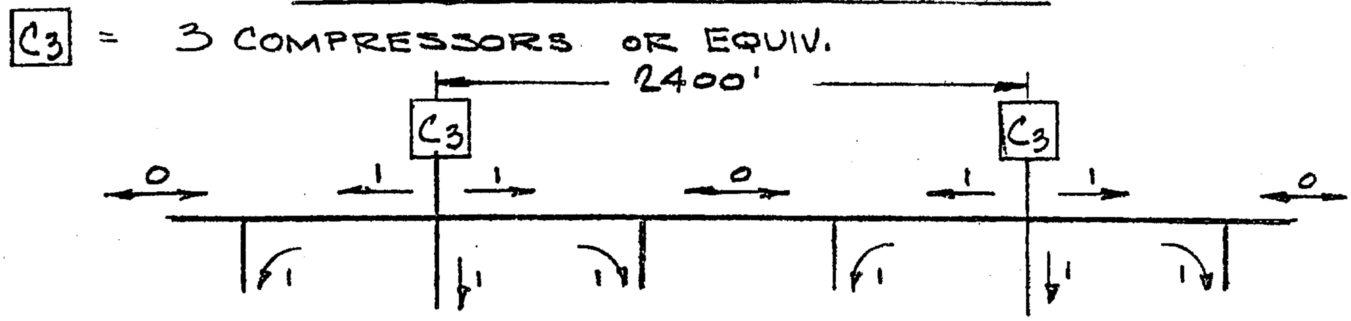

Fig. III: Case III - 8 Stations

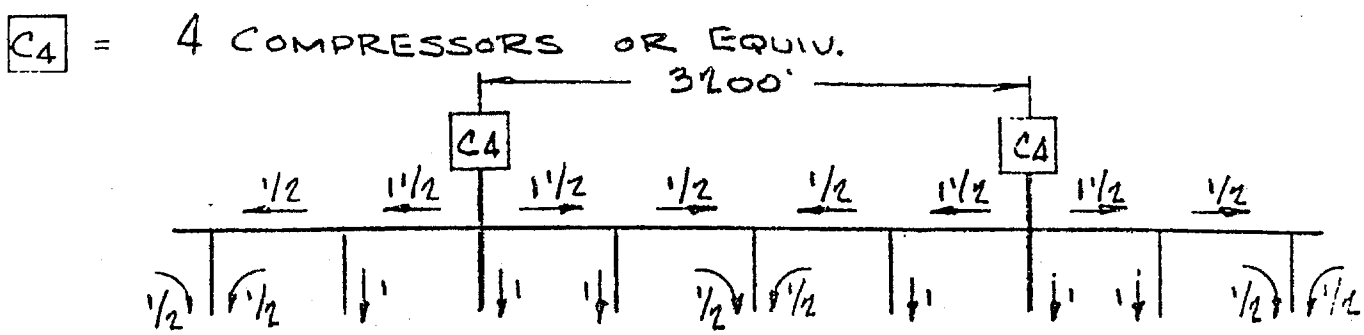

Fig. IV: Case IV - 6 Stations

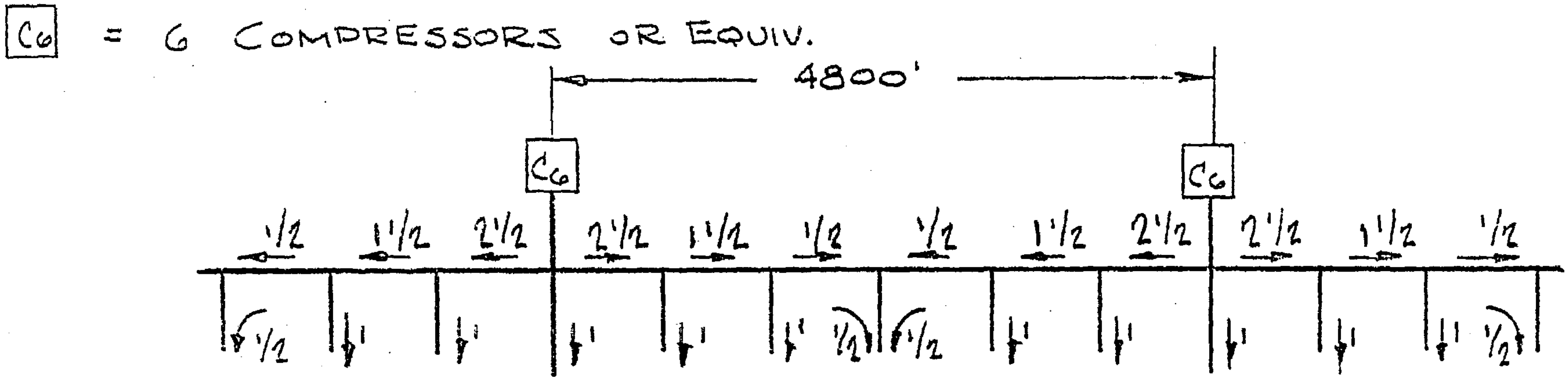

Fig. V: Case V - 4 Stations

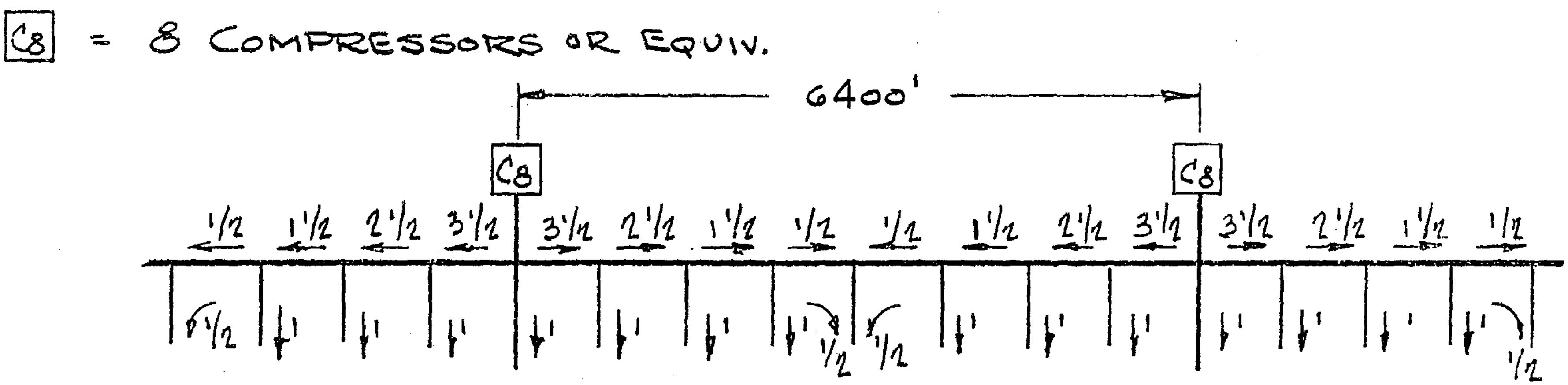

Fig. VI: Case VI - 3 Stations

2. Pressure Drop in Normal Balanced System:

2.1 Pressure Drop in 3 in. IPS, Schedule 5 Pipe Header:

$$\frac{\Delta P}{L} = \frac{f\ g^2}{30\,\rho\, d_L} \times 10^{-9} \text{ psig/ft} \qquad (1)$$

Where:

$g = \text{lb/hr ft}^2$

$f = \frac{.046}{Re^{.2}}$

$\rho = \text{lb/ft}^3$

$d_L = \text{ft}$

$Re = \frac{g\ d_L}{\mu}$

$$\frac{\Delta P}{L} = \frac{.046}{Re^{.2}} \times \frac{g^2}{\rho d_L} \times .033 \times 10^{-9}$$

$$= 1.53\ \frac{g^{1.8}\ \mu^{.2}}{\rho d_L^{\ 1.2}} \text{ psig/ft}$$

At ambient temperature and 20 ata:

