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Collider Tunnel/Niche Temperature Requirements

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Project Management:
Superconducting Accelerators

MEMORANDUM

Date: Monday, October 12, 1992

To: J. Rees

From: G. Dugan G. Dugan **92 4740 E B 116.0940 0015**

Subject: Collider Tunnel/Niche temperature requirements

This memo discusses the impact of the use of an extended temperature range requirement on the technical systems in the Collider tunnel.

The baseline temperature environment for the technical systems in the Collider tunnel is $75^o \pm 5^o$ *F*. The indicated range is intended to cover all temperature variations, both spatial and temporal, in the tunnel and niches. This environment has been assumed for baseline estimates of the electronics which will be in the niches, and has been used in specifying the requirements for many of the major technical components in the tunnel (e.g., the CDM's and CQM's).

The detailed design of the tunnel cooling system has led to the appreciation that a less expensive system can be realized if the baseline temperature requirement cited above is relaxed. The purpose of this memo is to provide a discussion of the impact of that relaxation on the technical systems which have to live in this environment.

The details of the impacts on the technical systems are presented in Attachment 1, from Rainer Meinke; and in Attachment 2, which contains information from the engineers in ASD responsible for the design and implementation of the niche electronics. These details are summarized in Table 1. The table spells out, for each tunnel/niche component, the primary consideration which must be considered if the temperature environment is changed, and an estimate of the consequences of a relaxation of the component temperature environment to 55°–90° *F* , a range which is associated with the less expensive tunnel cooling system.

The major consequences of this extended temperature range are:

(a) a reduction in reliability of the systems which are most critical to the reliability of the Collider and the protection of the magnets (i.e., the quench protection system, the corrector system, and the beam loss monitor systems). The mitigation of this reliability loss has a cost which is conservatively estimated as in excess of $11M. These costs have been estimated using the information provided in Attachment 2. In that Attachment, estimates are made of the fractional decrease in system reliability resulting from the use of the baseline system in the extended temperature environment. Based on the assumption of scaling between the fractional system reliability decrease and the fraction of the total number of parts which must be upgraded to mitigate the reliability decrease, the cost of mitigating the effect of the extended temperature environment has been roughly estimated as the product of the BCE cost of the electronics in the niches times the fractional degradation in system reliability. The details are shown in Table 2. In the case of the

beam instrumentation, as discussed in Attachment 2, an additional $1M has been added for additional calibration efforts. This is described as a conservative estimate because the detailed design of these systems is not sufficiently advanced to be able to do a real tradeoff of reliability vs temperature environment in terms of cost. It is anticipated to be technically challenging to meet the Collider reliability budget for these systems even in the baseline temperature environment. In the judgement of the engineers responsible for these systems, the job will only get substantially more demanding with the extended temperature environment.

(b) introduction of additional sources of alignment errors associated with large thermal gradients in the extended temperature environment. The absolute alignment requirements on this accelerator are more demanding than on any previous machine, and it is also much larger in physical size. Again, the extended temperature environment makes a very difficult problem even more difficult. The alignment shifts associated with thermal gradients may be able to be compensated for if they can be predicted: this may be possible in some cases, although distortions of the geometry of the tunnel, if they occur, would seem to be very difficult to predict. Because of the lack of a detailed plan for alignment at this time, it is difficult to quantify the cost of the extra work which would be required by the extended temperature environment. However, it is clear again that the extended temperature environment will make one of the most difficult parts of building the Collider even more difficult.

(c) additional thermal stresses on the tunnel components associated with large thermal gradients in the extended temperature environment. These thermal stresses are possible sources of leaks in the Collider cryovacuum system.

(d) a rather inhospitable environment for repairs to niche systems. The less expensive cooling scheme associated with the extended temperature requirement implies a temperature of 88° F in the niches. This temperature will be about the same whether the machine is on or off in this scheme. Thus, niche component maintenance and repair will have to be done at this temperature. This is not a good work environment for personnel debugging and repairing complex technical systems. Again, this effect is hard to quantify but will surely be felt during operations.

In addition to the issues noted above related to the extended temperature environment itself, there is a concern with one of the features associated with some of the versions of the less expensive system used to realize the extended temperature environment. These systems utilize large volumes of air to cool the niches and the tunnel; the air is subsequently discharged to the external environment. These large air volumes can transport radioactive air and dust from from the tunnel to the surface. Such discharges may potentially result in release of radioisotopes into areas occupied by laboratory employees or the general public in excess of laboratory radiation guidelines. This problem is still being studied.

In summary, the information in this memo is intended to be used to determine the optimum tradeoff between the advantages of a cooling system which meets the baseline requirements and one which delivers the extended temperature environment. Although the estimates made here are only approximate, it should be appreciated that the cost of coping with the extended temperature environment for the Collider technical systems is at least $11M, and when one adds the additional impacts discussed above, could well be substantially more.

Attachments

cc: R. Meinke
D. Plant
T. Toohig
J. Watson

cc w/o attms: T. Bush
J. Ives
D. Johnson
T. Kozman
T. Lundin

TABLE 1:
Estimate of the impact of an extended temperature environment on Collider tunnel technical systems

Component	**Baseline Temperature requirement:** ***Niche and Tunnel- 75°±5° F***	**Considerations determining the requirement**	**Extended Temperature requirement:** ***Niche and Tunnel- 55°-90° F***	**Consequences of extended temperature requirement**
Corrector power supplies	Niche Temperature: 80° F maximum	Reliability	Niche Temperature: 90° F maximum	Est cost increase: $4.4M
Quench Protection system	Niche Temperature: 80° F maximum	Reliability	Niche Temperature: 90° F maximum	Est cost increase: $1.1M
Instrumentation/ Timing	Niche Temperature: 80° F maximum	Reliability and calibration	Niche Temperature: 90° F maximum	Est cost increase: $4M
Control system components in niches	Niche Temperature: 80° F maximum	Reliability	Niche Temperature: 90° F maximum	Est cost increase: $1.8M
Magnet alignment: local	Tunnel spatial, temporal gradient: 10° F maximum	Closed orbit control	Tunnel spatial, temporal gradient: 35° F maximum	Requirement for additional alignment step at operating temperature
Magnet alignment: global	Tunnel spatial, temporal gradient: as small as practical	Circumference requirement	Tunnel spatial, temporal gradient: 35° F maximum	Unknown
Tunnel geometry	Tunnel spatial, temporal gradient: as small as practical	Closed orbit control and circumference requirement	Tunnel spatial, temporal gradient: 35° F maximum	Unknown
Magnet cryostats (insulating vacuum)	Tunnel spatial, temporal gradient: as small as practical	Outer cryostat vacuum leaks to air caused by frequent thermal expansion and contraction at interconnects	Tunnel spatial, temporal gradient: 35° F maximum	Possibility of reduction in reliability of insulating vacuum seals at interconnect
Beam Scraper	Tunnel temporal (short-term) gradient: 10° F maximum	Alignment relative to closed orbit	Tunnel temporal (short-term) gradient: 35° F maximum	Requirement for additional scraper adjustments during operation (reduction in time for experiments)
Work environment	Niches, tunnel (beam off): 80° F maximum	Safety and efficiency of tunnel workers	Niches, tunnel (beam off): 90° F maximum	At a minimum, decreased efficiency during niche component repairs