$\rho = .20 \text{ lb/ft}^3$

$\mu = .0484 \text{ lb/ft hr}$

$$\frac{\Delta P}{L} = 4.148 \times 10^{-12}\ \frac{g^{1.8}}{d_L^{\ 1.2}} \qquad (2)$$

Also $g = \frac{\dot{M}}{A} = \frac{\dot{M}}{\frac{\pi}{4} d_L^{\ 2}}$

Where $\dot{M}$ = flow rate in lb/hr

By substituting this into equation (2), we find:

$$\frac{\Delta P}{L} = 6.4064 \times 10^{-12} \frac{\dot{M}^{1.8}}{d_L^{4.8}} \text{ psig/ft} \qquad (3)$$

It becomes obvious that the effect of pipe diameter is tremendous. A change from 3 in. to 4 in. IPS, Schedule 5 pipe will reduce the pressure drop by a factor 3.52.

2.2 <u>Pressure Drop in 8 in. IPS, Sch. 5 Pipe Header at Ambient Temperature and 1.05 Ata:</u>

ρ = .01066 lb/ft^3

μ = .0482 lb/ft hr

$$\frac{\Delta P}{L} = 7.832 \times 10^{-11} \frac{g^{1.8}}{d_L^{1.2}} \text{ psig/ft} \qquad (4)$$

or

$$\frac{\Delta P}{L} = 1.21 \times 10^{-10} \frac{\dot{M}^{1.8}}{d_L^{4.8}} \text{ psig/ft} \qquad (5)$$

2.3 <u>Pressure Drop in 3 in. IPS, Schedule 5 Header:</u>

Unit Flow Rate $\dot{M}$ = 396.5 lb/hr

Unit Distance L = 800 ft

Header I.D. d_L = .278 ft

$$\frac{\Delta P}{L} = 6.406 \times 10^{-12} \frac{\dot{M}^{1.8}}{d_L^{4.8}}$$

$\Delta P = 2.389 \times 10^{-6}\ \dot{M}^{1.8}$ for 800 ft pipe run

$\dot{M}$	1/2	1	1-1/2	2	2-1/2	3	3-1/2
$P_{D_1} = \Delta P$	.033	.115	.239	.40	.60	.83	1.09

2.4 Pressure Drop in 8 in. IPS, Sch. 5 Header:

Unit Flow Rate $\dot{M}$ = 396.5 lb/hr

Unit Distance L = 800 ft

Header I.D. d_L = .7 ft

$$\frac{\Delta P}{L} = 1.21 \times 10^{-10} \frac{\dot{M}^{1.8}}{d_L^{4.8}}$$

$$\Delta P = 5.363 \times 10^{-7} \dot{M}^{1.8} \text{ for 800 ft pipe run}$$

$\dot{M}$	1/2	1	1-1/2	2	2-1/2	3	3-1/2
$P_{S_1} = \Delta P$	.0073	.0255	.0529	.0888	.133	.184	.243

3. Pressure Drop in Unbalanced System Due to One Compressor Breakdown:

3.1 To determine the flexibility of the Cases I through VI, it was assumed that one compressor would suffer downtime. The loss in flow from the one compressor would have to be supplied by the other compressors remaining onstream. The capacity of all compressors must be increased to handle this contingency. In general, if "n" compressors are used, the capacity of each must be increased by a factor of $\frac{n}{n-1}$ over the normal rating to provide sufficient capacity of the remaining compressors to carry the load if one compressor fails.

Example: If 24 compressors are used, each delivers nominally 396.5 lb/hr for a total flow of 9,516 lb/hr. If one compressor fails, the 4.2% reduction in capacity must be distributed among the remaining 23 units. Therefore, each of the 24 compressors should originally be sized for: $\frac{n}{n-1}$ (396.5) lb/hr or 413.7 lb/hr.

396.5 lb/hr x 24 = 413.7 lb/hr x 23 = 9,516 lb/hr

When one compressor fails, higher than normal pressure drops will occur in the system due to the redistribution of the flow, the highest value being in the headers between the faulty compressor bank and the next good one. These pressure drops were evaluated for the hypothetical conditions of one compressor failure for each of the cases.

Only the change in pressure drop within the suction and discharge headers were evaluated. It was assumed that flow to and from the cold box and magnets at each station would remain constant and this portion of the system pressure drop would not be affected.

Table I shows a tabulation of normal pressure drops, pressure drops due to one compressor failure, and the changes in pressure drops (ΔP) for both the suction and discharge headers for each case.

3.2 In terms of energy doubler refrigeration, the most important pressure is that of the 8 in. IPS collection header. Temperature of the two-phase fluid in the magnets is determined by the local pressure. If we assume that the base pressure of the compressors is maintained at 1.0 atmosphere, then pressure drop in the header will determine the pressure at the exit of the magnet string. The entrance of the two-phase system at the turnaround box will have the exit pressure plus the pressure drop in the two-phase system.

TABLE I - a

SUCTION

# Stations	# Compr.	Compr. /Sta.	Compr. Cap. #/Hr	Normal Suc. Header Pres. Drop P_{S_1} (Psig)	(1) Compr. Failure Suc. Header Pres. Drop P_{S_2} (Psig)	(1) Compr. Failure Suc. Header Pres. Drop ΔP_S (Psig)
24	24	1	414	-0-	.0073	.0073
12	24	2	414	.0073	.0255	.0182
12	12	1	866	.0073	.0602	.0529
8	24	3	414	.0255	.0559	.0304
8	16	2	635	.0255	.0796	.0541
8	8	1	1360	.0255	.1932	.1677
6	24	4	414	.0602	.1143	.0541
6	18	3	560	.0602	.1262	.0660
6	12	2	866	.0602	.1748	.1146
6	6	1	1904	.0602	.4370	.3768
4	24	6	414	.1932	.2752	.0820
4	20	5	501	.1932	.2983	.1051
4	16	4	635	.1932	.3229	.1297
4	12	3	866	.1932	.3822	.1890
4	8	2	1360	.1932	.5300	.3368
4	4	1	3172	.1932	1.3662	1.1730
3	24	8	414	.4368	.5524	.1156
3	21	7	476	.4368	.5704	.1336
3	18	6	560	.4368	.6073	.1705
3	15	5	680	.4368	.6341	.1973
3	12	4	866	.4368	.6946	.2578
3	9	3	1190	.4368	.8182	.3814
3	6	2	1904	.4368	1.1244	.6876
3	3	1	4760	.4368	3.0640	2.6272

TABLE I - b

DISCHARGE

# Stations	# Compr.	Compr. /Sta.	Compr. Cap. #/Hr	Normal Dis. Header Pres. Drop P_{D1} (Psig)	(1) Compr. Failure Dis. Header Pres. Drop P_{D2} (Psig)	(1) Compr. Failure Dis. Header Pres. Drop ΔP_D (Psig)
24	24	1	414	-0-	.033	.033
12	24	2	414	.033	.115	.082
12	12	1	866	.033	.272	.239
8	24	3	414	.115	.2506	.136
8	16	2	635	.115	.3575	.243
8	8	1	1360	.115	.8720	.757
6	24	4	414	.272	.515	.243
6	18	3	560	.272	.566	.294
6	12	2	866	.272	.785	.513
6	6	1	1904	.272	1.962	1.690
4	24	6	414	.872	1.236	.364
4	20	5	501	.872	1.345	.473
4	16	4	635	.872	1.450	.578
4	12	3	866	.872	1.716	.844
4	8	2	1360	.872	2.380	1.508
4	4	1	3172	.872	6.142	5.270
3	24	8	414	1.962	2.480	.518
3	21	7	476	1.962	2.561	.599
3	18	6	560	1.962	2.735	.773
3	15	5	680	1.962	2.847	.885
3	12	4	866	1.962	3.119	1.157
3	9	3	1190	1.962	3.682	1.720
3	6	2	1904	1.962	5.049	3.087
3	3	1	4760	1.962	13.769	11.807