TABLE 2: ESTIMATED COST TO MAINTAIN RELIABILITY IN THE EXTENDED TEMPERATURE ENVIRONMENT

Niche Electronics System	BCE Cost of electronics	Estimated reliability degradation 80 to 90 F	Estimated cost to regain reliability
	(M$)	%	(M$)
Controls/Communications	6.72	27%	1.81
Beam Instrumentation	10.2	30%	3.06
Correction element power supplies	17.4	25%	4.35
Quench protection System	3.8	30%	1.14
Total	38.12		10.36

ATTACHMENT 1

Rainer Meinke Oct. 12,1992

Collider Tunnel and Niche Cooling

Introduction:
For reasons of radiation safety all presently existing large accelerators have been built underground. These underground locations have the additional merit of offering a very stable temperature environment, because they are minimally impacted by the annual ambient temperature variations. Since the dynamic aperture of large accelerators is only a few millimeters, the alignment of the accelerator magnets is a critical issue. Underground locations with their constant temperatures minimize thermal expansions of magnets and support structures and are therefore preferred. For the these reasons the Collider tunnel has been planned to be at a depth from 50 to 250 ft with a natural temperature of about 70 F.

A large fraction of control electronics and corrector power supplies for the Collider will be located in underground tunnel niches. The large distance between the utility shafts and the short lead requirement prevent other solutions. The total heat load generated per niche during operation is about 12 KW. The heat load in the tunnel is 5.8 W/ft, mainly generated by the corrector power leads. Without removing this energy by a cooling and ventilation system a steady increase in temperature over several years, starting from the natural value of 70 F, would result as recently calculated by PB/MK.

Experience over many years of operation at different accelerator laboratories has proven without any doubt that the failure rate of electronics increases rapidly above 70 F. At FNAL the temperature of most of the accelerator control electronics is monitored and the alarm level is set to 80 F. At 85 F the power supplies are switched off because serious damage has otherwise been observed. At DESY

temperatures above 80 F are rarely encountered. When the temperature actually reaches that level during the summer, meaningful accelerator operation was often found to be impossible. In general it has been established in industry that the reliability of electronic devices decreases with increasing temperature.

The following list summarizes the most important components of the Collider which are adversely effected by increased temperature.

- Corrector power supplies
- Quench protection system
- Precision timing system
- Alignment of magnets
- Circumference of beam orbit
- Insulation vacuum system
- Alignment of scraper system
- Radiation safety
- Hostile work environment during maintenance

The adverse effects caused by increased temperature are described in the following sections.

1) Reliability of Niche Electronics

- The corrector Power supplies, the quench protection system and the precision timing system are located in tunnel niches, where no access is possible during Collider operation. It is well established that the reliability of electronic components decreases rapidly with temperature (see SSC-SR-2020). Therefore the niche temperature should be held as low as is possible. All electronics in the tunnel niches is housed in racks. It is difficult to avoid hot spots in electronics racks unless complicated and expensive cooling systems are built into each individual rack. Without these the inside rack temperatures will exceed the ambient temperatures, emphasizing the need for low niche temperatures.

The availability of the Collider is strongly impacted by the large number of corrector dipole power supplies. It is presently not certain whether the required Collider availability of 80 % (see III A specs) can be guaranteed even at 75 F. Any temperature increase above this value compromises the reliability of the power supplies. At a niche temperature of 90 F the reliability of the power supplies is estimated to decrease by 30-50 % (see attachment 2). The likely effect of hot spots in the racks has been ignored in this estimate.

- The quench protection system of the superconducting magnets consists of quench detection electronics, quench heater firing units and the energy extraction system. The system design guaranties protection of the magnets under practically all circumstances. Failure of the quench protection system could result in false energy extraction triggers and increased maintenance time. The reliability of the complete system has been analyzed by the Research Analysis Corporation and concern has been expressed in their report. While the energy extraction system is hardly influenced by the ambient temperature, the quench detection system and the heater firing units reliability and lifetime are adversely impacted by increased operational temperatures (see attachment 2). Again the conclusion is that the niche temperature should be held at the lowest possible value.

- The precision timing system in the Collider is essential for controlling data acquisition of the beam instrumentation, i.e. mainly beam position monitors (BPM) and beam loss monitors (BLM). Many types of failures arising in the BLM system cause an immediate, automatic beam abort. The reliability of this system is therefore of extreme importance for the overall availability of the Collider. During routine operation of the Collider not all BPM's are required for control of the beam in the machine. In contrast to this situation 100 % availability of the BPM's is required during the approximately six month long commissioning phase of the Collider.

As described in attachment 2, it would be possible to design electronics which is functional at 90 F. The construction of such

electronics would certainly be more costly. In case of large temperature gradients in the tunnel and/or varying operational temperatures in the niches extra calibration effort would be required.

2) Alignment of Magnets

- Quadrupole magnets are the most demanding components in the Collider concerning alignment. In adjacent half cells, quads have to be aligned relative to each other with a precision of 0.4 mm. The alignment tolerance to the adjacent BPM and sextupoles are 0.2 mm (see III B Collider Spec). If the alignment of all magnets could be done at the final operational temperature in the tunnel, temperature in this case would hardly be of any concern. A complete survey and smoothing of the Collider is very labor intensive (six month) and expensive. Without an appropriate tunnel and niche cooling system, the final smoothing of the Collider has to be done at a temperature different from the operational temperature.

The top ring of the Collider is supported by steel structures about 1.5 m above the tunnel floor. It seems prudent to limit thermal expansions in height of the magnet support stands to values considerably smaller than the alignment tolerances given above. If we tolerate excursions of the upper magnets in the vertical direction of 0.1 mm, the tunnel temperature has to stay constant (both spatially and temporally) to about

$$dT = dL/(L\ c) = 0.1/(1.5\ 10^{3}\ 1.25\ 10^{-5}) = 5.3\ C \quad \sim 9.5\ F$$

c : thermal expansion coefficient of steel

3) Circumference of Beam Orbit

- The circumference of the Collider has to be adjusted relative to the HEB circumference for the bucket to bucket beam transfer with a tolerance of +/- 5 cm (see the discussion *"Problems Caused by Machine Circumference Errors During the HEB to Collider Transfer"*

following this memo). Furthermore the lengths of both arcs has to be equal within about the same tolerance limit. Otherwise the interaction points in the west and east IR's will not be simultaneously at the locations of the minimum beta at each point. It is difficult to estimate how the Collider circumference changes with temperature. If we make the extreme assumption that the chain of all magnet cryostats around the ring behaves like a continuous steel pipe without expansion joints, even slight temperature variations would cause large circumferencial changes.

$$dL = c\ L\ dT$$

Taken L as the length of an arc, i.e. about 30 Km and dT = 1 C (1.8 F) one gets:

$$dL = 1.25\ 10^{-5}\ \ 3\ 10^{4} = 0.375\ m$$

In reality bellows in the vacuum vessel of the interconnect region will strongly mitigate this effect. At the moment the stiffness of these bellows is unknown and the expansion is difficult to estimate. Furthermore variations in stiffness of these bellows could cause unpredictable movements of magnet strings, causing a loss of magnet alignment precision. Given the large effect (0.375 m) above and the alignment tolerances of the magnets the lowest possible variation in tunnel temperature seems prudent.

- The tunnel geometry itself might be impacted by large variations of tunnel temperature. Since the tunnel niches are located on the inside of the circular tunnel, the temperature on this side will be higher than the outer tunnel wall which is somewhat shielded by the magnet string. It would be complicated and costly to implement an air conditioning system that would equalize this radial temperature gradient. Changes in tunnel shape seem therefore unavoidable unless the niches are cooled without heating the tunnel. For this reason water cooling of the niches seem to be the preferred solution.

- The length of the tunnel would only remain constant under temperature fluctuations, if the soil surrounding the tunnel can withstand the resulting expansion forces. For a uniform material this would seem likely. For the Collider site with geological formation boundaries intersecting the tunnel this assumption seems risky and significant variations in tunnel length might occur. Furthermore, any difference in water content of the material surrounding the tunnel would increase the heat conductivity and heat capacity of this material. Such local effects could lead to changes in tunnel shape.

To summarize, it seems prudent to keep the tunnel temperature as close to the natural value as possible at all times after the magnet alignment.

4) Insulation Vacuum System

Tunnel temperature variations would cause movements of the outer bellows in the interconnect region between magnets. It seems likely that frequent movements of these bellows could cause vacuum leaks. For a certain time these leaks would not show up, since the incoming air would be cryo-pumped by the cold surfaces inside the cryostats. After the pumping capacity of all surfaces and the superinsulation has been saturated, the pressure would rise rapidly. It would be very difficult and time consuming to find such leaks and fix them. This situation presents a possible risk to the availibility goal. To avoid such downtime of the collider the tunnel temperature should stay as constant as possible during the lifetime of the Collider.

5) Alignment of Scraper System

The scraper system in the Collider is necessary to prevent beam halo from quenching the superconducting magnets and to improve the experimental conditions in the IR's. The jaws of the scraper system have to be adjusted transversely relative to the beam with a precision of less than 0.01 mm. These adjustments will be time consuming and will reduce the time available to the experiments. Changes in tunnel

temperature between experimental runs will certainly make these adjustments more difficult.

6) Radiation Safety

With an air cooling and ventilation system, appreciable air velocities will result in the tunnel. This air stream will pick up radioactive dust and transport it to the surface through the air return ducts. Filters are therefore necessary to prevent the release of activated dust into the environment. This will place an additional monitoring burden on the laboratory. Safe disposal of the filters will also require special care. From this point of view a tunnel cooling system with the lowest possible air velocity would be most advantageous. A water cooling system for the tunnel niches which have the highest overall heat load seems therefore favorable.

The effect of a worst case scenario, where the full beam intensity is lost close to a tunnel ventilation shaft, has to be investigated. But also in this respect water cooling of the niches instead of air cooling would have advantages.

7) Hostile Work Environment During Maintenance

Maintenance periods of the Collider have to be kept as short as possible in order to achieve the required availability. If the technicians have to work in an environment of 90 - 95 F, in the already difficult environment of the tunnel, their efficiency will certainly be reduced. Any repair work in the tunnel or the niches will require more time under these conditions. Lower temperatures will reduce stress and minimize the probability of errors during maintenance.

Del Larsen
9 Jan 92

Problems Caused by Machine Circumference Errors During the HEB to Collider Transfer

1. Introduction and Statement of the Problem

Operation of the Super Collider requires that dense bunches of protons be accelerated to 20 TeV. Since this can not be done in a single machine, a cascade of particle accelerators are needed, with each individual accelerator accepting the beam from the prior accelerator, accelerating the beam, and finally transferring its beam into the next accelerator. If the beam transfers are not done correctly, beam emittance growth can occur, or in the worst case the beam can be lost. Even in the cases where the beam is not lost, emittance growth decreases the density of the proton bunches, and this reduces the event rate of the collider. Beam emittance growth can occur in either the transverse or longitudinal phase space planes. The purpose of this note is to provide a first pass analysis of the problems caused by circumference errors as they relate to longitudinal emittance growth during the HEB to Collider beam transfer.

The transfer of the protons from the HEB into the Collider involves four issues related to longitudinal phase space.

1) The momentum of the protons must be at a level appropriate for storage in the collider.

$$P_{HEB}=P_{COLLIDER} \qquad (1)$$

2) The bunch separation must be the same in the HEB as it is in the Collider so that each bunch sees the correct phase of the RF voltage when it recirculates around the Collider.

$$\Delta s_{HEB}=\Delta s_{COLLIDER} \qquad (2)$$

3) Each bunch must be transferred at the correct time so that it occupies its correct place within the Collider. (This third issue of correct timing for the center of the bunches is termed "cogging".)

4) The momentum spread and longitudinal length of the proton bunches must be adjusted just before they leave the HEB so that they match into the longitudinal environment of the Collider. (A "bunch rotation" must be done that shortens the longitudinal length and increases the momentum spread of the proton beam just prior to ejection from the HEB.)