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Part 2

EVALUATION OF VARIOUS OPTIONS AND COSTS FOR THE COMPRESSION AND DISTRIBUTION OF COMPRESSED HELIUM GAS TO THE SATELLITE REFRIGERATION SYSTEM OF THE ENERGY DOUBLER

PREPARED UNDER FERMILAB SUBCONTRACT NO. 94199
BY CRYOGENIC CONSULTANTS, INC.
ALLENTOWN, PA.

FOR

FERMI NATIONAL ACCELERATOR LABORATORY
BATAVIA, ILLINOIS

10 April 1979

INTRODUCTION:

This report is a follow-up of CCI Report No. 390-107 and should have been part of that report. However, in the interest of time Report 390-107 has been issued in two parts; this report is Part 2.

Tables Ia and Ib of Report 390-107 show that all compressor combinations at as few as three compressor stations around the doubler are viable, except for three cases. These three cases show too much pressure drop. They are:

a) Four compressor stations with one compressor each.

b) Three compressor stations with one or two compressors at each station.

With the great variety possible, it was decided to contact manufacturers of screw compressors to evaluate the various options available. A total of five manufacturers were approached, three of which responded. These three manufacturers are:

Sullair Corporation, Michigan City, Indiana

Mycom Corporation, Torrance, California

Dunham-Bush, Inc., W. Hartford, Connecticut

To save power and lower the initial cost, the manufacturers were requested to consider staging of the compressors. The scope of the satellite refrigerator compressor system was discussed with the potential vendors in order to provide the necessary information for packaging.

The information requested of each manufacturer was the same. Based on their respective available tested equipment, each manufacturer was asked to select and submit packages suitable to fulfill the following requirements:

1. 1 atm suction, 20 atm discharge.
2. $\frac{1200}{N}$ gm/sec, where N is the number of stations. Information for three, four, and six stations was requested.
3. First and second stage compressor bodies were to be identical to minimize required spare parts.

4. Multiple first stages to a single or multiple second stage were suggested.

5. The option of having one first stage compressor sized for second stage operation was requested. This would allow use of a first stage as a second stage, should the second stage fail at a given location. (Note: Motor and oil cooler capacity are idential for first and second stages.)

6. All motors for first stages were to be identical, except where used as second stage alternates. All motors for second stages are to be identical.

7. If the manufacturer could suggest any additional cost saving techniques based on characteristics of his equipment, he was requested to do so. If the approach outlined above presented potential problems or inadvertent erroneous reasoning, it should be criticized accordingly.

8. Provide information about time required to repair compressors or replace major subcomponents.

INFORMATION SUPPLIED BY MANUFACTURERS:

1. All manufacturers state that they have compressors which will run 12,000 hours with no downtime. The failures which can occur are listed below with their approximate repair times:

a)	Compressor Bearings (Main)	4-8 hrs
b)	Replace Compressor Body	8 hrs
c)	Replace Motor	8 hrs
d)	Oil Pump Replacement	2-3 hrs
e)	Oil Filter Replacement	0-1 hr
f)	Slide Valve Controls	0-3 hrs

The first three items listed are major repair jobs and require that spare motors and compressor bodies are stocked. In order to reduce the cost of these items, it has been suggested to use the same compressor body for first and second stage compressors of the staged compressor package. The downtime actually experienced will vary with the expertise of the maintenance crew and the information supplied by the vendor.

2. In order to compare all combinations with the basic system of twenty-four compressors at twenty-four locations, information of Table I was supplied by two of the three vendors.

TABLE 1

	Case I (24 Compressors, 24 Locations)		
	Mycom	Dunham Bush	Sullair
H.P.:	350		371
Stages:	2		1
Cost:	$64,000		$55,000
Oil Removal:			$7,000
Total H.P.:	8,400		8,904
H.P./gps*:	(5.11 ± .1) *		7.42
Cost/Satellite:	$64,000		$62,000
Total Cost:	$1,536,000		$1,488,000

*grams per sec

With twenty-four compressors and 3 and 8 in. pipelines interconnecting all of the stations, length of downtime of the compressor is not extremely important.

3. The use of twenty-four single compressors at less than twenty-four separate stations does not change the overall picture materially from a standpoint of compressor cost and redundancy. There is a small saving in combining oil removal equipment. Space and concentrated power requirements will be more important factors for the determination of the cost.

4. Compressors at Six Stations.-

Table II shows the combinations as suggested by the vendors. Dunham-Bush proposes to use four parallel first stage machines followed by a single second stage compressor. Total number of first stage machines is still twenty-four and the loss of one first stage compressor reduces overall flow rate by 4%. The loss of

* Measured Value By FNAL.

TABLE II

(6 Stations, Compressors Staged as Shown)

	Mycom	Dunham Bush	Sullair
H.P.:	No Bid	1,218	1,108
		† (Case I)	(Alternate 6)
Stages:		2 [4x1]	2 [3x1]
Cost:		$157,379	$226,477
Oil Removal:		$10,000	$10,000
Subtotal:		$167,379	$236,477
Total Cost:		$1,004,274	$1,418,862
Total H.P.:		7,308	6,648
H.P./gps*:		6.09	5.54

*grams per sec

Option:
† Reference to MFG Quote Designation-All Types.
Dunham Bush 1st stage sized for 2nd stage service.
Add $9,309/station. Sullair 2/1 = 11,997 add'l. per Station.

the single second stage machine would reduce the output of the compressor station to nothing. According to Tables Ia and Ib of Report 390-107, the 3 and 8 in. pipelines are large enough to supply the necessary gas to the stricken station. Overall reduction in capacity would be 17%, unless one of the following is done:

a) Increase discharge pressure of all first stage machines for additional supercharging of the second stages.

b) Provide one spare second stage machine at six locations.

c) Equip one of the first stage machines at each of the six locations with a large enough motor to function as a second stage machine. In that case, some piping crossovers are required to change the function of the first stage machine.

The data of Table II indicate that the Sullair combination of machines does not have a significant price advantage over the case of twenty-four individual compressors. However, there is a significant saving in power.

The Dunham-Bush arrangement is attractive from a standpoint of price and power. Also, the Dunham-Bush combination provides the option to utilize one of the first stage machines as a spare second stage machine.

5. Compressors at Four Stations.

Table III provides the information supplied by the vendors. The two attractive offers are the Dunham-Bush and Sullair in terms of initial cost of the systems. Mycom has the lowest bhp; however, the power requirement of the Mycom offering may be on the optimistic side.

Loss of a first stage Dunham-Bush compressor can be tolerated in terms of pressure drop in both 3 and 8 in. lines. Loss of a Sullair first stage machine can also be tolerated from a standpoint of pressure drop. However the effect on the overall system is larger because in the case of Sullair there are only eight first stage machines. Loss of one of these machines reduces maximum available refrigeration by 12-1/2%. The loss of the single second stage machine cannot be tolerated. Dunham-Bush can provide one of the first stage machines as a second stage. Added cost to the overall system is then $72,000.

Sullair does not provide the same machine for first and second stages. A spare second stage machine needs to be provided for each of the four locations. Since loss of a first stage machine is barely permissible and a second stage spare machine is required, it is possible to combine the duties. The spare machine will be equipped in such a way that it can be used as a first or second stage machine. The cost of this spare machine adds $ to the Sullair total of Column 5 of Table III.