Since any given machine operates poorest at its lowest momentum, the machine that ejects the beam must be assigned the responsibility for preparing the appropriate beam characteristics prior to ejection. Thus, just prior to ejection from the HEB, beam manipulations within the HEB must be done so that the above four criterion

are met simultaneously.

In each ring the protons will take a certain amount of time to make one revolution around the machine, and the inverse of this time is the revolution frequency of that machine. In order to keep the phase of the rf voltage constant with respect to the center of the circulating bunches, the rf voltage must be an integral multiple of the revolution frequency. The particular integer multiplier for each machine is called the harmonic number. The harmonic number also corresponds to the number of proton bunches that can fit into each machine, since every rf cycle may be occupied by a single bunch. The bunch separation is thus equal to the circumference divided by the harmonic number.

$$\Delta s_{HEB} = C_{HEB}/h_{HEB} \; ; \; \Delta s_{COLLIDER} = C_{COLLIDER}/h_{COLLIDER} \qquad (3)$$

Errors in machine circumference directly affect the bunch separation. There are two possible ways to deal with the problem of machine circumference errors. 1) The error in bunch separation can be accepted as a bunch to bunch variable longitudinal emittance dilution; or 2) The circumference of the proton orbits can be changed by moving the orbit away from the design orbit. Each of these options will now be discussed.

2. Accepting the Circumference Error Without Correction.

At the time of writing of this note, it is assumed that the survey accuracy of the HEB and Collider will result in circumference construction errors of $\Delta C_{HEB} = 1.25$ cm and $\Delta C_{COLLIDER} = 10$ cm, respectively. The collider design circumference is $C_{COLLIDER} = 87.12$ km and the design circumference of the HEB is $C_{HEB} = 10.8$ km. It will be assumed here that during the transfer the center bunch of the protons to be transferred can be transferred exactly as desired. But even with this perfect transfer of the central bunch, the proton bunches at the extreme edge of the transferred batch will have a transfer error due to the circumference error in the HEB of $\Delta C_{HEB}/2 = 0.625$ cm. The proton bunches at the extreme edge of the transferred batch will have an additional transfer error due to the circumference error in the Collider of $\Delta C_{COLLIDER}/16 = 0.625$ cm. (Only 1/8th of the Collider is involved in any given transfer from the HEB.) The worst case transfer error due to circumference construction errors is thus 1.25 cm for those ~~and~~ proton bunches at the extreme edge of the transferred batch. The transfer error decreases linearly to zero with the distance of the bunch from the batch center.

At the time of transfer the bunch one-sigma half-width is designed to be 5.4 cm, and the bunch is assumed to have a gaussian longitudinal profile. The construction circumference errors will have the effect of offsetting the entire distribution of those bunches at the edge of the batch by 1.25 cm. The distribution will begin to do a collective oscillation around the design point, and over time filamentation of the phase space will cause a new distribution to be reached that is centered on the design point. Calculation of the eventual distribution is a complex problem that will not be addressed here. One can estimate that the one-sigma half-width of the eventual distribution will be close to the sum of the original value and the offset, 6.65 cm. Thus, the dilution of the longitudinal phase space due to the

circumference errors has a contribution of about 23% from the increased time width of the pulse. Even though the momentum width of the bunch is not affected by the timing error, the phase space ellipse that the bunch occupies has a larger momentum excursion than the design value. In the small amplitude limit the phase space trajectories can be treated as circular, and the dilution of the phase space due to the larger momentum excursions is thus also 23%. Therefore the total phase space dilution caused by circumference construction errors for those bunches at the extreme edge of the transferred proton batch is 52%. The phase space dilution for those proton bunches not at the extreme edge of the transferred batch is proportional to the square of the distance the bunch is from the batch center.

In this discussion it is assumed that the central bunch of protons can be transferred exactly as desired. Transfer of the central bunch is made much more difficult if the bunch separation in the HEB differs from that of the Collider. The easiest way to transfer the center bunch is if the rf frequency of the HEB is phase locked to that of the Collider, and the required phase difference needed for proper timing of the transfer is determined experimentally. This phase locking of the rf cavities will assure that the bunch centers remain fixed relative to each other. Phase locking of the rf cavities may not be possible if the bunch separation in the HEB is different than that of the Collider. The rf frequency of the HEB is equal to the velocity of the protons (essentially c) divided by the bunch separation in the HEB, and the rf frequency of the Collider is equal to six times the proton velocity divided by the bunch separation in the Collider,

$$f_{rfHEB} = v/\Delta s_{HEB} \ , \ f_{rfCOLLIDER} = 6v/\Delta s_{COLLIDER} \ . \qquad (4)$$

Thus, only if $\Delta s_{HEB} = \Delta s_{COLLIDER}$ will the ratio of the two rf frequencies be an integer. Thus, if the bunch separations are unequal, the phase of the two rf's can not be simply locked. It may be possible to combine a portion of each rf signal and observe the beats, but this would greatly increase the complexity of the cogging problem.

There are three problems presented by circumference construction errors if they are not corrected. A longitudinal phase space dilution of up to 52% results, the phase space dilution varies from bunch to bunch, and the complexity of the cogging problem is greatly increased.

3. Correcting Circumference Construction Errors by Offsetting the Design Orbit.

Although the physical circumference may be $C + \delta C$, where C is the design value and δC is the construction error, the orbit that the protons follow can be different than this by adjusting the magnetic field. For instance, if the machine is built too large, the magnetic field can be increased slightly. This will result in the protons having a slightly smaller bend radius than the physical radius resulting in a smaller circumference. The problem with this approach is that the beam will no longer be centered in the magnet chamber, with ominous possible results. The required displacement from the design orbit and time required for the beam to remain displaced will now be calculated.

As discussed above, the total circumferential construction error that must be made up for in the HEB is $\delta C_{HEB} = \Delta C_{HEB} + \Delta C_{COLLIDER}/8 = 2.5$ cm. The HEB circumference is related to the average HEB radius by the relation

$$C_{HEB} = 2\pi r_{HEB} \ . \qquad (5)$$

Differentiating each side leads to the expression

$$\delta C_{HEB}/C_{HEB} = \delta r_{HEB}/r_{HEB} \text{ , or } \delta r_{HEB} = \delta C_{HEB}(r_{HEB}/C_{HEB}) \ . \qquad (6)$$

Thus, with $\delta C_{HEB} = 2.5$ cm, $C_{HEB} = 10.8$ km and $r_{HEB} = 1.72$ km the amount of radial displacement needed to match the HEB circumference to the Collider circumference in the presence of presently estimated construction errors is $\delta r_{HEB} = 4.0$ mm.

If the beam is displaced from its design orbit particles may get lost over time. Thus another relevant parameter is the length of time that the protons must spend in the displaced orbit.

The amount of time the protons spend in the displaced orbit depends on the cogging scenario employed. Prior to ejection, the protons must have the correct momentum for injection into the collider, have the correct momentum spread and longitudinal length (accomplished by bunch rotation), and have the correct timing for the ejection. The bunch rotation must be done last, as the bunch rotation results in a beam matched into the Collider longitudinal environment; after bunch rotation the beam is no longer matched to the HEB longitudinal environment. Thus preparation for ejection can occur in one of two ways. The beam can reach its proper momentum first, and the cogging (setting the timing) can be done second, or the cogging can be done first and the beam can reach its proper momentum second.

If the beam reaches its proper momentum prior to cogging, and the magnetic field is maintained at a level appropriate to the design value, the length of time the protons will be in the displaced orbit is the full cogging and bunch rotation time, about 6 seconds. The time it takes for the protons to make one revolution around the HEB is $C_{HEB}/c = 36\mu s$. Therefore the 6 s cogging and bunch rotation time corresponds to 167,000 turns.

If the cogging is done prior to the beam reaching its proper momentum (but still at the magnetic flat-top) and the beam is accelerated or decelerated to the proper momentum after cogging, the beam position displacement will linearly increase over time during the final acceleration or deceleration. The amount of time needed for the acceleration or deceleration can be calculated by noting that the fractional change in orbit circumference is related to the fractional change in proton momentum by the following expression.

$$\delta C_{HEB}/C_{HEB} = (\gamma_{THEB})^{-2}\delta p_{HEB}/p_{HEB} \qquad (6)$$

In the above expression γ_{THEB} is the transition energy of the HEB divided by the rest mass energy of the proton, $\gamma_{THEB} = 35$. Thus, with $\delta C_{HEB} = 2.5$ cm, $C_{HEB} = 10.8$ km and $p_{HEB} =$

2 TeV the amount of momentum offset required to correct the circumference construction error is 5.7 GeV. During the acceleration ramp of the HEB the rate of momentum change is 1.8 TeV/c divided by 100 s, or 18 Gev/c/s. Thus, it will take 0.32 seconds to change the momentum by the required amount to correct for circumference construction errors. The time it takes for the protons to make one revolution around the HEB is $C_{HEB}/c = 36\mu s$. Therefore it will take $0.32s/36\mu s = 8800$ turns to change the momentum by an amount necessary to correct for circumference construction errors. Bunch rotation will require that the beam remain at full displacement for an additional one second, or 27,800 turns.

If circumference construction errors are to be corrected by displacing the equilibrium orbit away from the physical orbit, the maximum required displacement is 4 mm. If the displaced orbit is reached prior to cogging, the orbit must remain in the displaced position for 167,000 turns. If cogging is done prior to displacing the orbit, the orbit will be linearly displaced from the physical orbit over a period of 8800 turns, and then remain at the full displacement for an additional 27,800 turns during the bunch rotation just prior to ejection. Attempting to cog at an orbit other than the design orbit will also introduce additional difficulties in the cogging process.

ATTACHMENT 2

Superconducting Super Collider Laboratory
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Accelerator Systems Division

Memorandum

To: Duane Plant

From: Tim Savord

Date: September 30, 1992

Subject: Effect of Collider Niche Temperature on Quench Protection System

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As per your request, I am providing information concerning the impact of Collider niche temperature on the failure rate of electronic components within the Quench Protection System (QPS). This information is provided as an indicator of a trend in component failure rates as temperature is increased and is not intended to be a study of the overall Quench Protection System reliability.

Using values for integrated circuit junction temperatures of 11 degrees centigrade above niche ambient, as per the Research Analysis Corporation report titled "Reliability Analysis of the Quench Protection System for the Superconducting Super Collider Laboratory" (May 13, 1991), the temperature acceleration factors for failure rates have been determined for various types of integrated circuits and semiconductors (typical of those used in the Quench Protection System) for niche ambient temperatures of 80 degrees Fahrenheit and 90 degrees Fahrenheit. The temperature acceleration factors presented in Table 1, are for nonhermetic components as detailed in military handbook MIL-HDBK-217E (27 October 1986) with Notice 1 (2 January 1990). Since a device failure rate is the product of the temperature acceleration factor and several other important factors, the percent increase in a device's failure rate resulting from an increase in temperature is proportional to the increase in its temperature acceleration factor.

Table 1: Electronic Component Temperature Acceleration Factors

Niche Temp.	Junction Temp.	ALSTTL Logic	HCMOS Logic	OPTO Coupler	Linear	SCR
80 F (26.7 C)	99.9 F (37.7 C)	0.20	0.33	1.4	0.39	1.4
90 F (32.2 C)	109.8 F (43.2 C)	0.27	0.59	1.9	0.73	1.8
HDBK 217E Table No.	-	5.1.2.7-6	5.1.2.7-12	5.1.3.10.1-4	5.1.2.7-13	5.1.3.10.1-4
Increase in failure rate.	-	35%	78.8%	35.7%	87.2%	28.6%

Aluminum electrolytic capacitors, rated at 450 volts, are used extensively in the Heater Firing Units (HFUs) of the Quench Protection System (QPS). This type of capacitor with a 450 WVDC rating is not covered in MIL-HDBK-217E but life expectancy information is available from Philips Components, the manufacturer of HFU capacitors used in the Accelerator System String Test (ASST). The capacitors used in the ASST are Philips type 3186, operated at their design voltage of 450 WVDC. In the present HFU design, the ripple current through these capacitors is approximately 45 mA, a level that contributes negligibly to the temperature rise of the capacitor's core. Since ripple current contributes an insignificant amount, the capacitor's core temperature is assumed to be equal to the ambient temperature of the enclosure in which it is installed. As per Table 3-3 of the previously mentioned study from Research Analysis Corporation, the average temperature rise above room ambient within a typical QPS electronic enclosure is approximately 5 degrees Fahrenheit. The reduction in life expectancy of a typical HFU capacitor as niche ambient temperature is increased from 80 degrees Fahrenheit to 90 degrees Fahrenheit is detailed in Table 2. Information in this table has been derived from Philips Components 1990-91 Resistor/Capacitor Data Book, pages 92 and 93.