6. Compressors at Three Stations.-

Table IV provides the data as supplied by the compressor vendors. Again, Dunham-Bush is very low in price relative to Mycom and one of the Sullair offerings. Dunham-Bush can equip a first stage machine to double as a second stage machine. The loss of a first stage compressor reduces refrigeration to the doubler by 8%, while the loss of a second stage machine cannot be tolerated because of pressure drop and loss of refrigeration capacity. It may be worthwhile to provide a spare

T A B L E I I I†

(4 Stations, Compressors Staged as Shown)

	Mycom	Mycom	Dunham Bush	Sullair	Sullair
H.P.:	1,405	1,355	1,774	1,583	1,597
	(Case D1)	(Case D3)	(Case II)	(Alternate 4)	(Alternate 5)
Stages:	2 [3x1]	2 [2x1]*	2 [3x1]	2 [4x1] *	2 [2x1]*
Cost:	$362,500	$360,000	$190,917	$293,456	$205,775
Oil Removal:	Included	Included	$15,000	$15,000	$15,000
Subtotal:	$366,500	$375,000	$209,917	$312,456	$224,778
Total Cost:	$1,466,000	$1,500,000	$839,668	$1,249,824	$883,112
Total H.P.:	5,620	5,420	6,976	6,332	6,388
H.P./gps:	4.68	4.51	5.81	5.27	5.32

Options:

Dunham Bush 1st stage sized for 2nd stage service. Add $72,000 to total.

Sullair spare 1st stage compressor sized also for duty as a 2nd stage machine. Add   to total.

*Does not use same compressor body for both stages.

†See individual quotes for details on compressors and other options (Attachments 1, 2 & 3).

TABLE IV

(3 Stations, Compressor Stages as Shown)

	Mycom	Mycom	Dunham Bush	Sullair	Sullair
H.P.:	1,843 (Case C1)	1,872 (Case C3)	2,183 (Case III)	2,096 (Alternate 1)	2,204 (Alternate 3)
Stages:	2 [3x1]	2 [2x1]*	2 [4x1]	2 [5x2]	2 [2x2]*
Cost:	$550,000	$460,000	$234,160	$399,333	$268,824
Oil Removal:	Included	Included	$16,000	$16,000	$16,000
Subtotal:	$550,000	$460,000	$250,160	$415,333	$284,824
Total Cost:	$1,650,000	$1,380,000	$750,480	$1,246,000	$854,472
Total H.P.:	5,529	5,616	6,414	6,288	6,612
H.P./gps	4.60	4.68	5.345	5.24	5.51

Options:

Dunham Bush 1st stage sized for 2nd stage service. Add $54,000 to total price.
Sullair " " " " " " " Add $35,994 " " " (11,998 ea)
*Does not utilize same compressor body for both stages.

machine at each of the three compressor stations. Column 5 of Table IV is a reasonably priced Sullair offering. It appears that at least one spare machine per station should be equipped to either be a first stage or second stage machine.

7. SUMMARY AND CONCLUSIONS:

7.1 The information provided in the report is to be used to pursue a limited number of cases, attractive in price and operating characteristics.

7.2 The cost of the total compressor system for the satellite refrigerators can be reduced substantially by combining compressors into a small number of (three or four) compressor stations.

7.3 When pursuing Items 1 and 2 above, equipment layout drawings of the most likely compressors to be used needs to be made. From this, extra building and power system requirements will be determined. These requirements will reduce the initial cost advantage of the concentrated compressor stations.

7.4 Dunham-Bush has suggested the consideration of an option consisting of first stage screw compressor, coupled with a second stage reciprocating compressor of the type used for Model 1400 helium refrigerators. This option may compete favorably in price with the case of twenty-four single compressor stations.

7.5 The exact amount of controls, valving, piping, and instrumentation needs to be determined for the selected cases. A flow sheet will show the requirements of the system.