Table 2: HFU Capacitor Life Expectancy

Niche Temp.	Core Temp.	Life (K Hours)
80 F (26.7 C)	85 F (29.4 C)	90.5 K hrs
90 F (32.2 C)	95 F (35.0 C)	64.0 K hrs
Reduction in life expectancy.	-	29.3 %

As is evident from Tables 1 and 2, an increase in niche temperature from 80 degrees Fahrenheit to 90 degrees Fahrenheit, results in an increased failure rate for electronic components. Estimations of the impact of this temperature increase on the reliability of large electronic systems will require extensive studies of completed designs, but the general trend can be determined from individual component failure rates. For improved electronic system reliability and availability, the temperature in Collider niches should be held at the lowest practical value.

cc: B. Abel
C. Rostamzadeh
J. Saarivirta
R. Winje

Superconducting Super Collider Laboratory

Beam Instrumentation Department - Mail Stop 4005
2550 Beckleymeade Avenue
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(214) 708-3451

MEMO: September 29, 1992

TO: Gerry Dugan, Jerry Watson, Reiner Meinke, Duane Plant, Jeff Western

FROM: Bob Webber, ASD Beam Instrumentation Department Head

RE: 90°F vs. 80°F Collider Niche Temperature

The Beam Instrumentation Department is responsible for the Precision Timing system, and the Beam Position and Beam Loss Monitoring systems in the Collider Arcs (BPMs and BLMs). Electronics for these systems are housed in the niches. The Timing system is essential for controlling beam instrumentation data acquisition and other control functions in the niches. The BPM system is crucial for Collider commissioning and for adjustments necessary to optimize colliding beam luminosity during operation. The BLM system is a crucial equipment protection (from potential beam induced damage) and magnet quench prevention system.

There is general consensus that the proposed 10°F increase in allowed niche temperature is undesirable, however we have found it difficult to actually quantify the impact in terms of decrease in reliability or cost of maintaining reliability. Let me attempt to address the impact from a slightly different perspective.

Ignoring questions of long term reliability (failure rates are exponentially related to temperature), there is little question that electronics can be designed to be functional in ambient temperatures above 90°F; witness the modern automobile. However, questions of stability, calibration, and testing must be addressed. The SSC baseline equipment cost estimate was made by accelerator scientists and engineers from the perspective that the electronics systems would operate in normal room temperature environments. Allowances are not included to address wide temperature range stability or elevated temperature testing and calibration.

One solution to tunnel cooling suggest a 35°F gradient along a half sector. While this does not require a similar differential between end niches in a half sector, it certainly allows the possibility. This requires that critical electronics in these niches have temperature stable performance over this range. The Timing, BPM, and BLM systems certainly qualify as critical electronics, since their business is to measure beam properties determined by the performance of other technical systems and to maintain sensitive thresholds to trigger beam aborts on indications of impending disastrous beam loss.

Timing, BPM, and BLM electronics systems in the Collider Arcs are valued in the BCE at approximately $10 million, including about $0.75 million for design and testing. I estimate that providing for extended temperature range testing and calibration, design effort, and component costs will add more than $1 million to the price tag (mostly due to testing.) <u>This does nothing to address long term reliability questions.</u>

Providing a 90°F tunnel/niche cooling system without significant temperature gradients from niche to niche will reduce this increase only a small fraction since most of the cost comes from elevated temperature testing as opposed to wide range stability. A cooling system to provide 80°F ambient with little gradient will save nearly all of this estimated increase; and it will simultaneously solve the problem for nearly all other systems, including those that may be overlooked if a system-by-system solution to elevated temperature operation is required.

Return-Path: rosk@rillonia
Received: by rillonia.ssc.gov (4.1/SMI-4.1)
id AA00196; Thu, 1 Oct 92 13:05:06 CDT
Date: Thu, 1 Oct 92 13:05:06 CDT
Message-Id: <9210011805.AA00196@rillonia.ssc.gov>
From: rosk@rillonia (Robert Skegg)
To: hunt rosk@rillonia
Subject: Reliability changes, 80F/90F
Cc: gurd crivello@rillonia

Steve,

I have calculated effects on failure rate due to increase in air temperature for 74LS245N (Typical VME bus driver) and Actel A10201cc (FPGA) devices. The calculations were performed using data from MIL-HDBK-217E, Military Handbook, Reliability Prediction of Electronic Equipment. Results are as follows:

BEST conditions - ambient air blown directly on device (no pre-heating) @300-400 lf/m

Device	increase in failure rate due to 80F - 90F increase	
74LS240N	28%	
A10201cc	20%	(other factors are dominating the rate)

WORST condition - ambient air pre-heated an extra 20C by other on-board heat sources, then blown directly on device @300-400 lf/m

Device	Increase in failure rate due to 80F - 90F increase (actual air change 116F - 126F)
74LS240N	27%
A10201cc	27%

I also calculated the non-blown conditions for a 74LS240N, as might be found in an un-blown, or poorly engineered VME crate.

Increase in rate due to 80F - 90F increase	Increase in rate due to 116F-126F increase (20C pre-heating)
27%	27%

I also calculated effects on tantalum capacitors and found it to be in the range 3% to 6%. Semi-conductor devices will probably dominate over-all failure rates.

Overall, the failure rate for a 74LS240N increases 53% from the blown condition at 80F to the un-blown condition with 20C pre-heat at 90F.

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Electrical Engineering

MEMORANDUM

Date: **October 2, 1992**

To: **Duane Plant**

From: **William Merz**

Subject: **Impact of Temperature Change in Niches on Collider Correctors**

The impact of the proposed temperature change is a bit difficult to assess in a real analytical way prior to the actual design of the power system for the correction elements. However, some rule of thumb features on electronic component failure rates can be pulled from a couple of sources. In particular, MIL-HDBK-217C contains detailed information on failure rates by component type. A quick summary analysis of reliability relationships exists in the 1986 Central Design Group Conceptual Design Report for the SSC, SSC-SR-2020, on pages 478-486. In the latter source, the following rule of thumb can be found; "It is possible to increase reliability an order of magnitude by lowering the temperature 40° C and a factor of two by lowering the operating temperature 10° C". The reliability effect on different types of components will vary, but in general follow this kind exponential decrease with increasing temperature. Based on this reasoning, I estimate that that a decrease in reliability of 30-50% will result if the temperature is increased 10° F. This assumes all other factors affecting reliability remain constant. This loss of reliability can be recovered by derating components, or screening and burn-in of parts, or other methods at some cost increase. This is hard to quantify at this time also. Note that the CDG CDR cited above indicates that a switch from commercial grade parts to MIL-Spec parts can cost an order of magnitude different Even if the reliability can be recovered with a 10% cost increase, this will amount to $2-3 M.

At the moment, meeting the reliability allocation for the Collider Corrector system will be one of the major challenges in developing the power supplies. Increasing the niche ambient temperature from 80° F to 90° F will only exacerbate the difficulties to be encountered. To insure success and to improve system reliability, the niche temperature should be held as low as is practical.

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Controls Group, Accelerator Division
MEMORANDUM

TO: Steve Hunt. Communications Group Leader

FROM: Sam Crivello

DATE: October 2, 1992

SUBJECT: Effects of Niche temperature on Fiber Optics equipment

cc: Duane Plant. PMO

The effects of increasing the niche temperature on the reliability of fiber optics equipment was looked into. During this brief time, I was not able to locate data from studies that would directly show the change in MTBF (Mean Time Between Failure) with a change in temperature. I was able to locate a chart which outlined the operating temperature and humidity range required to ensure reliable operation. The following paragraphs summarize this chart.

From the operations manual from one of our ADM's (fiber optic Add Drop Mux). the following warning is stated, "There is a direct relationship between air temperature and optical transceiver performance. Optical transceivers are more temperature sensitive than electrical devices."[1] For natural convection the maximum inlet air temperature/dissipation limits are broken up into two operating conditions: Standard Operating Conditions (SOC) at a range of 4 - 38 deg C and Extended Operating Conditions (EOC) at a range of 2 - 49 deg C. However, for forced convection at 2 feet per second, SOC slides to 55 deg C and EOC to 65 deg C.

It can only be stated from this chart that forced air will be required in the fiber-optic racks and optical performance may be compromised. Further information relating MTBF and BER to temperature will be sought from the vendor for future reference.

1. Alcatel ADM 250. Operations manual. ALCL 365-910-102. Issue 4. November 1990. pg02.

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Electrical Engineering Department

MEMORANDUM

Date: **October 7, 1992**

To: **Gerry Dugan**

From: **Tim Savord**

Subject: **Increase in Cost Estimate of Collider Quench Protection Electronic Components**

The 1990 Baseline Cost Estimate for Collider Quench Protection System materials and labor, excluding installation, is $29,515.2K. I have reviewed the detailed work sheets and have determined that electronic components account for $3,869.3K of the total estimate. This cost estimate is for a system that fails in a safe manner but does not have redundancy to maximize accelerator availability. The cost estimate is also based upon the use of commercial grade electronic components.

The May 13, 1991, study report from Research Analysis Corporation, titled "Reliability Analysis of the Quench Protection System for the Superconducting Super Collider Laboratory," analyzed the design of the Tevatron Quench Protection System and projected the reliability of an equivalent system for the Collider. Section 6.1 of this report address reliability improvements achievable by upgrading electronic component quality. The use of "MIL quality" components was suggested and to quote from the report, "these parts usually cost anywhere from 2 to 10 times more."

In order to compensate for increased electronic component failure rates at elevated temperatures, commercial components can be replaced with "MIL quality" components. Not all components will be available in this grade, but those that can be replaced will be from 2 to 10 times more costly. If 33% of electronic components in the Quench Protection System can be replaced with "MIL quality" devices, the estimated increase in component cost will be in the range of $2,579.4K to $12,897.0K.

cc: B. Abel
D. Plant
R. Winje

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Electrical Engineering

MEMORANDUM

Date: **October 8, 1992**

To: **Gerry Dugan**

From: **William Merz**

Subject: **Cost Impact of Niche Temperature Change on Corrector Power Supplies**

In an effort to prepare a better estimate of the cost impact of a 10° F temperature change in the niche on the Collider Correctors, I have re-examined the baseline cost estimate. This estimate assumed commercial quality components for the electronics. It was recognized at the time that for a system of several thousand power supplies, without some mitigating actions, the reliability requirement could not be met using typically achieved commercial reliability performance. For this reason, a reliability allocation was included in the estimate with no real thought as to how to spend the money. It was assumed that some combination of redundancy, derating or higher quality components would be used to reach the reliability requirement. But it was also assumed that the operating temperature would be around 25° C (77° F).

From the BCE work sheets, I find a total of about 18.8 M$ for the tunnel components of the corrector system. Removing the cable and other non applicable costs, 17.4 M$ remains. This amount does not include any labor for installation or testing, except that done by the supplier in delivering the assembled system components. If we assume about 20% of the cost of the delivered system is electronic components subject to reliability changes due to temperature, we arrive at a figure of 3.5 M$. Since all parts cannot be upgraded or need upgrading, I will assume about half of those costed to be subject to change to higher reliability parts. This amounts to upgrading of about 1.75 M$ of parts to a higher level

What does it cost to upgrade these parts from the commercial level to something with a high enough reliability to recover the 30 to 50% loss in reliability experienced due to the temperature rise? Changes from plastic packages for IC's can run from between 50 to 250% depending on the complexity of the device. Going from commercial plastic packages to MIL-Spec parts can cost anywhere from 2 to 10 times more, again dependent on the complexity of the device but also dependent the level of screening to which the device is subjected. The cost increase is due to the decrease in production yield and to the paper trail required for certification. Since it is likely that some parts will be of the ceramic variety to begin with, upgrades to MIL-Spec parts in some instances can be expected. An optimistic approach would be to assume that the average increase will amount to a factor of two. I would therefore guess that the cost impact of the temperature change to be about 1.75 M$, minimum, based on what

we know at this time.

It is clear that this analysis is fuzzy, but a better answer cannot be supplied until a more detailed design of the system is completed. It is possible that the mitigation done in the design of the system, to reach the baseline design reliability, can provide sufficient margin so that a temperature rise will not cause the system to not meet the overall specification. At the same time, it is also not clear that the baseline cost estimate contains enough money to meet the reliability specification, even without the temperature rise proposed. The conclusion is , that for this cost trade off study of cooling cost for power supply costs, we should use a value of 1.75 M$ to 15M$ for the range of possible expense. I believe that we will be at the lower end of this range in reality.

cc
D. Plant
T.Savord
R. Winje

From: Stephanie Knapp (10/7/92)
To: gurd@sscvx1
CC: Stephanie Knapp
GatorMail-Q FWD>heat in niches
Received: by qmail.ssc.gov (2.01/GatorMail-Q); 7 Oct 92 13:58:04 U
Received: by cannet.local (5.57/Ultrix3.0-C)
id AA19883; Wed, 7 Oct 92 13:54:28 -0500
From: hunt@cannet (Steve Hunt)
Message-Id: <9210071854.AA19883@cannet.local>
Subject: heat in niches
To: gurd@sscvx1
Date: Wed, 7 Oct 92 13:54:27 CDT
Cc: stephanie_knapp@qmail.ssc.gov
X-Mailer: ELM [version 2.3 PL11]

The baseline cost estimate for the Collider Controls Communications equipment that will be adversely affected by a rise in ambient temperature is $6.72M.

This figure is in 1990 dollars.

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From: Bob Webber (10/7/92)
To: Gerry Dugan
CC: webber
GatorMail-Q Beam Instrumentation electr
Received: by qmail.ssc.gov (2.01/GatorMail-Q); 7 Oct 92 13:18:12 U
Received: by hickory.ssc.gov (4.1/SMI-4.1)
id AA01204; Wed, 7 Oct 92 13:14:56 CDT
Date: Wed, 7 Oct 92 13:14:56 CDT
From: webber@hickory (Bob Webber)
Message-Id: <9210071814.AA01204@hickory.ssc.gov>
To: Gerry_dugan@qmail
Subject: Beam Instrumentation electronics in tunnel
Cc: webber

For Niche temperature arguments:

The BCE value of electronics equipment in the Collider Arc niches is $10.2M. This excludes costs for all cabling and sensor mechanics which is a part of the beamline. Total Collider Beam Instrumentation cost is $24.5M plus $4.66M of EDI. The difference between 24.5 and 10.2 includes many one of a kind items so I would prorate less than $1M of EDI toward the $10.2M of electronics.

Bob Webber

==========

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Electrical Engineering

MEMORANDUM

Date: **October 1, 1992**

To: **Duane Plant**

From: **William Merz**

Subject: **Comments on the Relocation of Collider Correctors to Surface Buildings**

This is a bad idea for many reasons. If this is an effort to reduce heat loads in the tunnel, this is clearly the wrong approach. Anyone familiar with power distribution systems understands that moving the source (power supply) farther away from the load is exactly the the opposite approach one takes if you wish to reduce losses in the system. In addition, the system cost increases for several reasons. Cabling costs will of course increase as the runs become longer. Power supply costs increase due to the increase in voltage requirements. Operating costs will increase due to the higher losses. Cooling requirements for the tunnel will increase. Additional cable tray will be required to accommodate the cable. The list goes on.

Some simple calculation results will illustrate the impact of this change.

1. Average cable run per power supply will increase from about 850 feet to about 14500 feet round trip, a factor of 17. There are about 200 power supplies per sector.
2. Since the cable resistance will increase by this same factor of 17, the voltage requirement will go from approximately 25 volts to 450 volts per power supply.
3. The cable losses will increase by the same factor. The average loss per linear foot of tunnel will go from about one watt per foot, for this system, to about 17 watts per foot. The average loss will be about 68 watts per foot in the shaft and about 34 watts per foot at the start of each half sector. The losses will decrease in a step wise fashion as each load is reached. The total heat load per half sector will increase from about 14.5 kW to about 245 kW.
4. About 8 additional cable trays will be required to hold the cable for the corrector power supplies going down the shaft. Four additional trays will be required at the start of each half sector. The number of trays will reduce along the tunnel length when sufficient numbers of cables have reached their loads.
5. A rough estimate of some of the cost impacts is as follows: Approximately $40 M in cable, $6 M in cable installation and $120 M for power supplies. These are incremental costs due to the relocation of the power supplies.

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Project Management Office/Beamlines Group

TO: Tim Toohig

FROM: Jeff Bull JB

DATE: September 29, 1992

SUBJECT: Radionuclide Release from the SSC Tunnel

I have been investigating the amount of activity released into the air and the dose equivalent to the maximally exposed individual for the three different tunnel ventilation schemes proposed by PB/MK. The nuclide production factors for the SSC tunnel were calculated by Graham Stevenson using the shielding code FLUKA, while the dose equivalent to the maximally exposed individual was determined using the EPA-approved computer code CAP88-PC.

For these calculations, the following parameters were assumed:

Linear Beam Loss:	10^4 protons/m/sec per ring
Collider Operating Time:	6000 hours per year
Collider Shaft Depth:	30.5 m (100 ft)
Tunnel Cross Sectional Area:	10 m^2
Exhaust Shaft Height:	10 m above ground level
Exhaust Shaft Diameter:	1.22 m

The design goal is such that no person should receive more than 0.1 mrem/yr effective dose equivalent from the emission of airborne radionuclides. The following table summarizes the amount of activity released and the annual dose equivalent to the maximally exposed individual.

	Option A	Option B	Option 9M
Ventilation Rate at the Shaft	70,000 cfm	40,000 cfm	11,000 cfm
Activity Released	30 Ci/yr	18 Ci/yr	5 Ci/yr
Dose Equivalent to the Maximally Exposed Individual	0.040 mrem/yr	0.040 mrem/yr	0.042 mrem/yr
Location of the Maximally Exposed Individual	250 m North	200 m North	200 m North

The breakdown of the major nuclides released is as follows: 56% ^{13}N, 26% ^{11}C, 17% ^{15}O, and 1% ^{41}Ar. All of these ventilation schemes result in approximately the same annual dose equivalent, and all of them meet the design goal.

I also investigated the effect of the stack height and diameter on the dose equivalent to the maximally exposed individual. These results are tabulated below are were calculated for ventilation option A.

Exhaust Shaft Height	5 m	10 m	20 m
Dose Equivalent to the Maximally Exposed Individual	0.080 mrem/yr	0.040 mrem/yr	0.014 mrem/yr

Exhaust Shaft Diameter	1.22 m (4 ft)	1.7 m (5.7 ft)	2.4 m (8 ft)
Dose Equivalent to the Maximally Exposed Individual	0.040 mrem/yr	0.056 mrem/yr	0.070 mrem/yr

As expected, a higher shaft decreases the dose equivalent by increasing the dispersion of the nuclides in the atmosphere before they settle back to the ground. The shaft diameter also has an effect on the dose equivalent. When the shaft diameter is decreased, the exhaust velocity increases, thus expelling the nuclides higher into the air. This in effect increases the height of the exhaust stack, and thus decreasing the maximum dose equivalent.

cc
Sam Baker
Dick Briggs
Larry Coulson
Joe Coyne
Nikolai Mokhov
Geoff Stapleton
Jeff Western